

# Deep Ocean Reanalysis Experiment by using a 4D-VAR Adjoint Method

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## 1. Background

Data assimilation approaches have recently focused on the derivation of an optimal synthesis of observational data and model results for better descriptions of the ocean state [e.g., Stammer et al. JGR, 2002]. The synthesis efforts so far have mainly directed the attention to the upper ocean since observations of changes in the properties of ocean waters have been restricted to surface or intermediate-depth waters [e.g., Levitus et al., Science, 2000]. Based on high quality observational survey, recent studies have found an important fact that the deepest waters of the major ocean have warmed significantly during the recent decades [e.g., Fukasawa et al., Nature, 2004]. This bottom water warming is of particular interest as it can be closely related to changes in the global thermohaline circulation and warming trend of the global ocean.

## 2. Data Assimilation System

### a. Ocean general circulation model

GFDL/MOM3 1° X 1°, 45levs, Global

### b. Assimilated elements

Temp & Salinity CTD, XBT, MBT, APB, DRB, Argo, ...  
 SST Reynolds SST  
 SSH Anomaly TOPEX/POSEIDON

### c. Control variables

Surface fluxes Heat, fresh water, momentum  
 Initial Conditions T, S, U, SSH

### d. Cost function

Total cost  $J = J_b + J_o + J_p$   
 Background cost  $J_b = (x - x_b)^T B^{-1} (x - x_b)$   
 Observational cost  $J_o = \sum (H_m M_m(y) - y_m)^T R^{-1} (H_m M_m(x) - y_m)$   
 Smoothness cost  $J_p = (\nabla \cdot x)^T P^{-1} (\nabla \cdot x)$

## 3. Details of Model and Observational Data

### a. Optimization of model parameters

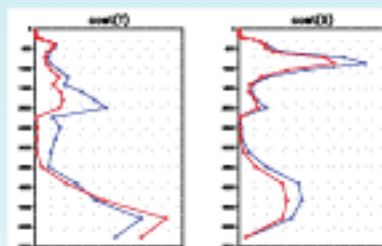


Fig. 1. Cost for global averaged temperature and salinity.

### b. Input observations

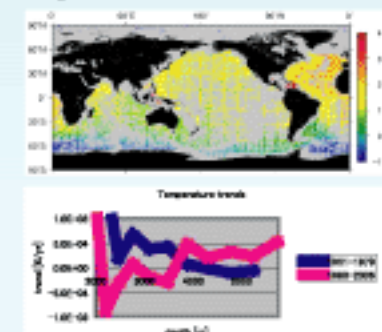


Fig. 2. Distribution of EN3 dataset (upper) and temperature trend in the deep ocean (lower).

Figure 1 shows the cost for global averaged temperature and salinity (difference between simulation and observation). We have optimized vertical diffusive coefficient of the OGCM by using 'Green function calibration' [Menemenlis et al., 2005]. As a result, the cost is effectively reduced (blue curves => red curves). Such a parameter adjustment is crucial for better description of the deep ocean state.

Figure 2 shows distribution of the input observations (EN3 dataset; upper panel) at 4000m-depth during the assimilation period (1957-2006).

The bottom water warming below 4000m-depth is found in this dataset (lower panel), which is consistent with the recent studies [Fukasawa et al., Nature, 2004 and Kawano et al., GRL, 2005]. WOCE revisit & Mirai Cruise play an important role in the deep ocean survey.

## 4. Sensitivity Experiment

An adjoint calculation was executed to detect the origin and the causal dynamics of the bottom water warming in the North Pacific. The adjoint solution enables us to estimate the sensitivity to fluctuations of the model variables thereby leading to the identification and characterization of the origin and pathways of waters [e.g., Fukumori et al., JPO, 2002].

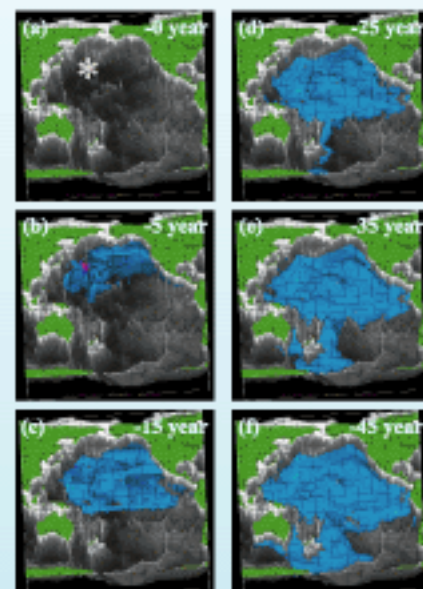


Fig. 3. Adjoint variable of temperature: (a) 0-year, (b) 5-year, (c) 15-year, (d) 25-year, (e) 35-year, and (f) 45-year backward calculation.

Left panels show a result of the backward calculation of adjoint variables in the case of temperature fluctuation input at a point where the bottom water warming was observed (marked by \* in the upper-left panel). The adjoint signal can be traced back to the Southern Ocean over a roughly 50 year period.

The distribution of adjoint variables of the net air-sea heat flux for the same artificial cost input (Fig. 4) implies that the bottom water warming in the North Pacific is likely to stem from the change in air-sea heat flux in the Southern Ocean (white arrow) via oceanic wave activities. Recent field and modeling studies provide a basically consistent view [e.g., Nakano and Sugimoto, JPO, 2002].

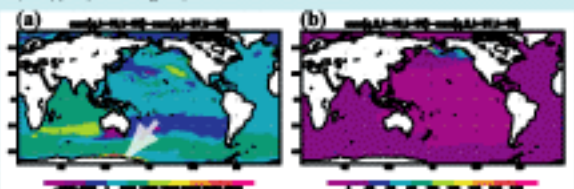


Fig. 4. Adjoint variable of net air-sea heat flux: (a) full and (b) adj-diff component calculation.

## 5. Ocean Reanalysis Dataset (1957-2006)

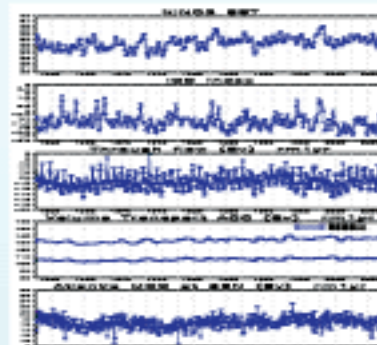


Fig. 5. Estimated climate indices during 1957-2006.

Figure 5 shows the time series of climate indices estimated from our ocean reanalysis dataset. The obtained reanalysis dataset shows good consistency with previous knowledge of important climate events.

The bottom water warming in the North Pacific is successfully reproduced in our reanalysis field (Fig. 6), which can lead to better understanding of the warming

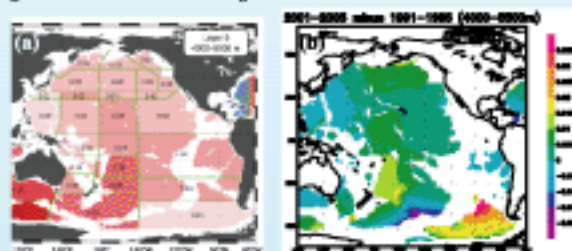


Fig. 6. Bottom water warming in the Pacific Ocean below 4000m-depth: (a) observed heat content trend and (b) estimated temperature trend.

## 6. Concluding Remarks

By using a 4-dimensional variational adjoint method, we have obtained an oceanic reanalysis data set for 1957-2006 focusing on the deep ocean state estimation. The reconstructed field, which has dynamical consistency, reflects most of the familiar gross features of past studies. Hence, our product is useful for understanding long-term oceanic variabilities inclusive of the bottom water warming.

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