Interannual variabilities of eastern subtropical mode waters in the North and the South Pacific identified from reanalysis datasets obtained by 4DVAR data assimilation.

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INTRODUCTION

Surface water masses, such as mode waters in subtropics (see Hanawa and Talley, 1999), are important because they characterize the interior circulation according to their volumetric modes. Moreover, since they circulate in the thermocline remaining their properties, they are important for the climate variability in the interannual to decadal time scale. Therefore the understanding of mechanism responsible for their dynamical behaviors is necessary for the climate study. However, the interannual variability of subtropical mode waters in the North Pacific is not understood sufficiently especially for the eastern subtropical mode water (ESTMW) identified recently by Hautala and Roemmich (1998).

The climatological formation mechanism of the ESTMW has been studied by Toyoda et al. (2004) and the importance of the preconditioning of mixed layer in the formation region has been demonstrated (Fig. 1). In summer and autumn, strong easterly winds enhance evaporation and enrich salinity of surface water. Subsequently, this salty water is carried northward by easterly induced Ekman transport. In addition, the low level cloud cover prevent insolation and suppress the SST increase in the eastern part of the subtropics. By these superimposed effects, the cold salty surface water appears in the ESTMW formation region before winter and, eventually, the locally deep mixed layer corresponding to the ESTMW is generated in winter there in spite of the moderate cooling flux. In this study, we investigate whether the interannual variability of this mode water can be explained by variations in these factors of surface forcing.

In doing so, we use a newly-derived reanalysis dataset obtained by our 4-dimensional variational (4D-VAR) data assimilation experiment that synthesizes all available observational data within the framework of an ocean general circulation model (OGCM). Since the advantage of the 4D-VAR approach is that it creates a dynamically self-consistent dataset, it provides the best possible time-trajectory fit to the observations offering greater information content on the oceanic state than can be derived from models or data alone (e.g., Stammer et al., 2002; Masuda et al., 2003).

Following a description of the methodology and dataset, features of the interannual variability of the ESTMW in the North Pacific is described using the reanalysis dataset. After summary, preliminary results on the difference between the North and the South Pacific ESTMWs are presented.

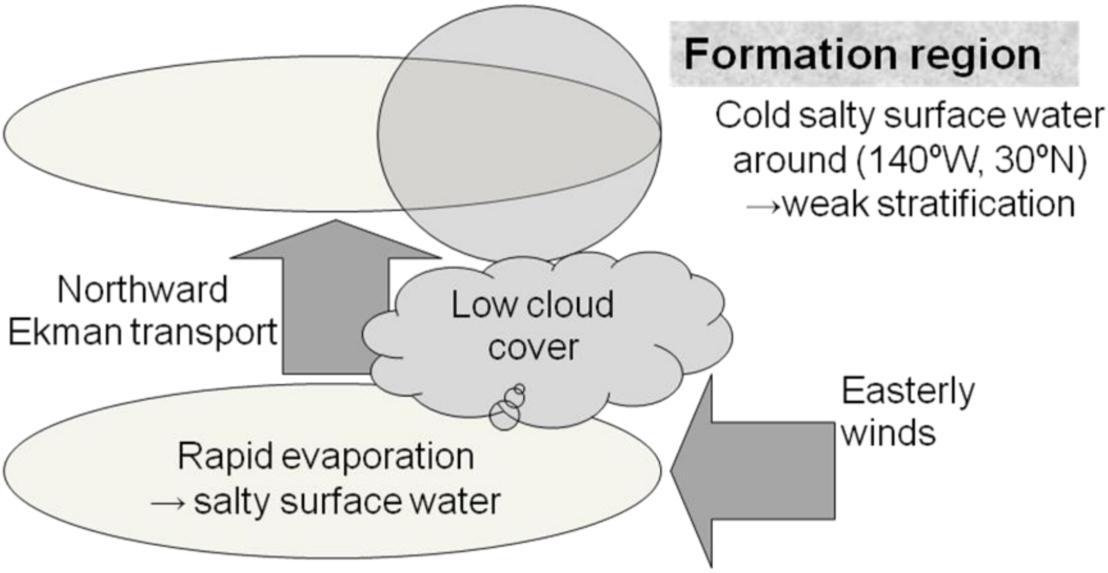

Figure 1. Schematic view of the preconditioning of winter mixed layer in the formation of the ESTMW, shown by Toyoda et al. (2004).

Data

The reanalysis dataset used in this study was derived from the 4D-VAR assimilation system used by Masuda et al. (2003) and Awaji et al. (2003). The OGCM is version 3 of the GFDL Modular Ocean Model (MOM3; Pacanowski and Griffies, 1999). Our assimilation system has been constructed for the global ocean with a horizontal resolution of 1 degree both zonally and meridionally and has 36 vertical levels.

To generate the first guess field for our data assimilation experiments, this model was firstly performed without assimilation (hereafter referred to as the "simulation run") by using 10-daily interannual forcings. For the surface momentum, sensible, long-wave radiative, and fresh water fluxes in this simulation run, data from the 6-hourly National Centers for Environmental Prediction Department of Energy Atmospheric Model Intercomparison Project (NCEP-DOE-AMIP-II) dataset have been used. These are provided on a 1.9^{o} latitude by 1.875^{o} longitude grid. Latent heat flux was estimated from NCEP's Optimally Interpolated Sea Surface Temperature (OISST) field by applying the commonly used bulk formulae. In addition, the International Satellite Cloud Climatology Project (ISCCP; Kidwell and Poltar, 1988) dataset was used for the short-wave radiative flux.

In our 4D-VAR approach, an optimized 4-dimensional dataset is sought by minimizing a cost function (Masuda et al., 2003). The assimilation covers a time window of 10.5 years starting from 1990. We chose the initial conditions of model variables and air-sea fluxes (heat, fresh water, and momentum fluxes) as the control variables with the latter modified within the assimilation period as 10-day mean values (see Masuda et al. (2003) for more detail).

The assimilated elements in this study are temperature and salinity from the Fleet Numerical Meteorology and Oceanography Center (FNMOC) dataset, OISST values, and sea-surface dynamic-height anomaly data derived from TOPEX/Poseidon altimetry. In addition, the climatologies of the World Ocean Database 1998 (WOD98) are used as background data. All the observational data are averaged onto 1 degree by 1 degree bins and then compiled as series of 10-day means for the surface data and monthly means for the subsurface data. The resolution after 120 iterations of an adjoint calculation covering a total of 10.5 years is acceptable for our purposes since values of the cost function are then almost equivalent to errors in the assimilated input fields.

The dataset in the 1990s derived from the last cycle of the reanalysis run is used. An initial "shock-effect" is inevitably produced in association with the establishment of the initial conditions and although this almost disappears within one month, we have nevertheless rejected the whole of the first year (1990) and thus the analysis period runs from January 1991 to June 2000 in the following work. In addition, when validating and discussing the surface fluxes of the assimilated data, we use the 40-year European Centre for Medium-Range Weather Forecasts reanalysis (ERA40; Klinker, 1997) as well as the NCEP--National Center for Atmospheric Research reanalysis--2 (NCEP2; Kalnay et al., 1996). Also, we use the ISCCP dataset to investigate the summertime low-level cloud cover in the ESTMW region.

Results

Our 4D-VAR product reproduce the local deepening of wintertime mixed layer in the eastern subtropical North Pacific consistent with the previous observational studies, such as Hautala and Roemmich (1998). In addition, temperature-salinity-volume diagrams show that properties in this region are consistently reproduced with the WOA climatologies. These features provide an appropriate benchmark for assessing the applicability of our data to the investigation of the interannual variation. In this study, we shall define the ESTMW as the component with a volume greater than $2x10^{12}$ m^3 in each salinity class (in steps of 0.05 psu) and in each temperature class (in steps of 0.2^oC) and ranges between $16\text{-}22^oC$. In order to gain an insight into the mechanisms controlling the interannual variation in the ESTMW, we define a newly formed ESTMW volume as the maximum value of the existing ESTMW in winter minus the minimum value from the preceding autumn. The time series of this quantity is shown in Fig. 2a.

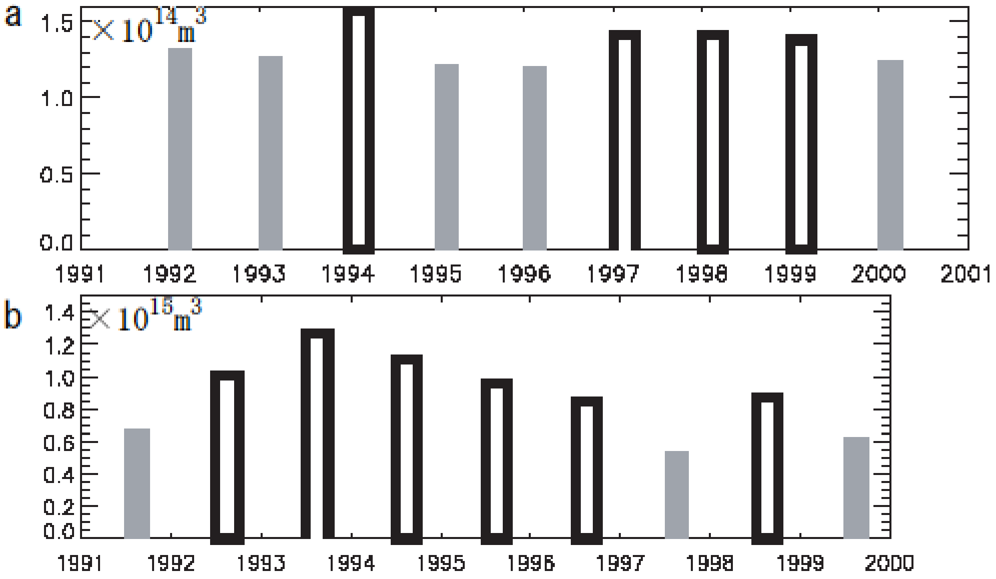

Figure 2. Newly formed volume of the ESTMWs in each winter form our reanalysis data (a) in the North Pacific and (b) in the South Pacific.

We carefully investigate the interannual variabilities in the forcing fields (see Toyoda et al. (for submission in 2007) for more detail). The salt convergence by Ekman transport in the ESTMW formation region increase remarkably from the middle of 1996 to the beginning of 1999, which correspond well to the large formations in these years. Next, the temperature difference anomaly between surface and 100 m depth in the preconditioning phase, which is a good measure for the strength of seasonal thermocline stratification shows that the strong (weak) stratifications correspond very well to the small (large) formations. In addition, by analyzing the ISCCP cloud dataset, we found this thermal stratification variability is explained mostly by low-level cloud, especially stratocumulus. The surface flux variability is also validated by comparing with NCEP2 and ERA40. Finally, the net heat flux anomaly in winter shows that weak (strong) cooling anomalies correspond well to the small (large) formations. NCEP2 and ERA40 validate our net heat flux anomaly there and, moreover, they indicate that more than half of the net heat flux variation is explained by the latent heat. In summary, as appears in Table 1, the interannual variability of the young formation of the ESTMW in the North Pacific is well explained by the interannual variability of these 3 surface forcing factors. This fact is consistent with the climatological formation mechanism.

Table 1. Interannual variabilities of the young formation of the ESTMW and the surface forcing factors in the eastern subtropical North Pacific.

Year	Young Formation	Salt Convergence	Thermal Stratification	Winter Cooling
1992	-		-	
1993	-		-	
1994	+		+	
1995	-	+		-
1996	-		-	-
1997	+	+		
1998	+	+		+
1999	+	+	+	
2000	-			-

In the South Pacific, there also exists the ESTMW (Wong et al., 2003). The associated mixed layer is deeper and distributes in broader region than in the North Pacific, which is mostly attributed to the fresh water flux, strong negative value in the subtropical South Pacific, while it is affected by the ITCZ in the North Pacific. The resultant surface salinity is more than 36 psu, whereas about 35.2 psu at maximum in the North Pacific. We analyze in a similar way on the interannual variability in the South Pacific ESTMW and compare the North and the South Pacific ESTMW.

Figure 2b shows the interannual variability in the new formation of the South Pacific ESTMW. It is shown that, though it may be imagine that they show similar variations affected by the strong equatorial interannual variability, the young formation of the North and the South Pacific ESTMWs do not show similar interannual variability. In addition, by analyzing the density variation, it is suggested that salinity contribution to density variation is larger in the North Pacific (43%) than in the South Pacific (30%). Moreover, in the South Pacific, temperature and salinity vary largely coherently. The correlation coefficient is 0.75 in the South Pacific while 0.06 in the North Pacific. This indicates the importance of the "speciness" anomalies in the South Pacific (e.g., Nonaka and Sasaki, 2007). Clarification of the mechanism responsible for these variabilities and the difference between the North and the South Pacific ESTMWs remains a subject for future work. In particular, the variability related to the ENSO is of interest.

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