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What is Happening in the East Sea (Japan Sea) ?: Recent Chemical Observations during CREAMS 93-96

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CREAMS (Circulation Research of the East Asian Marginal Seas) Expeditions have provided a rare opportunity to carry out precise measurements of salinity, temperature and chemical tracers extensively in all major basins of the East Sea (Japan Sea) in 1993-1996 for the first time in more than 60 years since Uda's investigation (Uda, 1934). Studies revealed unequivocal evidence that the East Sea Proper Water (ESPW), previously known as a single homogeneous water mass, is indeed made of several distinct water masses. CREAMS data further confirmed the earlier observations of Gamo *et al.* (1986) that properties in Deep Waters in the East Sea have been changing during at least the last 25 years. There is evidence, especially from the analysis of the DO profile, that these changes may result from a major change in the mode of deep water formation: from *bottom* water formation in the past to *intermediate/deep* water formation in recent years. The causes for these changes are not clear at the present time, but may include natural variation and may also reflect recent global changes in regional scale. A moving-boundary box model is presented to describe current observations, predicting the turnover time of the total deep and bottom waters to the cold surface waters to be ~80 years in 1996.

INTRODUCTION

With an area covering only 0.6% of the Pacific Ocean and an average depth of only 1700 meters, the East Sea (Japan Sea) is a typical mid-latitude marginal sea surrounded by Korea, Japan, and Russia.

In the early 1930s, Uda explored the seas around Korea by mobilizing 53 vessels and found that the entire basin of the East Sea below several hundred meters was filled with waters with quite uniform physico-chemical characteristics. Uda named this water body the East Sea Proper Water (ESPW). Gamo and Horibe (1983), however, showed that, based on CTD observations, temperature and salinity structures of ESPW are very similar to those in the open ocean, even though they have a much smaller range of variation, indicating different water masses within basins such as Deep Waters and adiabatic Bottom Waters.

CREAMS (Circulation Research of the East Asian Marginal Seas) Expeditions, a Korea-Japan-Russia international cooperative research program, have provided a rare opportunity to carry out precise measurements of salinity, temperature and chemical tracers in an extensive manner in all major basins of the East Sea in 1993-1996, for the first time in more than 60 years since Uda's investigation.

Complete chemical analysis including C-14, CFC-11 & -12, and tritium is still underway, and only preliminary observation of the basic hydrography and DO, will be presented and discussed in detail in this paper.

MATERIALS AND METHODS

Fig. 1 shows cruise tracks of the CREAMS '93 and CREAMS '96 Summer expeditions. Tracks for CREAMS '94 and '95 are similar to that in 1993. A major modification of the cruise track in 1996 was mainly due to the limitations imposed on study areas by Japanese and Russian governments within the framework of the new "Law of Sea" in 1996. Experiments carried out during the cruises were rather extensive including CTD observations, ARGOS and ALACE drifters, and current meter moorings in addition to chemical observations (for example, Takematsu, 1994, Kim, 1994 and Kim *et al.*, 1996).

Chemical observations consisted of Rosette sam-

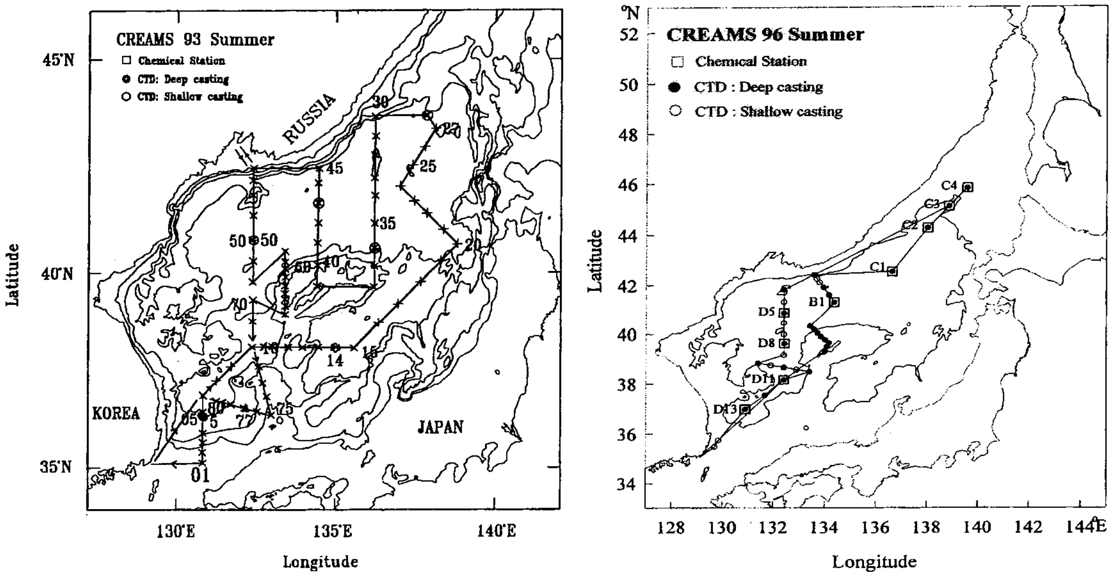


Fig. 1. Cruise tracks of CREAMS'93 and CREAMS'96S expedition. Tracks for CREAMS'94 and 95 are similar to that in 1993. A major modification of the cruise track in 1996 was mainly due to the limitation imposed on study areas by Japanese and Russian governments within the framework of the new "Law of Sea" in 1996.

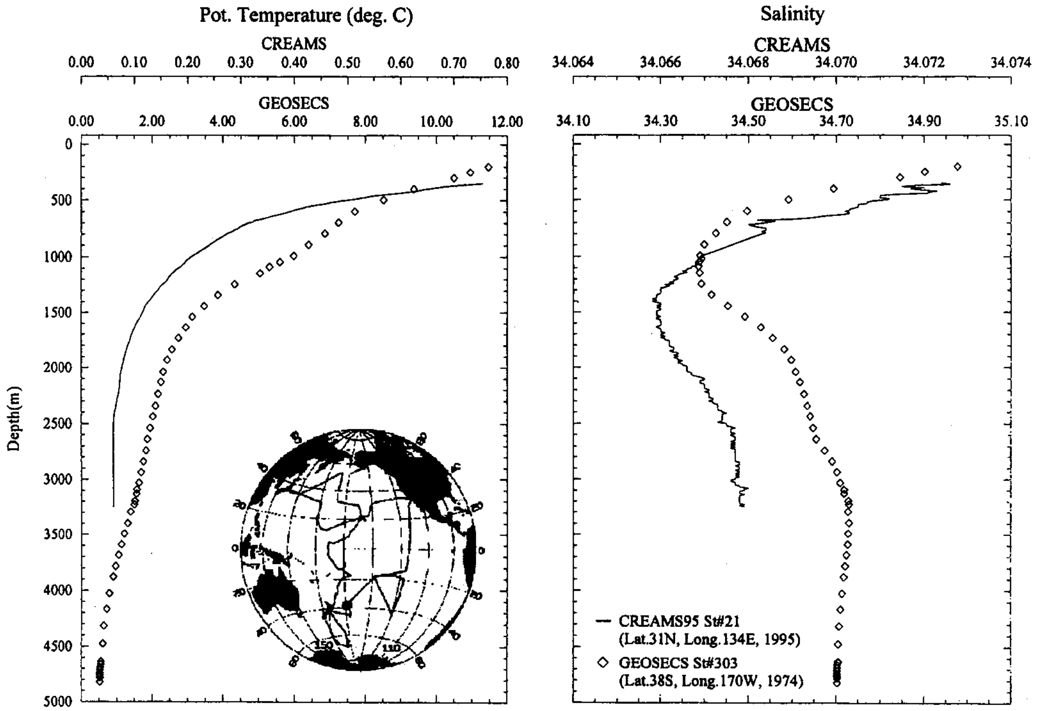


Fig. 2. Temperature and salinity profiles in the northern East Sea. Profiles at a station in the South Pacific, obtained during the GEOSECS Expedition (Ostlund *et al.*, 1987), are also shown for comparison, demonstrating the oceanic nature of the East Sea. While similarities in profiles are quite remarkable, it is worth noting that the range of variability is much smaller in the East Sea; one order of magnitude in temperature and even two orders of magnitude in salinity.

pling equipped with twelve 5-liter Niskin bottles, and continuous pCO_2 measurements in the surface waters and marine atmosphere along the track. Water samples were normally collected at 36 depths with three casts at one station. The average distance between consecutive bottles was 100 meters. Nutrients, DO, alkalinity, and pH were measured on board, and aliquots for C-14, tritium and the stable isotopes of oxygen and hydrogen were also taken for later studies. During the 1996 cruise, CFC measurements in the water samples were also carried out on board (Min *et al.*, 1996). In 1996, continuous DO profiles were also obtained with a DO sensor attached to CTD and were calibrated with bottle data.

Nutrient concentrations were measured by spectrophotometric methods described by Strickland and Parsons (Strickland and Parsons, 1977). Dissolved oxygen was measured spectrophotometrically after samples were fixed according to the procedure in the Winkler method (Park and Kim, 1996). pH was also measured spectrophotometrically (Clyton and Byrne, 1993). Alkalinity was measured by a potentiometric titration method (Millero *et al.*, 1993). pCO_2 measurements in seawater were carried out by an equilibration method with Weiss-type equilibrator and NDIR detector system.

RESULTS

The temperature and salinity profiles in Fig. 2, obtained in Japan Basin during CREAMS studies clearly show their oceanic characteristics. In the figure, typical oceanic profiles observed at a station in the South Pacific during the GEOSECS Expedition (Ostlund *et al.*, 1987), are also shown for comparison. Similarities in profiles are quite remarkable, while it is worth noting that the range of variability is much smaller in the East Sea: one order of magnitude in temperature and even two orders of magnitude in salinity. These data, thus, reveal unequivocal evidence that the ESPW, previously known as a single homogeneous water mass, indeed consists of several distinct water masses, as more easily seen in a (ϑ-S plot of Fig. 3. The names of these water masses are recently proposed as East Sea Central Water, East Sea Deep Intermediate Water, East Sea Deep Water and East Sea Bottom Water (For further discussions, see Kim *et al.*, 1996 and Takematsu *et al.*, 1996a).

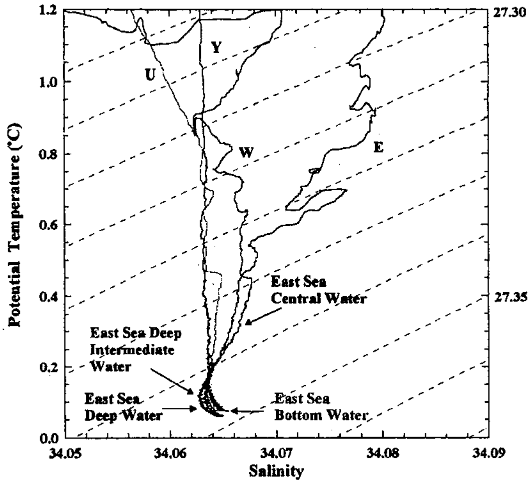


Fig. 3. The ϑ-salinity plot for deep waters in major Basins: E stands for the eastern Japan Basin, W for the western Japan Basin, Y for the Yamato Basin and U for the Ulleung Basin.

CREAMS data further confirmed the earlier observations of Gamo *et al.* (1986) that properties in Deep Waters in the East Sea have been changing at least during the last 25 years. Fig. 4 shows the potential temperature and dissolved oxygen profiles at a station in central Japan Basin at three different times from 1969 to 1996, clearly revealing changes in the East Sea, which can be summarized as follows:

1) An increase in potential temperatures of Deep Waters of over 0.1 degree C.

2) Deepening of the oxygen minimum from less than 1000 meters in the late '60s to below 1500 meters in 1996.

3) A decrease in thickness of adiabatic Bottom Waters and in their DO concentrations by 20 μmoles/kg.

DISCUSSION

There is evidence that the above observed changes may result from a major change in the mode of deep water formation: from *bottom water* formation in the past to *intermediate/deep* water for-

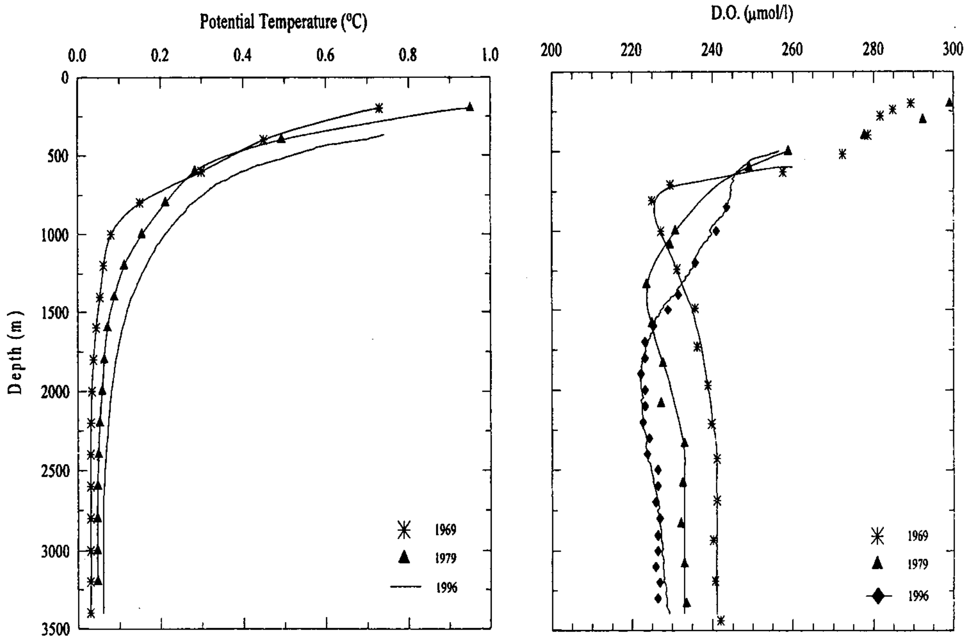


Fig. 4. Potential temperature and dissolved oxygen profiles at a station in central Japan Basin at three different times from 1969 to 1996, clearly revealing property changes in the East Sea. In 1996, a continuous DO profile was obtained with a DO sensor and then calibrated with bottle data and both profiles were shown in the figure (1969: Sudo, 1986; 1979: Gamo and Horiba, 1983; and 1996: CREAMS96S observation).

mation in recent years, as will be discussed in detail in following sections.

Fig. 5 shows profiles of potential temperature, salinity, and dissolved oxygen, as well as the ϑ-S plot at a station in western Japan Basin. Though there appears to be a slight difference in vertical structures between the western part and the eastern part of the Basin (Kim *et al.*, 1996), these profiles are quite typical for the entire Basin. This basin-wide homogeneity, even with continuous changes in deep water properties, is probably due to rapid horizontal mixing of deep waters within the Basin associated with horizontal currents. The existence of such strong seasonal current with the speed over 30 cm/sec has been verified by the deep-sea current meter mooring, carried out for more than three years during CREAMS studies (Takematsu *et al.*, 1996b).

Therefore, assuming that the system is in a quasi-steady-state mode, a steady-state one-dimensional advection-diffusion model (Craig, 1969; Gamo and Horibe, 1983) was applied to the profiles with the advection-diffusion equation,

$$0 = K(d^2q/dz^2) - w(dq/dz) + J$$

where K is the vertical eddy diffusion coefficient, w is the upwelling velocity, J is the term representing the non-conservative nature of dissolved oxygen, which is positive for production and negative for the consumption process, q represents the parameters; ϑ, S and DO, and z is the upward distance from the lower boundary. The steps for the model application were as follows:

1) Deep waters at depths from 800 meters to 2500 meters are divided into two layers, CW (Central Waters, 800-1500 m) and DW (Deep Waters, 1600-2500 m) according to linearity in the ϑ-S plot,

2) The potential temperature profile in each layer is fitted first for the mixing parameter K/w (=Z*) using a solution for a conservative tracer (J=0),

$$\vartheta = \vartheta_o + f(z)\,(\vartheta_m - \vartheta_o),$$

$$\text{with } f(z) = \frac{e^{z/z^*} - 1}{e^{z_m/z^*} - 1} \text{ and } z^* = \frac{K}{w}$$

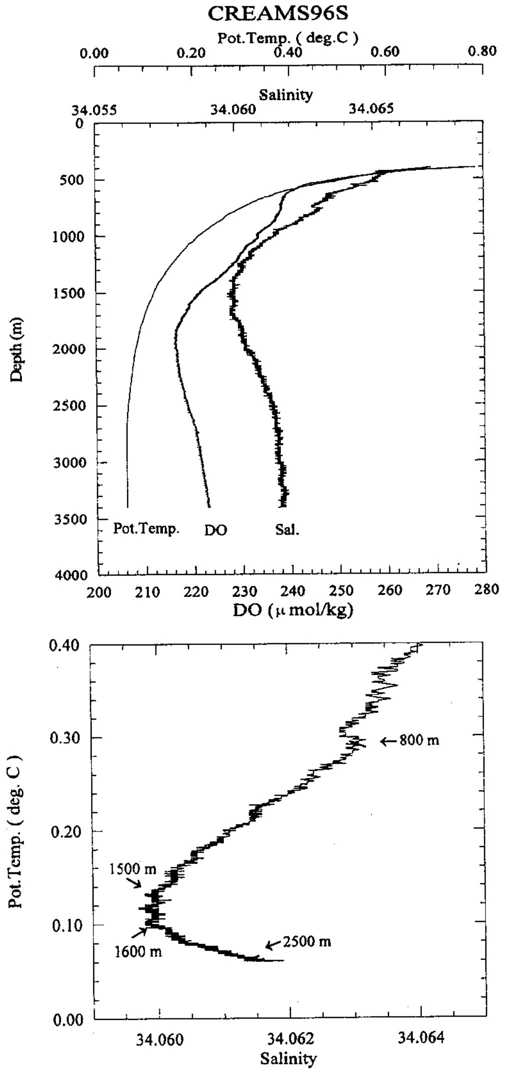


Fig. 5. Profiles of potential temperature, salinity and dissolved oxygen and the ϑ-S plot at a station in western Japan Basin. Deep waters at depths from 800 meters to 2500 meters can be divided into two layers; CW (Central Waters) and DW (Deep Waters) according to the linearity in the ϑ-S plot.

3) The DO profile at each layer is fitted for J/w using Z* values of the layers obtained from the step 2) using a solution for a non-conservative tracer with a constant J,

$$c - c_0 = (c_m - c_0)\, f(z) + \frac{J}{w}\,[z - z_m f(z)]$$

The model application is, in essence, solving two-boundary value problems and the boundary values used for fittings are listed in Table 1.

Table 1. The boundary values used for fitting the potential temperature and DO profiles with an advection-diffusion model.

Layer	Item	q at z_o	q at z_m	z*	J/W
East Sea	Depth (m)	1,500	800		
Central Water	Pot. Temp.(°C)	0.1183	0.2798	0.571	
(ESCW)	DO (μ mol/kg)	222	238		27.0
East Sea	Depth (m)	2,500	1,600		
Deep Waters	Pot. Temp.(°C)	0.0645	0.1082	0.564	
(ESDW)	DO (μ mol/kg)	219	219		-18.4

The results of the model are shown in Fig. 6. The curvature of the temperature profile shows that there is an upward vertical velocity (w>0) with mixing parameters, Z*, 0.57 km and 0.56 km for CW and DW layer, respectively. These values are similar to those obtained for Bottom and Deep Waters in the Pacific Ocean, 0.4~1.1 km (Chung, 1975). The J/w for DW is -18.4 μM/kg/km, showing the consumption of oxygen in deep waters, and is also comparable to the value, -43 μM/kg/km observed in the Pacific (Craig and Weiss, 1970). However, J/w for CW is +27.0 μM/kg/km, that is, "positive", which means a production of dissolved oxygen in CW (Central Waters) layer.

In fact, the only case for a positive J/w reported in deep waters is in Lake Baikal, where fresh surface waters may sink deep into the lake across the top boundary of hypolimnion episodically accompanied by the turbidity current produced by inflowing streams with fine sediments (Craig, 1994). The positive J value for DO in Central Waters strongly suggests a fresh input of surface waters in this layer in recent years.

The existence of bottom adiabatic layer strongly suggests that there used to be a bottom water formation process operating in the past. It is not clear, however, whether bottom water formation is completely shut off and is replaced by the deep water formation in the CW layer. Furthermore, absolute values for K, w, or J cannot be determined, and only ratios to w such as K/w and J/w are available at the present time. The study of C-14 for deep waters will provide a means by which individual parameters K, w, and J can be determined (Craig,

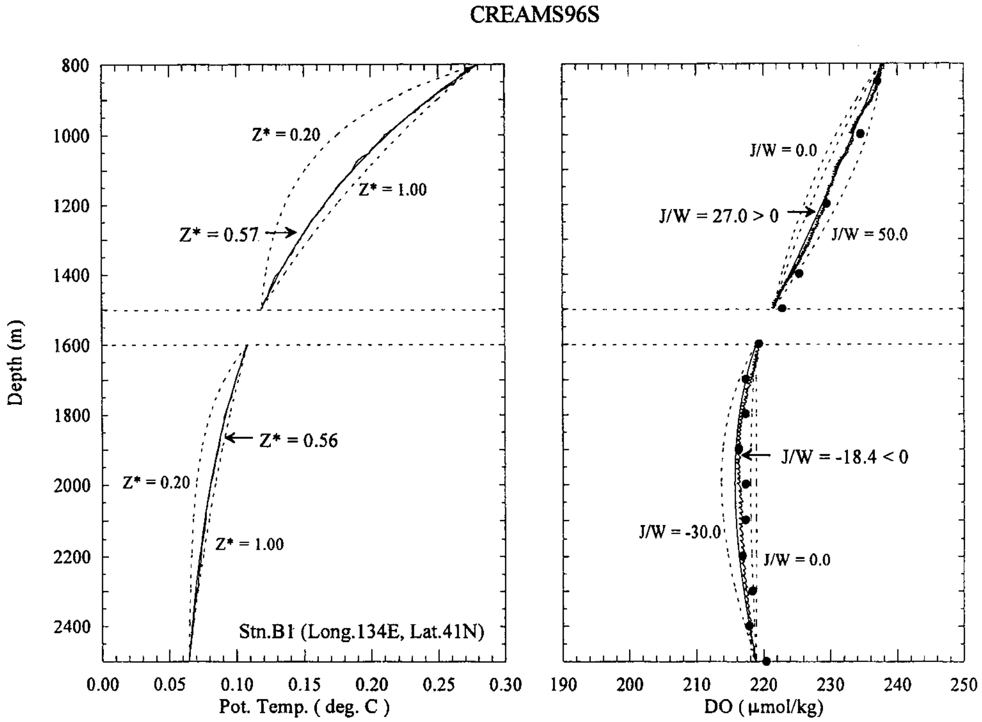


Fig. 6. The results of potential temperature and DO profiles by an one-dimensional advection and diffusion model. The curvature of the temperature profile shows that there is an upward vertical velocity (w>0) with mixing parameters, Z*, 0.57 km and 0.56 km for CW and DW layer, respectively, quite similar to those in the Pacific, 0.4~1.1 km (Chung, 1975). The J/w for DW is -18.4 μM/kg/km, showing the consumption of oxygen in deep waters. However, J/w for CW is +27.0 μM/kg/km, which means a production of dissolved oxygen in Central Water layer.

1969). Studies will also provide important clues on the age of the waters in deep and bottom layers, and are currently underway.

As an attempt to understand the change in mode of deep water formation, a simple 5-box model for the East Sea was developed as shown in Fig. 7. The details of model development and results are presented elsewhere (Park, 1997), and only the essence of the model is presented here:

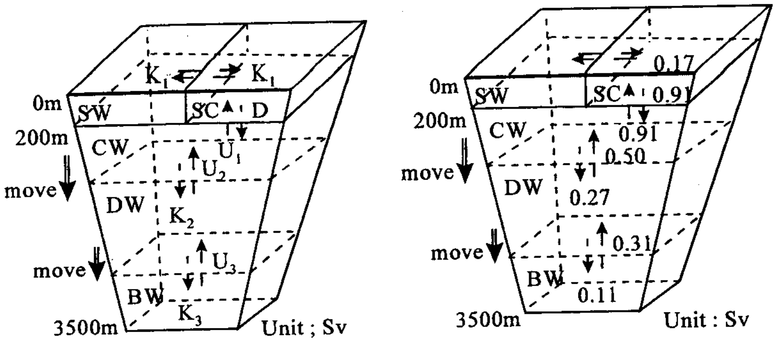
1) The East Sea waters are divided into 5 homogeneous waters: 2 boxes with fixed volumes (WSW, Warm Surface Waters; CSW, Cold Surface Waters), and 3 boxes with variable volumes (CW, Central Waters; DW, Deep Waters; and BW, Bottom Waters).

2) While the individual volume of CW, DW and BW can change with two moving boundaries, the sum of these three is constant.

3) The exchange of surface waters with deep waters can only occur between CSW and CW.

4) The boundary between CW and DW corresponds to salinity minimum depth or the depth for the potential temperature of 0.15°C (~1400 meters in 1996), which has been deepening 600 meters continuously for the last 30 years (Kim, 1996).

The model was calibrated with the tritium results obtained in 1987 by Watanabe *et al.* (1991). The model predicts that the rate of exchange between cold surface waters (CSW) and central waters (CW) is 0.91 Sv. This rate corresponds to ~80 years of the turnover time for total deep waters (Central waters, Deep Waters and Bottom Waters) to the cold surface waters, which has been continuously decreasing from ~160 years in 1960 as shown in Fig. 8. This is fairly comparable to the value obtained by Tsunogai *et al.* (1993) and Chen and Wang (1995) with static box models. The turnover time of the Central Waters, on the other hand, has increased to



Surface = 1.013 E12 m^2
Total Volume (V_{total}) = 1.690 E15 m^3
Vol(SW) = Vol(SC) =0.5x0.12V_{total}
Vol(CW) + Vol(DW) + Vol(BW) = 0.88V_{total}

$U_1 = D$
$U_2 - K_2 = 0.004169V_{total}/yr$
= Vol(800-1400)/30yr - Vol(2000-2500)/27yr
$U_3 - K_3 = 0.003601V_{total}/yr$
= Vol(2000-2500)/27yr

Fig. 7. A moving boundary 5-box model for the East Sea. The East Sea waters are divided into 5 homogeneous reservoirs: 2 boxes with fixed volumes (WSW, Warm Surface Waters; CSW, Cold Surface Waters), and 3 boxes with variable volumes (CW, Central Waters; DW, Deep Waters; and BW, Bottom Waters). While the individual volume of CW, DW and BW can change with two moving boundaries, the sum of these three is constant. The boundary between CW and DW corresponds to salinity minimum depth or the depth for the potential temperature of 0.15°C (~1400 meters in 1996), which has been deepening 600 meters continuously for the last 30 years (Kim, 1996). The model was calibrated with the tritium data by Watanabe *et al.*, (1991). The numbers in arrows are in unit of Sverdrup.

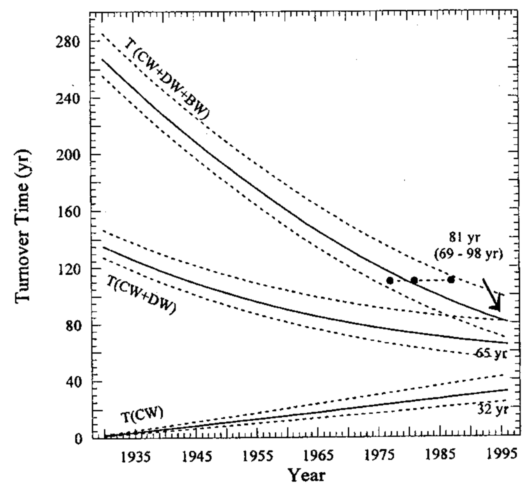


Fig. 8. The plot of turnover time of whole deep waters, Central Waters and Deep Waters, and Central Waters to CSW (Cold Surface Waters) as a function of time. The estimate of Tsunogai *et al.*, (1993) is also shown for comparison.

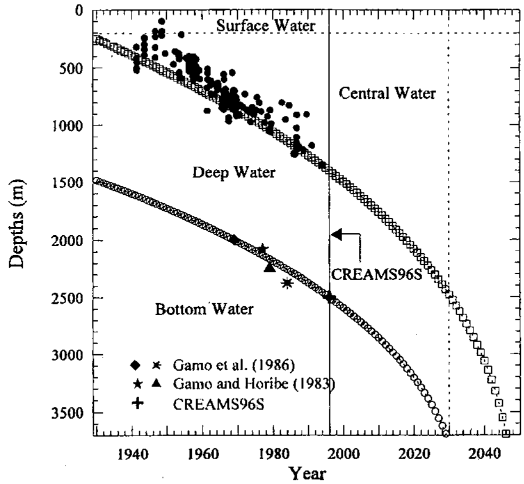


Fig. 9. The change in Deep Water structure through time in the East Sea predicted by the model. A hundred-year time scale from the year 1930 to 2030 is seen for transformation of structures from 2 layers into 3 layers and back to 2 layers.

over 30 years now, mainly due to the increase in reservoir size.

Another interesting prediction of the model, as shown in Fig. 9, is that the boundary between DW and BW will reach a depth of Deep Japan Basin, ~ 3700 meters, and the Bottom Water layer disappears in the year of 2030, resulting in a 2-layer structure (CW and DW), if the changes continue at the current speed. On the other hand, if we go backward in time, the boundary between CW and DW would reach a depth of 200 meters, and the CW layer disappeared in 1930, resulting in another 2-layer system (DW and BW). This prediction, thus, suggests a cycle of ~100 years in deep water ventilation in the East Sea, the meaning of which deserves further detailed investigation in the future.

What is the cause for this change in mode of bottom/deep water formation in recent years? Could there have been a natural oscillation of the mode in deep water formation in the East Sea, perhaps in a time scale of 100 years, suggested by the above model? Or could this be a special phenomenon operating only at this particular time in association with the recent Global Changes such as Global Warming, especially with a very small vertical stratification in the East Sea?

The application of chemical tracers, C-14, tritium, Ra-226, and CFCs, for example, in investigating oceanic problems similar to those discussed above have already been proven very powerful through numerous studies (as the best review, Broecker and Peng, 1982). The tracer application in the East Sea first started with a C-14 study by Gamo and Horibe (1983), which was followed by studies of Ra-226 (Harada and Tsunogai, 1986), Tritium (Watanabe *et al.*, 1991), CFCs (Tsunogai *et al.*, 1993) , and initial nutrients (Kim *et al.*, 1992; Senjyu and Sudo. 1994).

These previous studies, especially those using radioactive isotopes, have provided very important clues as to what is happening in the East Sea. Considering the fact that the East Sea is changing, however, we are seriously lacking in time series measurements of these tracers, in particular, which should deserve top priority in East Sea investigations in the future.

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