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New findings from CREAMS Observations: Water Masses and Eddies in the East Sea

KUH KIM[1], KYUNG-RYUL KIM[1], YOUNG-GYU KIM[1], YANG-KI CHO[2], JONG-YUL CHUNG[1], BYUNG-HO CHOI[3], SANG-KYUNG BYUN[4], GI-HOON HONG[4], MASAKI TAKEMATSU[5], JONG-HWAN YOON[5], YURI VOLKOV[6] AND MIKHAIL DANCHENKOV[6]
[1]*Department of Oceanography and Research Institute of Oceanography, Seoul National University, Seoul 151-742, Korea*
[2]*Faculty of Earth Systems and Environmental Sciences, Chonnam National University, Kwangju, 500-757, Korea*
[3]*Department of Civil Engineering, Sung Kyun Kwan University, Suwon, Korea*
[4]*Korea Ocean Research & Development Institute, Ansan P.O. Box 29, Seoul 425-600, Korea*
[5]*Research Institute for Applied Mechanics, Kyushu University, Kasuga, 816 Japan*
[6]*Far Eastern Regional Hydrometeorological Research Institute, Vladivostok, Russia*

CREAMS (Circulation Research of the East Asian Marginal Seas) is an international research program, which began in 1993 in order to understand the water mass structure and circulation in the East Sea. Since the beginning of CREAMS, there have been four cruises in the summer and two in the winter, covering most parts of the East Sea for the first time in more than 60 years since the historical survey reported by Uda (1934). CREAMS investigations have provided many new insights into the various aspects of oceanographic problems in the East Sea such as water masses, deep sea currents and circulation, eddies, particle fluxes and so on. In this paper, we briefly review understandings before CREAMS and summarize initial new findings from CREAMS expeditions in terms of water masses and currents.

INTRODUCTION

The East Sea is a semi-enclosed basin, divided into three major basins: the Japan Basin in the northern half of the sea which is almost 4,000 metres deep, and Ulleung Basin and Yamato Basin to the south which are about 2,200 metres deep. Water exchange with the North Pacific and the Sea of Okhotsk is very limited, because the Korea, Tsugaru, Soya and Tatar Straits have sill depths of 130 metres or less. Until recently, our knowledge of the hydrography and currents in the East Sea has been based upon the report of Uda (1934). Uda analyzed the physical and chemical data acquired in the entire East Sea in May 1932, and introduced schematic surface currents in the East Sea for the first time as shown in Fig. 1.

Tsushima Current

The Tsushima Current is most conspicuous as it carries warm and saline waters into the East Sea through the Korea Strait. This water flows out of the Sea through the Tsugaru and Soya Straits. The warm waters from the Korea Strait occupy the upper 100 meters in the southern half of the East Sea, and are separated from cold waters in the northern half of the sea by a polar front located at about 40° N (for general reviews, see Moriyasu, 1972 and Seung, 1992).

As the Tsushima Current determines the major features of the hydrography in the East Sea, the path of the Tsushima Current has become the subject of intensive modeling experiments. The pioneering work by Yoon (1982a-c) was followed by Kawabe (1982a, b). These models show that the Tsushima Current splits into two or three branches as it leaves the Korea Strait: one along the Japanese coast and the other along the east coast of Korea, which has been known as the East Korean Warm Current (EKWC) after Uda (1934). A third branch

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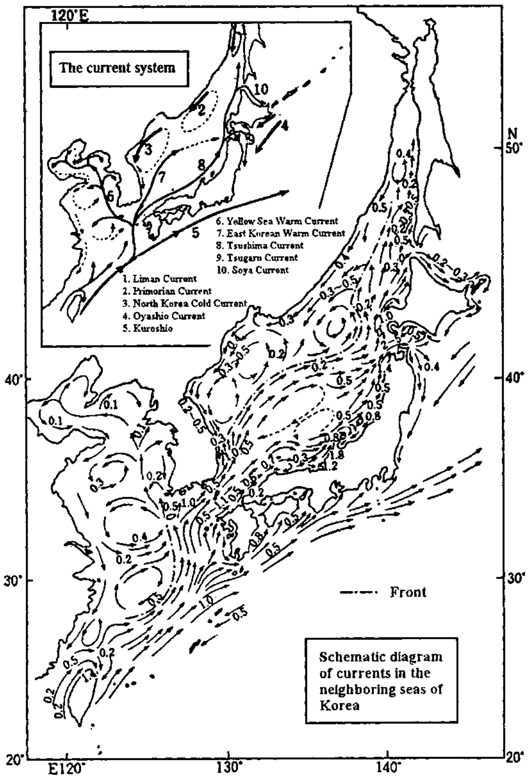


Fig. 1. Schematic diagram of currents in the neighboring seas of Korea, adopted in English from Uda (1934).

appears between these two branches when the transport of the Tsushima Current through the Korea Strait increases substantially in summer.

East Sea Proper Water

Noting the presence of abundant cold waters with temperatures below 1°C, Uda (1934) called this water "East Sea Proper Water" (ESPW), which makes about 86% of the East Sea waters (Yasui, *et al.*, 1967). In Fig. 2, we can see that the water at 300 m is completely isolated from waters in the North Pacific and the Okhotsk Sea with a nearly constant temperature at 1°C in the northern part, and at a slightly higher temperature in the southern part.

Since Uda (1934), it has been well known that these cold waters are very high in dissolved oxygen (DO). At 300 m DO varies in the range of 5.5-6.5 ml/l in the East Sea, fairly comparable to that in the North Pacific (5.0 ml/l or less). It is most interesting,

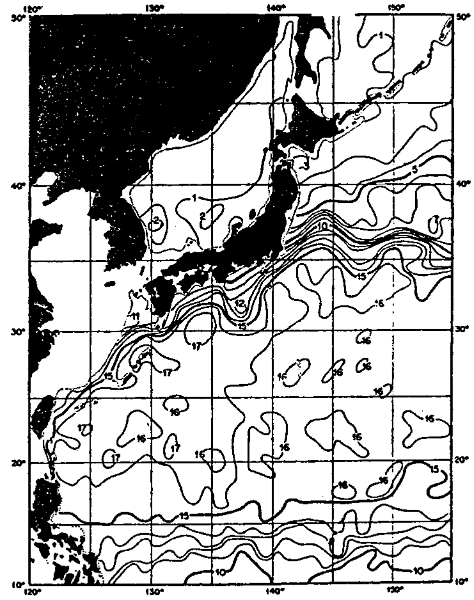


Fig. 2. Distribution of temperature (°C) at 300 m from Winterfeld and Stommel (1972).

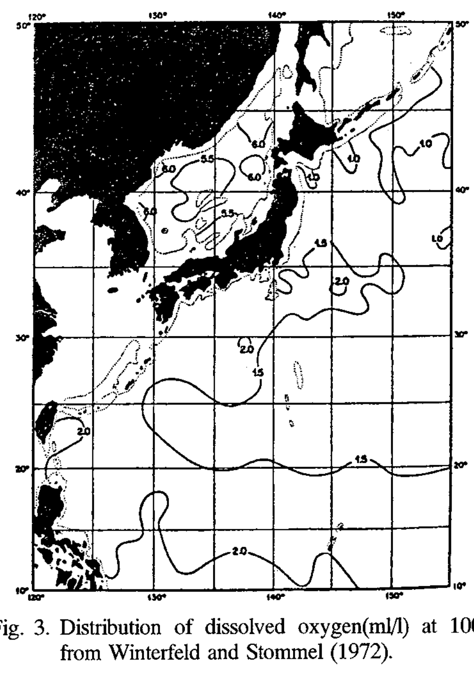


Fig. 3. Distribution of dissolved oxygen(ml/l) at 1000 m from Winterfeld and Stommel (1972).

however, that DO remains very high in deep waters of the East Sea as shown in Fig. 3, whereas DO concentration in the North Pacific is only about 1.5 ml/l. Because of this high DO concentration, an active ventilation process in the East Sea has been assumed, although little has been known on where, how and under what conditions such cold waters are formed in the winter, except for what has been studied in a few works such as Sudo (1986) and Seung and Yoon (1995).

Some recent findings

While it is as high as 12°C in winter time, the temperature of the bottom water in the Korea Strait is usually as low as 5°C or less in summer (Lim and Chang, 1969). The origin of this cold water, however, could not be traced until the peculiar characteristics of salinity minimum and dissolved oxygen maximum were found under the warm water near the Korea Strait in 1981 by Kim and Chung (1984). They named this water "East Sea Intermediate Water" (ESIW).

Furthermore, the EKWC did not appear at all in 1981 (Kim and Legeckis, 1986), contradicting historical knowledge and the results of numerical experiments. These observations strongly indicated the possibility that even the path of the Tsushima Current is closely related to the presence of the cold water. A simple model by Seung and Kim (1989) clearly demonstrated that the circulation of cold waters in the northern region can play an important role in separation of the warm current from the east coast of Korea.

CREAMS

Thus, critical questions have been raised concerning the circulation of the cold waters in the East Sea and dynamics governing the path of the Tsushima Current. CREAMS has been organized to address the following fundamental questions.

1) Where are areas of cold water formation in winter?

2) What is the circulation in the northern half of the East Sea?

3) What are the precise characteristics of waters in the East Sea?

4) What is the coupling mechanism between the warm current and the circulation of cold waters?

CREAMS is comprised of analysis of historical data, field observations, numerical modeling, and laboratory experiments. Scientists from Japan, Korea and Russia have been joining together to answer the above questions. There have been four cruises in the summer, two cruises in the winter, four workshops and two international symposiums since the beginning of CREAMS in 1993. As a part of the Cooperative Study of the Kuroshio (CSK), hydrographic surveys were previously organized by the Intergovernmental Oceanographic Commission and were conducted mainly in the southern warm region of the East Sea in 1965-1970. For the purposes of CREAMS the northern cold region has been the area of main interest. In particular, deep stations and long-term current data became available for the first time in this region. This article summarizes observation programs and introduces recent findings from CREAMS, which have been unknown before.

NEW FINDINGS FROM CREAMS

Fig. 4a-4d show CTD and chemistry stations taken during CREAMS summer cruises. Although the locations of hydrographic stations and moorings have been changed slightly each year due to some restrictions, it should be recognized that hydrographic data of highest precision were collected in most parts of the East Sea more than half a century after the historic report of Uda (1934). This paper, in particular, deals with the data taken in summer of 1995 at stations shown in Fig. 4c.

New Water Masses in the East Sea Proper Water

Vertical profiles of salinity reveal a broad minimum centered at about 1,500 meters in the Japan Basin, as shown in Fig. 5. Such a minimum was first found from a few specially selected CTD casts which reached a depth of 100 m above the bottom in 1994 and was later confirmed at most stations in the Japan Basin in 1995. It is extremely difficult to identify these characteristics in a linear scale temperature-salinity diagram of the water column from

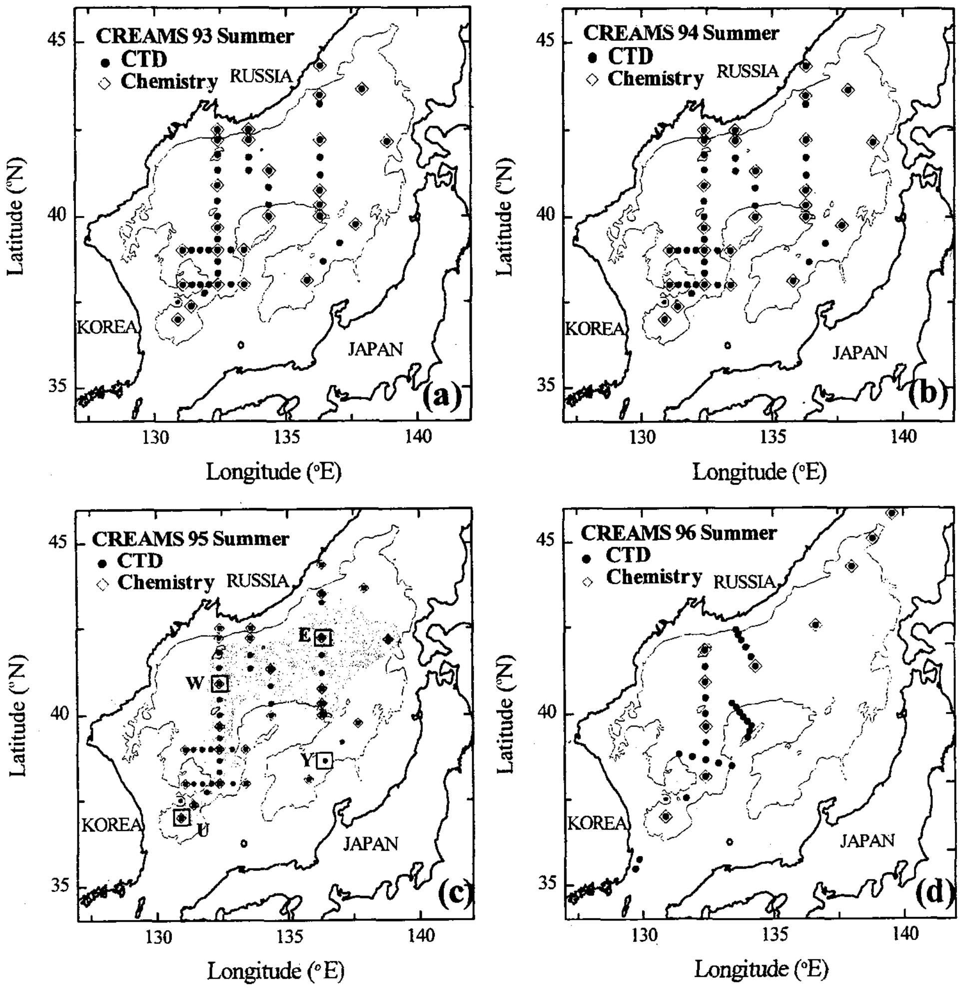


Fig. 4. Stations for CREAMS summer cruises: (a) July, 1993 (b) August, 1994 (c) July, 1995 (d) July, 1996.

the surface to the bottom for two reasons. First, temperature varies very little in deep waters below a few hundreds metres from the surface. Secondly, a salinity difference of only 0.002 psu accounts for this minimum for the temperature range of less than one tenth of a degree in deep waters.

Therefore, we introduce two-scale T-S diagrams, one of which has expanded scales of temperature and salinity for deep waters as shown in Fig. 6. Below the Tsushima Warm Water a salinity minimum exists, which corresponds to the ESIW. A secondary minimum is apparent around 0.10-0.15°C with salinity of 36.063 psu. The ubiquitous presence of this layer in the Japan Basin as shown in Fig. 4c indicates that this structure is a result of major thermohaline circulation in the East Sea and justifies a new name for this water. We propose to call it "East Sea Deep Intermediate Water (ESDIW)".

East Sea in Changes

It should be noticed that there is also a minimum DO a few hundreds metres below the deep salinity minimum (Fig. 5). CREAMS data together with previous data by Sudo (1986) and Gamo *et al.* (1986) show that the layer of DO minimum has deepened, as DO has continuously increased (decreased) significantly above (below) this layer for the last 30 years as shown in Fig. 7a. It is also found that temperatures at 1,000 metres and in the bottom water have increased by 0.1 and 0.02°C, respectively, during the same period (Fig. 7b). Together with the increase of DO above ESDIW, this temperature change implies active formation of mid-depth waters in recent years, as further discussed in an accompanying paper by Kim and Kim (1996).

All these observations strongly indicate that waters above and below the ESDIW at the present time are different in their origins. Therefore, we propose to distinguish these waters by giving different names; "East Sea Central Water (ESCW)" and "East Sea Deep Water (ESDW)", respectively. A full description of water masses is in preparation (Kim *et al.*, 1997).

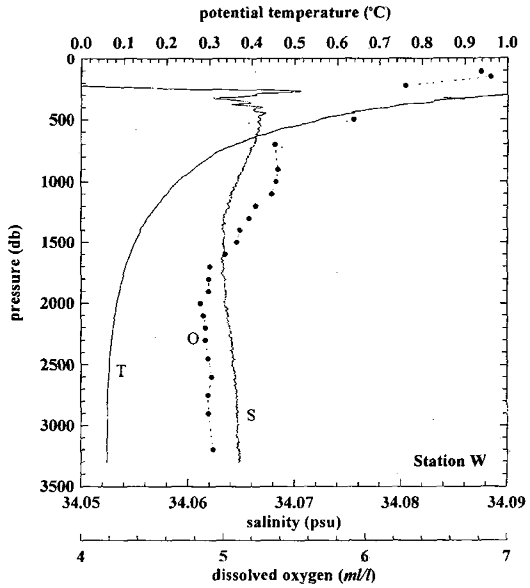


Fig. 5. Vertical profiles of temperature, salinity and dissolved oxygen taken in the western Japan Basin.

Eddies in deep and shallow waters

It is fascinating to examine the first long-term time series of currents taken in the Japan Basin, as shown in Fig. 8. At nominal depths of 1,000, 2,000 and 3,000 meters, low-passed currents are very weak until November. However, strong currents of 15-20 cm/sec suddenly began to fluctuate with a time scale of a few weeks to months, lasting through the following spring. It is easy to notice that the fluctuating currents are vertically coherent in deep waters. Strength of these currents is comparable to deep eddies observed elsewhere such as in the North Atlantic during the Mid-Ocean Dynamics Experiment (Freeland *et al.*, 1975; Schmitz, 1976; MODE-1 Atlas, 1977).

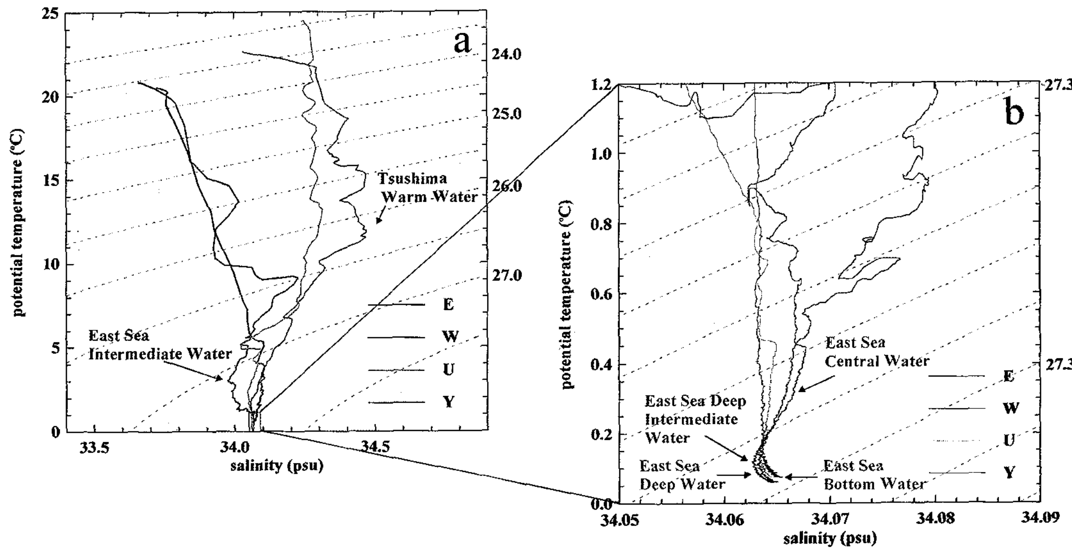
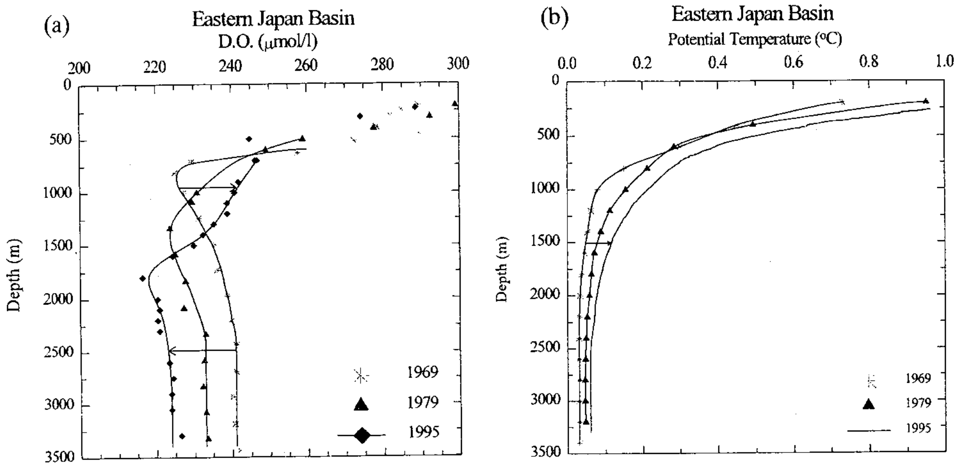


Fig. 6. Temperature-salinity diagram of full water column in (a) and waters colder than 1.2°C in (b) for E, W, U and Y stations shown in Fig. 4c.



1969 : Sudo (1986)
1979: Gamo and Horibe (1983)
1995 : CREAMS95S Observation

Fig. 7. Long-term variation of dissolved oxygen (a) and temperature (b).

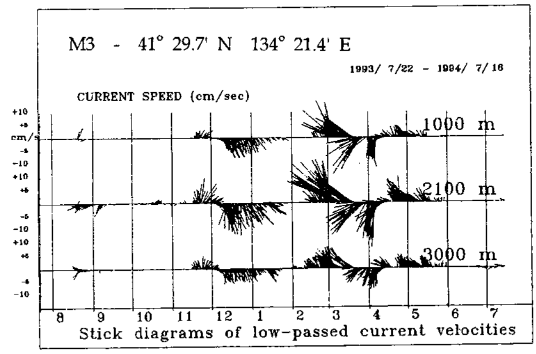


Fig. 8. Time series of currents at norminal depths of 1000 m, 2000 m and 3000 m taken in the central part of the Japan Basin from Takematsu *et al.* (1994).

Eddies were found not only in deep waters, but also in the surface layer, as shown in Fig. 9. Tracks of satellite drifters show eddies, whose diameters are about 100 km and whose speeds are about 20 cm/sec. There are two noteworthy points. First, these eddies were found in the northern area of the East Sea where the stratification is very weak except for a very shallow seasonal thermocline, so that there is little available potential energy for generation of eddies. Secondly, speeds of surface eddies are quite comparable to those from current meters in deep waters such as shown in Fig. 8.

It is interesting to relate the circular motion of the drifter between Primorye and Hokkaido to the sea surface topography from Topex-Poseidon. Fortunately, altimetry tracks crossed over the center of the eddy three times within one month and the sea slope remained almost unchanged around the eddy during this period. We may estimate the geostrophic current from slopes and compare with drifter speeds. The speed of the geostrophic current is about 28 cm/sec and drifter speeds are about 23 cm/sec. This comparison is good, considering that the drifter speed is an underestimation, for drifter positions were fixed two or three times every day during an 8-hour window of operation to economize the lifetime of drifter batteries. Furthermore, the drifter track coincides with an eddy which is warmer than its surrounding (Fig. 9). Three independent satellite data agree well in confirming the presence of the same eddy and in estimating similar speeds.

In addition to eddies in the Japan Basin the so-called Ulleung Warm Eddy was also observed in 1994-95, which had been a subject of continuous investigation for several years (Shin *et al.*, 1995). Despite seasonal changes in forcings including wind, heating and cooling, and variation of the influx through the Korea Strait, the eddy was traced by repeated CTD surveys for more than one year.

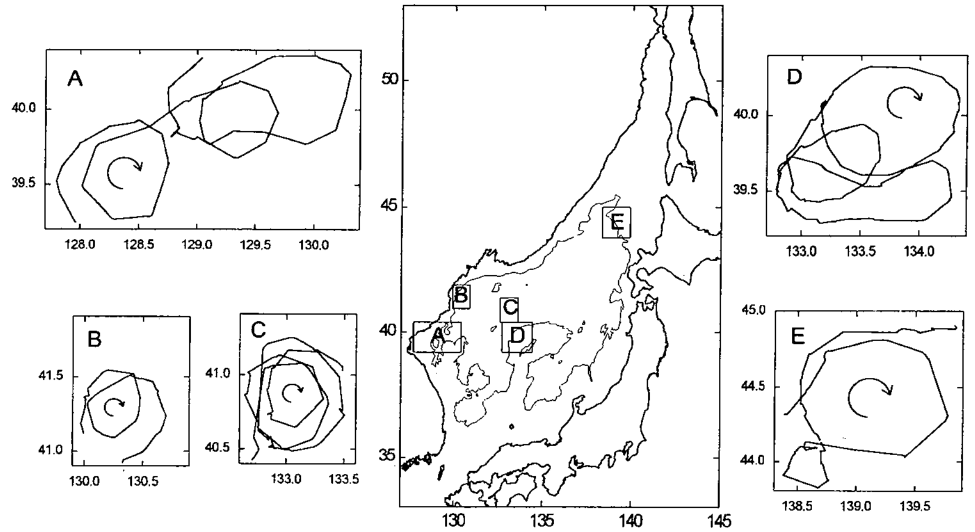


Fig. 9. Eddy motions tracked by satellite drifters.

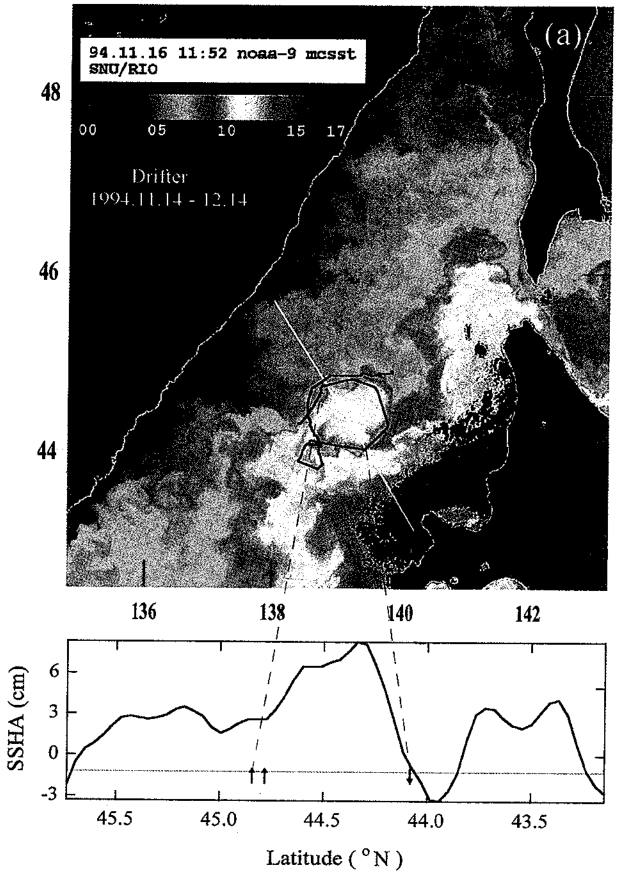


Fig. 10. An eddy observed simultaneously in a track of satellite drifter, altimetry and sea surface temperature.

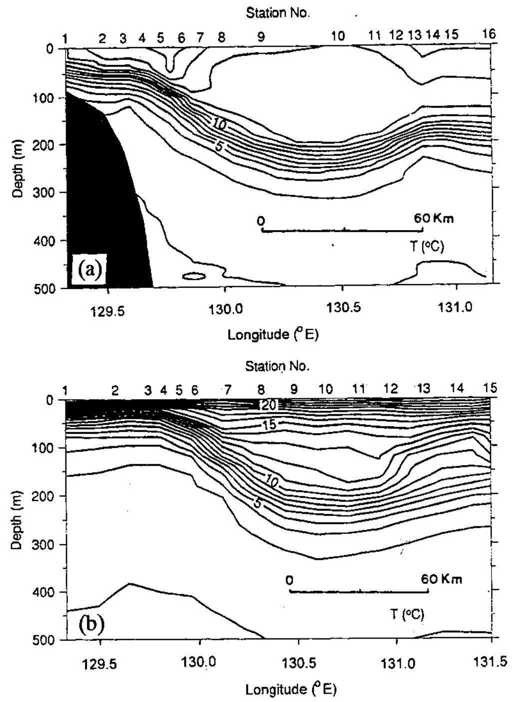


Fig. 11. Temperature section of Ulleung Warm Eddy observed in April (a) and July (b) of 1995, along 37° 20'N and 37° 50'N respectively.

The center of the eddy moved slowly northeastward with a speed of about 1 cm/sec from west to north of Ulleung Island, as the eddy entered the East Korean Bay after passing over the Korea Plateau. The vertical structure of the eddy was modified from April to July, 1995 as shown in Fig. 11; the homogeneous water of 12-13°C from the surface to 200 m shrank to 100-170 m as the permanent thermocline rose about 30 m during 80 days, although the diameter of the eddy remained unchanged at about 100 km.

Sediment Trap in the Japan Basin

A sediment trap (Parflux Mark 7G-13) with 13 time-series collectors was installed on one of current meter moorings at a depth of 2800 m, 300 m above the bottom, and collected settling particles every month from July 19, 1994 to August 5, 1995, at 39° 40'N and 132° 24'E in the southwestern Japan Basin. This is the first long-term sediment trap moored in the Japan Basin.

The initial results show that the annual mass flux was 96 g/m^2/yr., of which 66% consists of biogenic particles and about 32% consists of lithogenic particles. Among biogenic particles, biogenic silica (opal) was 41.1% of the total flux, the largest component of settling particles, and particulate organic matter and calcium carbonate comprise 8.5% and 16.4%, respectively. A pronounced fall bloom was observed during October 19-November 18, 1994, which provided 40% of the total annual flux. The reason why a spring bloom was not observed is still under investigation; it is possibly associated with rather abrupt changes in SML (Surface Mixed Layer) depths from the winter state to the summer state without any noticeable period of spring transition.

CONCLUDING REMARKS

CREAMS is now in an analysis and synthesis phase of the data collected in the last four years. The detailed structure of water masses and energetic currents in deep waters together with the complexity of satellite data strongly indicates that our knowledge on currents and circulation in the East Sea is still rather limited and inadequate. The structure of deep waters and detailed meso-scale variations of properties and currents are subject to further careful and rigorous investigation.

At the fourth CREAMS workshop held in Vladivostok February 12-13, 1996, the progress of CREAMS was evaluated and its expansion was recommended. Accordingly, CREAMS-I will be completed in 1997 and will be followed by CREAMS-II, beginning in 1998 for another five years. CREAMS invites new research programs and we hope to carry out an intensive observation program in 1999-2000, involving simultaneous multi-ship surveys in the entire East Sea and direct measurements of current fields utilizing both Lagrangian drifters and current meter moorings at key locations. It is very much desired to coordinate these efforts with NEAR-GOOS (NorthEast Asian Regional-Global Ocean Observing System) so that interior processes and boundary conditions can be related at the end of the program. Eventually, we hope to forecast short and long term changes of the ocean environment in the East Sea.

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