Properties and Drivers of Marine Heat Waves in the Northern South China Sea

QIANG WANG,a,b BO ZHANG,b,c LILI ZENG,a,b YUNKAI HE,b ZEWEN WU,b AND JU CHEN,a,b

a Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou, China
b State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China
c University of Chinese Academy of Sciences, Beijing, China

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ABSTRACT: The properties and heat budget of marine heat waves (MHWs) on the northern South China Sea (SCS) continental shelf are investigated. MHWs with warming amplitudes above 1.5°C occur mainly along the coast, and their temperature anomaly decreases toward the open sea. MHWs with 1–1.5°C warming and duration < 20 days dominate the northern SCS continental shelf. A heat budget analysis indicates that the main heat source is the sea surface net heat flux. Oceanic processes are dominated by the advection of mean temperature by the anomalous horizontal velocity (advha). The net contribution of advha always cools the upper layer of the ocean, resulting in the decay of MHWs. Active cross-slope water exchanges exist at the east and west sides of the northern SCS continental shelf edge, which makes the dominant contributions to the advha. In the MHW developing phase, the west (east) side makes a positive (negative) contribution to the advha. In the decay phase, both sides make a negative contribution to the advha, resulting in the rapid decay of MHWs. Although the contribution of advha to the heat budget varies along the northern SCS continental shelf edge, its net effect always cools the MHWs over the shelf. These results provide new insight into the characteristics and formation mechanism of MHWs on the northern SCS continental shelf; in particular, they clarify the respective contributions of air–sea flux and oceanic processes to MHWs.

SIGNIFICANCE STATEMENT: Marine heat waves (MHWs) are unusual warming events in oceans that heavily affect marine ecosystems and arouse great concern from citizens. MHWs are active in the northern South China Sea (SCS) continental shelf. On the northern SCS continental shelf, the sea surface net heat flux is the main heat source of MHWs, and ocean current anomalies always cool the upper layer of the ocean. Active cross-slope water exchange at the east and west sides of the northern SCS continental shelf edge is the main oceanic way that cools the water on the shelf, eventually resulting in the decay of MHWs.

KEYWORDS: Advection; Extreme events; Mixed layer; Warm water volume; Surface temperature; Oceanic variability

1. Introduction

Marine heat waves (MHWs) are unusual warming events in oceans, and they have been occurring with increasing frequency over the past few decades (Hobday et al. 2016; Oliver et al. 2017, 2018). Many MHW events have been recorded and are widely distributed on continental shelves and open seas (Hobday et al. 2018; Oliver et al. 2021). MHWs are not just a physical oceanographic phenomenon; it also exerts considerable influence on regional marine ecosystems (Geneviére et al. 2019). Discrete MHWs can drive a gradual change in species distribution and affect the diversity and mortality of commercial fisheries (Mills et al. 2013; Wernberg et al. 2013; Caputi et al. 2016). The increasing trend in MHW intensity and frequency has led to growing research interest (Collins et al. 2019).

The contributions of atmospheric and oceanic processes to MHW development vary in different oceans (Schlegel et al. 2017). Shortwave radiation and ocean advection anomalies contribute jointly to MHWs in the East China and South Yellow Seas (Tan and Cai 2018; Gao et al. 2020). In coastal waters off western Australia, MHW events are attributed to variations in heat advection by the Leeuwin Current and heat flux across the air–sea interface (Benthuyessen et al. 2014, 2018; Feng et al. 2013; Oliver et al. 2017). Local warming from the atmosphere dominates the MHW events in the northwest Atlantic (Chen et al. 2014). Long-lasting MHWs in the tropical Indian Ocean were recorded, which were maintained by downwelling Rossby waves (Zhang et al. 2021). Strong sub-surface MHWs in the tropical western Pacific Ocean were observed, and anomalous sea surface convergence and Ekman downwelling played an important role in its formation (Hu et al. 2021). Reduced heat loss from the ocean to the atmosphere and weak cold advection in the upper ocean can sometimes cause strongly positive temperature anomalies in the northeast Pacific (Bond et al. 2015; Di Lorenzo and Mantua 2016). Recent literature has provided a more detailed study of northeast Pacific MHWs, and double-peak and single-peak categories have been identified (Chen et al. 2021a). For the double-peak, the first peak is attributed to the surface heat flux, while the vertical entrainment and diffusion are responsible for the second peak 5 months later. For the...
single-peak category, vertical entrainment and diffusion are the leading contributors. A persistent and intense MHW event in the northeast Pacific during 2019–20 was observed, followed by a La Niña event, while other recorded double-peak events were associated with El Niño or neutral conditions (Chen et al. 2021b).

In the South China Sea (SCS), the occurrence frequency, intensity, and duration of MHW events have all increased under global warming (Li et al. 2019; Yao and Wang 2021) and are projected to continue increasing in future decades (Yao et al. 2020). El Niño–Southern Oscillation strongly regulates SCS MHWs (Liu et al. 2022). Both the sea surface net heat flux and ocean advection can cause extreme warming events at the basin scale (Xie et al. 2003; Xiao et al. 2018, 2020; Wang et al. 2021). The western boundary current (WBC) of the SCS is responsible for the advection of cooler water (Liu et al. 2004; Fang et al. 2013; Wei et al. 2016; Zhao and Zhu 2016; Zhao et al. 2017; Sun et al. 2020); weakening or a complete shutdown of the WBC contributes greatly to the warming of the SCS upper layer (Wang et al. 2021).

The SCS MHW events occur mainly on the continental shelf, especially in the northern SCS (Cai et al. 2016; Li et al. 2019; Yao and Wang 2021), where the SCS WBC divides the outer shelf edge from the open sea (Wang et al. 2013; Zhu et al. 2019). Multiple band-like currents flowing along the topography on the northern SCS continental shelf regulate an along-topography distribution of climatological temperature (Shu et al. 2018). Due to the instability of the SCS large-scale slope current, there are also active cross-slope water exchanges between the continental shelf and the open sea in the northern SCS (Wang et al. 2018, 2020; Liu and Gan 2020a). Due to the climatological temperature approximate belt-like distribution parallel to the slope (Chen et al. 2003), the cross-slope water exchanges imply potential contributions to the heat budget on the northern SCS continental shelf. Although the overall characteristics of the MHW properties in the SCS have been discussed in previous studies (Cai et al. 2016; Li et al. 2019; Yao et al. 2020; Yao and Wang 2021), details of MHWs in the northern SCS and their driving factors remain unclear, especially for the respective contributions of atmospheric and oceanic processes to MHW development.

The northern SCS continental shelf is close to the mainland, and its thermal state greatly modulates the ecosystem and economic activities. The frequency and intensity of MHWs on the northern SCS continental shelf are continuously enhanced, attracting wide attention. Their drivers urgently need to be elucidated to better understand and predict their variability. Therefore, this paper focuses on the properties and drivers of the MHWs on the northern SCS continental shelf.

The remainder of this paper is organized as follows. Data and methods are discussed in section 2. Section 3 describes the properties of MHWs on the northern SCS continental shelf. The MHW heat budget is analyzed in section 4. Finally, conclusions are given in section 5.

2. Data and methods

a. Data

Observation data for sea surface temperature (SST) are used, together with model output, for a range of ocean variables. Because of data availability, the period 1982–2017 is used in this study.

The SST data are from NOAA OISST version 2 (Reynolds et al. 2007), which is a daily and 0.25° × 0.25° gridded product from Advanced Very High Resolution Radiometer (AVHRR) satellite data, with bias correction using ship and buoy data.
The results from the OGCM for the Earth Simulator (OFES; Sasaki et al. 2007) are utilized in this study. OFES was run at 0.1° × 0.1° spatial resolution and 54 vertical levels, forced by NCEP–NCAR reanalysis data. The ocean velocity, temperature, and surface net heat flux used in this study are supplied by OFES. OFES provides output in the form of 3-day averages. The definition of an MHW is based on 11-day window data (see section 2b). Thus, the 3-day averaged data can also be used to investigate the heat budget of MHWs. For convenience, the OFES outputs are all interpolated to daily data using linear interpolation. The distribution of the mean intensity and duration of MHWs in the northern SCS derived from OFES generally resembles that derived from OISST (Fig. 1), which validates the use of OFES in the investigation of MHWs. The 90-day low-pass SST scatter diagram of OISST versus OFES validates the use of OFES on scales larger than or equal to seasonal time (Fig. 2a). A comparison of the SST anomaly, subtracting the 90-day low-pass SST, further confirms the validation of OFES on an intraseasonal scale (Fig. 2b). To investigate the differences in the life cycle of MHWs (see section 2b) expressed by OISST and OFES, a composite is produced from the MHW cases projected onto a time axis from 0 to 1 (Fig. 2c). Although the MHW of OFES is relatively weaker than that of OISST, it simulates a relatively real MHW evolution process.

Three mooring stations were located on the northern SCS slope. The sampling time interval was 1 h, and the vertical spatial resolution was 8 m at all stations. Velocity profiles at station DS01 (20.30°N, 117.67°E) were obtained from 18 September 2014 to 15 September 2015. Station DS02
(19.71°N, 116.99°E) acquired data from 20 September 2014 to 20 August 2018. Velocity profiles were obtained from 1 January 2014 to 12 June 2017 at station XS (17.29°N, 111.36°E). Any velocity larger than 3 times the standard deviation at that depth is defined as an invalid value. Short gaps caused by invalid data were subsequently filled by linear interpolation. A 48-h low-pass filter was applied to the velocity data to remove high-frequency signals, and the data were then averaged over 24 h (daily).

b. Definition of MHWs

Following Hobday et al. (2016), the climatology SST is defined relative to the time of year, using all data within an 11-day window centered on the time of year from which the climatological mean is calculated, i.e., Eq. (1).

An MHW is defined as an anomalously warm, discrete, and prolonged event, which is a period when the daily SST is above a particular threshold for at least 5 days. The threshold on the day of the year is defined as the 90th percentile of the daily temperature within an 11-day window centered on this day in all years, i.e., Eq. (2):

\[
T_m(j) = \sum_{y=y_e}^{y_e+i} \sum_{d=d_y-5}^{d_y+i+5} \frac{T(y, d)}{11(y_y - y_{y + 1})},
\]

\[
T_{90}(j) = P_{90}(j),
\]

where \(T_m\) is the climatology SST and \(T_{90}\) is the 90th percentile of the daily SST. Parameter \(j\) is the day of the year, and \(y_e\) and \(y_c\) are the start and end of the climatological base period, respectively. The term \(T\) is the daily SST on day \(d\) of year \(y\), and \(P_{90}(j)\) is the 90th percentile of \(X\), where \(X = [T(y, d)]_{y_e} \leq y \leq y_c, j - 5 \leq d \leq j + 5\).

Two MHW metrics are used in the study: the duration (days between the start and end dates) and the intensity (average of daily intensity anomalies measured in °C).

c. Upper-ocean temperature budget

The perturbation temperature budget equation, averaged from the sea surface to a fixed depth \(h_m\), can be written as follows (Benthuyes et al. 2014; Feng et al. 2008; Oliver et al. 2017):

\[
\frac{\partial T}{\partial t}_{\text{Tend}} = \frac{Q'}{\rho C_p h_m} - \langle \mathbf{u}' \cdot \nabla T \rangle - \langle \mathbf{u}' \cdot \nabla T \rangle - w \frac{(T - T_d)'}{h_m} \text{advh} - \left[ \frac{w' (T - T_d)}{h_m} \right]_{\text{advh}},
\]

where \(T\) is the temperature and \(h_m\) is set as 50 m, with \(\langle \cdot \rangle\) representing vertical integration \(\int_0^{h_m} dz\). Parameter \(T_m\) is the average temperature over the upper 50 m; \(T_d\) is the water temperature below \(h_m\) and is set to the value at 70 m. We also checked the values of \(h_m\) for 40 and 60 m and found that our results were not particularly sensitive to the choice of depth used to calculate \(T_m\). The term \(Q'\) is the sea surface net heat flux anomaly and is positive for heat input to the ocean; \(\rho = 1025\ \text{kg m}^{-3}\) is the reference density of seawater, and \(C_p = 4007\ \text{J Kg}^{-1} \text{K}^{-1}\) is the specific heat of seawater.
FIG. 4. Composite heat budget terms for all marine heat waves (MHWs) in the northern SCS. (a) Composite series of SST anomalies. (b) Composite heat budget terms in Eq. (1). (c) Comparisons between the contribution of net heat flux (Qnet) and temperature advection (i.e., the sum of all terms except for Qnet). (d) Advection of mean temperature by the anomalous horizontal velocity (advha); south (north) indicates the contributions of advection at the south (north) boundary. (e) Composite profiles of advha at the south boundary. The composite is produced as follows: the variable in each MHW is normalized to −1 in time, and then the variable of each MHW is composited. Gray dots indicate where the composite results exceed 95% significance (Student’s t test).

Vector \( \mathbf{u} = (u, v) \) is the zonal and meridional velocity pair, and \( w \) is the vertical velocity; \( \nabla = (\partial_x, \partial_y) \) is the horizontal gradient operator. The overbar indicates the climatological mean, and the prime indicates an anomaly.

The left-hand side of Eq. (3) is the rate of change or tendency of the upper 50-m averaged temperature (\( T_{\text{end}} \)). On the right-hand side, \( Q_{\text{net}} \) is the sea surface net heat flux anomaly forcing, \( \text{adv} \) is the advection of anomalous temperature by the mean horizontal velocity, \( \text{advh} \) is the advection of mean temperature by the anomalous horizontal velocity, \( \text{advv} \) is the advection of anomalous temperature by the mean vertical velocity, and \( \text{advva} \) is the advection of mean temperature by the anomalous vertical velocity.

In the northern SCS, the contribution of advection to the temperature anomalies can be represented by the temperature flux at the southern and northern boundaries (Feng et al. 2008; Gao et al. 2020). Following Lee et al. (2004), the contributions of advection at these northern and southern boundaries can be further written (using \( \text{advha} \) as an example) as

\[
\text{advha} = \frac{1}{\tau} \left[ \int_u u' \text{south} (T_{\text{south}} - T_o) \, dx \, dz \right]_{\text{south}} - \frac{1}{\tau} \left[ \int_u u' \text{north} (T_{\text{north}} - T_o) \, dx \, dz \right]_{\text{north}} + \frac{1}{\tau} \left[ \int_w w' \text{west} (T_{\text{west}} - T_o) \, dy \, dz \right]_{\text{west}} - \frac{1}{\tau} \left[ \int_w w' \text{east} (T_{\text{east}} - T_o) \, dy \, dz \right]_{\text{east}},
\]

where \( \tau \) is the volume of the box enclosed by the northern and southern boundaries and additional eastern and western boundaries. Parameter \( T_o \) is the daily average temperature in the northern SCS, which is used as the reference temperature in the heat advection. By including the \( T_o \) in the heat advection terms, unbalanced volume flux in one direction is assumed.
to carry waters with the same temperature as $T_o$, so that it does not have a net contribution to the advection (Lee et al. 2004; Feng et al. 2008).

3. Properties of MHWs in the northern South China Sea

The mean properties of MHWs over the past four decades were calculated (Fig. 1). The intensity isolines run belt-like parallel to the coastline, with decreasing values toward the open sea in the northern SCS (Figs. 1a,c). There are three high-value centers in Zhanjiang Bay, the Pearl River estuary, and offshore Shantou, where the maximum SST anomaly can reach 2°C. On the continental slope edge, the intensity decreases to $<1.5^\circ$C.

The mean MHW duration ranges from 12 to 15 days in the northern SCS and is longer on the western continental shelf than on the eastern shelf (Figs. 1b,d). In the northern SCS continental shelf (bounded by line A in Fig. 1a), there is a relatively significant spatial difference between OISST and OFES; however, the duration over the continental shelf of OISST is $13.1 \pm 0.7$ days, and OFES is $14.6 \pm 1.4$ days. The spatial variation in duration is less than 2 days, and their evolution processes are similar (Fig. 2c), which suggests the limited influence of the spatial duration difference between OFES and OISST on the validation of OFES to analyze MHW evolution. The small spatial variation also suggests that MHW occurrence and development are reasonably synoptic along the northern SCS continental shelf.

The SST averaged over the northern SCS continental shelf bounded by the black line in Fig. 1 is used to identify the northern SCS MHWs. The intensity-duration diagram of the MHWs is shown in Fig. 3. Approximately 50% of the MHWs have intensities in the range of $1^\circ-1.5^\circ$C. One-third of MHWs have intensities in the range $0.5^\circ-1.0^\circ$C, and only $\sim10\%$ exceed $1.5^\circ$C. In the OFES results, there are some MHWs with intensities $<0.5^\circ$C that do not appear in the OISST. This inconsistency indicates the slightly underestimated SST anomaly in the OFES. However, there are only six weak MHWs, $\sim7\%$ of the total number, which does not affect the composite analysis of the heat budget in the next section.
More than 80% of MHWs in the northern SCS continental shelf have a duration of less than 20 days, and ∼10% last between 20 and 40 days. MHWs longer than 40 days are rare, and only one case occurred in the OISST data (Fig. 3a).

The main features of the MHW intensity and duration on the northern SCS continental shelf from OISST and OFES are relatively similar, which validates the use of OFES output in the following heat budget analysis.

4. Air–sea heat flux versus ocean current for MHWs

To investigate the development of MHWs in the northern SCS continental shelf, a composite is produced from the MHW cases projected onto a time axis from 0 to 1. The developing, mature, and decay phases can be identified using the composite SST anomaly (Fig. 4a). In the developing phase, the net heat flux (Qnet) is the main source of warming, whereas the advection of mean temperature by the anomalous horizontal velocity (advha) always opposes the contribution of Qnet, cooling the upper layer of the ocean (Fig. 4b). In total, the oceanic process offsets 65% of the contribution of the atmospheric process (Fig. 4c). In the mature phase, Qnet weakens, and the negative advha strengthens, leading to an approximate equilibrium between the oceanic and atmospheric processes (Figs. 4b,c). In the decay phase, Qnet weakens sharply and becomes negative, and the advha continues to strengthen rapidly (Fig. 4b). The upper ocean begins to lose heat, which is mainly associated with oceanic processes (Figs. 4b,c). Therefore, the Qnet warms the upper ocean and induces an MHW outbreak in the northern SCS continental shelf; oceanic processes, which are dominated by the advha, cool the upper ocean, and cause the MHW to die out.

The continental shelf edge, indicated by the black line in Fig. 1, and the Taiwan Strait are the two pathways for the advha on the northern SCS continental shelf. The southern boundary (i.e., the continental shelf edge) is the main temperature advection (advha) pathway (Fig. 4d), which is concentrated on the east and west sides of the shelf (Fig. 4e). In the developing phase, the east and west sides make opposite contributions to the advha. In the decay phase, the temperature advection (advha) is negative on both sides, leading to a rapid enhancement of negative advha, which induces MHW decay.

The spatial distributions of each term are shown in Fig. 5. In the developing phase, a large positive Qnet is mainly
located in the center and east of the continental shelf, although the entire northern SCS continental shelf warms (Fig. 5a). Warming on the west side of the continental shelf is attributed to the positive advha (Fig. 4e), where a northward flow anomaly carries high mean temperature water from the south (Fig. 5a and Figs. 6a,b). Along the southern boundary of the continental shelf (i.e., line A in Fig. 1a), the temperature gradient perpendicular to line A is mainly negative (i.e., decreases northward; Fig. 6a). The onshore flow anomaly on the western side (Fig. 6b), jointly with the negative temperature gradient, induces a positive advha (\(-\partial T/\partial y\), where \(y\) indicates the direction perpendicular to line A). On the east side, the strong offshore flow anomaly plus a negative temperature gradient induces a large negative advha (Figs. 6a,b). In the mature phase, although Qnet decreases, the upper layer temperature anomaly reaches a maximum after early accumulation (Fig. 5b). The east side flow anomaly is still offshore and contributes negatively to the advha (Fig. 5b and Fig. 6b). The west side cross-slope flow anomaly weakens, which gradually weakens its positive advha (Fig. 4e). In the decay phase, Qnet becomes negative and the upper layer temperature anomaly weakens (Fig. 5c). The offshore flow anomaly dominates both the east and west sides at the continental shelf edge (Figs. 5c and 6b), which leads to a strong negative advha, resulting in the rapid decay of the MHW. The vertical temperature advection contributes little during the developing and mature phases (Fig. 4b and Figs. 5a,b). However, the vertical process contributes significantly to the decay of MHWs near the coast (Fig. 5c).

On the northern SCS continental shelf, the variations in the flow anomaly are mainly associated with wind stress anomalies (Fig. 7). In the developing and mature phases, the wind stress anomalies mainly blow toward the northeast (Figs. 7a,b), which induces an eastward flow anomaly along the coast (Figs. 5a,b). In the decay phase, the wind stress turned toward the southwest (Fig. 7c), driving the continental shelf flow to turn direction accordingly (Fig. 5c). The wind stress curl is one dominant factor modulating the cross-isobath movement over a widened shelf in the northeastern SCS (Gan et al. 2013; Liu et al. 2020b). During the developing and decay phases, a significant negative wind stress curl occupied the northeastern SCS (Figs. 7a,c). Responding to the negative wind stress vorticity input into the ocean, the ocean volume potential vorticity decreases. The decrease in potential vorticity will make the seawater tend to cross the isobath, flowing toward the deep sea (Fig. 6b). In the mature phase, there is a positive wind stress curl over the northeastern SCS (Fig. 7b), which weakens the offshore flow (Fig. 6b). On the western side of the continental shelf, the wind stress curl is mainly negative and gradually enhances from the developing phase to the decay phase (Fig. 7), which corresponds to the offshore flow between 112° and 113°E (Fig. 6b). The direction of cross-slope flow east of Hainan Island is mainly determined by the direction of the slope current, i.e., offshore (onshore) flow is induced by the southwest (northeast) slope current due to the block of Hainan Island.

Three mooring stations were used to investigate the flow anomalies on the east and west sides of the northern SCS slope (Fig. 8b). The northern SCS continent shelf average SST anomaly during the mooring observation period is shown in Fig. 8a, and the MHW events are marked in purple. The velocities of the MHWs are shown in Figs. 8c, 8e, and 8g, and composites of the MHWs projected onto a time axis from 0 to 1 are shown in Figs. 8d, 8f, and 8h. On the east side, the composite flow anomalies are mainly offshore and increase gradually with MHW development (Figs. 8d,f). On the west side, the flow anomalies are mainly northeastward and decrease during the MHW decay phase (Fig. 8h). The changes of OFES flow anomalies on both the east and west sides are generally consistent with the mooring observations, which confirms the validation of the OFES oceanic processes during MHWs.

5. Conclusions

Using the OISST and OFES datasets, the properties and heat budget of MHWs on the northern SCS continental shelf were analyzed. The intensity of MHWs is strong along the coast and decreases toward the open sea. MHWs with 1°–1.5°C warming and a duration of <20 days dominate the
northern SCS continental shelf. MHWs with warming of $0.5\text{--}1\text{C}$ account for approximately one-third of the total, and those $1.5\text{C}$ account for approximately one-tenth. Approximately one-tenth of the MHWs persist for 20--40 days; those with durations of $>40$ days are very rare, and only one case was identified from the OISST dataset.

The heat budget indicates that the net heat flux ($Q_{\text{net}}$) is the main driver of the MHWs on the northern SCS continental shelf. Oceanic processes, which are dominated by the advection of mean temperature by anomalous horizontal velocity ($\text{adv}_{\text{ha}}$), always cool the upper layer ocean, leading to the decay of MHWs. In the developing phase, $Q_{\text{net}}$ is stronger than the negative oceanic process contribution to the heat budget, which results in warming of the upper layer. In the mature phase, there is an equilibrium between the $Q_{\text{net}}$ and oceanic process contributions. In the decay phase, both the $Q_{\text{net}}$ and oceanic process contributions are negative, but the ocean process contribution is approximately 4 times that of $Q_{\text{net}}$.

The oceanic process contribution to the heat budget is dominated by $\text{adv}_{\text{ha}}$, which is attributed mainly to the temperature advection across the southern continental shelf edge in the northern SCS. The east and west sides of the continental shelf edge are the two major pathways; these make opposing contributions to the heat budget in the MHW developing phase (i.e., negative and positive on the eastern and western sides, respectively) but are of the same sign in the decay phase (i.e., both negative).

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Data availability statement. The OISST and OFES data for this paper are available at http://apdrc.soest.hawaii.edu/data/data.php.

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