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A new High-Resolution daily Mean South China Sea Ocean Reanalysis dataset: SCSORA

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Abstract. High-resolution three-dimensional (3D) ocean reanalysis data are essential for investigating multiscale ocean dynamics in the regional ocean and their impacts on energy transport, marine ecosystems, and climate change. The South China Sea (SCS), as one of the most eddy-active marginal seas in the global ocean, is characterized by complex 3D dynamical processes and frequent extreme ocean events, imposing urgent data demands on the scientific community. This paper presents a new South China Sea Ocean Reanalysis (SCSORA) dataset, with high resolution (1/30°) covering the period 2001–2024, which is generated by the second version of the South China Sea Operational Oceanography Forecast System (SCSOFSv2). SCSORA provides daily 3D fields of temperature, salinity, and current velocity, together with sea surface height (SSH).Three categories of observational data are assimilated into SCSOFSv2, including satellite-derived optimum interpolation sea surface temperature (OISST), along-track sea level anomaly (SLA) from AVISO, and *in-situ* temperature–salinity Argo profiles. Systematic validations against multisource satellite retrievals, *in-situ* observations, and existing reanalysis products demonstrates that SCSORA achieves satisfactory accuracy and reliability in reproducing sea surface temperature (RMSE: 0.34 °C), SLA (RMSE: 5.9 cm), and subsurface thermohaline structure. Kinetic energy spectral analysis reveals that SCSORA is capable of resolving ocean dynamical processes spanning from mesoscale to part of the submesoscale range. Representative applications demonstrate the potential of SCSORA in characterizing the spatiotemporal features of marine heatwaves (MHWs) in the SCS and in examining the 3D structural modulation of MHWs by mesoscale eddies, revealing distinct modulation mechanisms of different eddy polarities on the vertical structure of MHWs. SCSORA provides a critical 3D data foundation for the physical oceanography and extreme event research communities focusing on the SCS. It is publicly available at https://doi.org/10.12378/geodb.2026.2.005.V1 (Zhu et al., 2026).

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1 Introduction

The South China Sea (SCS) is the largest tropical marginal sea in the western Pacific Ocean, covering a total area of approximately 3.5 million km² with a maximum depth exceeding 5000 m (Tang et al., 2023; Wang, 2022). As a critical conduit connecting the Pacific and Indian oceans, the SCS not only constitutes a global hotspot of marine biodiversity, hosting extensive coral reef ecosystems, but also serves as a vital fishing ground for surrounding nations and one of the world's most heavily transited international shipping lanes (Guo et al., 2026; Madin et al., 2015). The SCS circulation is predominantly governed by the East Asian monsoon system: a cyclonic circulation driven by the northeast monsoon prevails in winter, while an anticyclonic circulation associated with the southwest monsoon dominates in summer. This seasonal reversal is further modulated by the intrusion of Kuroshio waters through the Luzon Strait, collectively giving rise to a complex and highly variable three-dimensional (3D) dynamical structure (Cai et al., 2020; Nan et al., 2015). This unique dynamical environment renders the SCS a natural laboratory for investigating mesoscale eddy generation and evolution, marine heatwaves (MHWs), and their associated ecological consequences (Zhu et al., 2025).

Mesoscale eddies represent one of the most prominent dynamical features of the SCS. Statistical analyses have demonstrated that mesoscale eddy activity persists throughout the year, with eddy radii typically ranging from 50 to 300 km and lifetimes spanning from several weeks to several months. These eddies preferentially form in several hotspot regions, including the western flank of Luzon Island, the coastal waters off eastern Vietnam, and the vicinity of the Xisha Islands (Lin et al., 2015; Zhang et al., 2016). Through their rotational flow fields and vertical transport mechanisms, mesoscale eddies exert profound influences on heat redistribution, thermohaline structure, mixed layer depth (MLD), and biogeochemical processes in the SCS (Guo et al., 2017; Pan et al., 2018; Yi et al.,2024). However, owing to the inherently two-dimensional nature of satellite altimetry products, the majority of existing eddy studies rely on sea level anomaly (SLA) data for eddy identification and tracking, leaving the 3D vertical structure of eddies and their internal thermohaline dynamical processes insufficiently understood. High-resolution, long-term 3D data-assimilated reanalysis datasets based on observational data are a key tool for overcoming this bottleneck. Marine heatwaves (MHWs), as extreme ocean warming events that have attracted increasing attention in recent years, have become a growing research focus due to their dynamical coupling with mesoscale eddies. (Bian et al., 2023; He et al., 2024; Oliver et al., 2018; Oliver et al., 2021; Song et al., 2025). Under the background of accelerating global warming, the frequency and intensity of MHWs have increased substantially. Oliver et al. (2021) demonstrated that the annual number of MHW days increased by 54% globally from 1925 to 2016. The SCS, as a region particularly sensitive to global warming, experiences exceptionally active MHW events that have already caused large-scale coral bleaching and inflicted severe impacts on fisheries and aquaculture industries (Cheung et al., 2020; Hughes et al., 2018; Yao et al., 2021). Nevertheless, the overwhelming majority of existing MHW studies in the SCS are based on satellite-derived sea surface temperature (SST) data, which confine the characterization of heatwaves to their two-dimensional surface manifestations. The subsurface vertical penetration structure of MHWs and the modulation mechanisms by which mesoscale eddies regulate the

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3D distribution of heatwaves remain critically underexplored (Bian et al.,2023; Li et al., 2022 Song et al., 2025; Wang et al.,2024).

Existing global ocean reanalysis products, such as GLORYS and HYCOM (Jean-Michel et al., 2021; Cummings et al., 2013), provide 3D temperature, salinity, and current fields, yet their spatial resolutions are typically 1/4° to 1/12°. For the SCS, a region of intense mesoscale and submesoscale eddy activity, such coarse global products are generally inadequate for accurately resolving mesoscale and sub-mesoscale eddy structures, and their data assimilation schemes are not specifically optimized for the local dynamical characteristics of the SCS (Castillo-Trujillo et al., 2023; He et al., 2025). Previous studies have demonstrated that high-resolution regional reanalysis systems specifically designed for individual ocean basins can more accurately reproduce key processes, including the kinetic energy distribution of mesoscale eddies, the seasonal variability of MLD, and coastal upwelling (Zhu et al., 2022). Despite this recognized need, the SCS currently lacks a systematically validated, community-accessible, high-resolution assimilation dataset. Such a dataset would simultaneously provide long-term 3D thermohaline and current fields alongside sea surface variables. Its absence severely constrains in-depth investigation of the 3D dynamical characteristics of mesoscale eddies and the vertical structure of extreme thermal events in the SCS.

To address this data gap, the present study generates a long-term, high-resolution 3D South China Sea Ocean Reanalysis (SCSORA) dataset, based on the second version of the South China Sea Operational Oceanography Forecast System (SCSOFSv2; Zhu et al., 2022). The SCSORA has been assimilated satellite-blended SST, along-track SLA, and Argo in situ temperature–salinity profile observations, and provides a complete 24-year (2001–2024) daily mean dataset including 3D temperature, salinity, and current velocity fields, as well as 2D sea surface height (SSH). In the present paper, the accuracy and reliability of the SCSORA are comprehensively assessed through systematic comparisons against OSTIA satellite SST, AVISO gridded SLA, and multiple categories of observations. Three representative application cases are then presented to demonstrate the scientific utility of the dataset. These cases include kinetic energy spectral analysis, spatiotemporal characterization of MHWs, and mesoscale eddy dynamics. The aim is to provide the SCS physical oceanography research community with a reliable and openly accessible 3D reanalysis data foundation. The remainder of this paper is organized as follows. Section 2 describes the data sources and methods. Section 3 presents systematic validation of SCSORA against multisource observations. Section 4 demonstrates three representative application cases. Section 5 provides conclusions and discussion. Data availability information is given in Section 6.

2 Data and methods

2.1 SCSOFSv2 Model Description

The SCSORA dataset employed in the present study is generated by SCSOFSv2. SCSOFSv2 covers the SCS and its adjacent waters (99–144° E, 4.5° S–28.3° N), with a horizontal resolution of 1/30° over the SCS domain. The model provides daily mean output fields comprising 3D temperature, salinity, density, current velocity (u, v, and w components), and SSH. The vertical coordinate adopts 50 σ layers with a double vertical stretching function (Shchepetkin et al., 2005), ensuring sufficient

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vertical resolution within the upper 300 m to accurately resolve the mixed layer and thermocline structure. The system employs an Ensemble Optimal Interpolation (EnOI) data assimilation scheme (Evensen, 2003; Oke et al., 2008), assimilating three categories of observational data: satellite-derived SST, along-track satellite SLA, and in situ temperature–salinity profiles. To account for asynchronous observations within the assimilation time window, the First Guess at Appropriate Time (FGAT) approach is adopted to reduce assimilation biases arising from observation timing errors. Open boundary conditions are applied along the northern, western, southern, and eastern boundaries of the model domain, with boundary values derived from interpolation of global reanalysis data. Further details regarding the configuration and optimization improvements of the SCSOFSv2 can be found in Zhu et al. (2022).

2.2 Data Source

The SST data assimilated into SCSOFSv2 are obtained from the daily mean Optimum Interpolation Sea Surface Temperature (OISST) product distributed by the National Oceanic and Atmospheric Administration (NOAA), with a horizontal resolution of 0.25°×0.25°. This product integrates multi-platform observations from satellites, ships, and buoys to generate a regularly gridded SST analysis field via the optimum interpolation algorithm (Reynolds et al., 2007). The National Centers for Environmental Information (NCEI) provides two versions of OISST: an AVHRR-only version that exclusively uses Advanced Very High-Resolution Radiometer (AVHRR) infrared satellite data, and an AVHRR+AMSR version that additionally incorporates Advanced Microwave Scanning Radiometer (AMSR) data. Since the AVHRR+AMSR product was discontinued in 2011, the present study consistently adopts the AVHRR-only version, whose time series extends from 1981 to the present. The data are downloaded from the NCEI website (http://www.ncdc.noaa.gov/oisst/data-access).

The SLA data assimilated into SCSOFSv2 are the along-track SLA observations from multiple altimeter satellites distributed by AVISO of the Centre National D'études Spatiales (CNES), including the Jason-1/2/3, TOPEX/Poseidon, Sentinel-6 series and so on (Taburet et al., 2019). The along-track SLA data have been processed with standard geophysical corrections, including dry and wet tropospheric delay, ionospheric delay, solid Earth tide, polar tide, and sea state bias corrections. The data are available at https://www.aviso.altimetry.fr/en/home.html.

The *in-situ* temperature–salinity profiles assimilated into SCSOFSv2 are obtained from Argo profiling floats of the International Argo Program, providing vertical profiles of temperature and salinity over the depth range of 0–2000 m (Argo Science Team, 1998; Roemmich et al., 2009). Argo data are downloaded from the Global Data Assembly Centre (GDAC) and subjected to quality control flag screening, retaining only profiles for which both temperature and salinity quality flags equal 1 (good), thereby excluding outliers and suspicious profiles. Prior to assimilation, Argo temperature–salinity profiles are vertically interpolated onto the standard depth levels corresponding to the original σ-coordinate system of the SCSOFSv2. Over the study period of 2001–2024, a total of 94,331 Argo profiles were obtained, of which approximately 12% were located within the SCS domain (Figure 1). Argo temperature–salinity profiles are also used in the validation presented in this study. It is worth noting that although Argo data are assimilated into the system, the profiles are first interpolated onto the standard vertical depth levels corresponding to the model σ-coordinate system prior to assimilation, resulting in a loss of sampling detail

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from the original depth levels. During validation, the model temperature–salinity analysis fields are interpolated onto the original measured depths of each Argo float, and pointwise biases are computed at the non-uniform native sampling depths of the Argo profiles. The root mean square error (RMSE) and bias are then calculated after interpolation, providing an assessment of the ability of SCSORA to reproduce the subsurface thermohaline vertical structure. The Argo data are available at https://argo.ucsd.edu/data/.

For SST validation, the present study employs the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) product distributed by the UK Met Office, which provides daily mean blended SST data at a horizontal resolution of 1/20° (Donlon et al., 2012). OSTIA integrates multisource satellite infrared and microwave SST observations together with *in-situ* measurements, generating a gap-free global SST analysis field via optimum interpolation. Given that OSTIA differs substantially from the OISST product assimilated by SCSOFSv2 in terms of data sources, blending algorithms, and spatial resolution, the two products are mutually independent, rendering OSTIA a suitable independent reference dataset for SST accuracy assessment. The OSTIA product is available at https://doi.org/10.48670/moi-00168.

To further evaluate the capability of the SCSORA in reproducing subsurface thermohaline structure in the eddy-active region of the northern South China Sea (NSCS), the present study incorporates the high-resolution glider temperature–salinity observation dataset publicly released by Qiu et al. (2025). This dataset is based on multiple dedicated observation campaigns targeting mesoscale eddies and submesoscale processes in the SCS, and is available at https://doi.org/10.57760/sciencedb.11996. The validation period spans 2015–2021, with observations concentrated in the eddy-active region of the NSCS; details are provided in Table 1. Across six cruises, a total of 8,591 temperature–salinity profiles are available, encompassing spring (April–June), summer (July–August), and autumn (September–October) seasons, enabling characterization of the seasonal thermohaline vertical structure in the eddy-active region of the NSCS. Since the glider data are not incorporated into any assimilation procedure of SCSOFSv2, they serve as a rigorous independent benchmark for evaluating the subsurface thermohaline accuracy of the SCSORA in dynamically complex eddy regions. Their high spatial resolution enables detailed characterization of the thermohaline fine structure within eddies.

The SLA validation data are the multi-satellite merged gridded SLA product (DUACS DT2021) distributed by AVISO, with a horizontal resolution of 1/8° and daily temporal resolution. This merged gridded product is generated by fusing along-track observations from multiple altimeters via optimum interpolation, and is independent of the raw along-track SLA data assimilated by SCSOFSv2 at the data processing level, making it suitable for assessing the SLA accuracy of the SCSORA and the spatial reproducibility of mesoscale eddy signals. The data are available at https://doi.org/10.48670/moi-00168.

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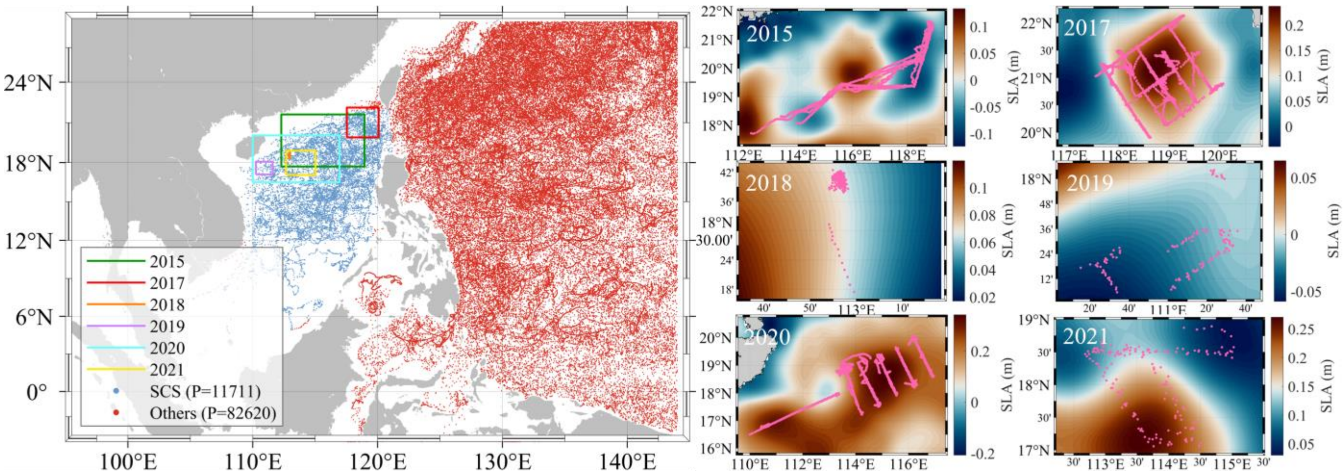

Figure 1. Spatial distribution of ARGO profiles and SLA fields along glider tracks in the SCS and adjacent regions for six years (2015, 2017, 2018, 2019, 2020, 2021). The left panel shows the locations of ARGO profiles. The right panels display SLA (in meters) during the glider observation periods for each year, with the corresponding glider tracks overlaid in pink.

Table 1. Glider Observation Details

Year	Longitude range (°E)	Latitude range (°N)	Number of profiles	Observation Periods
2015	112.3–119.0	17.7–21.6	1358	04/18-06/08
2017	117.5–120.1	19.9–22.1	2902	07/14-08/13
2018	112.9–113.0	18.3–18.7	239	04/22-05/23
2019	110.3–111.6	17.1–18.1	131	09/18-10/18
2020	110.0–117.0	16.5–20.1	3793	06/26-08/27
2021	112.7–115.0	17.1–18.9	168	05/09-07/29

2.3 Methods

2.3.1 Statistical tests

The performance of the model was assessed using various statistical metrics, such as the RMSE, correlation coefficient (R^2), and Bias. The following formulas were used:

$$RMSE=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i-y_i)^2}, \quad (1)$$

$$R^2=1-\frac{\sum_{i=1}^{N}(x_i-y_i)^2}{\sum_{i=1}^{N}(x_i-\bar{x})^2}, \quad (2)$$

$$bias=\frac{1}{N}\sum_{i=1}^{N}(x_i-y_i), \quad (3)$$

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where x_i is the observed value of pixel i, y_i is the SCSORA analysed value of pixel i, and $\overline{x}$ is the average of all true values.

2.3.2 MHW Statistical Method

MHW characteristics are identified following the definition of Hobday et al. (2016), whereby a MHW event is defined as a discrete period during which daily SST exceeds the climatological 90th percentile threshold for at least five consecutive days; two successive events separated by a gap of no more than two days are treated as a single continuous event. The annual 90th percentile threshold and climatological SST for date i are computed by pooling all daily SST values within an 11-day window centred on date i (i.e., days i − 5 to i + 5) across all years of the 2001–2024 baseline period, followed by smoothing with a 31-day moving average window. The code used to compute MHW metrics is obtained from https://github.com/ZijieZhaoMMHW/m_mhw1.0 (Zhao et al., 2019).

2.3.3 Eddy Detection Method

Mesoscale eddies in the SCS are identified and tracked using the Eulerian vector geometry-based automatic eddy detection method of Nencioli et al. (2010). This Eulerian vector geometry approach is characterized by a high successful detection rate (SDR) and a lower excessive detection rate (EDR) compared with alternative methods, and has been extensively validated across multiple ocean regions including the SCS, the Bay of Bengal, the subtropical counter current zone, the Gulf Stream, the North Pacific Ocean, and the Southern Ocean (Nencioli et al., 2010; Sun et al., 2019; An et al., 2022). The eddy identification and tracking procedure comprises three sequential steps: determination of eddy centers, delineation of eddy boundaries, and reconstruction of eddy trajectories. Eddy center detection requires the simultaneous satisfaction of four geometric constraints (Nencioli et al., 2010); in the present study, the parameters are set to A = 3 and B = 2, respectively. The eddy boundary is defined as the outermost closed streamline surrounding the eddy center, the eddy radius is defined as the mean distance from the boundary points to the eddy center, and eddy trajectories are determined by matching eddy center positions between successive time steps.

3 Results and Validation

3.1 SST Validation based on OSTIA

SCSORA reproduces SST trend patterns that are consistent with those of the satellite-based analysis product OSTIA (Figure 2). SST in the study region exhibits a pronounced warming trend, with the warming signal becoming increasingly evident after 2016 and reaching the highest positive anomaly levels of the entire study period by 2024. On interannual timescales, SST anomalies display a distinct alternating pattern of cold and warm phases, with negative anomalies predominantly concentrated around 2001–2010 and positive anomalies emerging during periods such as 2016–2024, indicating a significant warming trend. Furthermore, SCSORA accurately captures key interannual variability signals, including the pronounced warm anomaly associated with the strong El Niño event of 2009–2010 (Kim et al., 2011) and the marked warming episode during 2023–2024 driven by the combined effects of a sustained long-term warming trend and the re-emergence of

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large-scale ocean–atmosphere anomalies (Cheng et al., 2024; Terhaar et al., 2025). The RMSE of SST between SCSORA and OSTIA remains stable throughout the study period, ranging from 0.25 to 0.45°C with a mean RMSE of 0.34°C. These results indicate satisfactory model stability and demonstrate that SCSORA effectively reproduces both short-term fluctuations and long-term trends in SST.

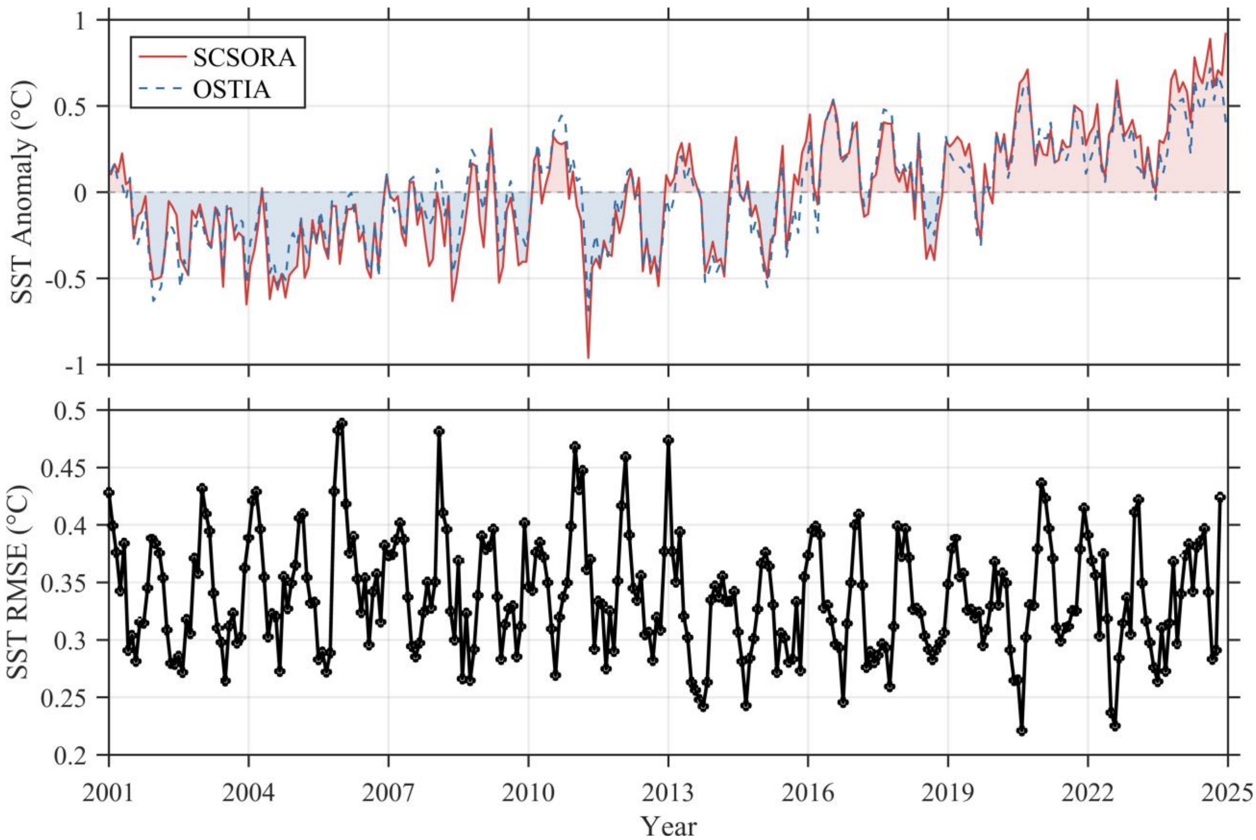

Figure 2. Time series of SST anomalies and RMSE relative to the 2001–2024 SST climatology. The comparison is shown between the SCSORA and OSTIA observational dataset. SST anomalies are computed as daily departures from the 2001–2024 climatological SST

3.2 SLA Validation based on AVISO

The AVISO multi-source satellite merged product represents an important reference dataset for SLA research and has been widely adopted in ocean model validation studies (Juhl et al., 2025; Kerry et al., 2024). SCSORA successfully captures the low-frequency variability of SLA over the period 2001–2024, exhibiting a high degree of agreement with AVISO satellite observations in terms of large-scale trends and interannual variability, with both datasets clearly exhibiting consistent multi-year oscillatory characteristics (Figure 3). In particular, the significant negative anomaly signals associated with La Niña events around 2010 and following 2016 are consistently reproduced in both datasets, demonstrating the reliability of SCSORA in capturing variability on interannual and longer timescales. The RMSE of SLA between the two datasets is generally maintained within the range of 4.5–9.7 cm and a mean value of 5.9 cm. The temporal stability of the error throughout the whole period

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indicates consistent and sustained model performance, confirming that SCSORA is capable of reproducing large-scale sea surface anomaly patterns with reasonable accuracy.

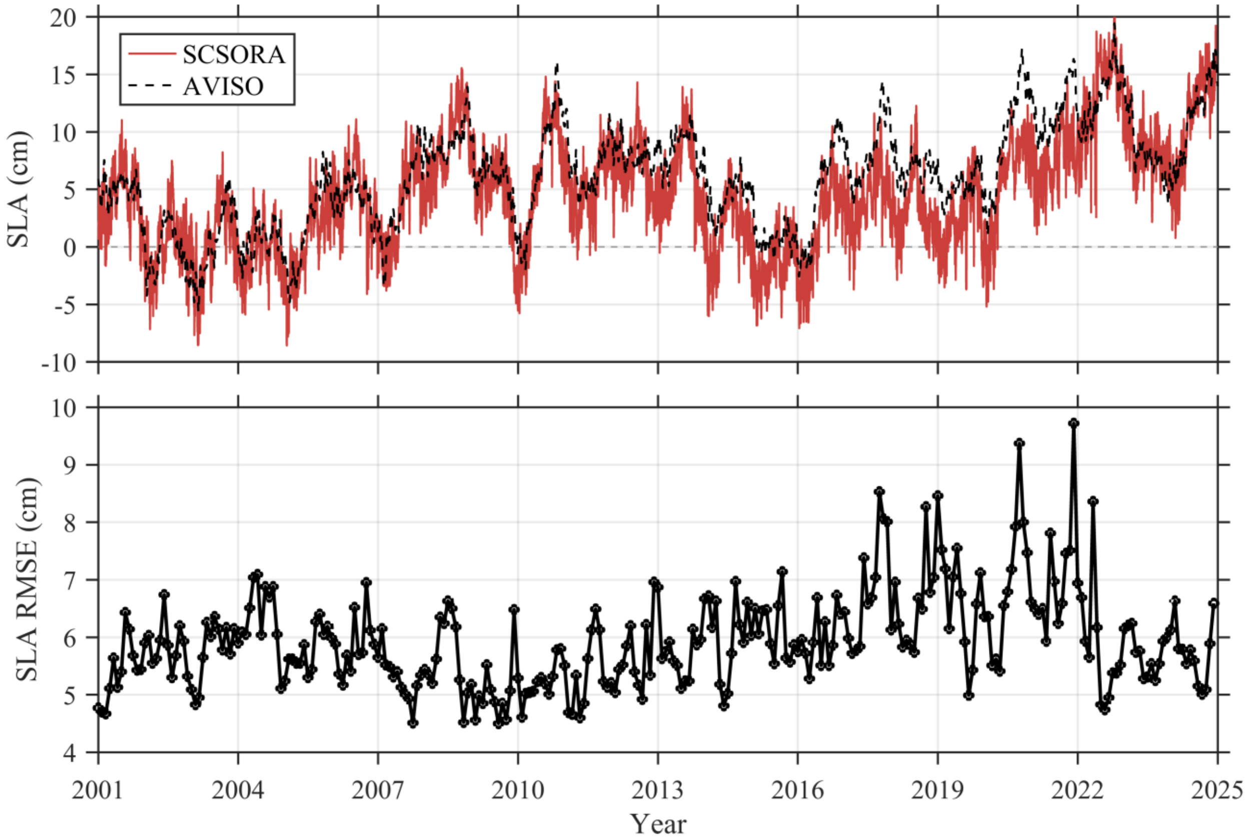

Figure 3. Time series of SLA and RMSE between the SCSORA and AVISO observations. RMSE represents the temporal deviation of the SCSORA from the observations over the same period.

3.3 Temperature/Salinity Validation Using In-Situ Observations

SCSORA shows generally well agreement with Argo float temperature–salinity profiles (Figure 4). Based on more than 10.9 million matched temperature samples, the validation results indicate a regression slope of 1.00, an R^2 of 0.99, and an RMSE of 0.56°C, demonstrating a high level of consistency between the SCSORA and observations throughout the entire water column. The corresponding statistics for salinity are a slope of 0.91, a R^2 of 0.91, and a RMSE of 0.06 PSU, respectively. The vertical bias distribution shows that temperature biases remain close to zero over most depth ranges, while relatively large variability is observed in the upper 200 m, likely associated with seasonal thermocline variability. A slight warm bias is present near the main thermocline at 200–600 m depth. For salinity, a negative bias is observed in the near-surface layer. Below 800 m, both temperature and salinity biases approach zero, and the spread decreases substantially.

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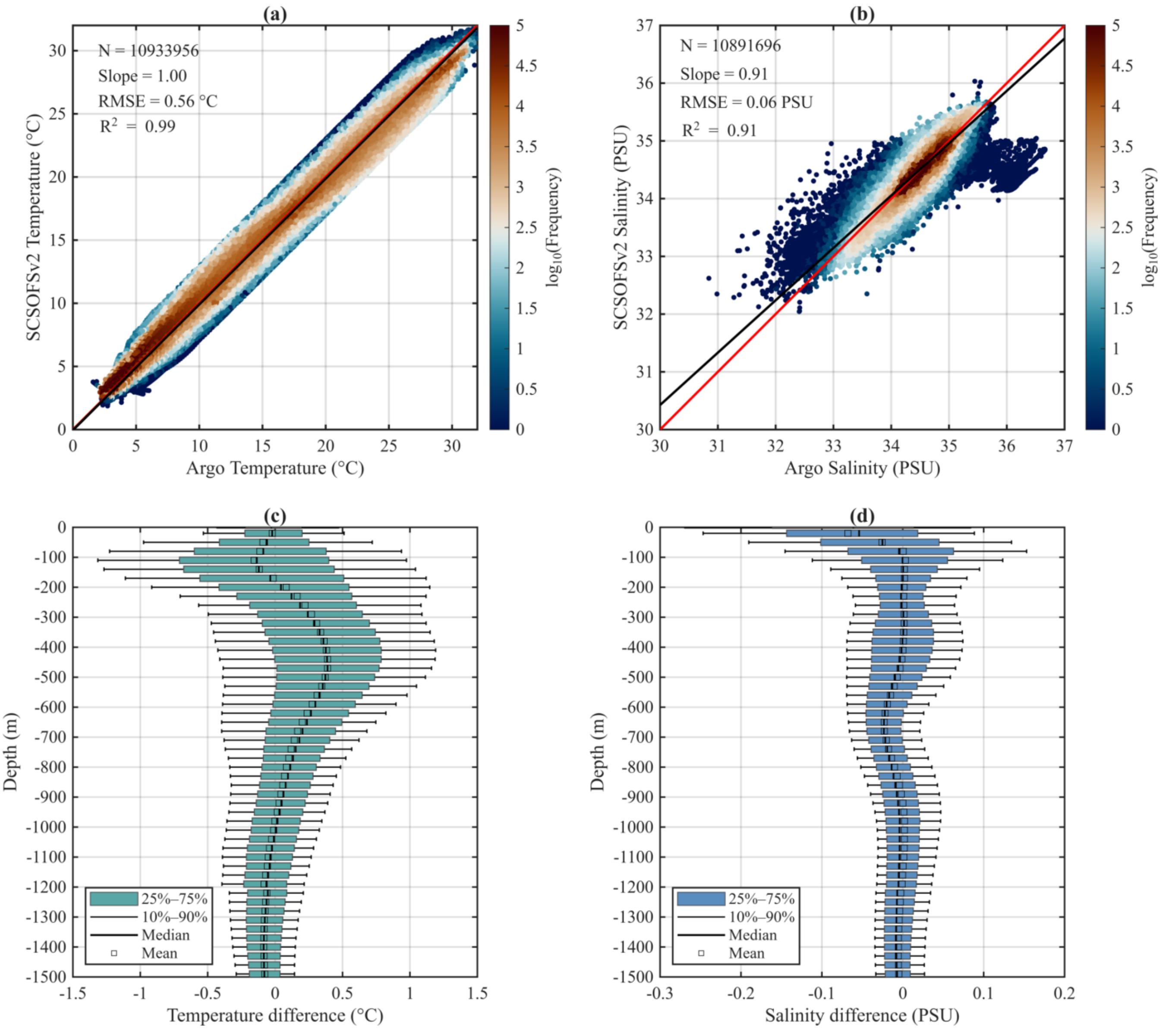

Figure 4. Comparison between SCSORA and ARGO observations. Panels a and b show scatter plots of temperature (T) and salinity (S) at observation points, with the 1:1 line indicated. The sample size is denoted by *N*. Panels c and d display the vertical distribution of analysis–observation differences (SCSORA minus ARGO) for temperature and salinity, illustrating the depth-dependent bias in the model.

Based on glider observations from six independent years (2015, 2017, 2018, 2019, 2020, and 2021), covering the depth range from the sea surface to 1000 m, the comparison indicates that the temperature differences between the SCSORA and the glider observations are generally small across all years. The mean biases throughout most of the water column remain within ±1.5°C (Figure 5). Relatively elevated spread is present in the surface layer of SCSORA, yet errors remain within 1.5°C throughout. Below 200 m, the interquartile range (25th–75th percentile) narrows substantially, indicating more stable model

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performance in the intermediate and deep layers. The salinity differences exhibit a depth-dependent structure similar to that of temperature: bias spread is larger in the upper and decreases progressively with depth. Across the six years, mean salinity biases below 400 m are generally close to zero, suggesting that SCSORA is capable of reproducing the halocline structures with reasonable fidelity. Overall, SCSORA demonstrates satisfactory agreement with the glider-observed temperature–salinity data, particularly in the subsurface and deeper layers, which demonstrates the reliability of the model in reconstructing subsurface thermohaline structures at the basin scale.

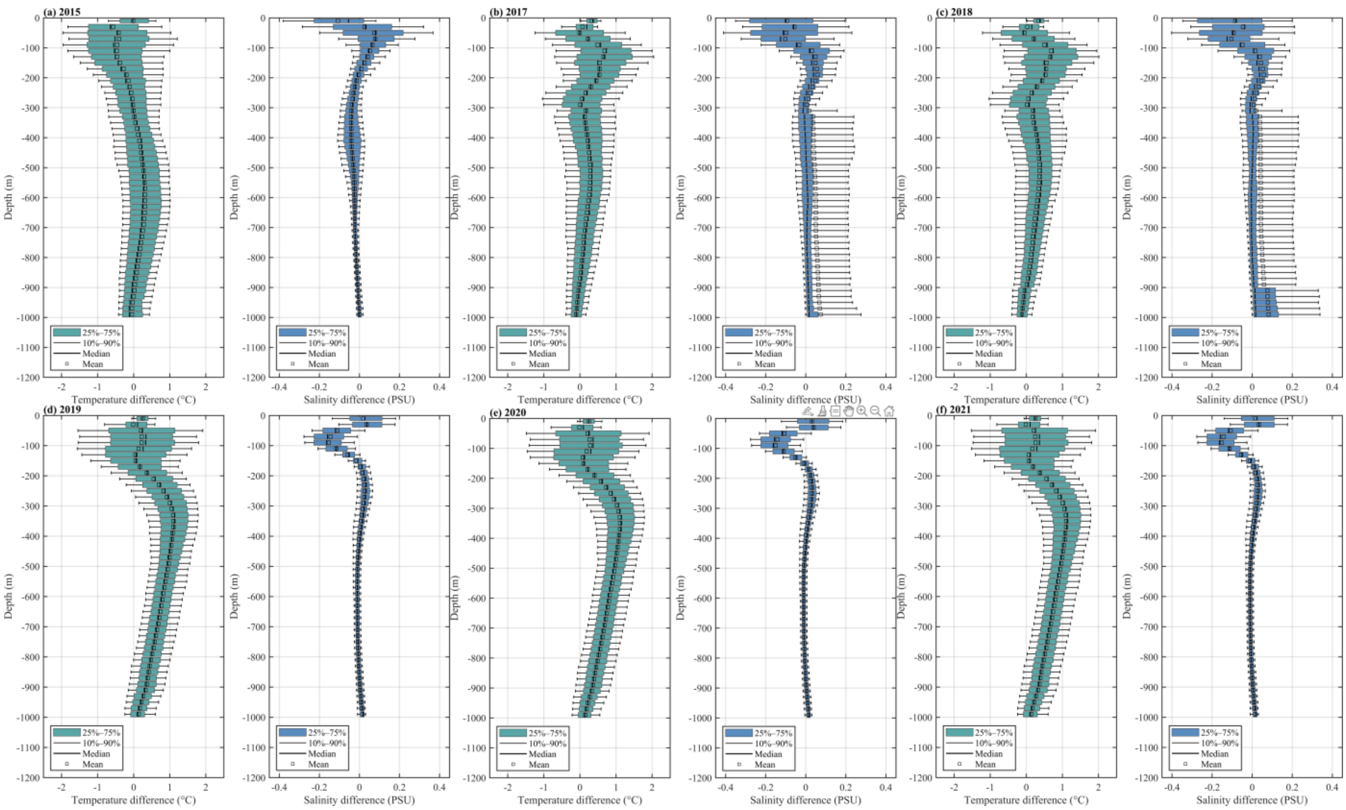

Figure 5. Vertical distribution of temperature (T) and salinity (S) differences between SCSORA and glider observations for each year. Each panel corresponds to a specific year, showing the model minus observed values, highlighting the depth-dependent bias of the model relative to the glider measurements.

3.4 Mixed layer depth

Climatological MLD is computed separately for the four seasons: spring, summer, autumn, and winter (Figure 6). Calculations of MLD are performed for SCSORA (left column) and GLORYS (middle column) using the standard criterion of a temperature difference threshold of $\Delta T = 0.2°C$ relative to the 10 m reference depth (Cheng et al., 2024). Both SCSORA and GLORYS exhibit good consistency in the spatial distribution of MLD across all four seasons, capturing the principal seasonal variability and regional contrasts between the deep SCS basin and the surrounding shelf and coastal regions.

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In spring, both products simulate relatively shallow MLD over most of the SCS (approximately 10–30 m), while deeper mixed layers exceeding 40 m appear in the central western Pacific region. The zonal mean profiles are in closed agreement throughout the domain, with a mean absolute error (MAE) of 3.5 m, indicating overall good consistency despite localized differences in the intensity of the deep mixed layer near 24° N.

In summer, under the strong stratification driven by solar heating, MLD shoals markedly in the northern western Pacific Ocean, with mean MLD maintained within 20–40 m across most latitude bands in both SCSORA and GLORYS. Agreement between the two datasets is the highest in this season, with a MAE of 3.0 m, demonstrating that SCSORA adequately reproduces the dominant physical mechanisms governing summer stratification. Nevertheless, both datasets exhibit MLD deepening in the southern part of the domain, which may be associated with enhanced vertical mixing driven by intensified southwest monsoon wind stress, precipitation effects, and salinity gradient changes (Thompson et al., 2014; Sallée et al., 2021; Chen et al., 2023). In addition, oceanic current dynamics and coastal upwelling may contribute to mixed layer deepening in the southern domain, producing a trend opposite to that observed in the northern region.

In autumn, the Asian monsoon system transitions gradually from the summer southwest monsoon to the winter northeast monsoon (Wang et al., 2009). As surface cooling intensifies and monsoon wind stress increases, MLD deepens again in the NSCS and the adjacent western Pacific Ocean, a seasonal evolution that is reasonably well reproduced by both products. The zonal mean profiles from the two products are broadly consistent in structure, with MLD of SCSORA simulating slightly shallower than that of GLORYS; the MAE is 2.0 m, indicating that SCSORA captures the physical characteristics of mixed layer deepening in this season.

In winter, it exhibits the most pronounced seasonal MLD signal of the year, closely associated with the vigorous winter monsoon forcing and substantial net heat loss at the ocean surface. Over the SCS and the adjacent northwestern Pacific Ocean, the winter northeast monsoon is accompanied by cold air intrusions and atmospheric cooling. These conditions enhance negative buoyancy flux and wind stress-driven mixing at the sea surface, leading to significant mixed layer deepening (Thompson et al., 2014; Thoppil et al., 2023). Both products simulate pronounced winter mixed layer deepening in the NSCS and the western Pacific region, consistent with the wintertime convective mixing process under monsoon forcing. The zonal mean profiles in winter also display the largest MLD values of the annual cycle, reaching up to 80 m north of 18° N, reflecting the basin-scale response to intense mixing driven by the winter northeast monsoon. The mean MAE between the two datasets in winter is 3.0 m.

Overall, the MAE between SCSORA and GLORYS remains at a relatively low level of 2.0–3.5 m across all four seasons, demonstrating that SCSORA is capable of reliably reproducing the seasonal variability of MLD in the SCS and adjacent regions, with an accuracy comparable to that of the well-established GLORYS reanalysis product.

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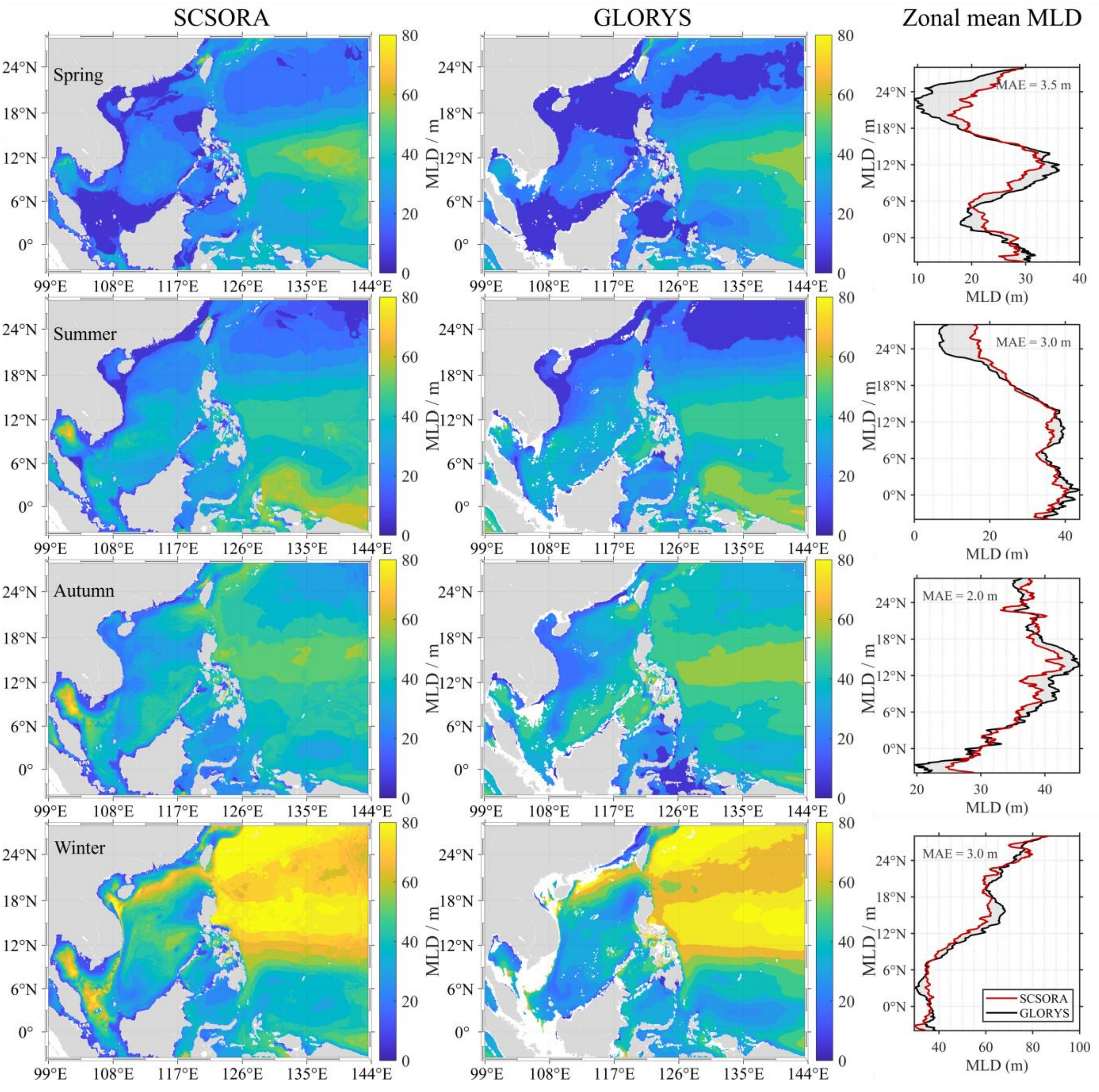

Figure 6. Seasonal climatological mixed layer depth (MLD) from SCSORA (left column) and GLORYS (middle column) for spring, summer, autumn, and winter, along with the corresponding zonal mean MLD profiles (right column; red: SCSORA, black: GLORYS). The mean absolute error (MAE) of zonal mean MLD between the two products is annotated in each right panel.

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4 Discussion

4.1 Spectral Energy Distribution

According to the validations in above, it is indicated that SCSORA is reliable and applicable in scientific research and operational contexts, SCSORA should be capable of reasonably reproducing the principal characteristics of the multiscale ocean dynamical processes, such as mesoscale eddies, MHW, upwelling, and oceanic fronts (Stammer et al., 1997; Stammer et al., 1998; Bian et al., 2023). In this section, we evaluate the potential advantages of SCSORA in characterizing dynamical processes from the mesoscale to the submesoscale according to frequency–wavenumber power spectral analysis. The frequency–wavenumber power spectral density (PSD) of surface current velocity in the study area (Figure 7) reveals that the spectral energy of all three products (SCSORA, GLORYS, and AVISO) is predominantly concentrated in the low-wavenumber, low-frequency domain ($K < 10^{-2}$ cpkm, $W < 10^{-3}$ cph). This indicates that dynamical variability in this region is governed by mesoscale eddies and basin scale low-frequency seasonal to interannual processes (Ferrari et al., 2009; Schubert et al., 2020; Villas et al., 2022). With increasing wavenumber and frequency, spectral energy decays systematically across all three datasets, consistent with the general characteristic of oceanic turbulent spectra whereby energy diminishes with decreasing spatial scale. Nevertheless, pronounced differences exist among the three products in their capacity to resolve energy in frequency–wavenumber space.

SCSORA exhibits the broadest and most continuous spectral energy distribution among three products, with spectral energy extending to relatively high wavenumbers (approximately 10^{-1} cpkm) and frequencies (approximately 10^{-2} cph), displaying a smooth and gradual decay in the transition from the mesoscale to the submesoscale. SCSORA is thus capable of effectively resolving ocean dynamical processes across multiple spatiotemporal scales, with particular strength in resolving submesoscale current variability at spatial scales of approximately 10 km, due to its about 4-km high horizontal resolution. GLORYS exhibits a spectral distribution similar to that of SCSORA from low to moderate wavenumbers; however, its energy begins to decay markedly as wavenumbers approach 10^{-2} cpkm and a progressive spectral rolloff becomes evident, reflecting the limitation of its effective resolution in characterizing high-wavenumber processes. In contrast, AVISO has the most restricted spectral coverage, with its energy largely confined to wavenumbers below approximately 3×10^{-3} cpkm. Consequently, the AVISO product primarily captures large-scale to mesoscale current variability and lacks the capability to resolve submesoscale processes due to its 25km low horizontal resolution.

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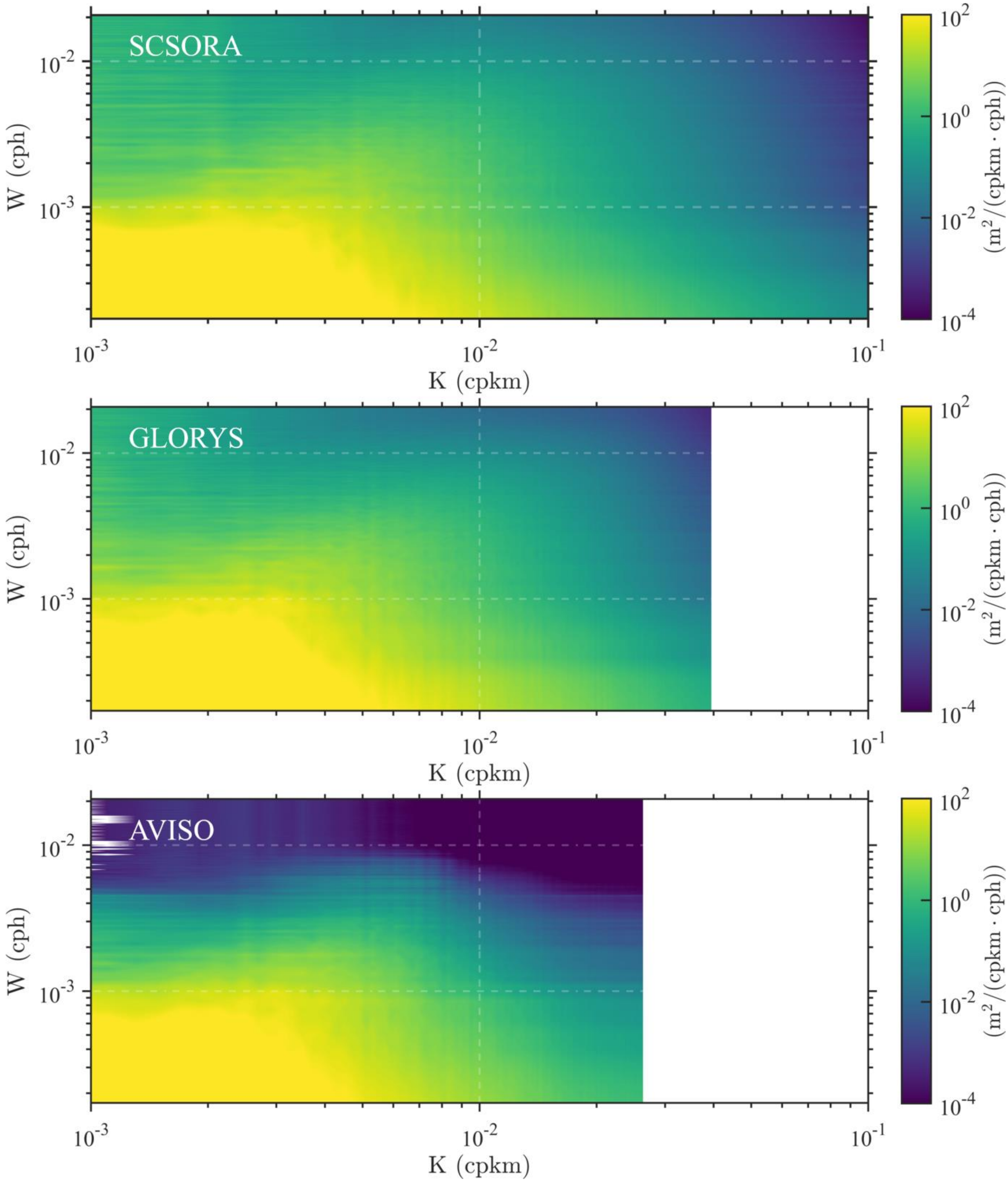

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Figure 7. Two-dimensional frequency-wavenumber power spectral density (PSD) of SSH from SCSORA (top), GLORYS (middle), and AVISO (bottom). The horizontal axis K denotes spatial wavenumber (cpkm, cycles per kilometer) and the vertical axis W denotes temporal frequency (cph, cycles per hour). The color shading indicates spectral energy density in units of m²/(cpkm·cph).

The one-dimensional spatial wavenumber spectrum of kinetic energy further reveals that spectral density amplitudes among the three products are in close agreement at low wavenumbers ($K < 10^{-3}$ cpkm), with values on the order of 10^4 m^2 s^{-2} $cpkm^{-1}$, indicating consistent representation of mesoscale to large-scale variability across all products (Figure 8). A pronounced spectral peak is evident in all three datasets near $K \approx 10^{-3}$ cpkm, indicating that energy is predominantly concentrated in low-frequency oceanic variability at spatial scales from hundreds to over one thousand kilometres. This is consistent with the well-established recognition of the SCS as a region of intense mesoscale eddy activity (Chen et al., 2011; Evans et al., 2022; Jin et al., 2024; Qiu et al., 2025). However, as wavenumber increases, differences among the datasets become progressively larger. The AVISO dataset decays rapidly beyond $K \approx 3 \times 10^{-3}$ cpkm, with a spectral slope approaching or steeper than k^{-3}, indicating that small-scale signals are substantially smoothed. This characteristic is inherently associated with the properties of satellite altimeter merged products, which are typically gridded using optimum interpolation methods that tend to attenuate high-wavenumber signals and suppress the representation of small-scale variability (Rio et al., 2016; Lguensat et al., 2019; Archer et al., 2020; Passaro et al., 2023). GLORYS exhibits a relatively gradual spectral decay at intermediate wavenumbers, but undergoes a rapid energy drop as wavenumbers approach 10^{-2} cpkm, reflecting the limitation of the model's effective resolution in characterizing high-wavenumber processes. In contrast, SCSORA exhibits a continuous spectral energy distribution across the submesoscale wavenumber range (10^{-2} to 10^{-1} cpkm), with a spectral slope intermediate between k^{-3} and k^{-2}, consistent with the spectral characteristics expected for the transition from mesoscale quasi-geostrophic dynamics to submesoscale ageostrophic processes (Capet et al., 2008; Callies et al., 2015; Zhang et al., 2016). This characteristic indicates that SCSORA is capable of resolving the energy distribution from the mesoscale to the submesoscale with reasonable fidelity, providing a more comprehensive representation of fine-scale oceanic dynamical variability. Furthermore, SCSORA retains comparatively rich spectral energy at high wavenumbers corresponding to spatial scales of approximately 10 km, indicating that it preserves a greater amount of small-scale current variability. In contrast, GLORYS and AVISO exhibit varying degrees of energy decay or spectral rolloff at these scales.

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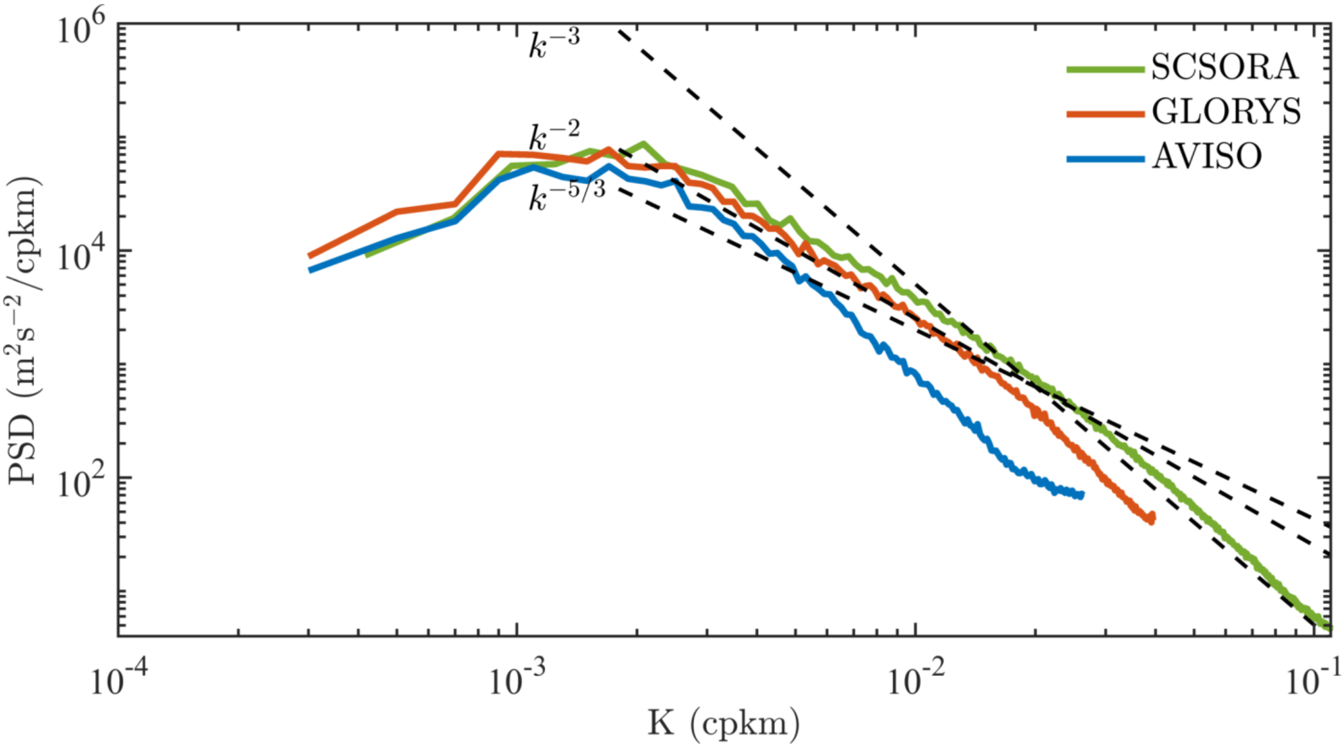

345 Figure 8. One-dimensional horizontal wavenumber power spectral density (PSD) of sea surface velocity from SCSORA (green), GLORYS (orange), and AVISO (blue). The horizontal axis K denotes spatial wavenumber (cpkm) and the vertical axis denotes spectral energy density (m^2s^{-2}/cpkm). Black dashed lines indicate theoretical spectral slopes of k^{-3} (Interior Quasigeostrophy), k^{-2} (Surface Quasigeostrophy with Ageostrophic Advection), and $k^{-5/3}$ (Surface Quasigeostrophy), serving as references for evaluating the energy distribution characteristics and turbulent dynamics consistency of each product across different spatial scales.

350 **4.2 Spatiotemporal Characteristics of Heatwaves**

MHWs are widely recognized as important drivers of marine ecosystem stress and regional climate variability (Frölicher et al., 2018; Oliver et al., 2018). The combination of high-resolution temperature data with dynamical process information is essential for understanding the spatial distribution and intensity evolution of MHWs. Statistical results for the period 2001–2024 indicate that the spatial distributions of MHW characteristics derived from SCSORA and OSTIA are broadly consistent
355 (Figure 9), with both datasets exhibiting pronounced spatial heterogeneity: MHW frequency in the NSCS is substantially higher than in the southern SCS, and maximum intensity likewise displays a north-high, south-low spatial pattern. The regions of strongest MHW intensity in both SCSORA and OSTIA are located at the Taiwan Strait. Compared with OSTIA, SCSORA resolves richer mesoscale spatial variability. The spatial distribution of mean MHW intensity is broadly consistent between the two products, with mean intensity generally below 1.5°C in the southern SCS and increasing progressively northward along
360 the coastline.

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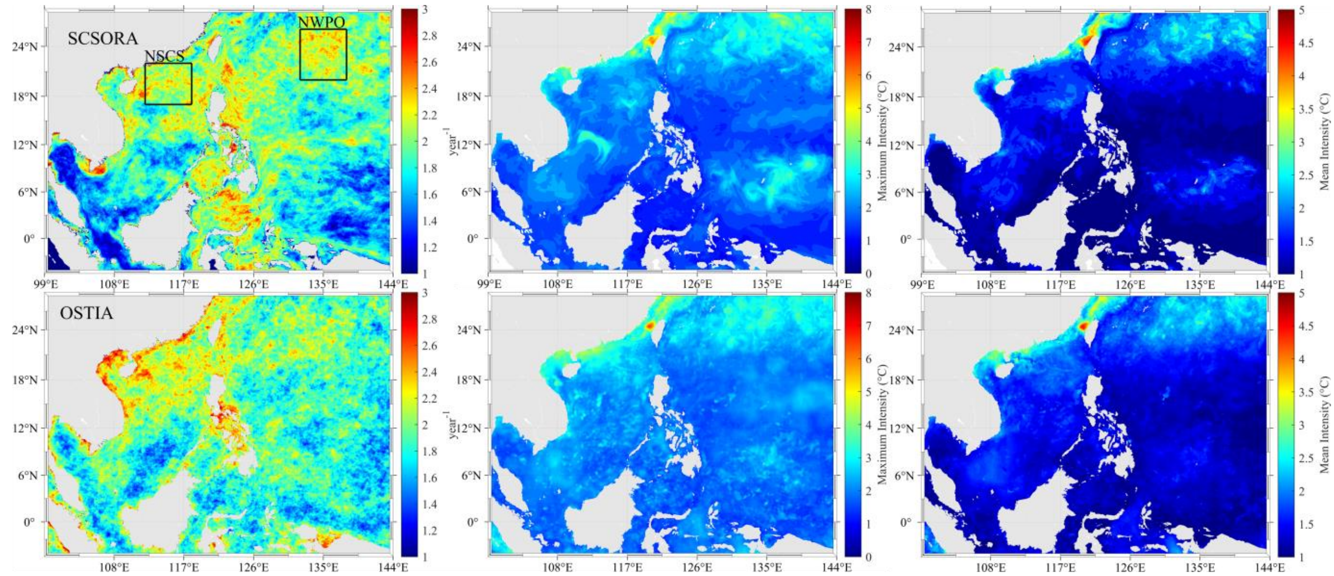

Figure 9. Spatial distribution of climatological marine heatwave (MHW) characteristics from SCSORA (top row) and OSTIA (bottom row), including annual MHW frequency (left column, units: events yr^{-1}), maximum intensity (middle column, units: °C), and mean intensity (right column, units: °C). Black boxes in the left column denote the NSCS and northwestern Pacific Ocean (NWPO) subregions selected for further analysis.

Two characteristic subregions, the NSCS and the NWPO, are selected to analyze the interannual variability of MHWs (Figure 10). In both subregions, SCSORA and OSTIA show good consistency in the interannual variability of MHW frequency and duration, both exhibiting an increasing trend that becomes particularly evident after 2010. In the NSCS, MHW events count during 2000–2010 are generally low and relatively stable, with no more than two events per year. From 2010 onwards, MHW events become progressively more frequent and longer-lasting, with SCSORA recording up to seven events in individual years, durations reaching 19 days, and cumulative intensities exceeding 25°C days. In the NWPO, both SCSORA and OSTIA reveal a pronounced intensification of MHW activity around 2015–2016, which closely coincides with the strong El Niño event of 2015–2016. ENSO modulates the occurrence of MHWs through atmospheric teleconnections that favour the seasonal persistence of large-scale high-pressure ridge systems, suppressing local vertical mixing and cooling, thereby providing favourable thermodynamic background conditions for the onset and maintenance of MHWs in this region (Holbrook et al., 2019; Sen Gupta et al., 2020; Gregory et al., 2024; Xie et al., 2025). Following a relatively quiescent period during 2017–2018, MHW activities reach another peak in 2020. This intensification is consistent with record-breaking MHW events reported in the northwestern Pacific Ocean in recent studies (Cheung et al., 2020; Noh et al., 2023), which are closely associated with anomalous strengthening of the western North Pacific subtropical high (WNPSH). This anomalous circulation pattern promotes sustained sea surface warming by enhancing shortwave radiation, reducing wind speed, and suppressing evaporative cooling, while La Niña-type background conditions and oceanic heat advection further amplify regional heat accumulation (Chen et al., 2023; Han et al., 2023; Yao et al., 2023). SCSORA records a cumulative intensity exceeding 25°C days in 2024,

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which is the highest value in the entire record period. OSTIA also exhibits a similar peak but with a slightly lower magnitude, suggesting that SCSORA may resolve finer-scale thermal structures, thereby capturing stronger localized MHW signals.

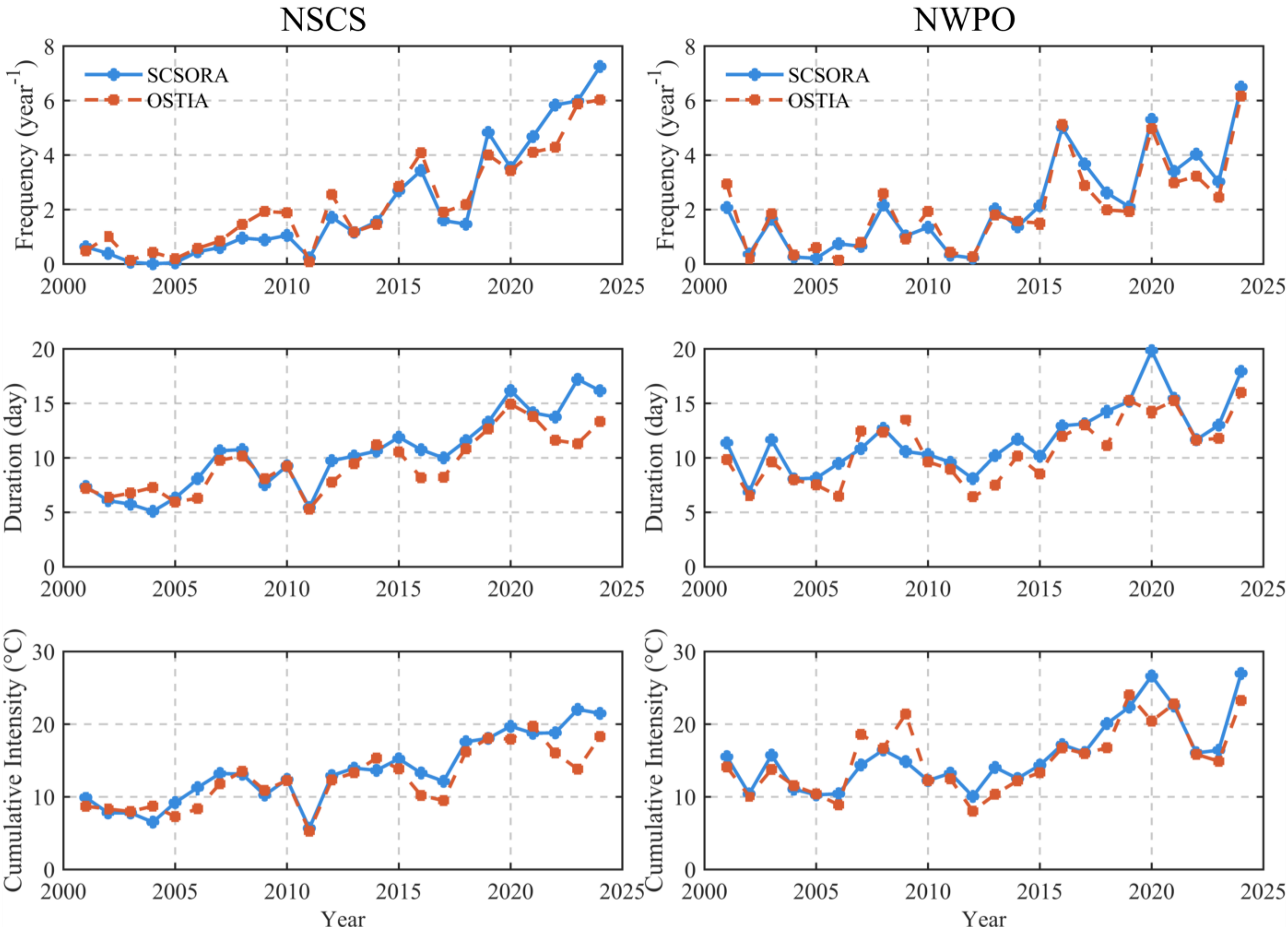

Figure 10. Interannual variability of marine heatwave (MHW) characteristics in the NSCS (left column) and the NWPO (right column) during 2001–2024, including annual frequency (top row, units: year^{-1}), mean duration (middle row, units: days), and cumulative intensity (bottom row, units: °C). Blue lines with circles and red lines with squares represent results derived from SCSORA and OSTIA, respectively.

Figure 11 presents the daily SST, climatology, and MHW threshold for the NSCS and NWPO subregions in 2024 from both SCSORA and OSTIA, with MHW events identified as periods exceeding the threshold highlighted in red shading. Overall, both datasets display a consistent seasonal cycle: SST reaches its minimum in winter (January–March) and its peak in summer (June–September), while the threshold curve lies distinctly above the climatology, defining the criterion for MHW identification (Hobday et al., 2016). In the NSCS, both SCSORA and OSTIA identify significant summer MHW events, though differences exist at the event scale. The SCSORA SST time series is relatively smooth with weak high-frequency fluctuations, yielding longer-duration events (maximum 34 days) and slightly lower peak intensities (0.71°C). OSTIA is more sensitive to

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high-frequency variations, capturing shorter events (maximum 23 days) with slightly higher peak intensities (0.75°C). In the NWPO, MHW signals are generally weaker overall, with shorter duration and lower intensity; both datasets detect six events, though SCSORA records a higher magnitude for the strongest event compared with OSTIA (0.64°C versus 0.46°C), suggesting that SCSORA responds more fully to mesoscale and background variability. These results further confirm that the two datasets exhibit good consistency in the seasonal evolution and principal occurrence periods of MHWs. SCSORA demonstrates clear advantages in temporal continuity and event stability, making it well suited for investigating MHW evolution and long-term trends, whereas satellite-reconstructed products such as OSTIA are more sensitive in capturing short-term extreme fluctuations but may be affected by observational uncertainties and therefore require validation against *in-situ* observations.

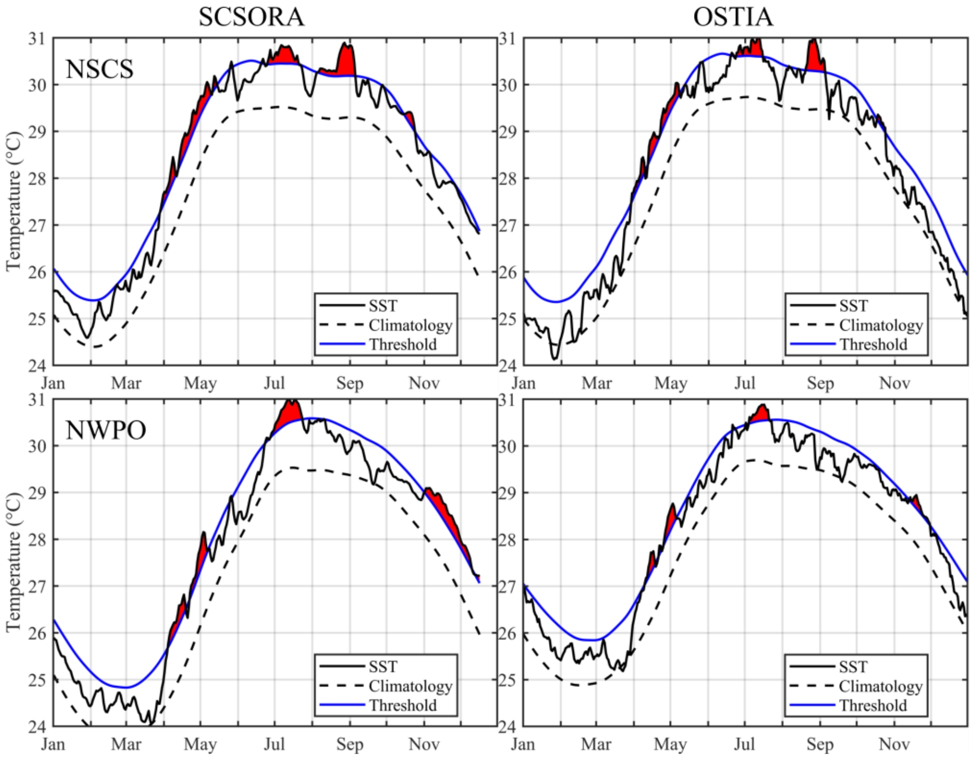

Figure 11. Seasonal evolution of area-averaged SST from SCSORA (left column) and OSTIA (right column) in the NSCS (top row) and the NWPO (bottom row) for the year 2024. Black solid lines indicate daily mean SST in 2024, black dashed lines indicate climatological mean SST, and blue solid lines indicate the MHW threshold (90th percentile of climatology). Red shading denotes marine heatwave (MHW) events where daily SST exceeds the threshold.

4.3 Mesoscale Eddy Dynamics and Marine Heatwave Modulation

Statistical results reveal that cyclonic eddies outnumber anticyclonic eddies in the eddy-active region of the SCS (102–122° E, 5–24° N) (Figure 12). SCSORA and AVISO satellite observations exhibit broadly consistent interannual fluctuations, though SCSORA resolves a slightly higher eddy count, which may be attribute to its higher horizontal resolution enabling the detection of mesoscale eddies that fall below the detection threshold of satellite altimetry. Regarding seasonal variability

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(Figure 12, lower panels), cyclonic eddies exhibit a bimodal distribution with two distinct peaks occurring in March–May and August–October, respectively. The spring peak is closely associated with the accumulation of available potential energy (APE) driven by deepening of the mixed layer during winter. Under strong winter wind forcing, the deepened mixed layer gives rise to substantial APE accumulation at horizontal density fronts. As surface heating intensifies in spring, the mixed layer shoals rapidly through restratification, releasing the deep frontal structure and triggering vigorous mixed layer baroclinic instability (MLI), which drives the formation of mixed layer eddies (Steinberg et al., 2022; Schubert et al., 2023). Furthermore, the approximately 2–3-month lagged response of baroclinic instability to eddy activity (Zu et al., 2024) further supports the interpretation that winter APE accumulation constitutes the primary mechanism driving the spring cyclonic eddy burst. The secondary peak in late summer to early autumn (August–October) is likely closely associated with typhoon forcing. This period coincides with the peak typhoon season, during which the intense cyclonic wind stress curl (WSC) generated by passing typhoons drives Ekman divergence, inducing upwelling of subsurface water while simultaneously injecting positive relative vorticity into the upper ocean; these two processes act in concert to promote the development of cyclonic rotational flow fields into mesoscale cyclonic eddies (Lin et al., 2025; Lu et al., 2026; Ma et al., 2021). In contrast, anticyclonic eddies exhibit weaker seasonal variability, displaying only a single broad peak spanning May to August.

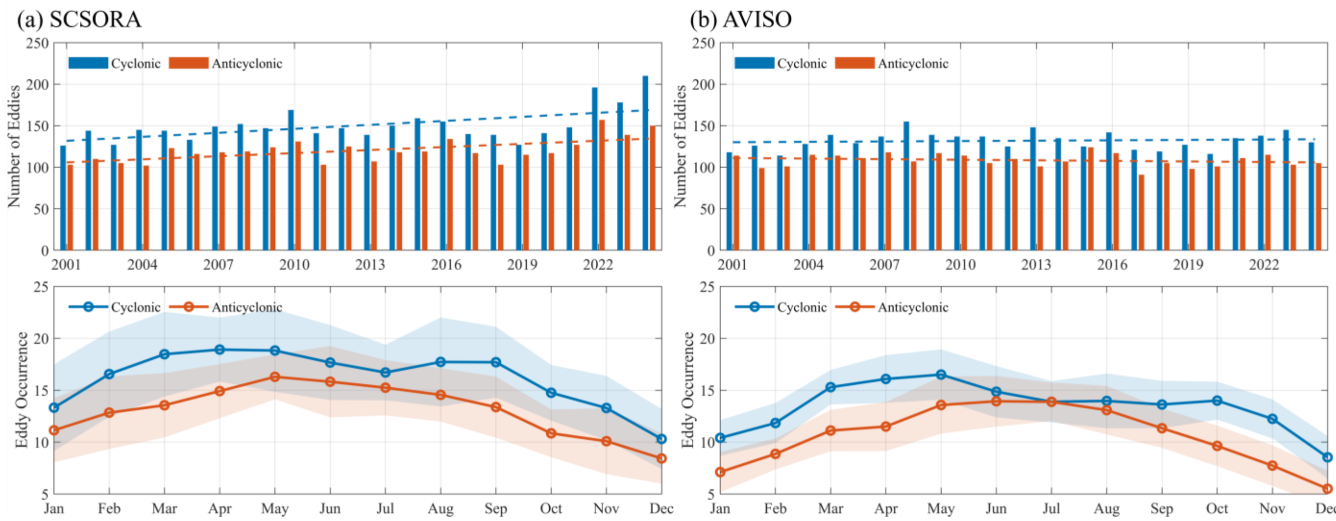

Figure 12. Statistical characteristics of cyclonic (blue) and anticyclonic (orange) eddies in the SCS identified from SCSORA (left column) and AVISO (right column). Top row shows the interannual variation in eddy numbers during 2001–2024, with dashed lines indicating the corresponding linear trends. Bottom row shows the monthly climatological eddy occurrence, with solid lines representing multi-year monthly means and shading indicating the interannual variability range for each month.

Over the period 2001–2024, both the annual count of mesoscale eddies and the frequency of MHW occurrence in the SCS exhibit pronounced positive trends (Figure 13). Prior to 2010, the background SST of the SCS was relatively low, and the positive SST anomalies induced by eddies were insufficient to consistently exceed the local climatological 90th percentile threshold required for MHW identification (Hobday et al., 2016), resulting in MHW frequency remaining at a relatively low level. After 2010, MHW frequency in the SCS increased systematically under the combined influence of a warming climatic

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background and eddy dynamics. From the perspective of the climatic background, sustained ocean warming driven by anthropogenic forcing has elevated background SST throughout the SCS, effectively narrowing the gap between ambient SST and the MHW trigger threshold (90th percentile), thereby rendering extreme heatwave events more probable (Oliver et al., 2021). Against this background, eddy-induced heat flux convergence directly drives the growth and maintenance of MHWs (Bian et al., 2023; Sun et al., 2026).

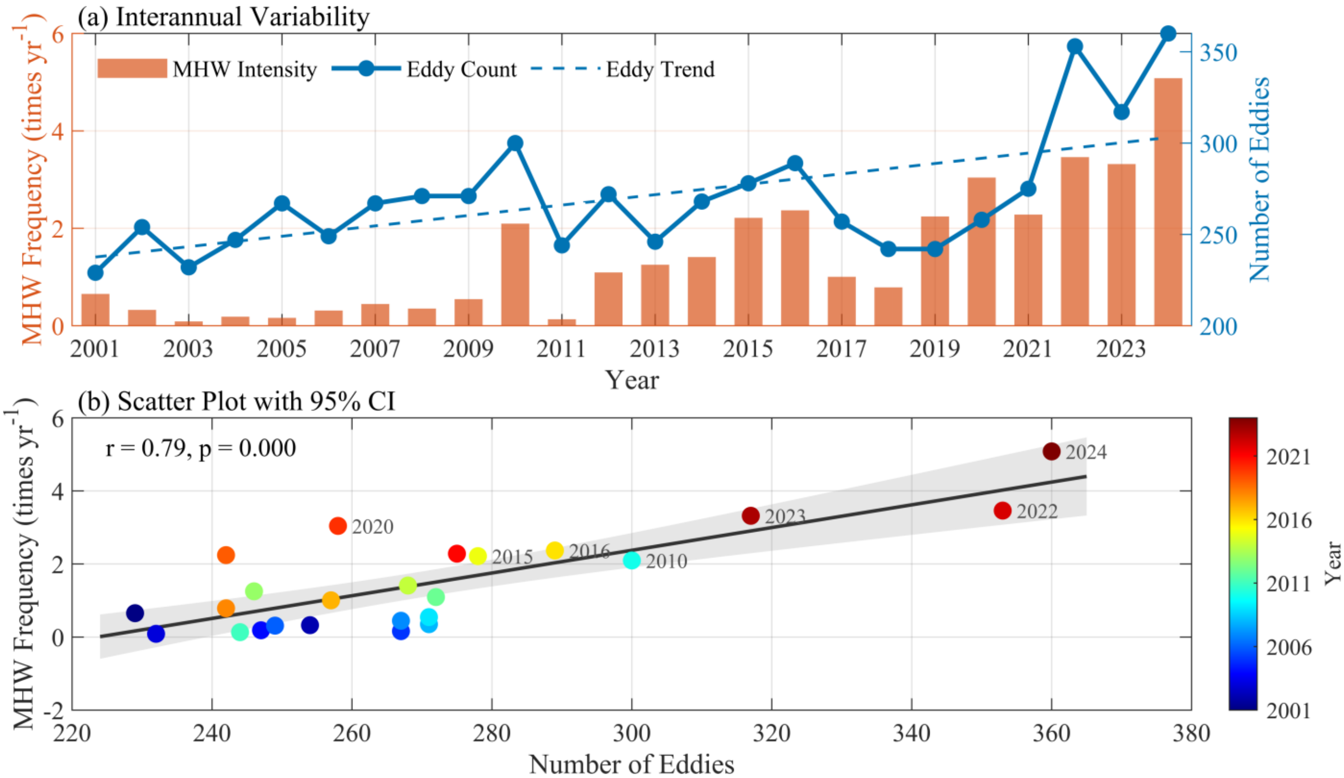

Figure 13. Interannual co-variability between MHWs and mesoscale eddies in the SCS. (a) Time series of annual MHW frequency (orange bars, left axis) and total eddy count (blue circles with line, right axis) during 2001–2024, with the blue dashed line indicating the linear trend in eddy count. (b) Scatter plot of annual MHW frequency versus eddy count, with point colors indicating the corresponding year, the black solid line representing the linear regression fit, and grey shading denoting the 95% confidence interval. The correlation coefficient r and p-value are annotated in the upper left corner.

A large number of research has employed the 90th percentile threshold to identify and characterize MHWs (He et al., 2024; Oliver et al., 2021; Sun et al., 2026; Wyatt et al., 2023; Yao et al., 2024); however, constrained by the limited availability of 3D temperature data, these studies have predominantly focused on the 2D spatial distribution of SST anomalies, with insufficient attention paid to the vertical penetration structure of heatwaves in the subsurface and deeper layers. In fact, mesoscale eddies are capable of transporting heatwave signals from the sea surface into the subsurface through their rotational flow fields and vertical transport mechanisms, giving rise to 3Dly structured heatwaves embedded within eddies (He et al., 2024; Zhang et al., 2016). The present study employs SCSORA to reveal the 3D distribution characteristics of heatwaves in typical eddy regions of the SCS from a 3D perspective (Figure 14). In regions dominated by anticyclonic eddies (Figure 14a), heatwave temperature anomalies ($T - T_{90}$) exhibit pronounced positive values at all depth levels. This phenomenon is closely related to the fundamental dynamical characteristics of anticyclonic eddies, whose convergent downwelling circulation depresses isopycnal surfaces and continuously transports warm water into the subsurface (He et al., 2024; McGillicuddy, 2016). Under this dynamical regime, heatwave signals propagate downward along the eddy axis, forming a 3D heatwave structure with strong vertical coherence and considerable penetration depth.

The 3D structure of heatwaves in regions dominated by cyclonic eddies (Figure 14b) presents characteristics opposite to those of anticyclonic eddies. The divergent upwelling circulation of cyclonic eddies elevates isopycnal surfaces and transports subsurface cold water upward (Cao et al., 2026; Liu et al., 2024; Qu et al., 2022), thereby suppressing the downward propagation of heatwave signals in the eddy center region. Nevertheless, constrained by the law of mass conservation, the upwelling at the eddy center must be compensated by downwelling at the eddy periphery, which transports surface warm water into the subsurface and generates localized warming effects at the eddy margins (Qu et al., 2022). As a result, MHW signals appear in arc-shaped or ring-shaped distributions at the eddy periphery, forming a spatial pattern characterized by cooling at the center and warming at the margins. This implies that, in the presence of cyclonic eddies, heatwave signals are not simply suppressed and eliminated but undergo spatial reorganization under eddy dynamics, migrating from the eddy center toward the subsurface periphery to form thermal accumulation zones that are more concealed yet remain ecologically significant.

Interestingly, in a eddy-pair configuration consisting of two anticyclonic eddies, both eddies exhibit significant positive temperature anomalies at the sea surface, yet markedly divergent structures emerge in the subsurface (Figure 14c). The left anticyclonic eddy possesses vigorous convergent downwelling circulation that continuously forces substantial volumes of warm water below the thermocline, producing a subsurface-enhanced heatwave (Song et al., 2025; Zhang et al., 2023). In contrast, the region dominated by the right anticyclonic eddy displays positive anomalies at the surface but negative anomalies in the subsurface, forming a subsurface-reversed heatwave. It can be attributed not only to the intrinsic mechanism whereby the weaker downwelling of the right eddy is insufficient to penetrate the thermocline (Song et al., 2025; Zhang et al., 2023), but also to the compensatory upwelling at the periphery of the stronger left anticyclonic eddy, which may extend into the inter-eddy region and generate additional cooling effects, thereby cooperatively amplifying the cold anomaly signal in the subsurface of the right eddy.

It is worth noting that anticyclonic eddies, cyclonic eddies, and eddy-pair configurations are all capable of triggering and modulating the 3D development of MHWs under appropriate conditions. Moreover, subsurface heatwave intensity in eddy regions frequently exceeds that at the sea surface, implying that relying solely on SST threshold criteria for heatwave identification and intensity assessment may substantially underestimate the actual ecological impact of subsurface heatwaves.

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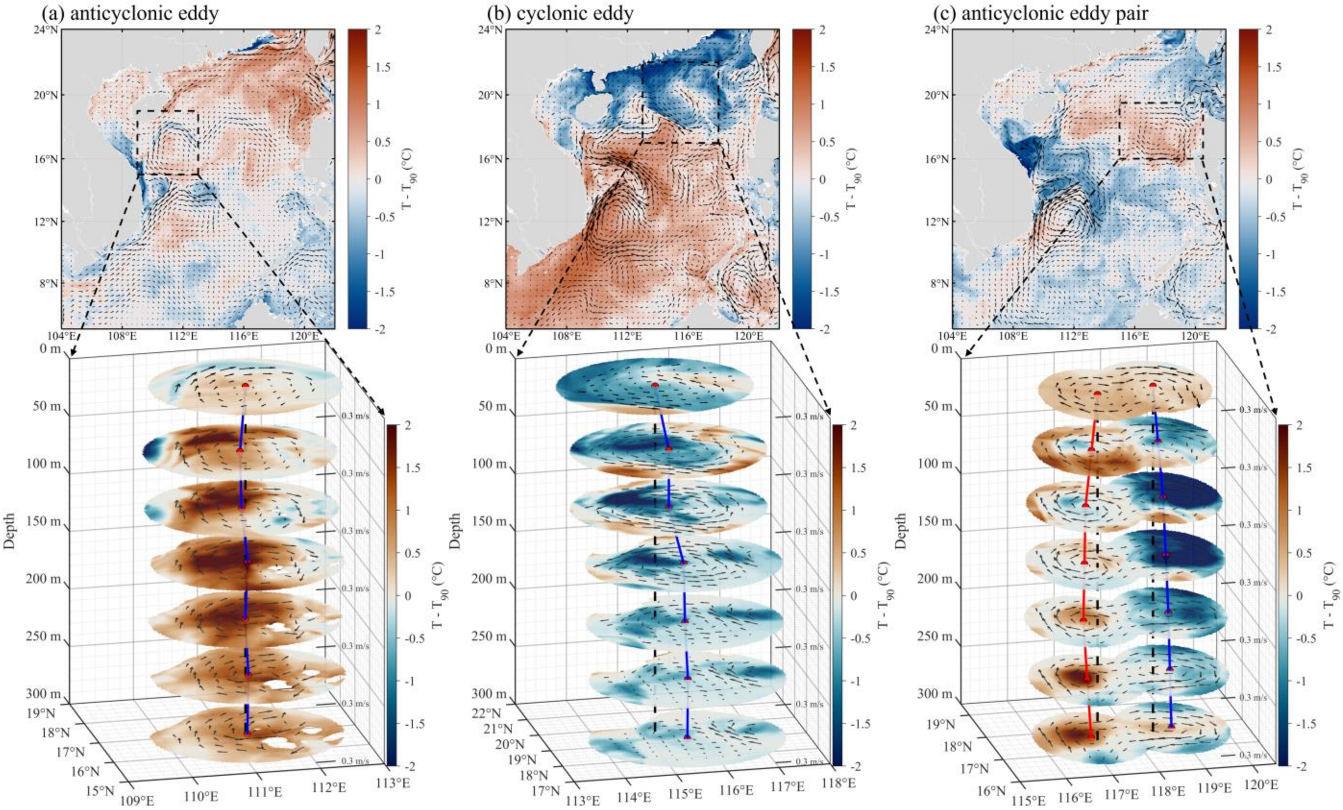

Figure 14. 3D structure of MHWs in representative eddy-controlled regions. Left, middle, and right columns correspond to an anticyclonic eddy, a cyclonic eddy, and a compound double-anticyclonic eddy structure, respectively. Top row shows the SST anomaly (T−T₉₀, units: °C) with black arrows indicating surface currents and black dashed boxes marking the eddy-influenced region. Bottom row shows the 3D vertical structure of MHW temperature anomalies (T−T₉₀) within the corresponding eddy region (depth range: 0–300 m), with black arrows on each horizontal slice indicating the current field at that depth level, and vertical colored lines marking the eddy center positions and their lateral displacement with depth

5 Data availability

The SCSORA dataset is publicly released in NetCDF format at https://doi.org/10.12378/geodb.2026.2.005.V1 (Zhu et al., 2026) and will be updated on a rolling basis. During the peer-review process, the full dataset is additionally accessible via a private FTP server (host: www.hellosea.org.cn, port: 60022, username: SCS_zhang, password: Sml123456).

6 Conclusions

The present study proposes a long-term, high-resolution (1/30°) oceanic reanalysis dataset for the SCS, named as SCSORA, covering the period 2001–2024, based on the SCSOFSv2, providing daily mean fields of 3D temperature, salinity, density, current velocity, and 2D SSH. The system employs the EnOI method in conjunction with the FGAT approach to handle asynchronous observations, assimilating satellite-derived OISST, AVISO Level 3 along-track satellites SLA, and *in*-

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situ temperature–salinity Argo profiles. Validation against independent observational datasets demonstrates that SST RMSE remains stable within the range of 0.25–0.45°C (mean 0.34°C) and SLA RMSE within 4.5–9.7 cm (mean 5.9 cm), indicating that SCSORA reliably reproduces both short-term oceanic variability and long-term trends. Vertical temperature and salinity biases are generally maintained within ±1.5°C and ±0.2 PSU, respectively, and converge substantially below 200 m depth. Frequency–wavenumber spectral analysis confirms that SCSORA outperforms coarser-resolution products in resolving spectral energy across mesoscale to submesoscale range. SCSORA is capable of capturing multiscale ocean dynamical processes, including mesoscale and submesoscale eddy activity, eddy-driven vertical transport, and mixed layer processes, and successfully reproduces the spatial distribution, occurrence frequency, and intensity characteristics of MHWs. The dataset enables the revelation of the 3D eddy-embedded heatwave structure formed under eddy modulation, as well as the distinct modulation mechanisms of cyclonic eddies, anticyclonic eddies, and eddy-pair configurations on subsurface MHWs. The high resolution and 3D nature of SCSORA provide more reliable data support for analyses of seasonal and interannual variability in the SCS, validation of regional ocean models, and long-term climate change monitoring.

Author contributions

Conceptualization: XMZ; Data curation: XMZ, XRZ; Formal analysis: XMZ, XRZ; Funding acquisition: XMZ; Investigation: XRZ, HLW; Methodology: XMZ, ZZ, GL, JL; Project administration: XMZ, HW; Software: XMZ, ZZ, GL; Supervision: XMZ, HW; Validation: XRZ, HLW; Visualization: XRZ; Writing – original draft: XRZ; Writing – review & editing: XMZ, XRZ. All authors have read and agreed to the published version of the manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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