FINER-SCALE SST FRONT OF THE SOUTHERN ECS IN WINTERTIME FROM SATELLITE AND SHIPBOARD DATA

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ABSTRACT We identify two distinct finer-scale frontal bands: "Mainland China Coastal Front" (MCCF) and "Kuroshio Front" (KF). The MCCF is along the 50-m isobath with large temperature gradient. The front is a boundary between the Mainland China Coastal Current and the offshore shelf waters. On the other hand, the KF is extending from the northeastern coast of Taiwan toward the northeast and into the shelf of south ECS. It forms a broad semicircle-shape and curving along 100-m isobath, it also deviates from eastward at around 26.5N-122E and leaves the shelf of ECS. This front should be the boundary between the Kuroshio water and the other shelf waters.

KEY WORDS: SST front, south ECS, Kuroshio

1. INTRODUCTION

The shelf of southern East China Sea (ECS) is an extremely dynamic oceanic region. It lies in an important geographical position of a transit between Mainland China and the western North Pacific. The shelf of southern ECS is bounded seaward by the 200 m isobath and connected to the broad shelf of ESC in the north and the South China Sea in the south through the Taiwan Strait (Figure 1). Major surface features of southern ECS include the Kuroshio Water (KW), the Taiwan Warm Current (TWC) and the Mainland China Coastal Water (MCCW). Over the father seaward continental slope, the Kuroshio flows along eastern side of the shelf, frequently intruding onto the shelf itself. A cold dome of subsurface Kuroshio water with counterclockwise circulation was observed at the edge of the shelf in the north of Taiwan in summer (Liu et al., 1992; Chuang and Liang, 1994). On its western side, the TWC with high temperature and high salinity generally flows out from the Taiwan Strait (Wang and Chern, 1988). Seasonal differences were more pronounced than intra-seasonal differences. During the on-shelf intrusion in winter, the Kuroshio was much closer to the shore than in summer. The counterclockwise circulation nearly disappeared, and the outflow of TWC joined with the intrusion Kuroshio Current after it left the Strait (Tang et al., 2000). In addition, the MCCW with low temperature and low salinity moving southeastward in winter and interacts with the intruding Kuroshio and moving northward TWC. This suggests a rather complicated flow pattern. As a consequence, the detailed feature of SST field and associated frontal behaviour in the southern ECS is not well understood. In this study, we utilize a long-term time series of AVHRR-derived SST images to examine the distribution and evolution of winter SST front in the southern ECS by using the entropy-based front detection method proposed by Shimada et al. [2005]. In the following section, we give brief descriptions on the satellite data and the edge detection method, and the present general characteristics of the wintertime (December-February) SST frontal systems in the southern ECS from a climatological point of view.

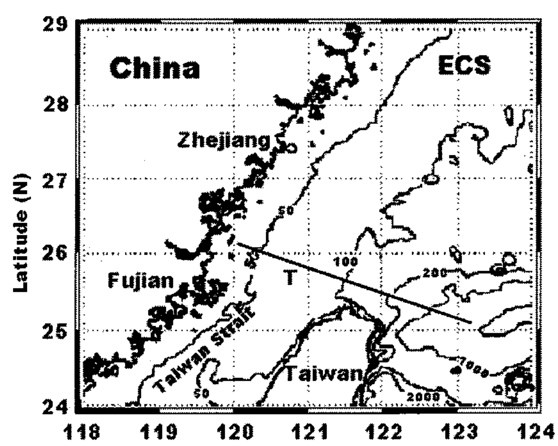

Figure 1. Study area and transect line of vessel-based survey during January 5~6, 2004.

2. DATA AND METHOD

2.1 NOAA-AVHRR SST and bathymetry data

The SST fronts are derived from NOAA-AVHRR SST images produced by the A-HIGHERS system (Sakaida et al., 2000). The 10-year (1996-2005) NOAA-AVHRR data library at Tohoku University collected the regional HRPTs received by Tohoku University and the National

Taiwan Ocean University. The A-HIGHERS comprises the following sophisticated processes: SST calculation, cloud detection, quality control, and optionally precise image registration. Each SST image is remapped to an equirectangular projection with a grid size of 0.01°. The study area is defined from (29N-117E) to (21N-124E). The numbers of the images are generally more than 173 per month, gathered from 5-6 satellite-passings a day.

2.2 Edge detection method for obtaining SST fronts

We adopt the edge detection method proposed by Shimada et al. (2005). The methodology allows us to detect SST fronts keeping original SST image resolution, which enables us to analyze finer-scale fronts near the coast as well as larger-scale fronts associated with major currents. Among the several kinds of composite front maps (e.g., Shimada et al., 2005), this study used monthly climatological maps of frontal SST gradient magnitude (GM). The GM is defined as below:

$$GM = \sqrt{(\partial T/\partial x)^2 + (\partial T/\partial y)^2}\ (°C/km) \quad (1)$$

where T is SST, and x and y axes are directed toward east and north, respectively. The GM is computed at all the frontal pixels for each image, and then monthly mean GM is computed pixel by pixel.

It is useful to classify SST fronts by the orientation of a front relative to the local bathymetry. It is measured by a normalized scalar product of the SST gradient and bathymetric gradient vectors at a frontal pixel as:

$$P = \frac{\nabla T \cdot \nabla H}{|\nabla T||\nabla H|} \quad (2)$$

where T is SST and H is water depth (H>0).

As proposed by Shimada et al. [2005], we represent probability maps of SST fronts with P value within the specified ranges during a time period. The probability ($p_{orientation}$) at a given pixel is calculated by dividing the number of times the P value falls within the specified range ($N_{orientation}$) by the number of times the pixel is a frontal pixel (N_{front}) as defined:

$$p_{orientation} = N_{orientation}/N_{front} \times 100.0\ (\%) \quad (3)$$

We then divide the domain of P into 5 ranges: warm fronts ($-1 \le P \le -0.6$), cross-isobath fronts ($-0.6 < P \le -0.2$, $-0.2 < P \le 0.2$, $0.2 < P < 0.6$), and cold fronts ($0.6 \le P \le 1.0$). As a result, five probability maps are made for a composite time period. In the following discussion, we pay attention to cold front probability maps. In fact, no significant patterns appear in cross-isobath front probability maps.

2.3 In situ data

For field observations, the R/V Ocean Research 2 of National Taiwan Ocean University conducted one cruise in our study area during January 5~6, 2004. The vertical temperature and salinity were measured by a Seabird (SBE 19) CTD at 14 different stations along a cross-shelf transect (marked as T on Figure 1). The CTD was lower to the depth of 5-m above sea bottom then towed to the surface. The longitude and latitude were positioned by the GPS while vertical measurements were taken.

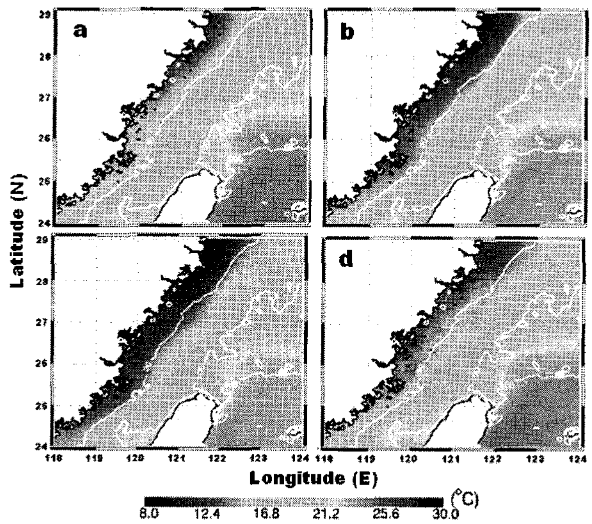

Figure 2. Climatological monthly mean SST images derived from NOAA AVHRR data. (a) December; (b) January; (c) February; (d) March.

3. RESULT

3.1 Climatological monthly mean SST fields

Climatological monthly mean SST fields in the southern ECS from November to the following March for 1995 to 2005 are shown in Figure 2. We can find the following major water distribution: the MCCW, the KW and the TWC.

In December, a cold-water tongue with SST less than 15°C extends southwestward from the ECS along the Chinese coast (Figure 2a). This cold tongue gradually intrudes into the Taiwan Strait in January (Figure 2b). The cold-water intrusion extends further southwestward in February (Figure 2c). In March (Figure 4d), the cold water (<15°C) starts to retreat. Meanwhile, the boundary between the transition water and KW/TWC becomes distinct in December-February. These seasonal variations are associated with the dominated winter monsoon in this area.

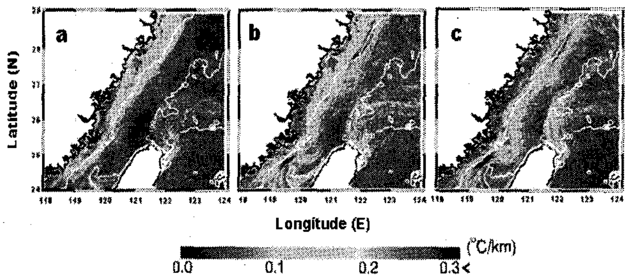

Figure 3. Climatological monthly mean maps of frontal SST GM in December (a), January (b) and February (c).

3.2 Climatological monthly maps of frontal SST GM

Figure 3 shows the monthly mean maps of frontal SST GM for winter (December-February). We can first identify a long frontal band with larger SST GM along the 50-m isobath near the Chinese coast. This band is associated with the MCCW in the Chinese coastal region. The intensity of SST GM increases and the area with large SST GM grows as the winter progresses from December to February. This will be referred to as "Mainland China Coastal Front (MCCF)" hereafter. This high-gradient band around the coast of China is located along the coastal shelf as 50-m isobath. The Kuroshio forms a frontal band on the northeastern side of the Taiwan. This band shows the largest SST GM (>0.2°C/km) in the region where the Kuroshio leaves from the Taiwan coast. The band GM becomes larger throughout winter. After leaving from the coast, the band has semicircle-shape curving along the 100-m isobath and deviates from it eastward at around 26.5N. This is called "Kuroshio Front (KF)" hereafter. The KF is formed between the Kuroshio water and the shelf water. The distinct frontal band represents the Kuroshio path in the northeastern shelf of the Taiwan.

3.3 Vessel-based Observation

The vessel-based survey during winter period of January, 2004 has also demonstrated strong vertical fronts in the southern ECS. Figure 4 shows the vertical distributions of temperature and salinity along the transect (T in Figure 1) interpolated using the 14 CTD stations. A relative high temperature and high salinity water exists in the east of 122.5E. On the other hand, a low temperature and low salinity coastal water protrudes off the eastern coast of China, with a temperature less than 17°C and salinity less than 32.5 psu in the upper layer. It is generally believed that the Zhejian-Fujian coastal current flows along the coast of Mainland China in winter time.

Along the transect T, both the temperature and salinity profiles (Figure 4a, b) show minimum in the western of the transect indicating a low temperature and low salinity water. As a result, a thermocline and halocline form atabout 35 m. It also indicates that the subsurface water of Kurshio intruded on to the shelf along the slope in the northeast of Taiwan. The intruded subsurface water uplifted to surface and mixed with the transition water of KW/TWC at around 122E. The temperature in the eastern of transect decrease sharply. Figure 4 clearly shows that the vertical gradient of the temperature and salinity are large in the Chinese coastal region. Meanwhile, the gradient of temperature is large in the northeast of Taiwan, though the salinity have barely any vertical variation on the off shelf region. Therefore, the difference water masses of Zhejian-Fujian coastal water in western and the intrusion Kurosho water in eastern form distinct temperature fronts.

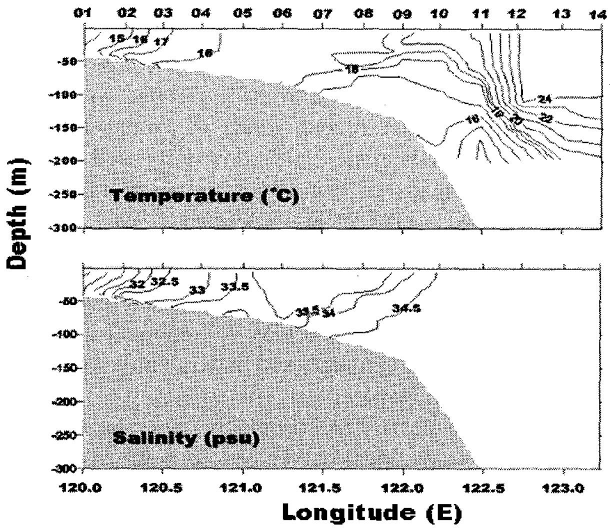

Figure 4. Vertical profile of temperature and salinity from the vessel-based along the transect line T during January 5~6, 2004.

4. DISCUSSION AND CONCLUSION

From Figure 3, it shows clearly that the Mainland China Coastal Front is a southern extension of the Zhejiang-Fujian Front defined in Hickox et al. [2000]. The Zhejiang-Fujian Front extends northward along the Chinese coast and connects the Jiangsu Front [Hickox et al., 2000]. In addition, the monthly mean SST image in January, 2004 shown in Figure 5a is confirmed that the cold water (< 15 °C) extends southwestward from the north along the Chinese coast, just as the vessel-based CTD profiles have clearly indicated (Figure 4). The cold front probability map (Figure 5b) in January shows the broad band with high probability (> 60%) along the 50-m isobath. This means that in the vicinity of the 50-m isobath, formation mechanism of the frontal band is strongly related with the water depth. Along the eastern coast of China from ECS to Taiwan Strait, the seas are shallow to a considerable distance from the shore. The thermal inertia of a water column on the shelf is linearly

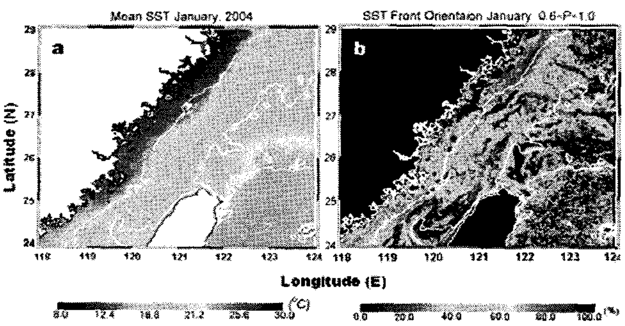

Figure 5. (a) Monthly mean SST image of January, 2004. (b) Cold front front probability maps in January.

proportional to the bottom depth. As a result, a sharp SST front forms between the coast and shelf water. The January SST GM map in Figure 3b indicates that the semicircle-shape fronts curve along the 100-m isobath and deviate eastward from the isobath at around 26.40N/122.00E. The large curvature patterns of large SST GM (0.18°C/km) are distributed widely between the shelf regions of 100- and 200-m depths. The wide distribution of the Kuroshio front position reflects large variability of the Kuroshio path. The monthly mean SST image in January, 2004 (Figure 5a) as well as the hydrographical data substantiates the view that, waters from the eastward intrusion of KW colliding with mixed shelf water around the shelf region, thus, a semicircle-shape oceanic front with sharp temperature gradient formed on the northern shelf of Taiwan. The warm KW (>20°C) intrudes on to the shelf beyond the 200-m isobath and reaches the 100-m isobath at around 26.4N/122.4E. The subsurface water of Kuroshio is usually uplifted and found to occupy the inshore portion of the northeast of Taiwan. The Kuroshio surface water that apparently overruns the shelf break is found immediately offshore of the subsurface water. A sharp temperature front is found between the two water masses that extends front the sea surface to near the bottom (Hsueh et al., 1992). Therefore, the meandering SST fronts of Kuroshio are formed between the warm KW and the relative cold mixed shelf water (<17°C). The Kuroshio appears to shift shoreward in fall and winter, and seaward in spring and summer. Especially in winter, the Kuroshio has the largest curvature of the axis (Tang et al., 2000). Namely, it shifts shoreward and meanders northward with its western boundary extending on to the shelf (Tang et al., 2000). Its width increases and its core speed decreases (less than 100 cm/s). These may be the reason for the wide Kuroshio front distributed shown in Figure 3.

As for the Kuroshio Front on the northeast of Taiwan, Hickox et al. (2000) have also detected and represented the front at the sane location by using the histogram-based edge detection method. Our study showed the wide distribution of the Kuroshio Front. It reflects large variability of the Kuroshio path (e.g., Tang et al., 2000). In winter, the Kuroshio axis shifts shoreward and has the largest curvature accompanying the increasing width and decreasing core speed (less than 100 cm/s). Further studies are required for an investigation of the mechanism of the Kuroshio front formation.

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