Ocean Reanalysis and its Application to Water Mass Analyses in the Pacific

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INTRODUCTION

Ocean analysis/reanalysis experiments are conducted with the MRI ocean data assimilation system MOVE/MRI.COM. The system adopts a multivariate 3DVAR scheme, in which adopted are a coupled temperature-salinity empirical orthogonal functional decomposition in vertical and horizontal Gaussian structure for the background error covariance matrix. The multivariate scheme enables us to estimates salinity field from temperature and remote-sensed sea level. The analysis/reanalysis experiments are conducted in global and the North Pacific with different model resolutions, which are contributions to the international research projects of GOOS/GODAE and CLIVAR/GSOP Ocean Reanalysis. Comparison of ocean state and water mass of the datasets with observation show how much the datasets are accurate. Using these analysis/reanalysis datasets, water mass distributions and variability have been investigated as an example of ocean climate variation.

In this paper, we introduce the system configuration of the ocean data assimilation systems concisely, simple validation of analysis/reanalysis datasets, and describe freshening of mid-depth subtropical gyre in the North Pacific as an example of application of the analysis/reanalysis datasets. We estimated a linear freshening trend between the main thermocline and the salinity minimum layer of the North Pacific Intermediate Water, mainly caused by isopycnal surface deepening due to warming. The freshening is due to global warming.

SYSTEM CONFIGURATION OF MOVE/MRI.COM AND ANALYSIS/REANALYSIS

The ocean General Circulation Model (GCM) used is MRI.COM, a multi-level GCM developed in MRI (Tsujino and Yasuda 2004, Ishikawa et al. 2005). Its three versions are used for the data assimilation systems. (1) global: It has a global domain within 75°S-75°N and 50 levels. The grid spacing in the zonal direction is 1° and that in the meridional direction is 0.3° within 5°S-5°N and 1° poleward of 15°S and 15°N. (2) North Pacific: It has a North Pacific domain within 15°S-65°N 100°E-75°W and 54 levels. The grid spacing is 0.5°. (3) western North Pacific: It has a western North Pacific domain within 15°N-65°N 115°E-160°W and 54 levels. The grid spacing is 0.1° around Japan (see also Usui et al. 2006). Atmospheric forcing fields used are NCEP-R1 and R2 (Kalnay et al. 1996, Kanamitsu et al. 2002), ERA40 (Uppala et al. 2005) and JRA25 (Onogi et al. 2007).

The ocean data assimilation system has four versions: (1) global (MOVE/MRI.COM-G, hereafter MOVE-G), (2) North Pacific (MOVE/MRI.COM-NP, hereafter MOVE-NP), (3) western North Pacific (MOVE/MRI.COM-WNP) (Usui et al. 2006) and (4) global and coupled atmosphere and ocean (MOVE-C, see Fujii, 2008). The systems (1)-(3) are operationally used from March 2008 in JMA for monitoring of the equatorial Pacific and providing JMA/MRI-CGCM with ocean initial condition and operational nowcasting and forecasting of ocean state around Japan. In the assimilation scheme, temperature and salinity fields are analyzed by a multivariate 3-dimensional variational method using coupled temperature-salinity empirical orthogonal functional decomposition (Fujii and Kamachi 2003). In situ temperature and salinity profiles, satellite altimetry and sea surface temperature data are used in the analysis. The result is inserted into the models through incremental analysis updates.

The analysis/reanalysis is conducted for three versions: global ocean (MOVE-G RA) for the period of 1948-2006, the North Pacific Ocean (MOVE-NP RA) for 1948-2005 with the atmospheric forcing NCEP-R1, and western North pacific (MOVE-WNP RA) for 1993-2005 with the atmospheric forcing NCEP-R2.

COMPARISON BETWEEN ANALYSIS/REANALYSIS DATASETS AND OBSERVATION

We compare the ocean state and water mass property derived from the analysis/reanalysis data with observation as simple examples of validation of the analysis/reanalysis datasets (see LeProvost et al. 2002 for metrics of the validation in detail).

At first, ocean state is investigated. Figure 1 shows comparison of distribution of the Kuroshio and Oyashio waters in a vertical zonal section along 144E in October 2000. Analysis/reanalysis (MOVE-NP RA) data recover well the Kuroshio water (subtropical water) with high temperature and high salinity south of 37N, the Kuroshio warm core ring around 39N, and Oyashio water (subpolar water) with colder and less saline water that surrounds the the Kuroshio warm core ring. Figure 2 shows comparison of salinity distribution of the North Pacific Intermediate Water (NPIW) with low salinity in a vertical meridional section along 165E. It is a combined figure with the different observation periods of April (right half) and September (left half) in 2000. The MOVE-NP RA shows the typical feature of the low salinity distribution of the NPIW.

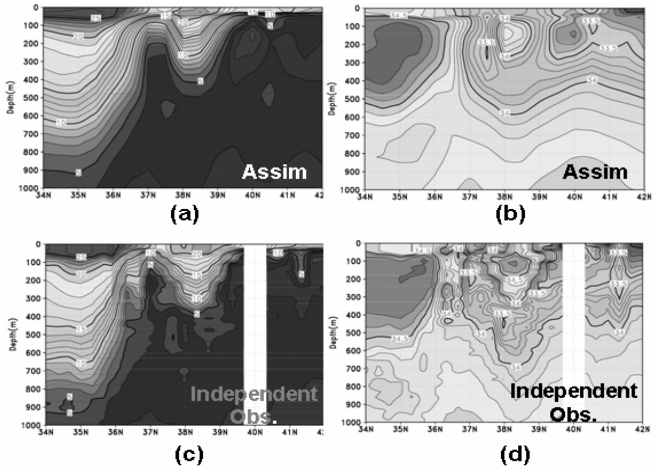

Figure 1 Comparison of distribution of the Kuroshio and Oyashio waters in a vertical zonal section along 144E in October 2000. (a) and (c): temperature, (b) and (d): salinity fields. (a) and (b): analysis/reanalysis (MOVE-NP RA), (c) and (d): independent ship observation.

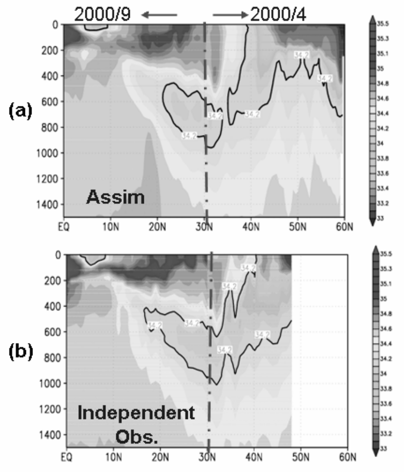

Figure 2 Comparison of salinity distribution of the NPIW with low salinity in a vertical meridional section along 165E in April (right half) and September (left half) 2000. (a): analysis/reanalysis (MOVE-NP RA), (b): independent ship observation.

We next investigate water mass property. Figure 3 shows the T-S diagram along 137E section. Main features of the mid-depth salinity minimum and surface Kuroshio water are recovered well, although surface exceptional data of low salinity that relates to surface precipitation are not recovered. Figure 4 shows the mean T-S property along each JMA repeat hydrography sections around Japan. Although on almost all lines the T-S property is recovered, the analysis/reanalysis data has bias in the bottom of the Japan Sea (PM) and confluence zone of Oyashio, Tsugaru current and Kuroshio (PH). In the North pacific, Figure 5 shows comparison of the mean water mass feature of climatological observation WOA01 and analysis/reanalysis MOVE-G RA on T-S diagram in the specific seven areas according to Emery (2001). The water mass property is recovered well with the salinity bias less than 0.05. Figure 6 shows a space-time distribution of barrier layer thickness (BLT) and isothermal line of 29C along the equator calculated from MOVE-G RA. Seasonality and interannual variation with ElNino of the BLT are represented. Relationship among BLT, thermal and velocity fields related to south Pacific tropical water and south equatorial current is examined from the dataset (Nakano and Fujii 2007, personal communication).

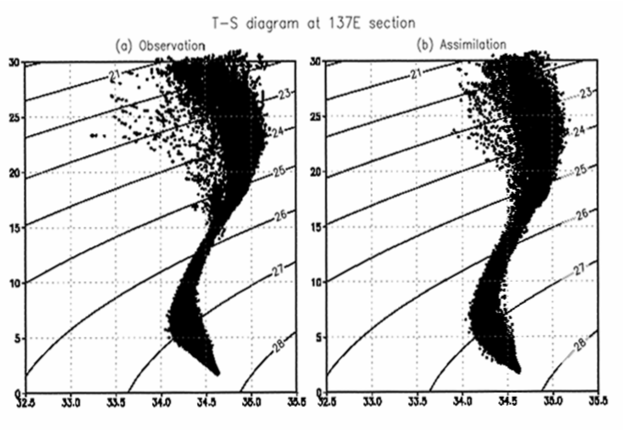

Figure 3 Water mass (temperature and salinity) feature on T-S diagram along 137E section. (a): ship observation, (b) MOVE-WNP RA.

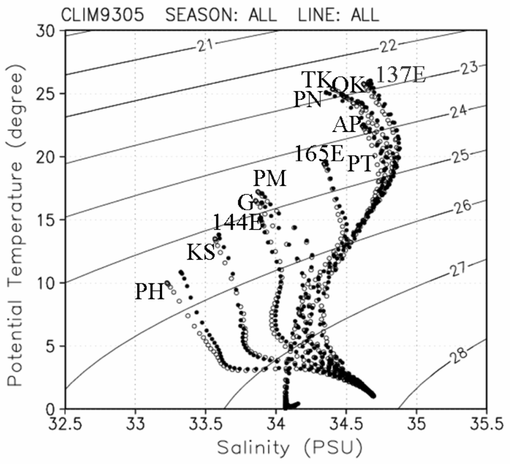

Figure 4 Mean water mass feature of ship observation (○) and MOVE-WNP RA (●) on T-S diagram along JMA hydrography sections in the western North Pacific.

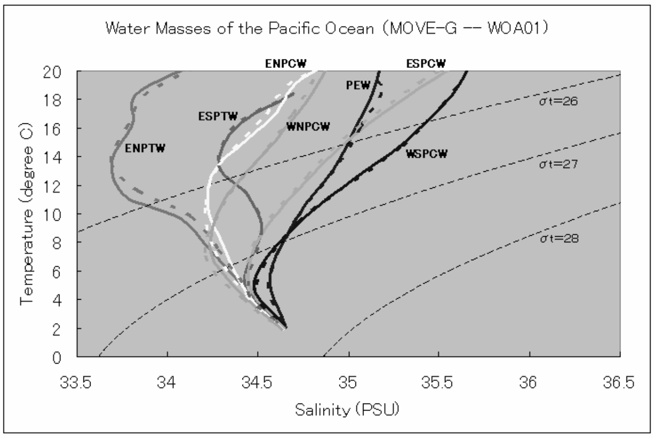

Figure 5 Mean water mass feature of climatological observation WOA01 (broken line) and MOVE-G RA (solid line) in the specific areas by Emery (2001). ENPTW (ESPTW): Eastern North (South) Pacific Tropical Water, ENPCW (WNPCW): Eastern (Western) North Pacific Central Water, PEW: Pacific Equatorial Water, ESPCW (WSPCW): Eastern (Western) South Pacific Central Water.

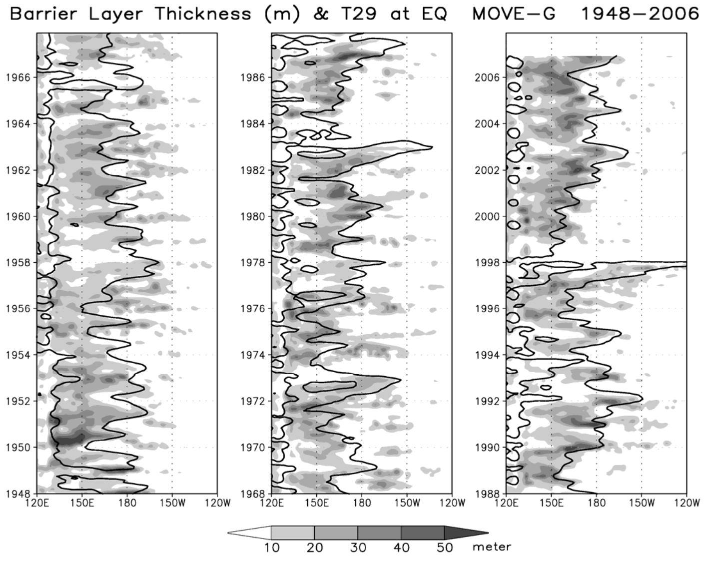

Figure 6 Distribution of barrier layer thickness and isothermal line of 29C along the equator.

MID-DEPTH FRESHENING

According to the IPCC Report in 2007, the average global surface temperature increased by 0.74 °C during the 20th century. This temperature change has been reported to be area dependent. Observational studies have shown the linear trend in the ocean heat content is increasing, particularly in the North Pacific subtropical region. Furthermore, the trend is expected to depend on depth. The area dependency of the temperature trend (warming) suggests changes in water properties. Recent investigations reveal freshening between the surface and the mid-depth layer in the North Pacific subtropical gyre (Nakano et al. 2007). Study of the long-term variability of the salinity is an important step toward monitoring and predicting climate changes such as global warming. We try to examine the salinity change by warming using the analysis/reanalysis dataset MOVE-G RA.

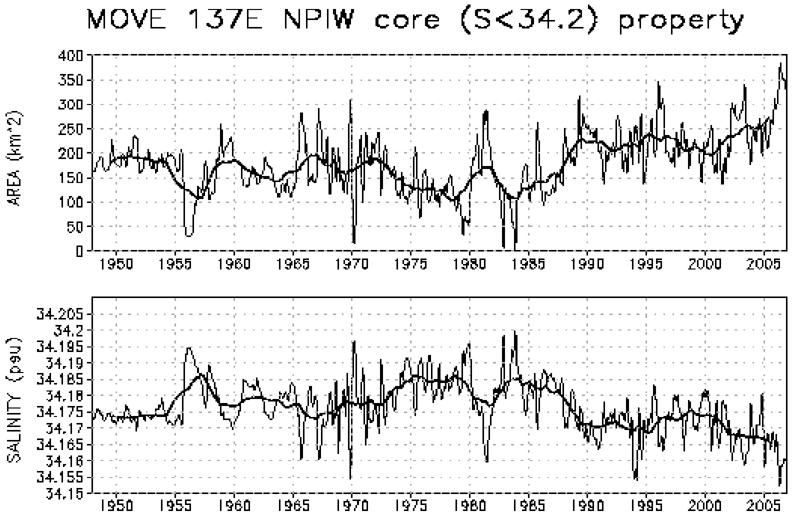

Figure 7 Time series of salinity minimum core size and averaged salinity value in the core calculated from the analysis/reanalysis dataset along 137E section. Thick solid line shows 3-year running mean.

Figure 7 shows time series of salinity minimum core size and averaged salinity value in the core of NPIW calculated from the analysis/reanalysis dataset along 137E section. The variability is similar to the observation (see Nakano et al., 2007). The core (with low salinity) size increasing and the mean salinity is decreasing. The linear trend is drawn in salinity of isopycnal surface with respect to the σ_θ ordinate along the 137°E section (Fig. 8). It shows the freshening occurs in the upper half of the NPIW core. The reason is clear with the schematic diagram by Nakano (2008) in Figure 9. In the region we have the vertical profile of salinity with minimum value at about 600-700m depth. In the case, when the pure warming (no change in salinity) occurred, the equi-density surface deepens. In the same equi-density surface of after the warming as before the warming, salinity decreases. It is clear, if we examine time variation of the averaged θ-S curve, σ_θ-S curve, and the depth of isopyucnal surface (Figure 10). Figure 10 (a) shows the warming and freshening in the mid-depth from early 1970s to early 2000s. We estimated how much the freshening on the isopycnal surface is due to warming in the subsurface layer. Using the mean salinity field for early 1970s and the mean potential temperature field for early 2000s, we calculated the potential density, and plotted the σ_θ-S diagram (Figure 10 (b) and (c)): It holds the salinity constant from early 1970s to early 2000s. A contribution to the freshening of the warming effect in the upper layer of the salinity minimum core is large. The rate is about 60-65% on 26.2σ_θ surface at about 500m depth and about 45-50% on 26.4σ_θ surface at about 550m depth (Matsumoto et al. 2008). It is similar to the result obtained from observation by Nakano et al. (2007). The depth of isopycnal surface is deepening by the warming effect above the salinity minimum layer (Figure 10 (c)). Consequently, one of the causes of freshening in the mid-depth layer along the 137°E section is isopycnal surface deepening due to warming in the subsurface layer.

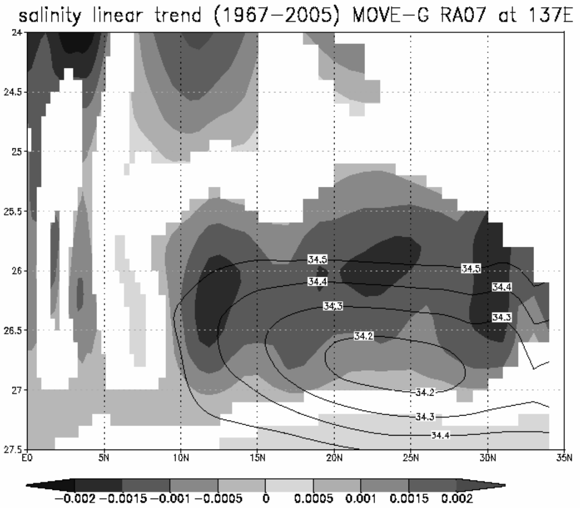

Figure 8 Linear trends in salinity of isopycnal surface with respect to the σ_θ ordinate along the 137°E section. Contours indicate the mean salinity for 1967-2005 at intervals of 0.1 between 34.2 and 34.5.

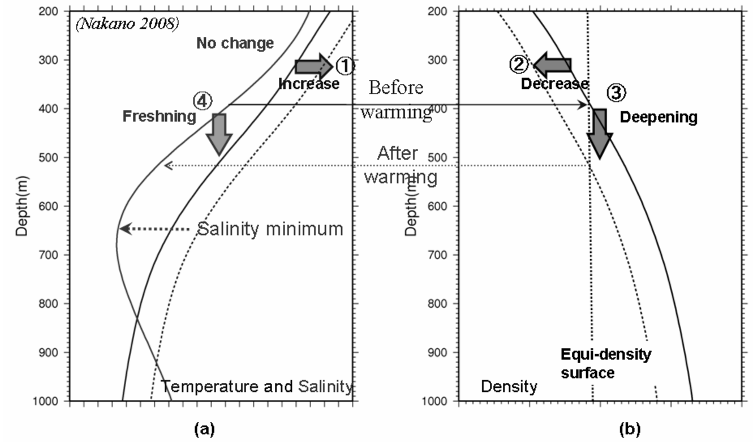

Figure 9 Schematic diagram of salinity change (mid-depth freshening) with pure warming (Nakano, 2008). Vertical distribution of temperature and salinity (a) and density (b).

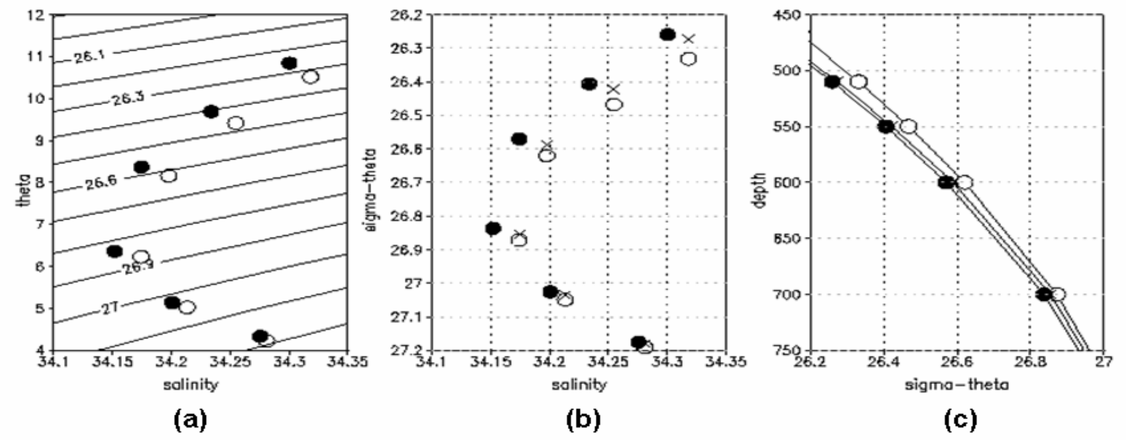

Figure 10 Time variation of the averaged (a) θ-S curve, (b) σ_θ-S curve, and (c) the depth of isopycnal surface for 22°-25°N of the center of the salinity minimum core along the 137°E section using MOVE-G RA. Open (closed) circle denotes the values calculated in each model vertical grid below 500 m depth in the early 1970s (early 2000s). Cross in (b) and (c) indicate the potential density calculated from the mean salinity field for early 1970s and the mean potential temperature field for early 2000s.

SUMMARY

Analysis/reanalysis using MOVE/MRI.COM is reported. Some examples of a simple validation show the datasets are useful for study of climate variability. We examined the freshening at mid-depth in the North Pacific subtropical gyre by using the datasets along the 137°E meridian section. We found a linear freshening trend between the main thermocline and the salinity minimum layer ($26.8\sigma_\theta$ surface). The freshening trend was mainly caused by isopycnal surface deepening due to global warming. The salinity change rate due to global warming is 60-65% on 26.2-26.3 σ_θ at about 500m depth and 45-50% on 26.4 σ_θ at about 550m depth in the North Pacific subtropical gyre.

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