Eastern equatorial Pacific Ocean T-S variations with El Niño

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[1] Temperature-Salinity (T-S) relationship variability in the pycnocline of the eastern equatorial Pacific Ocean (NINO3 region, 5°S–5°N, 150°W–90°W) over the last two decades is investigated using observational data and model simulation. A numerical model simulation using the MITgcm (Massachusetts Institute of Technology General Circulation Model) suggests that, during El Niño years, the water in the eastern equatorial Pacific Ocean becomes saltier (by 0.1 to 0.2) and warmer (by 0.5 to 1°C) on density surfaces within the pycnocline. This simulation is consistent with Conductivity-Temperature-Depth (CTD) data collected mostly during Tropical Atmosphere Ocean (TAO) mooring maintenance cruises. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4522 Oceanography: Physical: El Nino; 4536 Oceanography: Physical: Hydrography; 4231 Oceanography: General: Equatorial oceanography; 4255 Oceanography: General: Numerical modeling. **Citation:** Wang, O., I. Fukumori, T. Lee, and G. C. Johnson (2004), Eastern equatorial Pacific Ocean T-S variations with El Niño, *Geophys. Res. Lett.*, *31*, L04305, doi:10.1029/2003GL019087.

1. Introduction

[2] The eastern equatorial Pacific Ocean has been extensively studied, mainly because it plays an important role in El Niño/Southern Oscillation (ENSO) events [*Philander*, 1990]. During El Niño events, weakening of the easterly trade winds suppresses upwelling in the eastern equatorial Pacific Ocean, and sea surface temperature (SST) there increases. Hence the SST gradient between the western and eastern equatorial Pacific decreases, which further weakens the easterlies [see, e.g., *Meinen and McPhaden*, 2000]. While it is clear that the upper eastern equatorial Pacific becomes warmer during El Niño events [*Johnson et al.*, 2002], it is not clear whether and how the T-S (Temperature-Salinity) relationship in the pycnocline changes during these events. Such change in the T-S relationship might alter the air-sea interaction, which is crucial to ENSO adjustment, by changing the mixing in the region and therefore the SST accordingly.

[3] This paper investigates T-S relationship variability in the eastern equatorial Pacific Ocean over the last two decades to shed light on the relationship between El Niño events and eastern equatorial Pacific water property variations. Numerical simulation results from the MITgcm (Massachusetts Institute of Technology General Circulation Model) are compared with similarly analyzed Conductivity-Temperature-Depth (CTD) data.

2. Numerical Model

[4] The MITgcm is run with a near-global domain (78°S–78°N). The configuration is briefly described below [see *Marshall et al.*, 1997a, 1997b; *Lee et al.*, 2002 for detailed model description and setup]. Model resolution is 1° horizontally except within 10° of the equator where meridional resolution gradually decreases to 0.3°. There are 46 vertical levels with 10-m resolution in the upper 150 m of the model. The *Gent and McWilliams* [1990] isopycnal mixing scheme and the KPP mixed-layer formulation [*Large et al.*, 1994] are employed. The model is forced by National Centers for Environmental Prediction (NCEP) reanalysis products (12-hourly wind stress, daily diabatic air-sea fluxes) with time-means replaced by those of the Comprehensive Ocean-Atmosphere Data Set (COADS) [*da Silva et al.*, 1994]. Temperature and salinity at the model sea surface are further relaxed towards NCEP SST and climatological salinity [*Boyer and Levitus*, 1997], respectively. Such relaxation is in part to correct the inaccuracies in the fluxes. The simulation is spun up for 10 years prior to 1980, starting from rest using climatological temperature and salinity distributions [*Boyer and Levitus*, 1997]. The simulation then is run from 1980 to present. The results in the equatorial Pacific Ocean from 1980 to 1999 are analyzed in this study.

3. Model Results

[5] The model output includes 10-day averaged temperature and salinity fields. Our focus here is on the water in the pycnocline layer with potential density anomaly (σ_θ) ranging from 22 to 26 kg m^{-3} (see Table 4 of *Coles and Rienecker* [2001] for a summary of pycnocline bounds defined by different studies). The density interval between 22 and 26 kg m^{-3} is analyzed on 400 isopycnals at constant increments of 0.01 kg m^{-3}. We first calculate σ_θ from each pair of the 10-day averaged temperature and salinity. At each specific 10-day period, temperature values at all grid points in the NINO3 region (5°S–5°N, 150°W–90°W) are averaged on each of the 400 isopycnal surfaces. The same procedure is applied to obtain salinity profiles. The resultant fields are time-series of temperature and salinity for each

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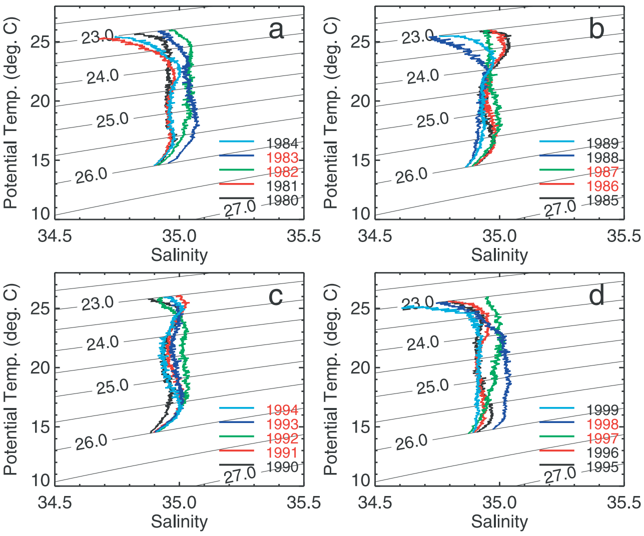

Figure 1. Annual mean T-S relationships from the numerical simulation in NINO3 region from 1980 to 1999. Panel a for 1980 to 1984, Panel b for 1985 to 1989, Panel c for 1990 to 1994, and Panel d for 1995 to 1999. The years written in red are the El Niño years.

isopycnal surface. Since water parcels move adiabatically on isopycnal surfaces, this averaging process is quasi-Lagrangian in the vertical, and tends to preserve water properties better than averaging on depth surfaces. The initial 10-day isobaric averaging will introduce some bias in short time scales, such as aliasing Tropical Instability Waves (TIWs). However, it will have few effects on the much longer interannual time scale that is the focus of the paper.

[6] These resultant 10-day averaged temperature and salinity time series are further averaged temporally over each calendar year to obtain annual-mean temperature and salinity profiles on each density surface. Annual-mean T-S relations from 1980 to 1999 reveal significant interannual variability (Figure 1). During El Niño years, middle to lower isopycnals ($24.5 \leq \sigma_\theta \leq 26$ kg m^{-3}) are much saltier (and therefore warmer). In other words, the T-S relationship shifts right (and up). For example, during the 1982–1983 El Niño, $\sigma_\theta = 25$ kg m^{-3} is about 0.05 to 0.1 saltier than the years before and after 1982–1983. A similar pattern is seen for the 1997–1998 El Niño as well as 1986–1987 and 1991–1994, all El Niño periods.

[7] Annual-mean salinity anomalies with respect to the 20-year average along a range of isopycnals ($22 \leq \sigma_\theta \leq 26$ kg m^{-3}) from 1980 to 1999 (Figure 2) reveal variations that are coherent with the occurrence of El Niño. Because the magnitudes of the variations are very different for the two ranges $22 \leq \sigma_\theta \leq 23$ kg m^{-3} (Figure 2a) and $23 \leq \sigma_\theta \leq 26$ kg m^{-3} (Figure 2b), two different color bars are used. The Southern Oscillation Index (SOI, Figure 2c), one indicator of ENSO variations, closely tracks the salinity anomalies on most isopycnals. In general, the correlations (Figure 2d) between the yearly SOI and the salinity anomaly are significant at 95% confidence level, while those near 24 kg m^{-3} and in the lower pycnocline are not.

[8] In summary, the numerical simulation suggests that there is some correlation in the NINO3 region between the occurrence of El Niño and changes of the T-S relationship. During El Niño years, warmer and saltier water is found on isopycnals within the pycnocline than in non-El Niño years.

4. TAO CTD Results

[9] CTD data collected since 1979, mostly during the TAO mooring maintenance cruises in the equatorial Pacific are analyzed to corroborate the model results. *McTaggart*

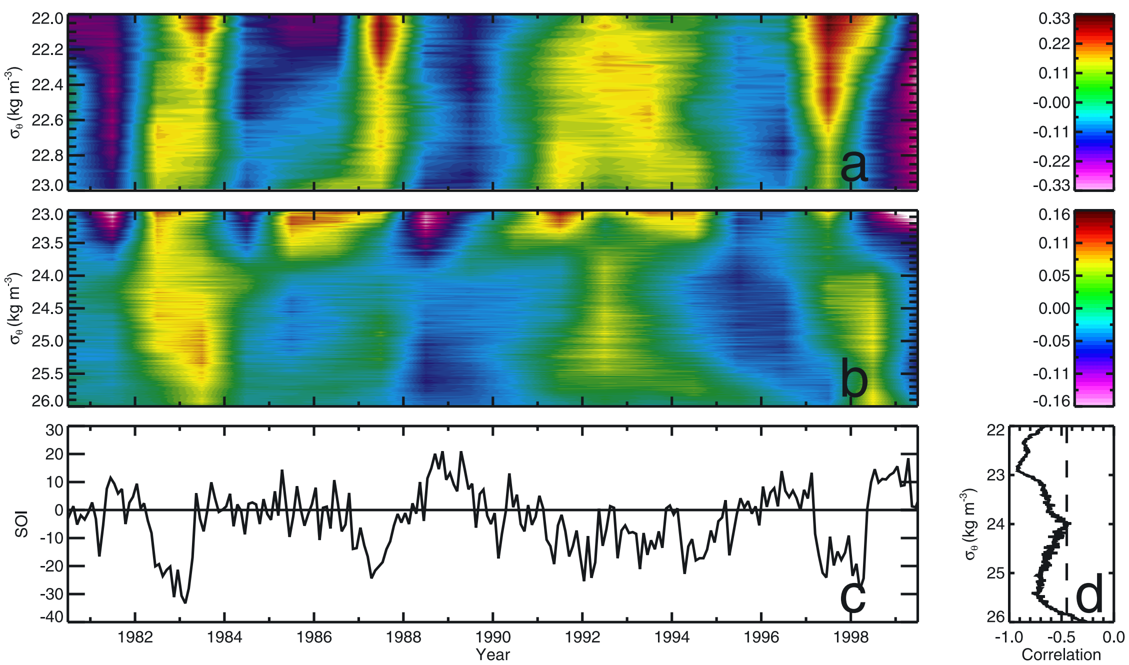

Figure 2. Model salinity anomaly on isopycnals (a) $\sigma_\theta = 22–23$ (kg m^{-3}) and (b) $\sigma_\theta = 23–26$ (kg m^{-3}) 1980 to 1999. (c) Low values of the Southern Oscillation Index (SOI) indicate El Niño events. (d) Correlation between the yearly SOI and the model salinity anomalies on isopycnals (solid line) generally exceeds the 95% confidence level (dashed line).

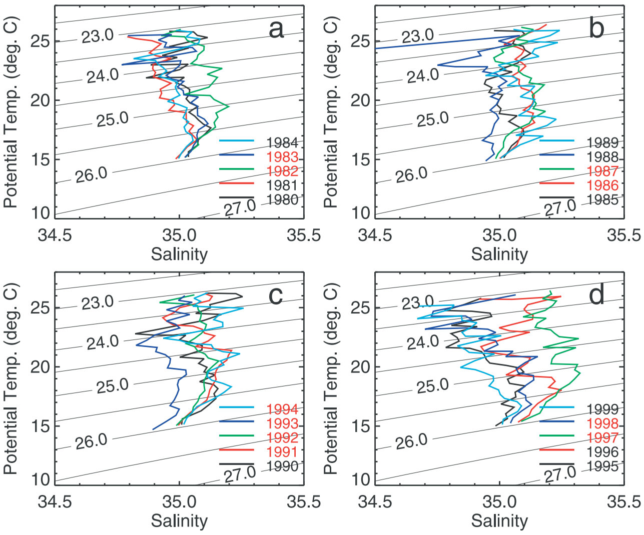

Figure 3. Annual mean T-S relationships from CTD stations mostly occupied during TAO mooring maintenance cruises in a sub-region (1°S–1°N and 150°W–90°W) of NINO3 region from 1980 to 1999. Panel a for 1980 to 1984. Panel b for 1985 to 1989, Panel c for 1990 to 1994, and Panel d for 1995 to 1999. The years written in red are the El Niño years.

and Johnson [2003] present a detailed description of processing and calibration of the TAO CTD measurements.

[10] Although extensive by oceanographic standards, the spatial and temporal distribution of the CTD stations is sparse and uneven over the whole NINO3 region from year to year. We therefore only use data from a sub-region (1°S–1°N and 150°W–90°W), in which the CTD casts were more evenly distributed with 51 casts per year on average. This choice is made to minimize potential bias caused by uneven spatial coverage. However, some biases may still exist.

[11] Annual T-S diagrams (Figure 3), obtained by averaging the temperature and salinity data in a manner similar to the processing of the model output, can be compared against the model simulation results (Figure 1). The observation-based T-S diagrams are much noisier than those from the model. This difference is likely owing to the sparse and uneven CTD measurements. However, the main pattern is qualitatively similar to that of the model: during the El Niño years, the water along given isopycnals is saltier than non-El Niño years. For example, in 1982, the water along σ_θ = 25 kg m^{-3} is about 0.2 saltier than that in 1981 and 1984. There is some difference between the model simulation and the CTD measurements. For instance, year 1989, which is not an El Niño year, has saltier water on a given isopycnal than the neighboring years. The CTD station distribution suggests that this is likely due to the sparsest spatial coverage of CTD casts in 1989 (25 casts and almost all occupied along the two meridians 110°W and 140°W).

[12] A very large meridional salinity gradient is found near the equator in the pycnocline across the Pacific Ocean, and an isolated maximum in the Equatorial Under-Current (EUC) in the east [*Johnson et al.*, 2002]. A northward or southward shift of that front by a tropical instability wave during a CTD survey could significantly influence the T-S inventory in the relatively small sub-region of NINO3. In addition, there is considerable seasonal T-S variability in the eastern equatorial Pacific pycnocline [*Lukas*, 1986; *Johnson et al.*, 2002] which could also influence the annual averages for the CTD data, especially when there is a significant seasonal bias to the sampling (e.g., 1992, 1993, and 1998 in which most CTDs were taken in boreal spring, February–May, and fall, September–November).

[13] To test if these sources of variability have a significant effect on the CTD-based averages, we subsample the model at the time and location of the CTD stations used. The subsampled averages (not shown) are much more similar to the CTD-based averages than are the model averages over the whole NINO3 region. However, the interannual T-S relationship variability for these subsampled averages has the same pattern as that obtained from the fully resolved average over the whole NINO3 region, i.e., saltier water in the pycnocline in the NINO3 region during El Niño years. We therefore believe that the CTD-based T-S inventory in the sub-region has not been overly influenced by seasonal variations. However, this test does not rule out the possibility that the CTD-based T-S inventory may have been influenced by shorter time-scale variability such as TIWs, which are not well simulated by the model.

5. Concluding Remarks

[14] Interannual T-S relationship variations in the eastern equatorial Pacific have been found during the period of 1980 to 1999. In situ observations and a numerical simulation suggest that water in the NINO3 region tends to become saltier (and therefore warmer) during El Niño years on isopycnals within the pycnocline, especially for water of $24.5 \leq \sigma_\theta \leq 26$ kg m^{-3}. An analysis of CTD data which includes a linear regression of T-S on isopycnals versus SOI, also supports this behavior [*Johnson et al.*, 2002]. The shift in T-S relationship corresponds to a significant change in the water properties of the eastern equatorial Pacific Ocean. For instance, during El Niño, water in the thermocline is saltier than any other water mass normally found in this region. Studies of data assimilation that employ statistical relationships between temperature and salinity should take this T-S variability into account. This shift in T-S relationship may alter the mixing in the region, which may change the SST and therefore the air-sea interaction. These shifts also provide useful hints of the pathway and origin of water in the pycnocline of NINO3 region by tracing back in time the tracer-tagged water [*Fukumori et al.*, 2004]. While the warming in the NINO3 region has been extensively studied, few studies investigate the increase of salinity in the pycnocline of the NINO3 region [*Mangum et al.*, 1986; *Johnson et al.*, 2000; 2002]. Evaporation-Precipitation (E-P) changes during El Niño events are unlikely to reach densities of 25 kg m^{-3}. Therefore, changes in circulation may be fundamental to the observed T-S variations. Investigation into the nature of such changes will be pursued in a separated study.

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