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Diagnosing long-term trends of the water mass properties in the East Sea (Sea of Japan)

Young-Oh Kwon,[1] Kuh Kim,[2] Young-Gyu Kim,[3] and Kyung-Ryul Kim[2]

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[1] Steady changes of temperature and oxygen concentration since the 1950s have been observed in the East Sea. In addition to temperature and oxygen, this study extends the analysis to salinity observations. Salinity has increased between 300 and 1000 m and decreased below 1500 m with a trend of about 0.06 and −0.02 psu/century, respectively. A simple diagnostic inverse model indicates that the changes in the intermediate depth (300–1000 m) were primarily due to a change in salinity at the surface outcrop, and those in the deep and bottom water were due to not only a warming of the surface source water but also a circulation change in the deep and bottom water, with similar magnitudes of contributions from the two factors. Both the observations and model consistently suggest that the water mass structures have changed during the last few decades. *INDEX TERMS:* 4243 Oceanography: General: Marginal and semienclosed seas; 4215 Oceanography: General: Climate and interannual variability (3309); 4283 Oceanography: General: Water masses; 4271 Oceanography: General: Physical and chemical properties of seawater; 1635 Global Change: Oceans (4203). **Citation:** Kwon, Y.-O., K. Kim, Y.-G. Kim, and K.-R. Kim (2004), Diagnosing long-term trends of the water mass properties in the East Sea (Sea of Japan), *Geophys. Res. Lett.*, *31*, L20306, doi:10.1029/2004GL020881.

1. Introduction

[2] *Levitus et al.* [2000] reported that the world ocean has warmed by about 0.3°C during the last five decades. The corresponding heat content increase in the ocean was at least one order of magnitude greater than the increase in the heat content of any other component of Earth's climate system [*Levitus et al.*, 2001]. In addition to the temperature changes, recent observations also revealed changes in salinity [e.g., *Dickson et al.*, 2002] and concentration of chemical tracers [e.g., *Bates et al.*, 2002].

[3] The East Sea (Sea of Japan) also experienced changes similar to those observed in the open ocean since the 1950s [*Kim et al.*, 2001]. Investigating changes in the marginal seas such as the East Sea has certain advantages, with important implications for the understanding of global ocean changes, since the marginal seas generally have a much shorter response time to a given surface forcing than the open ocean has. In particular, the East Sea provides a unique opportunity as a natural test bed to better understand a future global ocean change due not only to its short response time, but also its striking similarities with open oceans. The similarity in structures and processes has led oceanographers to often refer to the East Sea as a miniature ocean [*Kim et al.*, 2002; *Talley et al.*, 2003].

2. Observed Changes

[4] A series of observational studies reported long-term changes of temperature and dissolved O_2 concentration in the East Sea [e.g., *Gamo et al.*, 1986; *Kim and Kim*, 1996]. In addition to the temperature and O_2, this study extends the analysis to salinity observations. Salinity observed at station PM5 [*Minami et al.*, 1999] (Figure 1) had an increasing trend at 500 m and a decreasing trend at 2500 m since 1965 (Figure 2). The trends were 0.06 psu/century at 500 m and −0.02 psu/century at 2500 m. The trends were statistically significant at the 99% and 75% confidence levels, respectively.

[5] This study also extends the analysis to the four major sub-basins of the East Sea (Figure 1) to examine the regional differences and/or similarities in the observed long-term changes, since the most of the previous studies focused on the changes only in the Japan Basin, the northern half of the East Sea. To this end, we focused on the differences between the observations in two different years with basin-wide observations: 1969 and 1995. Our approach is justified by the continuous and nearly monotonic nature of the observed changes from the early 1950s to present, which was confirmed by time series studies [*Kim*, 1996; *Minami et al.*, 1999; *Riser et al.*, 1999]. Observations in 1969 consisted of two surveys. One was carried out in July 1969 and the other in September–November 1969 [*Nitani*, 1972; *Sudo*, 1986]. Observations from the CREAMS Expedition [*Kim et al.*, 1996] in August 1995 were used for comparison with the 1969 data. 10–16 profiles were available for each 2° × 2° region, which include A69 and A95 data for WJB.

[6] Differences between average profiles of temperature, salinity, and O_2 in 1969 and 1995 for the four sub-regions exhibited remarkable similarities in both sign and magnitude (Figure 3). These very small regional differences were consistent with the spatial homogeneity in the mean water mass properties throughout the East Sea [*Riser et al.*, 1999; *Kim et al.*, 2001].

[7] Temperature increased throughout the water column below the seasonal thermocline. The 26-year differences were as large as 0.5°C around 300 m and between 0.01 and 0.1°C below 1200 m (Figure 3a). The only exception was the cooling observed above 500 m in the Yamato basin. This cooling was independent of the seasonal difference between the observations since the seasonal thermocline is located

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[1] Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado, USA.

[2] OCEAN Laboratory/RIO, School of Earth and Environmental Sciences, Seoul National University, Seoul, Korea.

[3] Naval Systems Research and Development Center, Agency for Defense Development, Chinhae, Korea.

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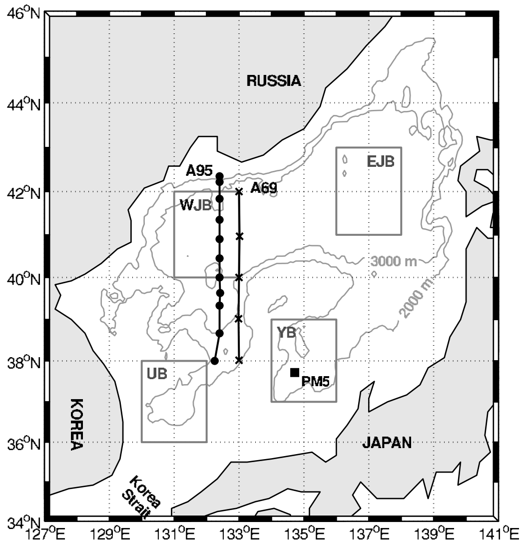

Figure 1. Locations of data used in this study. WJB, EJB, UB, and YB stand for the Western Japan Basin, the Eastern Japan Basin, the Ulleung Basin, and the Yamato Basin, respectively.

above 200 m in this region [*Kim*, 1996], and the 1995 data was observed in August, the warmest month of the year. *Minami et al.* [1999] also reported a cooling trend since the 1960s at 500 m from the time series at station PM5. The upper few hundred meters south of the polar front is directly influenced by inflow from the North Pacific through the Korea (Tsushima) Strait. It is interesting that the cooling in the upper Yamato Basin was consistent with the cooling in the western and central North Pacific that accompanied the phase shift of the Pacific Decadal Oscillation (PDO) around 1977 [*Mantua et al.*, 1997].

[8] Differences in salinity were more variable in the upper 700 m, but generally increased (Figure 3b), which was consistent with the trend from the time series at PM5 (Figure 2a). Below 700 m, all four regions had changes with the same sign and similar magnitudes. Salinity increased by as much as 0.01 psu between 700 and 1200 m, and decreased by about 0.004 psu below 1700 m.

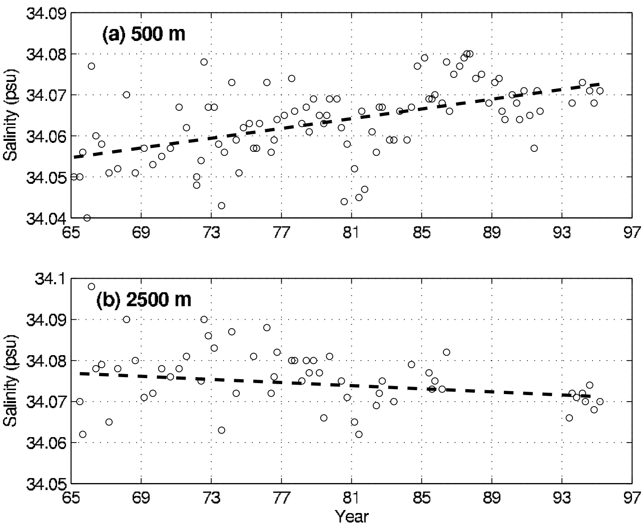

Figure 2. Salinity at PM 5 (37°43′N, 134°43′E) for (a) 500 m and (b) 2500 m. Dashed lines are the linear trends calculated by least squares fitting.

[9] O_2 concentrations revealed three different vertical modes of change found in all four regions. In the uppermost regime, shallower than the depth of the O_2 minimums in 1969 (~500–700 m), O_2 decreased by about 10–50 μM. In the second vertical regime, between the depth of the 1969 O_2 minimums and about 1300 m, O_2 uniformly increased. The maximum magnitudes of the increase were about 20 μM except in the Yamato basin, where it was 7 μM. Below 1300 m where the O_2 minimums in 1995 were found, O_2 decreased by about 20 μM in all four basins.

3. Interpretation of the Observed Changes

[10] Simple box models, using the observed changes of temperature and O_2 as constraints, suggested that the observed changes were consistent with a substantial shallowing of the ventilation system, from deep and bottom water ventilation before the 1950s to intermediate water ventilation since the 1950s [*Kim and Kim*, 1996; *Riser et al.*, 1999; *Kang et al.*, 2003].

[11] In this study, an alternative approach was adopted following *Bindoff and McDougall* [1994] (hereinafter referred to as BM94), who proposed an inverse model to diagnose changes between two groups of temperature and salinity observations separated in time. The inverse model separates the cause of the observed change of temperature and salinity into three categories, i.e., a pure temperature change in the surface source of the water mass due to a change in air-sea heat flux (= *pure warming* in BM94), a pure salinity change of the source due to a change in fresh water flux at the surface (= *pure freshening*), and an adiabatic change of the density structure (= *pure heaving*). (Refer to BM94 for the detailed method.)

[12] For the inverse modeling, two closely located synoptic sections of temperature and salinity were selected. The first section was observed along 133°E in October 1969 [*Sudo*, 1986] (A69 in Figure 1). The second section was

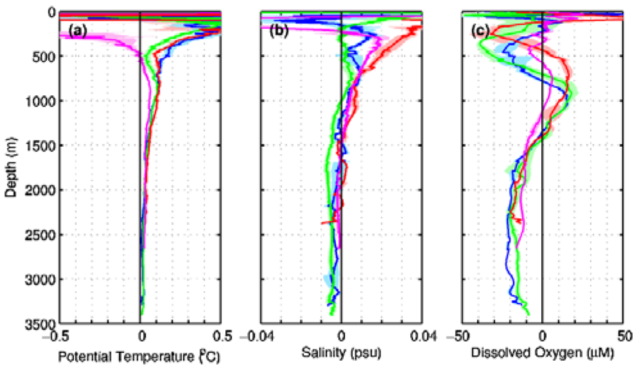

Figure 3. Profiles of 1995-mean minus 1969-mean along depth surfaces for each 2° latitude × 2° longitude region. Blue, green, red, and pink curves are from the WJB, EJB, UB, and YB, respectively. Shadings are the one standard error ranges. (a) Potential temperature, (b) salinity, and (c) dissolved O_2 concentration.

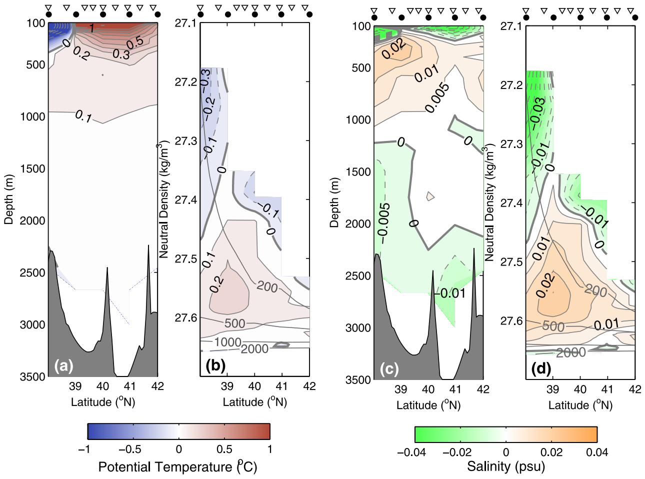

Figure 4. Difference sections between A95 and A69, i.e., A95 minus A69, for (a, b) temperature and (c, d) salinity. Differences were calculated along constant depths for (a, c) and along constant neutral density surfaces for (b, d). Average depths corresponding to the neutral density surfaces are also contoured in (b) and (d) for 200, 500, 1000, and 2000 m.

observed along 132°24′E in August 1995 [*Kim et al.*, 1996] (A95 in Figure 1). To calculate differences between the two synoptic sections separated by 26 years, A95 was interpolated to the latitudes and depths of A69.

[13] Temperature increased throughout the section with a very small meridional difference in magnitude (Figure 4a). The only exception was the cooling observed in the upper few hundred meters south of 39°N, which reached up to −7°C. However, the enhanced difference in the upper few hundred meters, for both the cooling and warming regimes, was substantially reduced when the differences were calculated along constant neutral density surfaces (γ_n) (Figure 4b). The maximum cooling along γ_n was only −0.3°C, while it was −5°C along the corresponding depth surface (∼200 m). For the warming regime, the maximum differences were 0.2°C on γ_n and 0.7°C along the corresponding depth. The warming below 500 m was almost twice as large when the difference was calculated along depth surfaces. Since any difference caused by a vertical displacement of density surface will be compensated when the difference is calculated along constant γ_n [*Levitus*, 1989], most of the cooling and more than 50% of the warming could be attributed to changes in the density structure. Salinity changes were at different signs for the intermediate depths and the deep and bottom water (Figure 4c). Salinity increased throughout the section between 200 and 1000 m, with a maximum increase of 0.02 psu around 39°N and 300–400 m. In the deep and bottom water below about 1500 m, salinity decreased by as much as 0.01 psu.

[14] The inverse model was applied to the pairs of temperature and salinity profiles at each of five latitudes. Both the minimum-norm solutions for the underdetermined case (Figures 5a–5e) and the single-process solutions for the overdetermined case (Figures 5f–5j) were obtained. Note that the solutions were calculated based on the γ_n coordinate [BM94], but displayed on corresponding average depths of the γ_n to assist the comparison with the previous figures. For all five latitudes, the solutions from the two approaches produced consistent results (Figure 5).

[15] The cooling in the upper 500 m at the southernmost station was diagnosed to be driven mainly by pure warming and pure heaving (Figures 5a and 5f). In particular, the major contribution from pure heaving was consistent with the reduced observed cooling on the γ_n (Figure 4b). This result was also consistent with the magnitude of the PDO-related cooling in the central North Pacific, which is probably the upstream source of the surface water south of the polar front in the East Sea. This cooling was less than 1°C [*Mantua et al.*, 1997], while the observed cooling in the East Sea was greater than 5°C. Changes in the branching of the Tsushima Current could also explain the large observed cooling. As is enters the East Sea through the Korea Strait, the Tsushima Current splits into two or three branches, whose number and location are highly variable [*Kim and Legeckis*, 1986]. Since each branch is associated with a strong temperature front, changes in the location and number of branches could produce temperature and density structure changes as large as those observed.

[16] Pure freshening dominated over the other two factors in the 300–1000 m depth range (Figure 5). This depth range corresponds to the layer where the salinity increase was observed (Figure 4c). This inverse model result suggests that the introduction and expansion of Central Water (CW) and High Salinity Intermediate Water (HSIW) during the 1990s at the corresponding depth range [*Kim*, 1996; *Kang et al.*, 2003] were due to a fresh water flux change at the surface outcrop of these intermediate depth water masses.

[17] Below 1000 m, pure warming and pure heaving dominated over pure freshening (Figure 5). This result is consistent with the observed warming trend of the winter surface air temperature in the northern part of the East Sea [*Kim et al.*, 2002], where the deep and bottom waters form

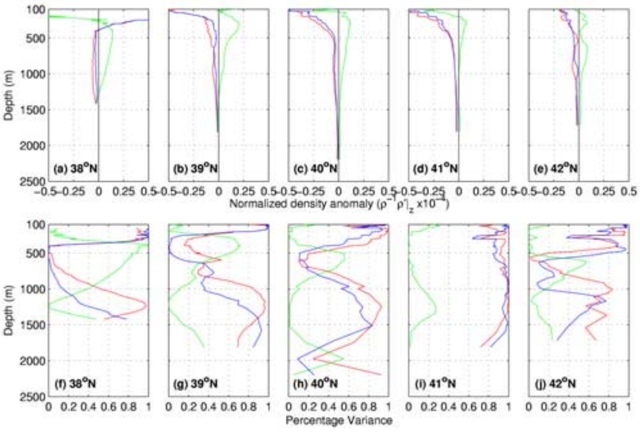

Figure 5. Solutions for the inverse model of BM94 applied to the changes between A95 and A69. Red, green, and blue curves indicate the strength of the changes due to pure warming, pure freshening, and pure heaving, respectively. (a–e) Density anomaly ($\rho^{-1}\rho'|_z$) contributed by each process for the minimum norm solution. (f–j) Percentage variance explained by each process alone calculated as the solutions for the single process model.

[*Kim et al.*, 2002; *Talley et al.*, 2003]. The comparable magnitude pure heaving and pure warming implied that not only the deep and bottom water mass properties have changed in association with the changes at the sea surface, but also the circulation in this depth range has changed substantially since the 1960s. It is conceivable that a diabatic change due to a source water change and an adiabatic density structure change are not completely independent, since any diabatic change would cause a dynamical re-adjustment.

4. Conclusion

[18] The long-term trend of salinity in the East Sea was analyzed. The change in salinity was marginally detectable and required some caution, because the accuracy of the salinity observations in the 1960s is considered to be no better than 0.01 psu [*Senjyu and Sudo*, 1993]. However, the consistent changes observed from various approaches, i.e., the time series (Figure 2), the difference between the averaged profiles from the four different sub-regions (Figure 3b), and the difference between the two meridional synoptic sections (Figures 4c and 4d), provided confidence in our results.

[19] The observations and simple diagnostic inverse modeling consistently suggested a change in the vertical mode of ventilation during the past few decades, i.e., from deep and bottom water formation in the past to intermediate water formation at present, and pointed to the resulting water mass structure changes as the main cause of the observed changes in the East Sea [*Kim and Kim*, 1996]. However, the diagnostic inverse model also suggested that not only diabatic changes at the surface outcrops but also adiabatic circulation changes could explain a significant portion of the observed changes in the deep and bottom waters. This view provides an adequate explanation for the widespread confusion between the overlapping names and definitions for the water masses in the East Sea. For example, the Upper portions of the Japan Sea Proper Water (UJSPW) [*Sudo*, 1986], CW, and HSIW occupy similar spatial and depth ranges [*Min*, 2002], but UJSPW was defined based on the 1960s observations while CW and HSIW were defined from the CREAMS observations in the 1990s. Thus, the overlapping of these definitions could be actually due to different water mass structures in the 1960s and 1990s.

[20] The observed potential temperature change in the East Sea was as large as those reported in the open oceans, while the salinity change in the East Sea was about an order of magnitude smaller. Comparison of the total heat and fresh water content changes between 1969 and 1995, based on the temperature and salinity profiles in the four sub-basins (Figures 3a and 3b), also elucidates the relative smallness of the salinity change. The rate of change for the heat content of the water column below 300 m was 0.74 ± 0.20 W/m^2, which corresponded to about 1% of the climatological mean surface heat flux in the East Sea [*Hirose et al.*, 1996]. The corresponding rate of change for the fresh water content was 0.00033 ± 0.00009 m/yr, which corresponded to only about 0.01% of the climatological mean evaporation-minus-precipitation [*Peixoto and Oort*, 1991]. Despite their relative smallness, salinity changes played a significant role in the water mass structure change especially in the intermediate depth. The water mass structure was sensitive to even small changes in salinity, because the vertical stability and the range of vertical variation of salinity were also very small in the East Sea, an order of magnitude smaller then those in the open ocean [*Kim et al.*, 2001]. The enhanced sensitivity due to the weak background vertical stratification, in addition to an order of magnitude smaller turn-over time (~100 years), makes the East Sea an excellent test basin for understanding the observed temperature and salinity changes in the global ocean.

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K. Kim and K.-R. Kim, OCEAN Laboratory/RIO, SEES, Seoul National University, Seoul 151-742, Korea.

Y.-G. Kim, Naval Systems Research and Development Center, Agency for Defense Development, P.O. Box 18, Chinhae 645-600, Korea.

Y.-O. Kwon, Climate and Global Dynamics Division, National Center for Atmospheric Research, P. O. Box 3000, Boulder, CO 80307–3000, USA. (yokwon@ucar.edu)