



Divergent responses of marine heatwaves to multiple typhoons in the nearshore South China Sea

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ABSTRACT

Marine heatwaves (MHWs) and typhoons are two extreme events that threaten coastal ecosystems, but their interaction remains far from fully understood. Based on in situ temperature observations from the Maritime Meteorological Observation Platform and 33-year reanalysis data, this study investigates the responses of MHWs to four typhoons (Khanun in 2017, Higos in 2020, Nangka in 2020 and Chaba in 2022) in the nearshore South China Sea. The reanalysis data are found to generally reproduce the observed temperature variations for the majority of the time. Results show three interaction outcomes between MHWs and typhoons: maintenance during Typhoon Higos, dissipation during Typhoons Khanun and Nangka, and generation during Typhoon Chaba. Further analysis reveals that the maintenance of the MHW was associated with the weak intensity of Typhoon Higos and its position to the left of the typhoon's track. The dissipation of the MHW resulted from seasonal cooling, which added to the cooling induced by Typhoons Khanun and Nangka. The generation of the MHW was attributed to the vertical mixing induced by Typhoon Chaba, which warmed the water near the seafloor. This study provides insight into the role of typhoons in modulating MHWs.

1. Introduction

Extreme events pose significant challenges to natural ecosystems and human society (Diakakis et al., 2015; Frölicher and Laufkötter, 2018; Smale et al., 2019; Zhang et al., 2021; Burger et al., 2022; Liu et al., 2025), particularly when they occur simultaneously or in close spatio-temporal proximity (Zscheischle and Seneviratne, 2017; Zscheischler et al., 2018; Gruber et al., 2021; Burger et al., 2022; Liu et al., 2023; Zhou et al., 2025). Typhoons, as one type of extreme events, can devastate critical habitats such as coral reefs and mangroves, and cause phytoplankton blooms (Wang, 2020; Cooke et al., 2022; Feehan et al., 2024). In coastal regions, typhoons can trigger storm surges and abrupt temperature variations, threatening coastal infrastructure and marine ecosystems (Lagmay et al., 2015; Wang, 2020; Medvedev et al., 2022; Heidarzadeh et al., 2025). Furthermore, marine heatwaves (MHWs), another type of extreme events, have significant biological and ecological impacts globally, leading to coral bleaching, mass mortality of coastal fish, and hypoxia (Bond et al., 2015; Smale et al., 2019; Hu

et al., 2021; Wyatt et al., 2023; Guibourd de Luzinais et al., 2024). A comprehensive understanding of these extreme events is critical for risk management and policy making, particularly in coastal regions characterized by growing populations and fragile ecosystems (Glenn et al., 2016; Zscheischler et al., 2018; Dzwonkowski et al., 2020).

Recently, the interaction between typhoons and MHWs has become a research hotspot. On one hand, the maintenance and development of typhoons depend on the heat from the upper ocean (e.g. Emanuel, 2003; Dare and McBride, 2011a; Tory and Dare, 2015). As extreme ocean warming events, surface MHWs can supply additional heat to typhoons, thereby creating a favorable condition for their strengthening (Pun et al., 2023; Choi et al., 2024; Radfar et al., 2024; Saranya et al., 2024). On the other hand, typhoons can inject substantial momentum and energy into the ocean, generating near-inertial waves with strong vertical shear (Cao et al., 2018; Raja et al., 2022) and driving intense turbulent mixing during their passage (Zhang et al., 2016; Zhang et al., 2021; Cheng et al., 2024). The intense mixing further induces surface cooling and subsurface warming, with the maximum anomalies

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occurring near or below the mixed layer base (Vincent et al., 2012; Zhang et al., 2021; Liu et al., 2022; Qiao et al., 2022; Cheng et al., 2024; Han et al., 2024). Consequently, typhoon-induced surface cooling may disrupt the evolution of surface MHWs (Pun et al., 2025), whereas subsurface warming can persist (Park et al., 2011; Zhang et al., 2016, 2023; Qiao et al., 2022) and potentially evolve into subsurface MHWs (Wang et al., 2025; Liu et al., 2026). Moreover, Saranya et al. (2026) reported that typhoon-induced near-inertial waves can modulate the upper-ocean temperature profiles and delay the onset of MHWs.

Although previous studies have documented various interaction mechanisms between typhoons and MHWs, these findings are derived from different regions or individual case events. It remains unclear whether distinct typhoon-MHW interaction patterns can emerge within the same region over multiple years, which motivates the present study. Based on in situ water temperature observations collected during the passages of multiple typhoons at the Maritime Meteorological Observation Platform, along with 33-year reanalysis data, we systematically examine the typhoon-MHW interactions in the nearshore South China Sea (SCS) and explore the underlying dynamics. These findings will deepen the understanding of typhoon-MHW interactions and contribute to the development of monitoring and response strategies for coastal extreme events in the SCS.

2. Data and methods

2.1. Data

The Global Ocean Reanalysis and Simulations (GLORYS) 12V1 product (https://data.marine.copernicus.eu/product/GLOBAL_MULT_1YEAR_PHY_001_030/description; Jean-Michel et al., 2021) provides daily mean sea water potential temperature, salinity and horizontal velocity data, which have a horizontal resolution of $1/12^\circ$ and 50 vertical layers. The GLORYS12V1 product is derived from the real-time global forecasting system of Copernicus Marine Environment Monitoring Service (CMEMS), which is forced at the surface by the European Center for Medium-Range Weather Forecasts (ECMWF) Reanalysis-Interim (ERA-Interim) and Reanalysis v5 (ERA5) data for recent years. The GLORYS12V1 product has been validated against

observations (Cai et al., 2021; Amaya et al., 2023a), and is widely used in MHW studies (e.g. Amaya et al., 2023b; Sun et al., 2023; Guo et al., 2024). Hence, the GLORYS12V1 data spanning from 1 January 1993 to 31 December 2025 were used in this study to detect MHWs. In addition, the shortwave radiation flux data from ERA5 (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>; Hersbach et al., 2023) were used for the temperature budget analysis.

In situ water temperature observations from the Maritime Meteorological Observation Platform (111.39°E, 21.44°N, Fig. 1), Bohe Marine Meteorological Field Experiment Base of the China Meteorological Administration, were used to capture the high-frequency ocean temperature variations during typhoon passage. The Maritime Meteorological Observation Platform is located in the nearshore region of the northern SCS, 6.5 km away from the coastline of Maoming City, Guangdong Province. Five 20-day observation records at 1-h interval were used in this study, covering the passages of Typhoons Hato (2017), Khanun (2017), Higos (2020), Nangka (2020) and Chaba (2022), respectively. Each observation record contained four layers of data: prior to 2022, the corresponding depths were 0.5, 2.5, 6.5, and 10.5 m, respectively; after 2022, they were adjusted to 1.0, 3.0, 8.0, and 14.0 m.

The National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature, version 2 (OISSTv2; <https://www.psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>; Reynolds et al., 2007; Huang et al., 2021) were also employed in this study. These data have a horizontal resolution of $0.25^\circ \times 0.25^\circ$ and a temporal interval of 1 day.

The track data for the five typhoons were obtained from the China Meteorological Administration (<https://tcdata.typhoon.org.cn/zjljsjj.html>; Ying et al., 2014; Lu et al., 2021). The tracks were recorded at 6-h intervals, with the temporal resolution increased to 3-h intervals for the 24 h prior to landfall in China. The bathymetry data were obtained from the National Oceanic and Atmospheric Administration (NOAA) ETOPO2022 global relief model data (<https://www.ncei.noaa.gov/products/etopo-global-relief-model>).

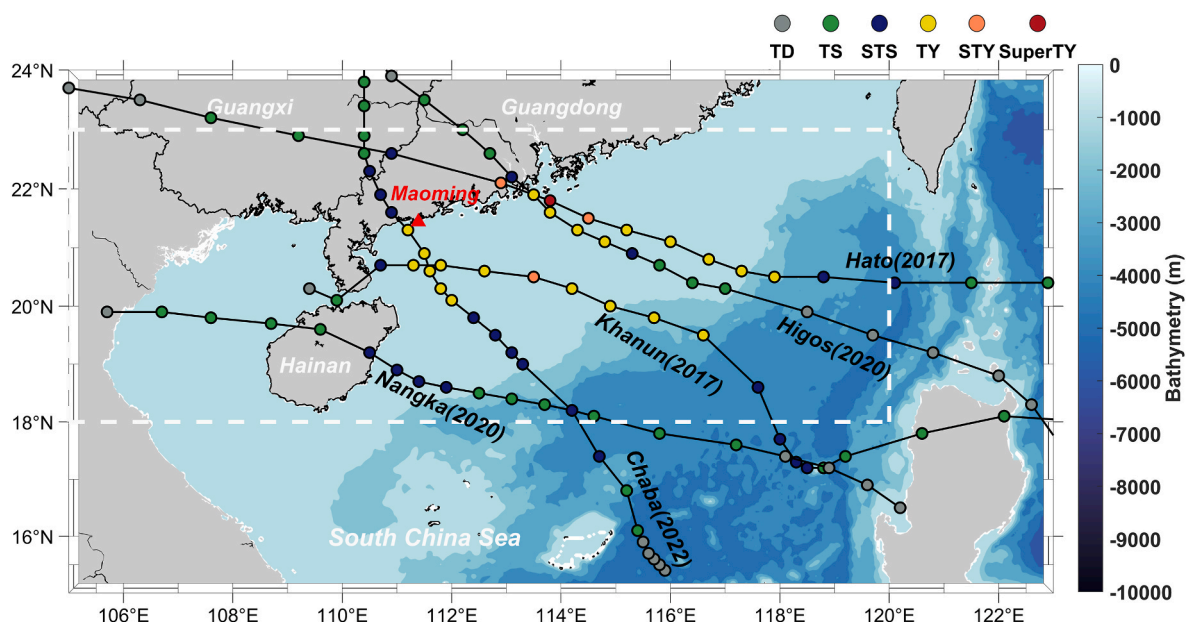


Fig. 1. Bathymetry of the northern SCS and typhoon tracks. The black curves denote the tracks of Typhoons Hato (2017), Khanun (2017), Higos (2020), Nangka (2020), and Chaba (2022). The colored dots denote the statuses of these typhoons (TD: tropical depression; TS: tropical storm; STS: severe tropical storm; TY: typhoon; STY: severe typhoon; SuperTY: Super typhoon). The red triangle indicates the location of the Maritime Meteorological Observation Platform. The white dashed box represents the study region. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.2. Methods

According to Hobday et al. (2016), a MHW is defined as an event lasting for five days or more, during which the temperature exceeds the 90th percentile threshold. This threshold is derived on a daily basis for the analysis years, using an 11-day moving window centered on the day of interest. In this study, we calculated the 90th percentile threshold and temperature percentiles at each grid and depth layer, based on the 33-year (1993–2025) GLORYS12V1 reanalysis data. We focused on the MHWs during the passages of the five aforementioned typhoons. The toolbox developed by Zhao and Marin (2019) (https://github.com/ZijieZhaoMMHW/m_mhw1.0) was adopted to detect MHWs.

The temperature budget (Jullien et al., 2012) was evaluated based on the GLORYS12V1 reanalysis data:

$$\frac{\partial T}{\partial t} = -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} - w \frac{\partial T}{\partial z} + D_l + D_z + I_z, \quad (1)$$

where T is the temperature, t is the time, u , v , and w are the zonal (x), meridional (y) and vertical (z) components of water velocity. On the right-hand-side of Equation (1), $-u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y}$ is the horizontal temperature advection (HADV), $-w \frac{\partial T}{\partial z}$ is the vertical temperature advection (VADV), $D_l = K_l \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)$ is the horizontal diffusion of temperature (HMIX) with K_l denoting the horizontal diffusion coefficient, $D_z = \frac{\partial}{\partial z} \left(K_z \frac{\partial T}{\partial z} \right)$ is the vertical diffusion of temperature (VMIX) with K_z representing the vertical diffusion coefficient, and $I_z = \left(\frac{Q_s}{\rho_0 C_p} \right) \frac{\partial f(z)}{\partial z}$ is the heating rate (FORCE), in which Q_s is the net surface solar heat flux, $f(z)$ determines the fraction of solar radiation at depth z , ρ_0 is the reference density (1025 kg/m³) and C_p is the specific heat capacity of seawater (3958 J/kg/°C; Miles et al., 2017).

Since the reanalysis data did not provide the vertical velocity, it was calculated using the seawater continuity equation:

$$\frac{\partial w}{\partial z} = -\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}. \quad (2)$$

Integrating from the surface gives:

$$w = w_0 - \int_0^z \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) dz, \quad (3)$$

in which,

$$w_0 = \frac{\partial \eta}{\partial t} + u \frac{\partial \eta}{\partial x} + v \frac{\partial \eta}{\partial y} \quad (4)$$

is the vertical velocity at the surface ($z = \eta$). Thereafter, we can calculate HADV and VADV. However, because the reanalysis data did not provide K_l and K_z , we cannot directly calculate HMIX and VMIX in the temperature budget. Instead, we approximately assessed VMIX by calculating the vertical velocity shear and gradient Richardson number:

$$S^2 = \left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2, \quad (5)$$

$$Ri = \frac{N^2}{S^2}, \quad (6)$$

where N is the buoyancy frequency calculated as:

$$N = \sqrt{-\frac{g}{\rho_0} \frac{d\rho}{dz}}, \quad (7)$$

where g is the acceleration of gravity, ρ is the ocean density. Shear instability is conventionally identified when Ri falls below 0.25. For the

real ocean, Dmitrenko et al. (2012) proposed a more lenient criterion, suggesting that shear instability can occur when Ri falls below 1. As for HMIX, previous studies have demonstrated that it can be neglected due to its small magnitude (e.g. Zhao and Chan, 2017; Cheng et al., 2024). Hence, it was not examined in this study.

The contribution of heat flux was included in the FORCE term. In the northwestern SCS, the optical properties of seawater have two distinct spectral distributions according to Jerlov's classification (Jerlov, 1976): one is close to type III, while the other resembles type IB and type II (Zhang et al., 2023). Near the coastline, the seawater was classified as type III due to its turbid nearshore conditions. Therefore, the fraction of solar radiation was calculated following Paulson and Simpson (1977).

3. Results

3.1. Comparison between observations and reanalysis data

Before investigating the interaction between typhoons and MHWs, we first compared the reanalysis data with multi-source observations. The GLORYS12V1 water temperature at its shallowest level (0.49 m) exhibited general consistency with the OISST data over the study period (Fig. 2), despite minor deviations. By comparing with in situ observations, the reanalysis data also captured the observed temperature variations for the majority of the typhoon periods (Fig. 3). Given that the GLORYS12V1 reanalysis data are derived from numerical models, some deviations from observations are inevitable. Specifically, the reanalysis data exhibited some deviations in simulating the temperature variations during Typhoons Hato (2017) and Chaba (2022). Additionally, the reanalysis data overestimated the temperature after Typhoon Khanun (2017), especially in the lower layer. We speculate that these deviations are attributed to the strong typhoon intensity or the close proximity of the typhoons to the Maritime Meteorological Observation Platform. Nevertheless, given that the MHW identification baseline is established from 33-year (1993–2025) temperature data, the deviations during short typhoon periods are unlikely to affect the MHW detection results. More importantly, the discrepancies between the GLORYS12V1 reanalysis data and in situ observations did not affect the identification of MHWs. According to the reanalysis data, the temperature during the passage of Typhoon Khanun (2017) dropped from above the 90th percentile threshold to below it, suggesting the decay of a MHW. The observed temperature was consistent with the reanalysis data before the typhoon but fell even lower after the typhoon, further confirming the decay of the MHW (Fig. 3b and Fig. S1a in the Supporting Information). Similarly, the reanalysis temperature after Typhoon Chaba (2022) was close to the 90th percentile threshold; the observed temperature was even higher than the reanalysis data, exceeding the 90th percentile threshold, confirming the generation of the MHW (Fig. 3e and Fig. S1d in the Supporting Information). Based on the aforementioned comparisons, we believe that the GLORYS12V1 reanalysis data are reasonable and can be used to investigate the MHWs in the nearshore SCS. Moreover, considering that no MHW was detected during Typhoon Hato (2017), we mainly focus on the responses of MHWs to Typhoons Khanun (2017), Higos (2020), Nangka (2020), and Chaba (2022).

3.2. Divergent responses of MHW to multiple Typhoons

Across the aforementioned four typhoon cases, three distinct typhoon-MHW interaction outcomes are identified: MHWs were maintained during Typhoon Higos (2020), dissipated during Typhoons Khanun (2017) and Nangka (2020), and generated during Typhoon Chaba (2022). In the following, we will show the evolution of these MHWs from several days prior to each typhoon's arrival to five days after its passage.

As shown in Fig. 4a and b, prior to the arrival of Typhoon Higos, the water temperature at the Maritime Meteorological Observation Platform was high, with the temperature percentile exceeding the 90th percentile

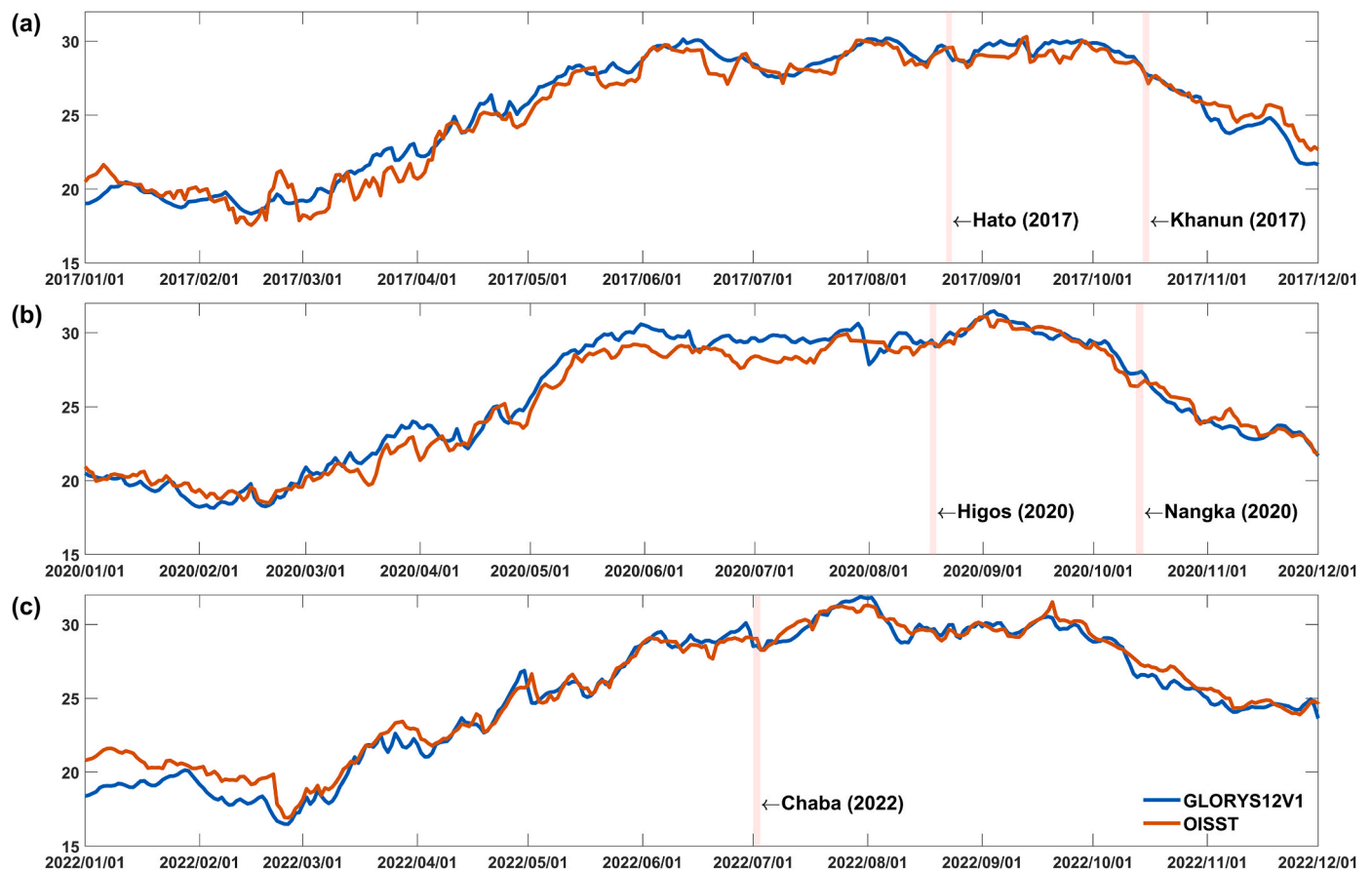


Fig. 2. Comparison between the OISST and GLORYS12V1 water temperature at the depth of 0.49 m at the Maritime Meteorological Observation Platform. The light red shadings indicate the durations of the five typhoons. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

threshold, suggesting that a MHW had already been generated here. After Typhoon Higos passed, the MHW persisted. In other words, Typhoon Higos had little impact on the MHW's evolution. This result is further confirmed by the spatial distribution of the MHW (Fig. 4c–j). The spatial distribution of the MHW at 15.81 m depth remained nearly unchanged from three days prior to the typhoon's arrival to five days after its passage (Fig. 4c–j). We speculate that this results from the combination of Typhoon Higos's weak intensity and the location of the MHW to the left of the typhoon's track (Fig. 1 and Fig. S2a in the Supporting Information). The oceanic response to a typhoon depends on its intensity (e.g., Dare and McBride, 2011b; Cheng et al., 2023), and weak typhoons typically cause minor changes in the ocean state (e.g., Cheng et al., 2024). Moreover, in the Northern Hemisphere, the oceanic response to a typhoon is weaker to the left side of the typhoon track than to the right side (e.g., Price, 1981; Doyle et al., 2014; He et al., 2022). Indeed, no significant sea surface temperature cooling was observed to the left side of Typhoon Higos's track during its passage (Figures S2b–j in the Supporting Information), further confirming its limited influence on this region. Thus, the weak Typhoon Higos had little effect on the ocean status to the left side of its track, and consequently on the existing MHW there.

For Typhoon Nangka (2020), a distinct pattern emerges. Five days before its arrival, the surface and bottom temperatures at the Maritime Meteorological Observation Platform exceeded 28.0 °C and 29.5 °C, respectively; three days after its passage, the surface and bottom temperatures dropped to 26.0 and 27.0 °C (Fig. 5a). Accordingly, the temperature percentile decreased sharply, from over 80% to below 20% at the surface and from over 90% to approximately 20% near the bottom (Fig. 5b), demonstrating the dissipation of a MHW. The MHW spatial

distribution (Fig. 5c–j) further confirms this dissipation, especially in the vicinity of the Maritime Meteorological Observation Platform. A similar phenomenon is found for Typhoon Khanun (2017) (Fig. S3 in the Supporting Information). Thus, these two cases are classified into the same category, even though the spatial patterns of MHW dissipation differ between them: during Typhoon Khanun, only the MHW along its track and near the Maritime Meteorological Observation Platform was decayed, whereas during Typhoon Nangka, the MHW across nearly the entire study region was decayed.

Although Pun et al. (2025) have reported that typhoons can suppress surface MHWs, we do not attribute the decay of these two MHW events entirely to Typhoons Nangka and Khanun. This is because the sea surface temperature cooling at the Maritime Meteorological Observation Platform during these typhoons was not obvious (Fig. 5a and Fig. S3a in the Supporting Information). Furthermore, given that both typhoons occurred in October, which is a transitional period between autumn and winter, the seasonal decline in water temperature may also contribute to the decay of these MHW events (Fig. S4 in the Supporting Information).

Typhoon Chaba (2022) triggered a bottom MHW at the Maritime Meteorological Observation Platform. Before its arrival, the water column was well stratified, with surface temperature exceeding 29.0 °C and bottom temperature below 24.0 °C (Fig. 6a). During the passage of Typhoon Chaba, the entire water column was quickly mixed, resulting in a nearly uniform temperature around 28.5 °C that persisted for almost ten days (Fig. 6a). Consequently, the temperature percentile near the bottom increased dramatically, from 60 to 70% to over 90% (Fig. 6b). The spatial patterns shown in Fig. 6c–j clearly reveal the typhoon-induced MHW at 15.81 m depth along the coast of Guangdong Province.



Fig. 3. Comparison between in situ observations and GLORYS12V1 water temperature during Typhoons (a) Hato (2017), (b) Khanun (2017), (c) Higos (2020), (d) Nangka (2020) and (e) Chaba (2022). In each subfigure, the orange curve represents the raw observation record, the red curve shows the daily mean observation, and the blue curve denotes the reanalysis data. The light red shading indicates the duration of the corresponding typhoon in the study region. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

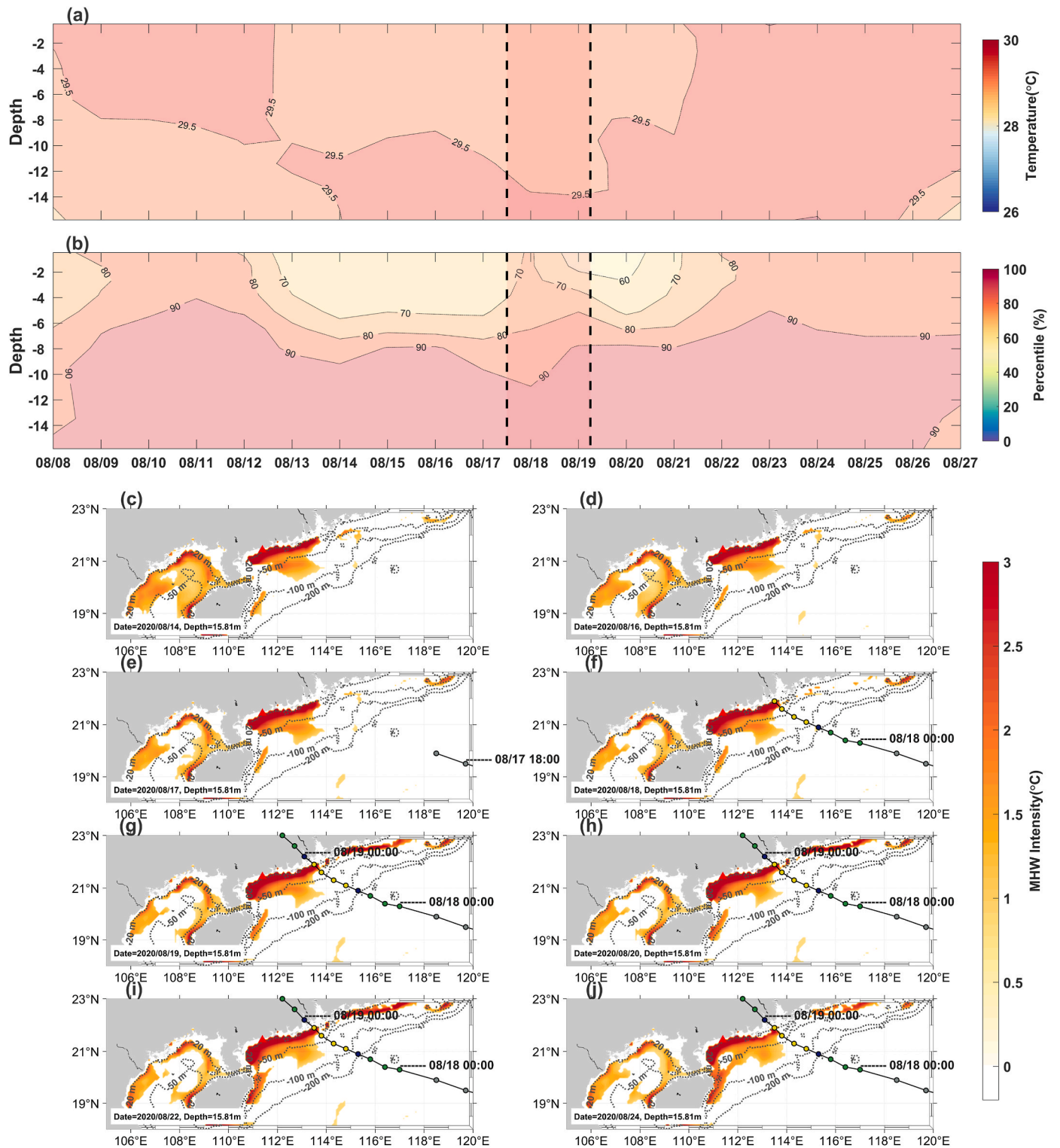


Fig. 4. The temperature variation and MHW evolution during Typhoon Higos (2020). (a) Temperature and (b) temperature percentile at the Maritime Meteorological Observation Platform. The black dashed lines indicate the duration of Typhoon Higos in the study region. (c ~ j) MHW evolution at 15.81 m depth during Typhoon Higos in the study region.

3.3. Diagnosis of temperature variability during typhoon-MHW interaction

To further understand the differences among the three typhoon-MHW interaction patterns, the temperature budget during Typhoons Higos (2020), Nangka (2020) and Chaba (2022) is analyzed using

Equation (1), taking the GLORYS12V1 temperature at the Maritime Meteorological Observation Platform as an example. Note that due to the constraints of the reanalysis data, only the temperature variability, HADV, VADV, and FORCE can be calculated (Fig. 7). The VMIX was assessed by the Ri (Fig. 8) and the HMIX was neglected. Moreover, the buoyancy frequency squared, which reflects the stratification intensity,

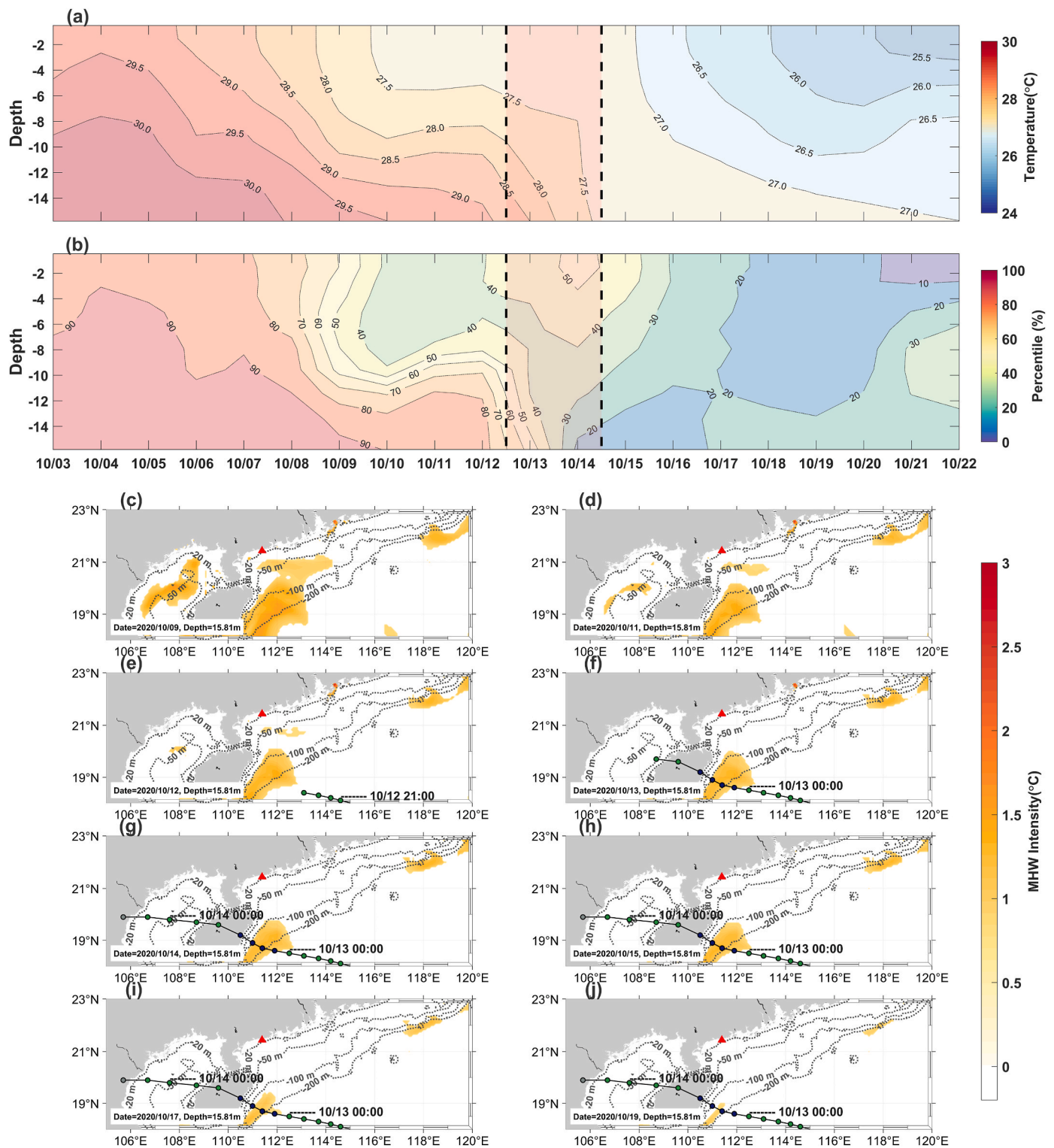


Fig. 5. Same as Fig. 4, but for Typhoon Nangka (2020).

is also shown in Fig. 8.

As illustrated in Fig. 7a, the temperature variability following Typhoon Higos was nearly positive throughout the water column until 23 August, indicating continuous warming of the water. This sustained warming contributed to the persistence of the MHW (Fig. 4). Although the temperature variability turned negative after 23 August, the cooling was slow, and the temperature percentile remained above the 90% threshold at some depths (Fig. 4). Consequently, the MHW persisted

after the passage of Typhoon Higos (Fig. 4). During this process, compared to the VADV (Fig. 7g) and FORCE term (Fig. 7j), the HADV (Fig. 7d) exhibited the closest correspondence to the temperature variability, yielding a correlation coefficient of 0.68 with a p -value substantially below 0.01. This indicates that the HADV was an important contributor to the observed temperature variability in this case.

In contrast, the decay of the MHW following Typhoon Nangka was attributed to the negative temperature variability (Fig. 7b), which

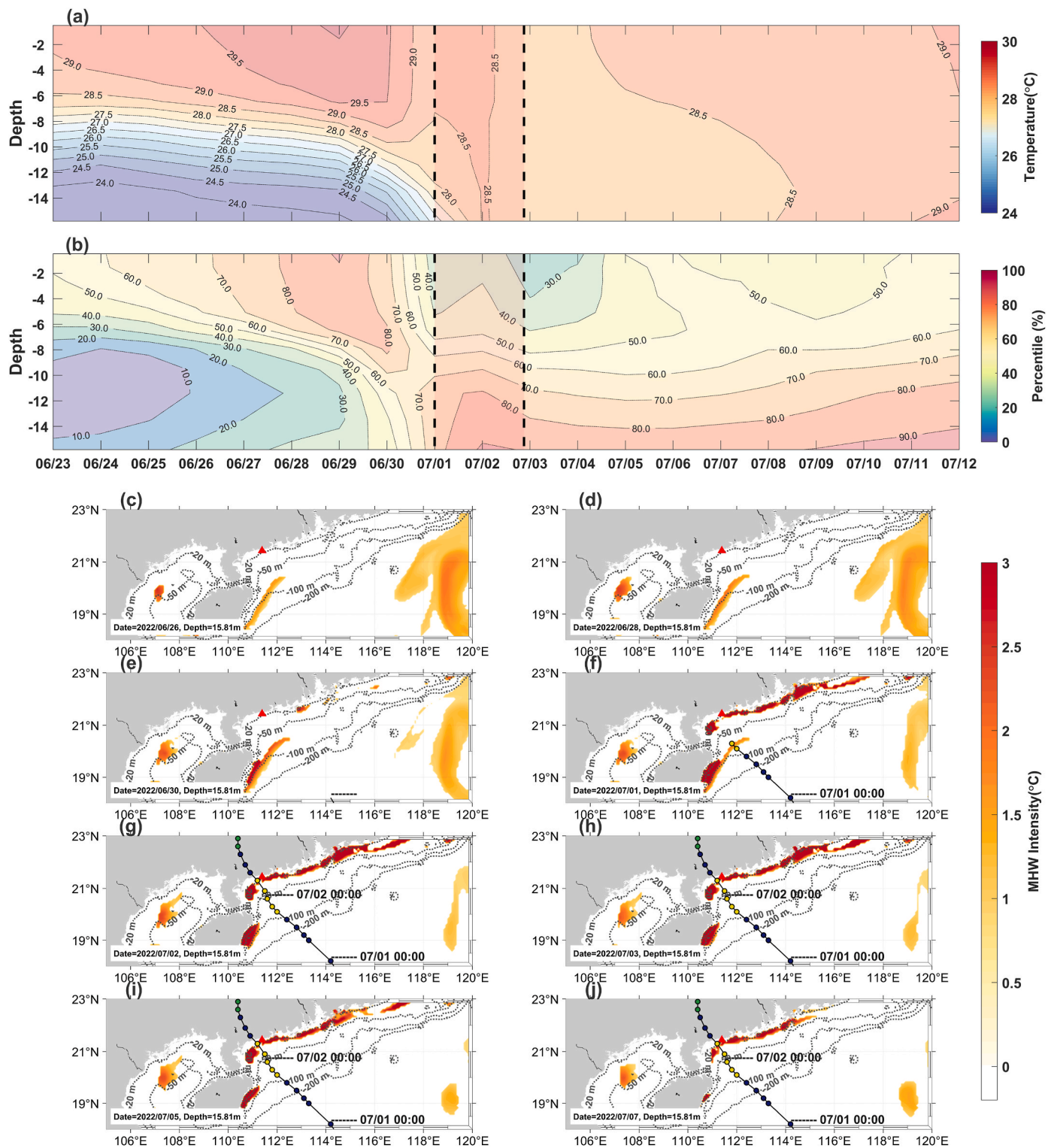


Fig. 6. Same as Fig. 4, but for Typhoon Chaba (2022).

significantly cooled the water (Fig. 5a). Both the HADV (Fig. 7e) and VADV (Fig. 7h) contributed to the cooling but exhibited distinct patterns, and neither closely resembled the temperature variability itself. Nevertheless, their combined effect modulated the temperature variability, yielding a correlation coefficient of 0.68. By contrast, the FORCE was positive (Fig. 7k) and thus cannot account for the negative temperature variability.

The situation for Typhoon Chaba was markedly different. As

displayed in Fig. 7c, following the typhoon's passage, positive temperature variability first emerged near the surface and then gradually extended to the seafloor over time. However, none of the HADV (Fig. 7f), VADV (Fig. 7i) and FORCE (Fig. 7l) exhibited a pattern similar to that of the temperature variability. In fact, their correlation coefficients with the temperature variability were very low, all below 0.30. More importantly, none of them showed clearly positive temperature variability at the bottom after 6 July, following which the temperature

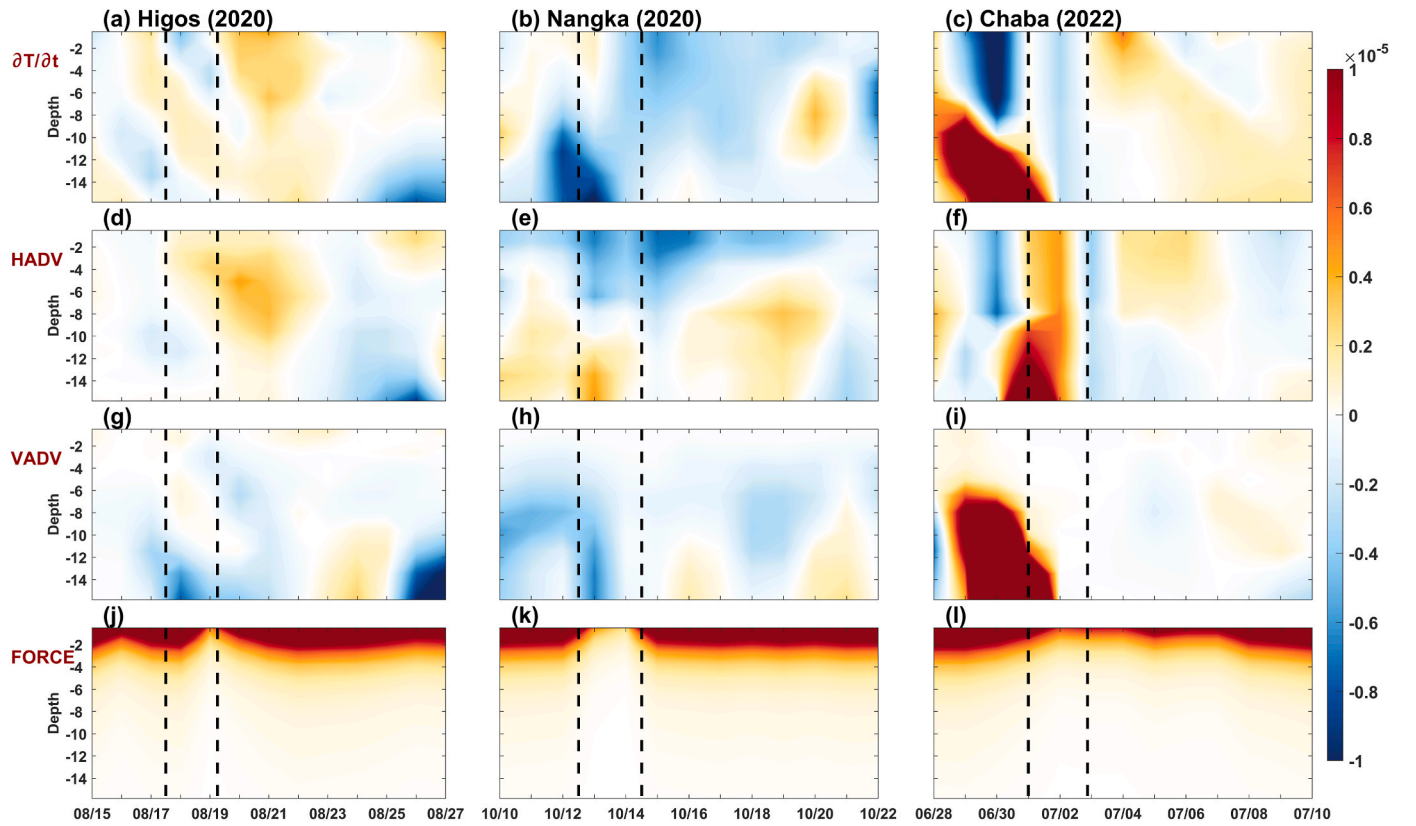


Fig. 7. (a, b, c) Temperature variability, (d, e, f) HADV, (g, h, i) VADV, and (j, k, l) FORCE during Typhoons (a, d, g, j) Higos (2020), (b, e, h, k) Nangka (2020), and (c, f, i, l) Chaba (2022). In each subfigure, the black dashed lines indicate the duration of the corresponding typhoon in the study region.

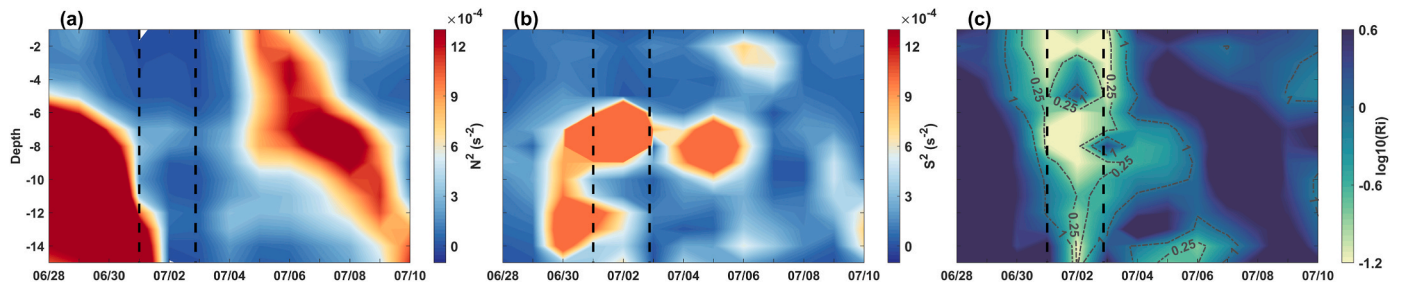


Fig. 8. (a) Buoyancy frequency squared, (b) shear squared, and (c) Ri in the log form during Typhoon Chaba (2022). In each subfigure, the black dashed lines indicate the duration of the corresponding typhoon in the study region. The gray dashed curves in (g, h, i) indicate $Ri = 0.25$ and $Ri = 1$.

percentile gradually exceeded the 90% threshold (Fig. 6b). In other words, none of the HADV, VADV or FORCE can be identified as a primary contributor to the MHW evolution after Typhoon Chaba (Fig. 6).

We next examined the stratification variation and VMIX induced by Typhoon Chaba. As the typhoon passed, the local stratification was quickly destroyed (Fig. 8a), accompanied by intense velocity shear (Fig. 8b). Consequently, shear instability occurred, leading to intense VMIX (Fig. 8c). According to the heat pump hypothesis for typhoons (Emanuel, 2001; Zhang et al., 2016), this VMIX warmed the bottom water (Fig. 6a). As the warmed bottom water reached the 90% threshold, a MHW was generated (Fig. 6). Hence, the VMIX induced by Typhoon Chaba accounted for the MHW generation, consistent with the findings of Liu et al. (2026).

4. Summary and discussion

Using in situ temperature observations from the Maritime Meteorological Observation Platform and 33-year GLORYS12V1 reanalysis data,

this study identifies three distinct interaction patterns between typhoons and MHWs in the nearshore SCS.

In the first pattern, Typhoon Higos (2020) had little influence on the existing MHW, which was maintained for more than one week after the typhoon's passage. Two factors contributed to this: the weak intensity of Typhoon Higos and the location of the MHW to the left side of the typhoon's track. The oceanic response to a typhoon is known to depend on the typhoon intensity (e.g., Dare and McBride, 2011b; Cheng et al., 2023), with weak typhoons typically causing minor changes in the ocean state (e.g., Cheng et al., 2024). Moreover, the oceanic response to a typhoon is asymmetrical, with more pronounced effects on the right side of the typhoon's track in the Northern Hemisphere (e.g., Price, 1981; Doyle et al., 2014; He et al., 2022). Therefore, both factors favored the maintenance of the existing MHW. Temperature budget analysis further reveals that the HADV dominates the temperature variability in this pattern.

In the second pattern, the existing MHWs rapidly decayed during the passage of Typhoons Khanun (2017) and Nangka (2020). The direct

cause is the cooling of the water, which no longer satisfies the MHW criterion (Hobday et al., 2016). A similar event has been reported in the East China Sea by Pun et al. (2025). However, the underlying mechanism identified in the present study differs from that described in Pun et al. (2025). As demonstrated by Pun et al. (2025), the immediate termination of the existing MHW was directly related to the substantial sea surface temperature cooling induced by Typhoon Bavi (2020), which reached up to 7 °C. In contrast, the sea surface temperature cooling caused by Typhoons Khanun and Nangka was not significant, amounting to below 0.5 °C. Actually, the seasonal decline in water temperature is a crucial factor for the observed MHW dissipation, as both Typhoons Khanun and Nangka occurred in October, the transitional period between autumn and winter. In this pattern, the combined effect of the HADV and VADV modulated the temperature variability.

In the third pattern, Typhoon Chaba (2022) induced enhanced vertical mixing, which warmed the bottom water and caused a MHW near the seafloor. This aligns with the findings of Liu et al. (2026), who identified three key contributing factors in such events: typhoon-induced intense vertical mixing, a relatively high temperature percentile prior to the typhoon, and a sufficiently long duration of warming. Furthermore, because vertical mixing dominated the generation of the subsurface MHW, neither the HADV nor VADV played a significant role in the temperature budget.

Moreover, across the three typhoon-MHW interaction patterns, the air-sea heat fluxes did not play an important role. This is consistent with previous studies, which have shown that the heat fluxes contribute little to the temperature variability in the mixed layer (e.g., Price, 1981; Zhang et al., 2016; Cheng et al., 2024).

Although this study reveals divergent responses of MHWs to typhoons in the nearshore SCS, these findings are derived from the GLORYS12V1 reanalysis data, which inherently carries some limitations. First, because the reanalysis data do not provide w , K_l or K_s , the temperature budget diagnosis is incomplete: the HMIX and VMIX cannot be directly calculated, and the w may be subject to larger uncertainty. Second, the dynamics underlying the typhoon-induced subsurface MHW remain insufficiently detailed. Near-inertial waves generated by typhoons are known to produce intense turbulent mixing via shear instability (e.g. Cao et al., 2018, 2019; Cheng et al., 2024). Nevertheless, the daily temporal resolution of the reanalysis data precludes a detailed examination of these near-inertial waves. Third, due to the coarse horizontal resolution of the reanalysis data, the complex coastal ocean dynamics (Glenn et al., 2016; Zhang et al., 2019; Liu et al., 2022) may not be well reproduced, which could influence the evolution of MHWs. Finally, although the reanalysis data generally capture the observed mean state and variability of ocean temperature, discrepancies still exist when compared with the satellite and in situ observations, particularly regarding the exact magnitudes during specific extreme events (Cai et al., 2021; Amaya et al., 2023a).

Understanding typhoon-MHW interactions is of great importance, as both typhoons and MHWs can threaten coastal ecosystems by devastating the critical habitats of coral reefs and mangroves (Wang, 2020; Cooke et al., 2022; Feehan et al., 2024) and by altering the optimal thermal tolerance ranges and physiological temperature thresholds of marine organisms (O'Connor et al., 2007; Thomson et al., 2014). When such events occurring simultaneously or in close temporal and spatial proximity may exacerbate the impacts on temperature-sensitive ecosystems (Dzwonkowski et al., 2020). Therefore, advancing our understanding of multiple typhoon-MHW interactions is not only a fundamental scientific goal but also a practical necessity for improving forecasting capabilities and developing effective adaptation strategies. Given the projected increase in the intensity of both typhoons and MHWs under global climate change, unraveling their coupled dynamics is also critical for informing ecosystem-based management and enhancing the resilience of vulnerable coastal communities in a warming world.

CRediT authorship contribution statement

Zhouhong Liu: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Xiaoting Zheng:** Writing – review & editing, Formal analysis. **Yuexin Luo:** Writing – review & editing, Formal analysis. **Shukui Cheng:** Writing – review & editing. **Anzhou Cao:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization, Funding acquisition. **Zhongkuo Zhao:** Writing – review & editing, Supervision, Data curation, Funding acquisition. **Xinyu Guo:** Writing – review & editing, Supervision. **Jinbao Song:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecss.2026.110279>.

Data availability

All data that support the findings of this study are included within the article (and any supplementary files).

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