



A Case Study on the Dynamics of Phytoplankton Blooms Caused by Tropical Cyclones in the Southeastern Arabian Sea

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ABSTRACT

A phytoplankton bloom was observed in the southeastern Arabian Sea after the passage of the anti-S-type track Tropical cyclone ARB 06 in 1998, which lasted for 22 days. The dynamic mechanism of the phytoplankton bloom was investigated with high-resolution satellite remote sensing data, reanalysis data and buoy data. The results show that the double thermocline structure hindered the uplift of deep nutrients to the surface before the tropical cyclone arrival. During and after the passage of the cyclone, the shallower thermocline disappeared, the deeper thermocline changed from 45.7 m to 76.5 m, the mixed layer deepened, and the upper oceanic stratification weakened. Additionally, a weak ocean eddy pair was enhanced gradually after the passage of cyclone. The relative vorticity of the ocean eddy pair was calculated. In the oscillation with a period of two days, the vorticity of the cyclonic eddy was stronger than that of the anticyclonic eddy, which enhanced a strong upwelling at a depth of more than 55 m for more than 10 days. The vertical current shear generated by the oscillation not only enhanced the vertical mixing, but also plays an important role in the distribution of phytoplankton blooms. The phytoplankton bloom was triggered by the nutrient below the thermocline into the sea surface, where a strong upwelling and weakened oceanic stratification occurred after the passage of cyclone. This study offers new insights on the mechanism of phytoplankton bloom induced by tropical cyclones and will be helpful for evaluating tropical cyclone-induced biological responses in future.

KEYWORDS:

Tropical cyclone; phytoplankton bloom; thermocline; ocean eddy pair; inertial oscillation; vertical current shear

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1. INTRODUCTION

Tropical Cyclones are an extreme weather phenomenon, which is a strong interaction between the atmosphere and the ocean, and can regulate the dynamic process of the upper ocean (Emanuel, 1999). The northern Indian Ocean is a tropical cyclone occurrence area, which comprises the Arabian Sea and Bay of Bengal. Compared to the Bay of Bengal, the ratio of tropical cyclone occurrence over the Arabian Sea is about 4:1 (Dube, Rao et al., 1997). Tropical cyclones usually occur in May and June, when they are associated with the southwest monsoon, and in November, when they are associated with sea level pressure (Evan and Camargo, 2011). The northern Arabian Sea is a semi-closed sea with a distinct monsoon climate. When oligotrophic conditions occur on the surface of the Arabian Sea, a rapid biological response can be achieved through tropical cyclones (Bulusu, Rao et al., 2002).

Up to now, there has been a lot of research on phytoplankton blooms on the water surface. Some studies suggested that the main contribution to the

phytoplankton blooms in the sea was strong Ekman pumping by the cyclone (Madhu, Maheswaran et al., 2002; Vinayachandran, 2003), and some authors believed that the main contribution was ocean currents and eddies associated with a cyclone strong enough to erode stratification (Gomes, Goes et al., 2000; Xia, Ge et al., 2022). In addition, the cyclonic wind stress of surface tropical cyclones can transport the cold-water rich in nutrients from the ocean bottom to the surface through dynamic processes such as coiling and mixing and upwelling (Lin, Liu et al., 2003; Zheng and Tang, 2007; Onitsuka, Morimoto et al., 2009; Zhang, Xie et al., 2014). Few studies have focused on the response of the double thermoclines in the upper ocean to phytoplankton bloom induced by cyclones in the Arabian Sea, and the distribution mechanism of phytoplankton blooms in the Arabian Sea is rarely studied. Severe cyclone storm ARB 06 occurred in the southeastern Arabian Sea on Dec.11, 1998. It made landfall on the Arabian Peninsula along an anti-S- type tropical cyclone track (Figure 1). Before the passage of the cyclone, there was an ocean eddy pair and a rare double thermocline in the study area. After the

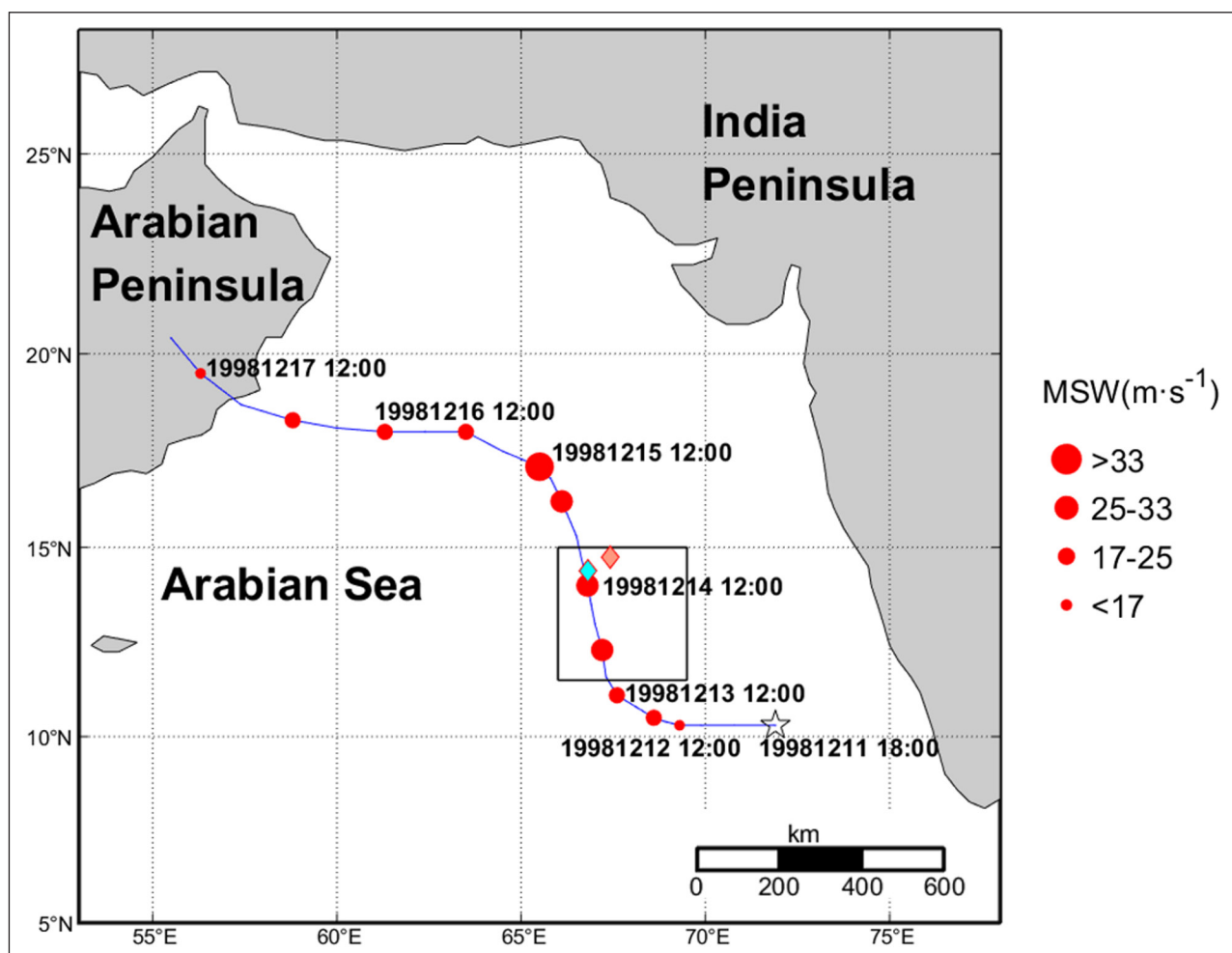


Figure 1 Track of tropical cyclone ARB 06. Locations of the tropical cyclone center are indicated by the red circles in the time format of year-month-date -hour. Diamonds mark the positions of the floats (Cyan diamond: 03/12/1998 66.81°E, 14.39°N; Red diamond: 29/12/1998 67.42°E 14.74°N). The circle size represents the maximum wind speed. The studied box A is indicated by the black square: 11.5°N–15°N, 66°E–69.5°E.

passage of the tropical cyclone, the double thermoclines in the upper ocean disappeared, and a phytoplankton bloom lasted for 22 days in southeastern Arabian Sea. Therefore, this paper mainly focuses on explaining the mechanism of the phytoplankton bloom induced by severe cyclone ARB 06 with an anti-S- type track in 1998. In addition, the effects of vertical current shear (VCS) on phytoplankton bloom distribution were studied using cyclone ARB 06 as an example.

2. DATA AND METHODOLOGY

Track of cyclone ARB 06 was obtained from the Joint Typhoon Warning Center (JTWC) (available at <https://www.metoc.navy.mil/jtwc/jtwc.html>), which provided cyclone forecasts for the Western Pacific and Indian Ocean basins. Data of tropical cyclone was at 6-hour intervals including time, wind speed and central location. The forward speed of tropical cyclone can be calculated according to the moving distance of the tropical cyclone center every 6 hours.

Reanalysis data on temperature and salinity profiles, sea surface height (SSH), sea current velocity, wind (The IFREMER CERSAT Global Blended Mean Wind Fields include wind components (meridional and zonal). The estimate of the 6-hour blended wind product uses all the remote surface winds derived from the scatterometer and radiometer available at the time.), Chl-a and nutrients profiles were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS). The product has been widely used in climate change research (Tranchant, Testut et al., 2008; Chambers, Cazenave et al., 2017; Bensoussan, Cebrian et al., 2019). The resolution of wind is 6 hours, and the resolution of other data is daily. The spatial resolution of temperature, salinity, sea surface height and sea current velocity was $(1/12)^\circ \times (1/12)^\circ$, and the spatial resolution of wind, Chl-a and nutrients was $(1/4)^\circ \times (1/4)^\circ$. Sea surface chlorophyll interpolation data from satellite observations, products are based on a multi sensors/algorithms approach to provide to end-users the best estimate. This product is a good indicator of phytoplankton (Liu, Zhang et al., 2019; Gbagir and Colpaert, 2020). It has a spatial resolution of $(4 \text{ km} \times 4 \text{ km})$ and a temporal resolution of 6 hours. (available at <http://marine.copernicus.eu/>).

The temperature and salinity records of the profiling buoys are available from the World Ocean Circulation Experiment (WOCE), a dataset published by the U.S. National Oceanographic Data Center (Woce Upper Ocean Thermal, 2009). The application of WOCE float data is mature, Davis showed that the WOCE float arrays were effective at mapping large-scale circulation patterns (Davis, 1998). Profiling floats report a number of times while on the surface in order to relay the full profile to a shore station. The profiling float number was 39398,

and their locations were 66.81°E 14.39°N and 67.42°E 14.74°N . The profile files contain only those data for which there is at least one profile (temperature or salinity). (Available at <https://doi.pangaea.de/10.1594/PANGAEA.725481/>).

We calculated the Ekman pumping velocity (EPV), vorticity and VCS using the Octave. The methodologies are as follows.

EPV

Enriquez and Friehe (Enriquez and Friehe, 1995) proposed Eqs (1) and (2) to compute the EPV caused by the spatial variation in wind stress. The velocity of upwelling can be calculated according to Eq (1).

$$w_E = \frac{1}{\rho f} (\nabla \times \tau) \quad (1)$$

where w_E is the EPV; $\rho = 1024 \text{ kg m}^{-3}$, f and τ are the seawater density, Coriolis parameter and wind stress, respectively. The curl of the wind stress can be calculated according to Eq (2).

$$\nabla \times \tau = \frac{1}{R \cos \phi} \left[\frac{\partial \tau_y}{\partial \lambda} - \frac{\partial}{\partial \phi} (\tau_x \cos \phi) \right] \quad (2)$$

where R , ϕ and λ are the radius of the earth and the geographic latitude and longitude, respectively; τ_x and τ_y are the zonal and meridional wind stress components, respectively.

Vorticity

The curl of a sea current vector (u, v) can be calculated based on Eq (3). By calculating the change of relative vorticity (ζ), the generation and extinction process of vortex field can be reflected (Schaeffer, Gramouille et al., 2017).

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \quad (3)$$

where u and v are the two velocity components along x and y directions, respectively.

VCS

The VCS can be calculated based on Eq (4). The formula is modified from the formula for vertical wind shear. Vertical wind shear refers to the change of wind in the vertical direction, usually the difference between the wind speed of 850 hPa and 200 hPa (Chan, Wang et al., 2019; Cui, Lv et al., 2022). Using the definition of vertical wind shear, we use the difference between the sea surface and the velocity at the underwater depth of 100 m to study the variation of ocean current with depth.

$$VCS = \sqrt{(u_0 - u_{100})^2 + (v_0 - v_{100})^2} \quad (4)$$

where u_0 and v_0 are the zonal and the meridional velocity components on the sea surface, respectively;

u_{100} and v_{100} are the zonal and the meridional velocity components at a depth of 100 m, respectively. VCS is the vertical current shear.

3. RESULTS

3.1 PATH OF TROPICAL CYCLONE AND WIND FIELD

Table 1 shows the changes in MSW and TS during the passage of the tropical cyclone. From Dec.12 at 18:00 to Dec.13 at 00:00, the cyclone formed and moved rapidly westward. From Dec.13 at 00:00 to Dec.15 at 12:00, the MSW strengthened, moved slowly and then rapidly northward, reaching an MSW maximum of $33.44 \text{ m}\cdot\text{s}^{-1}$ on Dec.15 at 06:00. The cyclone moved rapidly westward on Dec.15 at 12:00, and the MSW gradually weakened, and it made landfall on Dec.17 at 06:00.

LAT(°N)	Lon(°E)	TIME	MSW(M·S ⁻¹)	TS(M·S ⁻¹)
10.3	71.9	12/11/18	10.29	
10.3	70.8	12/12/00	12.86	5.57
10.3	69.9	12/12/06	12.86	4.56
10.3	69.3	12/12/12	12.86	3.04
10.4	68.9	12/12/18	15.43	2.09
10.5	68.6	12/13/00	18.01	1.60
10.8	68.1	12/13/06	23.15	2.96
11.1	67.6	12/13/12	23.15	2.96
11.6	67.3	12/13/18	25.72	2.99
12.3	67.2	12/14/00	28.29	3.64
13.0	67.0	12/14/06	30.87	3.74
14.0	66.8	12/14/12	30.87	5.24
15.3	66.5	12/14/18	30.87	6.86
16.2	66.1	12/15/00	30.87	5.04
16.8	65.8	12/15/06	33.44	3.43
17.1	65.5	12/15/12	33.44	2.14
17.5	64.5	12/15/18	33.44	5.33
18.0	63.5	12/16/00	23.15	5.54
18.0	62.4	12/16/06	20.58	5.39
18.0	61.3	12/16/12	20.58	5.39
18.1	60.0	12/16/18	20.58	6.38
18.3	58.8	12/17/00	18.01	5.96
18.7	57.4	12/17/06	18.01	7.14
19.5	56.3	12/17/12	15.43	6.75
20.4	55.5	12/17/18	12.86	6.04

Table 1 Position, time, intensity and translation speed of tropical cyclone ARB 06.

(MSW: maximum wind speed; TS: translation speed).

3.2 SSH, TEMPERATURE AND SEA SURFACE CURRENT

Under the forced action of cyclone wind stress, the upwelling was induced in the upper layer of the ocean within a range of hundreds of kilometers from the cyclone center, and surface water diverges outward from the cyclone center, resulting in the decrease of sea surface height near the cyclone, which has an important influence on the circulation structure of mesoscale vortices (Price, 1981; Liu, Lv et al., 2021). Before the arrival of ARB 06, there was a weak cyclonic eddy and a weak anticyclonic eddy in box A (Figure 2), forming a weak ocean eddy pair. Ocean eddy pairs can move water east or west faster than Rossby waves, resulting in an unusual transport of heat, nutrients, and carbon. The circulation caused by positive vorticity pushes the negative vorticity forward, while the circulation caused by negative vorticity pushes the positive vorticity forward, thus making the pair co-propagate (Schaeffer, Gramouille et al., 2017). The most striking feature of this process is that the cyclonic eddy strongly dominates the anticyclonic eddy (Kozlov, Artamonova et al., 2019). After the arrival of ARB 06, the cyclonic eddy increased, and the sea surface height in the cyclonic eddy area decreased significantly by $5 \sim 6 \text{ cm}$. During and after the passage of ARB 06, the westward transport capacity of the current to carry seawater is

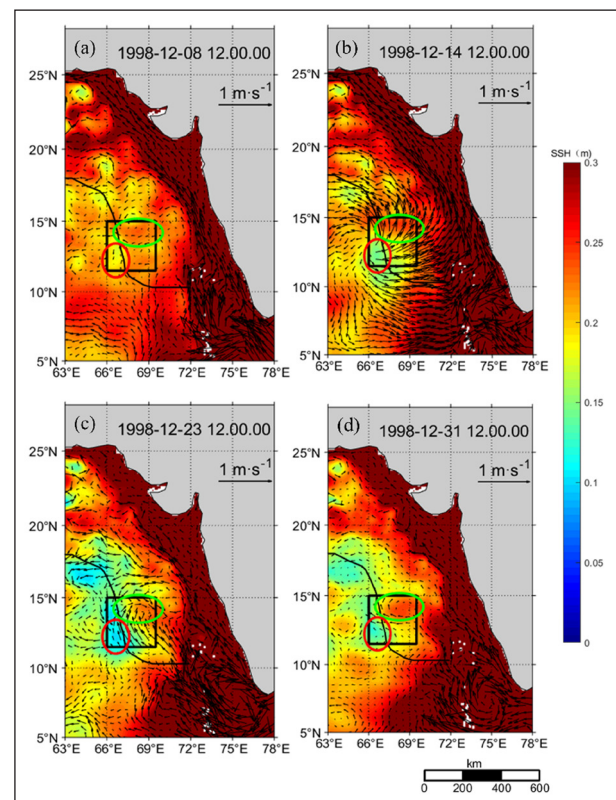


Figure 2 Sea surface current (unit in $\text{m}\cdot\text{s}^{-1}$) on Dec.8, Dec.14, Dec.23 and Dec.31 1998. The color bar represents the SSH (unit in m). Track of ARB 06 is indicated by the blue line. The red and green solid line elliptical rings mark the positions of cyclonic and anticyclonic eddies, respectively. Data: CMEMS 2022, <http://marine.copernicus.eu/>.

enhanced. In the next section, positive and negative sea vorticity are calculated to measure the intensity of cyclonic eddy and anticyclonic eddy respectively.

The lowest sea surface temperature (SST) drop occurred in the cyclonic eddy, while the average temperature in the anticyclonic eddy was higher than that in the surrounding region (Figure 3). A time series

of the spatially averaged temperature with depth in box A from Nov. 25 to Dec.31 is shown in Figure 4. Seawater cooling is an important response of the ocean to tropical cyclones, which is affected by the intensity, speed and other factors of tropical cyclones (Zhao, Shao et al., 2015). The sea temperature drop caused by tropical cyclone is mainly over 50 m, and the SST drop range

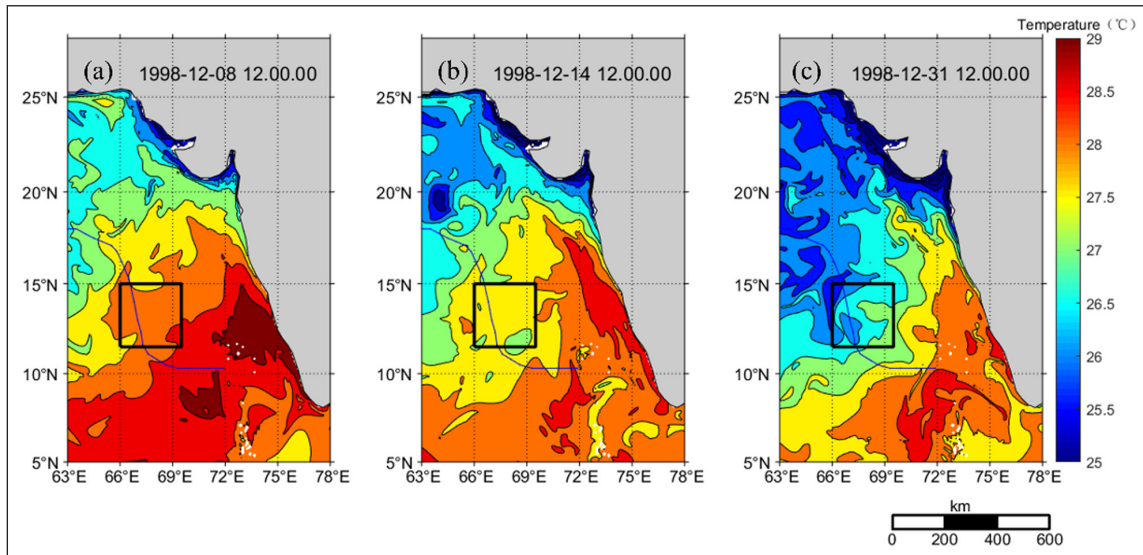


Figure 3 SST during and after the passage of ARB 06. Data: CMEMS 2022, <http://marine.copernicus.eu/>.

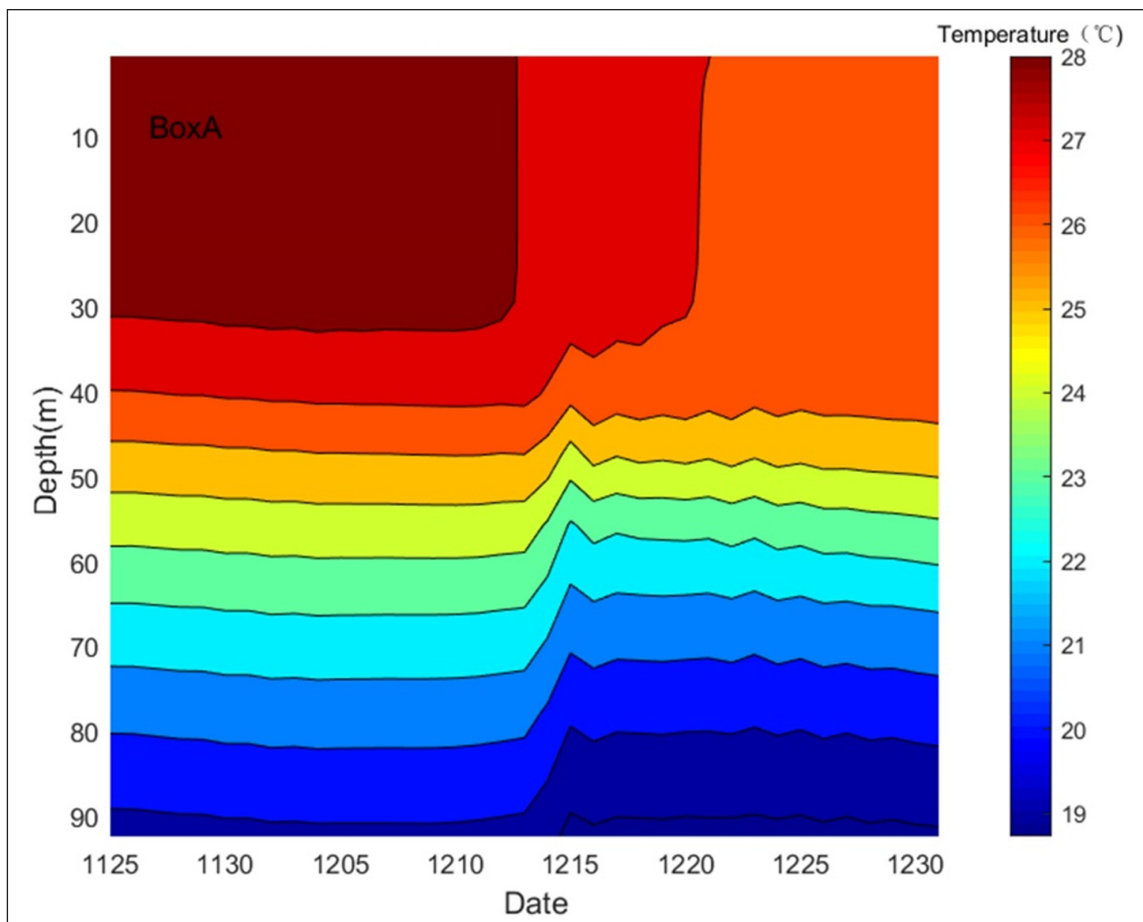


Figure 4 A time series of the spatially averaged temperature with depth in box A from Nov. 25 to Dec.31.

is about 1–1.5°C. Cold SST lasts for more than two weeks, which can effectively promote phytoplankton reproduction and have an important impact on marine primary productivity (Lin, Liu et al., 2003; Zheng and Tang, 2007).

3.3 CHL-A

Chl-a concentration before, during and after the passage of ARB 06 is presented in Figure 5. A high concentration of Chl-a appeared after the passage of the tropical cyclone center. A time series of daily averaged Chl-a is calculated

to investigate the variation of Chl-a concentration before, during and after the passage of ARB 06 in Figure 6. Before ARB 06, the concentration of Chl-a in box A was 0.19 mg·m⁻³ on Dec.10. After the passage of ARB 06, the concentration of Chl-a in box A increased significantly, with the maximum concentration rising to 1.65 mg·m⁻³, as evident by the increase in the sea surface Chl-a concentration by 8.68 times. From Dec.23 to Jan. 3 of the following year, the concentration of Chl-a dropped to 0.35 mg·m⁻³ gradually, which was close to the level of Chl-a concentration before ARB 06 passage.

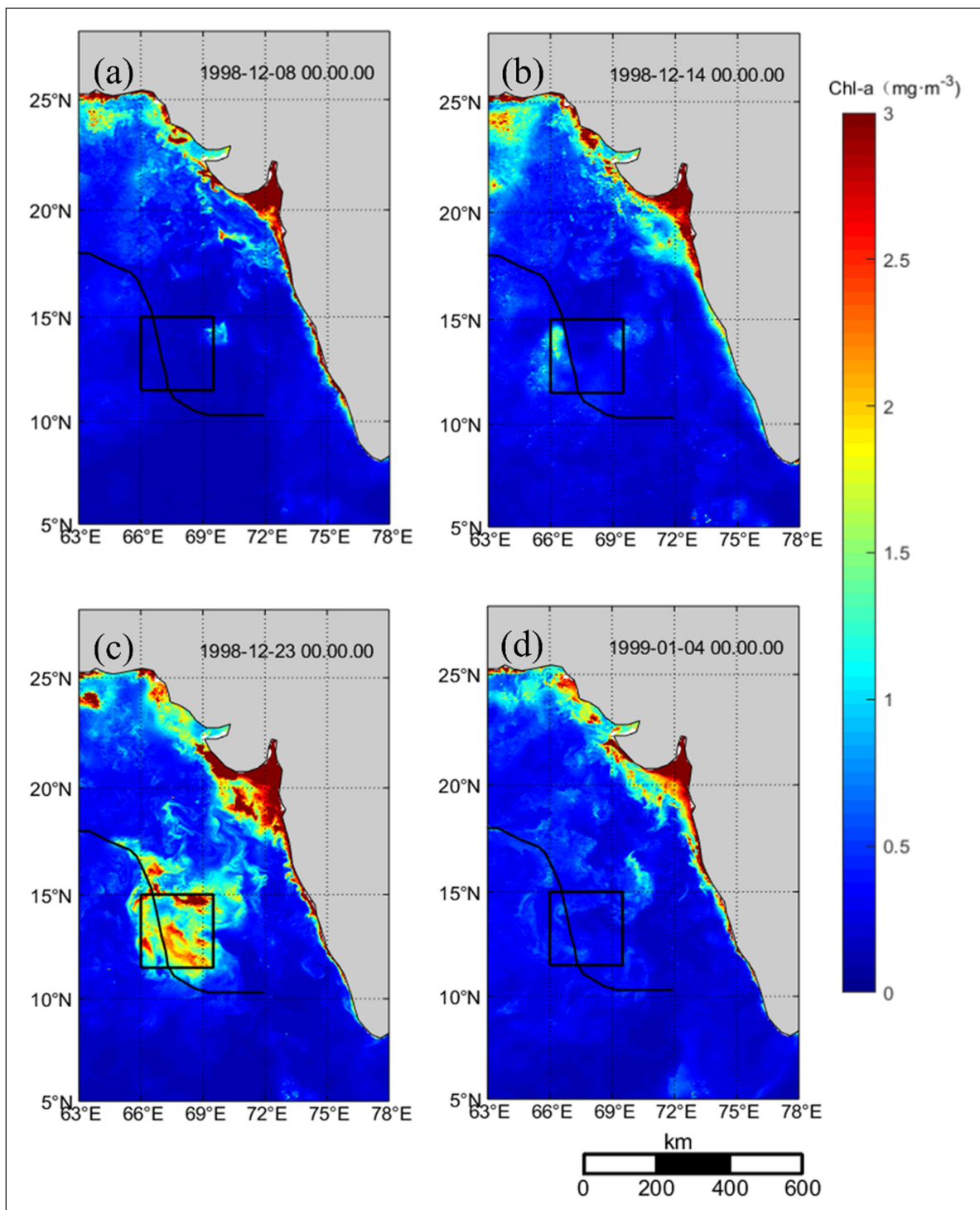


Figure 5 Daily mean Chl-a concentration during and after the passage of ARB 06. Data: CMEMS 2022, <http://marine.copernicus.eu/>.

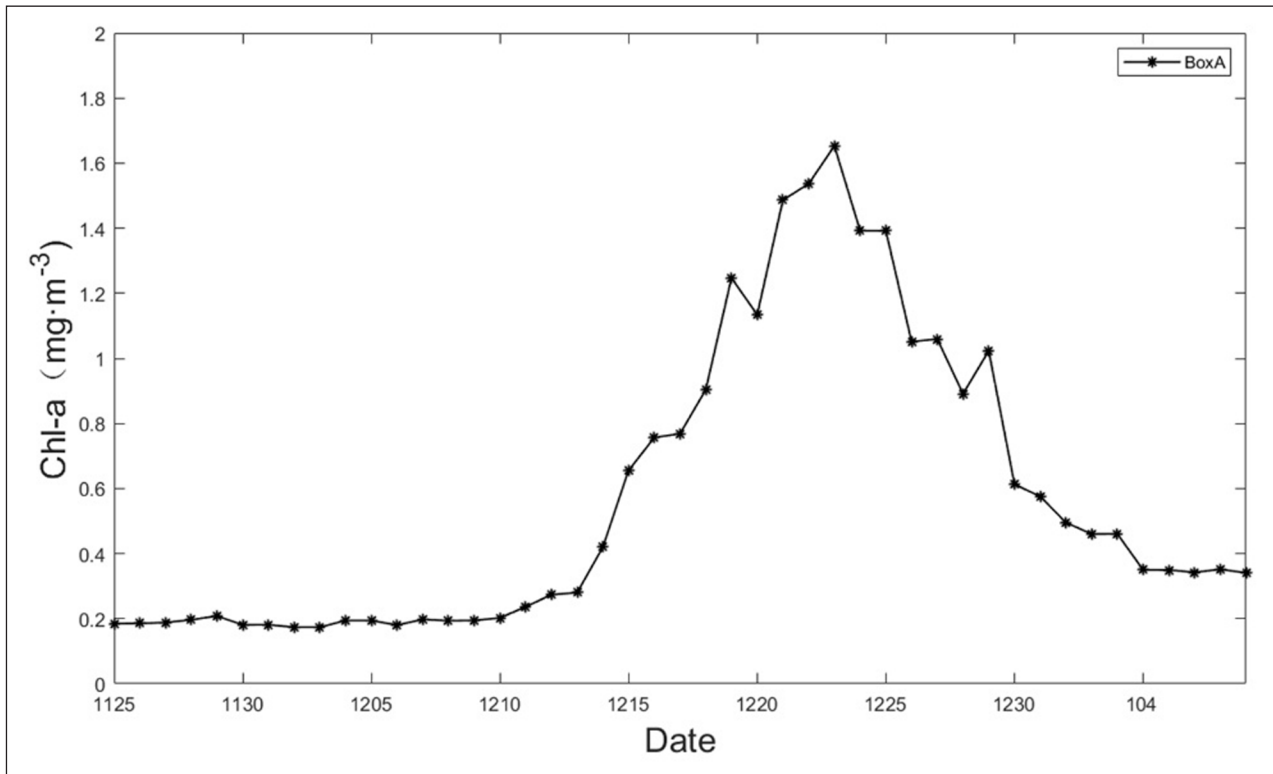


Figure 6 Time series of daily averaged Chl-a in box A from Nov. 25, 1998 to Jan. 8, 1999. Data: CMECS 2022, <http://marine.copernicus.eu/>.

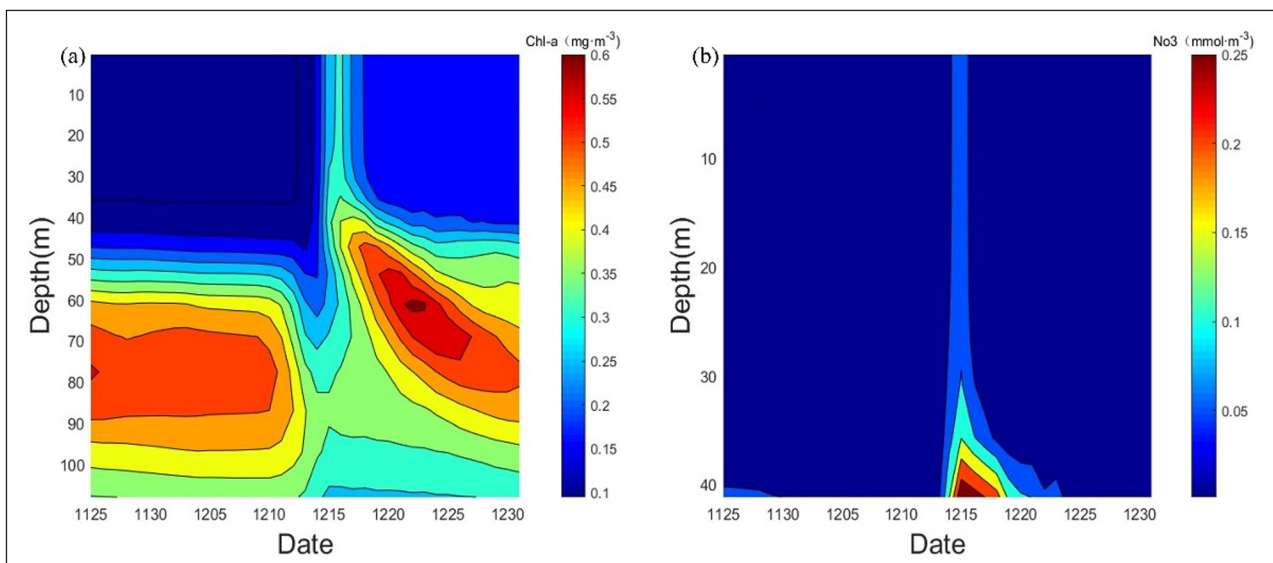


Figure 7 A time series of the spatially averaged concentration of Chl-a (**Figure 7a**), nitrate (**Figure 7b**) with depth in box A from Nov. 25 to Dec.31. Data: CMECS 2022, <http://marine.copernicus.eu/>.

A time series of the spatially averaged concentration of Chl-a with depth in box A from Nov. 25 to Dec.31 is shown in **Figure 7a**. A higher concentration layer of Chl-a lies in the depth ranges from 55 m to 110 m, which is more than $0.3 \text{ mg}\cdot\text{m}^{-3}$. As the tropical cyclone passed on Dec.14, Chl-a below the thermocline obviously penetrated the thermocline and rose to the mixing layer.

3.4 NUTRIENT

Nutrient provides one of the basic conditions for the phytoplankton bloom (Kanda, Ziemann et al., 1990). The nitrate concentrations at different depths with $z = -0.5 \text{ m}$, -40 m and -77.6 m according to the nitrate climatology data in December are shown in **Figure 8**. During and after the passage of the tropical cyclone, the nitrate concentration in box A remained at a depth of

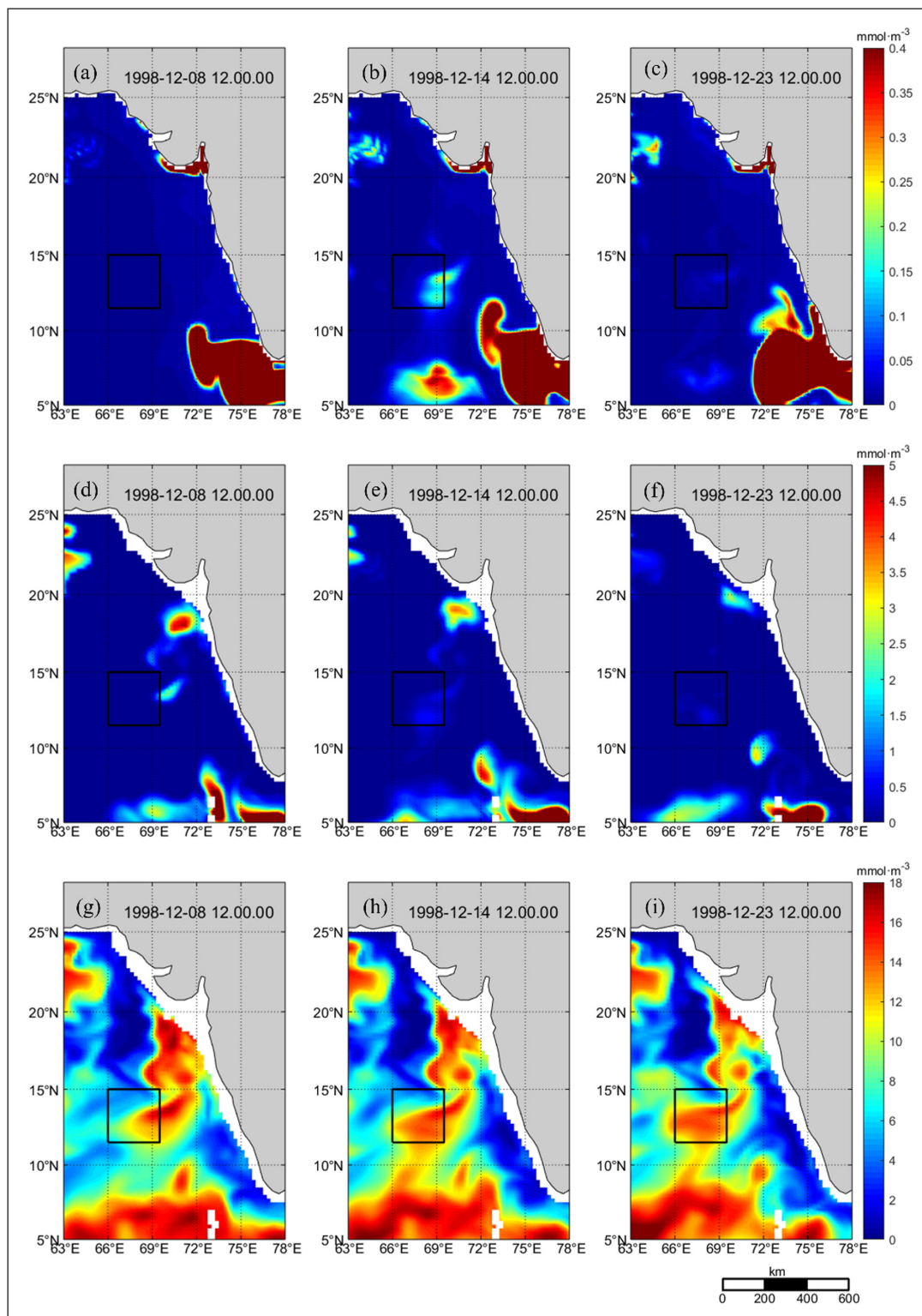


Figure 8 The nitrate concentrations at different depths with $z = -0.5$ m, -41 m and -77.6 m marked as (a, b, c), (d, e, f), (g, h, i) respectively. Data: CMEMS 2022, <http://marine.copernicus.eu/>.

about $15 \text{ mmol}\cdot\text{m}^{-3}$ at $z = -77.6$ m (Figure 8g, h, i). Before the passage of the tropical cyclone, the concentration of nitrate was less than $0.005 \text{ mmol}\cdot\text{m}^{-3}$ at $z = -0.5$ m and less than $0.001 \text{ mmol}\cdot\text{m}^{-3}$ at $z = -41$ m. After tropical cyclone transit, the maximum concentration of nitrate at $z = -0.5$ m and $z = -41$ m is greater than 0.2

$\text{mmol}\cdot\text{m}^{-3}$. Nitrate was transported westward during and after the passage of ARB 06. Combined with Figures 7b and 8, it can be seen that deep nitrate continued to rise for 10 days during and after the passage of tropical cyclone, providing a large amount of nutrients for the phytoplankton bloom.

4. DISCUSSION

Generally, with the arrival of tropical cyclone, cyclonic eddies would occur in the upper ocean, which may trigger a phytoplankton bloom (Lv, Zhao et al., 2020). The dynamic mechanism for the bloom of Chl-a has been well studied (Zhao, Han et al., 2013; Zhang, Xie et al., 2014; Zhao, Shao et al., 2015). Interestingly, there exists a weak anti-cyclone (cyclone) eddy on the right (left) side of the cyclone path, which forms a weak ocean eddy pair in box A (Figure 2). High concentrations of Chl-a and nutrients were all located in the nearshore side of box A. The phytoplankton bloom began on Dec.14, when the cyclone center located over the area in box A, then the Chl-a concentration continued to increase for nine days after the passage of ARB 06, increased by 8.68 times (Figure 6). There are two possible causes of the phytoplankton bloom. One is the direct entrainment mixing from preexisting subsurface chlorophyll (Figure 7a), with an order about $0.3 \text{ mg} \cdot \text{m}^{-3}$ of the Chl-a concentration; Due to the maximum concentration rising to $1.65 \text{ mg} \cdot \text{m}^{-3}$ after the passage of cyclone, the other one is the phytoplankton growth sustained by new nutrients which were brought into the euphotic zone from below (Figures 7b and 8). The possible driving mechanisms of the phytoplankton bloom in box A were analyzed.

4.1 THE ROLE OF STRATIFICATION

The vertical profiles of temperature and the buoyancy frequency from the floats at two different locations (Figure 1) are shown in Figure 9. For tropical cyclones with slow movement, the cooling center is generally located near the path of the cyclone (Price, 1981; Chu, Veneziano et al., 2000; Liu, Wang et al., 2009). In addition, the forcing time in the affected area is relatively long, so the local upwelling induced by Ekman pumping will have an overwhelming impact on the SST (Geisler, 1970; Zhang, Xie et al., 2014; Wu, Zhang et al., 2018). From December 13 to 14, the cyclone translated with a slow speed from 1.6 m s^{-1} to 3.74 m s^{-1} (Table 1), which might result in a significant surface ocean cooling (Bender and Ginis, 2000; Rao, Dash et al., 2007). Before and after the passage of ARB 06, the sea water temperature became cooler above the depth of 60 m with a maximum temperature drop about 2.3°C . According to the float data, we found that there was a shallow thermocline at 10 m on Dec.3, and the buoyancy frequency was about 0.036 s^{-1} . Combined with a deeper thermocline with the buoyancy frequency about 0.024 s^{-1} at the depth of 45.7 m, a double thermoclines formed in the upper ocean before the arrival of the cyclone, which could effectively prevent deeper nutrients from rising to the surface. On December 9, there was only one thermocline with the maximum buoyancy frequency 0.02 s^{-1} at the depth of 76.5 m. The

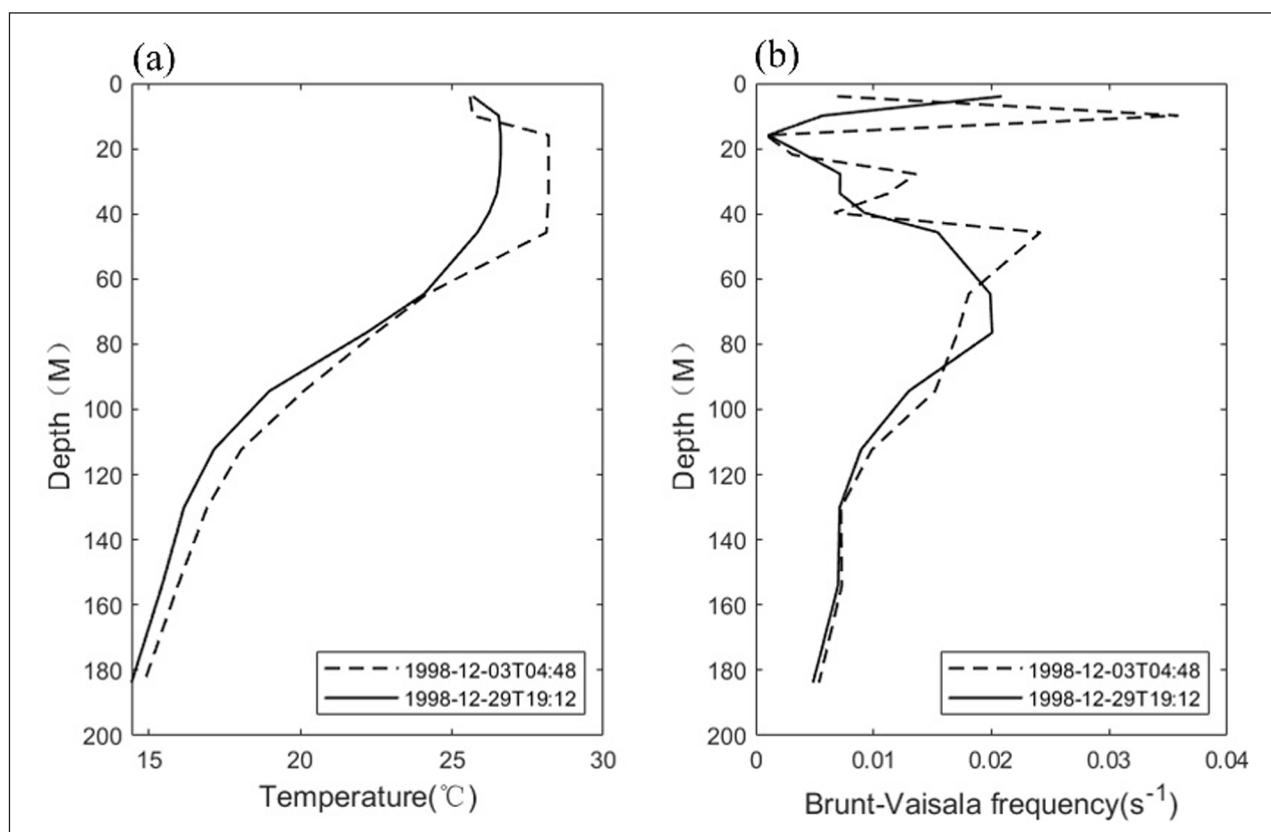


Figure 9 Vertical profiles of temperature and buoyancy frequency from floats before and after the passage of the tropical cyclone. Data: World Ocean Circulation Experiment (WOCE), <https://doi.pangaea.de/10.1594/PANGAEA.725481/>.

shallower barrier layer disappeared. As the mixing layer deepens, the upper ocean stratification weakens, which promotes the phytoplankton aggregation in the water (Lv, Ma et al., 2020; Lv, Zhao et al., 2020).

4.2 ROLES OF TROPICAL CYCLONE AND OCEAN EDDY PAIR

The mixing and EPV induced by tropical cyclone have been well studied. The EPV can be calculated based on Eqs (1) and (2) (Byju and Kumar, 2011). The EPV during the passage period of ARB 06 is shown in Figure 10. It took approximately 2 days for the tropical cyclone to pass over the study area. (Zheng, Ho et al., 2008) found that the duration of the sustained influence of a tropical cyclone near its path where the wind speed exceeds $17 \text{ m}\cdot\text{s}^{-1}$ is greater than the geographical adjustment time, the mesoscale vortex is more likely to be strengthened where a strong upwelling occurs. Additionally, for tropical cyclones with slow velocity and significant path deflection, the forcing time in the affected region is

relatively longer (Zhang, Xie et al., 2014). For ARB 06, its translational speed near box A slowed down (Table 1), and the deflection of the two translation directions was nearly 90° (Figure 1), which prolonged the forcing time of ARB 06 over the study area. During and after the passage of the tropical cyclone, the ocean eddy pair were significantly enhanced. In order to investigate the role of ocean eddy pair and understand the dynamic mechanism of phytoplankton blooms, various parameters related to vorticity were calculated.

Several studies have shown that near-inertial oscillations in the upper surface ocean are a direct result of local wind stress (Pollard, 1970; Klein, 1980; Dickey and Simpson, 1983). The response of the ocean to hurricane propagation is the deep propagation of near-inertial internal waves (Zhou, Tian et al., 2005). However, their production is not uniform across the hurricane-affected area, depending on ocean properties such as stratification and vorticity. In Figure 11 during the passage of the tropical cyclone, the wind stress increases rapidly, with

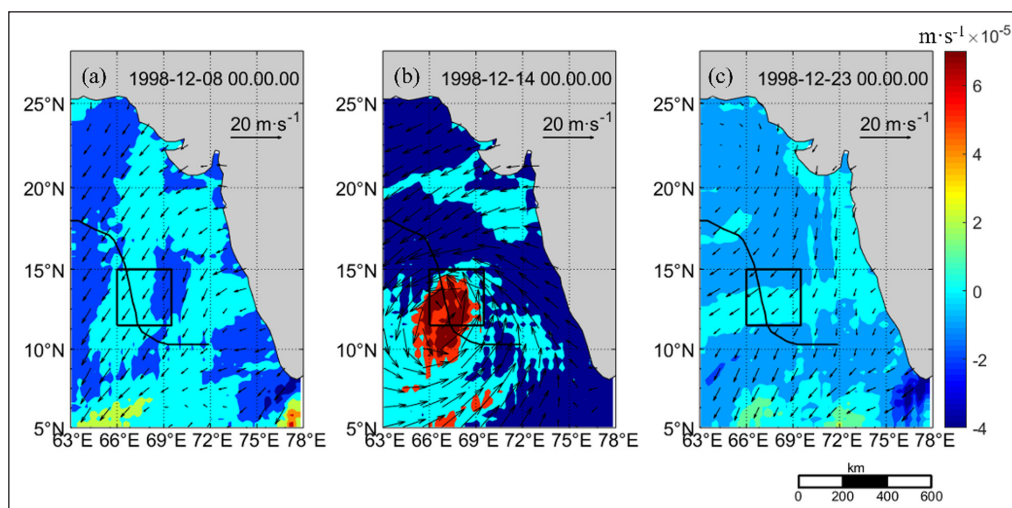


Figure 10 Surface wind speed (arrows) and EPV (colors) during the passage of the tropical cyclone. Data: CMEMS 2022, <http://marine.copernicus.eu/>.

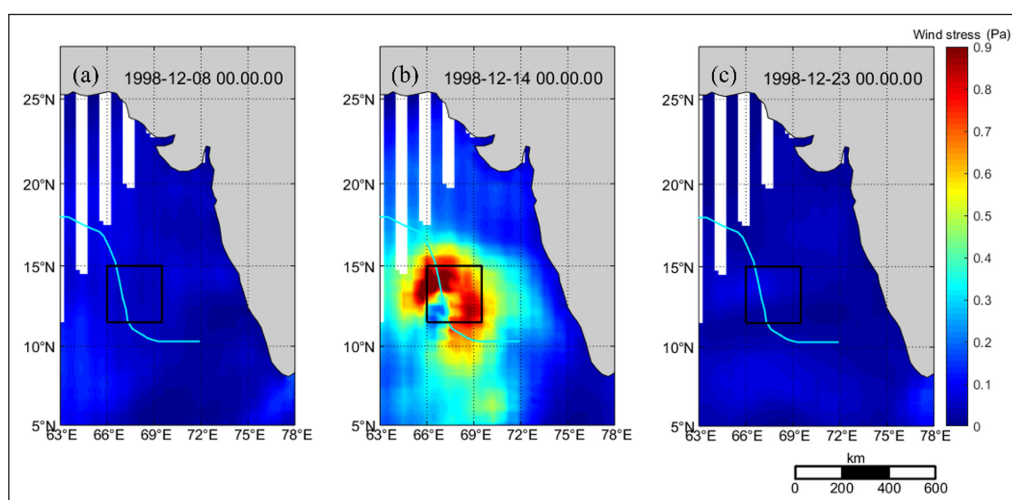


Figure 11 Wind stress (Pa) on Dec.8, Dec.14 and Dec.23. Data: CMEMS 2022, <http://marine.copernicus.eu/>.

the maximum intensity greater than 0.9 Pa, and the wind stress on the right side of the path is stronger than that on the left. As a result of the dramatic increase in atmospheric pressure, the entire column of water immediately produces a near-inertial internal wave. As the signal propagates downward, the amplitude of the near-inertial internal wave generally decreases with depth (Morozov and Velarde, 2008). A time series of the spatially averaged positive vorticity, the spatially averaged negative vorticity (absolute value), spatially averaged meridional current (c), spatially averaged zonal current (d), spatially averaged VCS (e) with depth in box A from Dec.01 to Dec.31 is shown in Figure 12. According to the comparison between Figure 12a and 12b, in the ocean eddy pair, the positive vorticity is stronger above

50 m, and the absolute value of negative vorticity is stronger below 50 m. The sea surface is dominated by cyclonic eddy, while the anticyclonic eddy below the mixing layer is dominated, which is consistent with the research results of Manucharyan et al (Manucharyan and Timmermans, 2013). During the passage of the tropical cyclone, strong vertical mixing occurred on Dec.14, in which the cyclonic eddy is enhanced above 30 m, and the maximum vorticity is about 0.34 s^{-1} (Figure 12a), and the anticyclonic eddy intensifies between $z = -40$ and -50 m , and the maximum vorticity is about 0.3 s^{-1} (Figure 12b). After the passage of tropical cyclone, the cyclonic and anticyclonic eddy with two days of oscillation period were strengthened, but the vorticity of cyclonic eddy was stronger than that of anticyclonic

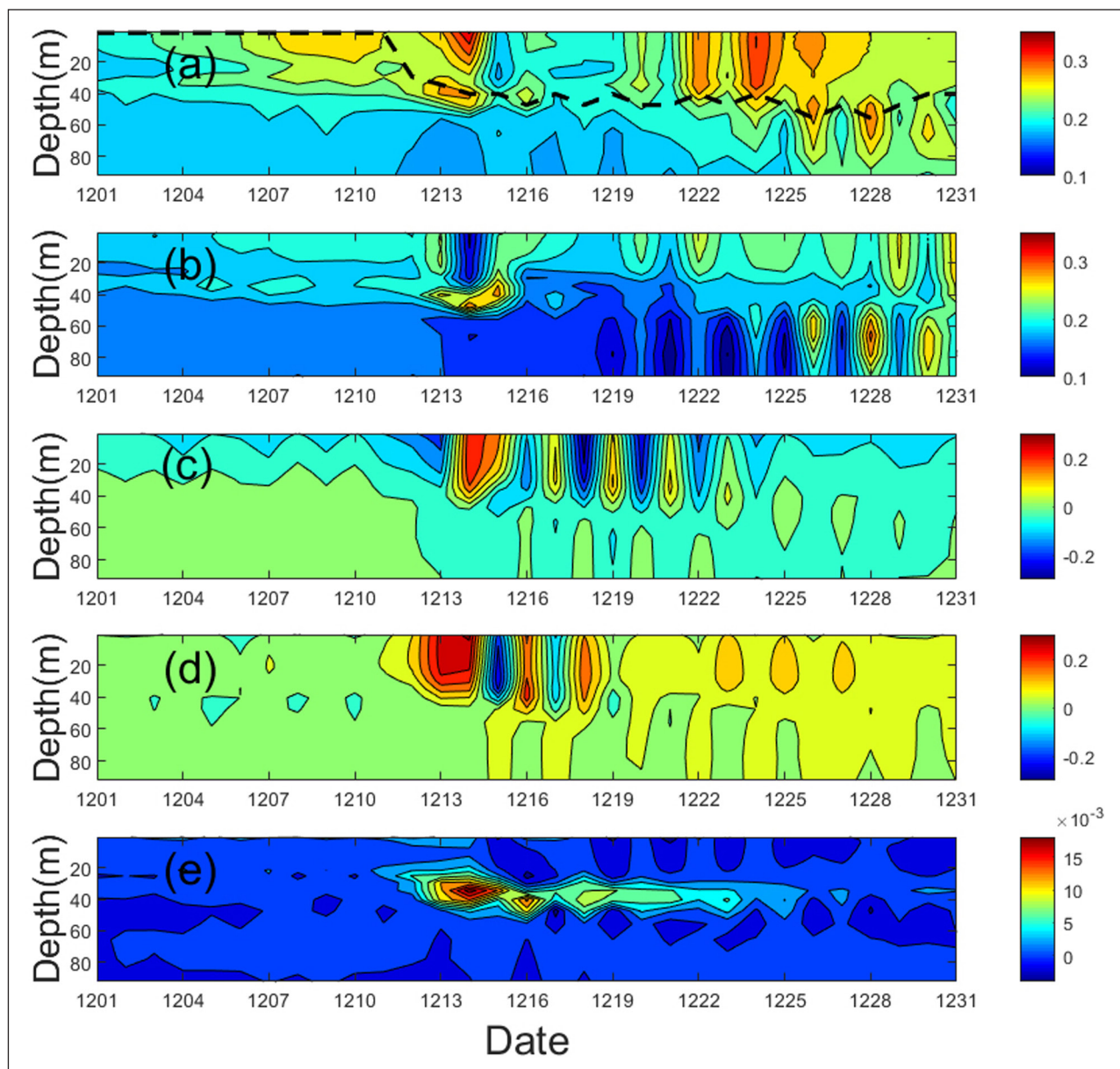


Figure 12 A time series of the spatially averaged positive vorticity (s^{-1}) (a), the spatially averaged negative vorticity (absolute value) (s^{-1}) (b), spatially averaged meridional current ($\text{m}\cdot\text{s}^{-1}$) (c), spatially averaged zonal current ($\text{m}\cdot\text{s}^{-1}$) (d), spatially averaged VCS (s^{-1}) (e) with depth in box A from Dec.01 to Dec.31. The dotted lines in a indicate the depth of the strongest VCS. Data: CMEMS 2022, <http://marine.copernicus.eu/>.

eddy and extended to the thermocline, creating a strong upwelling at the depth of about 55 m for more than 10 days. After Dec.25, the vorticity of cyclonic eddy decreases (Figure 12a), the vorticity of the anticyclonic eddy increases and was stronger than that of the cyclonic eddy (Figure 12b), the upwelling weakens, the concentration of Chl-a dropped rapidly after Dec.25 (Figure 6).

4.3 VCS

With the increase of depth, the near-inertial current vector rotation will produce significant VCS at the base of the mixing layer and the top of the thermocline layer, resulting in vertical mixing and deepening of the layer (Shay, 2009). Figure 12e shows the changes of mean VCS in box A at different depths with time series. Current shear is mainly located around $Z = -40$ m, and the strongest shear is located at the base of the oscillation (Figure 12a). It begins to strengthen on Dec.11 and reaches the strongest value of $1.9 \times 10^{-2} \text{ s}^{-1}$ when Dec.13 tropical cyclone passes through. It exists during the oscillation and serves as a link between the mixed layer and the thermocline layer. It strengthened the vertical mixing and played an important role in the rise of Chl-a and nutrients to the mixing layer. Figure 12c and 12d respectively show the changes of average meridional and zonal flow velocities in box A at different depths with time series. It is found that before Dec.19, the meridional current and the zonal current together determine the current shear along with the action of the oscillation, and after Dec.19, the meridional current has become the main factor determining the current shear. In this paper, the vertical shear of the whole layer from the sea surface to the depth of about 100 m is calculated, and its distribution is shown in Figure 13. There is a good correspondence between the region of current shear and the distribution of Chl-a, indicating that the current shear not only plays an important role in the vertical mixing and deepening of the layer, but also plays a major role in

the uplift of nutrients and other substances. Determines the distribution of phytoplankton blooms at the surface.

5. CONCLUSIONS

With high-resolution satellite remote sensing data, reanalysis data and buoy data, the mechanism of phytoplankton bloom were investigated during the passage of cyclone ARB 06 in 1998. According to the above analyses and discussion, the following conclusions can be drawn:

1. After the tropical cyclone center passed through box A, the concentration of Chl-a continued to increase for 10 days, and the average concentration of Chl-a increased to a maximum of about $1.65 \text{ mg} \cdot \text{m}^{-3}$ and increased by 8.68 times.
2. After the passage of tropical cyclone, the thermocline near the sea surface disappeared, the mixed layer was deepened and stratification in the upper ocean was weakened. Before the passage of ARB 06, there were double thermoclines in the study area. The deeper (shallower) thermocline was located at a depth of 45.7 m (9.9 m) on Dec.3, where the maximum buoyancy frequency was $N = 0.024 \text{ s}^{-1}$ ($N = 0.036 \text{ s}^{-1}$). After the passage of ARB 06, the single thermocline was located at a depth of 76.5 m on Dec.29, where the maximum buoyancy frequency was $N = 0.02 \text{ s}^{-1}$.
3. When ARB 06 passed through box A, the wind speed increased, it moved slowly, and it had a special turning path and a long enough forcing time. After the passage of the tropical cyclone, the ocean eddy pair was enhanced, where cyclonic eddy was stronger than anticyclonic eddy for 10 days. After Dec.25, the cyclone began to weaken, while the anticyclonic eddy had stronger vorticity, so the upwelling began to weaken.

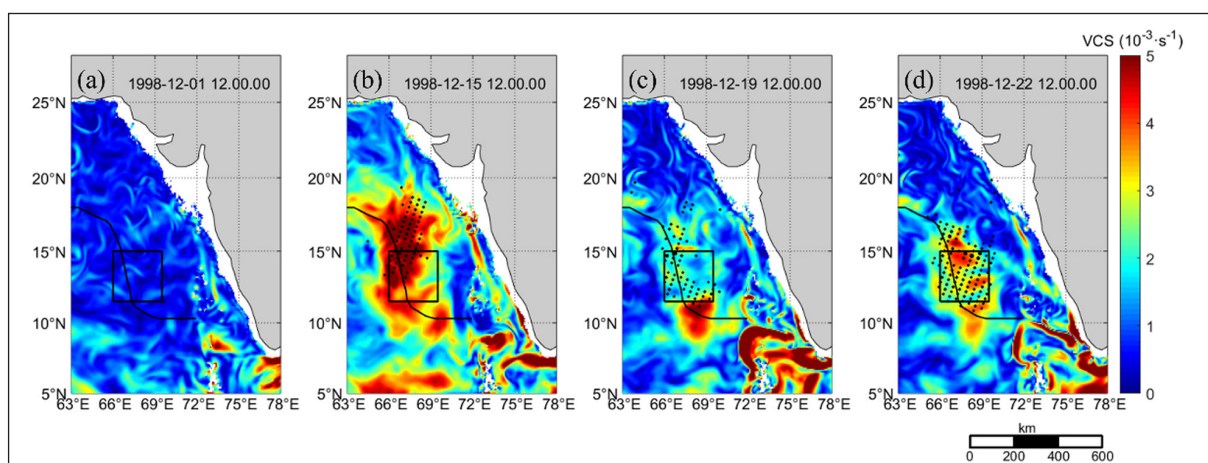


Figure 13 VCS (10^{-3} s^{-1}) on Dec.01, Dec.15, Dec.19 and Dec.22. The black dots represent the distribution of Chl-a ($>1 \text{ mg} \cdot \text{m}^{-3}$) the next day. Data: CMEMS 2022, <http://marine.copernicus.eu/>.

4. The VCS generated by the oscillation not only strengthens the vertical mixing, but also plays an important role in the distribution of phytoplankton blooms because it dominates the way nutrients and other substances rise.
5. The enhanced cyclone vortex maintained the upwelling for more than 10 days, thus raised high concentrations of Chl-a and nutrients into the mixing layer in the box A.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Conceptualization, Yusheng Cui and Haibin LÜ; methodology, Yusheng Cui and Haibin LÜ; software, Yusheng Cui and Xiaoqi Ding; validation, Yusheng Cui, Ziming Liu, Zhongnan Shan, Dawei Shi and Xiaoqi Ding; formal analysis, Yusheng Cui and Haibin LÜ; investigation, Yusheng Cui, Ziming Liu and Zhongnan Shan; resources, Yusheng Cui and Haibin LÜ; data curation, Yusheng Cui and Xiaoqi Ding; writing—original draft preparation, Yusheng Cui and Haibin LÜ; writing—review and editing, Yusheng Cui, Ziming Liu, Zhongnan Shan, Dawei Shi, Xiaoqi Ding and Haibin LÜ; visualization, Yusheng Cui, Zhongnan Shan and Ziming Liu; supervision, Yusheng Cui and Haibin LÜ; project administration, Yusheng Cui and Haibin LÜ; funding acquisition, Yusheng Cui and Haibin

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REFERENCES

- Bender, M** and **Ginis, I.** 2000. Real-Case Simulations of Hurricane Ocean Interaction Using A High-Resolution Coupled Model: Effects on Hurricane Intensity. *Mon Weather Rev.*, 128: 917–946. DOI: [https://doi.org/10.1175/1520-0493\(2000\)128<0917:RCSOHO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<0917:RCSOHO>2.0.CO;2)
- Bensoussan, N, Cebrian, E, Dominici, J-M, Kersting, DK, Kipson, S, Kizilkaya, Z,** et al. 2019. Using CMEMS and the Mediterranean Marine Protected Areas sentinel network to track ocean warming effects in coastal areas. *Journal of Operational Oceanography*.
- Bulusu, S, Rao, K, Rao, N** and **Murty, VsN.** 2002. Influence of a tropical cyclone on Chlorophyll-a Concentration in the Arabian Sea. *Geophys. Res. Lett.*, 29. DOI: <https://doi.org/10.1029/2002GL015892>
- Byju, P** and **Kumar, SP.** 2011. Physical and Biological Response of the Arabian Sea to Tropical Cyclone Phyan and Its Implications. *Marine environmental research*, 71: 325–330. DOI: <https://doi.org/10.1016/j.marenvres.2011.02.008>

- Chambers, DP, Cazenave, A, Champollion, N, Dieng, H, Llovel, W, Forsberg, R, et al.** 2017. Evaluation of the Global Mean Sea Level Budget between 1993 and 2014. *Surveys in Geophysics*, 38: 309–327. DOI: <https://doi.org/10.1007/s10712-016-9381-3>
- Chan, K, Wang, D, Zhang, Y, Wanawong, W, He, M and Yu, X.** 2019. Does strong vertical wind shear certainly lead to the weakening of a tropical cyclone? *Environmental Research Communications*, 1: 015002. DOI: <https://doi.org/10.1088/2515-7620/aaecac>
- Chu, P, Veneziano, J, Fan, C, Carron, M and Liu, WTL.** 2000. Response of the South China Sea to Tropical Cyclone Ernie 1996. *Journal of Geophysical Research*, 105: 20. DOI: <https://doi.org/10.1029/2000JC900035>
- Cui, Y, Lv, H, Shi, D, Xia, C and Dong, C.** 2022. A Comparative Study of the Landfall Precipitation by Tropical Cyclones ARB 01 (2002) and Luban (2018) Near the Arabian Peninsula. *Remote Sens.*, 14: 1194. DOI: <https://doi.org/10.3390/rs14051194>
- Davis, R.** 1998. Preliminary results from directly measuring middepth circulation in the tropical and South Pacific. *Journal of Geophysical Research*, 1032: 24619–24640. DOI: <https://doi.org/10.1029/98JC01913>
- Dickey, T and Simpson, J.** 1983. The sensitivity of upper ocean structure to time varying wind direction. *Geophysical Research Letters – GEOPHYS RES LETT.*, 10: 133–136. DOI: <https://doi.org/10.1029/GL010i002p00133>
- Dube, S, Rao, A, Sinha, P, Murty, TS and Bahulayan, N.** 1997. Storm surge in the Bay of Bengal and Arabian Sea: The problem and its prediction. *Mausam*, 48. DOI: <https://doi.org/10.54302/mausam.v48i2.4012>
- Emanuel, K.** 1999. Thermodynamic control of hurricane intensity. *Nature*, 401: 665–669. DOI: <https://doi.org/10.1038/44326>
- Enriquez, A and Friehe, C.** 1995. Effects of Wind Stress and Wind Stress Curl Variability on Coastal Upwelling. *Journal of Physical Oceanography – J PHYS OCEANOGR*, 25: 1651–1671. DOI: [https://doi.org/10.1175/1520-0485\(1995\)025<1651:EOWSAW>2.0.CO;2](https://doi.org/10.1175/1520-0485(1995)025<1651:EOWSAW>2.0.CO;2)
- Evan, A and Camargo, S.** 2011. A Climatology of Arabian Sea Cyclonic Storms. *J. Clim.*, 24: 140–158. DOI: <https://doi.org/10.1175/2010JCLI3611.1>
- Gbagir, A-M and Colpaert, A.** 2020. Assessing the Trend of the Trophic State of Lake Ladoga Based on Multi-Year (1997–2019) CMEMS GlobColour-Merged CHL-OC5 Satellite Observations. *Sensors*, 20: 1–16. DOI: <https://doi.org/10.3390/s20236881>
- Geisler, J.** 1970. Linear theory of the response of a two layer ocean to a moving Hurricane. *Geophysical and Astrophysical Fluid Dynamics – GEOPHYS ASTROPHYS FLUID DYNAM.*, 1: 249–272. DOI: <https://doi.org/10.1080/03091927009365774>
- Gomes, H, Goes, J and Saino, T.** 2000. Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal. *Continental Shelf Research*, 20: 313–330. DOI: [https://doi.org/10.1016/S0278-4343\(99\)00072-2](https://doi.org/10.1016/S0278-4343(99)00072-2)
- Kanda, J, Ziemann, DA, Conquest, LD and Bienfang, PK.** 1990. Nitrate and ammonium uptake by phytoplankton populations during the spring bloom in Auke Bay, Alaska. *Estuarine, Coastal and Shelf Science*, 30: 509–524. DOI: [https://doi.org/10.1016/0272-7714\(90\)90070-8](https://doi.org/10.1016/0272-7714(90)90070-8)
- Klein, P.** 1980. A Simulation of the Effects of Air-Sea Transfer Variability on the Structure of Marine Upper Layers. *Journal of Physical Oceanography – J PHYS OCEANOGR.*, 10: 1824–1841. DOI: [https://doi.org/10.1175/1520-0485\(1980\)010<1824:ASOTEO>2.0.CO;2](https://doi.org/10.1175/1520-0485(1980)010<1824:ASOTEO>2.0.CO;2)
- Kozlov, I, Artamonova, A, Manucharyan, G and Kubryakov, A.** 2019. Eddies in the Western Arctic Ocean From Spaceborne SAR Observations Over Open Ocean and Marginal Ice Zones. *Journal of Geophysical Research: Oceans*. DOI: <https://doi.org/10.1029/2019JC015113>
- Lin, II, Liu, WTL, Wu, C-C, Wong, G, Hu, CM, Chen, ZQ, et al.** 2003. New evidence for enhanced primary production triggered by tropical cyclone. *Geophys. Res. Lett.*, 30: 1718, 012003. DOI: <https://doi.org/10.1029/2003GL017141>
- Liu, X, Wang, M and Shi, WJJoGRO.** 2009. A study of a Hurricane Katrina-induced phytoplankton bloom using satellite observations and model simulations. 114. DOI: <https://doi.org/10.1029/2008JC004934>
- Liu, X, Zhang, S, Wang, T and Zeng, W.** 2019. Responses of the Cold-Core Eddy to the Passage of Typhoon. In: *Proceedings of the AGU Fall Meeting Abstracts*, 2019.
- Liu, Y, Lv, H, Zhang, H, Cui, Y and Xing, X.** 2021. Effects of ocean eddies on the tropical storm Roanu intensity in the Bay of Bengal. *PLoS one*, 16: e0247521. DOI: <https://doi.org/10.1371/journal.pone.0247521>
- Lv, H, Ma, X, Wang, Y, Xue, H and Chai, F.** 2020. Impacts of the unique landfall Typhoons Damrey on chlorophyll-a in the Yellow Sea off Jiangsu Province, China. *Regional Studies in Marine Science*, 39: 101394. DOI: <https://doi.org/10.1016/j.rsma.2020.101394>
- Lv, H, Zhao, X, Sun, J, Zha, G, Xi, J and Cai, S.** 2020. A case study of a phytoplankton bloom triggered by a tropical cyclone and cyclonic eddies. *PLOS ONE*, 15: e0230394. DOI: <https://doi.org/10.1371/journal.pone.0230394>
- Madhu, NV, Maheswaran, PA, Retnamma, J, Sunil, V, Revichandran, C, Thangavel, B, et al.** 2002. Enhanced biological production off Chennai triggered by October 1999 super cyclone (Orissa). *Current Science*, 82.
- Manucharyan, G and Timmermans, M-L.** 2013. Generation and Separation of Mesoscale Eddies from Surface Ocean Fronts. *Journal of Physical Oceanography*, 43: 2545–2562. DOI: <https://doi.org/10.1175/JPO-D-13-094.1>
- Morozov, E and Velarde, M.** 2008. Inertial oscillations as deep ocean response to hurricanes. *Journal of Oceanography*, 64: 495–509. DOI: <https://doi.org/10.1007/s10872-008-0042-0>
- Onitsuka, G, Morimoto, A, Takikawa, T, Watanabe, A, Moku, M, Yoshikawa, Y, et al.** 2009. Enhanced chlorophyll

- associated with island-induced cyclonic eddies in the eastern channel of the Tsushima Straits. *Estuarine, Coastal and Shelf Science*, 81: 401–408. DOI: <https://doi.org/10.1016/j.ecss.2008.11.018>
- Pollard, RT.** 1970. On the generation by winds of inertial waves in the ocean. In: *Proceedings of the Deep Sea Research and Oceanographic Abstracts*. 1970. DOI: [https://doi.org/10.1016/0011-7471\(70\)90042-2](https://doi.org/10.1016/0011-7471(70)90042-2)
- Price, J.** 1981. *Upper ocean response to a hurricane*. Woods Hole Oceanographic Institution. DOI: <https://doi.org/10.1575/1912/10271>
- Rao, A, Dash, S, Babu, I and Jain, I.** 2007. Numerical Modeling of Cyclone's Impact on the Ocean-A Case Study of the Orissa Super Cyclone Author(s): A. *Journal of Coastal Research*, 235. DOI: <https://doi.org/10.2112/05-0517.1>
- Schaeffer, A, Gramouille, A, Roughan, M and Mantovanelli, A.** 2017. Characterizing frontal eddies along the East Australian Current from HF radar observations. *Journal of Geophysical Research: Oceans*, 122. DOI: <https://doi.org/10.1002/2016JC012171>
- Shay, L.** 2009. Upper Ocean Structure: Responses to Strong Atmospheric Forcing Events, 192–210. DOI: <https://doi.org/10.1016/B978-012374473-9.00628-7>
- Tranchant, B, Testut, C-E, Renault, L, Ferry, N, Birol, F and Brasseur, P.** 2008. Expected impact of the future SMOS and Aquarius Ocean surface salinity missions in the Mercator Ocean operational systems: New perspectives to monitor ocean circulation. *Remote Sensing of Environment*, 112: 1476–1487. DOI: <https://doi.org/10.1016/j.rse.2007.06.023>
- Vinayachandran, PN.** 2003. Phytoplankton bloom in the Bay of Bengal during the northeast monsoon and its intensification by cyclones. *Geophysical Research Letters*, 30. DOI: <https://doi.org/10.1029/2002GL016717>
- Woce Upper Ocean Thermal, UOT.** 2009. Temperature and salinity records from profiling floats. PANGAEA.
- wu, R, Zhang, H, Chen, D, Li, C and Lin, J.** 2018. Impact of Typhoon Kalmaegi (2014) on the South China Sea: Simulations using a fully coupled atmosphere-ocean-wave model. *Ocean Modelling*, 131. DOI: <https://doi.org/10.1016/j.ocemod.2018.08.004>
- Xia, C, Ge, X, Lv, H, Zhang, H, Xing, X and Cui, Y.** 2022. A phytoplankton bloom with a cyclonic eddy enhanced by the tropical cyclone Phethai in eastern Sri Lanka. *Regional Studies in Marine Science*, 51: 102217. DOI: <https://doi.org/10.1016/j.rsma.2022.102217>
- Zhang, S, Xie, L, Hou, Y, Zhao, H, Qi, Y and Yi, X.** 2014. Tropical storm-induced turbulent mixing and chlorophyll-a enhancement in the continental shelf southeast of Hainan Island. *Journal of Marine Systems*, 129: 405–414. DOI: <https://doi.org/10.1016/j.jmarsys.2013.09.002>
- Zhao, H, Han, G, Zhang, S and Wang, D.** 2013. Two phytoplankton blooms near Luzon Strait generated by lingering Typhoon Parma. *Journal of Geophysical Research: Biogeosciences*, 118. DOI: <https://doi.org/10.1002/jgrg.20041>
- Zhao, H, Shao, J, Han, G, Yang, D and Lv, J.** 2015. Influence of Typhoon Matsa on Phytoplankton Chlorophyll-a off East China. *PLOS ONE*, 10: e0137863. DOI: <https://doi.org/10.1371/journal.pone.0137863>
- Zheng, G and Tang, D.** 2007. Offshore and nearshore chlorophyll increases induced by typhoon winds and subsequent terrestrial rainwater runoff. *Marine Ecology-progress Series – MAR ECOL-PROGR SER*, 333: 61–74. DOI: <https://doi.org/10.3354/meps333061>
- Zheng, ZW, Ho, CR and Kuo, NJJGRL.** 2008. Importance of pre-existing oceanic conditions to upper ocean response induced by Super Typhoon Hai-Tang, 35. DOI: <https://doi.org/10.1029/2008GL035524>
- Zhou, L, Tian, J and Wang, D.** 2005. Energy distributions of the large-scale horizontal currents caused by wind in the baroclinic ocean. *Science in China, Series D: Earth Sciences*, 48: 2267–2275. DOI: <https://doi.org/10.1360/04yd0125>

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