

NOTES AND CORRESPONDENCE

Did the Thermocline Deepen in the California Current after the 1976/77 Climate Regime Shift?

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ABSTRACT

The 55-yr California Cooperative Oceanic Fisheries Investigations (CalCOFI) dataset in the southern California Current reveals a significant surface-intensified warming and stratification (buoyancy frequency) change across the 1976/77 climate regime shift. However, the average depth of the thermocline, defined as the maximum gradient of temperature, did not change significantly across the regime shift. The maximum-gradient criterion for thermocline depth may be more appropriate than following an isotherm because the isotherm necessarily deepens in the presence of surface-intensified warming. As the surface heating changed the strength of stratification, it also changed the slope of the nitrate–temperature relation for the middepth waters (roughly 30–200 m). Thus, the quality of upwelled water may have been fundamentally altered after the shift.

1. Introduction

The California Current System (CCS) is highly variable and very productive. Many physical features—for example, stratification (Bograd and Lynn 2003; McGowan et al. 2003), coastal upwelling (Huyer 1983), mesoscale eddies (Davis 1985; Hickey 1998), cold filaments (Strub et al. 1991)—occur over various temporal and spatial scales, interacting with the marine ecosystem. Long-term changes of the biological response to physical climate forcing are of great interest, because the nonlinear ecosystem may not be linearly related to persistent environmental disturbances (Hsieh et al. 2005).

Roemmich and McGowan (1995, hereinafter RM95) identified a 70% decrease of macrozooplankton biomass and 1°C upper-ocean warming from 1951 to 1993 in the California Cooperative Oceanic Fisheries Investigations (CalCOFI) in situ dataset for the southern part of the CCS. They suggested that increased stratification caused less nutrient input to the upper ocean and de-

creased new production, which is a possible reason for the decrease of zooplankton biomass.

It is still unclear whether this is a secular trend, possibly due to greenhouse warming, or a transient signal associated with Pacific Ocean decadal variability (Mantua et al. 1997). Although the data length is not long enough to separate these two signals, the CalCOFI upper-ocean temperature is highly correlated with basin-scale climate regime shifts in 1976/77 and 1998/99 (Miller et al. 1994; Hayward et al. 1999; Peterson and Schwing 2003; Fig. 1). Interannual variations are also strong, with several large peaks of warm temperature in El Niño years (1957/58, 1983/84, and 1997/98). The long-term warming of the upper-ocean temperature appears to decrease after 1998 (Fig. 1), which could be an interannual anomaly or the start of a new cooler climate regime. Since the 1998/99 climate regime shift is still controversial, we focus here on only the 1976/77 climate regime shift with the cold regime defined as 1950 to 1977 and the warm regime as 1977 to 1998.

Previous studies of the 1976/77 shift (Bograd and Lynn 2003; McGowan et al. 2003; Di Lorenzo et al. 2005) all describe this warming and attempt to quantify a deepening of the thermocline after the shift. RM95 show that averaged temperature sections of lines 80 and 90 (Fig. 2) manifest surface warming up to 1°C. The

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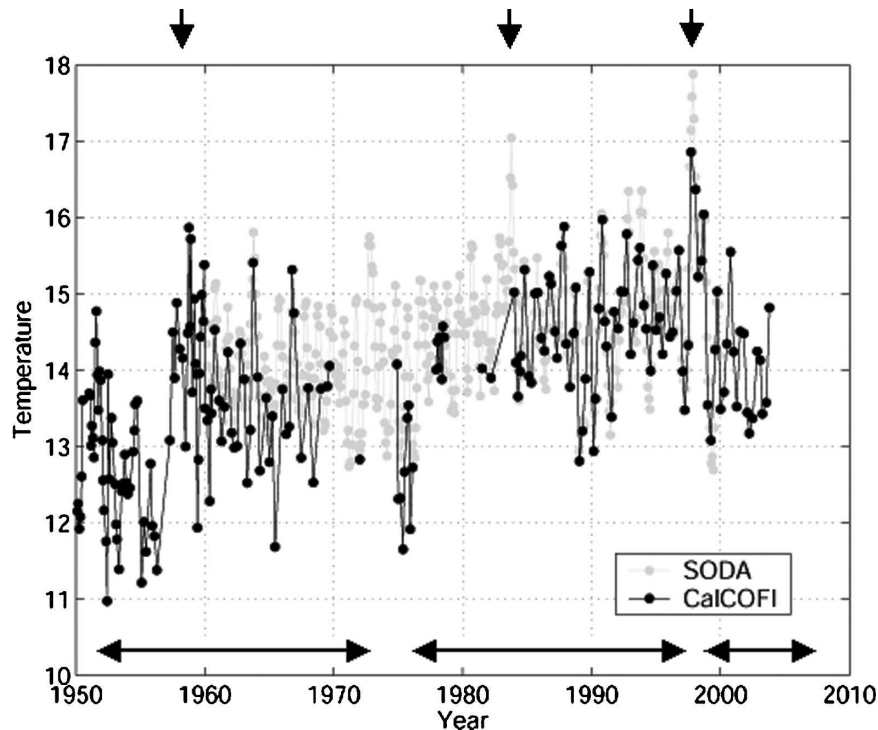


FIG. 1. The upper-ocean temperature average from the surface to 100-m depth along line 80. The black dots are calculated with the CalCOFI observations, and the gray dots are from Simple Ocean Data Assimilation (SODA; courtesy of B. Giese, Texas A&M). The SODA dataset was resampled as the same stations of line 80. The arrows above the plot represent El Niño year (1957/58, 1982/83, and 1997/98), and the arrows below the plot indicate different climate regime periods (cold regime from 1950 to 1976; warm regime from 1977 to 1998).

warming signature penetrates below 200 m, which is well below the thermocline. Bograd and Lynn (2003) use temperature harmonics calculated with the CalCOFI dataset to estimate that the average depth of the thermocline (defined as the 12°C isotherm) increased from 64 to 76 m. Di Lorenzo et al. (2005) use objective maps of the 26.4 σ_t isopycnal depth, which varies between 180 and 220 m, as a proxy of the thermocline in CalCOFI to show that it deepened by 18 m after the 1976/77 shift. Both of these definitions of the thermocline reflect the upper-ocean warming but not the stratification changes of the water column structure.

Notice that defining thermocline depth based on isothermal depth or isopycnal depth will inevitably result in a deepening after surface-intensified warming. This definition does not adequately represent the structural change in the *stratification* of the water column. In this note, we examine long-term stratification changes in terms of the thermocline (pycnocline), defined as the depth with maximum vertical temperature (density) gradient, and the buoyancy frequency. The maximum gradient definition can provide a more direct link to the nutrient flux associated with the ecosystem response.

This is similar to the approach of Palacios et al. (2004) who use a vertical gradient criterion for thermocline depth to find coastal deepening and offshore shoaling of the thermocline in the CCS. However, they use state-spaced analyzed World Ocean Database 1998 (WOD98) records from 1950 to 1993 in eight CCS locations while we analyze raw data from the 1950–2004 CalCOFI dataset, yielding higher spatial coverage and resolution in the southern CCS.

We ask the fundamental question: Did the thermocline deepen in the southern California Current after the 1976/77 climate regime shift? The answer is then related to possible changes in nutrient fluxes and their biological implications. The CalCOFI program and the data used in this study are briefly introduced in section 2, and observed stratification changes are shown quantitatively in section 3. These results and their biological implications are discussed in the last section.

2. Data

CalCOFI is a unique ongoing program to support long-term observations in the Southern California Bight. Temperature and salinity have been measured

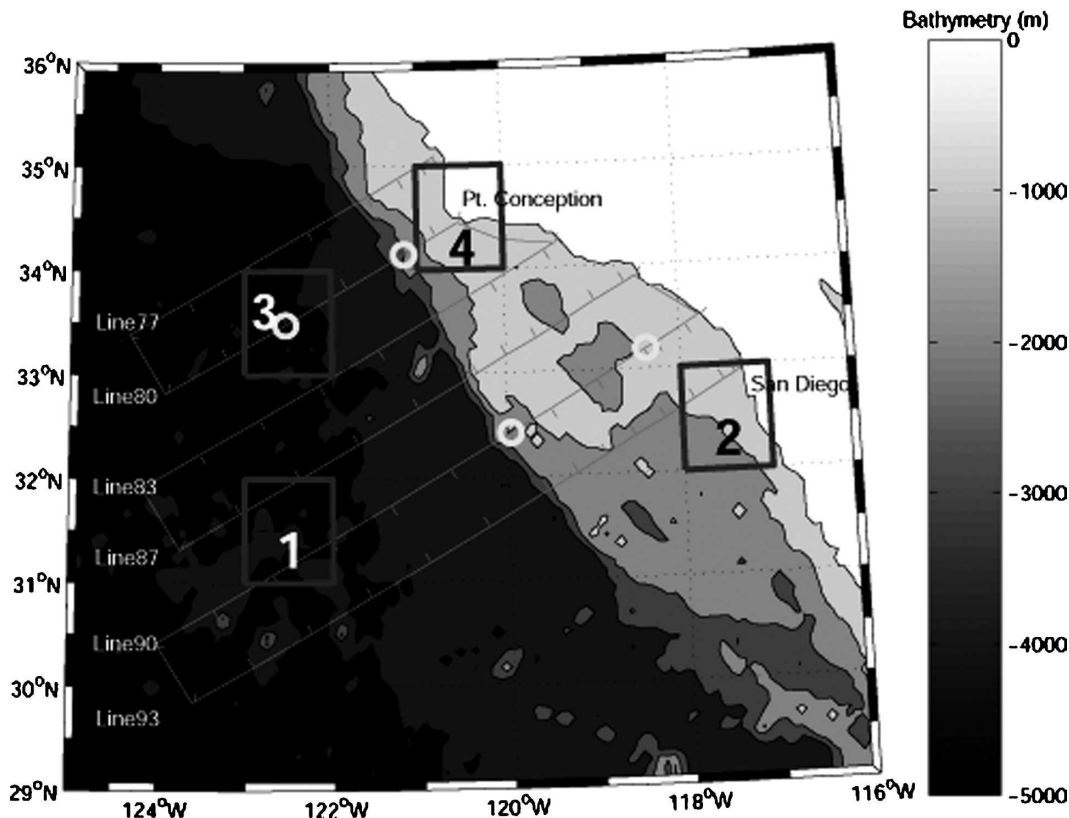


FIG. 2. The current station map of CalCOFI observations (<http://www.calcofi.org>). Boxes with numbers represent four of the eight locations studied by Palacios et al. (2004). Four circles are the locations with the most nitrate measurements before 1976. Inshore group includes 36 stations landward from the 2000-m bathymetry, and the rest of 66 CalCOFI stations are the offshore group.

since 1949. These 29 682 profiles are sampled at the standard depths (0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, and 500 m). The key period around the climate regime shift in 1976/77, however, does not have many samplings. Moreover, nutrient measurements have been routinely collected only since 1984 (Venrick 1998). The current CalCOFI cruise domain has 66 stations (Fig. 2), which have been repeated quarterly since 1984. The data analysis in this study is limited to these 66 nominal stations (11 744 profiles for each variable) to minimize spatial aliasing, and each profile was interpolated by a piecewise cubic spline method (Akima 1970) to obtain 1-m vertical resolution.

Stratification is quantified using four variables: thermocline depth (D_{thermo}), pycnocline depth (D_{pycno}), thermocline temperature (T_{thermo}), and maximum buoyancy frequency (N_{max}). The variable D_{thermo} (D_{pycno}) is calculated for each profile as the depth with the maximum vertical gradient of temperature (density). T_{thermo} is defined as the temperature at D_{thermo} , and N_{max} is calculated from the density profile. Notice that N_{max} occurs at D_{pycno} . Monthly mean climatologies

are computed for each station and subtracted from each station's time series because variances differ greatly among stations in CalCOFI dataset; that is, a domain average is not appropriate for representing every station.

Both D_{thermo} and D_{pycno} tend to be shallower at inshore stations than at offshore stations. This motivates dividing the 66 CalCOFI stations into two groups, "inshore" and "offshore" groups. Hayward and Venrick (1998) defined inshore and offshore CalCOFI regimes according to key physical-biological features. In the inshore regime, chlorophyll concentrations are high, and pycnocline and nutricline are shallow, and vice versa in the offshore regime. We examine stratification changes for very similar inshore and offshore station groupings, roughly corresponding to the shelf region and deep-water region of CalCOFI.

3. Results

The anomalies of D_{thermo} (Fig. 3a) and D_{pycno} (Fig. 3b) are dominated by decadal variations of alternating positive (deepening) and negative (shoaling) values. No

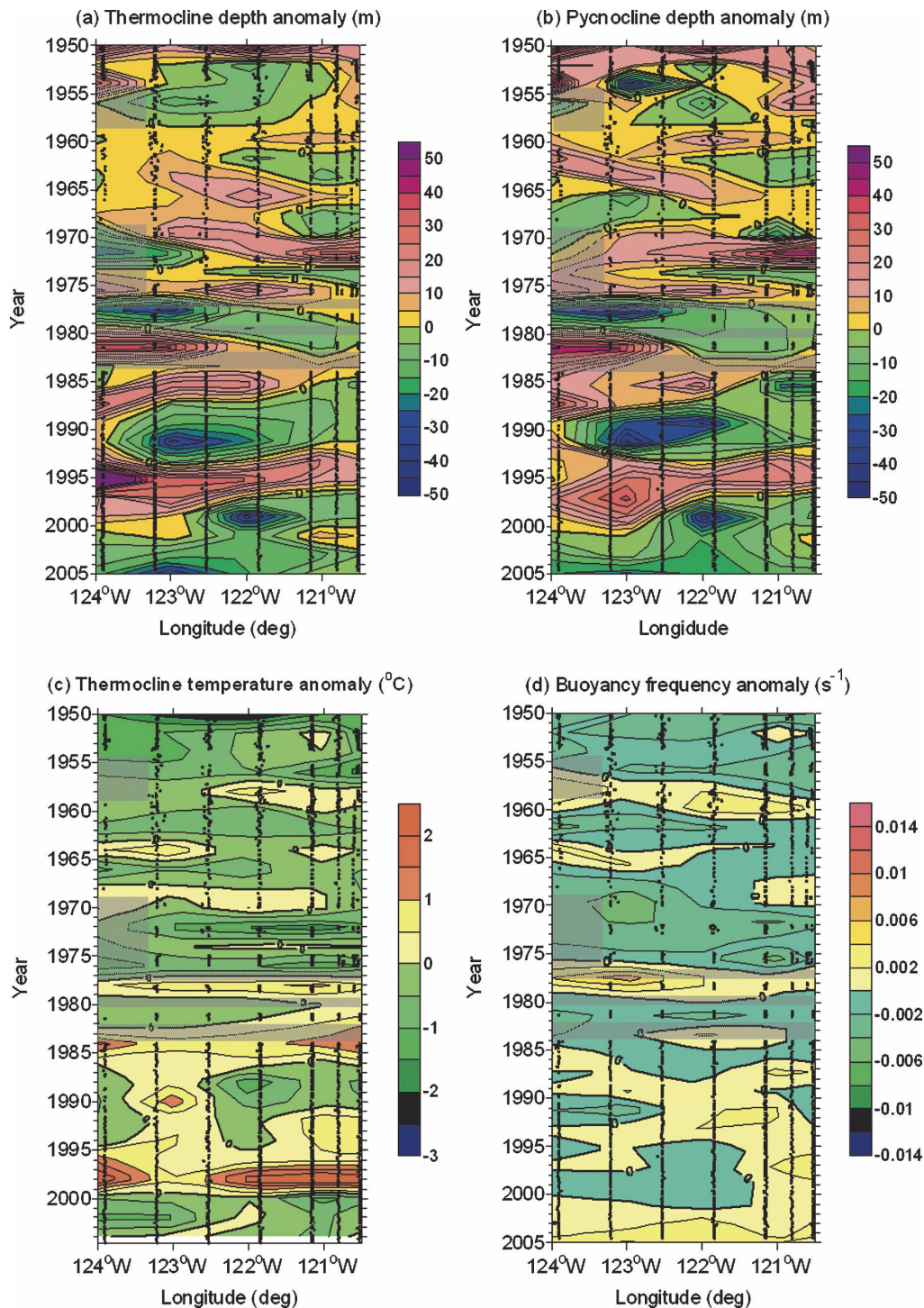


FIG. 3. Hovmöller diagrams for line-80 (a) thermocline anomalies, (b) pycnocline anomalies, (c) thermocline temperature anomalies, and (d) buoyancy frequency anomalies at the pycnocline. All the nominal lines in the CalCOFI grid (Fig. 2) showed similar patterns.

clear evidence of a climate regime shift occurs in these plots for any of the CalCOFI lines. Time series of D_{thermo} and D_{pycno} were additionally examined for each station (figures not shown), and they also reveal no

significant trend. Objectively mapped monthly CalCOFI data (Di Lorenzo et al. 2005) show results consistent with Figs. 3a,b (figures not shown) as well. Means of the probability density functions (PDFs) of

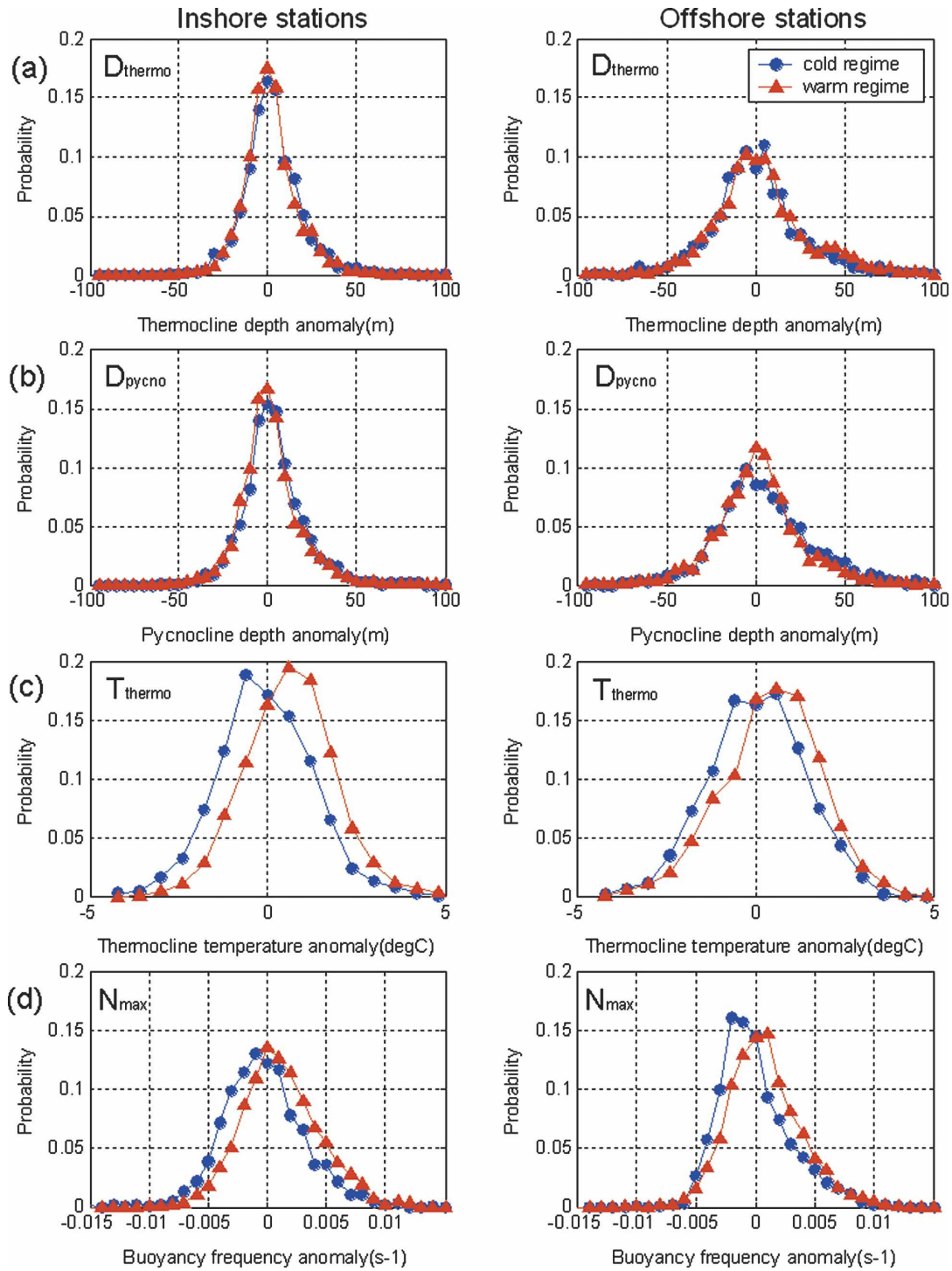


FIG. 4. PDFs of the four variables as in Fig. 3. (left) Inshore stations (Fig. 2) and (right) offshore stations (Fig. 2). Blue lines represent the cool regime (1950/76), and red lines represent the warm regime (1977/98).

these D_{thermo} and D_{pycno} anomalies also have no significant differences between the cool regime and the warm regime, even when the grouping the observations into inshore (Fig. 4, left panels) and offshore (Fig. 4, right panels) stations.

In contrast, T_{thermo} anomalies (Fig. 3c) are persistently negative in the cool regimes while they retain the positive signs in the warm regime. PDFs of the T_{thermo} anomalies (Fig. 4c) also clearly indicate the shift to the warm regime in 1976/77 with a significant mean change

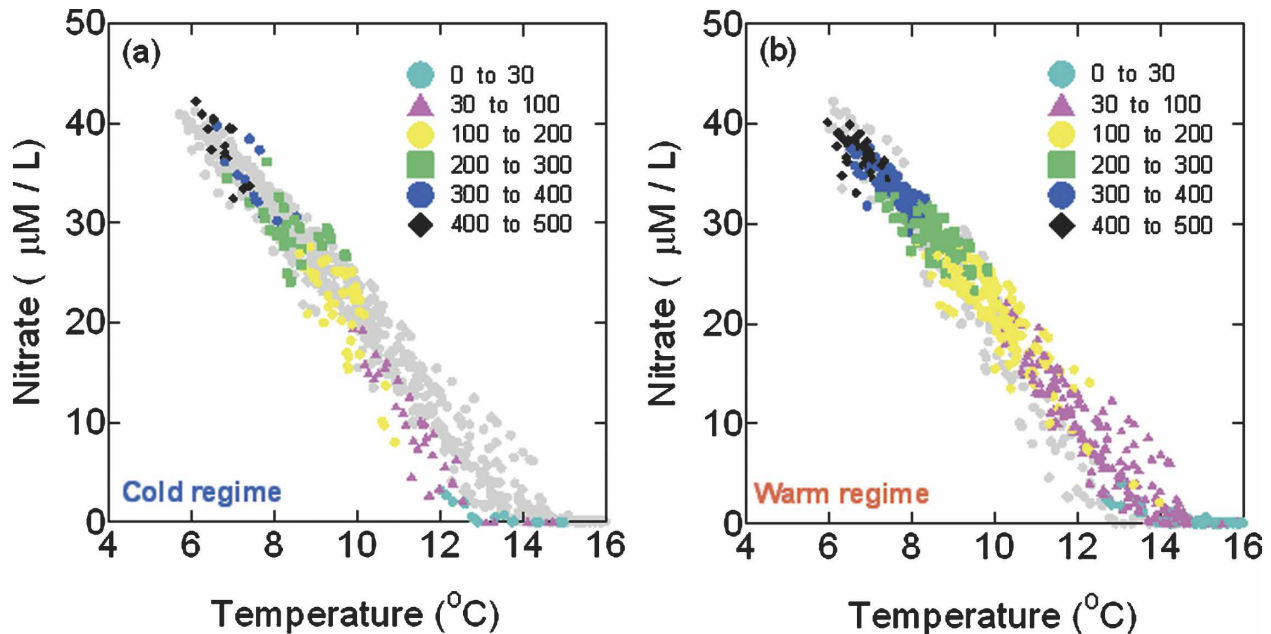


FIG. 5. Nitrate–temperature scatterplots in the (a) cool regime and (b) warm regime. Colors represent sampling depth ranges and gray background dots are plotted to compare with the other regime. The slope of nitrate vs temperature changed after the climate regime shift by the surface-intensified warming for the middepth waters (30–200 m).

of about 1°C . Note that the warming signal in Figs. 3c and 4c is not simply a result of the strong El Niño events occurring after 1976/77. The number of data observed during the 1997/98 El Niño period is 186, which occupies only 3% of all the data for the warm regime from 1977 to 1998. The surface-intensified warming rendered the upper ocean more stable after the 1976/77 shift as indicated by the significantly higher N_{max} values (Figs. 3d, 4d).

The thermocline depth is often used as a proxy for nutricline depth (Bograd and Lynn 2003; McGowan et al. 2003) because of the lack of nutrient data. Nitrate is the important limiting factor for the primary production in the California Current. We therefore examine whether changes occurred in the well-known nitrate–temperature negative relationship across the regime shift. Nitrate has 4818 profiles from 1977 to 1998; however, unfortunately it was rarely sampled before the 1977 climate regime shift (193 samplings), with even fewer sampling locations within the current CalCOFI grid (151 samplings). We therefore focused on the four stations—80.60, 80.80, 90.37, and 90.60—that have the highest samplings (Fig. 2). Figure 5 shows the nitrate–temperature relationship for station 90.37 (the circle on line 90, closer to the coast) before and after the 1976/77 shift, which is representative of all four stations. There are four nitrate profiles measured at station 90.37 in two winter cruises before the 1976/77 shift, and nitrate was sampled almost every year from 1983 to 1997 (22

winter profiles). Only winter (January–March) observations are used because the nitrate sampling is the highest in winter before the shift and it characterizes the important antecedent ocean conditions to the upwelling season.

The nitrate–temperature relation shows an important change after the 1976–77 climate regime shift (Fig. 5). The nitrate–temperature relation for the middepth waters, from roughly 30 to 200 m, changes slope across the shift. In the middepth waters, higher values of nitrate for a given temperature occur after the shift because of the upper-ocean warming. The deep waters (>200 m) and surface waters (<30 m), in contrast, do not exhibit any significant changes in their temperature–nitrate relationship. This is because the deep water was not directly affected by the surface heating and because surface waters are dominated by biological uptake of nitrate, which occurs on time scales much shorter than long-term variations of upwelling.

4. Discussion

A detailed analysis of the raw 55-yr CalCOFI data confirms that thermocline temperature, T_{thermo} , warms after the 1976/77 climate regime shift (Figs. 3c, 4c). But the analysis clearly reveals that the thermocline depth, D_{thermo} , remains essentially constant across the regime shift (Figs. 3a, 4a), although it does vary on decadal time scales. The surface-intensified warming after the 1976/77 shift (Fig. 1) resulted in an increased tempera-

ture difference across the thermocline, a higher buoyancy frequency, N_{\max} (Figs. 3d, 4d), and a more stable upper ocean.

Palacios et al. (2004) suggested that the coastal thermocline deepened while the offshore thermocline shoaled for key stations throughout the California Current after the 1976/77 shift. However, within the CalCOFI grid (Fig. 2), two of their four stations (locations 1 and 4 in Fig. 2) show no significant trend in their state-space analysis. A higher-resolution analysis, using all the CalCOFI station data, results in no significant change in thermocline depth across the shift, even when grouping stations into coastal and offshore regions (Figs. 4a,b). Furthermore, our results are not sensitive to the specific choices for the time intervals of the regimes.

Roemmich and McGowan (1995) suggested that the surface warming increased the temperature difference across the thermocline resulting in less lifting of the thermocline by the coastal upwelling. Both thermocline depth and stratification strength (the buoyancy frequency at the pycnocline) affect the nutrient flux due to coastal upwelling because they influence the source of upwelled water. As the surface heating changed the strength of stratification, it also changed the slope of the nitrate–temperature relation (Fig. 5) for the mid-depth waters (roughly 30 to 200 m). The 12°C isotherm, which many previous studies have used as a proxy of thermocline depth, is associated with increased nitrate values after the shift. But since the stratification also increased, the depth from which upwelled waters are mixed to the surface may have changed (Lentz and Chapman 2004). Further study is needed to determine how these changes might have interacted to affect upwelling, mixing, cross-shelf transport of nutrient, and vertical nutrient fluxes to the euphotic zone. The temperature–nitrate relationship of the middepth waters may be a key indicator of the quality of upwelled water that contributes to sustaining primary production in the euphotic zone.

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