Freshening of the Upper Thermocline in the North Pacific Subtropical Gyre Associated With Decadal Changes of Rainfall

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Abstract. Repeated observations in the North Pacific subtropical gyre near Hawaii reveal pronounced freshening (~0.15 ‰) and cooling (~0.5°C) of the upper thermocline from 1991 through 1997. The freshening appears progressively later on deeper isopycnals consistent with subduction of surface salinity anomalies at higher latitudes and subsequent southward advection. Winter rainfall anomalies in the central North Pacific are dominated by the El Niño/Southern Oscillation (ENSO) phenomenon and by the Pacific Decadal Oscillation (PDO), with the wet phase of the PDO leading the observed freshening. The reversal of the freshening trend in the upper thermocline is related both to extreme drought near Hawaii during the 1997-98 ENSO, and to protracted drought associated with the PDO. The density compensation of decadal thermal anomalies by salinity implies that they do not disperse dynamically. An even stronger implication is that the hydrological cycle is a key component of decadal variability in the North Pacific.

Introduction

Much progress has occurred in observing, understanding and predicting ENSO, and attention has turned towards decadal variability of the coupled ocean-atmosphere system in the Pacific sector. Decadal variability is as important as ENSO to observe, understand and predict because it has significant effects on climate in many places around the world, because these effects may combine with those of ENSO to produce climate extremes, and because these natural decadal variations must be taken into account in attempting to identify anthropogenic changes to the Earth's climate. Because the climate states associated with decadal variations persist for several years or more, their impact on society may be greater than the effects of ENSO.

Among other hypotheses about Pacific decadal variability, it has been suggested that decadal variability in the North Pacific interacts with ENSO through subduction of upper ocean thermal anomalies in the subtropics (possibly forced by ENSO), and their subsequent reemergence in the eastern equatorial Pacific upper ocean (Gu and Philander, 1997).

A number of recent model and empirical studies of decadal variability of the North Pacific Ocean have made unwarranted assumptions that salinity doesn't vary, or that any variability is explained by a time invariant T-S relationship. A more sophisticated assumption sometimes used is that a relatively stable T-S relationship that varies regionally and possibly seasonally exists below the surface mixed layer, (e.g., Emery and Wert, 1976). Thus, knowledge of temperature is considered sufficient to determine the density field in the ocean interior, and thermal anomalies are subject to Rossby wave dispersion (cf. Liu and Shin, 1999). However, the Earth's hydrological cycle is subject to climate variability that includes salinity variations not simply correlated with temperature variations (e.g. Lukas and Lindstrom, 1991; Webster and Lukas, 1992). I show here that the T-S relationship in the North Pacific subtropical gyre varies on climate time scales and that these variations are related to rainfall variability in a highly nonlinear way.

Observations

Ocean Time Series

There are very few long-term observations of the Pacific Ocean that can be used to quantify and improve our understanding of decadal modes of climate variability, and most concern only near-surface variations. Long-term observations of temperature profiles are available, but their space-time distribution has varied on climate time scales, making interpretation difficult at best. As suggested above and shown later, conclusions about ocean dynamics and thermodynamics based on temperature alone are potentially very misleading. All but a handful of the long time series of subsurface salinity are along the coasts, rather than in the deep ocean interior. A notable exception is the time series from Ocean Station Papa in the northeast Pacific (Tabata et al., 1986; Overland et al., 1999). The Hawaii Ocean Time-series (HOT) program was established, in part, to help address these deficiencies (Karl and Lukas, 1996).

The HOT Station ALOHA is 100 km north of Oahu, Hawaii at 22°45'N, 158°W (Fig. 1) in approximately 4800 m of water. The site has been occupied 10-12 times each year from October 1988 through January 2001. Station visits last about 3 days, and include 36 hours of 3-hourly "burst" CTD profiling of temperature and salinity over the upper 1000 m, required to average out the ubiquitous baroclinic tides which are a strong source of noise for ocean climate studies. Many other observations, including carbon cycle related biogeochemistry, are made during each cruise (Karl and Lukas, 1996).

Rainfall

The NOAA CMAP rainfall dataset (Xie and Arkin, 1997) is used here to study variability that may be related to salinity variations, both at the surface and in the interior of the subtropical gyre. Variation in summertime rainfall over the central North Pacific (CNP) is relatively small, but there are pronounced differences in the winter season peak rainfall rate and its timing (Fig. 2a). During the first half of the 1980s, CNP winter rainfall is relatively high and relatively low during 1990-94. From 1995-1997, winter rainfall is relatively high, with two of the highest years in the record. The monthly departures from the 1979-1997 climatology (not shown) reveal that events of a month or two dominate, which is consistent with storm track variability. There is, however, an underlying decadal variation, with a peak in the mid-1980s, a minimum in 1990, and another peak in 1996. This decadal variation is relatively small in comparison to the intraseasonal variability, but it is coherent over a large area of the ocean, and the anomalies persist for several years. Thus, we may expect a cumulative impact on upper ocean salinity.

While monthly observations are not adequate to resolve all of the important forcing, they give us some insight. Because of the variable timing of the maximum precipitation during each winter (Fig. 2a), we average the January through March rainfall observations as a gross indicator of the “winter hydrological cycle imprint” on the mixed layer subduction process.

The dominant empirical orthogonal function (EOF) of winter rainfall over the North Pacific consists of an out-of-phase relationship between the midlatitude storm track and the tropics (Fig. 3a), accounting for about 28% of the total variance (Fig. 2b). There is a node along 30°N over much of the North Pacific, and the Hawaiian Islands are in a relative maximum. The temporal modulation of this pattern is dominated by the 1982-83, 1986-87, and 1991-92 ENSO events bringing drier conditions in the band between 10°N and 30°N, and wetter conditions along the storm track and the west coast of North America. La Niña lead to wetter conditions in the subtropics during the winter of 1989.

EOF2 is dominated by the decadal variation discussed above, accounting for about 17% of the total variance (Fig. 2b). Elongated regions of maximum variability trend from southwest to northeast (Fig. 3b), consistent with the results of Overland et al. (1999) in the eastern North Pacific. There is an apparent connection of the maximum in the CNP between 30-45°N with the western tropical Pacific region. The nodal line on the equatorward side of this region extends from just north of the Hawaiian Islands to the coast of California. Of particular note is the trend-like increase of rainfall in the CNP from 1990 to 1997. We believe that this is the cause of the freshening of the upper pycnocline at ALOHA that is discussed below.

Salinity

The annual mean North Pacific sea surface salinity (SSS; e.g. Levitus and Boyer, 1994) shows an elongated maximum (>35 psu) centered along 25°N, from about 150°E to 135°W. This salinity maximum lies under a zonal band where there is a net loss of freshwater from the ocean to the atmosphere, on average, but the surface salinity maximum is about 500 km north of the maximum freshwater loss. This is due to the northward Ekman flow driven by the easterly Trade Winds, and to the cumulative loss of freshwater along the trajectory of the surface water parcels. The meridional SSS gradient reverses under the region of net loss due to southward flow of fresher waters from the storm track region (cf. Fig. 1) under the influence of the midlatitude westerlies. The SSS maximum is in a region of convergence associated with the Subtropical Front, where SST anomalies have a relative maximum (Nakamura et al., 1997). At this front, waters are subducted into the pycnocline during late winter each year, forming the shallow salinity maximum of the central North Pacific Ocean observed at ALOHA. Wind, rainfall and evaporation are subject to interannual and decadal variations, and these cause low frequency salinity changes near the Subtropical Front that appear in the pycnocline with some delay at ALOHA, as well as near-surface variations at ALOHA.

The time series of nonseasonal salinity departures in potential density coordinates (relative to the first 11 years of HOT observations) shows a pronounced salinity decrease in the upper pycnocline between 1991-97 at ALOHA (Fig. 2c). The salinity anomalies appear to propagate downwards with time (Fig. 2c). This is similar in nature to the downward penetration of decadal thermal anomalies in the central North Pacific Ocean (Deser et al., 1996), suggested to be a manifestation of thermocline ventilation (Luyten et al., 1983). The range of variation of salinity averaged over the 24.2-25 σ_θ layer (Fig. 2d) is 0.3 psu, with a change in the sign of the trend beginning in 1998. This signal is also observed in the mid-pycnocline (25-26 σ_θ), however the trend reversal occurs later than in the shallower layer, and the magnitude is smaller. The increasing salinity in the upper pycnocline coincided with the ENSO-related drought around Hawaii in 1998.

Discussion

An outstanding issue related to decadal ocean dynamics is the degree to which subducted thermal anomalies are **not** density-compensated by salinity anomalies of opposite sign, and therefore dynamically active (Liu and Shin, 1999). In potential density coordinates the salinity anomalies described here are **exactly** compensated by temperature anomalies, and the freshening trend corresponds to a 0.5°C cooling on certain isopycnals, comparable to the anomalies estimated by Deser et al. (1996). Thus, we expect this signal to act as a passive tracer, subject to mixing but not to baroclinic wave dispersion. If the freshening trend observed at ALOHA is due to anomalous subduction, the increased rainfall in the CNP subduction zone must be compensated by greater heat losses from the upper ocean. Such coherent variations in the thermal and freshwater forcing over a portion of the central North Pacific may partially explain the dominance of density-compensated fronts there (Rudnick and Ferrari, 1999).

The mixed layer T-S characteristics that are transmitted to the upper pycnocline by subduction are those at the time of deepest mixing. This gives rise to a nonlinear relationship between low frequency variations in upper pycnocline T-S characteristics and the high frequency forcing associated with winter storms (Stommel, 1979). Midlatitude storms are responsible for much of the rainfall over the North Pacific Ocean (Figs. 1 and 2). Interannual and decadal variations of the storm tracks and intensity result in substantial large-scale changes in precipitation and heat fluxes (Nakamura and Izumi, 2000).

Is the delay between the time history of EOF2 and the appearance of salinity anomalies at ALOHA consistent with this scenario? Subducted mixed layer anomalies, or the impact of anomalous subduction rates, appear first in the upper pycnocline at the HOT site because advection is faster near the surface and because the ventilation location is closer than for deeper isopycnals (Huang and Qiu, 1994; Huang and Russell, 1994). The delay from subduction to arrival at ALOHA is about 1 year for densities between 24 and 24.6 σ_θ, and about 3-4 years for density levels between 25 and 26 σ_θ. The downward penetration lag for the salinity signals at ALOHA is grossly consistent with this estimate, which assumes that the geostrophic gyre circulation and the subduction locations do not vary. It is unlikely that the trajectories for anomalous water parcels follow mean streamlines because low frequency Rossby waves are ubiquitous in the North Pacific, and it is certain that the ventilation region for a particular isopycnal varies from year to year. It is difficult however to take the interaction of Rossby waves and subduction into account without recourse to a very sophisticated model.

Conclusions

These observations of coherent thermohaline forcing of the North Pacific subtropical gyre suggest that it is crucial for testing of hypotheses about decadal climate variability to understand and model the coherent decadal variations of heat and freshwater forcing associated with storm track and intensity changes. Further, because of the nonlinearity of the subduction process, it is necessary to properly model the air-sea fluxes of heat, moisture, and momentum within the relatively few, but very intense, winter storms that affect any one area of the mid-latitude North Pacific during a particular year. Until coupled climate models can reproduce the character of the observations reported here, no strong test of decadal climate hypotheses is possible. Finally, it is important to map out the extent and evolution of the subducted freshening signal. The proposed Argo array of profiling floats could accomplish that, if implemented soon enough.

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References

Deser, C., M.A. Alexander, and M.S. Timlin, 1996: Upper-ocean thermal variations in the North Pacific during 1970-1991. J. Climate, 9, 1840-1855.

Emery, W.J. and R.T. Wert, 1976: Mean TS curves in the Pacific and their application to dynamic height computation. J. Phys. Oceanogr., 4, 613-617.

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

Huang, R.X., and B. Qiu, 1994: Three-dimensional structure of the wind-driven circulation in the subtropical North Pacific. J. Phys. Oceanogr., 24, 1608-1622.

Huang, R. X. and S. Russell, 1994: Ventilation of the subtropical North Pacific. J. Phys. Oceanogr. 24 (12), 2589-2605.

Karl, D.M. and R. Lukas, 1996: The Hawaii Ocean Time-series (HOT) Program: Background, rationale and field implementation. Deep-Sea Res. II, 43, 129-156.

Levitus, S. and T.P. Boyer, World Ocean Atlas 1994, Volume 3, Salinity, NOAA Atlas NESDIS 3, U.S. Government Printing Office, Washington, D.C., 99 pp., 1994.

Liu, Z. and Shin, S.-I., 1999: On thermocline ventilation of active and passive tracers. Geophys. Res. Lett. 26, 357.

Lukas, R. and E. Lindstrom, 1991: The Mixed Layer of the Western Equatorial Pacific Ocean. J. Geophys. Res., 96(suppl.), 3343–3357.

Luyten, J., Pedlosky, J. and Stommel, H. J. Phys. Oceanogr. 13, 292 (1983).

Luyten, J., J. Pedlosky, and H. Stommel, 1983. Climatic inferences from the ventilated thermocline. Climatic Change, 5, 183-191.

Nakamura, H., G. Lin and T. Yamagata, 1997: Decadal climate variability in the North Pacific during the recent decades. Bull. Am. Met. Soc., 78, 2215-2225.

Nakamura, H. and T. Izumi, 2000: Interannual and decadal modulations recently observed in the Pacific stormtrack activity and East Asian winter monsoon. J. Clim., submitted.

Overland, J.E., S. Salo, and J.M. Adams, 1999: Salinity signature of the Pacific Decadal Oscillation. Geophys. Res. Lett., 26, 1337-1340.

Rudnick, D.L. and Ferrari, R., 1999: Compensation of Horizontal Temperature and Salinity Gradients in the Ocean Mixed Layer. Science 283, 526-529.

Stommel, H., 1979: Determination of watermass properties of water pumped down from the Ekman layer to the geostrophic layer below. Proc. Natl. Acad. Sci. U.S., 76, 3051-3055.

Tabata, S. B. Thomas, and D. Ramsden, 1986: Annual and interannual variability of steric sea level along Line P in the northeast Pacific Ocean. J. Phys. Oceanogr., 16, 1378-1398.

Webster, P. J. and R. Lukas, 1992: TOGA COARE: The Coupled Ocean-Atmosphere Response Experiment. Bull. Amer. Met. Soc., 73, 1377-1416.

Xie and Arkin, 1997: Global Precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs, Bull. Am. Met. Soc., 78, 2539-2558.

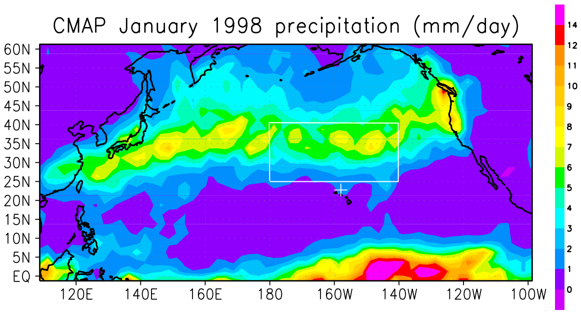

Figure 1. Daily average rainfall (mm/day) for the month of January 1998. The region enclosed by the box in the central North Pacific is used in subsequent figures. The white cross indicates the location of the Hawaii Ocean Time-series station.

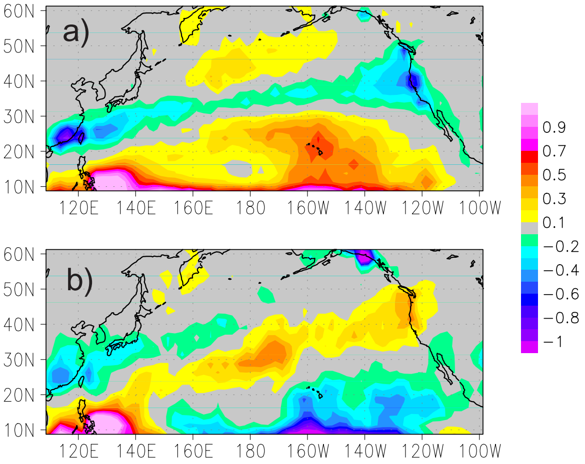

Figure 3. Spatial patterns for the first two empirical orthogonal functions of wintertime rainfall variations.

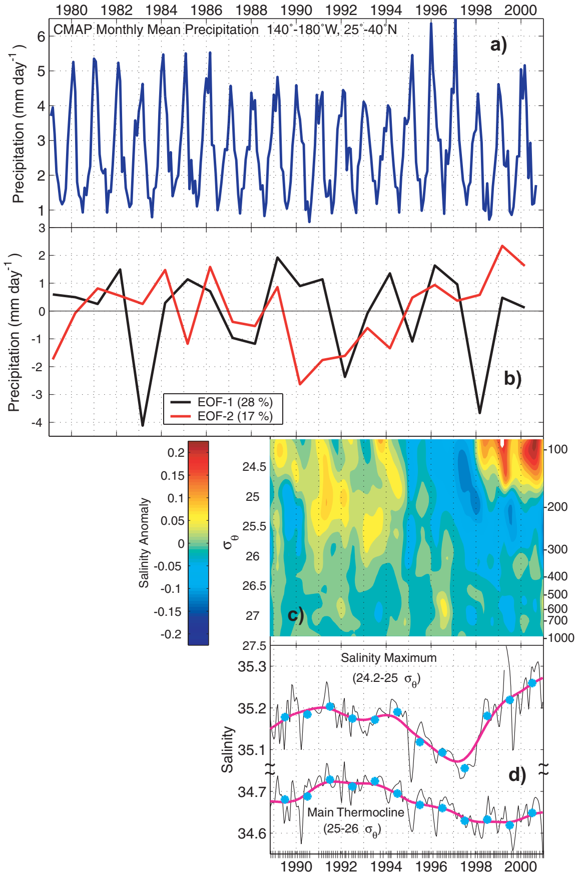

Figure 2. (a) Time series of monthly rainfall (Xie and Arkin, 1997) over the North Pacific area indicated in Fig. 1. (b) Time series of the first two EOFs of winter rainfall over the central North Pacific. The percentage of total variance accounted for by each EOF is indicated. (c) Time series of salinity anomaly versus potential density. The scale along the right axes indicates the mean depth of the corresponding isopycnal surface. (d) Time series of layer- averaged salinity for the salinity maximum layer and the main thermocline. Light lines connect individual cruise values. Heavy lines are smoothing cubic splines. Closed circles are annual averages. Tick marks along the time axes indicate the timing of individual HOT cruises.