GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 9, PAGES 1329-1332, MAY 1, 1999

Pacific thermocline bridge revisited

Niklas Schneider[1], Stephan Venzke[2], Arthur J. Miller[1], David W. Pierce[1], Tim P. Barnett[1], Clara Deser[3], and Mojib Latif[2]

Abstract. The coupling on decadal time scales of the mid-latitude and tropical Pacific via an oceanic 'bridge' in the thermocline is investigated using ocean general circulation model hindcasts and a coupled ocean atmosphere model. Results indicate that in the tropics decadal anomalies of isopycnal depth are forced by Ekman pumping and are largely independent of the arrival of subducted anomalies in the thermocline that originate in the mid-latitudes of either hemisphere. In the coupled model, temperature anomalies on isopycnals show little coupling from the tropics to the northern hemisphere, but are lag correlated between southern hemisphere mid- and low-latitudes. However, anomaly magnitudes on the equator are small. These results suggest that the oceanic 'bridge' to the northern hemisphere explains only a small part of the observed decadal variance in the equatorial Pacific. Coupling to the southern mid-latitudes via temperature anomalies on isopycnals remains an intriguing possibility.

Introduction

It has been hypothesized that decadal climate variability can be caused by coupling of the central North Pacific to the equatorial Pacific via thermal anomalies that propagate in the oceanic thermocline (Gu and Philander 1997). Time mean pathways of subducted waters deduced from trace gases (McPhaden and Fine 1988), oceanic density (Johnson and McPhaden 1999) and ocean general circulation models (Liu et al. 1994, McCreary and Lu 1994, Rothstein et al. 1998) are consistent with this oceanic 'bridge'. In the northern hemisphere most paths connecting the mid-latitudes with the equatorial regions pass through the low-latitude western boundary currents. In contrast, large parts of the southern hemisphere mid-latitudes are connected to the equatorial region through a direct, mid-ocean route (e.g. Johnson and McPhaden 1999).

While observed upper ocean temperature anomalies appear to propagate from the northern mid-latitudes to the equatorial region (Zhang et al. 1998), consideration of wind stress anomalies using simple steady-state models of the oceanic circulation indicates that tropical variability is mainly driven by low-latitude winds (Schneider et al. 1999). To resolve this controversy we investigate simulations with a full-physics ocean model driven by observed atmospheric forcing, and with a sophisticated coupled ocean-atmosphere model. Results indicate that decadal variability within the tropics and the equatorial region is dominated by tropical wind forcing and is largely independent of the arrival of thermal anomalies from the northern mid-latitudes. This is inconsistent with suggestions that Pacific decadal climate variability results from coupling of the northern mid-latitude and equatorial region via an oceanic 'bridge' in the thermocline. An influence of southern-hemisphere anomalies on the equatorial region remains a possiblity.

The propagation of thermal anomalies in the upper ocean is governed by the three dimensional oceanic circulation and is therefore best viewed in a reference frame of constant density surfaces (isopycnals). Thermal anomalies can either be caused by undulations of isopycnals, governed by planetary wave dynamics (Huang and Pedlosky 1999, Liu 1999a, b), or by changes of temperature on the isopycnal in the presence of compensating salinity anomalies, in which case thermal anomalies behave like a passive tracer. Since historical observations are currently inadequate to estimate subsurface salinity anomalies (T. Suga and K. Hanawa, personal communication) with the exception of a few sections (Kessler 1999) these two effects cannot be distinguished from data alone. Rather, a combination of data, ocean model hindcasts and coupled ocean-atmosphere model simulation needs to be considered and is presented in the following.

Oceanic Observations

Oceanic density and the depth of isopycnal surfaces are estimated from observations (White 1995) of anomalous temperature and mean salinity in the upper 400 m of the Pacific north of 20°S from 1969 to 1996. This was done using, at every horizontal position, both the mean vertical salinity profile and the mean temperature-salinity relationship. Consistent with the compensating effect of salinity on density at the depth of the 25.5 σ_Θ surface, isopycnal displacements are reduced by use of the latter technique compared to the former, most prominently poleward of 15°N. However, all results presented here are robust. In the following, isopycnal displacements from the first technique are shown, since temperature anomalies poleward of 15°N are caused by diabatic processes (Schneider et al. 1999) and it is therefore unclear if the temperature-salinity relationship remains constant. All estimates were low-pass filtered to focus on decadal variability with time scales longer than 6.5 years.

The 25.5 kg m^{-3} σ_Θ isopycnal connects the northern mid-latitude and equatorial Pacific (Johnson and McPhaden 1999, Lysne et al. 1997). Its depth anomalies have enhanced variance in the Kuroshio region at 30°N and in a broad swath that extends southwestward from the subduction region in the central North Pacific to the western subtropical and equatorial Pacific (Miller and Schneider 1998). In this region coherent anomalies propagate from the central North Pacific to the

[1] Scripps Institution of Oceanography, La Jolla, California
[2] Max-Planck-Institut für Meteorologie, Hamburg, Germany
[3] National Center for Atmospheric Research, Boulder, Colorado

Paper number 1999GL900222.
0094-8276/99/1999GL900222$05.00

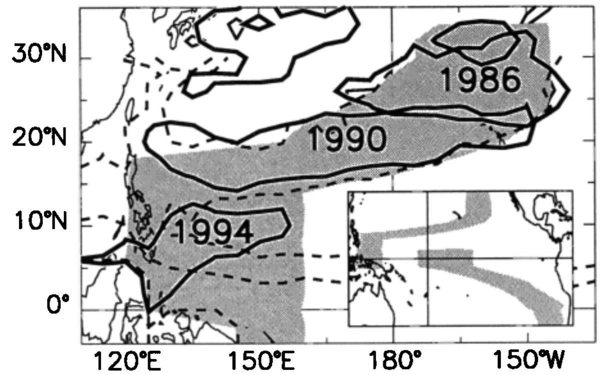

Figure 1: Depth anomalies of the 25.5 kg m^{-3} σ_Θ isopycnal. Shown is the contour corresponding to a shallowing of the surface by 10 m. Heavy lines denote data from years 1986, 1990 and 1994 (as indicated). Anomalies of the in-between years 1988 and 1992 (not shown) are consistent with a coherent propagation from the central North Pacific to the subtropical western Pacific of the depth anomaly over the eight year period (Miller and Schneider 1998). Dashed lines are 2.4 and $4.5 \cdot 10^{-10}$ m^{-2} s^{-1} isopleths of potential vorticity estimated from the vertical distance of the mean 25.3 and 25.7 kg m^{-3} σ_Θ isopycnals. Shading denotes area of zonal averaging used in Figure 2. Shaded areas in the inset show ventilation paths of the coupled model and are used in Figure 3.

subtropics (Figure 1) along contours of potential vorticity. This indicates that anomalies are advected by the mean flow as suggested previously by an analysis of isothermal displacements (Schneider et al. 1999).

In order to observe the propagation along this path for the entire data set, the zonal average of depth anomalies is formed along this path as delineated in the main part of Figure 1. Poleward of 15°N the region is marked by contours of potential vorticity and equatorward of 15°N by the region of enhanced variance between the western coast of the Pacific and 160°E. The result (Figure 2 a) shows a positive depth anomaly, corresponding to anomalous deep isopycnal and warm conditions, that originated in the central North Pacific from 1972 to 1977 and propagated to the south to reach 18°N about eight years later. At the same time, a positive depth anomaly occupied the region south of 18°N, whose maximum predated the arrival of the signal from the mid-latitudes. After the climate shift of 1976/77 (Trenberth and Hurrell 1994, Graham 1994, Miller et al. 1994), a negative depth anomaly, corresponding to shallow isopycnals and cold temperature anomalies, propagated with similar speeds from the central North Pacific to the south and appeared to spread all the way to the equatorial western Pacific. Analysis of simple, steady state, wind-forced models (Schneider et al. 1999), rather than of general circulation models considered here, indicated that this apparent spread results from tropical wind forcing and is not a result of the arrival of subducted signals from the mid-latitudes as concluded elsewhere (Zhang et al. 1998).

Ocean Hindcasts

To test the hypothesis that low-latitude isopycnal depth anomalies are due to wind forcing rather than due to the arrival of subducted anomalies from the mid-latitudes, an ocean general circulation model (Wolff et al. 1997) was forced by observed fluxes (Da Silva et al. 1994) of momentum and heat for the time period from January 1949 to December 1993 (Venzke 1999). In addition, surface temperatures were restored to observed, time-dependent values (Parker et al. 1995). This restoration partially overrides the forcing by anomalous surface heat fluxes but ensures that anomalies of sea surface temperature conform to observations. The simulation of isopycnal displacement averaged over the same area as described above compares well with observations (Figure 2 b). To determine if the anomalies equatorward of 18°N can be

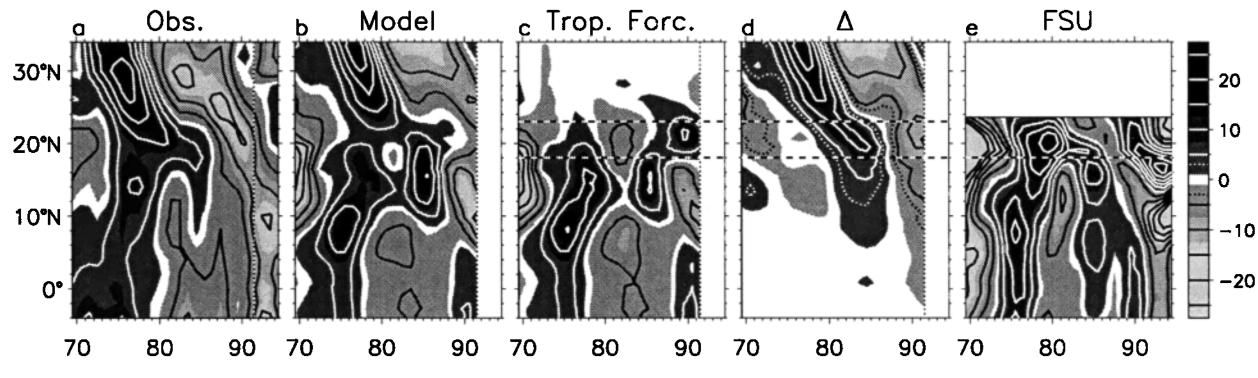

Figure 2: (a) Decadal anomalies of the depth of the 25.5 kg m^{-3} σ_Θ isopycnal zonally averaged in the shaded region of the main part of Figure 1. (b) Same as (a) but from results of an oceanic circulation model (Venzke 1999) forced with observed anomalies of surface wind stress (Da Silva et al. 1994), heat flux (Da Silva et al. 1994) and surface temperature (Parker et al. 1995). (c) Results from an experiment in which the anomalous atmospheric forcing was restricted to the area equatorward of 18° latitude. To avoid artificially generated curl of the wind stress a linear transition to zero anomalous forcing extended from 18° to 23° latitude (indicated by dashed lines). (d) Difference of 25.5 kg m^{-3} σ_Θ isopycnal depth anomalies of simulations with full forcing (b) and tropical forcing (c). The additional dotted contours mark differences with magnitudes of 3 m. (e) Depth anomalies obtained by forcing the ocean general circulation model with wind stress anomalies assembled by the Florida State University (Stricherz et al. 1992, 1997). Anomalous wind stress was estimated from the pseudo-stress by a constant drag coefficient of 10^{-3}. As in (c) wind-stress anomalies were applied within 18° latitude of the equator, and ramped to zero at 23° latitude. In all plots the contour interval is 5 m, light shading denotes negative depth anomalies, corresponding to a shallowing of the isopycnal, and dark shading represents positive depth anomalies (see the gray-scale on the right). The vertical dotted lines in (a) to (d) mark the end of the model experiment. All results have been smoothed using a low-pass filter with a half power at 6.7 years.

explained by the arrival of mid-latitude anomalies or by tropical wind forcing, an additional experiment was carried out in which the anomalous atmospheric forcing and relaxation of surface temperature anomalies were restricted to the area equatorwards of 18° latitude in both hemispheres. The resulting isopycnal depth anomalies poleward of 18°N are indeed reduced to nil, while the simulation equatorward of 18° latitude is largely unchanged (Figure 2 c) in both hemispheres. The difference between the simulations indicates that mid-latitude anomalies from the north (Figure 2 d) propagate into the equatorial region (Lysne et al. 1997). However, their magnitude, of the same order as reported by Lysne et al. (1997), is less then 10% of the observed equatorial values and explains little of the variance there. Remaining differences between the simulation and the observations, especially the large shallowing in the early 1990s, are within the observational uncertainties of oceanic wind stress as shown (Figure 2 e) by a repeat of the ocean hindcast using only anomalous tropical wind stress derived from a different analysis (Stricherz et al. 1992, 1997).

In summary, the hindcast experiments suggest that Ekman pumping in the tropics rather than the arrival of subducted anomalies from the mid-latitudes of either hemisphere explains the observed decadal variability of isopycnal depth in the equatorial region.

Coupled Model Results

Since the observed subsurface temperature record comprises only one warm and one cold event in the mid-latitudes, it is too short to unequivocally determine the importance of coupling of the central North Pacific to the tropics via anomalies in the thermocline. In addition, an assessment of the role of salinity compensated temperature anomalies and of coupling to the southern hemisphere mid-latitudes are not available from data. To obtain more degrees of freedom and to investigate the roles of salinity compensated temperature anomalies and of the southern hemisphere, a 130 year integration of a coupled ocean atmosphere model (Frey et al. 1997) is considered. The simulation produces both realistic El Niño and decadal variability in the North Pacific (Pierce et al. 1999).

As in observations, North Pacific decadal variability in the coupled model is associated with the generation of subducted anomalies that travel equatorwards in the oceanic thermocline (Pierce et al. 1999). The zonal average of depth anomalies of the 25.5 σ_Θ surface along the subduction path (shown in the inset of Figure 1) indicates that the meridional speeds of the anomalies on both hemispheres are close to observations (Figure 3). As in observations, simulated isopycnal depth anomalies equatorward of 10-15° latitude are independent from propagating anomalies originating in the mid-latitudes (Figure 3) and are forced by the tropical wind stress (Barnett et al. 1999, Pierce et al. 1999).

The lagged correlation of temperature anomalies on isopycnals along the subduction path shows that they propagate to the equatorial Pacific and indicates that the model correctly simulates this pathway (McPhaden and Fine 1988, Johnson and McPhaden 1999, Liu et al. 1994) on both hemispheres (Figure 3). However south of 10°N on the northern hemisphere, the magnitude of the correlation drops to 0.3 (Figure 3) and the amplitude of the subducted temperature anomalies is only 1/20°C. The mid-latitude signal is overwhelmed by the effect of anomalous advection across the mean temperature gradient on isopycnals. On the southern hemisphere, the signal can be traced to the edge of the equatorial undercurrent, even though the magnitude of the temperature anomalies there are again small (1/10 to 1/20°C).

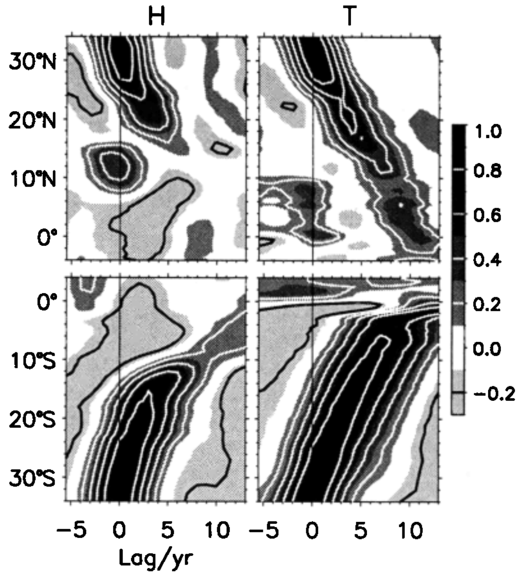

Figure 3: Lagged correlation with anomalies at 32° latitude of (left column) isopycnal depth anomalies of the 25.5 kg m^{-3} σ_Θ isopycnal and (right column) of salinity compensated temperature anomalies between the 25.0 and 26.0 kg m^{-3} σ_Θ isopycnals. Anomalies were zonally averaged on paths (shown in the inset of Figure 1) that are designed to capture the variance of temperature on isopycnals and that follow contours of potential vorticity. Correlations were formed with anomalies equatorwards of 32° latitude for the northern (top) and southern (bottom) hemisphere. Contour interval and shading are explained by the gray scale on the right. Results are from an extended integration of a coupled ocean-atmosphere model (Frey et al. 1997, Pierce et al. 1999).

Summary

The coupling of extratropical and tropical Pacific Ocean via an oceanic 'bridge' involves two distinct processes, the propagation of isopycnal depth anomalies, governed by planetary wave dynamics, and the advection of temperature anomalies on isopycnals that are accompanied by compensating salinity anomalies. Ocean hindcast experiments suggest that tropical wind-stress anomalies force decadal variability of isopycnal depth in the equatorial Pacific. This implies that tropical Ekman pumping overwhelms isopycnal depth anomalies that originate from the mid-latitudes. Lack of basin-wide observations of oceanic salinity and surface fresh water flux precludes an analysis from observations or ocean hindcasts of salinity compensated temperature anomalies along isopycnals. However, results from an extended coupled model integration suggest that tropical wind forcing also causes anomalous advection across the mean temperature gradient on isopycnals that dominates over anomalies formed in the northern mid-latitudes. Thus, tropical wind forcing rather than an oceanic 'bridge' to the northern mid-latitudes dominates the generation of thermal anomalies on decadal time scales in the equatorial Pacific ocean. In contrast, anomalies of temperature on isopycnals reach the equatorial system from the southern hemisphere via a direct path as hypothesized previously (Johnson and McPhaden 1999) but are small upon arrival. The testing of this model result requires long term observations of temperature and salinity in the upper ocean of the southern hemisphere and their analysis in terms of isopycnal depth and temperature on isopycnals. These observations are currently not available except for a few, limited sections (Kessler 1999). Finally, the importance of the arrival of thermal anomalies on isopycnals to the state of the equatorial Pacific needs to be determined from targeted modeling studies.

Acknowledgments. This work was supported by NSF (OCE97-11265), by DOE (DE-FG03-98ER62605), by the NOAA via the Experimental Climate Prediction Center (NA77RJ0453 ECPC) and via the Consortium for the Ocean's Role in Climate (NA47GP0188), and by the European Union's SINTEX programme.

References

Barnett, T. P., D. W. Pierce, M. Latif, D. Dommenget and R. Saravanan, Interdecadal interactions between the tropics and midlatitudes in the Pacific Basin, *Geophys. Res. Lett.*, *26*, 615-618, 1999.

Da Silva, A. M., C. C. Young and S. Levitus, Atlas of surface marine data 1994, Volume 1: Algorithms and procedures, NOAA Atlas 6, U.S. Department of Commerce, NOAA, NESDIS, 83pp, 1994.

Frey, H, M. Latif and T. Stockdale, The coupled model ECHO-2. Part I: The tropical Pacific, *Mon. Wea. Rev.*, *125*, 703-720, 1997.

Graham, N. E., Decadal scale variability in the 1970's and 1980's: Observations and model results, *Clim. Dyn.*, *10*, 135-162, 1994.

Gu, D. F. and S. G. H. Philander, Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics, *Science*, *275*, 805-807, 1997.

Huang, R. X. and J. Pedlosky, Climate variability inferred from a layered model of the ventilated thermocline, *J. Phys. Oceanogr.*, *29*, 779-790, 1999.

Johnson, G. C. and M. J. McPhaden, Interior pycnocline flow from the subtropical to the equatorial Pacific Ocean, *J. Phys. Oceanogr.*, in press, 1999.

Kessler, W. S., Interannual variability of the subsurface high-salinity tongue south of the equator at 165°E, *J. Phys. Oceanogr.*, 29, in press, 1999.

Liu, Z., Planetary waves in the thermocline: Non-Doppler shift mode, advective mode and Green mode, *Quart. J. Royal Meteor. Soc.*, in press, 1999a.

Liu, Z., Forced planetary wave response in a thermocline gyre, *J. Phys. Oceanogr.*, in press, 1999b.

Liu, Z. G., S. G. H. Philander and R. C. Pacanowski, A GCM study of tropical-subtropical upper-ocean water exchange, *J. Phys. Oceanogr.*, *24*, 2606-2623, 1994.

Lysne, J. A., P. Chang and B. Giese, Impact of the extratropical Pacific on equatorial variability, *Geophys. Res. Lett.*, *24*, 2589-2592, 1997.

McCreary, J. P. and P. Lu, Interaction between the subtropical and equatorial ocean circulations - The subtropical cell, *J. Phys. Oceanogr.*, *24*, 455-497, 1994.

McPhaden, M. J. and R. A. Fine, A dynamical interpretation of the Tritium maximum in the Central Equatorial Pacific, *J. Phys. Oceanogr.*, *18*, 1454-1985, 1988.

Miller, A. J. and N. Schneider, Interpreting the observed patterns of Pacific Ocean decadal variations, in *Biotic Impacts of Extratropical Climate Variability in the Pacific*, edited by G. Holloway, P. Müller and D. Henderson, pp. 19-27, University of Hawaii, 1998.

Miller, A. J., D. R. Cayan, T. P. Barnett, N. E. Graham and J. M. Oberhuber, Interdecadal variability of the Pacific Ocean: Model response to observed heat flux and wind stress anomalies, *Clim. Dyn.*, *9*, 287-302, 1994.

Parker, D. E., C. K. Folland, A. C. Bevan, M. N. Ward, M. Jackson and K. Maskell, Marine surface data for analysis of climate fluctuations on interannual-to-century time scales, in *Natural Climate Variability on Decadal to Century Time Scales*, National Academy Press, 241-250, 1995.

Pierce, D. W., T. P. Barnett and M. Latif, Connections between the Pacific Ocean Tropics and Midlatitudes on decadal time scales. *J. Climate*, submitted, 1999.

Rothstein, L. M., R.-H. Zhang, A. J. Busalacchi and D. Chen, A numerical simulation of the mean water pathways in the subtropical and tropical Pacific Ocean, *J. Phys. Oceanogr.*, *28*, 322-342, 1998.

Schneider, N., A. J. Miller, M. A. Alexander and C. Deser, Subduction of decadal North Pacific temperature anomalies: Observations and dynamics, *J. Phys. Oceanogr.*, *29*, in press, 1999.

Stricherz, J. N., J. J. O'Brien and D. M. Legler, Atlas of Florida State University tropical winds for TOGA 1986-1985, Florida State University, Tallahassee, FL, 250 pp., 1992.

Stricherz, J. N., D. M. Legler and J. J. O'Brien. TOGA pseudo-stress atlas, 1985-1994. Volume II: Pacific Ocean, Florida State University, Tallahassee, FL, 158 pp., 1997.

Trenberth, K. E. and J. W. Hurrell, Decadal atmosphere-ocean variations in the Pacific, *Clim. Dyn.*, *9*, 303-319, 1994.

Venzke, S., Ocean-atmosphere interactions on decadal time scales, Ph.D. dissertation, 99 pp., Universität Hamburg, Germany, January 1999.

White, W. B., Design of a global observing system for gyre-scale upper ocean temperature variability, *Prog. Oceanogr.*, *36*, 169-217, 1995.

Wolff, J.-O., E. Maier-Reimer and S. Legutke, HOPE, the Hamburg Ocean Primitive Equation Model, Technical Report, DKRZ, 1997.

Zhang, R.-H., L. M. Rothstein and A. J. Busalacchi, Origin of upper-ocean warming and El Niño changes on decadal scales in the tropical Pacific Ocean, *Nature*, *391*, 879-883, 1998.

T. P. Barnett, A. J. Miller, D. W. Pierce, and N. Schneider, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0224. (e-mail: tbarnett@ucsd.edu, ajmiller@ucsd.edu, dpierce@ucsd.edu, nschneider@ucsd.edu)

C. Deser, National Center for Atmospheric Research, P. O. Box 3000, Boulder, Colorado 80307-3000. (e-mail: cdeser@ucar.edu)

M. Latif and S. Venzke, Max-Planck-Institut für Meteorologie, Bundesstr. 55, D-20146 Hamburg, Germany. (e-mail: latif@dkrz.de, venzke@dkrz.de)

(Received January 08, 1999; revised March 11, 1999;
accepted March 15, 1999.)