Double SST fronts observed from MODIS data in the East China Sea off the Zhejiang–Fujian coast, China

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A B S T R A C T

We report a double coastal front system off the Zhejiang (Zhe) and Fujian (Min) Provinces in the East China Sea in winter. In addition to the well-known Zhe–Min offshore coastal front along 50 m isobath, a secondary near-shore coastal thermal front along 20 m isobath is also apparent in December and January. The fronts were observed by Moderate Resolution Imaging Spectroradiometer (MODIS) at monthly mean nighttime sea surface temperature (SST) during 2000–2013 in terms of SST gradients. Our results showed temporal and spatial variations of the two fronts as follows: (1) both offshore front and near-shore front often co-exist between 26.5°N and 29.5°N in December and between 28.0°N and 29.5°N in January. However, only the offshore front is apparent in November and February. (2) The near-shore front is narrow (4–16 km), while the offshore front is three to four times wider (16–48 km). (3) In contrast to the well-known offshore front which exists throughout the winter with a strong intensity, the near-shore front has a shorter lifetime with a weak intensity, and has been overlooked by previous studies. Finally, we proposed that the bottom bathymetric gradients may play an important role in the frontogenesis of the double fronts.

1. Introduction

The Zhe–Min coastal front, also known as a part of the East China Sea coastal front system, is located in the coastal water off the Zhejiang Province (referred to Zhe) and Fujian Province (referred to Min) in the East China Sea. It exists as either a thermal front or a salinity one with apparent seasonal variations in terms of its location, width and intensity (Chen, 2009; Tang, 1995, 1996). It has been shown that the Zhe–Min coastal fronts are closely associated with fish abundance (Huang et al., 2010; Zhu and Iversen, 1990). For instance, the Zhoushan fishing ground, the largest coastal fishing ground in China, is located just around the Zhe–Min frontal zone. Thus the fronts along the Zhe–Min coast, especially the Zhe–Min coastal front, are of great importance for fishery in China.

Since the early 1980s, many studies on the sea surface temperature (SST) fronts along the Zhe–Min coast have been conducted by means of traditional field investigations, satellite remote sensing data analysis and numerical simulations. They usually focused on the front detection methods, front features, spatial and temporal variations of the front, mechanisms for frontogenesis, and the impact of the front on the biochemical environment.

Features of the Zhe–Min coastal fronts, such as the location, intensity and seasonal variability, as well as the mechanism of frontogenesis, have been studied based on datasets collected by field investigations at various time and sites since 1980s. Generally, the Zhe–Min coastal SST front is most pronounced in winter but disappears in summer (Hickox et al., 2000; Huang et al., 2010; Tang, 1996). In winter, the Zhe–Min coastal SST front extends from the mouth of Qiantang River southward to 27°N along 50 m isobath with a width of 73.5 km and an intensity of 0.08 °C/km (Tang, 1995, 1996; Tang and Zheng, 1990; Zheng and Tan, 1989; Zheng et al., 1985). The Zhe–Min Coastal Current and Taiwan Warm Current are two essential factors to form the Zhe–Min coastal front in winter, and this SST front is caused by differential advection of the cold Zhe–Min coastal water and warm shelf water affected by the Taiwan Warm Current (Tang, 1995, 1996).

With the advent of operational satellites and accessible to long time series of SST data, many studies related to Zhe–Min coastal fronts have been carried out. Besides the improvement of front delineation techniques (Pi and Hu, 2010; Sun et al., 2012), the spatial distribution and temporal variations of Zhe–Min coastal fronts are widely studied using satellite-derived SST data (Belkin and Cornillon, 2003; Belkin and O’Reilly, 2009; Belkin et al., 2009; Chang et al., 2006, 2008; Guo et al., 1995; He et al., 1995; Hickox et al., 2000; Huang et al., 2004; Huang et al., 2010; Lee et al., in press; Lou et al., 2005; Tseng et al., 2000; Yuan et al., 2005; Zheng and Klemas, 1982). Moreover, it was...
pointed out in Huang et al. (2010) that, the coastal fronts in the Yellow and East China Seas are all located along the sharp bathymetry gradient in the inner shelf along the coasts.

In addition, the numerical simulation has also been used in some studies related to Zhe–Min coastal front (Cao, 2004; Liu, 2009; Park and Chu, 2006). The spatial and temporal features of oceanic fronts in the Yellow/East China Sea were simulated and analyzed, however, the mechanism of frontogenesis for the Zhe–Min coastal front was not discussed in detail.

In this study, apart from the well-studied Zhe–Min coastal front in the offshore waters (hereinafter referred to as the offshore front), the satellite-derived SST imagery shows that there exists a secondary SST fronts in the near-shore waters. For instance, the Moderate Resolution Imaging Spectroradiometer (MODIS) SST and its gradient imageries in January of 2007 show that there are double coastal SST fronts (Fig. 1). On the west side of the offshore front along 50 m isobath, there is a secondary near-shore coastal front (hereinafter referred to as the near-shore front) along 20 m isobath. This near-shore front has not been reported yet. In this study, we explore the temporal and spatial variations of the double SST fronts, especially the near-shore front, by analyzing their features using MODIS SST data from 2000 to 2013. We also present a potential frontogenesis mechanism for the double SST fronts.

2. Material and methods

2.1. Study area

After browsing the MODIS SST and its gradient images during 2000–2013, we noticed that the offshore and near-shore fronts coexist mainly along the Zhe–Min coastal area. Thus the study area has been selected as shown in a red box in Fig. 2. In addition, the isobaths are marked in white in Fig. 2a and b, and the gradient magnitudes are shown in Fig. 2b. The bathymetry data are from the ETOPO2v2 Global Gridded 2-minute Database (2006) provided by the National Geophysical Data Center (NGDC) of the U.S. National Oceanic and Atmospheric Administration (NOAA). Water depth (blue) and the gradient magnitude (red) along a transect line shown in Fig. 2 are plotted in Fig. 3. The bottom depth increases step-wise from the near-shore to offshore sea. A rapid bump of the gradient (≥ 1 m/km) is apparent between isobaths of 20 m and 50 m, and this region is called the maximum bathymetric gradient zone (MBGZ) in this study. In the MBGZ, the steepest topography occurs at the water depth of 35 m or so. The bottom topography changes slowly when water depth is less than 20 m or deeper than 50 m.

2.2. Satellite-derived SST

Due to the diurnal SST variances caused by different solar radiation during the day and night (Robinson, 2010), SST fronts are better observed in nighttime SST imagery than in daytime data. Therefore the nighttime SST data of MODIS-Terra and -Aqua from 2000 to 2013 were used in this study. The Level 3 mapped data with a spatial resolution of 4 km × 4 km were downloaded from the U.S. National Aeronautics and Space Administration (NASA) website (http://oceancolor.gsfc.nasa.gov). The infrared SST data are usually contaminated by clouds. In order to reduce the data gaps caused by cloud covers and have a sufficient available spatial coverage, we used monthly mean SST to observe coastal fronts here. According to the observations based on the 13-year MODIS monthly SST data, we observed that both SST fronts occur in Zhe–Min coastal waters mostly in December and January, sometimes in November and February. Thus, we finally selected the MODIS nighttime monthly mean SST data in four months of November to February during 2000–2013 to explore the spatial and temporal variations of the SST fronts.

2.3. Merging SST data

Although the MODIS monthly mean SST data were used in this study, some data gaps still cannot be avoided due to the heavy cloud coverage in winter. The local passing times during the night for MODIS-Terra and -Aqua are at 10:30 PM and 1:30 AM with an interval of 3 h. Thus, the data gaps in Terra and Aqua may occur in different areas. Therefore, in order to get a dense spatial coverage of SST, we merged the SST data of MODIS-Terra and -Aqua using linear regression. Fig. 4 shows the scatter plot and frequency histogram of SST differences between MODIS-Terra and -Aqua SST data. The time span of MODIS data is from November to February during 2002–2013.

Fig. 1. MODIS monthly mean sea surface temperature (SST, °C) (a), and its gradient magnitude (°C/km) (b), in Zhe–Min coastal waters of the East China Sea in January of 2007. White lines are isobaths of 20 m and 50 m, respectively. The region of interest is marked in red boxes.
Note that MODIS-Terra and MODIS-Aqua were launched into orbit in 1999 and 2002, respectively.

The gray line in Fig. 4a is a 1:1 line indicating no-bias between MODIS-Terra and -Aqua SST data, and the red line was obtained using their data by linear regression of least-squares fitting. It is apparent that scatters concentrate in the vicinity of the 1:1 line, and the coefficient of determination (R-squared) is up to 0.959. Furthermore, the distribution of SST difference between MODIS-Terra and -Aqua SST data is shown in terms of a frequency histogram in Fig. 4b. The curve of the probability density function of normal distribution with the calculated standard deviation is overlaid as a green line. Apparently, the histogram shows a more concentrated pattern than the normal distribution. All these indicate the MODIS-Terra and -Aqua SST data are highly linearly correlated by the following equation:

\[
SST_{Aqua} = 0.985 \times SST_{Terra} + 0.111.
\]

The monthly MODIS-Terra and -Aqua SST data are merged with their linear relationship of Eq. (1). For each month, the merged SST at every point is assigned to MODIS-Aqua SST data when there is an available MODIS-Aqua SST data, and is assigned to a value according to Eq. (1) when there is no available MODIS-Aqua SST data but there is an available MODIS-Terra SST data. No data is assigned when neither MODIS-Aqua nor -Terra SST data are available.

### 2.4. Calculation of SST gradient magnitude

A gradient method is commonly used to recognize and determine oceanic fronts (Huang et al., 2010; Tang, 1995; Tang and Zheng, 1990; Wall et al., 2008). Thus, in this study, after we obtained the merged SST using MODIS-Terra and -Aqua data, SST gradients were calculated by

\[
GM = \sqrt{(\partial T/\partial x)^2 + (\partial T/\partial y)^2}/4 \ (\degree C/km)
\]

where \(x\) and \(y\) denote the number of grid points (distance) in zonal and meridional directions, and the eastward and northward is positive for \(x\)- and \(y\)-coordinate. \(T\) and \(GM\) indicate the merged SST and the magnitude of its gradient, respectively. Note that, since the MODIS data has a spatial resolution of 4 km x 4 km, the SST gradient magnitudes were divided by 4 in Eq. (2). Note that, however, the maximum frontal gradients usually increase when we move from low-resolution to high-resolution data, and moving from high- to low-resolution data smooths gradients.

### 3. Results

The arithmetic mean of monthly mean SST during 2000–2013 could easily lead to statistical features of SST fronts in this study. However, since the \(GM\) is usually noisier than the SST itself, we noticed that the averaged results were greatly affected by extreme \(GM\) pixels. Therefore, for a better presentation of features of the SST fronts, the occurrence probability was used in this study. The probability of a front occurring is defined as the percentage of the number of the \(GM\) greater than 0.1 \(\degree C/km\) contained in the total number of available \(GM\) at every pixel, which was calculated using the monthly \(GM\) data from November
to February during 2000–2013. The occurrence probability of SST fronts indicated by colors in percentage in four separate months is shown in Fig. 5.

Note that, a pixel with a GM of greater than 0.1 °C/km was considered as a place a SST front occurred in this study. The threshold (0.1 °C/km) for the occurrence of coastal fronts here was determined according to our observations using monthly mean nighttime MODIS SST during 2000–2013. It is of a similar magnitude to the thresholds (e.g., 0.08 °C/km) used in previous studies (Tang, 1996; Tang and Zheng, 1990). Likewise, based on the occurrence probability derived by GM, we say the front is significant when the probability is greater than 40% at a pixel in Fig. 5. The occurrence probability of 40% has been indicated as black lines with red number 40 in Fig. 5.

From the spatial distribution of occurrence probability of a SST front in Fig. 5, a secondary near-shore coastal thermal front along 20 m isobath is apparent in December and January to the west of the well-known Zhe–Min offshore coastal front along 50 m isobath. Thus, there exists a double coastal front system off the Zhejiang and Fujian Provinces in the East China Sea in winter. Compared with the bottom topography distribution in Fig. 2, we conclude that the region with rapid change in water depth (MBGZ, bathymetric gradient magnitude ≥ 1 m/km) is just between the isobaths of 20 m and 50 m, which is approximately between these two fronts. Namely, the two fronts are separated by the MBGZ and located on the near-shore side or on the offshore side of the MBGZ.

More specifically, to the north of 28°N in Fig. 5, both the near-shore and offshore coastal fronts occur significantly in December and January, while usually only the offshore front appears in November and February. South of 28°N, two separate fronts can be observed in December, while only the offshore front occurs in November, January and February. Thus the off-shore coastal front has been in existence off the Zhe–Min coast in the East China Sea throughout winter, while the near-shore front only occurs in December and January. Until now this near-shore SST front has not been reported yet. Furthermore, the occurrence probability of both the near-shore and offshore coastal fronts increases from November to January, and can reach above 80% in January. In February, the offshore front still shows a high occurrence probability, while the near-shore front almost disappears.

The spatial area covered by the occurrence probability for SST fronts greater than 40% in Fig. 5 indicates that the near-shore front occurring over a smaller area is less significant than the offshore one. As this coverage by isolines of 40% of occurrence probability also gives a general range for SST frontal locations. It can be seen that, the coverage of offshore front are generally consistent throughout winter, while the near-shore front migrates over a larger area in December than in January. Therefore the location of off-shore front is steadier than the near-shore one, and the near-shore front migrates more in December than in January.

To quantitatively analyze the spatial patterns of the coastal SST fronts, the occurrence probability of SST fronts along the transect line are further presented in Fig. 6. The geographic location of this transect line selected are shown in Figs. 1, 2 and 5, where the double SST fronts are significant and there is a long continuous time series of valid MODIS SST data.

As mentioned before, taking the occurrence probability of 40% as a threshold of a front occurring significantly, double SST fronts are apparent along this transect line in December and January in Fig. 6. However, the near-shore front is much weaker than the offshore one. In terms of the frontal occurrence probability, the off-shore SST front has a higher value over 60% during all four months, while the maximum of the near-shore one is only over 55% and still less than 60% in January.

In terms of the significant front width, the near-shore front is generally narrow with a width of about 12 km, and the offshore front is wide with a width over 16 km during December and January. Note that, the significant front width is estimated by counting pixel numbers with frontal occurrence probability over 40% and then multiplied by the pixel size of 4 km. Hence the accuracy of front width here is limited by spatial resolutions of SST data, and the actual front width may be narrower than that we estimated here.

In addition, by comparing the frontal locations and the red bathymetric gradient plots in Fig. 6, the near-shore front usually occurs at 4 to 16 km from the coast on shoreward side of the MBGZ, and the offshore front is located at about 32 to 60 km from the coast on the seaward side of the MBGZ. The MBGZ is located at 24 to 40 km or so from the coast along the transect line. Thus as mentioned before, the MBGZ is generally located between the near-shore and offshore SST fronts.

In addition to the spatial patterns, the temporal variations of GM of coastal fronts along the transect line from November to February during 2000–2013 were also demonstrated in Fig. 7. The frontal area delineated by black contour lines with a GM of 0.1 °C/km shows an apparent double frontal pattern along the transect line, and the frontal centers indicated by the maximum GMs varies with time, with a maximum up to ±8 km for
near-shore fronts, and ±12 km for offshore fronts. However, no clear trends are observed for both near-shore and offshore fronts. The near-shore front is about 4–16 km wide, while the offshore front is about 16–48 km wide. In addition, the temporal mean of $GM$ along the transect line are further plotted in Fig. 8. It can be seen that, although the averaged $GM$ of near-shore front is weaker than the offshore one, we can still distinguish between them easily. The large uncertainty in time series of Fig. 8 shows a large time variation of SST $GM$ along the transect line, and wind effects on this was further discussed later.

4. Discussion

4.1. Frontogenesis of the offshore front

Two primary currents exist in Zhe–Min coastal area in winter. One is the cold Zhe–Min Coastal Current mixed with runoff water from the Yangtze River and Qiantang River, and it is confined in a strip with water depths less than 50 m along the coast flowing from northeast to southwest (Wu et al., 2013; Zeng et al., 2012; Zheng and Tan, 1989; Zheng et al., 1985). The other is the Taiwan Warm Current with high salinity water from the Kuroshio Current and Taiwan Strait water, and it is located between isobaths of 50 m and 100 m flowing from southwest to northeast throughout the year (Su, 2001; Su and Pan, 1989; Zeng et al., 2012).

On the mechanism of frontogenesis for the Zhe–Min coastal SST fronts, studies have been conducted on the offshore front. Based on field investigations, Tang (1995, 1996) has pointed out that the offshore front is formed by cold Zhe–Min coastal water and warm shelf water, which are advected by the Zhe–Min Coastal Current and Taiwan Warm Current, respectively. However, how the frontal structure maintains a quasi-steady state along a specific isobaths for long time periods is still an issue to be resolved (Sharples and Simpson, 2009).
According to a study of dynamics of a surface-to-bottom coastal density front along a uniformly sloping continental shelf by Chapman and Lentz (1994), a steady balance within the front is established in the bottom boundary layer between vertical mixing and onshore advection of density, and at this point the front is “trapped” to a specific isobaths.

Therefore, in this study we speculate that the steep bottom bathymetric gradients between the isobaths of 20 m and 50 m (MBGZ) in the Zhe–Min coastal area play an important role in the maintenance of the density fronts.

Fig. 6. The occurrence probability of SST fronts at pixels along the transect line in November (a), December (b), January (c) and February (d) during 2000–2013. The horizontal axis is arranged by the number of pixels (4 km × 4 km for one pixel) away from the shoreline, and 22 pixels (points) in total are included in the transect line. The occurrence probability of SST fronts is labeled in the left vertical axis, and plotted in black. Correspondingly, the bathymetric gradient magnitude is labeled in the right vertical axis, and plotted in red. Two green dashed lines represent the bathymetric gradient contours of 1 m/km, and the region between these two lines is the MBGZ.

Fig. 7. The temporal variation of GM of coastal fronts along the transect line from November to February during 2000–2013. The horizontal axis is time. The vertical axis is the number of pixels (4 km × 4 km for one pixel) away from the shoreline. The GM is indicated by colors. The GM contours of 0.1 °C/km are labeled in black to indicate the frontal area. Two red dashed lines represent locations of bathymetric gradient contours of 1 m/km, and the region between these two lines is the MBGZ. Frontal centers determined by maximum GM in frontal areas are also marked by points, in blue for Nov., Dec., and Feb., and in cyan for Jan. The variations of mean frontal center locations are labeled by blue lines.
offshore SST front. As we observed in previous section, the offshore front is usually located on the offshore side of the MBGZ. As a further evidence of the impact of the Zhe-Min Coastal Current and bathymetry on the offshore front, the temporal variation of gradient magnitudes of monthly mean remote-sensing reflectance at 555 nm, R_{rs}(555), along the transect line with a large time variation is plotted in Fig. 9, which is similar to the SST GM in Fig. 8. High R_{rs}(555) values indicate high turbidity, and high turbidity gradient magnitudes suggest the boundary between currents. From both Figs. 9 and 10, it can be seen that the offshore and near-shore R_{rs}(555) fronts are apparent, and they, one of which is located on either side of the MBGZ, are similar with the SST fronts. Moreover, the Zhe-Min Coastal Current ranges over a distance of about 40 km offshore, and the maximum current velocities occur around 30 km offshore. Therefore, locations of the offshore side of the Zhe-Min Coastal Current are coincident with that of the MBGZ, where the offshore front is usually located. Thus it is possible that the Zhe-Min Coastal Current and bathymetry have a jointly important effect on the offshore front.

4.2. Frontogenesis of the near-shore front

Air–sea heat exchange, vertical mixing, and the advection of heat are responsible for the frontogenesis of SST fronts in the East China Sea, whereby the latter two mechanisms are strongly associated with the bathymetry (Huang et al., 2010). Therefore, it is possible that surface cooling plays an important role in the frontogenesis of the near-shore front in this study. In shallow well-mixed shelf seas the sea temperature follows closely that of the ambient air temperature with limited separate effect of solar heating (Prandle and Lane, 1995a,b). Thus, the net surface heat flux (Q_{0}) entering the ocean across the front water is primarily determined by the sensible heat flux due to air and surface water temperature difference in winter. Hence local time rate of coastal water temperature change (∂T/∂t) is proportional to the depth-normalized air — sea temperature difference parameter of (T_{air} − SST)/|H|. To investigate the potential mechanism for the occurrence of the near-shore front, the depth-normalized air — sea temperature differences (T_{air} − SST)/|H| along the transect line are given in Fig. 11. The monthly climatological mean of air temperature (T_{air}) data from November to February during 2000–2013 are used here, and the air
temperature data were downloaded from MERRA (Modern-Era Retrospective Analysis for Research and Applications), a NASA reanalysis for the satellite era using the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5). Negative values in Fig. 11 indicate that the ocean is being cooled.

It can be seen that no apparent monthly different effects of sensible heat flux on the water temperature changes occur in water deeper than 50 m. Therefore, the surface cooling does not affect deep water a lot. However, the shallower water with a depth less than 50 m is apparently affected, and water temperature varies a lot with time and water depth. More specifically, a rapid change of the parameter of \((T_{\text{air}} - \text{SST})/|H|\) is observed in Fig. 11 at the depth less than 20 m, namely the onshore side of the MBGZ, and the effects of surface cooling are less significant in February than that in the other three months in the entire transect. Compared with features of the near-shore SST front in this study, this suggests that the near-shore front is very likely formed by the interaction of surface cooling and bathymetry off the Zhe–Min coast.

In addition, due to effects of the MBGZ, the SST front affected by surface cooling is located to the near-shore side of 20 m isobaths and not in deeper waters, and thereby the near-shore front by surface cooling and offshore fronts by the Zhe–Min Coastal Current and Taiwan Warm Current can be observed at the same time. Afterwards, the near-shore front disappears in February with the difference of atmospheric and oceanic temperature becoming small as the ocean continuously loses heat, while the offshore front still exist in February because it is mainly caused by the Zhe–Min Coastal Current and Taiwan Warm Current, and the surface cooling is secondary.

As for the reason of this near-shore front with its extension only to the north of 27°N, we suppose that the differential cooling and advection are the basic causes. As we discussed above, the surface cooling, specifically the depth-normalized air — sea temperature difference, may play an important role on its frontogenesis. Along the Zhejiang–Fujian coast, firstly, as shown in Fig. 2a, the coastal sea area with water depth less than 20 m around and south of 27°N is much smaller than that north of 27°N. Secondly, with the decreasing latitudes, air — sea temperature difference decreases. Thirdly, as shown in Fig. 2b, the bathymetric gradient magnitude of the MBGZ around 27°N is not as large as that between 28°N and 30°N, and thus the surface cooling effect becomes smaller around 27°N. In addition, the southward cold Zhe–Min Coastal Current mixed with runoff water from Yangtze River and Qiantang River, and the northeastward Taiwan Warm Current can be observed at the same time. Afterwards, the southward cold Zhe–Min Coastal Current and Taiwan Warm Current with Kuroshio Current and Taiwan Strait water may also contribute a lot. However, all these need to be further studied or proved by numerical simulations and field measurement.

### 4.3. Effects of winds on SST fronts

In order to investigate the wind influence on these two fronts in this study, the time series of satellite-derived monthly averaged sea surface wind acquired by QuikSCAT and WindSat (Fig. 12) were used. However, no apparent relationship between wind stress and front location shifts has been observed (not shown), while we observed that the front intensity (namely the GM of fronts) increases with wind speed, especially for the near-shore front (Fig. 13). This can also be explained with surface cooling by surface latent and sensible heat flux related to wind speed. The positive effect of wind speed on the front intensity is more apparent for the near-shore front with a correlation coefficient of 0.32 than that for the offshore one with a correlation coefficient of 0.21. This may also mean that surface cooling is more important for the SST patterns in shallow water (water depth < 50 m) than in deeper water.

### 4.4. Effects of fronts on material transport

Traditionally it was believed that nutrients were transported from the South China Sea to the East China Sea, and recently it is reported that in winter the nutrients may be transported from the East China
Sea to the South China Sea as a source to support winter primary production on the northeast South China Sea (Chen, 2003; Han et al., 2013; Naik and Chen, 2008). As shown in Huang et al. (2015) using field observations of current, sea level, and bottom temperature from an array of 4 bottom-mounted acoustic Doppler current profilers (ADCPs) deployed during winter of 2008 along a cross-shelf section in the western East China Sea, the Zhe–Min Coastal Current has a much more distinct southwestward alongshore component than the north-eastward alongshore one of Taiwan Warm Current in winter. The Zhe–Min Coastal Current and Taiwan Warm Current play an important role in the frontogenesis of the offshore and near-shore fronts off Zhe–Min coast in this study. Thus, more understanding of the characteristics relevant to the double SST fronts in this study can explain more on the material transport (including nutrients) in the marginal China Seas (including the south Yellow and East China Seas, and the northern South China Sea). In addition, as shown in Huang et al. (2015), there is an intrinsic connection between the alongshore and cross-shore current components, and the northwestward cross-shelf transport is associated with southwestward alongshore currents, the southeastward cross-shelf transport is associated with northeastward alongshore currents. Although the near-shore front was not apparent as the offshore front with distinctive temperature and possibly salinity, understanding more on the characteristics and mechanisms of the fronts can provide a basic physical background for multidisciplinary studies, such as the material transport and biological responses.

5. Conclusions

In this study, to the west of the well-known Zhe–Min coastal front (referred to as offshore front in this study) along 50 m isobath, a second pronounced near-shore SST front unknown before was identified along 20 m isobath off the Zhe–Min coast using MODIS monthly mean SST in winter during 2000–2013. The double fronts are often observed in December and January, while usually only the offshore front is apparent in November and February. The near-shore front is about 4–16 km wide, while the offshore one is about 16–48 km. The offshore front occurs throughout the winter with a stronger intensity, while the near-shore front has a shorter lifetime, a weaker intensity.

Potential mechanisms leading to the generation of these fronts were discussed. We suggest that the steep bottom bathymetry between the isobaths of 20 m and 50 m (MBGZ) of the Zhe–Min coast play an important role in the coexistence of near-shore and offshore fronts. The MBGZ and surface cooling jointly play an important role in the formation of the near-shore front. The MBGZ, the Zhe–Min Coastal Current and Taiwan Warm Current jointly maintain the offshore front. The results of this study can further enhance the understanding of Zhe–Min coastal frontal system in winter, which should be of great interest for both physical oceanographers and marine biologists.

The near-shore SST front documented in this study has been overlooked before, which might have been caused by measurements with limited spatial and temporal resolutions used in previous studies. The conventional field observations are often limited in these two aspects. Using field measurements, the fronts with strong intensities can be delineated, while it is difficult to show the weak fronts with short lifetime and at small spatial scales. Previous studies based on satellite remote sensing data have not reported this near-shore front either. One reason might have been the use of SST data with relatively low spatial resolutions of 9 km or 25 km. This might have made it difficult to distinguish two nearby fronts. Another reason might have been the short lifetime of about two months, the weak intensity and the spatial migration features of the near-shore front. Even if the SST data with a high spatial resolution (1 km, or 4 km) were used, the conventional averaging in the seasonal or annual scale might have made the frontal information easily lost. Also, there is an obvious diurnal variation of SST during the day and night. Thus, observations using daytime SST may also ignore the existence of weak fronts (Robinson, 2010). Therefore, nighttime SST data have an advantage while observing coastal fronts.

Similar to the double SST fronts off the Zhe–Min coast in this study, such fronts also have been observed in other coastal areas, such as the northeast U.S. coast (Ullman and Cornillon, 1999, 2001). Therefore for areas with complex ocean circulations and bottom topography, it is possible to reveal yet undiscovered features using SST data with high spatial and temporal resolutions.

Note that both infrared and microwave remote sensing sensors can only measure the sea surface skin temperature. These satellite-derived SST data are commonly used to detect the surface oceanic fronts. However, it cannot provide information about fronts in sub-surface and deep water (Chu et al., 2005) and other properties such as salinity and currents. Therefore, field measurements are needed to further explore both features and frontogenesis of this near-shore front in this study.

**Fig. 13.** Scatter plots between near-shore (a) and offshore (b) front intensity (namely the GM of front) and wind speed. The parameters in different months are indicated by different colors, red for November, blue for December, green for January, and black for February. Black lines were derived by least-squares fitting.
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