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Box model analysis of the long-term dissolved oxygen variation in the Japan Sea Proper Water

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Abstract

It has been revealed that the formation of the Japan Sea Proper Water (JSPW) in both intermediate and deep layers has been stagnating since the 1960s, accompanying with a relatively active intermediate water formation. This study demonstrates such a situation using a simple vertical advection-diffusion box model. The box model qualitatively reproduced the interdecadal oscillation superimposed on the decreasing trend in the dissolved oxygen (DO) concentration throughout the JSPW. However, the simulated amplitude of the interdecadal oscillation in the DO concentration in the deep layers is very small compared with the observed one. This implies that the vertical diffusion is not the main cause of the interdecadal oscillation in DO in the deep layer.

Key words : *Japan Sea Proper Water, vertical advection-diffusion model, dissolved oxygen, interdecadal oscillation, linear trend*

1. Introduction

The Japan Sea is one of the East Asian marginal seas in the western North Pacific, surrounded by the Japanese Islands, Korean Peninsula, and Russian coast, with an average depth of 1667 m (Fig. 1). Because of its semi-enclosed shape and shallow sill depths, the layer below the main thermocline is occupied by the water mass produced in the Japan Sea, the Japan Sea Proper Water (JSPW). Though the JSPW is one of the most homogeneous water masses in the world (Worthington, 1981), in this study, we divide it into the intermediate and deep layers; the former refers to the depths around 1000 m and the latter indicates the layer below 1000 m. This classification is validated by the vertical distribution of water properties (Sudo, 1986; Senjyu and Sudo, 1993, 1994).

It is well known that the JSPW in the deep layer has been warming and decreasing in dissolved oxygen

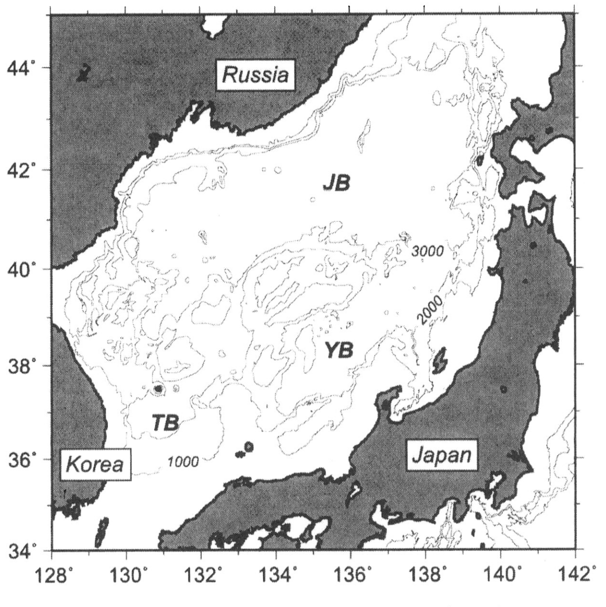

Fig. 1 Map of the Japan Sea with isobaths of 1000, 2000, and 3000 m. JB, YB, and TB denote the Japan Basin, the Yamato Basin, and the Tsushima Basin, respectively.

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(DO) concentration since the 1960s (Gamo et al., 1986; Kim and Kim, 1996; Minami et al., 1999). These trends imply a reduction of the deep water formation. As a cause of the stagnation, global warming is suggested (Gamo, 1999). On the other hand, the interdecadal oscillation with a period of about 20 years are reported in potential temperature (PT) and DO concentration at 2000 m in the JSPW (Watanabe et al., 2003). The interdecadal oscillation is associated with the Arctic Oscillation through the activity of cold-air outbreaks in winter (Cui and Senjyu, 2010).

Recently, on the basis of the hydrographic data in the Yamato Basin (Fig. 1) during the period of 1970-2004, Cui and Senjyu (2012) showed that the trends of warming and DO decreasing, and the interdecadal oscillations in PT and DO are common features found in the depth range of 500-2500 m (Fig. 2). Further, they revealed a minimum layer of the DO decreasing rate around 1000 m (Fig. 2 and Fig. 6). These facts suggest that the formation of the JSPW in both intermediate and deep layers has been stagnating since the 1970s, though there is a relatively active intermediate water formation. However, such a situation is somewhat self-contradictory and it is not certain yet whether the circumstance can be realized actually. In this study, we demonstrate this situation using a simple one-dimensional box model. Results from the box model analysis will give some information about the vertical mixing in the JSPW.

2. Model description

Since our interest is the temporal change of the vertical distribution of the DO concentration, a vertical advection-diffusion model with the deep and intermediate water supply is adopted. Needless to say, the horizontal processes are important for the spreading of the newly formed JSPW from the source region into the whole basin. However, for the qualitative explanation of the main features of the long-term variations in the DO profiles, the vertical one-dimensional model is adequate because of the much shorter timescale of the advection which is estimated to be 12-15 months (Senjyu and Sudo, 1996).

This model is similar to the one used in Minami et al. (1999), and consists of ten boxes with 200 m thickness (Fig. 3). The DO concentration in each box is governed by the equation

$$\frac{\partial O}{\partial t}=\kappa_O\frac{\partial^2 O}{\partial z^2}-W\frac{\partial O}{\partial z}-R$$

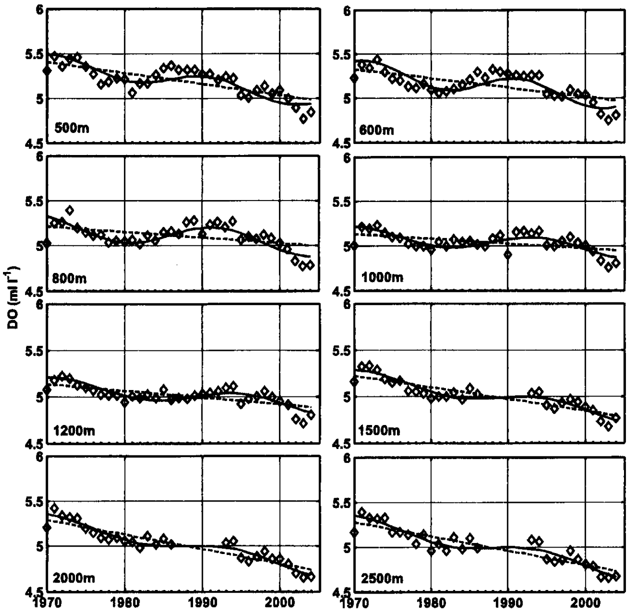

Fig. 2 Time series of the yearly mean DO concentrations from 1970 to 2004 at the eight standard layers in the Yamato Basin. For each layer, linear trend and fitted sinusoidal curve are shown by dashed and solid lines, respectively.

where t and z are time and depth, and O is the DO concentration. κ_O, W and R are the vertical diffusivity, upward advection velocity and DO consumption rate, respectively. As the surface condition, another box representing the layer ranging 0-500 m with a DO concentration of 5.36 mll^{-1} was imposed.

Firstly, to obtain an equilibrium state, oxygen-rich water (5.48 mll^{-1}) was supplied directly into the four bottom boxes (Box 7-10). The water supply is assumed to be equally injected into the four boxes. To conserve the volume of each box, the water in each box should move upward with the following speeds:

$$W_i=W_0 \quad (i=1, \ldots, 7)$$
$$W_8=(3/4)W_0, \quad W_9=(2/4)W_0, \quad \text{and} \quad W_{10}=(1/4)W_0$$

where W_0 is the upward advection velocity, which is equal to the velocity of injected water from the surface. After some tried and error examinations, the values of κ_O, W_0 and R were decided to be 1.2×10^{-4} m^{2}s^{-1}, 1.43×10^{-6} ms^{-1} (45 m yr^{-1}) and 9.0×10^{-3} mll^{-1}yr^{-1}, respectively. If we change the parameters, different equilibrium state can be obtained. However, the behavior of the solution would not change significantly. The obtained equilibrium state is shown in Fig. 4, and the results are comparable to the observational results in the 1960s (Minami et al., 1999; Kim et al., 2004).

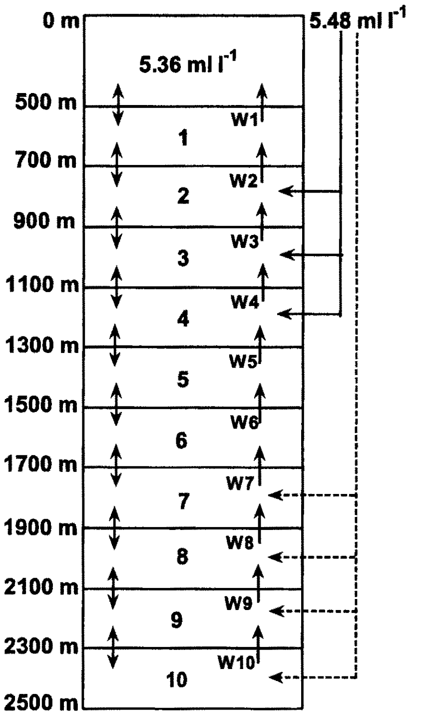

Fig. 3 Configuration of the vertical advection-diffusion model. Two way arrows are vertical diffusion and upward arrows indicate advection with velocity of Wi (i=1, ..., 10). Dashed and solid long arrows indicate the deep and intermediate water supply, respectively.

Then, the water injection was changed into Box 2-4 to represent the relatively active DO supply into the intermediate layer. The water was also assumed to be injected into the three boxes equally. Consequently, the upward velocities of the deeper 6 boxes (W_{10}-W_5) disappeared and those in the upper 4 boxes were:

$$W_i=W_0 \quad (i=1,\ 2),$$
$$W_3=(2/3)W_0 \quad \text{and} \quad W_4=(1/3)W_0$$

To demonstrate the observed situation, we carried out the two experiments: the intermediate water supply with the interdecadal oscillation (Exp. 1) and the intermediate water supply with the interdecadal oscillation and a linear trend in the surface layer (Exp. 2).

3. Results

3.1 Intermediate water supply with the interdecadal oscillation (Exp. 1)

As the first experiment (Exp. 1), we introduced a 20-year periodicity oscillation with amplitude of 0.12 ml l^{-1} in the DO concentration into the intermediate injected water. Variations of the DO concentration from 600 m to the bottom are shown in Fig. 5.

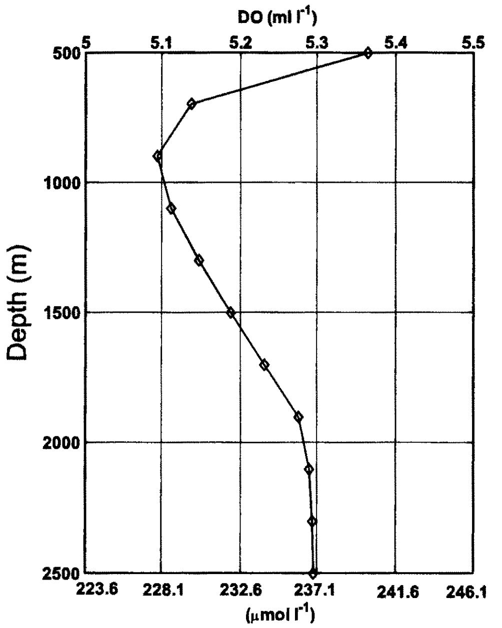

Fig. 4 Vertical distribution of the DO concentration at the equilibrium state.

The interdecadal oscillations are well simulated at the depths shallower than 1600 m. While at deeper depths in Box 6-10, though the oscillations still can be recognized, the amplitudes are much smaller than those in the upper layers. The interdecadal oscillations below Box 4 are due to the diffusion from the upper boxes because it is the only mechanism to transport DO into these boxes.

The vertical profile of the linear decreasing rates in the DO concentration from the Exp. 1 is shown in Fig. 6, along with that from the observations in the Yamato Basin. Though the negative rates (decreasing trends) were found throughout the depths, the minimum layer of the decreasing rate around 1000 m, as found in the observed profile, is not reproduced by the Exp. 1. The negative rates from the Exp. 1 in the depths shallower than 2000 m are smaller than observations, especially in the depth range of 600-1000 m.

3.2 Intermediate water supply with the interdecadal oscillation and a linear trend in the surface layer (Exp. 2)

Since a decreasing trend is also observed at a depth of 500 m in the Yamato Basin (Fig. 2), we added another assumption on the surface water with a decreasing trend of -0.012 mll^{-1}yr^{-1} (Exp. 2). Other conditions are same as those used in Exp. 1.

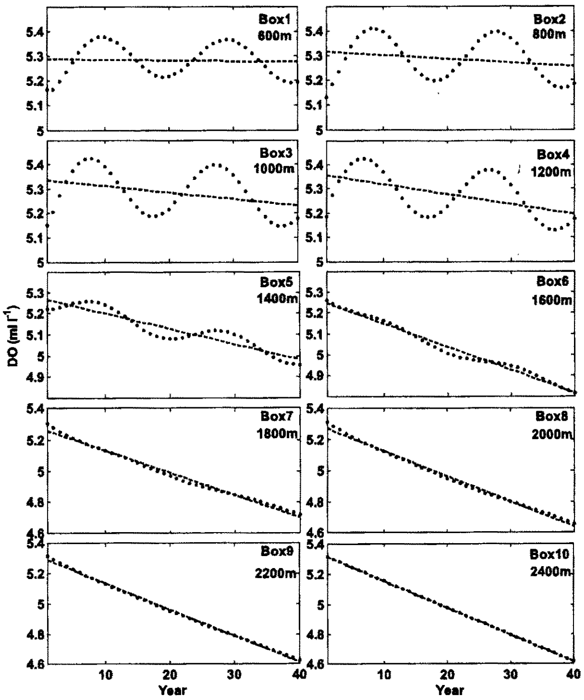

Fig. 5 Time series of the simulated DO concentration in each box from Exp. 1. Dots are model output and dashed lines denote the linear trend.

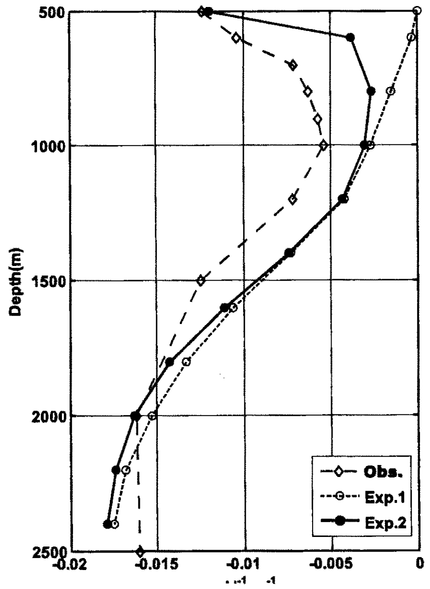

Fig. 6 Vertical distributions of the linear decreasing rates in the DO concentration below the depth of 500 m.

Variations of the DO concentration in each box from Exp. 2 are shown in Fig. 7. Similar to the results from Exp. 1, the interdecadal oscillation and decreasing trends are well simulated in Exp. 2, though the amplitudes of the oscillation in Box 7-10 are still very small compared with those in the upper boxes. The decreasing rates throughout the depths became clearer than those in Exp. 1 (Fig. 5).

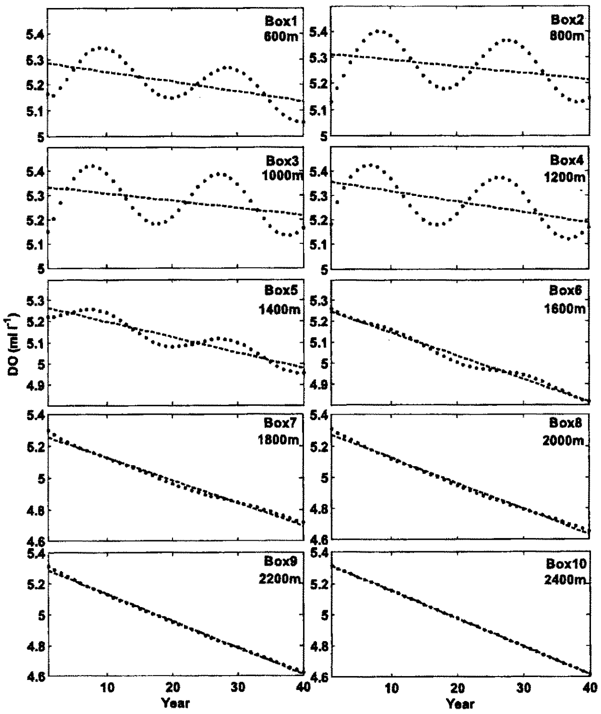

Fig. 7 Same as Fig. 5 except for Exp. 2.

The vertical distribution of the linear decreasing rates in the DO concentration from Exp. 2 is also shown in Fig. 6. The minimum layer of the decreasing rate is qualitatively reproduced around the depth of 800 m, though the negative rates at depths shallower than 2000 m are still smaller than those of observations. Since the decreasing rates at the depths of 1000-1600 m are almost the same between Exp. 1 and 2, the reproduced minimum layer of the decreasing rate is due to the added linear variation in the surface water.

These results demonstrate that the continuous slowing down of the overall JSPW formation can be realized even under the condition of continuous oxygen-rich water supply into the intermediate layers.

4. Remarks

The vertical advection-diffusion model with the intermediate water supply qualitatively reproduced the interdecadal oscillation superimposed on the decreasing trend in the DO concentration throughout the JSPW. However, there are some discrepancies between the model results and the observed DO variations.

The amplitudes of the interdecadal oscillation below the depth of 1600 m (Box 6-10) were much smaller than those in Box 1-4. The observed amplitude of the interdicadal oscillation also shows a decreasing tendency with depth, but the amplitude below the depth of 1000 m are about a half of those in the 500-800 m layers (Fig. 2). The interdecadal oscillations in Box 5-10 are due to the vertical diffusion because there are no vertical advections of W_5-W_{10} under the assumption of the intermediate water supply (Fig. 3). This can be confirmed by the time lags delaying with depth in the DO variations of Box 5-10. Since the interdecadal oscillation observed in the Yamato Basin shows the almost simultaneous variation throughout the water column with larger amplitudes than those of the simulation, the vertical diffusion is not the main cause of the interdecadal oscillation in the deep layers. In this model, we assumed that there is only the intermediate water formation. However, the deep water might be formed with an interdicadal periodicity as well. The larger amplitude observed at 2500 m (0.074 mll^{-1}) than those at the 1500-2000 m layers suggests this possibility (Fig. 2 and Cui and Senjyu, 2012).

Below the depth of 2000 m, the linear decreasing rates in the DO concentration from Exp. 1 and 2 increase with depth, while the observational rates are almost constant (Fig. 6). The difference between the observations and model results is possibly due to the vertical mixing in the bottom layer. It is known that the Bottom water characterized by the extreme vertical homogeneity in water properties is distributed below about 2000 m in the Japan Sea (Gamo and Horibe, 1983). Senjyu et al. (2005) estimated the vertical diffusivity of $O(10^{-3})$ m^2s^{-1} in the Bottom water, which is one order of magnitude larger than that used in this model. Some mechanisms for the large vertical diffusivity in the Bottom water were proposed: geothermal heating, breaking of near-inertial internal waves and submesoscale eddies with large vertical extension (Senjyu et al., 2005).

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