Tracer experiments for appearance of the giant jellyfish, Nemopilema nomurai, in the southern Japanese coastal area of the Pacific Ocean in summer 2005

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Tracer experiments for appearance of the giant jellyfish, *Nemopilema nomurai*, in the southern Japanese coastal area of the Pacific Ocean in summer 2005

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Abstract

Numerically-tracking the tracer particles being assumed as the giant jellyfish, *Nemopilema Nomurai*, reveals its transport processes to the southern Japanese coastal area of the Pacific Ocean in summer 2005. The velocity fields, which are calculated by the high-accuracy numerical model developed for the Japan Coastal Ocean Predictability Experiment (JCOPE) system, are used in the tracer experiments. The experiments simulate transport paths of the jellyfish. It is clarified that the existence of a broad southward current toward the Pacific Ocean along the west coast of Kyushu caused the appearance of jellyfish in the southern Japanese coastal area of the Pacific Ocean. Then, near-shore Kuroshio path efficiently leaded the jellyfish to flow into the Seto Inland Sea. In addition, the jellyfish appeared there originated from the Changjiang estuary.

Key words : *giant jellyfish, JCOPE, tracer experiment, Yellow and East China Seas, Seto Inland Sea*

1. Introduction

Nemopilema nomurai is one of the largest jellyfish species with a bell diameter of 2 m and wet weight of 200 kg (Omori and Kitamura, 2004)[1]. The main habitat of this species is in the East China, Yellow and Bohai Seas (Omori and Kitamura, 2004) [1]. This species is also transported by the Tsushima Warm Current, which is a separation branch of the North Pacific subtropical gyre in East Asian marginal seas (Minato and Kimura, 1980[2]; Lie and Cho, 1994[3]; Guo et al., 2006) [4], from the Yellow and East China Seas to the Japan Sea via the Tsushima/Korea Straits (Fig. 1). The transport of this species is usually in small numbers. However, in 1920, 1958, 1995, 2002, 2003 and 2005, a population explosion of the jellyfish occurred in the Japan Sea causing a serious damage to fisheries. Thousands of jellyfish were trapped daily in set-nets (Kawahara et al., 2006) [5], so set-nets were damaged because of the large size and heavy mass, and the fish caught were killed by its poison.

In autumn to winter, the jellyfish was moreover carried to the Pacific Ocean from the Japan Sea via the Tsugaru Straits which is at the north of Japan, and then it moved toward the south along the Japanease coast (Yasuda, 2004[6]; Kawahara et al., 2006) [5]. In 2005, however, it was the first time that the jellyfish was found in the southern Japanese coastal area of the Pacific Ocean in summer (August to September). Figure 2 shows the sighting point of the jellyfish in late August to early September 2005 on the JSNFRI web site.

(Japan Sea National Fisheries Research Institute, URL: http://www.jsnf.affrc.go.jp/).

Although this figure shows a part of the jellyfish actually existed, we can see that the jellyfish appeared not only in the Japan Sea but also in the southern Japanese coastal area of the Pacific Ocean and the Seto Inland Sea.

Reisen and Isobe (2006) [7] targeted on the population explosion in the Japan Sea and clarified the reason of its occurrence in 2002 and 2003 by carrying the tracer experiments. The present study focuses on the appearance of the jellyfish in the southern Japanese coastal area of the Pacific Ocean in August and September 2005. Although it is easily predicted that the jellyfish were transported to the Pacific Ocean from the East China Sea, the detailed processes are unknown. So, the tracer experiments are carried out to simulate the transport path of the jellyfish. And then, the physical causes of its appearance there are revealed.

Because of the existence of the Kuroshio between the

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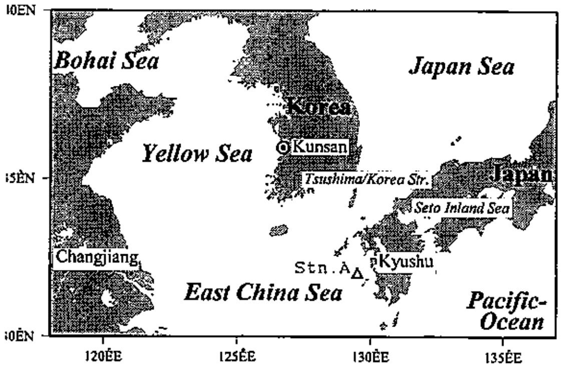

Fig. 1. Study area.

East China Sea and Pacific Ocean, a numerical model which can simulates the behavior of the Kuroshio is needed in the experiments. We use velocity fields calculated by a high-accuracy numerical model which covers the northwestern Pacific Ocean.

In the experiments, the results in 2005 are compared with those in 2003 when the jellyfish did not appear in the southern Japanese coastal area of the Pacific Ocean in summer.

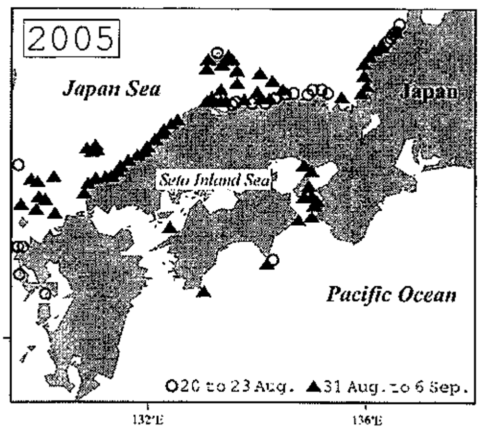

Fig. 2. Sighting point of *Nemopilema nomurai* in 2005 from JSNFRI web site (URL: http://www.jsnf.affrc.go.jp/).

2. Velocity fields

The velocity fields are calculated by the nested model which is developed for the Japan Coastal Ocean Predictability Experiment (JCOPE) system (Miyazawa and Yamagata, 2003[8]; Kagimoto et al., 2007)[9]. This JCOPE model is based on the Princeton Ocean Model for generalized coordinate of sigma (POMgcs; Blumberg and Mellor, 1987)[10]. A high-resolution, regional model with spatial grid of 1/12 degree and 45 levels is embedded in a low-resolution basin-wide model with a spatial grid of about 1/4 degree and

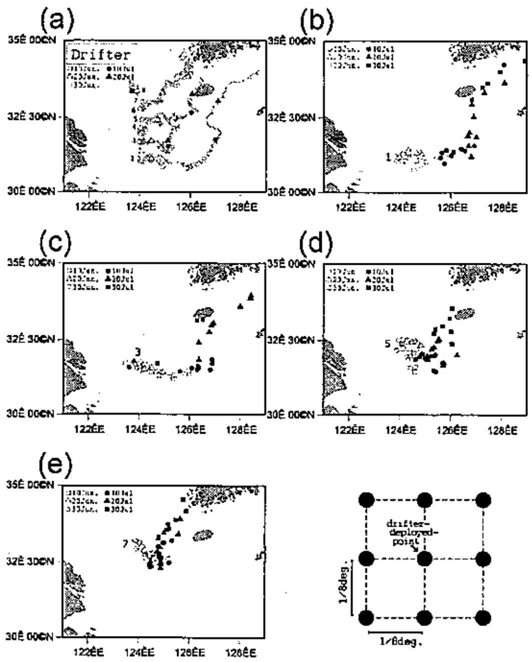

Fig. 3. Trajectories of eight satellite-tracked drifters (No. 1 to 8) deployed on 8th and 9th June 2003 along 124°E (a) (Matsuno et. al., 2006) and distributions of nine tracer particles tracked computationally (b to e). Tracer particles are released around the positions where the drifters were deployed. Their disposition is shown in lower-right panel. The symbols in these panels are plotted every 10 days from 10th June.

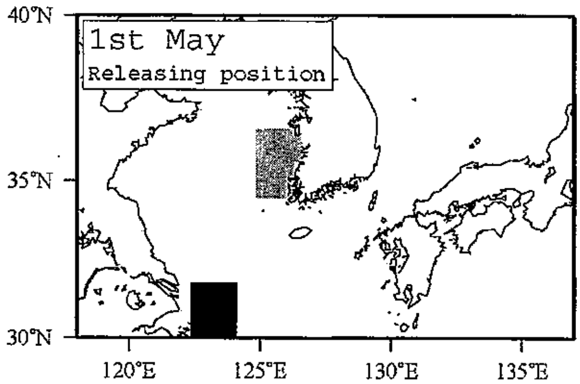

Fig. 4. Releasing positions of tracer particles in tracer experiments in 2003 and 2005. Grey and black particles show the departure from the offshore of Kunsan and Changjiang estuary, respectively.

21 levels. The former model domain covers the northwestern Pacific Ocean (12°-62°N, 117°-180°E) and its lateral boundary condition is specified using the one-way nesting method (Guo et al., 2003)[11] from the latter model.

The JCOPE model is driven by wind stress, heat and salt fluxes. The wind stress and heat flux fields are calculated

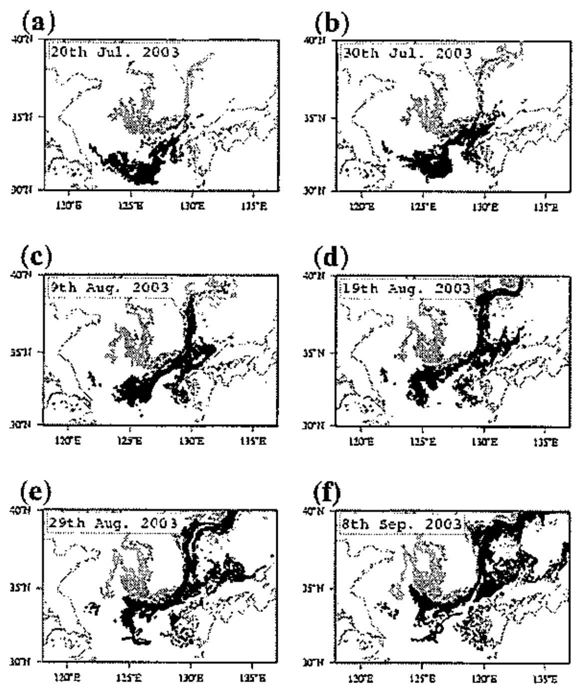

Fig. 5. Distributions of tracer particles in summer 2003. The date is shown in each panel.

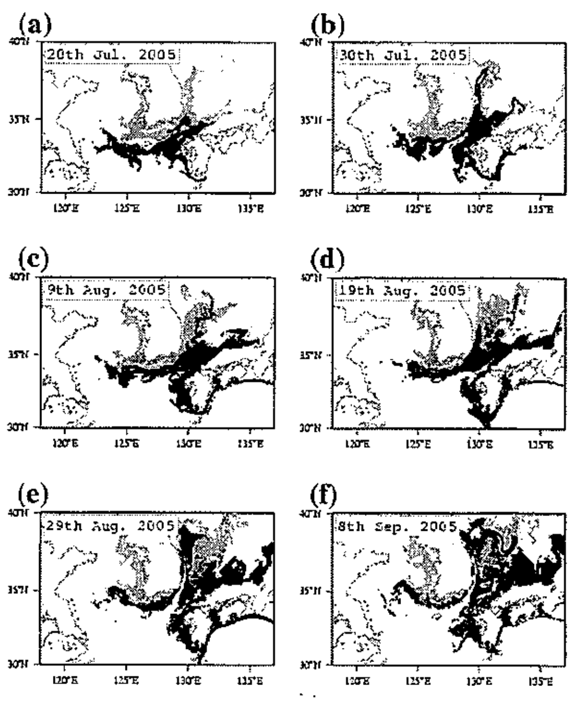

Fig. 6. Distributions of tracer particles in summer 2005. The date is shown in each panel.

from the 6-hourly QuikSCAT Near-Realtime (NRT) data product and NCEP/NCAR re-analysis data using the bulk formula. The salinity at the sea surface is restored to the monthly mean climatology with a time scale of 30 days. Various weekly mean data are created from sea surface height anomaly (Jason-1 and Geosat Follow on), sea surface temperature (NOAA/AVHRR), and subsurface temperature /salinity profiles including the ARGO data (GTSPP). These data are assimilated into this model.

The main object of development of the JCOPE model is to simulate connections between the Kuroshio path variations and mesoscale eddy activities. It shows a good performance (Miyazawa and Yamagata, 2003[8]; Miyazawa et al., 2004[12]; Miyazawa et al., 2005)[13]. So, this model reproduces the velocity fields of the Kuroshio region (eastern part of the East China Sea). In addition, Chang and Isobe (2003) [14] indicated that the surface flow pattern of the Yellow and East China Seas is considerably dependent on the wind stress, so that this model, which is forced by the re-analysed wind stress data, may reproduce the flow pattern of those areas.

For confirmation, the validation of the velocity fields is carried by comparing the behavior of the satellite-tracked drifters and tracer particles released into the velocity fields. Figure 3(a) shows the trajectories of eight drifters (No. 1 to 8) deployed on 8th and 9th June 2003 along 124°E (Matsuno et al., 2006) [15]. The symbols in this panel are plotted every 10 days from 10th June. No. 1, 3, 5 and 7 drifters are used in the validation, because the tracking periods of No. 2, 4 and 8 drifters are very short and the behavior of No. 6 drifter is almost the same as that of No. 7 drifter.

Tracer particles are numerically tracked with the Euler-Lagrange method (section 3.1). Nine particles are released around each drifter-deployed (No. 1, 3, 5 and 7) point in the velocity fields calculated by the JCOPE model.

The disposition of the nine particles is shown in the lower-right panel of Fig. 3. The releasing date is also matched the drifter-deployed date.

Every 10 days distributions of the particles from 10th June 2003 are shown in Figs. 3(b) to (e). The trajectories of the particle agree with those of drifter except for No. 3 particles. The speed of No. 1 particles is the same as that of No. 1 drifter, while the speed of No. 2 and 3 particles is 10 to 30 days slower than that of No. 2 and 3 drifters.

Above results suggest that the JCOPE model briefly reproduces the flow pattern of the Yellow and East China Seas, although the flow speed may be slower at some places. We consider that the velocity fields of Yellow and East China Seas in 2003 is sufficiently applicable to tracking the jellyfish. In addition, the velocity fields in 2005 ought to be able to be used for the tracer experiments.

3. Tracer experiments

3.1 Descriptions of tracer experiments

To avoid the complexities, two assumptions are introduced for tracking the tracer particles being assumed as the jellyfish. One is that the jellyfish does not migrate vertically. The knowledge about the vertical migration is too little to be adopted into the tracer experiments. Reisen and Isobe (2006)[7], which clarified that wind distributions trigger the population explosion of the jellyfish in the Japan Sea in 2002 and 2003 by the tracer experiments, suggested that there is difference in the behavior of tracer particles between explosion (2002 and 2003) and non-explosion (2000, 2001 and 2004) years at the surface layer only.

The tracer particles are therefore fixed to the sea surface layer (5 m below the sea surface) and follow the horizontal velocity calculated by the JCOPE model in our experiments.

Another is that jellyfish is not preyed by other biota and has no mortality during its transport processes. That is, the number of tracer particles is not changed throughout the experiment. The tracer particles are tracked with the Euler-Lagrange method. The position of tracer particle $X_{t+\Delta t}$ at time $t+\Delta t$ can be calculated by the following equation:

$$X_{t+\Delta t} = X_t + U\Delta t + \frac{1}{2}\left[\frac{\partial U}{\partial t} + (U \cdot \nabla)U\right]\Delta t^2 \qquad (1)$$

where U denotes the horizontal velocity vector at 5 m below the sea surface calculated by the JCOPE model.

3.2 Tracer experiments representing behavior of jellyfish in 2003 and 2005

In starting the tracer experiments, releasing date and position of tracer particles are needed.

Nemopilema nomurai has some stages in its life cycle. Ephyra, one of these stages, is liberated from the sedentary polyp and begins its planktonic life in the ocean, after which the ephyra grows to become a mature jellyfish. From the laboratory rearing experiments, Kawahara et al. (2006)[5] elucidated the liberation occurs between water temperature of 13 and 23°C. The locations where the polyp exists are in coastal areas along China and western Korean Peninsula (Kawahara et al., 2006)[5]. The sea surface temperature in those areas corresponds to the liberal temperature in May and June (Reisen and Isobe, 2006)[7]. In addition, in recent years, young jellyfish has been observed around the offshore of Kunsan and the Changjiang estuary (see Fig. 1) in early May (S. Uye, Hiroshima University, Japan, pers. comm.). Above facts leads us to know that the jellyfish (ephyra) may begin to drift at the two areas in early May. The releasing positions of the tracer particles are therefore set around those two areas on 1st May 2003 and 2005 (Fig. 4). The grey and black particles denote the departure from the offshore of Kunsan and the Changjiang estuary, respectively.

Figures 5 and 6 show the every ten days results of the experiments from 20th July to 8th September 2003 and 2005,

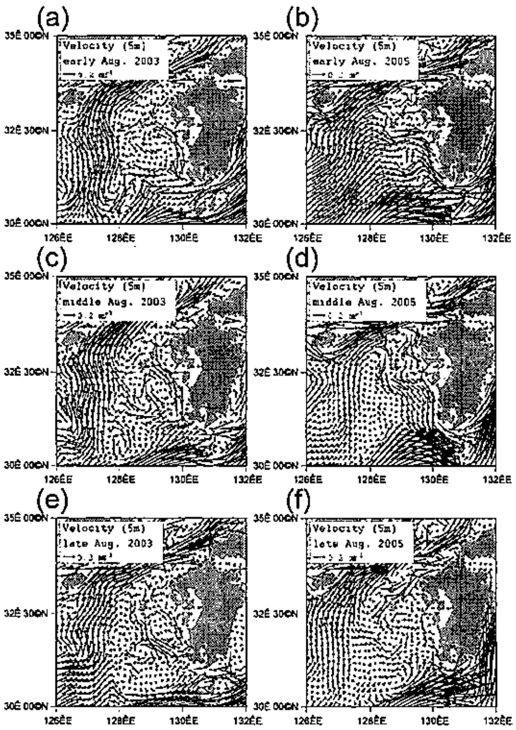

Fig. 7. 5 m depth velocity fields at the western coastal area of Kyushu averaged during 1st to 10th (early), 11th to 20th (middle) and 21st to 31st (late) August in 2003 (a, c, e) and 2005 (b, d, f).

respectively. The date is shown in each panel. We can see that many particles are transported to the Japan Sea in both years. While, a part of the black particles is transported to the Pacific Ocean along the west coast of Kyushu in 2005 (Fig. 6), although the particles accumulate on the western coastal area of Kyushu in 2003 (Fig. 5). According to Fig. 2, the jellyfish appeared in the Pacific Ocean and the Seto Inland Sea in late August to early September 2005. The experiments in 2005 show that the particles are continuously transported to the Pacific Ocean from late July (Fig. 6) and flow into the western part of the Seto Inland Sea in early August (Fig. 6c). The large mass of the particles, however, flows from the western to the southern side of Kyushu in middle August (Fig. 6c, d), after which, many particles close to or flow into the Seto Inland Sea in next ten days (Fig. 6e). In addition, a part of them flows into the eastern part of the Seto Inland Sea in early September (Fig. 6f), just like Fig. 2. So, the experimental results reasonably agree with the fact that the jellyfish appeared in the southern Japanese coastal area of the Pacific Ocean from late August to early September 2005 and did not appear there in summer 2003.

The experiments clarified the transport paths of the jellyfish to the Pacific Ocean in summer 2005, that is, from the Changjiang estuary via the western coastal area of

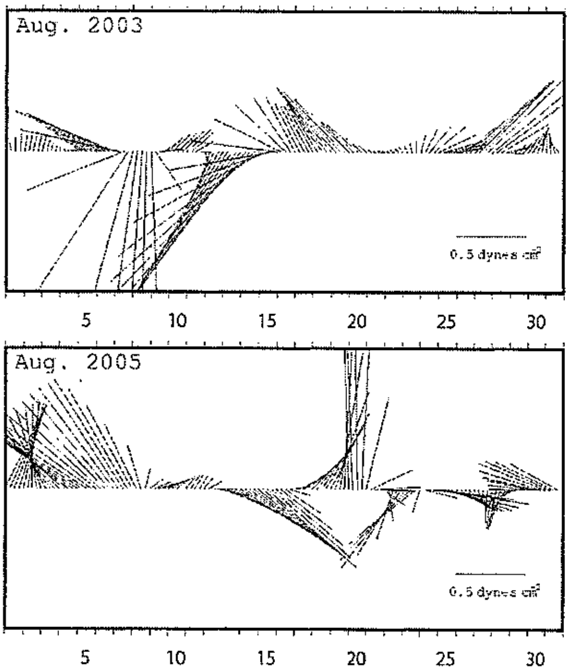

Fig. 8. Stick diagram of 24-hourly box averaged wind stress (6-hourly QuikSCAT) in August 2003 (upper) and 2005 (lower) at the west side of Kyushu (Stn. A, see Fig. 1).

Kyushu. The jellyfish flowed into the Pacific Ocean from western coastal area of Kyushu in middle August.

4. Discussion

In this study, the displacement of the tracer particles depends on only the velocity fields, so that the velocity fields in 2005 induced the appearance of jellyfish in the southern Japanese coastal area of the Pacific Ocean. Figure 7 shows 5 m depth velocity fields at the western coastal area of Kyushu averaged during 1st to 10th (early), 11th to 20th (middle) and 21st to 31st (late) August in 2003 and 2005. Although the cyclonic eddy was prominent throughout August 2003, the broad southward current toward the Pacific Ocean was strong in middle August 2005. That is the reason why the jellyfish was transported to the Pacific Ocean from the western coastal area of Kyushu in middle August 2005, and it accumulated there in 2003.

The flow pattern at the western coastal area of Kyushu is complicated and has a large variability (e.g., Lie et al., 2001[16]; Guo et al., 2003)[11]. Guo et al. (2006)[4] indicated the seasonal variation in the flow pattern in this area by the tracer experiments. It is not easy to clarify the detailed mechanism of the variability in the flow pattern in the western coastal area of Kyushu.

As one possibility, we focus the wind stress. The wind stress is one of the most important factors for the surface

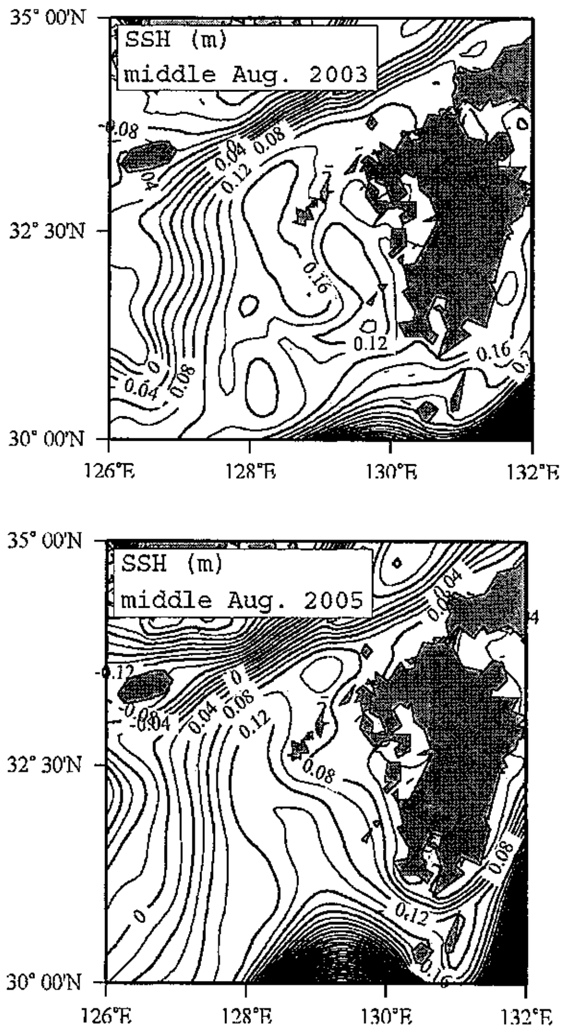

Fig. 9. Sea surface height at the western coastal area of Kyushu in middle August 2003 (left) and 2005

current. Figure 8 shows the time series of 24-hourly box averaged wind stress (6-hourly QuikSCAT) in August 2003 and 2005 at the west side of Kyushu (Stn. A, see Fig. 1). The northwesterly and southwesterly winds were strong in middle August 2005, that is, the winds always have a westerly component for the period. While, the easterly component was dominant in 2003. there was no westerly component in middle August 2003. The Ekman flow induced by those winds therefore may lead the southward current in 2005.

Figure 9 shows the sea surface height in middle August 2003 and 2005. The sea surface gradient due to the landward wind strees suggests the existence of the topographic trapped current toward the Pacific Ocean at the western coastal area of Kyushu in 2005. The broad southward current may consist of those two flows induced by the westerly component of the wind stress.

Figure 10 shows velocity fields around the southern Japanese coastal area of the Pacific Ocean averaged during

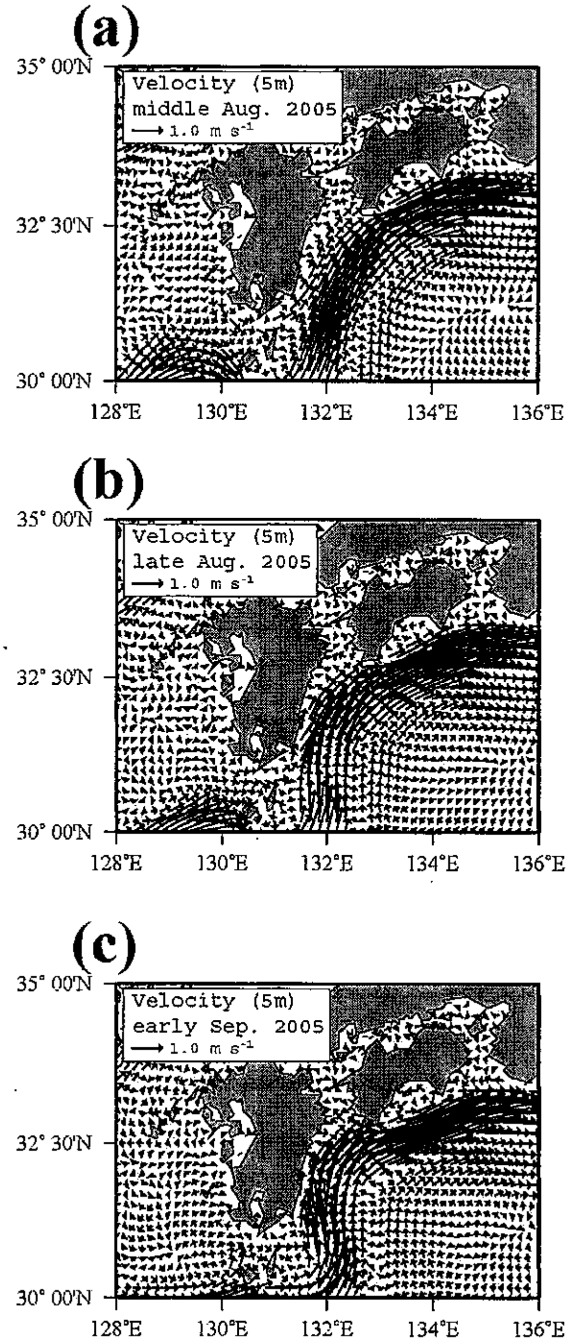

Fig. 10. Velocity fields around the southern Japanese coastal area of the Pacific Ocean averaged during 11th to 20th (middle), 21st to 31st (late) August and 1st to 10th (early) September in 2005.

11th to 20th (middle), 21st to 31st (late) August and 1st to 10th (early) September in 2005. We can see that the Kuroshio took a near-shore path in August to September 2005. So, the jellyfish, which was transported to the Pacific Ocean in middle August 2005, moved toward the north along the east coast of Kyushu and flowed into the Seto Inland Sea efficiently.

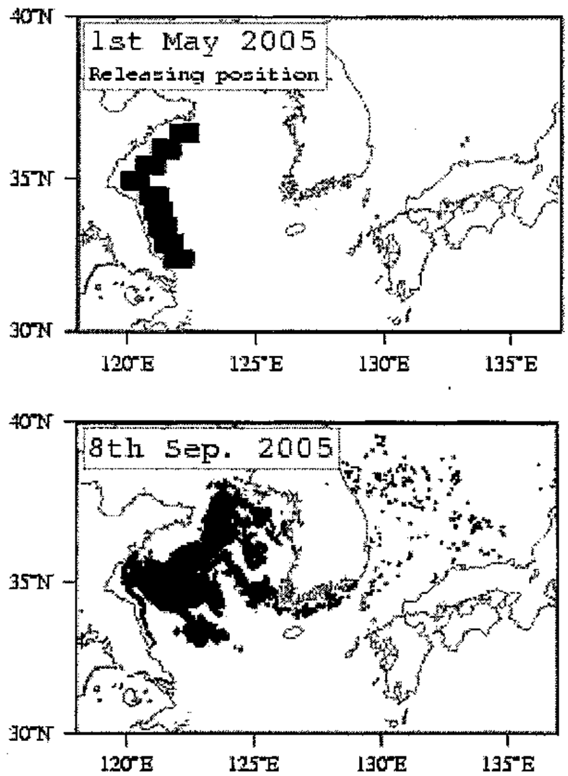

Fig. 11. As the previous tracer experiments except for releasing position. Upper panel shows the releasing position on 1st May 2005. Lower one shows the distribution of particles on 8th September 2005

5. Summary

Numerically-tracking the tracer particles revealed the transport path of the giant jellyfish appeared in the southern Japanese coastal area of the Pacific Ocean in summer 2005. The transport path was from the Changjiang estuary (East China Sea) to the Pacific Ocean via the western coastal area of Kyushu. The broad southward current at the western coastal area of Kyushu transported the jellyfish to the Pacific Ocean in middle August 2005. This current might be induced by the wind which had a westerly component during this period. And then, the jellyfish flowed toward the north along the east coast of Kyushu and efficiently flowed into the Seto Inland Sea, because the Kuroshio took a near-shore path.

In above experiments, the particles were released on 1st May. In reality, the release of jellyfish (ephyra) seems to occur continuously around early May. So, additional tracer experiments starting on 21st April, 11th and 21st May were conducted. The distributions of the particles in summer in these experiments were almost the same as that in above experiments (not shown).

The two releasing positions, offshore of Kunsan and the Changjiang estuary, are decided based on the personal communication from Prof. S. Uye. It is conceivable that liberation of the jellyfish also occurs at the other areas. So, the same tracer experiment as previous experiments but for the releasing position of the northern coastal area of the Changjiang estuary (upper panel of Fig. 11) was carried out. The releasing date is 1st May 2005. The lower panel of Fig. 11 shows the result on 8th September. We can see that most particles remain in the Yellow Sea and the particle is not transported to the Pacific Ocean. This result supports the calculation result that the jellyfish appeared in the southern Japanese coastal area of the Pacific Ocean originated from the Changjiang estuary.

From the sighting report shown in Fig. 2, the jellyfish was not sighted in coastal area of southern Kyushu in 2005. The results of our study seems to be inconsistent with the report. The sighting information itself, however, was not provided from each prefecture in the southern Kyushu (JSNFRI web site). So, the jelly fish should exist in the area in reality as suggested by this study.

Reisen and Isobe (2006) [7] included the random walk and tide-induced residual current into their experiments. These effects are not included in our experiments which qualitatively investigated the behavior of the jellyfish. These effects may have to be included for quantitative arguments.

Acknowledgements

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