Volume transports through the main straits of the East China Sea based on HYCOM reanalysis data

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Abstract. Volume transports through the main straits of the East China Sea and the inter-annual variations are determined based on HYCOM reanalysis data in the period from 1993 to 2012. The annual mean transports through Taiwan Strait (TS) and Tsushima Strait (TUS) are approximately 1.24Sv (1Sv=10^6m^3/s), and 2.41Sv, respectively. This suggests that the onshore intrusion of Kuroshio water crossing the shelf break of the East China Sea is around 1.17Sv. These estimations are consistent with the previous studies. Furthermore, the volume transports of other channels connecting the East China Sea with the open ocean also have been checked, which are 27.78Sv, 28.55Sv and 1.93Sv through East of Taiwan (TE), Tokara-Osumi Strait (TOS) and the Ryukyu Islands chain (RK), respectively. The Kuroshio transport of HYCOM reanalysis data is larger than the climatological value pointed out from the earlier studies. However, it is much closer to the new analysis value (28.1Sv) based on the observation of Japan Meteorological Agency during the period between 2003 and 2006. The possible reasons also have been addressed. The long-term trend suggests that the transports of TS and TUS have been increased slightly, while those of ET and TOS have been decreased.

1. Introduction

The East China Sea is located on the north-western side of the Pacific Ocean with one of the widest continental shelf in the world (as shown in Figure 1). It is connected with the open Ocean to the south and the Yellow Sea to the north, also is interlinked with the Japan Sea through the Tsushima Strait and with the South China Sea through the Taiwan Strait. The Kuroshio, as the most important western boundary current in the North Pacific Ocean, flows northward along the out edge of the continental shelf break of the East China Sea, which has a significant impact on the temperature, salinity, nutrients and the circulation structure of Bohai Sea, Yellow Sea and the East China Sea [1-3]. The Kuroshio enters the East China Sea at the eastern side of Taiwan Island (Taiwan-Taketomi-jima line) and flows north-eastward along the edge of the continental shelf of the East China Sea, and eventually goes back to the north-western Pacific Ocean after passing through the Tokara Strait. Apparently, numerous of studies have been carried out according to this subjects [4-10]. To date, studies of the Kuroshio Current in the PN section (black line as shown in Figure 1), located in the central East China Sea from (125°12E, 30°N) to (128°15E, 27°30N), and the TK section, have focused on climatological structures and spatial patterns based on hydrographic data acquired in one or a few cruises. The long term temporal and spatial variabilities of the Kuroshio Current remain unclear. Furthermore, the Taiwan Strait and Tsushima Strait are the channels connecting the South China Sea and the Japan Sea with the East China Sea, respectively. The Taiwan warm current and Tsushima warm current are the...
typical dynamic characteristics in these straits. According the previous studies, even if the volume transports through then Taiwan Strait and the Tsushima Strait are equivalent, part of water could be mixed with the Kuroshio water as the water flows along the East China Sea shelf break due to the meso-scale processes [7]. But, it is not possible only using the observation data to estimate the water exchange across the entire East China Sea shelf break. Numerical model approaches are adopted for the evaluation of this connectivity of transports over the shelf [8] [11]. However, usually the simulations are focused on climatological or seasonal situations and patterns, the inter-annual variations of volume transports through the main straits of the East China Sea has not been possible from observations. Alternatively, the simulated results from a widely approved, long-term, high-resolution general ocean circulation model with a realistic bathymetry are employed in present study.

The paper is organized as follows. A short description of the numerical model is given in the next section. Section 3 shows the volume transports through the main straits of the East China Sea estimated from the reanalysis simulation data and the paper ends up with conclusions in section 4.

**Figure 1.** Bathymetry of the East China Sea. Position of sections is also shown for reference. TS: Taiwan Strait; ET: East of Taiwan; RK: Ryukyu Islands; TOS: Tokara – Osumi Strait; TUS: Tsushima Strait. The black line indicates the location of PN section.

### 2. Data

The HYCOM reanalysis data, which is the output of the Hybrid Coordinate Ocean Model/Navy Coupled Ocean Data Assimilation model, had been used to analyse the inter-annual variations of the volume transports through the main straits (TS, ET, RK, TOS and TUS) of the East China Sea. The HYCOM is an oceanic general circulation model (OGCM) with primitive equations, which has been widely used for different diverse range of applications, not only large-scale circulation but also the coastal region [12, 13]. These HYCOM reanalysis data have been widely used to study the climatological structures and seasonal variations of the Kuroshio Current. The spatial resolutions of the reanalysis data used in this paper are 0.08° × 0.08° in horizontal and 40 layers in vertical, respectively. For the study region, where the water depth is generally shallower than 200m, there are
23 layers. The mesoscale variability also can be captured in the output data, which is significant on the circulations in the East China Sea region. The reanalysis data is daily output and covers the time period from 1993 to 2012. Further details of the reanalysis data could be found on the following website: https://hycom.org/dataserver/gofs-3pt0/reanalysis. In this study, HYCOM reanalysis covering the continental shelf break of the East China Sea region (24°-35°N, 117°-130°E) is analysed.

3. Kuroshio volume transports

According to the connectivity of the ocean currents in the East China Sea, the volume transports through Taiwan Strait and Tsushima Strait should be balance with the flux of the Kuroshio onshore intrusion.

The long term mean volume transport through the Taiwan Strait (TS) is 1.24Sv (shown as the black line with dots in Figure 2) with the standard deviation of 0.17Sv (Table 1). The result agrees with the previous studies estimated from in-situ hydrographic data, which is approaching 1.2Sv [14]. The maximum flux (~1.5Sv) is occurred in the year of 2006 and minimum (~0.9Sv) in the year of 2012.

The time mean volume flux of Tsushima Strait (TUS) is almost 2.41Sv with the standard deviation of 0.25Sv (Table 1), which is slightly weaker than the 2.65Sv suggested by Isobe et al., (2008) according the historical obviations.

As mentioned above, the inflow and outflow of the East China Sea should be balanced. Since the volume transport through TUS is larger than that through TS almost 1.17Sv, the residual part must be supplied from the onshore intrusion of the Kuroshio across the continental shelf break. Thus, the HYCOM reanalysis data suggests that the onshore intrusion of Kuroshio water crossing the shelf break of the East China Sea is around 1.17Sv. Furthermore, the transport of TUS has been increased slightly faster than that of TS during this period. In other words, the onshore intrusion of the Kuroshio also has been enhanced from 1993 to 2012.

The Kuroshio, the famous western boundary current, flows into the East China Sea at the east of Taiwan Island along the out edge of the continental shelf break. The results suggest that the long term mean volume transport through section ET is 27.78Sv. The time series has been shown in Figure 2 as then red line with square markers, and the standard deviation is 0.17Sv during the period of 1993 and 2012. Also we consider the Tokara Starit and Osumi Strait together as the exit of Kuroshio flow out of the East China Sea. The total water transport through section TOS is 28.55Sv with the standard deviation of 1.78Sv. The results suggest that both of the transports through ET and TOS are larger

![Figure 2. Volume transports through the main straits of the East China Sea: the red lines with squares and triangles present the annual averaged volume transports of ET and TOS, respectively; the black lines with dots and stars present the annual averaged volume transports of TS and TUS, respectively.](image-url)
than the simulated climatological values of 23.83Sv and 21.93Sv. There are two possible reasons: First, the Kuroshio Current of HYCOM reanalysis data has been overestimated; Second, previous studies estimated Kuroshio transport based on the observed data with the cruise-dependent resolution. It shows a significant regime shift around 1976 following with a sharp increase trend (Figure 3). The earlier analysis and model simulated climatological value of Kuroshio may depend on the focusing period. Because the observation of Japan Meteorological Agency during the period between 2003 and 2006 suggests that the Kuroshio transports through Tokara Strait is around 28.1Sv [15], which is much closer to the present results. Due to the lack of the actual observation data about the Kuroshio Current, it remains unclear and needs more investigations. Unlike the transports of TS and TUS, the Kuroshio transport suggests slight decreasing trend during this period.

The volume transport through the Ryukyu Islands (RK) is around 1.93Sv. Thus, the volume transports through the TS, ET, RK, TOS and TUS, which are the main channels of the East China Sea, are almost balance.

It should be pointed out that even though the HYCOM data reanalysis adopts a 3D variational scheme assimilates multiple observations (satellite altimeter observations, satellite, and in-situ sea surface temperature and in-situ vertical temperature and salinity profiles from XBTs, Argo floats, and moored buoys), direct evidence of the current measurement is still needed. Besides, the global gridded analysis product has not considered tides and their effect on circulation, which are quite significant in continental (marginal) seas. Thus, the volume transports through the main straits of the East China Sea and their inter-annual variations require more investigation in the future.

Table 1. Long term averaged volume transports through the main straits of the East China Sea.

| Straits | Volume transports (1Sv = 10^6 m^3 /s) |
|---------|--------------------------------------|
| TS      | 1.24±0.17                            |
| ET      | 27.78±1.99                           |
| RK      | 1.93±0.15                            |
| TOS     | -28.55±1.78                          |
| TUSc    | -2.41±0.25                           |

Positive value represents onshore (into the East China Sea) transports.

Figure 3. Redrawn depiction of Kuroshio volume transport of PN section and Tokara section as indicated by in-situ hydrographic data from different cruises [17].
4. Conclusions
Volume transports through the main straits of the East China Sea and the inter-annual variations are determined based on the HYCOM reanalysis data in the period during 1993 and 2012. The annual mean transports through Taiwan Strait (TS) and Tsushima Strait (TUS) are approximate 1.24Sv (1Sv=10^6m^3/s), and 2.41Sv, respectively. The volume transports of other channels connecting the East China Sea with the open ocean also have been checked, which are 27.78Sv, 28.55Sv and 1.93Sv through East of Taiwan (ET), Tokara-Osumi Strait (TOS) and the Ryukyu Islands chain (RK). The result suggests that the onshore intrusion of Kuroshio water crossing the shelf break of the East China Sea is around 1.17Sv, which are consistent with the previous studies. However, the Kuroshio transport may highly depend on the study period. It remains unclear and needs more investigations in the future.

Acknowledgments
This work was supported by National Key Research and Development Project (2018YFD0900906), National Natural Science Foundation of China (Project 41706023 and Project 41806118), the Natural Science Foundation of Jiangsu Province (Grants No. BK20170871 and No. BK20170875). The authors also would like to thank the editor and the anonymous reviewers for their work on this paper.

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