Frequency dependence and vertical structure of ocean surface kinetic energy from global high-resolution models and surface drifter observations

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Key Points:

• We examine global maps, frequency content, and vertical structure of ocean near-surface kinetic energy with drifter data and two models.
• Modeled near-inertial and tidal kinetic energy values are sensitive to wind forcing frequency and parameterized damping, respectively.
• Models capture latitude- and frequency-dependence in observed ratio of zonally averaged 0 to 15 m depth kinetic energy reasonably well.

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Abstract

The geographical variability, frequency content, and vertical structure of near-surface oceanic kinetic energy (KE) are important for air-sea interaction, marine ecosystems, operational oceanography, pollutant tracking, and interpreting remotely sensed velocity measurements. Here, KE in high-resolution global simulations (HYbrid Coordinate Ocean Model; HYCOM, and Massachusetts Institute of Technology general circulation model; MITgcm), at the sea surface (0 m) and 15 m, are respectively compared with KE from undrogued and drogued surface drifters. Global maps and zonal averages are computed for low-frequency (periods longer than 2 days), near-inertial, diurnal, and semi-diurnal bands. In the low-frequency band, near the equator, both models exhibit KE values that are too low relative to drifters. MITgcm near-inertial KE is too low, while HYCOM near-inertial KE lies closer to drifter KE, probably due to more frequently updated atmospheric forcing. In the semi-diurnal band, MITgcm KE is too high, while HYCOM lies closer to drifters, likely due to the inclusion of a parameterized topographic internal wave drag. We assess the KE vertical structure by considering the ratio of zonally averaged KE in 0 m/15 m model results and undrogued/drogued drifter results. Over most latitudes and frequency bands, model ratios track the drifter ratio to within error bars. All frequency bands except the semi-diurnal band display measurable vertical structure. Latitudinal dependence in the vertical structure is greatest in the diurnal and low-frequency bands. As in a previous comparison of HYCOM and MITgcm to current meter observations, HYCOM generally displays larger spatial correlations with the drifter observations than MITgcm does.

Plain Language Summary

It is important to map and understand ocean surface currents because they affect climate and marine ecosystems. Recent advances in global ocean models include the addition of astronomical tidal forcing alongside atmospheric forcing, and the advent of ever-more-powerful computers that can resolve ever-finer features. Consequently, high-resolution global models that include tidal forcing can simulate several types of oceanic motions with some degree of realism. Here we evaluate ocean surface currents in high-resolution simulations of two different ocean models through comparison with observations from surface drifting buoys. We examine near-inertial motions, forced by fast-changing winds, semi-diurnal tides, forced by the astronomical tidal potential, diurnal motions, arising from tidal and other sources, and low-frequency currents and eddies, forced by atmospheric fields. Global patterns in the models and drifters are broadly consistent. The two models differ in their degree of proximity to drifter measurements in the near-inertial band, most likely due to different update intervals for atmospheric forcing, and in the semi-diurnal band, most likely due to different damping schemes. The vertical structure of the currents, as measured by drifter flows at the surface vs. 15 meters depth, is tracked reasonably well by the models, although differences are found in some frequency bands.

1 Introduction

Oceanic surface currents are relevant for a range of multi-disciplinary scientific topics and operational applications (Elipot & Wenegrat, 2021). For instance, surface currents are major actors in two crucial components of the climate system, the air-sea transition zone (Cronin & Coauthors, 2019) and marine ecosystems (Lévy et al., 2018). Maps of surface currents are useful for understanding ocean dynamics, assessing operational ocean modeling, enabling search-and-rescue missions, and tracking oil spills, plastics, and other marine pollutants. Many of these applications, including predicting Lagrangian trajectories of water parcels in the near-surface ocean, understanding air-sea transfer, and others, require knowledge not only of currents but also their vertical structure near the oceanic surface (Olascoaga et al., 2020).
Despite the importance of near-surface currents, not enough is known about their space-time variability. Here, we examine geographical maps, frequency content, and vertical structure of near-surface velocity variance (KE), in two different high-resolution global ocean models and in observations from NOAA’s Global Drifter Program (GDP). Our quantification of vertical structure on a global scale is novel. The three-way comparison between two models and drifter observations points towards improvements that need to be made in the models and in interpretations of drifter data.

Mapping near-surface oceanic currents on a global scale is a formidable task. Quantifying high-frequency motions such as near-inertial flows (e.g., Pollard & Millard, 1970; Alford, 2003a, 2003b; Furuichi et al., 2008; Chaigneau et al., 2008; Simmons & Alford, 2012), semi-diurnal and diurnal tides, and the internal gravity wave continuum (Garrett & Munk, 1975) requires high-frequency sampling (e.g., at approximately hourly intervals). Time series from moored current meters can be used to separate high-frequency motions from lower-frequency motions including Ekman flows, mesoscale eddies, and the oceanic general circulation. Another advantage of mooring lines is the delivery of observations below the ocean surface. However, moored data are expensive to deploy and are available only at a relatively small number of geographical locations (see, e.g., Figure 1 of Luecke et al., 2020). Global-scale surface currents can be computed from satellite altimeter measurements of sea-surface height (SSH), providing that tides are removed and the geostrophic assumption is applied to the tide-corrected SSH fields. However, altimetry cannot detect near-inertial or Ekman flows, due to the negligible SSH signal in these motions. Altimetry measurements are also infrequent in time; the repeat time of the TOPEX/Jason series, for instance, is about 10 days. The geostrophic velocities computed from altimetry leave out high-frequency contributions to the velocity and hence KE fields.

The drifting buoys, or drifters, of the GDP (Lumpkin et al., 2017) yield a global dataset of near-surface ocean velocity in situ estimates. The drifter dataset allows for division of KE into several frequency bands, e.g., low-frequency, near-inertial, diurnal, and semi-diurnal, and has been used in many previous studies of oceanic flows. Maximenko et al. (2009) mapped the mean dynamic topography with drifters. Elipot and Gille (2009) used drifters to examine Ekman flows in the Southern Ocean. Thoppil et al. (2011) found relatively close agreement in low-frequency KE between high-resolution global simulations of the HYbrid Coordinate Ocean Model (HYCOM; Chassignet et al., 2009), the backbone operational model of the US Navy, and drifters. Recently, drifters have also been used to quantify high-frequency motions such as tides (Poulain & Centurioni, 2015). Kodaira et al. (2015) compared M2 tidal currents in a multi-layer tide model (without atmospheric forcing) to currents inferred from drifters. Zaron and Elipot (2021) found generally good agreement between tidal currents in satellite-altimetry constrained tidal models and drifters. Elipot et al. (2016) derived an hourly drifter product and demonstrated that it resolves motions at a wide range of frequencies. Yu et al. (2019) compared KE, over various low- and high-frequency bands, from the hourly drifter dataset and output from a high-resolution Massachusetts Institute of Technology general circulation model (MITgcm; Marshall et al., 1997) simulation, designated as LLC4320 and described in more detail in section 2.2.

The model-data comparison in Yu et al. (2019), performed over a wide range of frequency bands, was made possible by the emergence of a new class of high-resolution global ocean models that simultaneously include astronomical tidal forcing and atmospheric forcing (e.g., Arbic et al., 2010, 2012, 2018; Buijsman et al., 2020; Müller et al., 2012; Waterhouse et al., 2014; Rocha, Chereskin, et al., 2016; Rocha, Gille, et al., 2016). In these models, internal tides and mesoscale eddies co-exist and interact (Shriver et al., 2014; Buijsman et al., 2017; Nelson et al., 2019). As shown first in Müller et al. (2015) and later in other studies (e.g., Rocha, Chereskin, et al., 2016; Savage et al., 2017a, 2017b; Qiu et al., 2018; Torres et al., 2018; Luecke et al., 2020), such models are beginning to partially
resolve the internal gravity wave (IGW) continuum (Garrett-Munk spectrum; Garrett & Munk, 1975).

Global IGW models, especially HYCOM and MITgcm LLC4320, have been widely used by the community, to plan for field campaigns (e.g., J. Wang et al., 2018), understand interactions between motions at different length and time scales (e.g., Pan et al., 2020), and provide boundary forcing for higher-resolution regional models (Nelson et al., 2020). HYCOM and MITgcm LLC4320 have been used to quantify the relative contributions of low- and high-frequency motions to SSH and KE as a function of geographical location (e.g., Richman et al., 2012; Savage et al., 2017a, 2017b; Rocha, Chereskin, et al., 2016; Rocha, Gille, et al., 2016; Qiu et al., 2018; Torres et al., 2018). The energetics of different classes of oceanic motions are of interest in their own right (Ferrari & Wunsch, 2009). Global IGW models offer the potential for examining energy exchanges between different classes of oceanic motions, as has been seen in observations (Le Boyer & Alford, 2021). Quantitative mapping of low- and high-frequency motions is important for satellite missions including the Surface Water Ocean Topography (SWOT) mission (Morrow et al., 2019), planned for launch in 2022, which will measure SSH at high resolution in two-dimensional swaths. Remote sensing missions focused on measuring near-surface ocean velocities, such as the existing airborne Sub-Mesoscale Ocean Dynamics Experiment (S-MODE) mission (Rodriguez et al., 2020), the proposed Sea surface Kinematics Multiscale monitoring mission (SKIM; Ardhuin et al., 2019) and the proposed Winds And Currents Mission (WACM; Rodriguez et al., 2020), will benefit from quantification of high- and low-frequency KE as well.

Because HYCOM and MITgcm LLC4320 are widely used, it is important to compare these models to observations. A summary of early model comparisons of HYCOM and MITgcm LLC4320 tidal simulations with observations is provided in Arbic et al. (2018). Up to that point, HYCOM, and to a lesser extent MITgcm LLC4320, had been compared to time-series observations from moored instruments, and global maps of SSH from satellite altimetry. IGW results from MITgcm LLC4320 have also been compared to along-track Acoustic Doppler Current Profiler (ADCP) data (Rocha, Chereskin, et al., 2016; Chereskin et al., 2019).

This paper uses model and drifter comparisons to focus on the geographic variability, frequency content, and vertical structure of near-surface KE. Yu et al. (2019) showed that LLC4320 semi-diurnal tidal KE was too strong, and near-inertial KE too weak, relative to drifter observations. Here, we build upon the Yu et al. (2019) study through intercomparison of HYCOM, MITgcm LLC4320, and drifters. The HYCOM and MITgcm LLC4320 simulations differ in several respects, and we anticipate that they will perform differently in comparisons to drifters. We especially anticipate differences in the near-inertial bands, due to more frequent updates of the wind fields in HYCOM (3 hours) relative to MITgcm LLC4320 (6 hours), and in the semi-diurnal tidal band, due to the lack of a parameterized topographic wave drag in MITgcm LLC4320. In HYCOM simulations, a parameterized topographic internal wave drag is included in order to roughly account for the damping of tidal motions due to breaking small-scale internal tides that are unresolved in global models (Arbic et al., 2010, 2018; Ansong et al., 2015; Buijsman et al., 2016, 2020). Ansong et al. (2015) demonstrated that the SSH signature of internal tides in HYCOM is closer to altimetry observations when the HYCOM simulations contain a wave drag than when they do not contain a wave drag. Here we examine the impact of including wave drag (as in HYCOM) vs. excluding it (as in LLC4320) on near-surface semi-diurnal KE. A better quantification of the vertical structure of near-surface currents will aid our understanding of the air-sea exchange of heat, momentum, and gases, and of the dispersal of pollutants and biologically important tracers (Elipot & Wenegrat, 2021). The vertical structure of velocity has important implications for the ongoing S-MODE airborne mission and proposed satellite missions focusing on surface ocean velocity measurements (Ardhuin et al., 2019; Rodriguez et al., 2020). These missions will
need information on the frequency dependence of vertical structure in order to interpret the implications of surface current measurements for subsurface oceanic conditions.

To our knowledge, a detailed global examination of the vertical structure of near-surface KE, for both high- and low-frequency motions, has not been done before. As in Yu et al. (2019), we use both undrogued and drogued drifters which provide estimates of oceanic velocity at 0 m (sea surface) and 15 m, respectively. Accordingly, we compare model results at 0 m to undrogued drifter results, and model results at 15 m to drogued drifter results. We also compute the ratio of zonally averaged KE in undrogued drifters to zonally averaged KE in drogued drifters, and compare the drifter ratio to the ratio of zonally averaged 0 m KE to zonally averaged 15 m KE in the models. Error bars on the drifter ratios are large, especially for near-inertial and tidal motions, and windage (erroneous slips of water past drifters) are a known problem in undrogued drifter observations (Section 2.3). Nevertheless, clear vertical structure is seen in all of the frequency bands except the semi-diurnal band, and the model ratios, which suffer from completely different biases and errors, follow the drifter ratio over most latitudes and most frequency bands. We provide some discussion on the causes of the vertical structure. The vertical structure of the diurnal band is especially interesting because of the multiple forcing mechanisms in this band (diurnal tides, wind-forced near-inertial waves which overlap with the diurnal band near 30° latitude, and diurnal cycling of Ekman and submesoscale flows).

2 Data and Methods

2.1 HYCOM simulation

The global HYCOM simulations employ nominal 1/25° horizontal grid spacing and 41 hybrid layers (Bleck, 2002) covering the vertical direction. HYCOM employs terrain-following coordinates in shallow waters, and isopycnal coordinates in the subsurface open-ocean. In the near-surface open-ocean, the uppermost 14 layers are in z-mode, with seven z-levels, having spacing ranging from 1.00 to 6.87 m, in the uppermost 30 m. The HYCOM “0 m” (surface) results actually represent the mid-point of the uppermost layer. The HYCOM “15 m” results represent interpolations to 15 m. The interpolation largely reflects results from the HYCOM level at 13.185 m, which lies in between adjacent levels at 8.38 and 18.55 m; the latter three depth values represent mid-depth points of the respective vertical layers in which they lie. HYCOM employs the widely used K profile parameterization (KPP) scheme (Large et al., 1994) for vertical mixing. Atmospheric forcing fields from the U.S. Navy Global Environmental Model (Hogan et al., 2014) are applied every three hours. We use a 360-day record of hourly snapshots of surface and 15-meter horizontal velocity fields, starting on 1 January 2014, and produced with a 75 second baroclinic timestep.

HYCOM’s tidal forcing includes the two largest diurnal components (K_1 and O_1) and the three largest semi-diurnal components (M_2, S_2, and N_2). The self-attraction and loading (SAL) term is taken from the altimetry-constrained TPXO8 barotropic tide model (Egbert et al., 1994; Egbert & Erofeeva, 2002). The HYCOM parameterized topographic wave drag scheme, taken from Jayne and St. Laurent (2001), is tuned to minimize the M_2 surface elevation errors with respect to TPXO8. Following Ngodock et al. (2016), an Augmented State Ensemble Kalman Filter (ASEnKF) reduces the area-weighted error of the surface tidal elevations, computed with respect to TPXO8 in waters deeper than 1000 m and latitudes equatorward of 66°, to 2.6 cm.

2.2 MITgcm LLC4320 simulation

LLC4320 is a global MITgcm simulation with nominal 1/48° horizontal grid spacing and 90 vertical z-levels. There are 13 z-levels in the uppermost 30 m, with thickness
ranging from 1.0 to 4.6 m. The LLC4320 “15 m” velocities are taken from the 9th grid cell from the surface, which spans 13.26 to 16.1 m depth. LLC4320 also employs the KPP vertical mixing scheme. LLC4320 is forced by the full luni-solar astronomical tidal potential and by six-hourly atmospheric fields from the 0.14° European Centre for Medium-Range Weather Forecasting (ECMWF) operational model analysis, starting in 2011. The LLC4320 baroclinic time step is 25 s. We use a year-long record of near-surface horizontal velocity fields, saved as hourly snapshots and starting on 12 November 2011.

We have found that the tidal forcing in the LLC4320 simulation has been overestimated by a factor of 1.1121, while the self-attraction and loading (SAL) term (SAL; Hendershott, 1972; Ray, 1998) has been inadvertently omitted. The effects of these errors in the tidal forcing on tides in the LLC4320 simulation will be reported in detail elsewhere. In the results shown here, the LLC4320 KE in semi-diurnal and diurnal bands are not corrected for these effects. In short, the overly large tidal forcing is not enough to explain discrepancies between LLC4320 and drifter observations. As noted above, the MITgcm LLC4320 simulations do not employ a parameterized topographic wave drag.

2.3 Ocean Surface Drifters

In-situ estimates of ocean near-surface velocities are obtained from the NOAA’s GDP (Lumpkin et al., 2017) which maintains an array of surface drifting buoys, currently tracked by the Global Positioning System and previously by the Argos system. We use version 1.04c of the hourly high-frequency dataset (Elipot et al., 2016) containing 17,324 individual surface drifter trajectories from October 1987 to June 2020, totalling ~166M estimates of hourly positions and velocities. The spatial coverage of the drifter dataset is global, yet inhomogeneous with higher data density in convergence zones in the middle of ocean gyres and sparse observations at the equator due to Ekman divergence, which tends to disperse drifters away (Elipot et al., 2016).

Drifter data are intrinsically Lagrangian, in contrast to the Eulerian model output that we compare to the drifter results. Nevertheless, segments of velocity time series from drifters are considered to estimate kinetic energy locally; we assign the mean geographical position of a trajectory segment to each estimate before bin averaging. Lagrangian sampling leads to spectral smearing as drifters convolve spatial and temporal oceanic variability (Yu et al., 2019; Zaron & Elipot, 2021). Lagrangian spectra have lower and wider tidal peaks, which do not stand above the background as much as peaks in Eulerian spectra do. In addition, tidal lines in both Lagrangian and Eulerian spectra widen due to interaction with currents and eddies, which renders the tides less coherent or stationary (e.g., Ray & Zaron, 2011; Shriver et al., 2014; Zaron & Egbert, 2014; Ponte & Klein, 2015; Kerry et al., 2016; Buijsman et al., 2017; Savage et al., 2017a; Zaron, 2017; Nelson et al., 2019).

We utilize both drogued and undrogued drifter data, in waters deeper than 500 m. Drogued drifter displacements, which comprise 48% of the trajectories in the dataset, are expected to be representative of ocean velocity at 15-m depth with an estimated erroneous slip of the water past the drifter of 0.7 cm s\(^{-1}\) downwind per 10 m s\(^{-1}\) wind speed (Niiler & Paduan, 1995). Undrogued drifters, which comprise 52% of the dataset, are expected to represent ocean velocities at the surface (0 m), but with a slip of an order of magnitude larger compared to drogued drifters [8.6 cm s\(^{-1}\) per 10 m s\(^{-1}\) wind speed, (Lumpkin & Pazos, 2007)]. As such, undrogued drifter observations likely exhibit larger downwind velocity errors but these are yet to be comprehensively distinguished from real oceanic processes. For example, locally wind-driven velocities at the surface are more energetic than at 15-m depth because of vertical shear at a broad range of frequencies through Ekman dynamics (Elipot & Gille, 2009; Lilly & Elipot, 2021), or through surface gravity wave processes and their associated Stokes drift (Polton et al., 2005). Yet, undrogued drifters qualitatively capture the same KE features as drogued drifters (Yu –6–
et al., 2019). In particular, as shown by Yu et al. (2019) and further confirmed here, results are nearly identical in the semi-diurnal band, suggesting that a correction for the wind slip or an adequate assessment of its magnitude would need to be informed by an unknown dependency on frequency and to take into account the entire frequency spectrum of the observable wind forcing. In addition, typical estimation errors for the hourly drifter velocity estimates (Elipot et al., 2016) are between 2 and 5 cm s\(^{-1}\) (see Figure S2 of Yu et al., 2019) with unknown frequency distribution. As such, a comprehensive assessment of the velocity errors from drogued and undrogued drifters, and how these errors affect kinetic energy estimates in various frequency bands, is beyond the scope of this study. The general agreement of the vertical structure ratio in models and drifters, seen in spatial maps and zonal averages, supplies some confidence that the vertical structure ratio computed from drifters is meaningful, noisy though it may be.

2.4 Frequency Rotary Spectra

As in Yu et al. (2019), we compute frequency rotary spectra (Gonella, 1972; Mooers, 1973) of model and drifter velocities. Frequency rotary spectra allow us to decompose velocity variance as a function of frequency, and to separate clockwise versus counterclockwise motions. This clockwise vs. counterclockwise separation is especially important in the case of near-inertial oscillations. Velocity time series are split into 60-day segments overlapping by 50%, detrended, and multiplied by a Hann window. The discrete Fourier transform of \(u+iv\), where \(u\) and \(v\) respectively denote the zonal and meridional velocity components, is then computed for each segment. The Fourier coefficients are multiplied by their complex conjugates to form spectral estimates which are then averaged over segments and multiplied by a factor that accounts for variance lost to the Hann window operation. Following Yu et al. (2019), the velocity variance, which is decomposed as a function of frequency in the spectra, is interpreted as kinetic energy; no factor of 1/2 is included in our KE calculations.

Also as in Yu et al. (2019), the rotary spectra are integrated over specific frequency bands: semi-diurnal (\(\pm[1.9, 2.1]\) cpd), diurnal (\(\pm[0.9, 1.1]\) cpd), high frequency (> 0.5 cpd and < −0.5 cpd), and near-inertial (\(\pm[0.9, 1.1]\) f, where \(f\) is Coriolis frequency). Low-frequency kinetic energy is taken as total kinetic energy, computed as the time-mean of the squares of the zonal velocity time series plus the time-mean of the squares of the meridional velocity time series, minus high-frequency kinetic energy, the latter computed from the spectra.

Our definitions of the bands present some challenges for near-inertial motions. First, the near-inertial band as defined above covers only the “local” near-inertial KE. Near-inertial motions, like low-mode internal tides, can propagate over long distances (Alford, 2003a; Simmons & Alford, 2012), and in such cases their frequency is no longer equal to the local value of \(f\). Second, our analysis, like that of Yu et al. (2019), does not distinguish between near-inertial and diurnal motions where the definitions of these bands overlap, namely, within 24.1-37.5° of latitude.

3 Results

In order to characterize KE and its vertical structure, we consider zonally and globally averaged velocity rotary spectra (Elipot & Lumpkin, 2008), geographical 1° by 1° maps of KE calculated by integrating spectra over the frequency bands defined earlier, and zonal averages of these KE maps. Thus, all of the results shown in this paper represent spatial averages. To reduce computational time, model outputs are first subsampled on 1/4° grids (without performing any spatial averaging) before computing spectra and applying spatial averaging. Spatial averages are only computed when more than 50% of the points in a 1° by 1° bin are deeper than 500 m, and shallower gridpoints are discarded in the computation. The drifter averages are computed in a similar manner.
Zonally-averaged rotary spectra for undrogued and drogued drifters, and at 0 m and 15 m in the models, visualized as a function of frequency and latitude, display relatively similar KE levels and structures (Figure 1). Peaks corresponding to diurnal frequencies (near ± 1 cpd) and semi-diurnal frequencies (near ± 2 cpd), and a large low-frequency continuum (near 0 cpd) are evident in all six subplots. Ridges of near-inertial energy, which follow the negative of the Coriolis frequency, from ~1.7 cpd at 60°N to ~1.7 cpd at 60°S, are also evident in all six subplots of Figure 1. Near 30° latitude, the inertial ridge overlaps with the diurnal peaks in the anticyclonic domain (at negative frequencies in the northern hemisphere, and positive frequencies in the southern hemisphere). The low-frequency peak, around zero cycles per day, is broader in frequency in the drifters than in the models. The models exhibit semi-diurnal tidal peaks that rise above the background more dramatically than the peaks in the drifter spectra. The models also display a “peaky” or “picket fence” distribution of energy at high-frequency tidal harmonics, with little energy in between the harmonics, as noted in previous studies (e.g., Müller et al., 2015; Savage et al., 2017b). In contrast, the drifter tidal peaks do not stand out above the background as strongly as in the models, as discussed earlier and in Zaron and Elipot (2021).

Another faint but striking feature of these latitude-frequency rotary spectra is the presence of translated images of the near-inertial ridge at −f ± 1, 2, 3 cpd in both the drifter spectra and in the model spectra. The model spectra additionally exhibit mirror images of the inertial ridge at f ± 0, 1, 2, 3 cpd. These features were previously seen in a similar figure in Yu et al. (2019) for drifters and MITgcm LLC4320, and for drifter data only in Elipot et al. (2016) up to 12 cpd. Elipot et al. (2016) speculated that these features may be representative of small departures from circular geometry for inertial oscillations, or of triad interactions between near-inertial waves and internal waves at tidal frequencies, but also noted that their magnitudes depended to some extent upon the processing applied to the drifter data to obtain hourly velocity estimates. The fact that these features are also observed in the models suggest that they might be representative of real, as yet uncharacterized, oceanic processes.

The relative energy levels in the different bands are more easily compared in globally averaged rotary spectra, for which the anticyclonic domain is assigned here to positive frequencies and the cyclonic domain to negative frequencies, as in the southern hemisphere (Figure 2). The highest energy levels, associated with large-scale currents, mesoscale eddies, and Ekman flows, are seen in high and wide peaks at low frequencies (around zero). Whereas the near-inertial anticyclonic ridge is clearly visible in frequency-latitude spectra (Figure 1), in globally averaged spectra, that ridge is instead spread unevenly between 0 and 1.7 cpd in the anticyclonic frequency domain, weighted by the latitudinal distribution of the spectral estimates. As a result, energy levels are generally higher below the semi-diurnal frequency band in the anticyclonic domain than in the cyclonic domain. Semi-diurnal and diurnal tidal peaks are clearly visible in both the model and drifter spectra but rise above the background much less in the drifter spectra than in the model spectra, as is made especially clear in the insets of Figure 2. The insets illustrate the wider and lower semi-diurnal tidal peaks in Lagrangian spectra in comparison to Eulerian spectra. As noted earlier, in the higher frequency part (e.g., > 2 cpd) of the IGW continuum, spectra are much peakier in the models, especially HYCOM. The IGW continuum falls off more steeply in HYCOM than in MITgcm LLC4320, because of the lower resolution (coarser grid spacings) in HYCOM. The continuum is more elevated and smoother in the drifter spectra, and displays a noise floor at 12 cpd which is about one decade higher than MITgcm LLC4320, and more than two decades higher than HYCOM. This noise floor depends on the tracking-system for drifters: as shown by Yu et al. (2019), when only GPS-tracked drifters are considered instead of Argos-tracked drifters (Elipot et al., 2016), the spectral level and spectral slope at the highest frequencies for drifter spectra is in approximate agreement with MITgcm LLC4320 (see Figure 2 of Yu et al. (2019)). Many small but distinct spectral peaks that do not necessarily correspond to tidal constituents.
Figure 1. Zonally averaged rotary spectra of KE in 1° latitude bins between 60°S and 60°N for undrogued and drogued drifters (panels a and b), for HYCOM at 0 m and 15 m (panels c and d), and for MITgcm LLC4320 at 0 m and 15 m (panels e and f). Only frequencies between -5 and 5 cycle per day (cpd) are displayed. The frequency resolution is 1/60 cpd. The common decimal logarithmic color scale is displayed at the bottom right.
Figure 2. Globally averaged rotary spectra of KE from undrogued and drogued drifters (red curves), from 0 m and 15 m HYCOM (blue curves), and from 0 m and 15 m MITgcm LLC4320 (green curves). Anticyclonic and cyclonic frequencies are assigned to positive and negative frequencies, respectively. The vertical gray lines indicate 145 tidal frequencies in both positive and negative frequency domains. The two insets show the same spectra but with a focus on diurnal and semidiurnal anticyclonic frequencies (right) and cyclonic frequencies (left). The vertical dotted lines in the insets show the $O_1$, $K_1$, $M_2$, and $S_2$ frequencies.

are seen in the drifter spectra for frequencies higher than 4 cpd. The amplitude and frequency of these peaks depend also on the drifter tracking system (see Figure 2 of Yu et al. (2019)) and may be artifacts of the estimation methods for drifter position and velocities (Elipot et al., 2016).

3.1 Low-frequency KE

Global maps of low-frequency KE highlight well-known large-scale currents and the mesoscale eddies they spawn, both of which are dominant in equatorial regions, western boundary current regions such as the Gulf Stream and Kuroshio, and the Antarctic Circumpolar Current (Figure 3, panels a-f). Low-frequency Ekman flows also contribute to these surface and near-surface patterns (Lumpkin & Johnson, 2013). At both depth levels, HYCOM overestimates the drifter observations in the near-equatorial southern Indian Ocean and in the Pacific off the Western coast of South America, while MITgcm LLC4320 overestimates the drifters in the eastern North Atlantic Ocean and parts of the Southern Ocean. MITgcm LLC4320 also features an incorrect positioning of the Gulf Stream, which does not veer to the northeast as it does in HYCOM and the drifters. The same Gulf Stream patterns were noted in surface velocities computed from satel-
Figure 3. Global maps of low-frequency (> -0.5 cpd and < 0.5 cpd) kinetic energy (KE) from undrogued and drogued drifters (panels a and d), from HYCOM at 0 m and 15 m (panels b and e), and from MITgcm LLC4320 at 0 m and 15 m (panels c and f). The ratios of undrogued to drogued drifter KE, and 0 m to 15 m KE for the HYCOM and MITgcm LLC4320 simulations are shown in panels g, h, and i, respectively. Note the decimal logarithmic color scale for the ratio maps. The spatial correlations between the drifter maps and HYCOM and MITgcm LLC4320 maps are indicated in the upper left corners of panels a, d, and g, with HYCOM values in blue to the left of MITgcm LLC4320 values in green. The spatial correlations between HYCOM and MITgcm LLC4320 maps are indicated in the upper left corners of panels b, e, and h.

Despite these local differences, the correlations between all these maps (∼0.70) indicate the same level of global spatial agreement between the results from drifters and the models on one hand, and between the results from two models on the other hand.

Maps of the ratio of undrogued to drogued KE (Figure 3, panel g) and the ratio of 0 m to 15 m KE in the models (Figure 3, panels h-i) display some similarities, despite the noisiness inherent in the drifter map. The mid- to high-latitude northeast and southeast Pacific Ocean, for instance, display relatively large values of the ratio in all three maps. In the near-equatorial Pacific relatively low values of this ratio are seen in all three maps. The spatial correlation between the model ratio maps (0.51) is significantly higher than the spatial correlation between either model and the drifters. The HYCOM correlation with the drifter ratio map (0.37) is slightly higher than the MITgcm LLC4320 correlation with the drifters (0.33).

Zonally averaged low-frequency KE in both models is generally comparable to, but lower than, drifter KE (Figure 4, panels a and b). The models and drifters all exhibit a peak of energy at the equator, but the peak values in HYCOM and especially MIT-
gcm LLC4320 are too low, the latter by a factor of about two. This disagreement between models and drifters near the equator should be interpreted with caution as the sampling density from drifters near the equator is low (Figure 3, panels a and d). In the mid- to high-latitudes of the southern hemisphere, MITgcm LLC4320 lies closer to drifter observations while HYCOM KE is too low. With the exception of the energetic peak near 35°N, over most mid- to high-latitudes in the northern hemisphere, both models are too low.

The ratios of zonally averaged model 0 m KE to zonally averaged model 15 m KE track the corresponding ratios in the drifters (zonally averaged undrogued drifter KE to zonally averaged drogued drifter KE) reasonably well (to within error bars) over most latitudes (Figure 4c). Maximum values of the KE ratio are seen at high latitudes in both hemispheres in the drifters and in HYCOM, whereas MITgcm LLC4320 does not track this high-latitude behavior. Neither model tracks the relatively high drifter ratios between about 15-30°S well. We speculate that the poor agreement in this latitude band may be due to a relative lack of drogued drifter data in the South Pacific, which could introduce a bias in the ratios. The greater energy in the undrogued drifters over most latitudes (represented by values of the ratio greater than one) may be due in part to their wind bias as noted earlier. However, the relative closeness of this KE ratio in results from models, which do not suffer from a wind bias, to the drifter results suggests that wind bias alone is unlikely to account for all of the vertical structure seen in Figure 4c.

### 3.2 Near-inertial KE

Near-inertial KE is generally larger in mid-to-high latitudes than it is near the equator for both observational and model results, with the largest values found in the north Pacific (Figure 5, panels a-f), as shown in previous studies (e.g., Alford, 2003b; Chaigneau et al., 2008; Elipot et al., 2010). Faint but distinct relative maxima of KE are evident in the maps for the models around 30° where our analysis picks up tidal motions and wind-driven inertial motions that are both near-diurnal at that latitude. MITgcm LLC4320 systematically underestimates the drifter results over most of the ocean, while HYCOM is in generally better agreement though it still underestimates the drifter results in the northern Pacific. Near-inertial KE is conspicuously lacking in MITgcm LLC4320 over the Antarctic Circumpolar Current south of 45°S. In both models, near meridional streaks of near-inertial KE stand out, probably related to individual tropical cyclones and storms present in the model forcing fields within their respective integration years. The drifter maps do not show such features which should be averaged out by the many years of drifter data used for this analysis. The different forcing years of the models and the multi-year nature of the drifter dataset may explain why the spatial correlations between these maps at both levels are lower than seen in, for instance, the low-frequency band; the two model maps correlate at 0.60 at the surface and at 0.58 at 15 m depth. The drifter maps correlate with the model maps at approximately equivalent levels, albeit slightly better in HYCOM compared to MITgcm LLC4320 (0.60 versus 0.51 at the surface, and 0.54 versus 0.45 at 15 m).

The ratio maps for the two models appear similar but exhibit relatively low correlation between them (0.48). They both indicate that near-inertial KE is slightly larger at the surface compared to 15 m. Some unexplained discontinuities in these maps are noticeable near 30° latitude which may be due to overlapping dynamical processes of a different nature taking place there (tidal vs. wind-driven). The ratio map for the drifters is extremely noisy, and exhibits very low correlation with the model ratio maps.

In the zonal averages (Figure 6), as anticipated from the global maps, near-inertial KE is significantly higher in HYCOM than in MITgcm LLC4320, up to a factor larger than 4.5 at 54.5° S at the surface and at 15 m. As noted before, this discrepancy in model near-inertial KE levels may arise from the lower-frequency wind forcing in MITgcm LLC4320.
Figure 4. Zonally averaged low-frequency (> -0.5 cpd and < 0.5 cpd) kinetic energy (KE) from (a) undrogued drifters and 0 m model levels, and (b) drogued drifters and 15 m model levels. Ratios of zonal averages of undrogued/drogued drifter KE, and 0 m/15 m model KE, are shown in (c). The gray shaded region in each panel indicates the latitudes where the near-inertial and low-frequency bands exhibit some overlap (see Fig. 1). The shading around each curve corresponds to two standard errors of the calculated 1° zonal averages from the geographical maps.
Figure 5. Global maps of near-inertial (±[0.9, 1.1]f) KE from undrogued and drogued drifters (panels a and d), from HYCOM at 0 m and 15 m (panels b and e), and from MITgcm LLC4320 at 0 m and 15 m (panels c and f). The ratios of undrogued to drogued drifter KE, and 0 m to 15 m KE for the HYCOM and MITgcm LLC4320 simulations are shown in panels g, h, and i, respectively. Note the decimal logarithmic color scale for the ratio maps. The spatial correlations between the drifter maps and HYCOM and MITgcm LLC4320 maps are indicated in the upper left corners of panels a, d, and g, with HYCOM values in blue to the left of MITgcm LLC4320 values in green. The spatial correlations between HYCOM and MITgcm LLC4320 maps are indicated in the upper left corners of panels b, e, and h.
(6 hours) compared to HYCOM (3-hour). Rimac et al. (2013) demonstrated that near-inertial KE in models is highly sensitive to coupling period, with hourly forcing yielding KE three times higher than 6-hourly forcing. Flexas et al. (2019) found relatively low wind-power input to the near-inertial motions in MITgcm LLC4320, due to the 6-hourly updates in the wind forcing. Near-inertial KE in HYCOM follows the drifters relatively well in the northern hemisphere between about 10-30°N and in the southern hemisphere. In the southern hemisphere, at the surface, the undrogued drifter near-inertial KE is however systematically slightly higher than HYCOM, perhaps because of underestimated windage of the undrogued drifters within strong wind environments. In contrast, at 15-m depth, HYCOM is in closer agreement with the drogued drifters in the southern hemisphere. At latitudes between about 35-60°N, HYCOM KE values, though closer to the drifters than MITgcm LLC4320 values are, are still substantially lower than the drifters. Separation of the zonal averages into basins demonstrates that the main cause of the discrepancy is located in the North Pacific Ocean (Figure 7). The reasons for the North Pacific discrepancy in HYCOM are unclear, but may be related in part to the 3-hourly coupling period of the NAVGEM atmospheric model to HYCOM, which, though more frequent than the 6 hour coupling period for MITgcm LLC4320, may still be insufficiently frequent. Another potential cause of the discrepancy is that the model outputs are of one year duration, while the drifter data span multiple years. However, separation of the drifter data into different years (not shown) produced year-to-year differences in the zonal averages that are much smaller than the differences between the models and drifters seen in Figure 7a.

The ratios of zonally averaged undrogued to drogued drifter KE are still noisy, but are consistently between about 1 and 2, except in a few latitude bands (Figure 6c). Over most latitudes, the ratio of 0 m to 15 m KE in both models follows the drifter ratios relatively well, within error bars. The model ratios are larger than one, but are generally not much larger than one–values of 1.1 are typical.

### 3.3 Diurnal KE

The most energetic common spatial feature of the diurnal KE maps for the drifters, HYCOM, and MITgcm LLC4320 at both depth levels (Figure 8, panels a to f) corresponds to wind-driven near-inertial motions around ±30° latitude. Another common spatial feature is a global pattern associated with baroclinic tidal energy constrained equatorward of ~30°. The latter pattern is clearly seen in the models, but is less visible in the drifters because of the higher noise level in drifter data. The drifters however seem to capture well-known diurnal internal tide hotspots such as in the western north Pacific. Compared to HYCOM, MITgcm LLC4320 seems to underestimate the wind-driven motions, probably because of its less frequent wind forcing (6-hourly compared to 3-hourly). In contrast, MITgcm LLC4320 seems to overestimate the tidally-forced diurnal motions, probably because of its lack of parameterized topographic wave drag. HYCOM does include a wave drag, but the drag is tuned for semi-diurnal tides, not diurnal tides, which may as a result be over-damped. Some faint but distinguishable diurnal KE features exist at both depth levels along the Agulhas Return Current and the Antarctic Circumpolar Current, in both models but not in the drifter maps, perhaps because of the noise level and poor sampling. The spatial correlations at both levels between models (0.76 and 0.75) indicate that the models capture similar KE patterns. At both depth levels, the spatial correlations between the drifter results and the model results suggest that HYCOM better captures the observations (0.80 and 0.84) than MITgcm LLC4320 does (0.61 and 0.69).

The KE depth ratio maps for the models (Figure 8, panels h and i) are generally similar, allowing us to distinguish wind-driven diurnal motions with low shear around ±30°, but otherwise exhibit a modest correlation between each other (0.54). The mod-
Figure 6. Zonally averaged near-inertial (±[0.9, 1.1]f) KE from (a) undrogued drifters and 0 m model levels, and (b) drogued drifters and 15 m model levels. Ratios of zonal averages of undrogued/drogued drifter KE, and 0 m/15 m model KE, are shown in (c). The gray shaded region in each panel indicates the latitudes where the near-inertial and low-frequency bands exhibit some overlap (see Fig. 1). The shading around each curve corresponds to two standard errors of the calculated 1° zonal averages from the geographical maps.
Figure 7. Zonally averaged near-inertial KE, as in Fig. 6a and b, but with North Atlantic and North Pacific Ocean basins examined separately. Note that in this figure, both undrogued/0 m and drogued/15 m results are displayed on both subplots.
Figure 8. Global maps of diurnal (±[0.9, 1.1] cpd) KE from undrogued and drogued drifters (panels a and d), from HYCOM at 0 m and 15 m (panels b and e), and from MITgcm LLC4320 at 0 m and 15 m (panels c and f). The ratios of undrogued to drogued drifter KE, and 0 m to 15 m KE for the HYCOM and MITgcm LLC4320 simulations are shown in panels g, h, and i, respectively. Note the decimal logarithmic color scale for the ratio maps. The spatial correlations between the drifter maps and HYCOM and MITgcm LLC4320 maps are indicated in the upper left corners of panels a, d, and g, with HYCOM values in blue to the left of MITgcm LLC4320 values in green. The spatial correlations between HYCOM and MITgcm LLC4320 maps are indicated in the upper left corners of panels b, e, and h.

In the model results, we separate the stationary (sometimes referred to as phase-locked or coherent) diurnal tidal motions from other diurnal motions using a tidal harmonic analysis, here of the two largest constituents (K\textsubscript{1} and O\textsubscript{1}). Diurnal KE maps obtained from harmonic analysis, shown in Figure 9 (panels a to d), display enhanced regions near 30°, but these do not dominate the maps as dramatically as in Figure 8 because the wind-driven KE, which is not stationary, is not captured in the harmonic analysis. Substantial KE regions are also noticeable equatorward of 30°, especially in the well-known diurnal tide hotspot in the western Pacific or along beams of baroclinic motions emanating from topographic features (Y. Wang et al., 2021). Except in specific locations such as the Sea of Okhotsk, Aleutian Island chain, the Campbell Plateau, and Kerguelen Plateau, diurnal KE computed from tidal harmonic analysis drops off steeply poleward of 30°, the cutoff values separating freely propagating from evanescent diurnal motions. For both models, some diurnal KE is captured poleward of 30° by the harmonic analysis around some prominent topographic features in the Southern Ocean (for instance around the Kerguelen Plateau and the Campbell Plateau) or within the Alaskan Archipelago.
Figure 9. Global maps of diurnal KE calculated from harmonic analysis of diurnal tidal constituents $K_1$ and $O_1$ for HYCOM at 0 m and 15 m (panels a and c), and from MITgcm LLC4320 at 0 m and 15 m (panels b and d). The ratios of 0 m to 15 m KE for the HYCOM and MITgcm LLC4320 simulations are shown in panels e and f, respectively. Note the decimal logarithmic color scale for the ratio maps. The spatial correlations between HYCOM and MITgcm LLC4320 maps are indicated in the upper left corners of panels a, c, and e.

in the North Pacific. These features should correspond to strong barotropic tidal currents there, and some evanescent diurnal baroclinic tidal energy, unable to propagate far from their generation regions. The features seen in the total diurnal KE model maps within the Agulhas Return Current and the Antarctic Circumpolar Current are absent in these harmonic analysis maps, suggesting that these are wind-driven in nature.

The 0 m to 15 m ratio maps for the diurnal KE from the harmonic analysis (Figure 9, panels e and f) are difficult to interpret but appear to be the result of superimposed long-wavelength patterns of barotropic tidal motions and short-wavelet patterns of baroclinic tidal motions within the tropical regions, and superimposed patterns of barotropic tidal motions and residual wind-driven motions at extratropical latitudes.

The spatial correlations of the model diurnal KE maps from the harmonic analysis are slightly higher than for the total diurnal KE maps (0.82 for 0 m and 0.83 for 15 m). In contrast, the spatial correlation between models of the ratio maps is lower (0.41, Figure 9e) than for the total diurnal KE ratio maps (0.54, Figure 8h).

Zonal averages (Figure 10) confirm that HYCOM lies closer to the diurnal peaks in the drifter results near 30°S and 30°N, while MITgcm LLC4320 diurnal energy is too weak in these peak regions. Equatorward of these peaks, MITgcm LLC4320 diurnal energy is generally too strong relative to drifter results, especially near 20°N, the latitude of the northwestern Pacific internal tide hotspot, while HYCOM KE is generally com-
parable to drifter values. The model diurnal tide harmonic analysis KE values are significantly weaker than the model total diurnal KE values computed from integration of the frequency spectra in the diurnal band. This confirms that the diurnal band consists of other motions (nonstationary diurnal tides, diurnal cycling of Ekman and submesoscale flows, and, in latitudes near 30°, near-inertial flows) as well as stationary diurnal tides.

The ratios of zonally averaged model 0 m KE to zonally averaged model 15 m KE in the diurnal band (Figure 10c) are complicated, as anticipated, and are revealing of model strengths and weaknesses. The ratio of undrogued to drogued drifter diurnal KE is close to two near the equator, and greater than two at high latitudes, with relatively small error bars. The MITgcm LLC4320 total diurnal KE ratio follows the drifter ratio comparatively well over low- and mid-latitudes but is too low at high latitudes. The HYCOM total diurnal KE ratio follows higher latitude drifter values more closely, and also follows the mid-latitude drifter ratio well, but is much higher than the drifter ratio in latitudes equatorward of about 20°. Yet, recall that HYCOM tracks the absolute drifter KE values equatorward of 30° more closely than MITgcm LLC4320 does (panels a and b). The ratio of 0 m to 15 m diurnal tidal harmonic analysis KE lies relatively close to unity over all latitudes, suggesting that stationary diurnal tidal motions are not a major contributor to the vertical structure of KE seen in the diurnal band.

### 3.4 Semi-diurnal KE

Global maps of semi-diurnal kinetic energy (Figure 11, panels a to f) display known hotspots of semi-diurnal internal tide motions near, for instance, Hawai’i, the French Polynesian islands, and the western Pacific. The KE values are substantially higher in the simulations, especially MITgcm LLC4320, than in the drifter observations. The hotspots are visible in the drifter maps, but less so because of the higher noise level in the drifter data. As highlighted in panels b and e, in HYCOM, the semi-diurnal kinetic energy is spuriously large in a patch of the high-latitude North Pacific, south of the Aleutians, due to a known numerical instability there (Buijsman et al., 2016). As is generally seen in other frequency bands, spatial correlations between model KE maps at both 0 and 15 m are higher (0.82 and 0.83) than the spatial correlations between either model KE map and the drifter KE maps, which range between 0.62 and 0.72. Spatial correlations between HYCOM and drifter KE maps are slightly higher than spatial correlations between MITgcm LLC4320 and drifter KE maps.

The ratio maps for the semidiurnal KE band differ substantially from ratio maps in other frequency bands. For both models (panels h and i), the ratio values are generally close to 1 indicating low differences of KE levels between the surface and 15 m. However, the spatial patterns are rather different, resulting in a modest correlation between the two model ratio maps (0.44). The ratio map for the drifters is again noisy (panel g), yet shows, as in the model maps, values closer to 1 than in other frequency bands. Interestingly, the spatial correlation between the drifter ratio map and the HYCOM ratio map is about twice as large as for MITgcm LLC4320 (0.13 compared to 0.07). Though still admittedly small, this marked difference may be due to the ability of HYCOM to represent higher 0 m to 15 m ratio values in the Southern Ocean (and Gulf of Mexico) as is seen in the drifter observations.

In the zonal averages (Figure 12, panels a and b), as demonstrated by Yu et al. (2019), MITgcm LLC4320 KE is higher than drifter KE over all latitudes, by a factor of up to four. As indicated in Section 2.2, MITgcm LLC4320 had an overly large tidal forcing, and lacked the self-attraction and loading (SAL) term, but these effects are not large enough to explain the discrepancy between MITgcm LLC4320 and drifter observations. Over most latitudes, HYCOM lies closer to the drifter KE than MITgcm LLC4320 does. A notable exception to this pattern is seen in northern hemisphere high latitudes, where the numerical instability in North Pacific HYCOM, mentioned earlier, is exhibited.
Figure 10. Zonally averaged diurnal (±[0.9, 1.1] cpd) KE from (a) undrogued drifters and 0 m model levels, and (b) drogued drifters and 15 m model levels. Ratios of zonal averages of undrogued/drogued drifter KE, and 0 m/15 m model KE, are shown in (c). The zonally averaged diurnal KE from harmonic analysis (“HA”, in legend) is also plotted for HYCOM (dash-dotted curve) and MITgcm LLC4320 (dashed curve). The gray shaded region in each panel indicates the latitudes where the diurnal and near-inertial frequency bands overlap (see Fig. 1). The shading around each curve corresponds to two standard errors of the calculated 1° zonal averages from the geographical maps.
addition, the semi-diurnal KE in HYCOM is still substantially larger than the drifter KE, in contradistinction to the closer agreement seen in comparisons of HYCOM internal tide SSH signatures with altimetry (Ansong et al., 2015; Buijsman et al., 2020). This illustrates the value of comparing models with velocity observations as well as SSH observations.

In sharp contrast with results in other frequency bands, the ratios of zonally averaged undrogued to drogued drifter KE and 0 m to 15 m model KE in the semi-diurnal band are consistent with values of unity, to within error bars (Figure 12c), implying that there is on average no vertical structure in the semi-diurnal band compared to the other bands. However, the large error bars on the drifter and model results may encompass the possibility of a small spatially-varying shear.

Motivated by the “wider and lower” semi-diurnal tidal peaks in drifter spectra compared with model spectra (see insets of Figure 2), we examine in Figure 13 how the model vs. drifter semi-diurnal zonal average comparisons change if the $\pm [1.9, 2.1]$ cpd semi-diurnal band defined by Yu et al. (2019) is widened to $\pm [1.6, 2.4]$ cpd in incremental $\pm 0.1$ cpd.
Figure 12. Zonally averaged semi-diurnal ($\pm [1.9, 2.1]$ cpd) KE from (a) undrogued drifters and 0 m model levels, and (b) drogued drifters and 15 m model levels. Ratios of zonal averages of undrogued/drogued drifter KE, and 0 m/15 m model KE, are shown in (c). The shading around each curve corresponds to two standard errors of the calculated 1° zonal averages from the geographical maps.
Table 1. Mode and median values of mapped ratios of KE of undrogued to drogued drifters, HYCOM at 0 m to HYCOM at 15 m, and MITgcm LLC4320 at 0 m to 15 m, in four different frequency bands.

<table>
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<th>Mode values</th>
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<th>Diurnal</th>
<th>Semi-diurnal</th>
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<td>Median values</td>
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4 Vertical structure: Global averages and discussion

This section provides further discussions of KE vertical structure as diagnosed by ratios of surface (0 m) to 15 m KE. Mode and median values of these ratios, for undrogued to drogued drifters, and for 0 m to 15 m levels in both models, for all frequency bands displayed in our 1° by 1° global maps, are given in Table 1. The global mode and median values are consistent with significant vertical structure, with surface (0 m) values enhanced compared to 15 m values, for the low-frequency, near-inertial, and diurnal bands. The low-frequency and diurnal bands generally display the largest values, followed by the near-inertial band. The semi-diurnal band has the least vertical structure, with most reported values being near one.
Figure 13. Zonally averaged semi-diurnal KE estimates from drifters and model levels calculated by gradually widening the band of frequency integration from $\pm [1.9, 2.1]$ cpd to $\pm [1.6, 2.4]$ cpd as indicated in the title of each subplot. Uncertainty estimates are omitted here for clarity. In panels c and d, the gray shaded areas indicate the latitudes where the frequency bands of integration overlap with the near-inertial bands. The legend boxes in panels a and b are applicable to all panels.
bic profile of depth, yielding increasing viscosity values from a finite surface value, a sub-
surface maximum, and decreasing values below, down to a background viscosity at the
base of a boundary layer. When such a cubic profile is applied to the wind-driven Ek-
man momentum equation for the surface boundary layer, this results in a frequency-dependent
shear which is minimum at the inertial frequency and increases away from the inertial
frequency (Elipot, 2006). This theoretical framework is useful to understand how the lo-
cally wind-driven component of oceanic currents (Lilly & Elipot, 2021), from the iner-
tial frequency to the low-frequency motions, can be sheared in the upper 15 m of the ocean,
as seen here in models and observations. In addition, upper-ocean stratification mod-
ulates the ultimate penetration depth of wind momentum (Large & Crawford, 1995; Craw-
ford & Large, 1996; Elipot & Gille, 2009; Dohan & Davis, 2011; Lilly & Elipot, 2021).
The reported values of the 0 m to 15 m KE ratio in the drifters and the models are there-
fore consistent with these expectations.

To aid in interpreting the vertical structure of motions that are not directly wind-
driven, such as diurnal tides, semi-diurnal tides, and mesoscale eddies and currents (the
latter arising indirectly from wind forcing), it is useful to compute the first three ver-
tical modes (e.g., Gill, 1982; Arbic et al., 2018, among many), for semi-diurnal and di-
urnal frequencies, as well as for zero frequency (the latter representing the quasi-geostrophic
limit). We use five different deep-ocean profiles in a US Navy climatology (Helber et al.,
2013), at 10°S, 206°E and at four different latitudes (50°N, 10°N, 6°N, and 50°S) along
210°E. The values of the 0 m to 15 m KE ratio computed from these low vertical modes
were greater than one, but only by small amounts (ranging from 1.0001-1.0047), less than
the near-inertial values seen in Figure 6c and much less than the low-frequency and to-
tal diurnal values seen respectively in Figures 4c and 10c. The low vertical structure ra-
tios in the vertical normal mode analysis are consistent with the lack of vertical struc-
ture seen in our semi-diurnal results and diurnal tidal harmonic analysis results, both
of which are almost entirely due to tidal motions. We note that semi-diurnal and espe-
cially diurnal tidal currents do have a surface-intensified profile (Timko et al., 2013, their
Figure 5), but this surface intensification is over vertical scales that are significantly larger
than 15 m.

The lack of vertical structure between 0 and 15 m in the low vertical mode anal-
ysis is inconsistent with the higher amount of vertical structure seen in our low-frequency
and total diurnal results which are likely a superposition of different types of dynamics.
Additional physics, such as wind-driven Ekman and other motions, is taking place in the
diurnal and low-frequency bands (and in the near-inertial band). The upper-ocean ver-
tical structure in the total diurnal results (Figure 10c) is likely due to non-tidal effects,
such as near-inertial flows (in latitudes where they overlap), diurnal cycling in Ekman
flows (Price et al., 1986; Price & Sundermeyer, 1999; W.-Y. Sun & Sun, 2020) and sub-
mesoscale flows (D. Sun et al., 2020). Regarding the latter possibility, however, we note
that the grid spacings in the global models examined here are not sufficient to fully re-
solve submesoscale eddies (Capet et al., 2008).

The “interior quasi-geostrophic” component (Lapeyre & Klein, 2006) of low-frequency
large-scale currents and mesoscale eddies is dominated by barotropic and low baroclinic
modes (Wunsch, 1997), or, in an alternative view, by a “surface mode” that is strongest
at the surface and approaches zero flow at the seafloor (LaCasce, 2017), due to the in-
fluence of bottom topography (LaCasce, 2017) and/or bottom and topographic wave drag
(Arbic & Flierl, 2004; Trossman et al., 2017). The surface mode described by LaCasce
(2017) decays with depth at the ocean surface, as do the traditional low baroclinic modes.
In addition, low-frequency motions may also have a substantial “surface quasi-geostrophic”
component (Lapeyre & Klein, 2006; LaCasce & Wang, 2015), which is surface intensi-
ified and may therefore contribute to the weaker motions at 15 m depth relative to the
surface. However, the simplest explanation for the vertical structure seen at low-frequencies
(Figure 4c) is that it is due to Ekman flows, which exhibit substantial variation over short vertical scales (Elipot & Gille, 2009; Lilly & Elipot, 2021).

A more thorough explanation of the vertical structure in low-frequency, near-inertial, and diurnal flows awaits future work.

5 Summary

Near-surface ocean kinetic energy (KE) is an important factor in a variety of problems, including but not limited to air-sea interaction, pollution transport, and satellite mission planning. Such applications require better quantification and understanding of the space-time variability of near-surface oceanic KE, including its frequency dependence and vertical structure (Elipot & Wenegrat, 2021).

In this paper, we have compared KE in undrogued and drogued drifters, which respectively represent flows at the sea surface (0 m) and 15 m depth, to the 0 m and 15 m KE in two different high resolution simulations, MITgcm LLC4320 and HYCOM. The main results employed in the comparisons consist of rotary frequency spectra, and maps and zonal averages made from spatially averaging the rotary spectra over specific frequency bands. We compare both KE levels, at 0 m and 15 m, and the ratio of 0 m to 15 m KE, which we take as a measure of vertical structure. The MITgcm LLC4320 and HYCOM simulations both include tidal forcing alongside atmospheric forcing, implying that the ocean model outputs include high-frequency near-inertial flows, barotropic and baroclinic tides, and an internal gravity wave (IGW) continuum spectrum alongside low-frequency large-scale currents, mesoscale eddies, and Ekman flows. The three-way comparison between drifters and two models allows us to assess the strengths and weaknesses of all three products. The drifters are unable to map the IGW continuum at the highest frequencies, due to a prohibitive noise floor. The drifters can, however, can provide global maps of KE in Ekman flows, large-scale currents, mesoscale eddies, near-inertial motions, semi-diurnal tides, and diurnal motions. Diurnal motions include diurnal tides, and diurnal cycling of Ekman and submesoscale flows. In latitudes near 30°, our definitions of diurnal and near-inertial flows overlap, such that near-inertial motions are included in our diurnal results. The stationary component of diurnal tides can be computed separately from other diurnal motions via a tidal harmonic analysis. Maps and zonal averages indicate that stationary diurnal tides are a relatively small component of the KE seen in the diurnal band.

Following Yu et al. (2019), who compared KE in the MITgcm LLC4320 simulation to drifters, we find that near-inertial motions in MITgcm LLC4320 are too weak while semi-diurnal tidal motions are too strong. Here we find that the HYCOM KE values lie closer to the drifters in both the near-inertial and semi-diurnal tidal bands, but for different reasons. In the near-inertial band, HYCOM is stronger than MITgcm LLC4320 due to more frequently updated atmospheric forcing fields. In the semi-diurnal tidal band, HYCOM is weaker than MITgcm LLC4320, due primarily to the parameterized topographic internal wave drag, which simulates the energy lost due to unresolved wave generation and breaking processes, and which is employed in HYCOM but not in MITgcm LLC4320. While HYCOM semi-diurnal tidal KE lies closer to the drifters than MITgcm LLC4320 KE does, the HYCOM semi-diurnal KE is still stronger than the drifter KE if the Yu et al. (2019) definition of semi-diurnal band is employed. However, if we widen the definition of semi-diurnal band from that employed in Yu et al. (2019), the HYCOM tidal KE lies closer to the drifters over most latitudes, while MITgcm LLC4320 semi-diurnal KE is too high. Widening the definition of the semi-diurnal band to accommodate comparisons to drifters may be justified, due to the inherently “wider” nature of Lagrangian spectra relative to Eulerian spectra (Zaron & Elipot, 2021). To be more sure of this interpretation, both HYCOM and MITgcm LLC4320 could be seeded with numerical particles and the resulting Lagrangian velocity spectra could be more directly
compared to drifter spectra from the actual ocean; this computationally expensive un-
dertaking is left as a topic for future investigation.

Our conclusion that damping parameterizations are necessary for attaining real-
istic semi-diurnal tidal energy levels is consistent with the results of Ansong et al. (2015),
who demonstrated that the sea surface height signature of internal tides in HYCOM is
closer to altimetry observations when the HYCOM simulations contain a wave drag than
when they do not.

We have shown here that HYCOM also lies closer to drifters than LLC4320 does
in the diurnal band, which overlaps with the near-inertial band under the definitions em-
ployed here. In addition, we have shown that low-frequency (<0.5 cpd) motions in both
models are generally too weak, especially near the equator, that both models suffer from
weak near-inertial motions in the northern mid-to-high latitudes, and that numerical in-
stabilities yield overly large tidal HYCOM semidiurnal KE in the North Pacific.

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We find that HYCOM generally has higher spatial correlations with drifter obser-
vations of KE than MITgcm LLC4320 does, across a wide variety of frequency bands.
This result is consistent with Luecke et al. (2020)’s finding that the spatial correlations
between HYCOM and mooring observations of KE and temperature variance are higher
than the correlations between MITgcm LLC4320 and mooring observations.

We investigate the vertical structure of KE, within all of the frequency bands con-
sidered, through global maps, zonal averages, and global mode and median values of a
vertical structure ratio, defined as 0 m KE to 15 m KE in the models and undrogued KE
to drogued KE in the drifters. With some exceptions noted earlier, in the zonal average
results, the models capture the latitude- and frequency- dependence of the vertical struc-
ture ratio relatively well. The low-frequency, near-inertial, and diurnal bands display sig-
nificant vertical structure, while the semi-diurnal band shows little vertical structure. Ek-
man flows, and their diurnal cycling, likely explain some of the vertical structure seen
in the low-frequency and diurnal bands. On a point-by-point basis, the model vs drifter
comparisons of the ratios are not as close. The maps of the ratio in the drifters are rather
noisy, and spatial correlations between the model ratios and drifter ratios are always less
than spatial correlations of the absolute KE between models and drifters.

In ongoing work, we will determine whether the HYCOM and drifter comparison
is improved with the employment of data assimilation in operational HYCOM. We will
also compare the near-surface KE in coupled high-resolution atmosphere and MITgcm
ocean simulations, in which the atmosphere is coupled to the ocean much more frequently
than in MITgcm LLC4320, to drifters.

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