GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 12, PAGES 2449-2452, JUNE 15, 2001

Subduction of Decadal North Pacific Thermal Anomalies in An Ocean GCM

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Abstract. A new version of the GFDL Modular Ocean Model (MOM 3) is used to simulate interannual and interdecadal variability over the entire Pacific basin from January 1948 to April 2000, forced by NCEP reanalysis atmosphere-ocean fluxes. The MOM 3 with high resolution and sophisticated physics realistically reproduces the subduction of temperature and salinity anomalies associated with decadal climate variability in the North Pacific. Two major decadal subduction events (one warm and salty in the 1970s, and another cold and fresh in the 1980s) are demonstrated in this paper. In the 1970s temperature anomaly signal propagates along the subduction pathway into the western boundary at 18° N. The time needed to propagate from the midlatitude outcrop sites into the western boundary is about 5 years, shorter than that suggested by previous advection-based analyses. It is further shown that the simulated temperature and salinity variations coincide in such a way that cold (warm) anomalies tend to be accompanied by fresh (salty) anomalies along the subduction pathway, indicating that they are largely compensating in terms of density on the decadal time scales. The implication of such compensated thermal anomalies subducted from the midlatitudes are discussed with respect to the tropical variability and ocean data assimilation issues.

1. Introduction

Recent observations (e.g., *Levitus et al.*, 1994) suggest that subduction of thermal anomalies, consistent with the ventilated thermocline theory (*Luyten et al.* 1983; *Fine* 1987; *Liu* 1999; *Huang and Pedlosky* 1999), can be an important mechanism for decadal thermocline variability around the subtropical ocean gyre in the North Pacific (e.g., *Deser et al.* 1996; *Schneider et al.* 1999). Via the subduction process, surface thermal anomalies from midlatitude outcrop sites can be transmitted to the upper thermocline, after which they may persist and propagate within the subtropical gyre. A preferential subduction pathway has been identified around the North Pacific subtropical gyre in association with decadal climate changes in the 1970s and the 1980s, respectively (*Zhang and Liu* 1999). It has been further argued that subducted anomalies, by remotely modifying thermal structure and sea surface temperature in the tropical Pacific Ocean, may play a potential role in low-frequency climate change and the modulation of El Nino in the tropics (*Gu and Philander* 1997; *Zhang et al.* 1998).

Our present understanding of decadal thermocline variability in the North Pacific is very limited, and some basic questions are still unresolved (e.g., *Miller et al.* 1994; *Latif and Barnett* 1994; *Barnett et al.* 1999; *Schneider et al.* 1999). One important question is the nature of subduction associated with the generation and propagation of thermal anomalies. While observed temperature data suggest a subduction signal associated with decadal thermocline variability, the degree of compensation between salinity and temperature for density has not been established because of the lack of long-term, basinwide salinity observations (e.g., *Levitus* 1989). Is there subduction of salinity anomalies in the midlatitude outcrop region as of temperature anomalies? If so, do the subducted salinity anomalies propagate in the same pathway as temperature anomalies so that they compensate with respect to density on decadal time scales? Another important issue is the degree of oceanic connection between the midlatitude and tropics through the subtropical thermocline. The extent to which subducted thermal anomalies can propagate from the midlatitude outcrop region to the low-latitude western boundary, and the time scale involved are in debate (e.g., *Zhang et al.* 1998; *Schneider et al.* 1999). Clearly, data analyses based on limited observations are not sufficient to resolve these uncertainties; the interpretation of observed data through realistic ocean models provides an additional means to address the problem.

While previous ocean GCMs appear to have had difficulty simulating subduction process from the surface into the thermocline, we present here what appears to be a realistic simulation of subduction of decadal North Pacific temperature and salinity anomalies in the 1970s and the 1980s, and their subsequent pathways around the subtropical gyre (i.e., the so-called subduction pathway) using the latest version of the Geophysical Fluid Dynamics Laboratory Modular Ocean Model (MOM 3).

2. Ocean Model (MOM 3) and Experiment

The ocean model used in this work is the MOM 3 (*Pacanowski and Griffies* 1999; *A. Rosati, M. Harrison and V. Balaji*, private communication). The main advances in MOM 3 relative to other previous MOM versions are in the model's physics, numerics and parallelization, including the KPP vertical mixing scheme, an explicit free surface treatment, and the *Gent-McWilliams* parameterization for mixing associated with mesoscale eddies. The model domain in this work covers the entire Pacific basin from 55.5°S to 65°N, 107° E to 70°W with horizontal resolution of 1° longitude by 1° latitude (but 0.33° latitude between 10°S-10°N). It has 40 vertical levels with a constant 10 m resolution in upper 210 meters. The model incorporates realistic continents and bottom topography; solid boundaries are adopted at 55.5°S, with model temperature and salinity restored to monthly climatology (*Levitus* 1982) poleward of 44.5°S.

All atmospheric forcing fields are from NCEP reanalysis products, including surface wind stress, surface air temperature and so on. Bulk formulae are used to calculate latent and sensible heat fluxes. The fresh water flux in the model includes two terms.

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Paper number 2000GL012779
0094-8276/01/2000GL012779$05.00

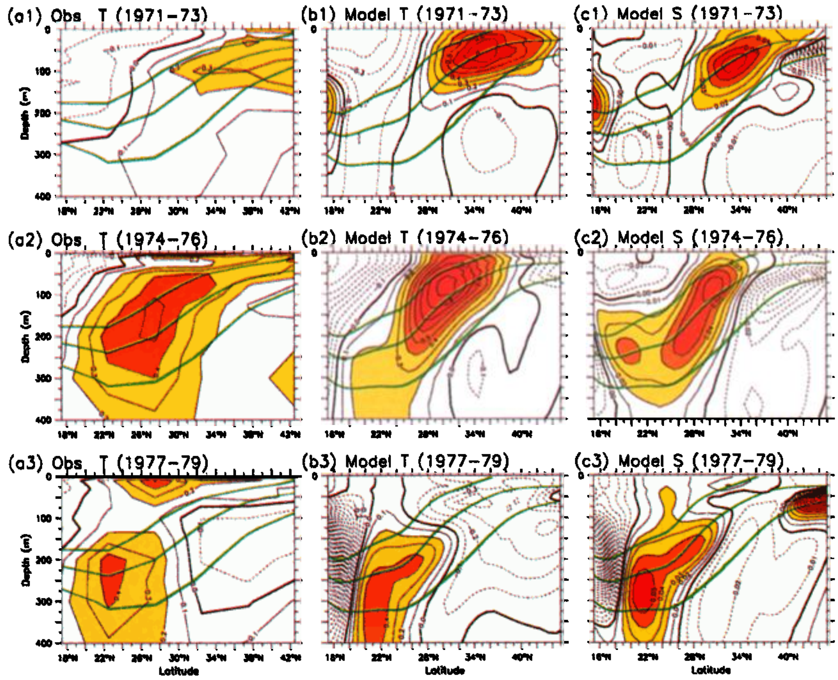

Figure 1 Meridional sections of the observed temperature anomalies (left column), and of the simulated temperature (middle column) and salinity (right column) anomalies along the longitude band 170°-145° W for 1971-73 (upper row), 1974-76 (middle row), and 1977-79 (low row), respectively. The contour interval is 0.1°C for temperature and 0.01 psu for salinity; the dashed lines are for negative anomalies. Superimposed are the corresponding long-term mean isopycnals of 1025.0, 1025.5, and 1026.0 kgm^{-3} (green lines), respectively.

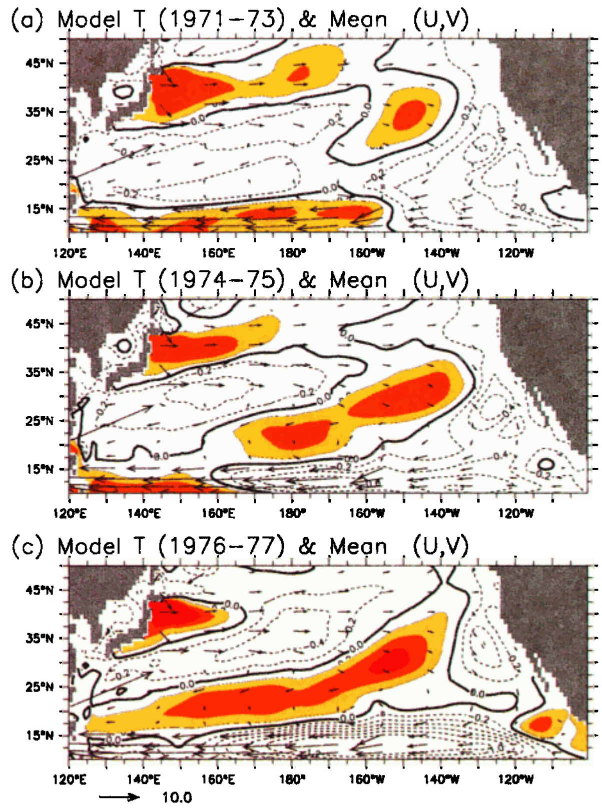

Figure 2 Horizontal structure of the simulated temperature anomalies (contour interval is 0.2°C; the dashed line for being negative) averaged in the upper 50-300 meters for (a) 1971-1973, (b) 1974-75, and (c) 1976-1977, respectively. Superimposed are the long-term mean current vectors averaged in the upper 5-0-300 meters.

One term is concerned with the differences in evaporation and precipitation. The second term is essentially a restoring boundary condition on sea surface salinity, by which the model top-level salinity is restored to the *Levitus* (1982) seasonally-varying climatology with a relaxation time of 10 days.

The model, initiated from the *Levitus* (1982) temperature and salinity fields, is integrated for 20 years with the NCEP reanalysis climatological forcing fields. The model is then integrated further with the reanalysis monthly forcing from January 1948 to April 2000. Monthly anomalies are obtained relative to the corresponding model climatology derived from January 1948 to December 1999. In this paper, we present yearly anomaly fields by simply averaging monthly anomalies within each calendar year.

3. Results

For purposes of comparison, we utilize observation-based temperature anomalies analyzed by *Levitus et al.* (1994). In the following, we will focus on two major subduction events associated with decadal climate variability over the North Pacific (one warm and salty in the 1970s, another cold and fresh in the 1980s, respectively).

Fig. 1 shows the vertical structure of the observed and simulated temperature anomalies during 1971-79 (the left and middle column panels). In both observations and the model simulation, significant warm anomaly can be observed around the midlatitude outcrop region in the early 1970s (Fig. 1a1 and Fig. 1b1), the signal being stronger in the model simulation. In the middle 1970s (Fig. 1a2 and Fig. 1b2) for both observed and simulated analyses, there is a striking warm anomaly tongue from the sea surface into the thermocline, penetrating downward and southward. By the late 1970s (Fig. 1a3 and Fig. 1b3), both observed and simulated warm anomalies have become detached from the surface and appears to be subducted both downward and southward approximately along the mean density surfaces into the thermocline around the subtropical gyre. The spatial patterns and

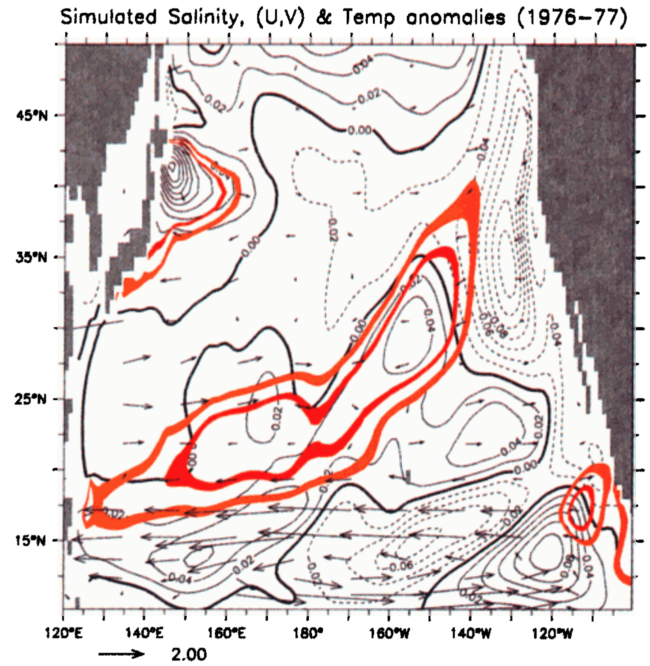

Figure 3 Horizontal distribution of the simulated salinity anomalies (contour interval is 0.02 psu; the dashed lines for negative anomalies) averaged in the upper 50-300 meters for 1976-1977. Superimposed are the corresponding current anomalies (vectors) and temperature anomalies (shaded thick lines indicating 0.2°C and 0.4°C contours; see Fig. 2c), respectively.

time evolution of temperature anomalies are indicative of the ventilated thermocline around the subtropical gyre, consistent with previous theoretical prediction (e.g., *Luyten et al.* 1983; *Huang and Pedlosky* 1999).

The detailed pathways of the warm subduction event around the basin are illustrated in Fig. 2. In the 1960s through the early 1970s, the North Pacific Ocean was in a warm phase, characterized by a dominant positive temperature anomaly in the western and central midlatitudes, surrounded by a negative anomaly along the western coast of North America and in the eastern and central subtropics. The simulated temperature anomaly pattern exhibits a coherent propagation around the northeastern-to-southwestern part of the subtropical gyre. In the early 1970s, there emerged a warm anomaly in the surface layer around (150° W, 35°N). After subduction, the anomaly then followed approximately the mean circulation (see current vectors) and was swept southwestward towards the western subtropics and tropics. In the middle 1970s (Figs. 2b-c), the warm anomaly signal had arrived at the western boundary. In 1976-77 (Fig. 2c), we can see a trans-Pacific broad swath that extended southwestward from the subduction sites all the way into the western boundary, a similar pattern is observed (e.g., *Zhang et al.*). Thus, at a speed of about 3 cms^{-1}, the model warm anomaly propagated westward from the outcrop region in 1971-73 (Fig. 2a) into the western boundary in 1976-77 (Fig. 2c). The time for the anomaly to propagate from the outcrop sites into the low-latitude western boundary at 18° N was about 5 years, much shorter than previously estimated (8 years) in terms of mean advection (e.g., *Schneider et al.* 1999). *Liu* (1999) has recently investigated the thermocline response around the subtropical ocean gyre to surface wind stress and buoyancy forcing, suggesting that the propagation of thermocline temperature anomalies would be better understood in terms of planetary wave dynamics, rather than simple advection by mean subtropical flow. In this way, the propagation speed of the subducted temperature anomalies can differ substantially from that of the mean flow particularly in the south-western part of the North Pacific subtropical gyre.

The evolution of the simulated salinity anomalies is shown in the right panels of Fig. 1. Due to the partially restoring boundary condition for sea surface salinity in the model, the simulated anomalies are expected to be weak. Nevertheless, there is a clear pattern of decadal salinity variability around the subtropical gyre. In the early 1970s (Fig. 1c1), a pronounced salinity increase can be seen in the upper pycnocline around the outcrop sites. With time, the high salinity anomaly propagated downward and southwestward (Fig. 1c2), similar to the temperature anomalies. In the middle and late 1970s, the positive salinity anomaly became detached from the sea surface and was subducted into the pycnocline (Fig. 1c3). Note that the temperature anomalies were basically mirrored in salinity fields, indicating that salinity anomalies are compensating the effect of temperature anomalies on density. Fig. 3 illustrates the horizontal distribution of salinity and current anomalies averaged in the upper 50-300 meters for 1976-1977. It is evident that temperature anomalies were accompanied by salinity anomalies of the same sign so that compensation of temperature and salinity does exist on decadal time scales along the subduction pathway (from the outcrop sites to the western subtropics around 150° E) where current anomalies were quite small. There were areas where temperature anomalies were not well coincident with salinity anomalies, but accompanied by large current anomalies particularly south of 18° N. This indicates that temperature and salinity are dynamically active in these regions.

Deser et al. (1996) have illustrated the cold subduction event in the 1980s. For a direct comparison, we show a plot in Fig. 4

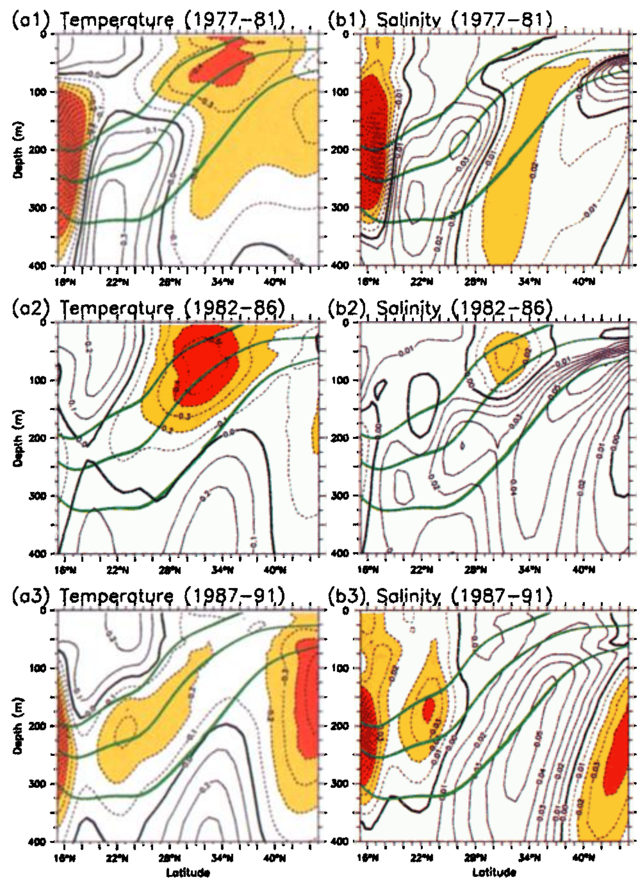

Figure 4 The same as in Fig. 1b and Fig. 1c but for 1977-81, 1982-86, and 1987-91, respectively.

for temperature anomalies during 77-91 (the left panel), exactly similar to the observed analyses by Deser et al. (see their Fig. 10). With a sharp phase transition in the late 1970s from warm to cold state in the North Pacific, a cold anomaly emerged in the midlatitude outcrop region in the late 1970s (Fig. 4a1), representing the initial stage of its subsequent subduction into the thermocline. Similar to the warm and salty subduction event in the 1970s, a cooling anomaly was accompanied by a freshening trend particularly at depth (the right panels of Fig. 4). In the early 1980s, the freshening and cooling signal appeared progressively downward and southward along the mean density surface. In 1987-91 (Fig. 4b3), we can see a cooling (~0.3° C) that is accompanied by a freshening (~0.04 psu) at about 200 m. It is, however, evident that the correspondence between the cold anomalies and fresh anomalies is not as good in this case.

4. Discussion

It is, to our knowledge, the first time that an OGCM has realistically simulated the subduction of thermal anomalies and their subsequent subduction pathway around the subtropical gyre in association with decadal climate variability in the North Pacific. The success is apparently due to the improved physics, including the KPP scheme for vertical mixing, the *Gent-McWilliams* scheme for isoneutral mixing and stirring of tracers, as well as the high horizontal and vertical resolution in the present model configuration.

With complete data sets from the model, we are able to demonstrate the subduction of temperature and salinity anomalies around the subtropical gyre in the North Pacific Ocean. By this mechanism, surface temperature anomalies can be transferred downward into the thermocline from the midlatitude outcrop region. Then, along the mean water pathway, the subducted anomalies extend southward and westward through the central/western subtropics into the low-latitude western boundary. For the warm and salty event in the 1970s, we have seen a tongue of positive temperature and salinity anomalies that originates from the midlatitude outcrop region at about (150°W, 35°N) and extends southward and westward in the direction of the gyre flow into the western boundary. A similar pattern exists for the cold and fresh event in the 1980s. The temperature and salinity anomalies coincide in such a way that a cold (warm) anomaly tends to be compensated by a fresh (salty) anomaly in the thermocline, demonstrating that the compensation of temperature and salinity anomalies exists along the subduction pathway on decadal time scale.

As suggested from observations (e.g., *Zhang et al.* 1998), the simulation shows that within about 5 years warm and salty anomaly signals can propagate from the midlatitude outcrop site in the early 1970s all the way into the low-latitude western boundary region in 1976-77 (Fig. 3). This could affect the tropical thermocline as these persistent thermal anomalies further propagate equatorward with the well-defined tropical currents downstream into the tropical Pacific Ocean. In due course, they would be expected to spread into the equatorial thermocline and alter the thermal structure and surface heat balance there, which, in turn, could initiate an atmospheric response with teleconnections back to the North Pacific midlatitudes. Thus, the subduction pathway may present a mechanism that can connect surface anomalies in the outcrop region to the thermocline variations in the western subtropics and the tropics.

The results of the compensation phenomenon between temperature and salinity anomalies along the subduction pathway have implications for data assimilation in ocean models. As commonly performed, due to the lack of salinity observations, only temperature observations are assimilated into ocean models, correcting temperature fields but leaving salinity fields unchanged. This will result in a potential problem in the subtropics where there are strong and persistent compensated thermal signals and where subducted anomalies can have a direct effect on the tropics downstream. Since temperature and salinity anomalies tend to be compensated in their effect on density (i.e., like passive tracers), assimilation of ocean temperature observations *only* into an OGCM will distort the temperature-salinity relationship in the model. This will likely produce artificial density anomalies and further initiate velocity anomalies. With this issue in mind, it is clear that methods should be developed to take into account salinity-compensated effects on density in ocean temperature data assimilation procedures.

Acknowledgments. We are indebted to A. Rosati, M. Harrison, V. Balaji, R. Pacanowski and others at GFDL/NOAA for their help and numerous support in setting up the GFDL MOM3 at the IRI We would like to thank P. Chang, S. Levitus, A. Busalacchi, Y. Tourre, R. Kleeman, R. X. Huang, T. Yamagata, P. Gent, and N. Schneider for their helpful comments. This research is supported by the IRI and its sponsors (RHZ, SZ), and by the Frontier Research System for Global Change of Japan (TK).

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(Received December 18, 2000; accepted March 1, 2001.)