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Mesoscale eddies in the Japan Sea*

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Abstract: The isotherms at 100 m depth in the Japan Sea in May and June, 1987 show isolated warm and cold eddies of 30 km to 160 km diameters and two to three fronts with meanders of wavelength 100 to 400 km. The climatological data from 1900 to 1970's indicate that the surface currents determined with GEK have best correlation with the temperature gradients at 100 m compared with those at the surface and at 200 m. These meanders and eddies may be explained as instabilities in mid-ocean thin jets. Field experiment and numerical modeling plans are proposed for obtaining data sets of temperature fields with AXBT's for two months and corresponding eddy resolving numerical models of the Japan Sea.

1. Introduction

In "The Ocean" (SVERDRUP *et al.*, 1942), the Japan Sea was described as "comparable to the Arctic Mediteranean on a small scale." However, it is more appropriate to explain it as a miniature ocean, since it possesses a western boundary current as the East Korean Warm Current, a mid-ocean jet as one or two branches of the Tsushima Current, a polar front as a northern boundary of the Tsushima Current and the deep water formation in the northern area (ICHIYE, 1984).

Although some mean pictures of the circulation of the Japan Sea are neat and well-defined, quasi-synoptic ones are not, as discussed below. We do not try to analyze or explain rather chaotic features of these pictures but to attract attention to them and will propose some experimental and modeling programs to understand basic dynamics that are manifested in them.

2. Isotherms at 100 m depth

Figures 1 and 2 show the isotherms at 100 m depth for May and June, 1987 from Ten Day Marine Report of Japan Meteorological Agency. These charts are not unusual but common. They show complicated features of fronts and isolated cold and warm eddies with diameters ranging from 30 km to 160 km. We also can see fronts or steep gradients in isotherms and their meanderings on both charts. In fact there may be two or three fronts, that is, nearshore one, offshore one and the one further north, each with different meander wavelengths. Table 1 lists statistics on eddy diameters and wavelengths of these meanderings, though these numbers are only approximate because of crude nature of methods of their estimation.

It is noted that some meander patterns, particularly cold water intrusions southward from the northern front and warm water intrusions northward from the southern front can be traced from May to June as indicated by numbers in Figs. 1 and 2. Also some cold and warm mesoscale eddies can be identified for two months, though they were combined or split between May and June.

Table 1. Wavelengths of meanders of the fronts (km) and diameters (long axis) of isolated eddies (km).

Wavelengths	May:	southern	240±68	(5)*
		middle	197±53	(6)
		northern	318±25	(3)
	June:	southern	174±35	(7)
		middle	183±42	(7)
		northern	250±90	(5)
Diameters	May:	cold	61±22	(7)
		warm	54±23	(7)
	June:	cold	90±33	(6)
		warm	62±27	(6)

* Numbers in the parentheses are number of the pairs of the crests or number of the eddies of cold or warm nature.

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Although some meanders and mesoscale eddies can be traced for two months as shown in Figs. 1 and 2, it is noted that these features are not stationary as described in conventional schematic patterns (INOUE, 1974) of the Japan Sea circulation. Because of their short time scale in fluctuations and their large gradients, the climatological (long-term) average of the isotherms does not indicate these features nor the conventional concept of the three branches of the Tsushima Current as described before (INOUE, 1974). In order to prove this point the climatological mean isotherms computed from the data collected from the early twentieth century up to 1971 for May and June are shown in Figs. 3 and 4 (JODC, 1978). These charts indicate large temperature gradients in the southern part of the Japan Sea with indications of two fronts structures in some portions and meanders of the isotherms.

Comparison of Figs. 3 and 4 with Figs. 1 and 2 shows very little common features between the averaged and quasi-synoptic temperature patterns. It is also important to note that both averaged and quasi-synoptic isotherms at the 100 m depth do not agree well with the current of transport patterns of numerical models by many authors (YOON, 1981; SEKINE, 1986; KAWABE, 1986; ENDO and TAKANO, 1985), though isotherms represent to some degree the streamlines in the upper layer as discussed in next section.

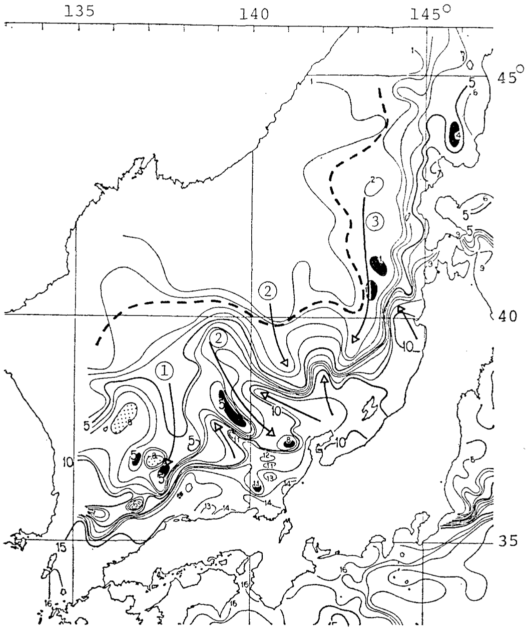

Fig. 1. Isotherms at 100 m depth in May, 1987. Cold and warm intrusions are numbered in order to be traced in June isotherms. Polar front is indicated by a broken line. Cold eddies are shaded. Warm eddies are dotted.

3. Currents and 100 m isotherms

Water masses or temperature-salinity relations in the Japan Sea are rather homogeneous except in the upper tens of meters (YASUI *et al.*, 1967; MORIYASU, 1972). Therefore, the 100 m depth isotherms fairly well represent the isopycnals and thus the streamlines as in the Gulf of Mexico (ICHIYE, 1962).

In order to correlate the currents in the upper layer and 100 m-isotherms quantitatively, the averaged currents with GEK from 1953 to 1977 compiled by JODC (1979, referred to as C) are compared to the averaged temperature distributions at the surface, 100 m and 200 m compiled by the same agency (JODC, 1978; referred to as H). We chose from the summer data of C the mean GEK speed above 0.2 kts so that the

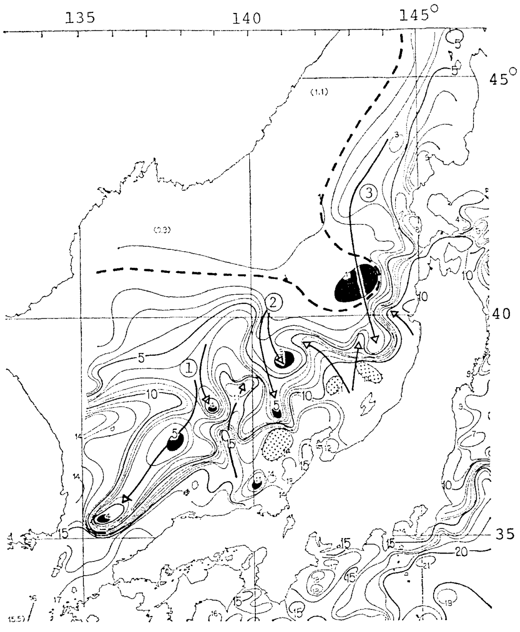

Fig. 2. Isotherms at 100 m depth in June, 1987. See legend of Fig. 1.

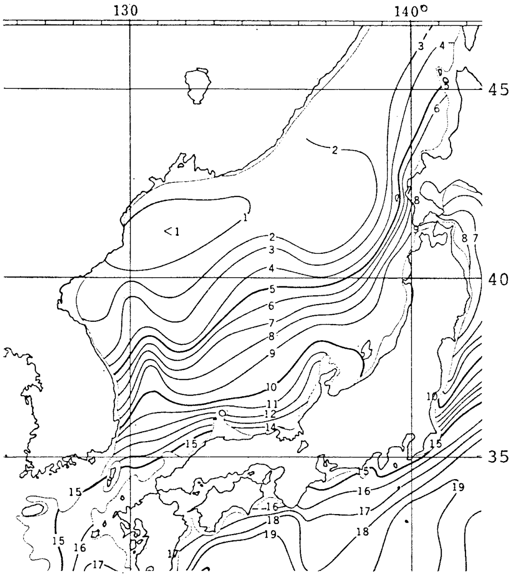

Fig. 3. Isotherms at 100 m from the climatological mean from 1900 to 1972 (JODC, 1978) in May.

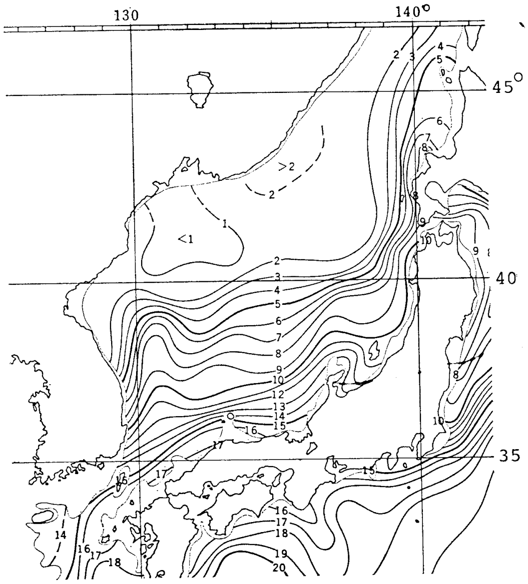

Fig. 4. Isotherms at 100 m from the climatological mean from 1900 to 1972 (JODC, 1978) in June.

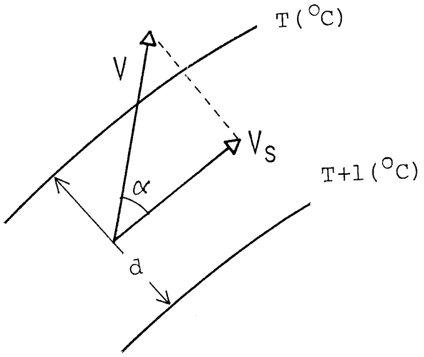

Fig. 5. Schematical figure for determining correlations between the GEK speed and the temperature gradients. Velocity component V is calculated by $V_s = V\cos\alpha$ (V_s: velocity by GEK).

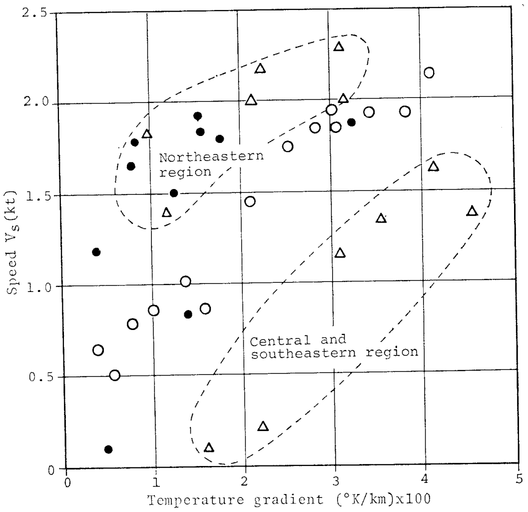

Fig. 6. Averaged GEK speeds (JODC, 1979) against temperatue gradients at 0 m, 100 m, and 200 m depth. Closed circles, open circles and triangles indicate correlation with 0 m, 100 m and 200 m temperature gradients, respectively.

velocity vector in an arrow shows its direction. These arrows were overlaid on 0 m, 100 m and 200 m temperature charts of May and June of H. Then the two isotherms of one degree of difference that include the velocity vector were selected and the velocity component along their mean direction V_s was computed, as shown schematically in Fig. 5. The distance of the two isotherms d was measured to represent temperature gradient. The velocity components V_s and the temperature gradients in (°C/km)×100 are plotted in Fig. 6 for 0 m-, 100 m- and 200 m- isotherms with different notations. It is seen that the 100 m isotherm gradients are best correlated to the speed with correlation coefficients of 0.92±0.13, whereas those of 0 m and

200 m are 0.78±0.32 and 0.45±0.28, respectively. It is not surprising that the 200 m isotherms show less correlation coefficients with the speed, since the GEK values are for the surface current. In fact, the 200 m data points form two sets of correlation with the speed. One set consists of stations in the northeastern region of the Japan Sea where the Tsushima Current seems to dominate. The other set consists of stations in the central and southwestern part of the Japan Sea where some permanent eddies are found with weak currents and the strong Tsushima Current is too close to the coast to be included in the two 200 m isotherms.

Although the data sets are rather crude in their measurement and also current and temperature data were not measured simultaneously, Fig. 6 seems to indicate that the upper layer streamlines may be represented by the 100 m isotherms. There are some problems to identify the isotherms determined quasi-synoptically with the streamlines and to interpret isolated warm and cold area as mesoscale eddies. However, without any better data we would consider the 100 m isotherms as representing streamlines.

4. Mid-ocean thin jets and mesoscale eddies

The quasi-synoptic isotherms in Figs. 1 and 2 indicate at least two fronts off the Japanese coast in the Japan Sea with another front that was not so continuous as the other two.

Since large isotherm gradients represent strong currents as discussed in the last section, these fronts are closely related with the mid-ocean thin jets. Their dynamics, particularly meanderings and stability problems were discussed by FLIERL and ROBINSON (1984). Their stability calculation indicates that perturbations of wavelengths longer than 150 km are stable and generate meanders of the jet as observed in Figs. 1 and 2. Therefore, shorter scale disturbances that are unstable would be amplified and generate mesoscale eddies with their diameters of the order of 100 km or less, though their dynamics could not handle the process of eddy generation, since it is highly non-linear.

KIELMANN and KÄSE (1987) could simulate the mesoscale eddy generation of the mid-ocean in the North Atlantic Ocean, the Azores Current by numerical modeling. They could demonstrate growth of meanders of the jet and detachment of the isolated eddies on both sides of the jet. Their jet has a width of about 60 km and its meanders grow for the wavelength of 50-300 km with a maximum growth rate on about 100 km scales at *e*-folding time of about 8 days. Though the horizontal temperature gradient that generates a geostrophic jet in their model is smaller than that of Figs. 1 and 2 and reaches deeper than 400 m, the wavelengths of the meanders, diameters of detached eddies and growth time scale seem to be comparable with those observed in the 100 m isotherms of Figs. 1 and 2. Thus it is not out of line to consider that the space scales of the order of 10 to 20 km and the time scales of 5 to 10 days are adequate to resolve processes of meander development of the fronts and detachment of isolated mesoscale eddies in the Japan Sea.

It is necessary to construct numerical models of 5 to 10 km grid size and of 5- to 10-level vertical resolution with a suitable time step appropriate for adopted dissipation parameters in order to diagnose the observed results and to understand the processes of instability and eddy shedding. Unless the eddy resolving models are constructed, the circulation in the Japan Sea and perhaps in other oceans will not be properly understood.

5. Concluding remarks and proposed work

With some evidences from previous observed data and by theoretical arguments, we got a conclusion that the eddy resolving circulation field of the Japan Sea can be determined by obtaining temperature fields at 100 m depth at least every ten days. Next we will discuss feasibility of the field experiment to achieve this purpose with available technology.

The field experiment is anticipated to be of short duration but intensive efforts. In the Japan Sea area, the satellite IR images may be useful in spring and even in early summer, with better chance of good weather. Thus we envision the experiment to be carried out for six times ten days apart for two months from late spring to early summer. With space resolution of at least 20 to 30 km, tentative tracks to obtain 100 m depth temperatures fields are shown in

Fig. 7 superposed on climatological GEK data. These tracks are mostly from SE to NW to cut across the Tsushima Current which forms two or three thermal fronts as discussed before. The distances between tracks are about 50 km to resolve the meander wavelength of the fronts, although these distances are slightly too coarse to catch some isolated eddies. It is planned to collect temperature data at least 10 km apart on each track. The total length of the proposed tracks is about 11,800 km or 6,375 n miles with turn-around route length, 4,000 km at the initial and terminal points of all the tracks. Therefore the total operational distance is about 8,550 n miles. If one moving vehicle has to do such data collection within ten days, one to two airplanes have to obtain desired results. Otherwise at least eight ships are necessary for two months

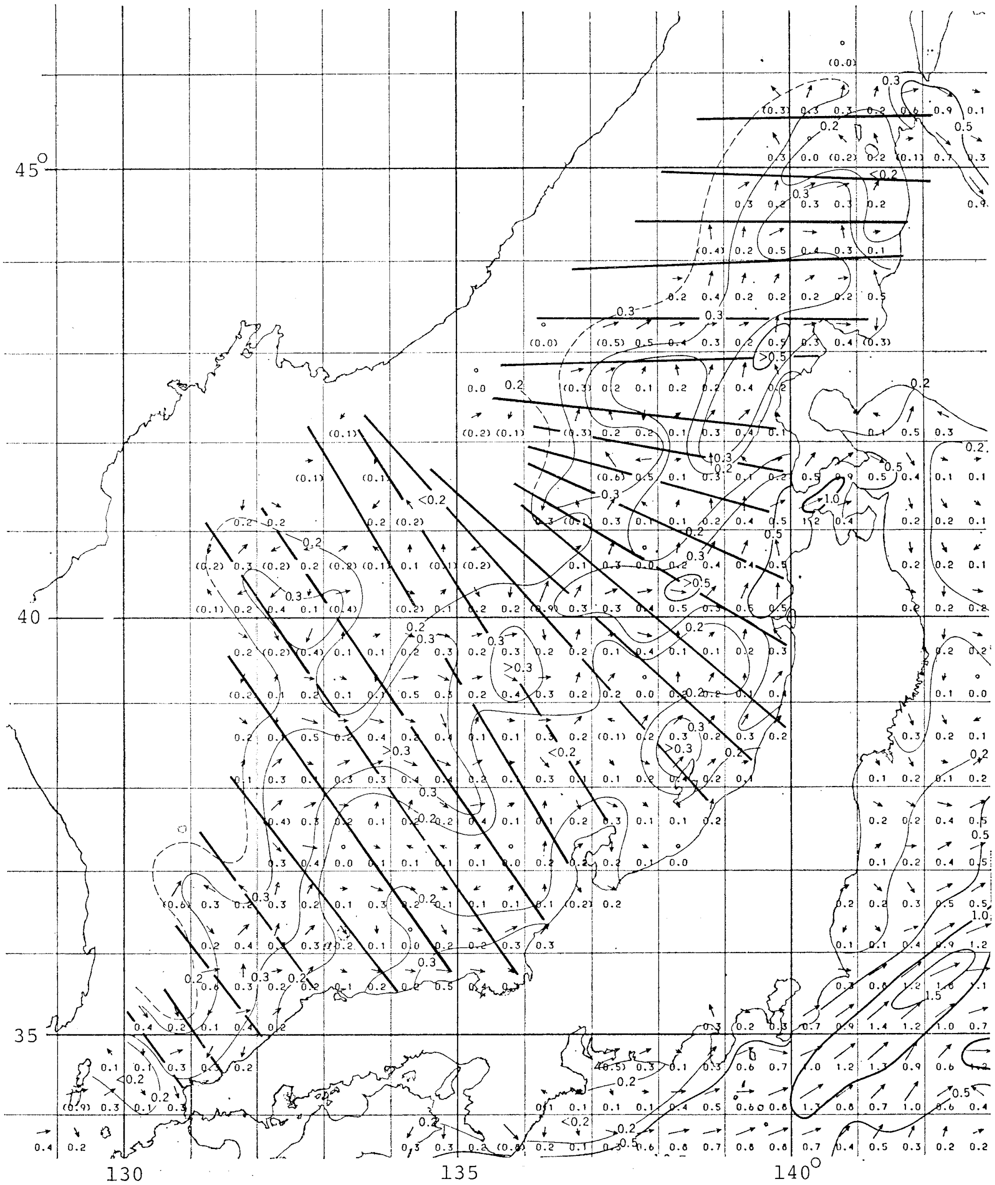

Fig. 7. Proposed flight or cruise tracks to collect temperature data at 100 m depth and in the thermocline within ten days.

with about one day rest for two working days for each ship.

With airplanes of cruising speed of 100 kts, two airplanes can fly all the tracks within about forty flying hours for each plane. Since data needed are temperature at 100 m depth and also in the thermocline, conventional XBT's or airborne AXBT's that can reach 500 m are sufficient. Since for each experiment of ten days apart the number of these XBT needed is about 1,200 and thus the total is about 7,200. The total cost for AXBT's is about $720,000 with $100 for each. If shipborne XBT's are used, the cost may be one third of this amount, though the ship time may cost much more than airplane operation, particularly if the planes are operated as a part of exercises by Japanese Self Defense Force, US Armed Services, or even jointly with USSR Border Patrol forces. Therefore, a whole budget of performing a core experiment may be not so extravagant, considering vast amounts of data bases to be collected and to be used by oceanographers not only in Japan but in the whole world.

Although we proposed the tracks for collecting temperature data in Fig. 7, these can be greatly modified by examining satellite IR images before and during the field experiment period. As explained before, late spring and early summer satellite IR images show best constrast in the Japan Sea and the previous data indicate that the surface temperature signatures represent temperature distributions below the surface in this season of the year. Therefore we can eliminate some tracks that would not intersect any interesting features like mesoscale eddies or meanders.

Rather sharp thermoclines develop in spring and early summer in the Japan Sea between 100 m and 200 m (JODC, 1978). The depth of these thermoclines can be used to determine geostrophic flows in the upper layer instead of the temperature at 100 m depth. An echosounder of 200 kHz is available now commercially. A device enhancing the signal of the thermocline may be developed to record its depth along a ship's course (personal communication by Aubrey Anderson of Dept. of Oceanography, TAMU). Then four ships of about 13 kts can cover the course tracks shown in Fig. 7 within seven days. XBT's may be used sparingly mainly for calibration. Then airplane versus ship for covering the tracks simply depend on cost and availability of either platform. Combination of both platforms is also possible. However, use of 200 kHz echosounder needs preliminary calibration and development of signal enhancement of the recorder.

Eddy resolving numerical modeling of the Japan Sea was actually started in 1985 by ENDO and TAKANO (1985). It was a five-level, prognostic model with surface wind stress and surface heat and water flux prescribed. The bottom topography is included as realistically as possible. The grid size is 0.25 degrees in longitude and latitude. This model will be upgraded with increase of vertical resolution up to 10 and reduction of the grid size to 0.05 degrees both in longitude and latitude. Since effects of the bottom topography seem to be small on the circulation above the thermocline, the same topography will be used. However, in order to confirm the effects of the bottom topography, the previous model will be run for flat bottom and for uneven bottom.

Acknowledgment

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日本海の中規模うず

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要旨： 1987年5月と6月の深さ 100 m での等温線は，直径が 30〜160 km の数個のうずと，100〜400 km の波長でまがりくねる前線を示している。GEK から求められる表層流速と，0 m, 100 m, 200 m の深さでの水温の水平勾配との相関をしらべると，100 m の深さでの勾配との相関がもっともよい。うずと前線は，外洋の薄い噴流の不安定性で説明できそうである。これらの現象をさらによく理解するための観測・数値モデリング案を提示する。