A numerical study on seasonal variations of the Taiwan Warm Current*

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Received Apr. 25, 2004; revision accepted May 29, 2004

Abstract Princeton Ocean Model (POM) is employed to investigate the Taiwan Warm Current (TWC) and its seasonal variations. Results show that the TWC exhibits pronounced seasonal variations in its sources, strength and flow patterns. In summer, the TWC flows northeast in straight way and reaches around 32°N; it comes mainly from the Taiwan Strait, while its lower part is from the shelf-intrusion of the Kuroshio subsurface water (KSSW). In winter, coming mainly from the shelf-intrusion of the Kuroshio northeast of Taiwan, the TWC flows northward in a winding way and reaches up around 30°N. The Kuroshio intrusion also has distinct seasonal patterns. The shelf-intrusion of KSSW by upwelling is almost the same in four seasons with a little difference in strength; it is a persistent source of the TWC. However, Kuroshio surface water (KSW) can not intrude onto the shelf in summer, while in winter the intrusion of KSW always occurs. Additional experiments were conducted to examine effects of winds and transport through the Taiwan Strait on the TWC. In winter, northerly winds enhance the shelf-intrusion of the Kuroshio and spread northward, but hamper the northward inflow from the Taiwan Strait. In summer, the effect of the winds is confined in the surface layer, and less obvious than that of winter. Transport through the Taiwan Strait influences the TWC significantly. With the Taiwan Strait closed in the simulation, the TWC would be dramatically weakened.

Key words: Taiwan Warm Current, Kuroshio intrusion, seasonal variations, numerical simulation

1 INTRODUCTION

The Taiwan Warm Current (TWC) flows to the north all year round between the 50m and 100m isobaths, and dominates in the circulation of the western part of the East China Sea (ECS). Since it was found in 1960’s, it has been extensively studied mainly based on hydrographic data and current observations.

Regarding its sources, Guan and Mao (1982) inferred from current observations from 1930’s to 1970’s that in summer the TWC originates only from the Taiwan Strait. From hydrographic studies, Weng and Wang (1984) indicated that in summer the upper layer water originates mainly from the Taiwan Strait while all the lower layer water comes from shelf-intrusion of the Kuroshio subsurface water (KSSW) northeast of Taiwan. Inoue (1981) suggested the TWC sometimes reaches all the way up to the mouth of Changjiang (Yangtze) River. Furthermore, Weng and Wang (1984) indicated that in summer the upper layer water could reach 31°N, while the lower layer water could extend further north near 32°N line. Recently, winter pattern of the northward spreading of the TWC has also been studied. Zhang and Wang (2003) believed that in winter the TWC can extend to 31°N even under the influence of northerly.

However, mixing and diffusion make it difficult to study the circulation accurately using hydrographic data. Mechanism-oriented analytical and numerical studies (Qiu and Imasato, 1990; Liu and Su, 1993; Liang and Su, 1994) have deepened our understanding of Kuroshio intrusion into the ECS and sources of the TWC. But the models they used are too simple to understand in details many aspects of the TWC such as its sources, strength and seasonality. This paper aims to present the detailed features of the TWC in a comprehensive numerical model and study its sources, strength, flow patterns and their seasonality.

* Contribution No.4613 from the Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China.

Supported by the National Basic Research Program of China (No. G1999043803).
2 METHODS

Princeton Ocean Model (POM) is used to simulate the circulation in the East China Sea and discuss the northward intrusion of the TWC mentioned above. It has the following features: (1) Arakawa C grid, (2) sigma coordinate in the vertical, (3) free surface, (4) a second-order turbulence closure model for vertical viscosity.

The model domain is from 24°N to 42°N and from 118°E to 132°E, which covers the Bohai Sea, Yellow Sea and East China Sea. The realistic bathymetry data with the resolution of 5' x 5' were from IOCAS (Institute of oceanology, Chinese Academy of Sciences). Horizontal resolution of 5' x 5' and 10 vertical sigma coordinate levels were used in modeling. Four open boundaries are set at the Taiwan Strait, Suao-Yonagunijima Channel (east of Taiwan Island), the Tokara Strait and the Tsushima Strait. The monthly mean transports are used as boundary values (Table 1) (Lee et al., 2001, Teague et al., 2002)

| Table 1 Volume transport at open boundaries (Unit: Sv) |
|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Suao-Yonagunijima Channel | 23.1 | 21.2 | 20.5 | 25 | 24.38 | 20 | 23.75 | 25 | 22.5 | 18.75 | 25 | 27.5 |
| Taiwan Strait | 0.93 | 0.88 | 1.08 | 1.59 | 2.08 | 2.35 | 2.76 | 3.10 | 2.51 | 1.46 | 0.76 | 0.72 |
| Changjiang water discharge | 0.011 | 0.012 | 0.016 | 0.024 | 0.034 | 0.04 | 0.051 | 0.045 | 0.04 | 0.033 | 0.023 | 0.014 |
| Tsushima Strait | 1.7 | 2.2 | 2.8 | 2.75 | 2.7 | 2.8 | 3.0 | 3.1 | 3.5 | 3.5 | 3.1 | 1.8 |

UWM/COADS climatological monthly mean sea surface wind stress, net sea surface heat flux and short wave radiation are used to run the model. Levitus climatological monthly mean temperature and salinity data are used as initial and boundary conditions. The model was integrated for 5 years. The last year monthly mean fields are used to analyze in the following sections.

3 RESULTS

All factors which may contribute to the seasonality of the TWC are taken into account in the model so as to expect that the seasonality of the TWC can be successfully reproduced. Modeled TWC in various seasons are described later in this paper. February, May, August and November were selected to represent winter, spring, summer and autumn, respectively. Fig.1 and Fig.2 show circulation fields at 20m and 50m layers in four seasons, from which the modeled TWC and its seasonal variations in its sources, strength and flow patterns can be observed.

3.1 Seasonal variations of sources of the TWC and Kuroshio intrusion

As mentioned above, the TWC originates from two sides of the Taiwan Island. The key issues are how important the each source and how they behave in different seasons. Both transport through the Taiwan Strait and shelf-intrusion by the Kuroshio varies largely with season. To illustrate the behaviors of the shelf-intrusion by Kuroshio, two additional separated experiments for February and August were conducted and a tracer was used to trace the shelf-intrusion and the movement of Kuroshio water on the shelf. In each experiment, the value of the tracer was set 100 at the Suao-Yonagunijima Channel as boundary value. Fig.3 and Fig.4 shows respectively the vertical section of the tracer and temperature along 123°E, where the axis of the TWC is always located, and the distributions of tracer in the ECS at 20m and 60m layers are shown in Fig.5.

In summer, transport through the Taiwan Strait is larger than that of other seasons, thus most of the water of the TWC comes from the Taiwan Strait. In details, the upper part of the TWC originates from the Taiwan Strait while the lower part comes from the shelf-intrusion of KSSW (Fig.1c, Fig.2c). From Fig 1c, it can be found that there is a weak current area located in 123°-125°E/26°-27°N, between the Kuroshio and the TWC. And an area with near zero tracer values appears in 26°-30°N in the upper layer (Fig.3b, Fig.5b). All the facts lead to a conclusion that the Kuroshio surface water (KSW) can not intrude onto the shelf in summer. However, at the lower layer, the weak current area disappears and the northward currents appear in the area (Fig. 2c). The upwelled KSSW with high salinity (not shown) and low temperature (Fig.4b) spreads northward beneath the water from the Taiwan Strait to the mouth of Changjiang River, and upwells again along the seashore off Zhejiang Province, so, in the upper