Reply to referee #2 of

"GEST: A multi-scale dynamics-based reconstruction of global ocean surface current"

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Responses to Referee Comments:

(RC: referee comments | AC: authors comments)

RC1: This paper presents a sea surface current product at a depth of 15 meters called GEST (Geostrophic-Ekman-Stokes-Tides) and compares it with other surface current products. This work shows some meaningful and interesting results, but there are still critical flaws present. Therefore, I believe that this paper is not suitable for publication in the journal Earth System Science Data, which aims to present original and high-quality datasets.

AC1: Thanks for your valuable comment. It is a great honor that you consider it interesting and meaningful to our ocean current product at a depth of 15 m reconstructed from drifter observations and the characteristics of Ekman current. Although more researchers are focusing on high-precision ocean current reconstructions, existing studies mainly utilize surface geostrophic and Ekman currents to model the physical inversion of global or regional oceans, neglecting the contribution of mesoscale eddies, sub-mesoscale dynamics, and small-scale wave motion. In particular, previous studies have demonstrated the effects of tidal current and Stokes drift on ocean current dynamics (e.g., Constantin, A., 2006; Sheehan et al., 2017; Onink et al., 2019), and any reconstruction model of the ocean current that ignores tidal current and wave-induced Stokes drift would be incomplete.

In addition, most of the presently similar ocean current products do not considerate the relative position of the wind-driven friction depths (ranging from a few meters to several hundred meters) versus the drogue of drifters (i.e., 15m). As a result, shallower wind-driven current is blended into the reconstruction process, which reduces the correlation with drifter observations.

Furthermore, drift measurements are used to correct for geostrophic and Ekman currents in previous products (e.g., GlobCurrent data), which deprive an independent validation process. In contrast, the GEST product has obtained comparable or even better results at low and mid-latitudes without assimilating any drift observations.

The GEST product also incorporates multiscale features and unifies the vertical depth of the reconstructed dataset by the verification for local applicability of Ekman current and the attenuation for tides and Stokes drifts, which result in a substantial improvement on previous products.

As detailed below, substantial responses and revisions have been made following your comments and suggestions.

RC2: As pointed out by the authors, there are presently similar data products available, such as OSCAR, GEKCO, and the GlobCurrent project. Concerning data precision, GEST does not fundamentally surpass GlobCurrent in terms of enhancement (Figure 14), as the resolution of satellite data remains unaltered. While the inclusion of tidal currents and Stokes drift might enhance accuracy in specific regions (Figure 8), this, however, results in a time span limited to only 2013-2019, which is significantly shorter than the extensive coverage of the traditional dataset (from 1993). Given comparable data accuracy, the study has not presented us with well-founded reasons to exclusively use this product. Personally, I might still favor the use of GlobCurrent (http://globcurrent.ifremer.fr/) which spans over 20 years.

AC2: Despite the obvious success of presently similar data products that have advanced the ocean current reconstruction process, the phenomenon of mesoscale eddies, sub-mesoscale dynamics you suggested in question 5, and small-scale fluctuations existing in the ocean have been neglected. The GEST dataset incorporates four ocean flow fields with emphasis on wave-induced Stokes drift as well as the tidal current, and finally achieves higher accuracy over coastal and equatorial regions, which is also endorsed by you.

As you mentioned, GEST does not completely outperform GlobCurrent product on a global scale in Figure 14, but alternates better performances in the latitudinal bands 30° N-50° N and 40° S-60° S. This is related to the fact that the GlobCurrent dataset utilizes drifter observations in the calculation of the CNES-CLS13 MDT and Ekman current, and the region where Ekman current shows high correlation with drifter observations lies roughly in the westerly zone (30° N-50N and 40° S-60° S), contributing to the high reconstruction accuracy of this latitudinal bands. Instead, the reconstruction accuracy of the GEST product without the assimilation of drift observations is about 4 cm/s and 0.3 cm/s higher over the OSCAR product and the GlobCurrent dataset. This suggests that the GEST product not only provides independent data validation but also improves reconstruction accuracy compared to the GEKCO and GlobCurrent products that utilize drift data and use it as a validation set.

Besides, GEST dataset is also characterized by the consideration for the local applicability of the Ekman current, ensuring that the Ekman layer reaches the vertical position of the drogue (i.e. 15 m). It improves the correlation of the Ekman current with the drifter observations by about 15 %.

Regarding the data spanning, it is available to provide the 0.25° resolution GEST dataset before 2013 as a supplementary product if anyone needs it. In our algorithm for ocean current reconstruction, a portion of the data is used for model training and the rest is used for the prediction of the flow field. Typically, the data involved in training is not included in the output product, so the previous GEST product has only provided current forecasts since 2013.

RC3: The comparison of different velocity combinations in Section 3.5 yields insightful outcomes, clarifying the roles (positive or negative) played by Stokes drift and tidal currents. So, I recommend considering the submission of this paper to an alternative journal, rather than ESSD. In terms of the dataset's intrinsic merit, this study does not yield a novel and compelling product. Additionally, I propose visualizing the results in Table 1 using a bar chart, as it would provide a more intuitive depiction.

AC3: The Earth System Science Data (ESSD) journal encourages submissions on original data or data collections that are of sufficient quality. The intrinsic value of the GEST dataset lies in the accurate and independent reconstruction process, including the verification of the wind-driven friction depth with local applicability, the independent validation without assimilating drifter data, and the innovative reconstruction of the sea surface flow field from a multi-scale perspective. As you suggested, the comparison of reconstruction error for different combinations of models in Section 3.5 can demonstrate the role of tidal current and Stokes drift in the upper ocean. In addition, the importance of multiscale reconstruction can be confirmed by the higher global reconstruction accuracy compared to GlobCurrent and OSCAR data.

Moreover, following your suggestion, we visualized the results of Table 1 using the bar chart in Figure A1 (page 27 line 474). In contrast to abstract tables, a bar chart makes the performance of the four models visible at a glance.

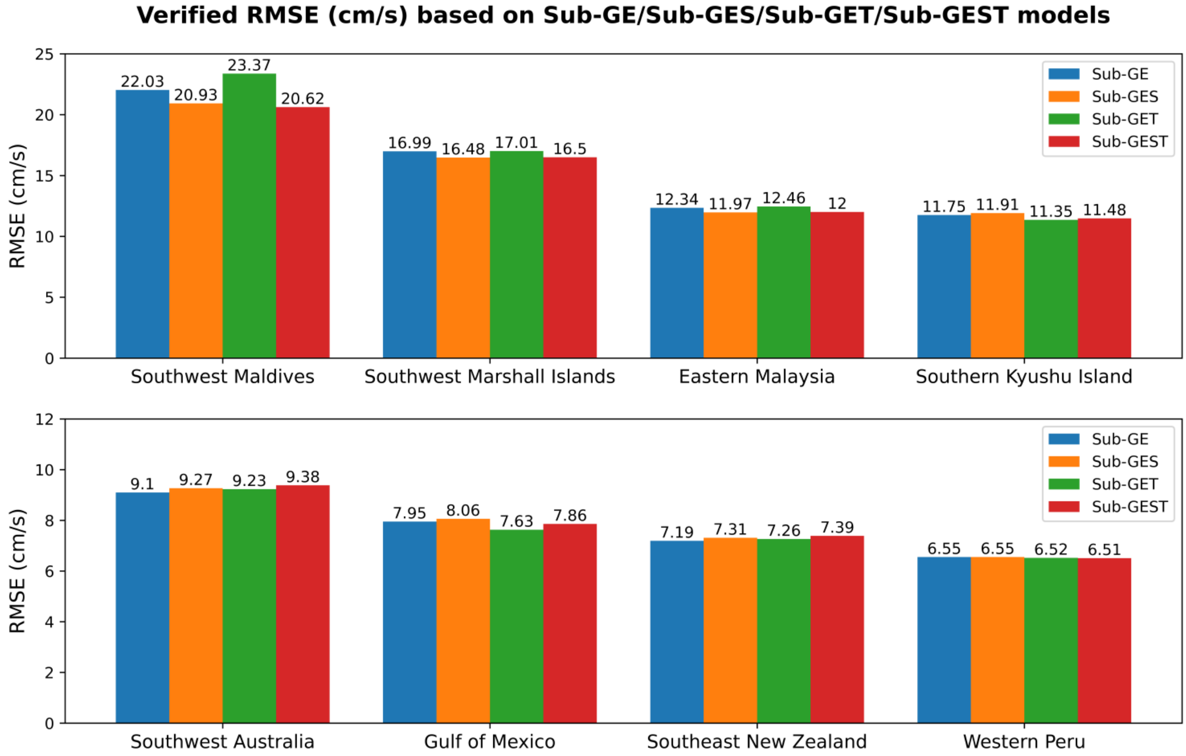

Figure A1: The reconstructed RMSE (cm/s) based on Sub-GE (blue) / Sub-GES (orange) / Sub-GET (green) / Sub-GEST(red) models in Southwest Maldives, Southwest Marshall Islands, Eastern Malaysia, Southern Kyushu Island, Southwest Australia, Gulf of Mexico, Southeast New Zealand, and Western Peru.

RC4: The authors compare products with 1-degree resolution and 0.25-degree resolution and indicate that the 0.25-degree product better approximates the real ocean currents, which is not a surprising result. Undoubtedly, a 1-degree product cannot capture mesoscale eddies, and its accuracy is certainly lower than that of the 0.25-degree product. This fact is widely recognized and should not constitute the primary conclusion of this paper.

AC4: As the reviewer suggested the increased resolution of the flow field captures more mesoscale eddies with spatial scales around 50-200 km, which certainly contributes to the improvement of accuracy. These eddies have small horizontal scales, which usually require a horizontal resolution of at least the order of 10 km for ocean circulation models to depict the basic features more effectively. Thus the coarse resolution of the 1° data set does not effectively capture the mesoscale information, resulting in lower accuracy than the 0.25° resolution data.

In addition, our ocean current reconstruction model also contributes to the accuracy of the dataset, allowing the multi-scale information to be well exploited and the wind-driven current to be more accurate. Through quantitative studies, we revealed that the reconstruction error was reduced from 14.61 cm/s at 1-degree resolution to 9.36 cm/s at 0.25° resolution under the influence of the improved resolution and the multi-scale reconstruction algorithm.

We have updated the expression of the conclusion as follows,

Revised (page 1 lines 23-27): "Furthermore, by quantitatively analyzing the reconstructed products with 1° and 0.25° resolution, we find an improvement in accuracy of about 5.6 cm/s due to the multi-scale algorithm and higher resolution that reveals more details of ocean currents especially mesoscale eddy energy associated with geostrophic currents."

Revised (page 26 lines 459-464): "The quantitative analyses demonstrate a notable enhancement in reconstruction accuracy of about 5.6 cm/s due to the increase in resolution (from 1-degree to 0.25-degree) and the multi-scale reconstruction algorithm."

RC5: L68-70. "In the actual ocean … can be broadly divided into large-scale ocean circulations, micro scale internal waves and storm surges." This comment appears to lack thorough consideration, as it does not encompass mesoscale and sub-mesoscale processes. While only few observations can directly reflect sub-mesoscale processes, the authors should not dismiss their significant roles in the upper ocean, especially considering the increasing awareness of sub-mesoscale processes in recent years (e.g., JC McWilliams 2016). Relevant discussions are indispensable in this paper. In my view, incorporating sub-mesoscale processes could potentially significantly enhance the data accuracy.

AC5: Thanks for your professional comment. We have conducted a comprehensive literature review, a portion of which is presented below. Further, we have incorporated and corrected the relevant content related to the mesoscale and sub-mesoscale processes within the revised manuscript.

The mesoscale dynamics dominated by mesoscale eddy energies have a strong influence on upper ocean dynamical processes and have been extensively studied by many scholars previously. Chen et al., (2021, 2022) proposed an independent identification scheme that relates eddy surface signature to its interior property, compensating for the lack of spatial resolution of altimeter products that leads to the missing identification of eddies. They found that roughly 1/4 of additional floats are identified by the verified Argo-alone criteria as onboard eddies outside altimetrically derived ones and the observed divergence and dispersion of eddy propagations are inextricably linked to ocean currents, winds, and topographic effects.

Meanwhile, sub-mesoscale dynamical processes have only recently been recognized and received more attention than large-scale circulation, mesoscale eddies and small-scale fluctuations. The generation of the sub-mesoscale current relies on mesoscale eddies and strong flow fields, which provides a dynamical conduit for energy transfer towards microscale dissipation and diapycnal mixing, accumulating an essential part of the total ocean kinetic energy.

For example, the sea surface density field contains rich variability over sub-mesoscale O (0.1-10) km length scales (e.g., McWilliams, J.C., 2016) that often manifest as density fronts and filaments. Sub-mesoscale density fronts are pervasive on continental shelves in high-resolution coastal models, observed within 10 km from shore. Wu et al. (2020) identified coastal density fronts (which they categorized into alongshore and cross-shore-oriented fronts, with the mean front length reaching 6-8 km, and depth <30 m) under weak wind conditions, and further analyzed their dynamical processes. Generated on the periphery of eddies formed during the growth of barotropic and baroclinic instabilities, many fronts are curved, with a radius of curvature comparable to the radius of the eddy. Shakespeare et al., (2016) analyzed the qualitative impact of curvature on the behavior and stability of density fronts in the ocean. They found that the curvature could change the cross-front (radial) force balance from a geostrophic balance to a cyclogeostrophic balance (a three-way force balance where the pressure and Coriolis forces must combine to provide a net inward centripetal force), as well as modify the potential vorticity of the system and the along front (angular) force balance.

Gula et al., (2015) studied the generation process of sub-mesoscale topographic vortex in the context of island wakes in the Gulf Stream region based on high-resolution realistic simulation. It can be viewed as generic for boundary slope currents moving anticyclonically/cyclonically around a basin (meaning that the flow has the coast on its left/right in the Northern Hemisphere), generating strong positive/negative vorticity within the bottom boundary layer, separating over complex topography, and forming a street of sub-mesoscale vortices. This process highlights a mechanism by which the interaction of a balanced flow with a sloping topography transfers energy from the larger-scale incident flows to sub-mesoscale flows and provides a way toward loss of balance and energy dissipation. Whereas Srinivasan et al., (2019) focused on sub-mesoscale vortex filaments at midlatitudes, with small bulk Rossby number in the lee of topography. It was found that the generation and separation of bottom boundary layers form tilted shear layers with high vorticity and vertical shear, and the horizontal shear instability of these tilted shear layers on the slope generates sub-mesoscale vortical filaments. They also traced the evolution of unstable vortex filaments and the eventual formation of long-lived sub-mesoscale coherent vortices from both horizontal and vertical directions, suggesting that these processes are as ubiquitous in the oceans as the slope currents that produce it. However, they are unaccounted for in standard oceanic models on a global scale, and their impact will need to be parameterized.

As opposed to mesoscale eddies, sub-mesoscale information, which is densely and widely distributed, has not been captured by the current altimeter observations. Xia et al., (2022) developed an identification of sub-mesoscale eddies using SAR images based on the machine learning method (CAE-Net), and achieved better results than other models. Yurovsky et al. (2022) identified the structure of sub-mesoscale eddies along the Black Sea coast based on UAVs and analyzed the dynamics of the vortices, as well as the interactions with the wave-induced current. They found that the vortices with a diameter of ~200-400 m and an orbital velocity of ~0.15-0.30 m/s have a surprisingly high vorticity (the Rossby number Ro~15), and may have significant impacts on vertical circulation, energy transfer between large-scale motions and small-scale turbulence, and suspended matter transport.

Having gained a more detailed understanding of the dynamical processes at the mesoscale and sub-mesoscale described above, we modify our previous imprecise expressions as follows.

Revised (page 3 lines 76-77): “In the actual ocean, however, the movement of upper oceans is the result of multiple environmental driving mechanisms, and can be broadly divided into large-scale ocean circulations, mesoscale eddies, sub-mesoscale dynamics, and small-scale internal waves and storm surges.”

Revised (page lines 429-433): “Also, the generation of the sub-mesoscale dynamics (e.g., density fronts, vortical filaments, and eddy streets) relies on mesoscale eddies and strong flow fields, which contributes to the energy transfer to microscale dissipation and diapycnal mixing, accumulating a significant part of the total kinetic energy of the oceans (Williams, 2016; Shakespeare et al., 2016; Srinivasan et al., 2019; Xia et al., 2022; Yurovsky et al., 2022).”

Revised (page 27 lines 468-471): “In the future, complex mechanisms (e.g., planetary waves, mesoscale eddies, and sub-mesoscale processes) will be integrated into standard ocean models as well as parameterized for their effects to enhance the reconstruction accuracy of the sea surface current.”

Honestly, the purpose of this paper is to investigate whether the incorporation of tidal current and Stokes drift contributes to the upper ocean currents reconstruction. In the future, such sub-mesoscale processes will be integrated into ocean reconstruction models, and accurately quantified on a global scale to improve the reconstruction accuracy of the sea surface currents, with the help of the deep mining and nonlinear parsing capabilities of the artificial intelligence techniques.

RC6: The inclusion of explanatory files and variable descriptions is crucial for a well-rounded and usable dataset. I downloaded the data provided by the authors (https://doi.org/10.5281/zenodo.7767202) and performed a preliminary processing. The current state of the dataset, containing only a data matrix in the NC file, is clearly inadequate for effective utilization. I strongly recommend that the authors take the necessary steps to rectify this issue and provide the essential context and information that will significantly enhance the dataset's quality and utility. If the authors truly intends to create a valuable dataset, they should invest more time in the dataset itself. It is evident that they has not drawn upon established exemplary datasets as references, such as (https://data.marine.copernicus.eu/product/MULTIOBS_GLO_PHY_REP_015_004/description).

AC6: Sincerely thank you for the reminder. There is a pivotal role for the data description file in the creation of datasets and it provides users with the ability to quickly understand the data set and utilize it efficiently.

We referred to the description of the GlobCurrent data and other products provided by the Copernicus Marine Service websites, finding that the websites provide detailed descriptions of variables such as geographical coverage, spatial scales, temporal extent, temporal resolution that we have neglected before. The explanatory documentation we added is as follows. We have also learned from the expression of the data in the NC file and updated the variable descriptions for the GEST product (https://doi.org/10.5281/zenodo.8262564).

Below is a basic descriptive information of the GEST data and we will follow up with further refinements.

The Description of GEST Ocean Surface Current product

1. Summary

The GEST Ocean Surface Current product represents an estimation of ocean surface current at 15 m depth, incorporating multi-scale physical processes such as Geostrophic and Ekman currents, wave-induced Stokes drift, and Tidal currents. This global daily product covers the period of 2013-2019, with a spatial resolution of 0.25°. It is likely to be a good indicator of the real ocean circulation.

2. General information of the product specification

Product name	GEST Ocean Surface Current (G: Geostrophic current; E: Ekman current; S: Stokes drift; T: Tidal current)
Geographical coverage	Global Ocean Lat 89.875° S to 89.875° N Lon 0.125° E to 359.875° E
Spatial resolution	0.25° × 0.25°
Temporal extent	1 Jan 2013 to 31 Dec 2019
Temporal resolution	Daily
Depth	15 m
Variables	Eastward sea water velocity (U) Northward sea water velocity (V)
Feature type	Grid
Data assimilation	None

Format	NetCDF-4

3. Details of variable descriptions

Variables name in the NetCDF file and Unit	**Details**
u_15m (Centimetre per second)	Geostrophic velocity + Ekman velocity + Stokes velocity + Tidal velocity: zonal component standard_name : eastward_sea_water_velocity Land_mask=-9999 Fill_value=0
v_15m (Centimetre per second)	Geostrophic velocity + Ekman velocity + Stokes velocity + Tidal velocity: meridional component standard_name : northward_sea_water_velocity Land_mask=-9999 Fill_value=0
Latitude	89.875° S to 89.875° N
Longitude	0.125° E to 359.875° E

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