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Model Evidence for Interdecadal Pathway Changes in the Subtropics and Tropics of the South Pacific Ocean

ZHANG Rong-Hua*[1,2] (张荣华) and WANG Zhanggui[3] (王彰贵)

[1] *Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland, USA*

[2] *College of Global Change and Earth System Science, Beijing Normal University, Beijing* 100875

[3] *National Marine Environmental Forecasting Center, State Oceanic Administration, Beijing* 100081

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ABSTRACT

Numerical simulations using a version of the GFDL/NOAA Modular Ocean Model (MOM 3) are analyzed to demonstrate interdecadal pathway changes from the subtropics to the tropics in the South Pacific Ocean. After the 1976–77 climate shift, the subtropical gyre of the South Pacific underwent significant changes, characterized by a slowing down in its circulation and a southward displacement of its center by about 5°–10° latitude on the western side. The associated circulation altered its flow path in the northwestern part of the subtropical gyre, changing from a direct pathway connecting the subtropics to the tropics before the shift to a more zonal one after. This effectively prevented some subtropical waters from directly entering into the western equatorial Pacific. Since waters transported onto the equator around the subtropical gyre are saline and warm, such changes in the direct pathway and the associated reduction in equatorward exchange from the subtropics to the tropics affected water mass properties downstream in the western equatorial Pacific, causing persisted freshening and cooling of subsurface water as observed after the late 1970s. Previously, changes in gyre strength and advection of temperature anomalies have been invoked as mechanisms for linking the subtropics and tropics on interdecadal time scales. Here we present an additional hypothesis in which geographic shifts in the gyre structure and location (a pathway change) could play a similar role.

Key words: water pathway, interdecadal changes, ocean modeling, South Pacific Ocean

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1. Introduction

Various observational and modeling studies have demonstrated interdecadal changes over the Pacific sector that took place in 1976–77, the so-called climate shift (e.g., Miller et al., 1994; Zhang et al., 1998; Zhang and Liu, 1999). In the ocean, the associated changes have been documented extensively (e.g., Levitus et al., 1994; Zhang et al., 1999, 2001; McPhaden and Zhang, 2002; Zhang et al., 2008). After the 1976–77 climate shift, one striking feature in the tropical Pacific Ocean was a persistent (decade-long) cooling at subsurface in the western and central equatorial Pacific, with a warming to the east (e.g., Stephens et al., 2001).

Several studies suggest that extratropical processes can affect mean ocean state and its variability in the equatorial Pacific by shallow meridional overturning circulations [i.e., the so-called subtropical cells (STCs); McCreary and Lu, 1994], which act to modulate meridional transport of mass, heat and salt. Two possible ways by which an extratropical ocean can alter the equatorial thermal structure have been proposed (e.g., Gu and Philander, 1997; Zhang et al., 1998; Kleeman et al., 1999): either the changes in STC strength or advection of heat and salt anomalies by mean circulation (subduction).

The causes of interdecadal changes in the tropical Pacific as observed in the late 1970s are still in debate; the dramatic shift of the ocean thermocline has not been explained consistently (e.g., Guilderson and

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*Corresponding author: ZHANG Rong-Hua, rzhang@essic.umd.edu

Schrag, 1998; Luo et al., 2003; Luo et al., 2005; Zhang and Busalacchi, 2005; Luo et al., 2009). Current description and understanding of interdecadal variability over the Pacific are not complete, especially as it pertains to the subsurface South Pacific Ocean (e.g., Chang et al., 2001; Giese et al., 2002). Clearly, data analyses based on limited observations are not sufficient to resolve these uncertainties; interpretations of observed data through realistic ocean models provide an additional means to address the problem.

Here, we present evidence for interdecadal pathway changes associated with the South Pacific subtropical gyre in the late 1970s, using a model simulation from a version of the Geophysical Fluid Dynamics Laboratory Modular Ocean Model (MOM 3). It is shown that, after the 1976–77 shift, waters in the South Pacific Ocean that flow from the eastern subtropics directly to the western equatorial Pacific have changed their pathways in such a way that some subtropical waters are prevented from directly entering into the western equatorial Pacific. The changes in the direct pathway and the associated reduction in equatorward water exchange from the subtropics to the tropics affected water mass properties downstream in the western equatorial Pacific, leading to persisted freshening and cooling of subsurface water as observed after the late 1970s.

2. Ocean model (MOM 3) and experiment

The ocean model used in this work is the MOM 3 (Pacanowski and Griffies, 1999). The main advances in MOM 3 relative to previous other MOM versions are in the model's physics, including the K-profile parameterization (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

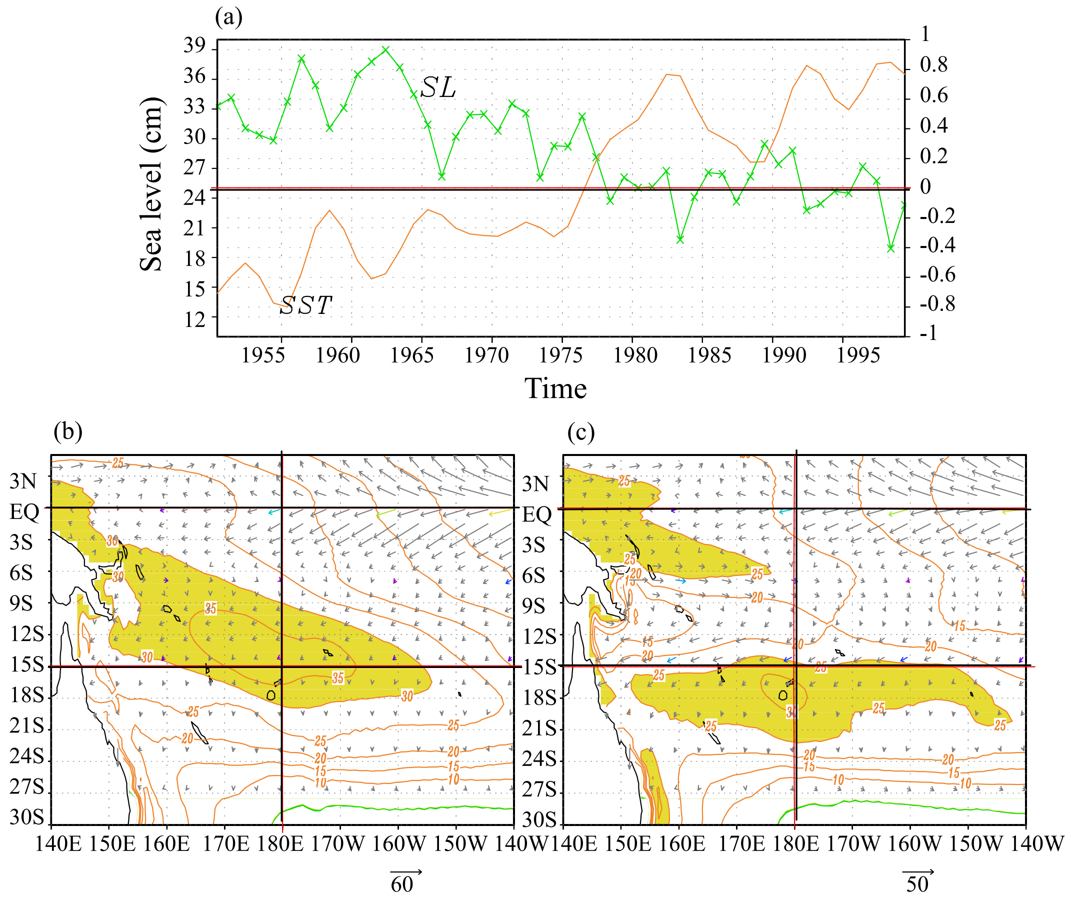


Fig. 1. Time series of sea level averaged over the region (10°–20°S, 160°E–160°W) and of the Niño3 SST anomalies (a), and horizontal distributions of annual-mean sea level (contours) and surface currents (vectors) calculated for the period 1960–75 (b) and for the period 1980–95 (c), respectively. The contour intervals are 5 cm in (b) and (c); the units of the current scale (the given arrow) in (b) and (c) are cm s^{-1}.

Pacific basin from 55.5°S to 65°N, and 107°E to 70°W with horizontal resolution of 1°×1° (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 from World Ocean Atlas (WOA) (Levitus et al., 1994) poleward of 44.5°S.

All atmospheric forcing fields are from NCEP reanalysis products (Kalnay et al., 1996). Bulk formulae are used to calculate latent and sensible heat fluxes. The fresh water flux in the model includes the differences in evaporation and precipitation, and a restoring term for sea surface salinity, by which the model top-level salinity is restored to the WOA seasonally-varying salinity climatology with a relaxation time of 10 days. The model is integrated for 20 years using climatological forcing fields from the NCEP reanalysis, followed by using interannually varying monthly forcing fields from January 1948 to April 2000. Some model results were presented by Zhang et al. (2001), and Zhang and Zebiak (2002).

3. Interdecadal changes in the Pacific Ocean

The model simulation exhibits significant low-frequency ocean variability in the entire Pacific basin (e.g., Zhang et al., 2001). For instance, in the tropical Pacific, interdecadal changes are clearly evident from simulated ocean fields; an example is shown in Fig. 1a for the decadal phase transition that took place in the late 1970s. To illustrate this more clearly, we have calculated the mean state for two periods, one from 1960 to 1975 and another from 1980 to 1995. Figure 2 shows interdecadal changes in annual-mean salinity and temperature along the equator. During the late 1970s, there was a pronounced salinity decrease in the upper pycnocline of the equatorial Pacific basin; thereafter a freshening persisted in the entire equatorial Pacific (Fig. 2a). Equatorial temperature fields also underwent significant interdecadal fluctuations (Fig. 2b). Before the middle 1970s, there was a warming at subsurface in the western-central tropical Pacific and a cooling to the east; thereafter, an opposite state emerged: a warming at the sea surface in the eastern tropical Pacific, but a cooling at subsurface in the west. Relative to the period 1960–75, the equatorial thermocline during the period 1980–95, as represented by the depth of 20°C isotherm, shoaled in the western and central equatorial Pacific, but deepened in the eastern equatorial Pacific (Fig. 2b). Note that if taking the depth of the maximum vertical temperature gradient as the thermocline depth, there are significant differences between these two parameters (the depth of the maximum vertical temperature gradient and the 20°C isotherm depth) in representing the decadal changes in the thermocline depth for the two periods, a result identified by Yang and Wang (2009). It can be shown that when adopting the depth of the maximum vertical temperature gradient to represent the thermocline depth, the equatorial thermocline shoaled across the entire equatorial Pacific (figures not shown).

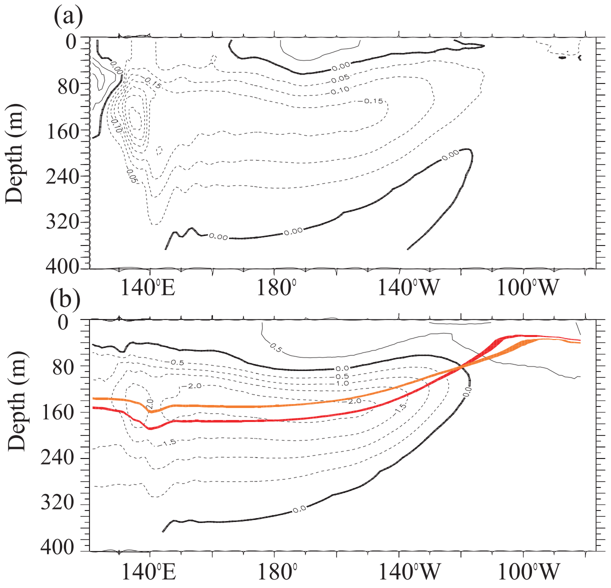


Fig. 2. Interdecadal changes in annual-mean salinity (a) and temperature (b) along the equator, formed by the differences between a field averaged during the period 1980–95 and during the period 1960–75. Contour intervals are 0.05 psu in (a) and 0.5°C in (b). Superimposed in (b) are the 20°C isotherms for the two periods (the red line for 1960–75, and the orange line for 1980–95).

These interdecadal changes were not restricted to the near-equatorial (5°N–5°S) band, but in fact appeared throughout the latitude band of the subtropical gyre in the South Pacific. Figure 3 illustrates the changes in simulated salinity fields at 10°S during the two periods. On average, a high salinity core is located at subsurface around 100–200 m depth, which can be traced all the way to the eastern subtropics where a high salinity ridge penetrates from the South Pacific subtropics to the tropics and further into the equator. After the late 1970s, there were large upward displacements of the pycnocline in the tropics. For example, the salinity contour of 35.3 psu [practical salinity unit, a unit of measurement of salinity similar to part per thousand (ppt)], which was at a depth of 300 m near the date line during the period 1960–75, was displaced upward to 230 m depth during the period 1980–95. Fur-

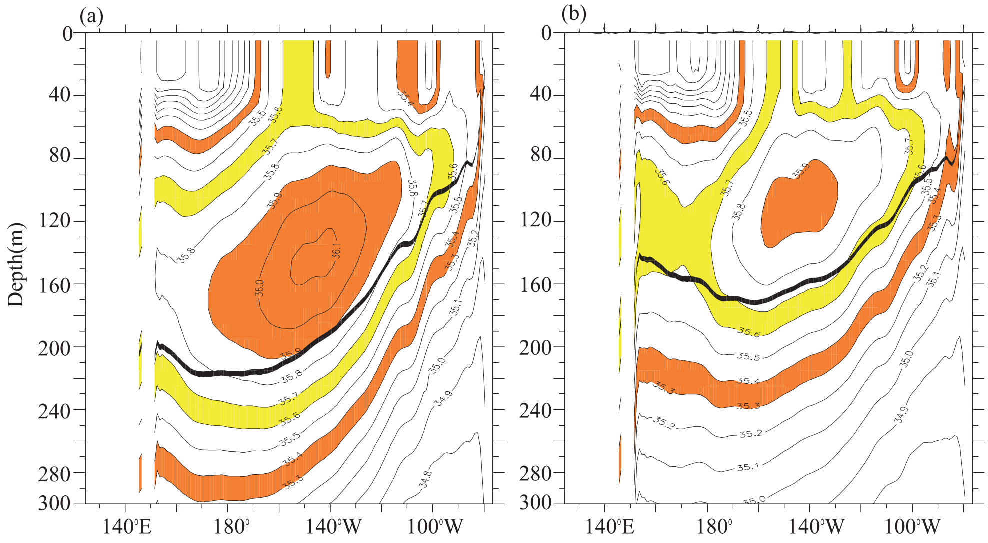


Fig. 3. Longitude–depth sections of annual-mean salinity fields along 10°S for the two periods 1960–75 (a) and 1980–95 (b). Contour interval is 0.1 psu. Superimposed are the corresponding 20°C isotherms (the bold black lines).

thermore, the salinity values in the core region decreased significantly, from 36.1 to 35.9 psu during the period 1980–95. It appears that the southward retreat of the high salinity ridge resulted in a freshening (~0.2 psu) in the entire upper pycnocline of the tropical South Pacific. In addition, it is seen that the vertical displacement of isohalines was even greater than that of isotherms. For example, after the 1976–77 climate shift, the 20°C isotherm was shifted upward by 40 m while the salinity contour of 35 psu moved upward by 70 m.

These interdecadal changes in temperature and salinity fields suggest that their perturbations coincide in such a way that cold anomalies tend to be accompanied by fresh anomalies at depth. For instance, during the period 1980–95, a cooling at subsurface in the western equatorial Pacific was accompanied by a freshening. This indicates that temperature and salinity fields tend to have compensating effects on density on the interdecadal time scales.

The persistent shift of subsurface waters in the western tropical Pacific after 1976 could be due to the changes in the vertical structure of temperature and salinity in response to local surface winds. This would require a similar shift in surface winds that would affect the tilt of the thermocline and pycnocline along the equator. Indeed, there were changes in the thermocline depth in 1976 (e.g., Guilderson and Schrag, 1998). A shallower thermocline in the west was supported by subsurface temperature data (e.g., Levitus et al., 2005) and was also consistent with overall weaker zonal winds in the tropics. However, tropical air–sea interactions apparently can not explain why the subsurface cooling and freshening should persist interdecadally, since El Niño cycles would, on interannual time scales, reverse the cooling and warming signals at subsurface depths in the western Pacific. The persistent cooling at subsurface in the west even during cold phase (La Niña conditions) suggests that a systematic change in the ocean, independent from a direct, local wind forcing, needs to be involved. While an upward displacement of the thermocline in response to tropical winds can, to some extent, account for the change in temperature fields, a vertical movement of the pycnocline can not explain the significant decrease in salinity fields at depth (Fig. 2a). It is more likely that the coherent changes in salinity and temperature fields reflect a shift in water mass characteristics in the western tropical Pacific after 1976, consistent with their covarying distributions in a density-compensating sense (Fig. 2). In addition, since interdecadal signals extended far to the subtropics of the South Pacific, higher latitude ocean processes other than the tropical air–sea coupling appear to be involved. Taking these arguments together, we propose a pathway change mechanism which is supported by ocean general circulation model (OGCM)-based analyses as follows.

4. Changes in the subtropical gyre and associated pathways

The subtropical gyre is the largest circulation system in the South Pacific, which rotates in an anticyclonic direction and constitutes a mass of saline and warm waters. The associated mean circulation dictates a direct pathway from the subtropics to the tropics around the South Pacific subtropical gyre; waters originating from the eastern subtropics follow the mean circulation northwestward towards the western equatorial Pacific, transporting mass, heat and salt onto the equator, having direct impact on water mass characteristics downstream in the equatorial Pacific.

The subtropical anticyclonic gyre of the South Pacific underwent interdecadal changes in the late 1970s. This can be clearly seen in sea level fields simulated from the free surface OGCM. To illustrate the changes, Figs. 1b–c present the horizontal patterns of the annual-mean sea level and surface currents for the two periods, 1960–75 and 1980–95. The mean sea level shows the center of the subtropical anticyclonic gyre, which is deepest in the subtropics and near the western side, stretching from the Solomon Islands to Tahiti. Associated with the climate shift, gyre-wide changes in sea level were clearly evident. For example, during the period 1960–75 (Fig. 1b), sea level was high over the entire gyre, with the values being over 35 cm in the central regions (14°S, 175°E) and the contour of 30 cm stretching from the Solomon Islands southeastward to 155°W and 18°S. During the latter period (Fig. 1c), sea level was lowered over a wide area across the gyre, with its values at the center (19°S, 180°) being only about 30 cm. Thus there existed more than 5-cm differences in sea level over the central area of the gyre during these two periods. Furthermore, such drops in sea level were not uniform in the horizontal. The largest drop in sea level was located in the northwestern part of the gyre around the Solomon Islands, from 30 cm during the former period (Fig. 1b) to below 15 cm during the latter period (Fig. 1c). Consequently, there existed a strong slope in sea level of about 20 cm between 20°S and 10°S during the period 1980–95, giving rise to a strong westward geostrophic flow in the region (Fig. 1c).

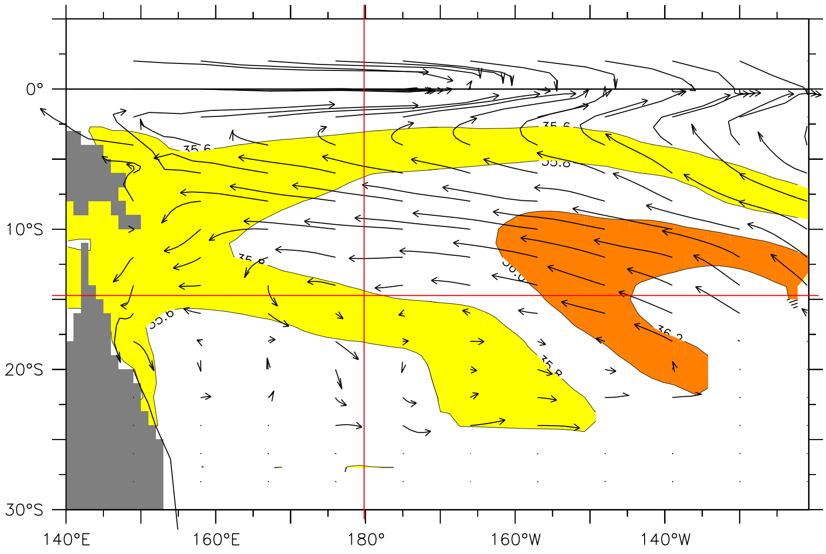
Associated with the 1976–77 shift, the center of the South Pacific subtropical gyre indicated a clear meridional migration. As indicated in sea level (Figs. 1b, c), the main center was displaced southward from 14°S during the period 1960–75 to 20°S during the period 1980–95. Also apparent was the change in the shape of the South Pacific subtropical gyre, being oriented from a southeast-northwest direction in the former period to an east-west direction during the latter period. As a result, after the late 1970s, the subtropical gyre shrank significantly in its spatial extent (Fig. 1c).

These changes clearly indicated a weakening of the subtropical gyre during the period 1980–95 (e.g., McPhaden and Zhang, 2002). The meridional transport across 18°S between the western boundary and the subtropical gyre center (18°S and 180°) at depths from 50 m to 850 m decreased from about 17 Sv during the period 1960–75 to 14 Sv during the latter period. Thus, the rotation of the water masses with the subtropical gyre or its water volume underwent a systematic reduction. In the 1960s through the middle 1970s, the subtropical gyre in the South Pacific Ocean was strong (in a spinning-up phase). Thereafter, the gyre was weakened significantly, with the decelerated circulation and decreased water volume within the gyre.

Furthermore, associated with the 1976–77 climate shift, not only the strength of the subtropical gyre, but the actual flow paths from the subtropics onto the equator were changed on the northwestern side of the gyre (Figs. 1b, c). To present the flow pathway, we have performed isopycnal analyses. Figure 4 demonstrates the parcel trajectories over a six-month period evaluated on the 24.2 isopycnal surface. As shown, the flow pattern exhibited a clear change in the subtropics and tropics during the two periods. For the 1960–75 period (Fig. 4a), a pathway was found to originate from the subtropical eastern outcrop region and extend directly into the low-latitude western Pacific through the central and western tropics. As such, the gyre circulation brought high-salinity subtropical waters all the way onto the equator, which was manifested as a ridge of high salinity that penetrated northwestward from the subtropics into the tropics. After the late 1970s (Fig. 4b), the changes in the subtropical-to-tropical exchange pathways are evident on the northwestern side of the gyre: some direct flow paths were actually shut down at latitudes 5°–10°S west of the date line. As a result, some subtropical waters flowed westward to the western boundary, without directly entering into the equatorial region, which acts to affect salinity distribution in the northwestern region of the gyre. As such, the salinity ridge from the subtropics did not penetrate northward onto the equator, leading to the salinity that was relatively low in the regions where the subtropical waters did not reach directly. For example, the contour of 35.6 psu was located around 10°S near the date line during the period 1980–95 (Fig. 4b), while it was at 3°S during the period 1960–75 (Fig. 4a). Quantitatively, the equatorward transport across 9°S between the depths of 50 and 850 m dropped from 16.7 Sv before the shift to 14.0 Sv after the shift.

Thus, it is shown that the weakened gyre circulation and particularly the change in flow path after 1976 act to affect the equatorward transport of mass, heat and salt onto the equator. In particular, after 1976, the source waters for the western equatorial Pacific contained a smaller proportion of subtropical waters originating from the South Pacific which are saline and warm. This altered the water mass characteris-

(a) 1960-75



(b) 1980-95

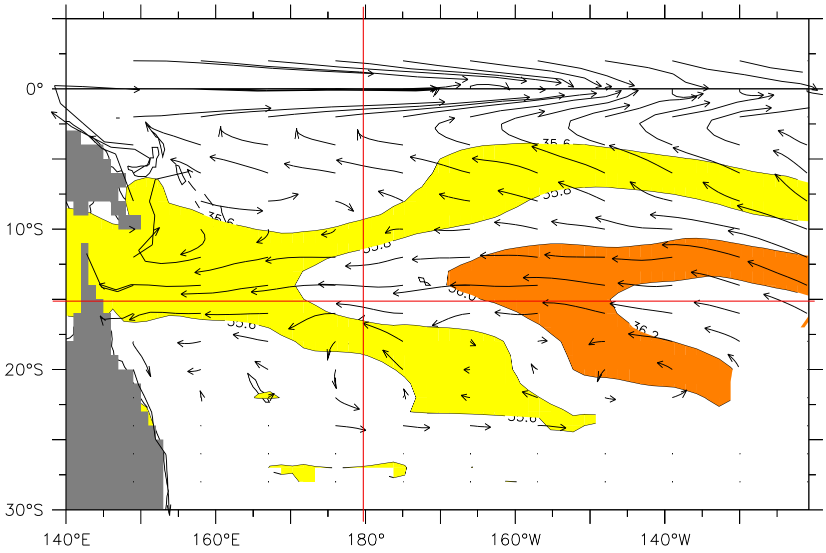


Fig. 4. Parcel trajectories over a 6-month period evaluated on the 24.2 isopycnal surface, using annual-mean velocity fields for the periods 1960–75 (a) and 1980–95 (b). The shaded areas indicate those where salinity is between 35.6 psu and 35.8 psu (yellow in color), and between 36.0 psu and 36.2 psu (orange in color), respectively.

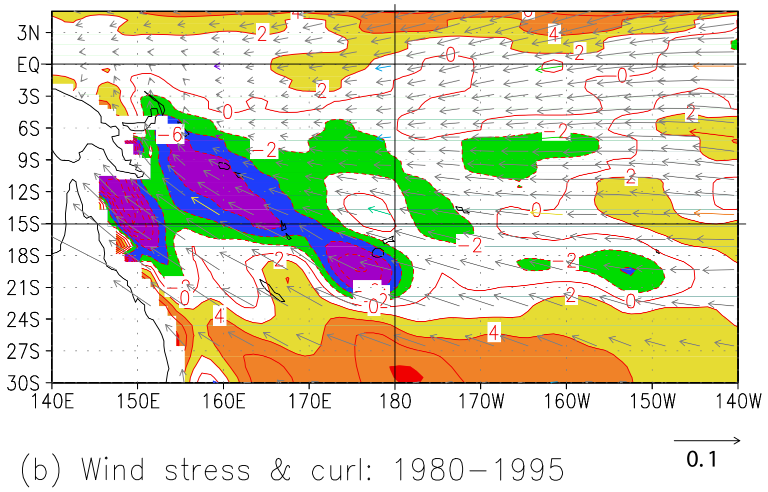
tics and thus the temperature and salinity structures along the equator. The reduced contributions of saline and warm waters from the subtropics to the equatorial Pacific can be responsible for the simulated shift in salinity and temperature fields at subsurface depths of the equatorial Pacific as observed in the late 1970s.

5. Discussion

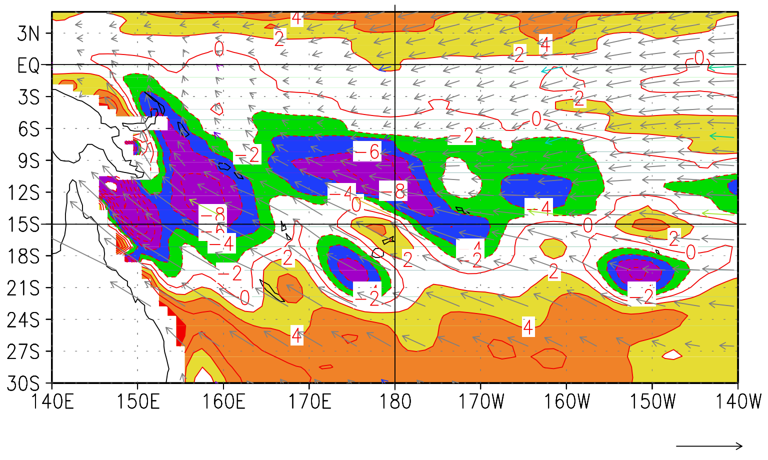
A gap in our understanding of the 1976–77 climate shift pertains to the subsurface ocean due to the lacking of basinwide observations. Ocean modeling has recently improved significantly, allowing much more realistic simulations of the ocean circulation and its variability. A version of GFDL/NOAA OGCM (MOM 3) is used to describe and understand interdecadal changes in the Pacific Ocean. Using complete output fields from the model and employing various isopycnal and trajectory analyses, we have documented the interdecadal changes in the subtropical gyre of South Pacific and the associated pathways from the subtropics to the tropics.

The “1976 Pacific climate shift” was characterized

(a) Wind stress & curl: 1960−1975



(b) Wind stress & curl: 1980−1995



(c) Difference in wind stress & curl

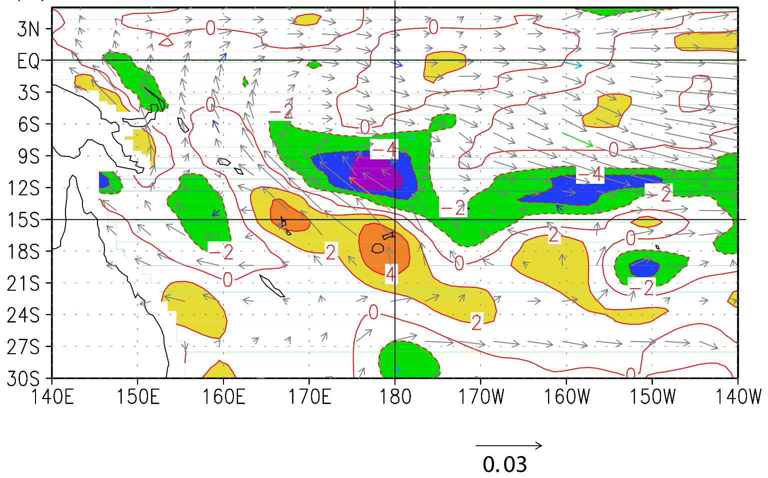


Fig. 5. Horizontal distributions of annual-mean wind stress (vectors) and its curl (contours) for the period 1960–75 (a) and for the period 1980–95 (b), and of their interdecadal changes which are formed by the differences during the periods 1980–95 and 1960–75 (c). The contour intervals are 2.0×10^{-8} N m^{-3} for the curl fields; the unit of the wind stress scale (the given arrow) is N m^{-2} .

by freshening and cooling at subsurface depth of the western and central tropical Pacific. While previous studies have suggested some possible mechanisms for interdecadal change in the thermal structure of the tropical Pacific Ocean. Here we propose another potential mechanism: actual flow paths connecting the subtropics to the tropics in the South Pacific Ocean may have changed. After the late 1970s, the weakened circulation and pathway changes in the northern portion of the South Pacific subtropical gyre reduced the salty and warm water supply from the subtropics to the western equatorial Pacific, causing persistent freshening and cooling in the western equatorial regions. This pathway perspective represents a straightforward way to explain decadal changes in temperature and salinity fields in the western equatorial Pacific as observed in the late 1970s. Note that this pathway framework has been also utilized to explain the connections of thermal anomalies off and on the equator in the tropical Pacific during the onset of El Niño events on interannual time scales (e.g., Zhang et al., 1999; Zhang and Rothstein, 2000).

The mechanisms for causing changes in pathways from the subtropics to tropics of the South Pacific Ocean can be ascribed to basin-scale surface wind variability over the South Pacific (Fig. 5), rather than local air-sea interactions in the tropics. In particular, the wind changes in the subtropics are involved since STCs are mainly driven by extratropical winds (McCreary and Lu, 1994). As shown in Fig. 5, during the period 1980–95, there is a weakening of the trade winds in the tropical region (north of 10°S) but a strengthening in the western subtropics (10°–20°S). These changes in surface winds and the associated curl fields during the two periods (Fig. 5) are consistent with the southward shift of the subtropical gyre and the weakened gyre circulation after the climate shift. Also, the extratropical wind changes can be related with air-sea interactions in the water formation regions. Detailed time evolution and chronicle relationships among changes in the ocean and atmosphere, in the subtropics and tropics, need to be examined further. Also, the pathway changes presented in this paper can be sensitive to the use of the reanalysis atmospheric forcing fields (i.e., the NCEP reanalysis data); more modeling experiments are clearly needed to confirm these results using other atmospheric forcing data.

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