4. Overview of the Kuroshio

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1. Overview of the Kuroshio

The Kuroshio is recognized as the western boundary current of the North Pacific subtropical gyre. Along with the Gulf Stream of the North Atlantic, they are two major currents in the Northern Hemisphere. Figure 1 shows the current velocity based on the vector mean of the moving velocities of the surface drifters. The Kuroshio flows almost along the shelf-slope from the coast of Luzon Island near 16°N to the coast of the Boso Peninsula near 35°N. The North Equatorial Current, which flows to the west, is divided into the north and south along the coast of the Philippines. The northward current is called the Kuroshio, and the southward current is called the Mindanao Current. Figure 2 shows the trajectories of the surface drifters that flowed near the coast of Luzon Island on the Kuroshio (black and blue) and the surface drifters that flowed near the coast of Mindanao Island on the Mindanao Current (red). The boundary between the subtropical gyre and tropical gyre exists near 12°N-13°N. Theoretically, the gyre boundary should coincide with the strongest latitude of the trade winds, but the strongest latitude of the annual mean trade winds in the North Pacific is approximately 15°N. The gyre boundary is located to the south.

The Kuroshio, which flows northward along the coast of Luzon Island, reaches the coast of Taiwan, but part of it flows into the South China Sea from the Luzon Strait between Luzon Island and Taiwan. Of the 109 surface drifters that flowed northward along the coast of Luzon Island, 17 flowed into the South China Sea; therefore, the flow was not negligible. Figure 3 shows the trajectories of the surface drifters that flowed near the coast of Taiwan on the Kuroshio. Of the 367 surface drifters, 40 (red) turned eastward on a clockwise warm eddy east of Taiwan. The remaining 327 flowed into the East China Sea between Taiwan and Iriomotejima (island). Four of theses (orange) flowed through the Taiwan Strait into the South China Sea. Of the surface drifters that flowed northeast on the shelf-slope of the East China Sea, 24 (green) left the Kuroshio and headed north on the East China Sea toward the Tsushima Strait. Six flowed into the Sea of Japan through the Tsushima Strait as the Tsushima Warm Current. Other surface drifters flowed into the Pacific Ocean through the Tokara Strait between Amami-oshima (island) and Tanegashima (island), or through the Osumi Strait between Tanegashima and the Osumi Peninsula. There were 23 surface drifters (blue) passing through the Osumi Strait. Thus, the Kuroshio repeatedly branches from the coast of Luzon Island, which is the source, to the east of Kyushu.

The volume transport of the Kuroshio is 25-30 Sv (Sverdrup: $10^6 m^3/s$) in the East China Sea but this increases to 40-50 Sv off Shikoku. It is speculated that this is because the Ryukyu Current flows northeast through the intermediate layer on the Pacific side of the Nansei Islands and joins. The Kuroshio, which flowed eastward or east-northeastward along the shelf-slope south of Shikoku and Honshu, passed between the Izu Islands and separated from Honshu near the Boso Peninsula. The theoretical latitude of separation is 42°N-43°N, which is the peak of westerlies in the North Pacific, but in reality, it separates from the coast near 35°N. This process is called premature separation from the coast, and its mechanism has not yet been elucidated. The premature separation did not occur in a numerical model with a grid spacing of 1-degree latitude/longitude. Hurlburt et al. (1996) reproduced the premature separation for the first time using an eddy-resolved numerical model with a lattice spacing of 1/8-degree latitude and longitude. For this reason, it is estimated that a mesoscale eddy of several tens of kilometers plays an important role in the premature separation from the coast.

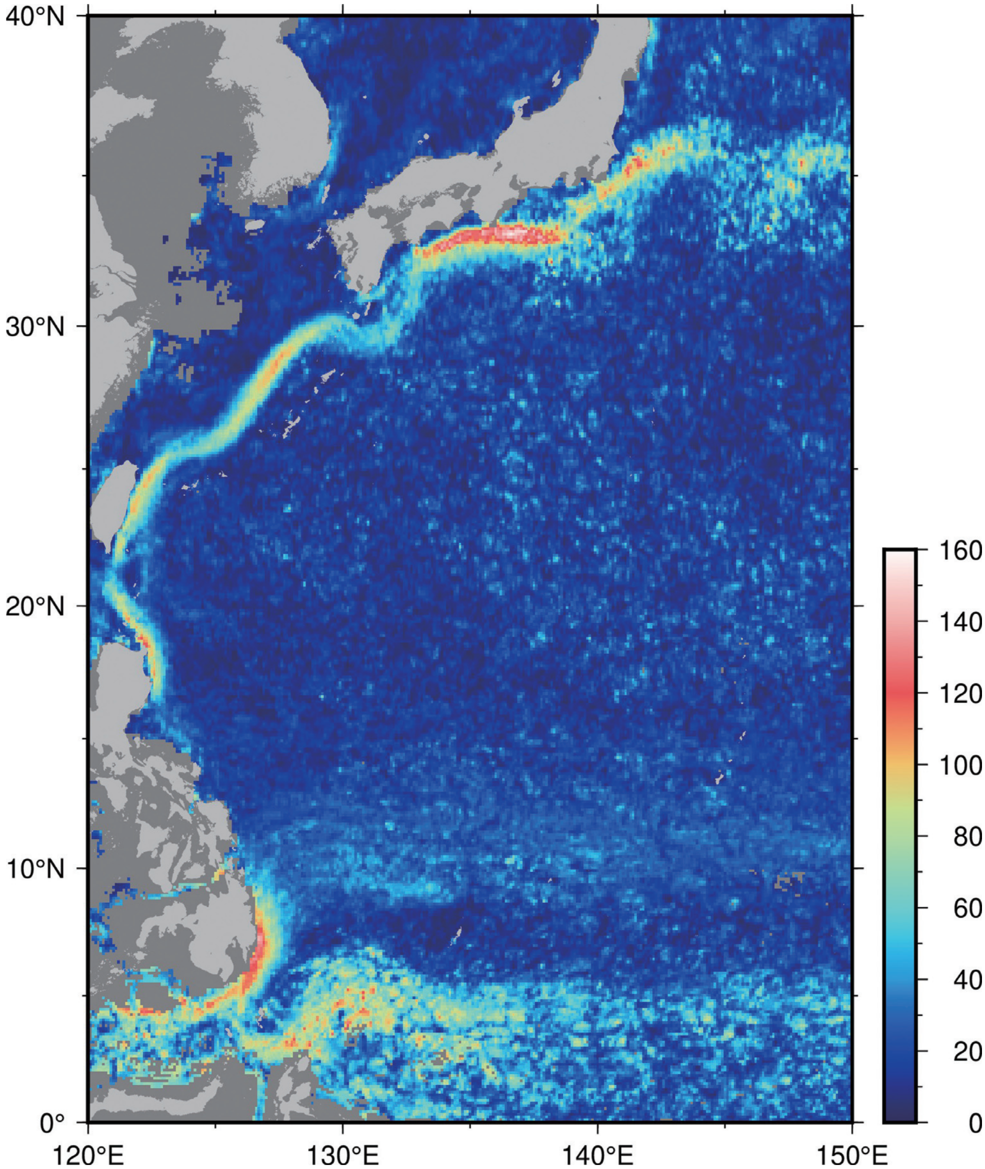

Figure 1 Current velocity (cm/s) based on the vector mean of the moving velocities of the surface drifters.

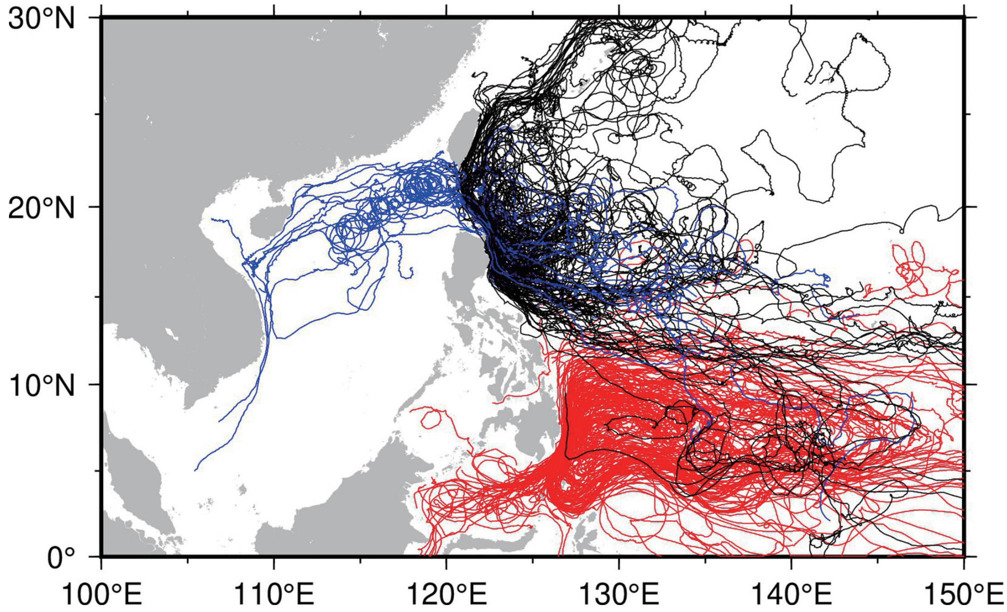

Figure 2 Trajectories of surface drifters passing along the coast of Mindanao Island (red), along the coast of Luzon Island (black), and trajectories of surface drifters flowing from the Luzon Strait into the South China Sea through the coast of Luzon Island (blue).

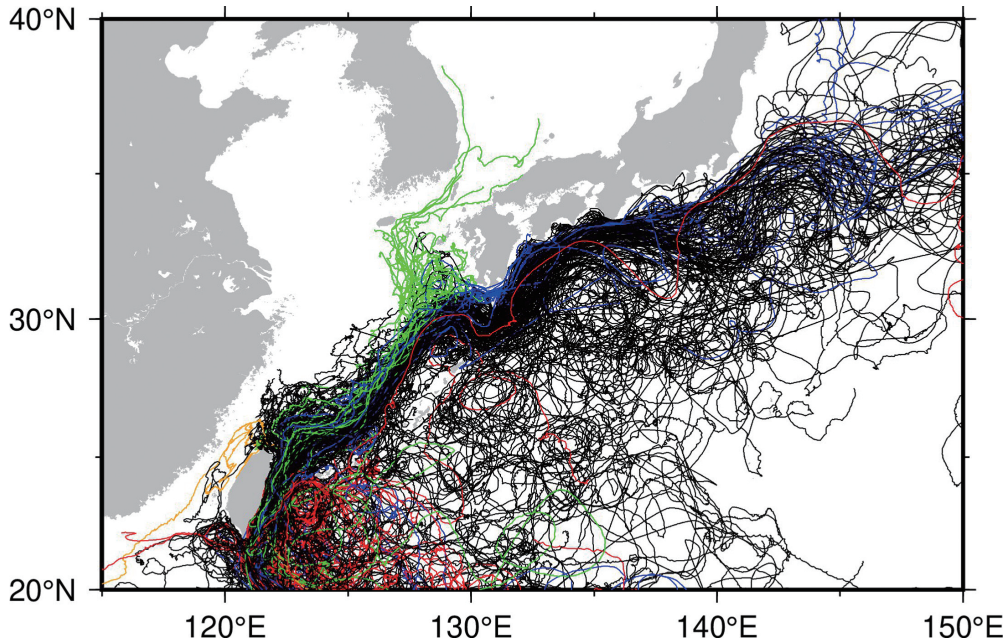

Figure 3 Trajectories of surface drifters passing along the coast of Taiwan. Surface drifters that did not enter the East China Sea through the coast of Taiwan (red). Surface drifters that flowed from the East China Sea through the Taiwan Strait into the South China Sea (orange). Surface drifters that left the Kuroshio and moved northward in the East China Sea (green). Surface drifters that flowed into the Pacific Ocean through the Osumi Strait (blue).

2. Kuroshio Path South of Shikoku and Honshu

Although the Kuroshio path in the East China Sea is almost constant, the Kuroshio path from the Tokara Strait to the Boso Peninsula can vary significantly over a few months. Since the Kuroshio has a great impact on the navigation of ships, the Japan Coast Guard continuously monitors it around Japan and publishes it as the Quick Bulletin of Ocean Conditions (QBOC). There have been publications twice a month since 1960, once a week since April 2001, and daily on weekdays since August 2006. Figure 4 shows the four types of paths of the Kuroshio south of Shikoku and Honshu, according to the QBOC. The Kuroshio that flows into the Pacific Ocean through the Tokara Strait between Amami-oshima (1) and Yakushima (2)/ Tanegashima (3) flows almost along the shelf-slope, away from the shelf-slope near Cape Shionomisaki at the southern end of the Kii Peninsula, and often passes through depths north and south of Mikurajima (5) between Hachijojima (4) and Miyakejima (6) (Figure 4, blue). This path was once known as a straight path. It has been known that the Kuroshio has a period of meandering south away from the shelf-slope in the south of Shikoku and returning to the vicinity of Miyakejima (Figure 4, red). This meander which lasts for one to several years, is called a large meander. Kawabe (1985) named the path that is the same as the straight path until near Cape Shionomisaki and then passes south of Hachijojima as the offshore non-large meander (Figure 4, green). The offshore non-large meander lasts for only a few months at the longest, whereas a straight path can last for more than a year. Yoshida et al. (2014) found that among the offshore non-large meander that passes south of Hachijojima, the path south of 32°N (Figure 4, black) is detached from Cape Shionomisaki as well as the large meander. It is named the large meander east (LME) because the trough of the meander (southernmost point) is further east than the conventional large meander. The conventional large meander that flows south of 32°N and passes north of Hachijojima has been renamed the large meander west (LMW). Simultaneously, the offshore non-large meander that passes south of Hachijojima, which does not flow south of 32°N, was renamed the non-large meander south (NLMS), and the conventional straight path that passes north of Hachijojima, which does not flow south of 32°N, was renamed the non-large meander north (NLMN). Like the NLMS, the LME lasts up to a few months.

There were long-term large meander periods, and the LMW and the LME continued seven times for more than one year for 50 years, 1970-2019 (Figure 5). The longest large meander started in the latter half of July 1975 and continued for four years and nine months and a half until the latter half of April 1980. However, from the latter half of June to the latter half of July 1977, the Kuroshio cut off the meandering part and temporarily became the NLMN path. The seventh long-term large meander period, which started in the fourth week of August 2017, was still ongoing as of February 2022 and is four years and six months long. There are four patterns in the frequency of appearance of the LME in seven long-term large meanders, which rarely appear in the long-term large meanders of 1975-1980 and in the entire period in the long-term large meanders of 1981-1984 and 1999-2001. In the long-term large meander of 1986-1988, 1989-1991, and 2004-2005, the LME rarely appeared in the first half and appeared more often in the second half. In the long-term large meander that began in 2017, many LMEs appeared early and then disappeared.

Until 2006, only three short-term large meanders of more than one month and less than one year had occurred. However, since 2007, ten short-term large meanders have occurred, and the longest short-term large meander has continued for seven months from September 2008 to March 2009. Most of these short-term large meanders are LMEs.

Immediately before the start of the long-term large meander, the small meander that occurred east of

Tanegashima (3) moved eastward to become a large meander (ex. Yoshida, 1961). Figure 6 shows the transition of a small meander when a long-term large meander occurred in 2004. When the small meander first occurred southeast of Tanega-shima (black), the Kuroshio moved away from the eastern shelf-slope of Kyushu. The small meander grows to the east (purple), then the northern part moves eastward (blue > green) and moves away from the shelf-slope in the south of Shikoku. Further eastward, it detaches from Cape Shionomisaki (orange), and this time, the upstream part attaches to the eastern shelf-slope of Kyushu, and the LMW is completed (red). A small meander that causes detachment from Cape Shionomisaki is a necessary condition for the formation of a long-term large meander.

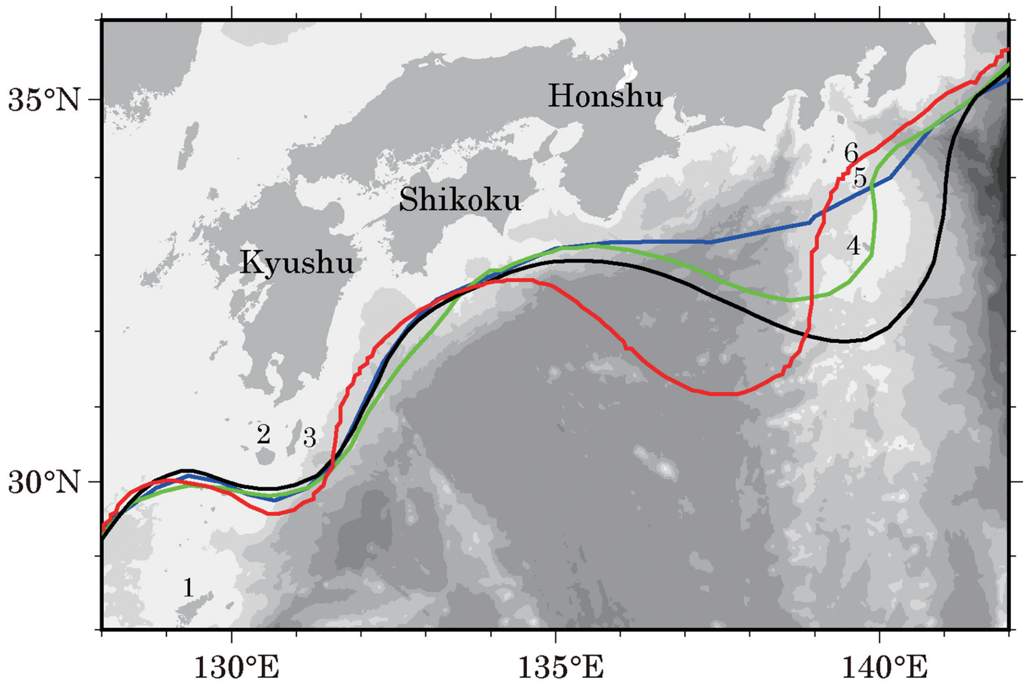

Figure 4 Four typical paths of the Kuroshio according to the Quick Bulletin of Ocean Conditions. Non-large meander north (NLMN: blue), non-large meander south (NLMS: green), large meander east (LME: black), large meander west (LMW: red). The numbers represent the islands. Amami-oshima (1), Yakushima (2), Tanegashima (3), Hachijojima (4), Mikurajima (5), Miyakejima (6).

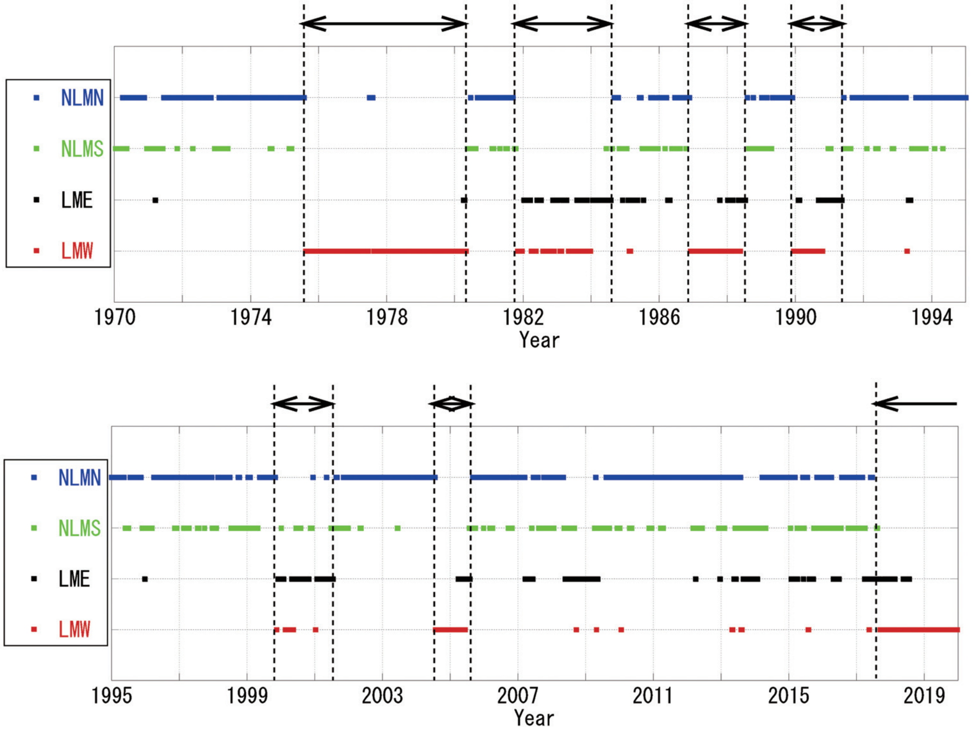

Figure 5 The type of the Kuroshio path 1970-2019. Both arrows indicate a long-term large meander period.

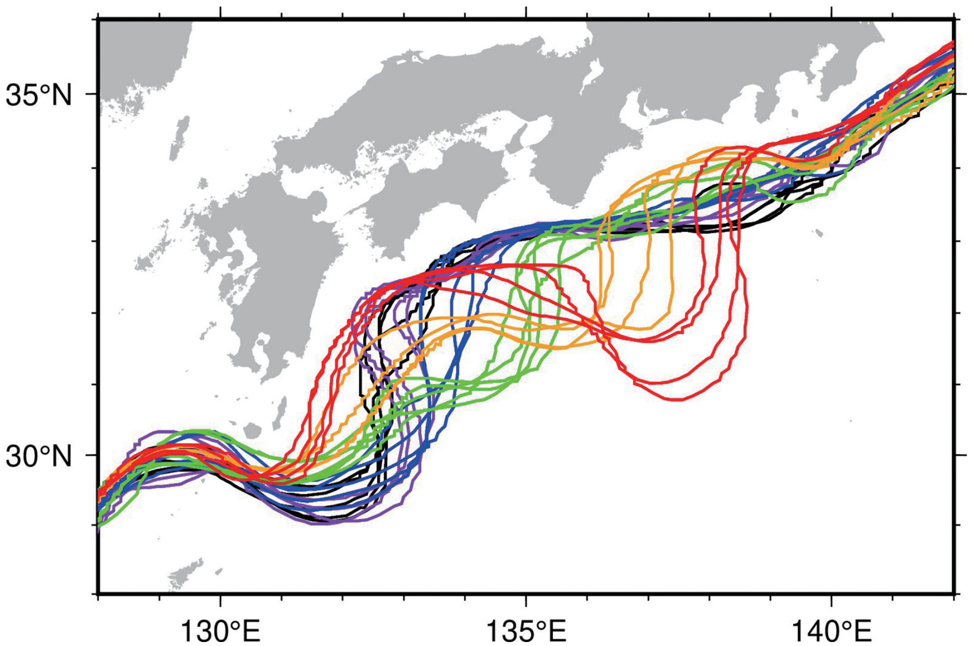

Figure 6 The Kuroshio paths from the first week of February to the third week of August 2004 according to the Quick Bulletin of Ocean Conditions. The time series is black > purple > blue > green > orange > red.

References

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