Some Properties of the Warm Eddies Generated in the Confluence Zone of the Kuroshio and Oyashio Currents

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ABSTRACT

The size, movement and maximum core temperature of warm eddies off Japan are discussed on the basis of 154 examples of warm eddies from various sources during the 17 year period 1957–73, inclusive. The warm eddies generated in the confluence zone of the Kuroshio and the Oyashio Currents are distributed in a rather restricted area of the sea and have an elliptical form with an average diameter of about 70 n mi. The eddies usually move to north or northeast with speeds of 0.3–2.0 n mi day^{-1} along the contours of the continental slope. As the eddies move north their size and the maximum core temperature gradually decrease.

1. Introduction

In the region of the Kuroshio current east of Japan, large-scale anticyclonic eddies are generated on its left side and cyclonic eddies on its right. The eddies form in the zone of confluence between the Kuroshio and the Oyashio. The anticyclonic eddies have warm cores which are considered to represent water separated from the protruding ridges of the meandering main stream axis.

Kawai (1955), Sugiura (1955a, b), Masuzawa (1955a, b) and Ichiye (1955) have discussed several characteristic features of Kuroshio anticyclonic eddies, after Iselin (1948) first pointed out the presence in the Slope water of an anticyclonic eddy associated with the Gulf Stream. Afterward, Kuroda (1968) focused his attention on the northernmost warm eddies which he named the warm eddies off Kushiro. Kawai (1955) and Yamamoto and Wakaki (1970)

TABLE 1. Reference sources.

The reference sources	Volume, number, date, and pages	Institutions
The ten-day marine report	Nos. 392, 418, 426, 438, 410, 445, 571, 611, 599, 613, 634, 644, 649, 662, 680, 697, 712, 716, 722, 682, 725, 727, 697, 710, 782, 785, 788, 791, 815, 818, 719, 932, 868, 971, 965	Japan Meteorological Agency
Results of marine meteorological and oceanographical observations	Nos. 27—P. 17, 28—P. 26, 29—P. 17, 30—P. 30, 31—P. 32, 33—P. 23, 34—P. 25, 35—P. 23, 38—P. 29, 39—P. 14	Japan Meteorological Agency
Results of oceanographical observations	1959, Vol. 1, Figs. 2–4; 1959, Vol. 2, Figs. 2–4; 1960, P. 4, P. 5, P. 6	Tohoku Regional Fisheries Research Laboratory
Reports of oceanic conditions in the northwestern sea area of the northern North Pacific Ocean	1970—June, Oct., Nov.–Dec., 1971—June, July, Aug., Sep., 1972—June, 1973—June	Tohoku Regional Fisheries Research Laboratory
State of the adjacent seas of Japan	1965—May, 1967—April–June, 1968—Feb.–Mar., 1969—July–Sep., Oct.–Nov., 1971—April–May, Oct.–Dec., Feb.–Mar., 1972–April–June	Maritime Safety Agency
Reports of oceanic conditions in the northern North Pacific Ocean	Vol. 6, No. 2—P. 12, Vol. 11, No. 1—P. 11, No. 4—P. 5	Hakodate Marine Observatory
Reports of oceanic conditions in the Tohoku sea district	1967—Sep., Oct., Feb., Aug., July 1968—July, 1972—Feb., May, June, July, Sep., Oct.	Institutions of the Tohoku Sea District
Proceedings of the interagency congress of the Tohoku sea district	1970—P. 26, P. 28, P. 29, P. 30, P. 31, P. 32, P. 33, P. 34, P. 35. 1971—P. 2, P. 6, P. 7, P. 8, P. 9, P. 10, P. 4, P. 11	Institutions of the Tohoku Sea District
Reports of oceanic and fisheries conditions	1972—Nos. 14 and 19	Kushiro Fisheries Experimental Stations
Reports of oceanic and fisheries conditions	Nos. 20 and 73	Fisheries Information Service Center

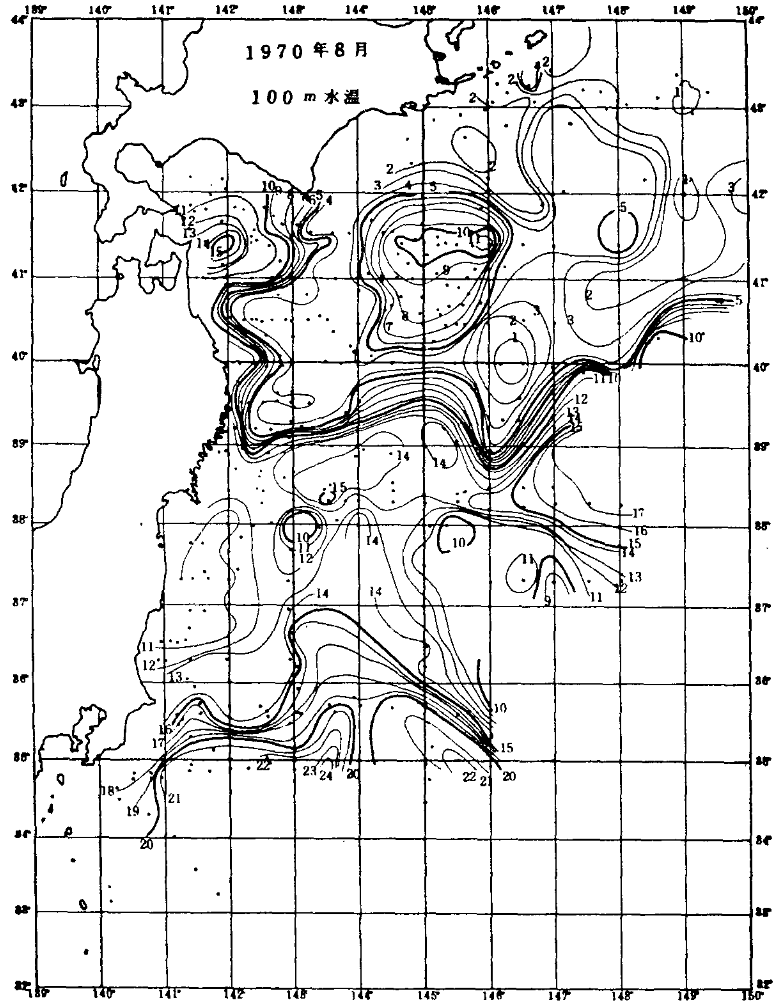

FIG. 1. Isotherms (°C) at a depth of 100 m during August 1970 [from the *Proceeding of the 21st Interagency Congress of Tohoku Sea District* (1971)].

indicated the possibility of energy supply in the surface layer from the temperature increase during the summer, while Thompson and Gotthardt (1971) described the life history of interception by the Gulf Stream. Saunders (1971) and Gotthardt (1972, 1973) presented detailed descriptions of the Gulf Stream anticyclonic eddies while Kitano (1974) described the changes observed in a Kuroshio anticyclonic eddy.

Several questions arise from the discussions mentioned above. Is there an area in which the warm eddies are most frequently generated from the Kuroshio? Can we find the mode or the range in the size distribution of the warm eddies? What is the direction and the speed of movement of the eddies? Is there any change of the maximum core temperature during the movement? Does the maximum core temperature change with latitude? Generally, such questions are very difficult to answer because of the need for many cases of warm eddies actually generated in the confluence zone.

2. The approach

Fortunately, many research vessels operated by several institutions of the Japanese Government have cooperatively taken oceanographic observations in a grid over the sea area adjacent to the Japanese Islands almost simultaneously for 17 years from 1957 through 1973. The institutions have published the observed data as well as isotherm charts at 100 m. Table 1 lists the sources of the isotherm charts. The charts provide 154 examples of typical warm eddies, which were clearly identified.

Fig. 1 shows isotherms at 100 m depth which suggest the presence of an anticyclonic eddy. Fig. 2 shows GEK observations from the same period which

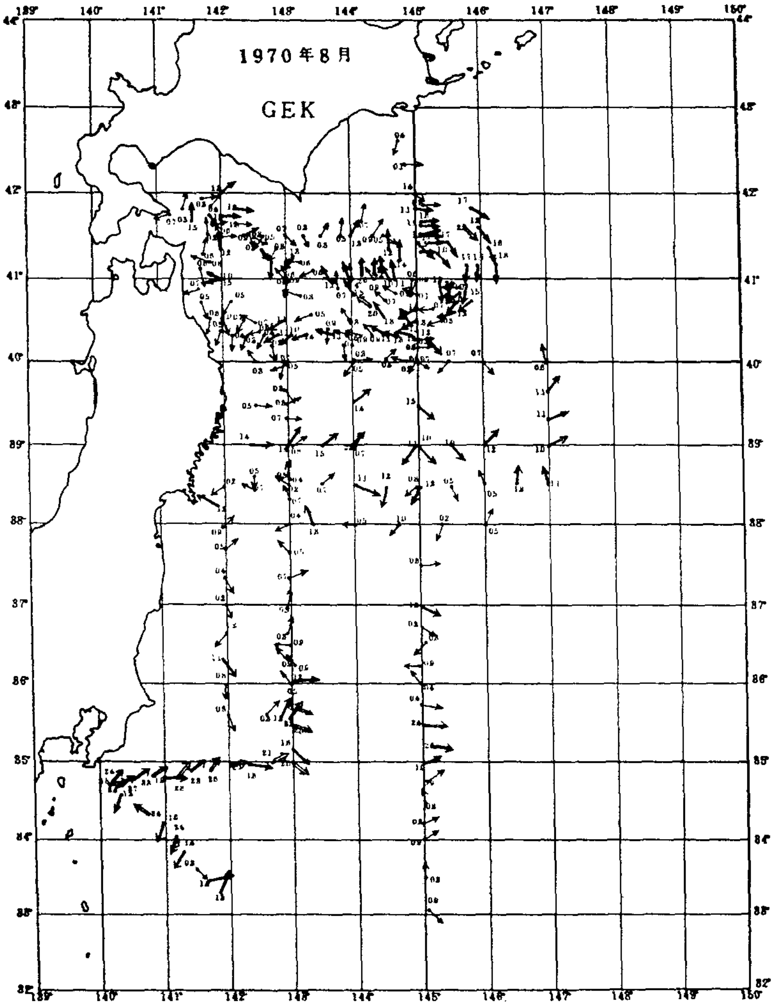

Fig. 2. GEK chart during August 1970 [from the *Proceeding of the 21st Inter-agency Congress Tohoku Sea District* (1971)].

unquestionably indicate the eddy. The anticyclonic eddy was found just north of the Oyashio Front, the sharp thermal boundary between 39 and 40N, and centered at about 145E, 41N. The eddy was nearly circular; its mean diameter was 100 n mi and its maximum core temperature 11°C. Fig. 3 shows schematically how a warm eddy may be generated. In the first stage, an anticyclonic meander of the Kuroshio protrudes to the north. In the next stage, the cold water on both sides of the meander pinches the warm eddy off from the main stream. In the final stage the occluded warm water is displaced northward away from the Kuroshio. The warm eddies were identified by the presence at 100 m depth of more than two closed isotherms at 1°C intervals. Closed isotherms based on only two observation stations were not considered to be representative eddies in the present analysis. Even though the above-mentioned conditions were satisfied, several questionable eddies were not adopted based upon the configuration of the isotherms. Two eddies were adopted on the basis of only one station in the northern sea area.

The eddies are of more or less elliptical form. The large and small diameters of the warm eddies are measured on the basis of the outermost, closed isotherm. The mean diameter is calculated from the arithmetical mean value of the large and small diameters. The intersection of the large and small diameters is taken as the position of the eddy.

3. Geographical distribution

Fig. 4 shows the geographical distribution of the warm eddies. Looking over the distribution chart, we first notice that few eddies develop in the confluence zone either very far off shore or very near shore.

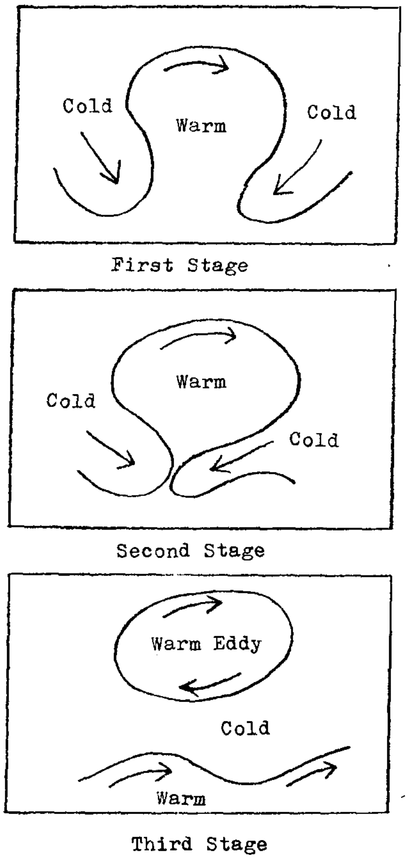

FIG. 3. Schematic chart for the generation mechanism of a warm eddy.

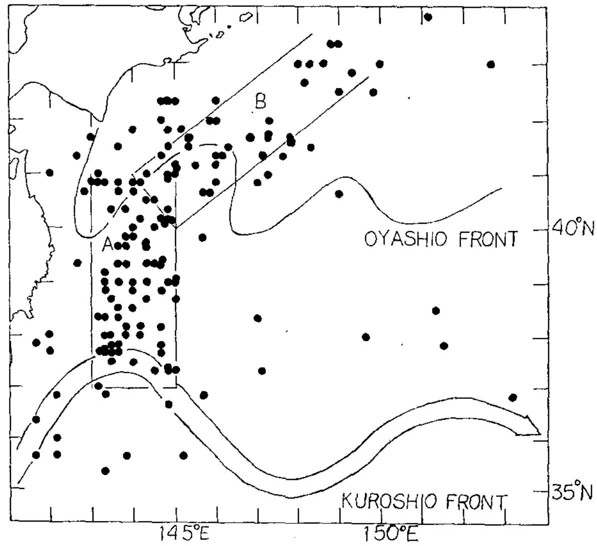

FIG. 4. Geographical distribution of warm eddies generated in the confluence zone during the 17 years from 1957 to 1973. The dots show the sites of the warm eddies.

Eddies are most frequently found in the region, designated by A, from 37 to 41N and 143 to 145E, and in the region designated by B, which may be considered as a continuation to the northeast of region A. Region A is centered ~100 mi off northern Honshu, lying roughly between the 2000 and 7000 m isobaths.

There are two remarkable thermal fronts at subsurface depths in the Tohoku area; the southern, called the Kuroshio Front, and the northern, the

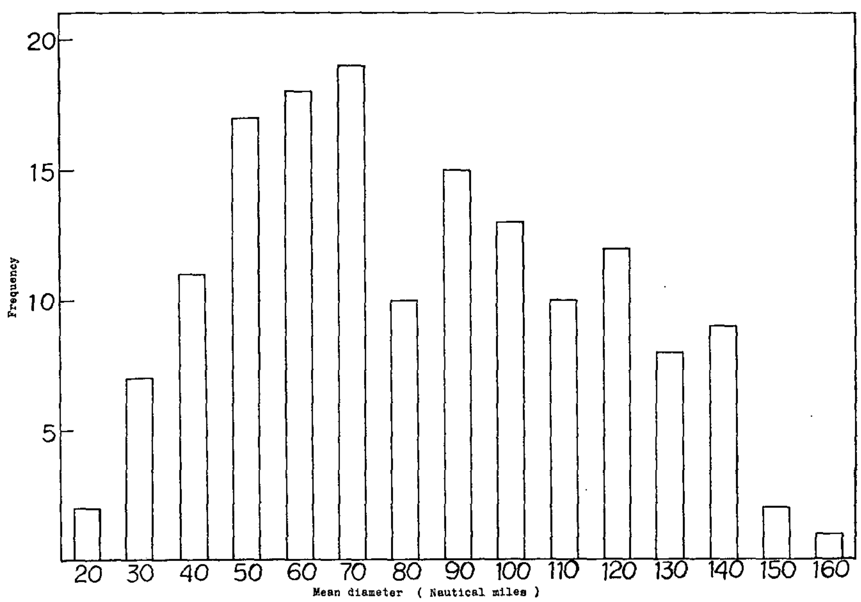

FIG. 5. Distribution of the mean eddy diameters.

Oyashio Front according to Kawai (1973). The transition area is the intermediate sea area between the fronts.

The region A corresponds to a northward corridor from the first ridge of the meandering Kuroshio Front in the transition area between the mean positions of the Kuroshio and Oyashio Fronts. This fact suggests that the eddies form from the first ridge of the meandering main stream axis and then move northward. The schematic mean position of the Kuroshio Front in Fig. 4 is determined from the figures presented by Kawai (1955), Masuzawa (1955a) and Uda (1964). The site of Oyashio Front in Fig. 4 is indicated after the sources quoted in Table 1. The first trough of the Oyashio Front is found along the meridional plane of 143E; as a result, the first ridge in the sea area is found between 144 and 146E. These sites are not fixed, but the locations given represent normal values.

Region B is elongated to the northeast from 40°30′N, 144°30′E with a width of about 80 mi. The region lies about 120 mi off the western coast of the Hokkaido Islands between the 5000 and 7000 m isobaths. The northeastward elongation of region B suggests a possible northeastward movement of the warm eddies separated from the first ridge, or possibly the second ridge, of the Oyashio Front.

Several warm eddies are scattered over the wide zone between the Oyashio and the Kuroshio Fronts. These warm eddies must have been separated from the second or third ridges of the meandering Kuroshio Front. These geographical distributions are in agreement with the results proposed by Sugiura (1955a, b), Kawai (1955) and Kuroda (1968).

4. Size and shape

The frequency distribution for the mean diameter of warm eddies is presented in Fig. 5. The mean diameters range widely, from 20 to 160 n mi, but are mostly found in the more restricted range of 50 and 120 n mi. The upper limit of about 160 n mi seems real. However, eddies smaller than 20 n mi in diameter are probably not observable by the present network stations which are spaced usually at intervals ⩾ 10 n mi. The mode of the mean eddy diameter is 70 n mi. The frequency distribution of the ratio of the large to the small diameter is presented in Fig. 6. As already noted the warm eddies are generally not circular but are mostly elliptical. The ratio's distribution is characterized by a pronounced skewness which is maintained by a still unknown and complicated energy balance existing among the different water masses. The ratio lies mostly within the range from 1.0 to 2.0,

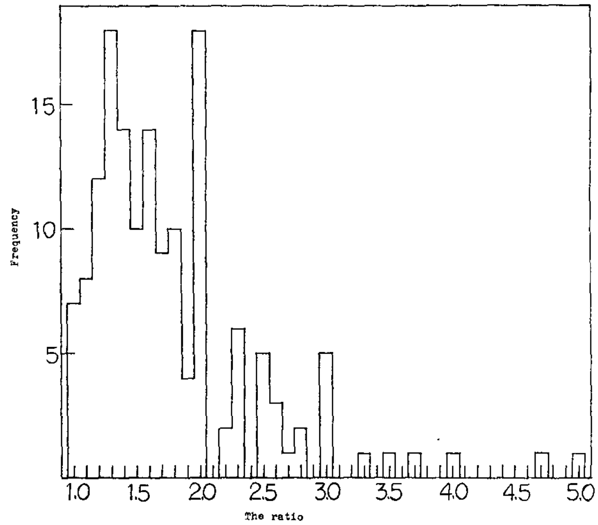

FIG. 6. The frequency distribution of the ratio of the major to the minor axial dimensions.

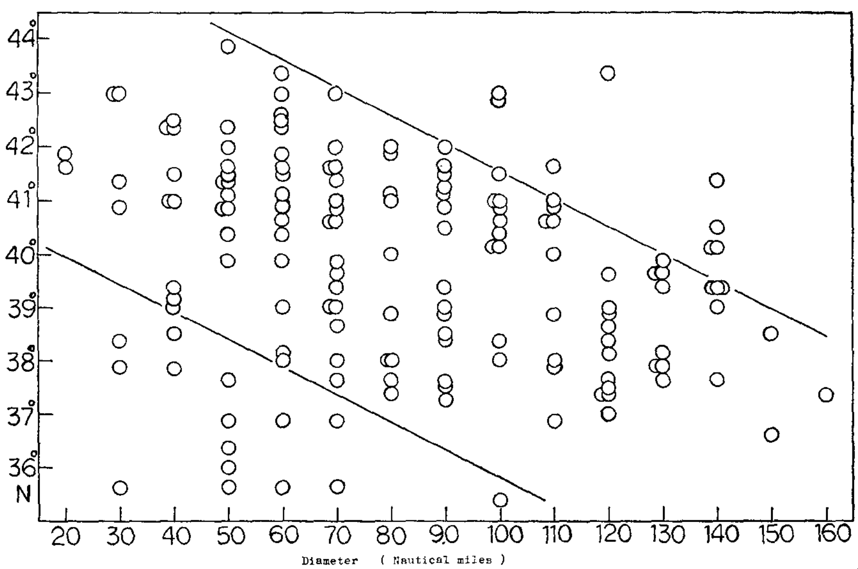

FIG. 7. Eddy diameter vs latitude.

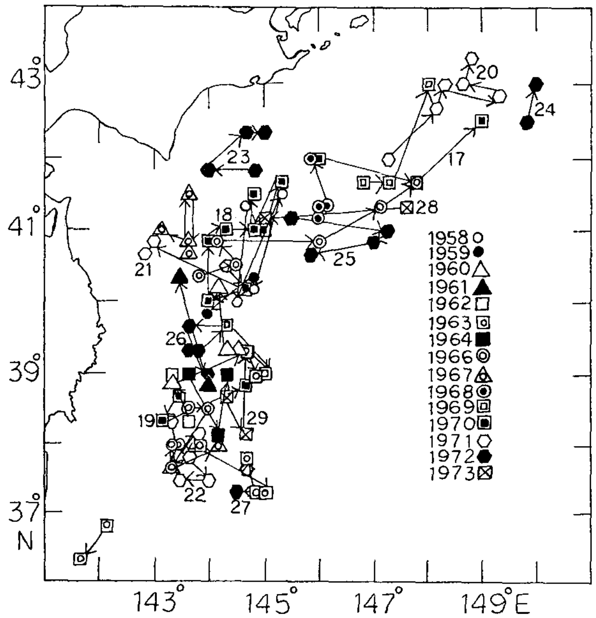

FIG. 8. The movement of warm eddies (indicated by the arrows).

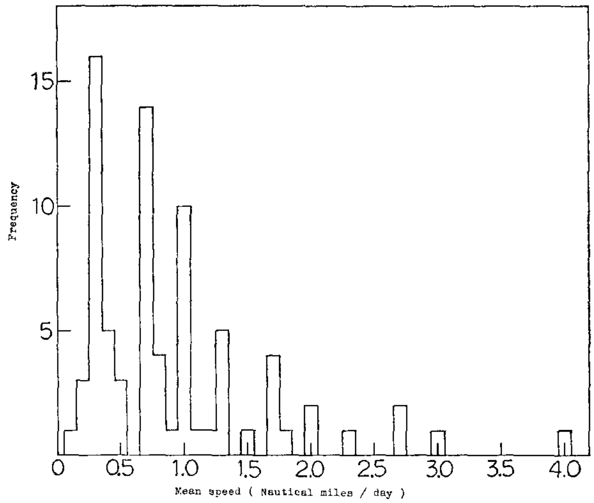

FIG. 9. Mean speed of the warm eddies.

with a large proportion between 1.3 and 1.6. Warm eddies in the latter range can be designated as the "common type." The primary mode is found at a ratio of about 1.3. However, a few eddies have been found with ratios in the range from 3.3 to 5.0. Such an extremely modified warm eddy may represent an unstable state; that is, the eddy may easily disintegrate into several separated smaller eddies (Saunders, 1973). The tendency of the diameter of an eddy to change with latitude is indicated in Fig. 7. With few exceptions, the diameter generally tends to decrease as the eddy moves northward. This decrease may result from the disintegration of large eddies or from the diffusion of kinetic and internal energy during the northward displacement. All of the eddies in the upper right corner outside of the envelope are found offshore of 144°00′E, but 80% of the eddies in the lower left corner outside of the envelope are found inshore of 144°00′E. Suda (1936) mentioned the possible decrease in the size of such eddies as they move to the north.

5. Movement

From the observations over the period 1958 to 1973, it was possible to trace certain eddies for periods of several months. Twenty-nine such eddies for different years are identified in Fig. 8; several eddies in certain years could be traced. The movement of each eddy is indicated by arrows. The numbers in the figure are for identification.

The warm eddies of region A show a strong tendency to move northward, but some moved south or westward. On entering region B, the eddies moved northeastward.

The mean speed of the eddies, calculated from the routes shown in Fig. 8, has the frequency distribution shown in Fig. 9. The eddies move mostly with a mean

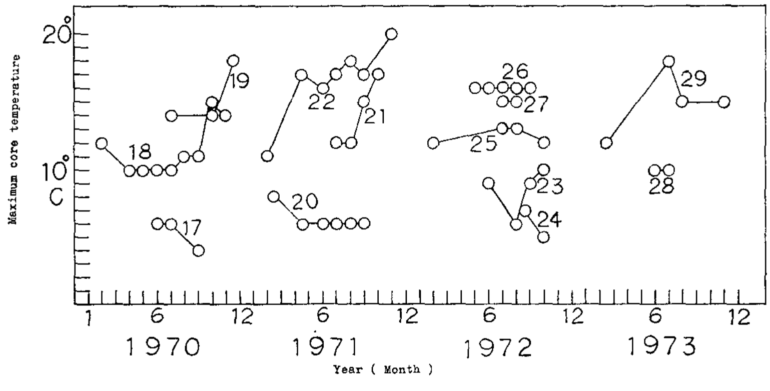

FIG. 10. The changes of the maximum core temperature of the warm eddies during the four years from 1970 through 1973.

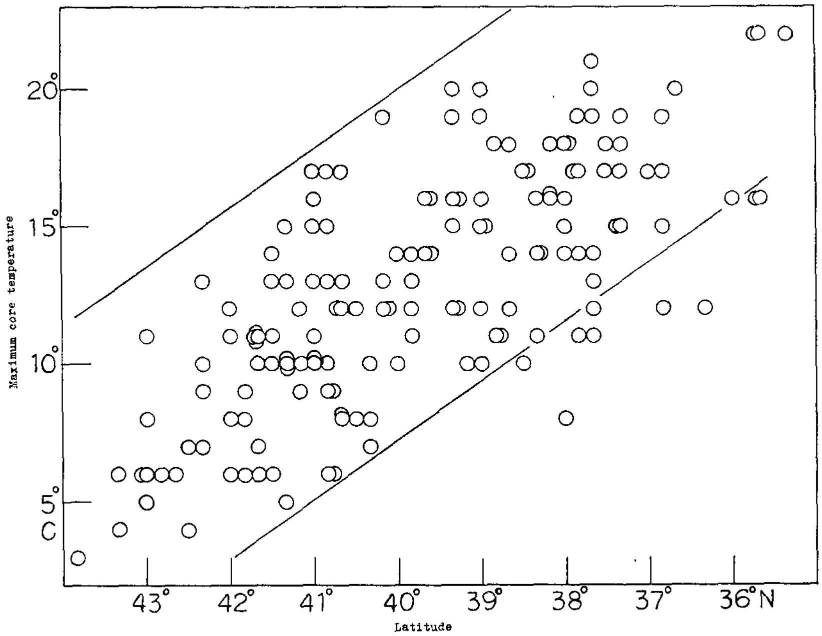

FIG. 11. The maximum core temperature versus latitude.

speed between 0.3 and 2.0 n mi day^{-1} with a mode of roughly 0.5 n mi day^{-1}.

6. The maximum core temperature

The maximum core temperature (MCT) of the warm eddies is defined as the temperature of the innermost closed isotherm in a thermal field represented by isotherms at intervals of 1°C. Fig. 10 shows the changes of the maximum core temperature for 13 warm eddies which can be clearly identified during the four years from 1970 through 1973. The movement of these eddies is shown in Fig. 8. Each eddy is identified by the same number in both Figs. 8 and 10.

The seasonal changes in the MCT of the eddies can be grouped into three categories. Category A, which includes eddies 19, 22, 26, 27 and 29, is characterized by the highest maximum core temperature of about 17°C. These warm eddies were apparently generated at the first ridge of the Kuroshio main stream axis. The maximum core temperature for eddy 26 is remarkably constant during five months between May and September. The rapid increase of MCT in the cases of eddies 22 and 29 may have resulted from interception with the warm water mass.

Category B, including eddies 18, 21 and 25, is characterized by somewhat lower MCT's, between 10 and 17°C. Most encounters with these eddies occurred farther north than those of category A. The lower temperature of the eddies may represent mixing with the cold Oyashio water. The rapid increase of MCT for eddies 18 and 21 may also have resulted from the interception of warm water masses.

The warm eddies 17, 20, 23, 24 and 28 belong to category C which is characterized by the coldest MCT with values ranging between 4 and 10°C. These eddies were observed farthest north (Fig. 8), in region B. The MCT of eddy 20 remained almost constant.

The duration of the warm eddies ranged from 2 to 10 months. A clear correlation among the eddies belonging to the same category is not indicated because of the absence of data during November, December and January when the most intense overturning is going on.

The general tendency of the latitudinal changes of the MCT is indicated in Fig. 11. The MCT of the warm eddies shows a gradual decrease following northward displacement.

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REFERENCES

Gotthardt, G. A., 1972: Anticyclonic and cyclonic eddies observed in the North Atlantic research area during 1971. *Trans. Amer. Geophys. Union*, **53**, 393 (abstract).

——, 1973: Observed formation of a Gulf Stream anticyclonic eddy. *J. Phys. Oceanogr.*, **3**, 237–238.

Ichiye T., 1955: On the behavior of the vortex in the polar front region. *Oceanogr. Mag.*, **7**, 115–132.

Iselin, C. O'D., 1948: Some recent developments in the study of the Gulf Stream. *J. Marine Res.*, **7**, 317–329.

Kawai H., 1955: On the polar frontal zone and its fluctuation in the waters to the northeast of Japan. *Bull. Tohoku Reg. Fish. Res. Lab.*, **4**, 1–46.

——, 1973: Hydrography of the Kuroshio Extension. *Kuroshio, Its Physical Aspects*, H. Stommel and K. Yoshida, Eds., University of Tokyo Press, 235–341.

Kitano K., 1956: Note on the eddies generated around the turbulent jet flow. *J. Oceanogr. Soc. Japan.*, **12**, 121–124.

——, 1974: Note on the Kuroshio anticyclonic eddy. *J. Phys. Oceanogr.*, 4, 670–672.

Kuroda T., 1968: The warm water mass off Kushiro with special reference to recent conditions. *Bull. Jap. Soc. Fish. Oceanogr.*, **12**, 42–47.

Masuzawa J., 1955a: An outline of the Kuroshio in the eastern sea of Japan. *Oceanogr. Mag.*, **7**, 29–48.

——, 1955b: A note on the Kuroshio farther to the east of Japan. *Oceanogr. Mag.*, **7**, 97–104.

Saunders, P. M., 1971: Anticyclonic eddies from shoreward meanders of the Gulf Stream. *Deep Sea Res.*, **18**, 1207–1219.

——, 1973: The instability of a baroclinic vortex. *J. Phys. Oceanogr.*, **3**, 61–65.

Suda, K., 1936: On the dissipation of energy in the density. *Geophys. Mag.* **10**, 131–243.

Sugiura J., 1955a: On the transport in the eastern sea of Honshu (Part 1). *Oceanogr. Mag.*, **6**, 153–163.

——, 1955b: On the transport in the eastern sea of Honshu (Part 2). *Oceanogr. Mag.*, **7**, 21–48.

Thompson, B. J., and G. A. Gotthardt, 1971: Life cycle of a North Atlantic anticyclonic eddy. *Trans. Amer. Geophys. Union*, **52**, 241 (abstract).

Uda M., 1964: On the nature of the Kuroshio, its origin and meanders. *Studies on Oceanography*, University of Tokyo Press, 89–107.

Yamamoto K., and S. Wakaki, 1970: The warm eddy off Kushiro. *Proceedings of the 19th Interagency Congress Tohoku Sea District*, Interagency Congress, Tohoku Sea District.