Decadal Variation of the Geostrophic Vorticity West of the Luzon Strait

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Abstract: Merged satellite altimeter data (from 1993 to 2008) are used to study the decadal variation of geostrophic vorticity west of the Luzon Strait. The decadal variation of the geostrophic vorticity west of the Luzon Strait indicates that the Kuroshio intrusion and separated anticyclonic eddies from the Kuroshio are stronger in 1995-2000 than that in 2001-2004. Between 1995 and 2000, along with the intensification of the anticyclone separated from the Kuroshio intrusion west of the Luzon Strait, the cyclone south of the Kuroshio intrusion is strengthened. This result proved the close relationship between eddy shedding and the growth of the cyclone south of the Kuroshio front. In 1995-2000, when the anticyclonic vorticity west of the Luzon Strait was increased, at the same time, the decrease thermocline thickness and the Kuroshio transport east of Luzon Island are found by analyzing the Simple Ocean Data Assimilation datasets. This suggests that the decadal change in the Kuroshio intrusion and eddy shedding in the Luzon strait is influenced by the decadal change in thermocline thickness and Kuroshio transport east of the Luzon Island.

Keywords: Geostrophic vorticity, Luzon Strait, eddy shedding.

1. INTRODUCTION

The South China Sea (SCS) is a semi-enclosed, marginal basin of the western Pacific. The Luzon Strait, located from 18.5°N to 22°N with widths around 400km and depths over 2000 m, is the only deep channel connecting the SCS with the Pacific. The Kuroshio, as one of the western boundary currents of the North Pacific, deforms while crossing the Luzon Strait [1]. Anticyclonic eddies are found to be separated intermittently from the Kuroshio deformation in the Luzon Strait [2-4]. The eddy shedding phenomenon is reported as an event of non-deterministic nature and with large variety in frequency and behavior [4-7], which indicates variation of time scale longer than interannual may exist in these phenomena. Furthermore, these studies are mainly limited in the description of the Sea Surface Height (SSH) and the geostrophic velocity, in which the strength or the Geostrophic Vorticity (GV) of the anticyclonic eddies left unknown. The GV anomaly is the anomaly vorticity of the geostrophic circulation calculated from the SSH anomaly data. It is very important in the study of potential vorticity interaction between the SCS and the Pacific.

Moreover, it is suggested that the separation of the anticyclonic eddy from the Kuroshio intrusion is related with the cyclone generated by frontal instability in the south the Kuroshio intrusion [8], while the existence of the cyclone has not been proved by observation. By studying the GV anomaly west of the Luzon Strait, the relationship between the anticyclone from the Kuroshio intrusion and the cyclone from the south of the Kuroshio front will be discussed.

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Under the influence of the low potential vorticity water transported from the central North Pacific [9], the decadal variation of the thermocline thickness will intensify the Kuroshio transport in the recirculation area [10]. It is reported that the strength of the Kuroshio Extension recirculation gyre weaker in 1995-2001 and stronger in 2002-2005 [11].

As it is indicated by Jia *et al.* [8], the vertical thermal structure of the upper ocean may be important to the eddy shedding behavior. It is reported that there is decadal variation of the thermocline thickness east of the Luzon Strait [9]. Will these decadal signals influence the eddy shedding behavior from the Kuroshio in the Luzon Strait?

In this paper, using the merged T/P altimetry data, the geostrophic vorticity anomaly west of the Luzon Strait is calculated. Then the decadal variation of the GV is discussed. To explore the mechanism of decadal variation of GV, the relationship between the GV and the thermocline thickness, the Kuroshio Transport, is investigated using the Simple Ocean Data Assimilation (SODA) data.

2. DATA

SSH anomaly data sets were obtained from AVISO at seven-day intervals, with a 1/3° × 1/3° resolution gridded to a Mercator projection for the period between1992-2008. This data set combines sea surface altimetry from Topex/ Poseidon, ERS-1, ERS-2, Jason-1, and ENVISAT, respectively (depending on availability), into a product of merged sea level anomaly [12].

The SODA (Simple Ocean Data Assimilation) dataset v1.4.2 and v1.4.3 is used to obtain the ocean subsurface information. The SODA dataset is a global ocean retrospective analysis [13]. The ocean model is based on Parallel

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Ocean Program physics with an average 0.25°×0.4°×40-level resolution. Observations include virtually all available hydrographic profile data, as well as ocean station data, moored temperature and salinity time series, surface temperature and salinity observations of various types, and nighttime infrared satellite SST data. The output includes temperature, salinity, and horizontal velocity in a monthly-averaged form, mapped onto a uniform 0.5°×0.5°×40-level grid. The time period of the dataset SODA v1.4.2 ends on 2001, while the time period of the dataset SODA v1.4.3 starts on 2002. To get time series from 1993 to 2004, the dataset of v1.4.2 is connected with the dataset v1.4.3. These two SODA versions differ only in the forcing wind.

3. DECADAL VARIATION OF GEOSTROPHIC VORTICITY WEST OF THE LUZON STRAIT

The GV anomaly is the anomaly vorticity of the geostrophic circulation calculated from the Sea Surface Height (SSH) anomaly data. As it changes sign in anticyclonic eddy and in cyclonic eddy, it is used as an index to define the separation of the anticyclinc eddies from the Kuroshio [2]. It is also used to define the location, the size and the strength of the detached anticyclonic eddies. In this paper the variation of the GV was averaged in the eddy shedding area west of the Luzon Strait [2] and is used as an indicater of the eddy shedding and Kuroshio intrusion. If the GV is stronger, then Kuroshio intrusion is stronger and the separated anticyclonic eddy from the Kuroshio is stronger.

From the rms of the GV during 1992-2008 (Fig. **1**), variation of GV of about $2.1\times10^{-6}s^{-1}$ (larger than the mean GV in the same region described by Jia and Liu [2]) is observed in the region of (20.5°-21.75°N, 119.25°-120.25°E), which agrees very well with the eddy shedding region from the Kuroshio described by Jia and Liu [2]. This agreement suggests that variation of the GV in the eddy shedding area can be used to represent the strength of the detached anticyclonic eddy from the Kuroshio. The rms of the GV is relatively low in the meridional band along 121-122°E, which is the location of the main stream of Kuroshio

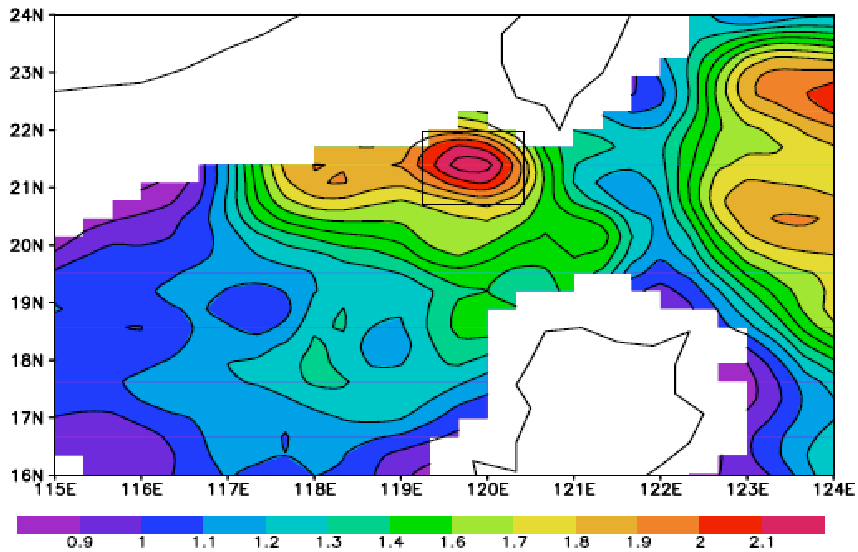

Fig. (1). rms of geostrophic vorticity in the Luzon Strait and north South China Sea. The rectangle marks the area (20.5-21.75°N, 119.25-120.25°E) we chose to calculate the mean GV in eddy shedding area. The area shallower than 150m is blocked to avoid the tidal error in the altimetry data.

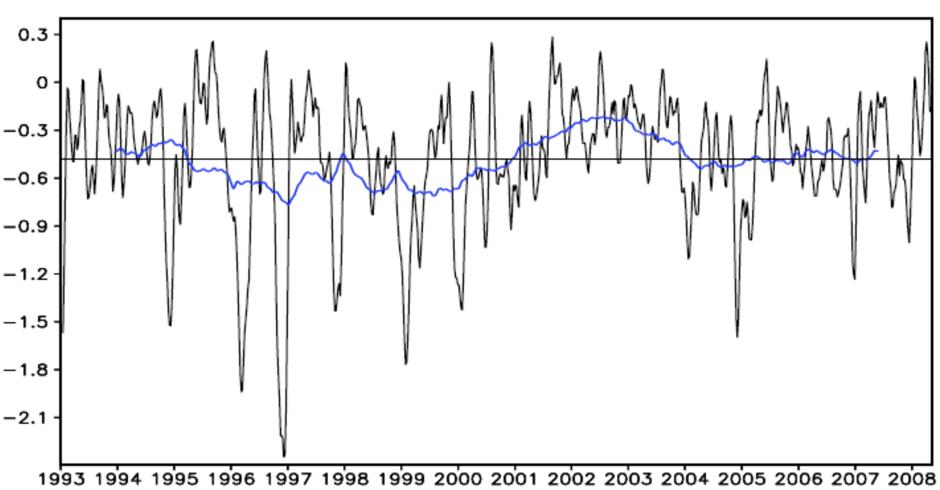

Fig. (2). The time serial of the GV averaged in the eddy shedding area(the black line), the 30d running mean is used to reduce high frequency variation. The thick blue line is 2 year running mean. The horizontal straight line is the mean of the GV.

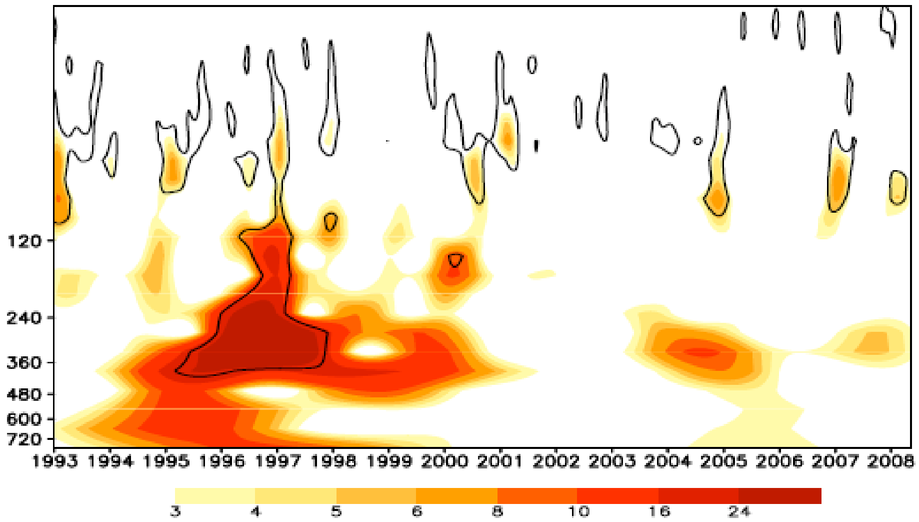

Fig. (3). Wavelet spectrum of the GV averaged in the eddy shedding area. The shading is the spectrum, the contour is the 95% significant level.

[14]. East of 122°E, large rms shows the activity of eddies in the Pacific.

The averaged GV anomaly in the region of eddy shedding is calculated and plotted in Fig. (**2**). The GV anomaly varies from $-2.3\times10^{-6}s^{-1}$ to $0.3\times10^{-6}s^{-1}$, mostly negative, because the variation of the GV is mainly caused by the intrusion of the Kuroshio and the formation and separation of the anticyclonic eddies. Besides the intraseasonal and seasonal variation of the GV anomaly, the decadal variation is also quite significant (Fig. **2**).

During the years of 1995-2000, the GV is much lower than that in the other years, indicating larger Kuroshio intrusion and stronger detached anticyclonic eddies. The minimum value of GV anomaly is -2.3×10^{-6} s^{-1} (Fig. **2**), which occurred in 1997. The amplitude of the GV anomaly in the eddy shedding area is about 2.4×10^{-6} s^{-1} during 1995-2000, almost twice as that in the year 2001-2004. The intraseasonal variation (for example, the 70-100day, 120-200day variation) and the seasonal variation during 1995-2000 are more obvious than those in other years (Fig. **3**). This result agrees with former observations of eddy shedding: In Jia and Liu's [2] work, from the listed eddy shedding time, there are more eddy shedding events in the year 1995-2000. In Yuan *et al.* [5] and in Wu and Chiang [6] work, there are more Kuroshio intrusion and more separated anticyclonic eddies reported in 1999-2000 than in 2001-2003. All these results indicate the existence of decadal change in the strength of Kuroshio intrusion and detached anticyclonic eddies although the time span of the observation is limited.

All the results indicate that decadal variation of the GV anomaly exists in the eddy shedding area. To understand more about the decadal variation of the GV anomaly, the difference of the GV anomaly averaged in the year 1996-2000 and in the year 2001-2003 is showed in Fig. (**4**). During 1996 to 2000, the GV in the anticyclonic eddy shedding region is about $1.2\times10^{-6}s^{-1}$ which is lower than that during 2001 to 2003 (higher than the mean GV in Jia and Liu's [2] work in this region), indicating stronger anticyclonic eddy shedding and Kuroshio intrusion during 1996 to 2000. At the surrounding of the intensified anticyclonic GV, there is a positive change in the GV (about $0.2\sim0.4$ $\times10^{-6}s^{-1}$), which indicates the intensifying of cyclonic eddies near the anticyclonic eddy.

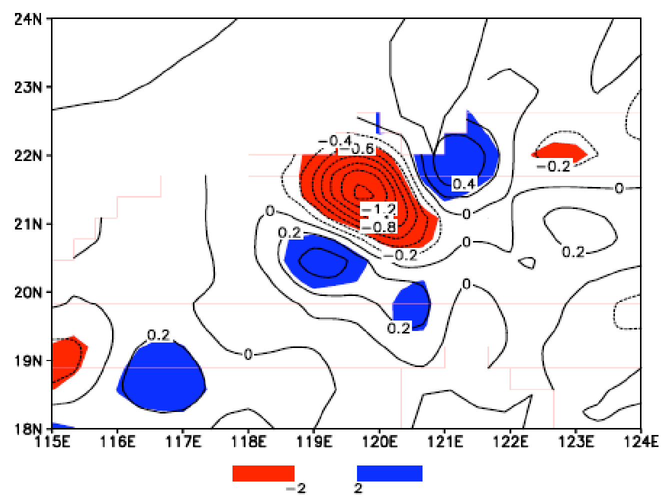

Fig. (4). The difference between the mean GV in strong eddy shedding year (1996-2000) and in weak eddy shedding year (2001-2003) (contour). Unit: $10^{-6}s^{-1}$. The shaded area shows the significant level of 95%. The area shallower than 150m is blocked to avoid the tidal error in the altimetry data.

There are mainly two regions in which cyclonic eddies are intensified according to the strengthening of the anticyclonic eddy: one is at about (20.5°N,119°E) south of the anticyclone, the other is at south of Taiwan Island, in the similar location of the Lanyu Cold eddy [15]. The cyclone in the south is almost at the same location as the cyclone mentioned by Liang [14, 16]. The close relationship between eddy shedding and the cyclonic eddy to the south of the Kuroshio intrusion was discussed by Jia *et al.* [8] using a numerical model. It was found in the modeling result that the cyclonic eddy south of the Kuroshio front caused by the frontal instability cleaved the Kuroshio intrusion and separated the anticyclonic eddy from the Kuroshio. The anti-phase variation of the GV in the anticyclonic eddy and the cyclonic eddy proved the important role of the cyclonic eddy in eddy shedding.

In summary, from the above observation and statistical results, there exists significant decadal change in the GV in the eddy shedding area (20.5°-21.7°N, 119°-120.3°E) west of the Luzon Strait. The decadal change in the GV indicates that there exist two different patterns in eddy shedding and Kuroshio intrusion around 2001: one can be interpreted as strong anticyclonic eddy shedding mode (during 1995-2000, with stronger intra-seasonal and seasonal variation of Kuroshio intrusion, stronger detached anticyclonic eddy and intensified cyclonic eddy south of the Kuroshio front) and the other can be interpreted as weak anticyclonic eddy shedding mode (during 2001-2004, with weaker intra-seasonal and seasonal variation in Kuroshio intrusion, weaker detached anticyclonic eddy and weaker cyclonic eddy south of the Kuroshio front). These results proved that the detachment of the anticyclonic eddy from the Kuroshio is caused by the cyclonic eddy south of the Kuroshio front. From Jia *et al.* [8], frontal instability of the Kuroshio front is the energy source of the cyclonic eddy south of the Kuroshio front, which influences the eddy shedding. From Sheremet [17] and Qu [18], the Kuroshio transport is a factor influencing the intrusion of the Kuroshio into the Luzon Strait. These studies indicate there may be similar change in the Kuroshio transport and in the stratification of the ocean near Luzon Strait.

4. DECADAL CHANGE IN THERMOCLINE THICKNESS AND KUROSHIO TRANSPORT EAST OF THE LUZON STRAIT

To better understand the mechanism of the decadal change in eddy shedding and Kuroshio intrusion, the thermocline thickness and Kuroshio transport are calculated using the SODA data.

Considering the nature of frontal instability of the Kuroshio front, the vertical thermal structure of the upper ocean may play important role in affecting the eddy shedding behavior. As discussed by Liu and Hu [9], the most apparent decadal change of the stratification east of Luzon Strait is in the thermocline thickness, which is influenced by low potential vorticity water transported from the central North Pacific along a subsurface pathway, following the subtropical gyre circulation. The question is whether there is any change of the thermocline thickness east of Luzon Strait during the period 1995-2000 and in 2001-2004?

The thermocline thickness is calculated between the sigma level 25 and 26, following the similar method in Liu and Hu [9]. The difference of the thermocline thickness is calculated between the strong eddy shedding year (1996-2000) and the weak eddy shedding year (2001-2003) (Fig. **5**). In the results from SODA data, the thermocline thickness increased about 10-30m east of Luzon Strait and Taiwan, reduced about 10-20m in the middle of the SCS during strong eddy shedding year. It is because in the period 1995-2000, more low potential vorticity water was transported to the east of the Luzon Strait [9]. The Kuroshio transport east of Taiwan (Fig. **6**) was increased by the thickening of the thermocline east of the Luzon Strait, which agrees with the results by Qiu and Miao [10]. In that paper, the intensification of Kuroshio transport in the recirculation area is reported as the result of the thickening of the thermocline thickness in decadal variation.

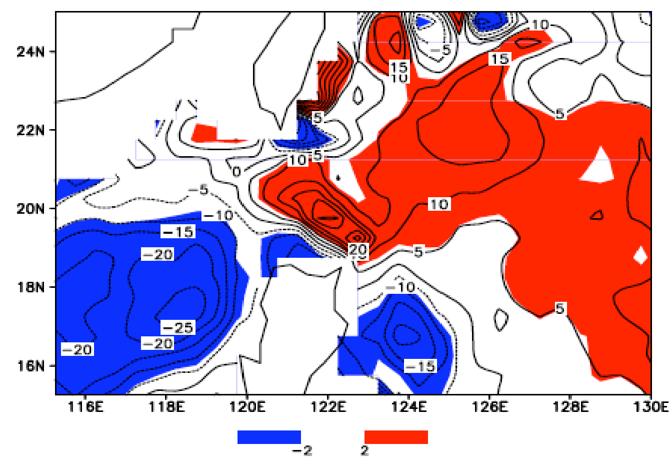

Fig. (5). The difference in thermocline thickness between strong eddy shedding year (1996-2000) and weak eddy shedding year (2001-2003). Unit: m. The shaded area shows the significant level of 95%.

However, according to Sheremet [17], Jia and Liu [8], Qu [18], and Liang [14], as per the theory of inertia and observation, when the Kuroshio transport increased, the Kuroshio will “leap across the gap” and less Kuroshio water will extend into the Luzon Strait. This conclusion suggests the strengthen of the Kuroshio transport east of Taiwan in 1995-2000 but it does not result in the strong eddy shedding mode in 1995-2000. The question is what caused the strong eddy shedding mode in 1995-2000?

Towards the South of the thickening area of the thermocline east of the Luzon Strait and Taiwan Island, there exists a decrease in the thickness of the thermocline east of the Luzon Island (at about 17.5°N) in 1995-2000. Did the decrease in thermocline thickness in 1995-2000 influence the Kuroshio transport across 17.5°N? Was there any impact of this decrease on the strength of eddy shedding and Kuroshio intrusion in the Luzon Strait?

The Kuroshio transport across 17.5°N and the Luzon Strait transport are calculated using the SODA data (Fig. **6**). The thickness decrease in thermocline east of Luzon Island caused the decrease in Kuroshio transport in the origin of Kuroshio (17.5°N). The Luzon Strait transport is lower in the years of 1996-2000, which agrees well with the increase of the GV anomaly and the strengthening of eddy shedding in these years. It is proved that stronger GV in the eddy shedding area represents stronger detached anticyclonic eddy and stronger Kuroshio intrusion into the Luzon Strait. This conclusion supports the inertia theory that stronger Kuroshio intrusion is caused by lower Kuroshio transport across 17.5°N. It indicates that the transport at the origin of the Kuroshio is more important to the eddy shedding and Kuroshio intrusion into the Luzon Strait. The Kuroshio transport at the origin is almost out of phase with the Kuroshio transport east of Taiwan in decadal time scale. This

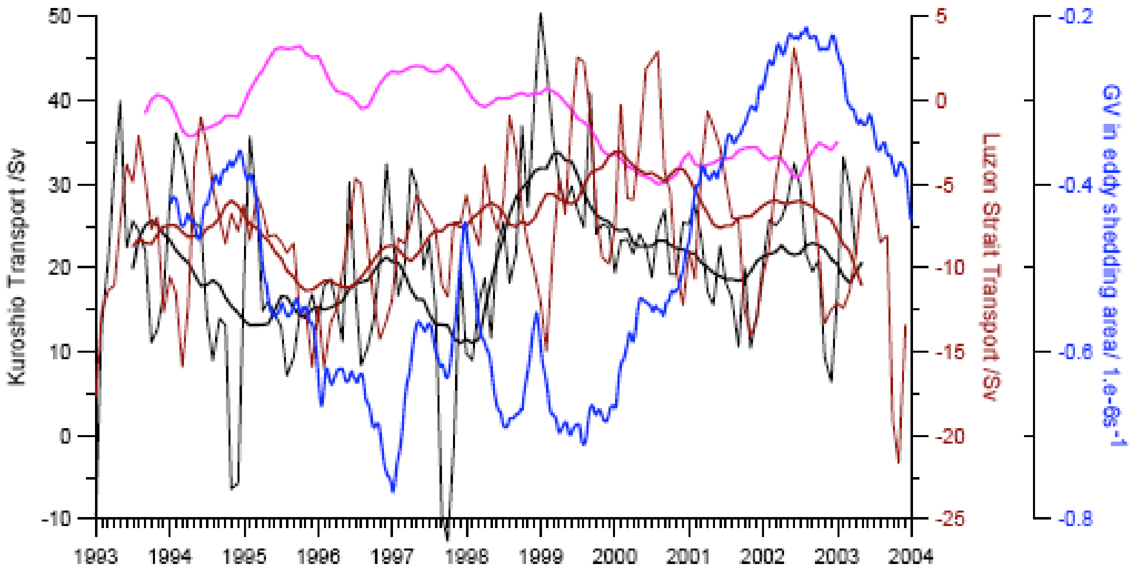

Fig. (6). Kuroshio transport across 17.5°N (the black line, the thick black line is the 13months running mean), the Luzon Strait Transport (the red line, the thick red line is the 13months running mean). The thick blue line is the 13 months running mean of the GV. The thick pink line is the 13 months running mean of the Kuroshio transport east of Taiwan.

interesting finding may motivate further study on Kuroshio intrusion in the Luzon Strait.

5. CONCLUSIONS AND DISCUSSIONS

From merged T/P satellite altimeter data (from 1993 to 2008), decadal variation of eddy shedding from the Kuroshio in the Luzon Strait is studied. During 1995-2000, eddy shedding and Kuroshio intrusion are stronger than that during 2001-2004. In 1995-2000, intensification of the cyclonic eddies south of the Kuroshio intrusion is found along with the strengthening of the detached anticyclonic eddies and Kuroshio intrusion. This finding helps to prove that eddy shedding is caused by the cyclonic eddies south of the Kusoshio intrusion whose growth is supported by the frontal instability [2]. Using SODA data, the change in thermocline thickness and in Kuroshio transport east of the Luzon strait is studied. It was found that the decrease in thermocline thickness and in the Kuroshio transport east of Luzon Island is responsible for the intensifying of the Kuroshio intrusion and eddy shedding in 1995-2000.

In this paper, the results are based on observation and on reanalysis data. To further explore the mechanism of the decadal change in eddy shedding and Kuroshio intrusion, numerical modeling work is needed.

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