Influence of coastal upwelling and El Niño–Southern Oscillation on nearshore water along Baja California and Chile: Shore-based monitoring during 1997–2000

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Received 14 March 2003; revised 15 July 2003; accepted 22 July 2003; published 4 March 2004.

[1] In order to determine the sensitivity of coastal upwelling tracers to seasonal wind forcing and El Niño–Southern Oscillation (ENSO) off Baja California and Chile, nearshore salinity, cadmium (Cd), and nutrients phosphate, silicate, nitrate+nitrite were monitored in surf zone waters at six locations along the North and South American coasts during 1997–2000. The clearest responses to upwelling favorable wind forcing were observed at the southern tip of Baja California (23.3°N) and off central-southern Chile (36.5°S). Upwelling tracers at 23.3°N were also the most sensitive to El Niño: average summer Cd and nutrient enrichments were 60% lower following El Niño than during the previous non–El Niño upwelling season. At two sites on the northern and central Chile coasts, conditions associated with El Niño resulted in salinity anomalies >1. Such large shifts in nearshore water properties suggest it may be possible to reconstruct past ENSO patterns from geochemical paleonutrient/paleosalinity proxy records preserved in nearshore archives such as mollusc or foraminifera shells. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4516 Oceanography: Physical: Eastern boundary currents; 4522 Oceanography: Physical: El Nino; 4875 Oceanography: Biological and Chemical: Trace elements; 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling; *KEYWORDS:* coastal upwelling, cadmium, nutrients, El Niño, Chile, Baja California

Citation: Takesue, R. K., et al. (2004), Influence of coastal upwelling and El Niño–Southern Oscillation on nearshore water along Baja California and Chile: Shore-based monitoring during 1997–2000, *J. Geophys. Res.*, *109*, C03009, doi:10.1029/2003JC001856.

1. Introduction

[2] Wind-driven coastal upwelling supplies nutrient-rich waters to the surface ocean and supports high levels of biological productivity characteristic of eastern ocean boundaries. The California Current and the Peru-Chile Current, the eastern boundary currents of the north and south Pacific Ocean, respectively, are among the most productive waters of the world ocean. Fish landings in eastern Pacific coastal upwelling regions account for nearly 20% of the global marine fish catch [*Food and Agriculture Organization (FAO)*, 1998]. Coastal upwelling occurs at eastern ocean boundaries when alongshore winds blow equatorward for at least several days. At midlatitudes, seasonal changes in solar radiation give rise to seasonally reversing land-sea pressure gradients and alongshore winds which are strongest in spring in both hemispheres [*Huyer*, 1983; *Strub et al.*, 1987; *Bakun and Nelson*, 1991; *Strub et al.*, 1998]. At low latitudes, alongshore winds are equatorward year-round but weaker, and intensify in the spring and summer [*Bakun and Nelson*, 1991; *Strub et al.*, 1998].

[3] On interannual and decadal timescales, dramatic shifts in nearshore productivity and ecosystems, many of which have significant biological, social, and economic consequences [*FAO*, 1998], have been linked to changes in atmospheric and oceanic circulation (e.g., the El Niño-Southern Oscillation (ENSO) [*Chavez*, 1996; *Chavez et al.*, 1999; *Thomas et al.*, 2001; *Ulloa et al.*, 2001] and the Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997;

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0148-0227/04/2003JC001856$09.00

Hare and Mantua, 2000; *Hollowed et al.*, 2001]). *FAO* [2000] estimated that the 1997–1998 El Niño event resulted in 15% and 44% declines in southeast Pacific fisheries catch in 1997 and 1998, respectively, a US$5 billion loss. The ability to forecast potential climate-related changes in coastal upwelling ecosystems would be very useful in directing fishing effort and formulating fishery policy [*Hoerling and Kumar*, 2000; *Yáñez et al.*, 2001]. However, little is known about nearshore responses to climate processes operating on multiyear timescales, in part because ship-based sampling is very resource intensive [*Lynn et al.*, 1982; *Smith et al.*, 2001]. The few existing long-term monitoring programs are by necessity limited to regional scales and monthly or quarterly sampling cruises (e.g., CalCOFI off southern California [*Lynn and Simpson*, 1987], IMECOCAL off Baja California [*Durazo and Baumgartner*, 2002], and IFOP off northern Chile [*Blanco et al.*, 2001]).

[4] *van Geen and Husby* [1996] proposed a way to overcome the limitation of resource intensive sampling by monitoring coastal upwelling tracers from shore. Their strategy was based on the observation that surf zone concentrations of nutrients and the nutrient-like trace element Cd experienced five-fold enrichments correlated with increased coastal upwelling intensity [*van Geen and Husby*, 1996]. Furthermore, a study in the Cape Blanco, Oregon, upwelling region showed that dissolved Cd was a more effective coastal upwelling tracer than nutrients because concentrations were unaffected by biological processes in newly upwelled waters supersaturated in CO_2 with respect to the atmosphere [*van Geen et al.*, 2000; *Takesue and van Geen*, 2002]. An added advantage of using this trace element as an upwelling tracer is that Cd is incorporated into the calcium carbonate shells/skeletons of many marine organisms [*Boyle*, 1981; *Shen et al.*, 1987; *Boyle*, 1988; *van Geen et al.*, 1992], which could potentially allow reconstructions of climate-related changes in coastal upwelling.

[5] With the ultimate goal of finding locations along the eastern Pacific margin where Cd/Ca-based paleoupwelling reconstructions might be possible, an interhemispheric network of 10 coastal upwelling monitoring sites at five latitudes was established in November–December 1996 through a multi-institutional collaboration supported by the Inter-American Institute for Global Change Research (IAI, http://www.iai.int). The specific objective of the 2-year pilot study was to characterize relationships between upwelling tracers (Cd, nutrients, salinity) and alongshore wind forcing at sites on the coasts of Baja California and Chile and in nearby semiprotected coastal embayments where sedimentary records might accumulate. The study period encompassed the strong 1997–1998 El Niño event and two subsequent years of La Niña conditions. Here we discuss results primarily from the five IAI coastal sites, and from a site at the northern California coast where monitoring began in 1991.

[6] We begin by describing large-scale circulation and hydrography in the northeast and southeast Pacific Ocean in section 2. Section 3 describes sampling and analysis procedures and data sets used to estimate alongshore wind forcing. In section 4 results from each of the monitoring sites are presented, and in section 5 we discuss the effectiveness of nearshore Cd, nutrients, and salinity as tracers of wind-driven coastal upwelling in the California and Peru-Chile Currents, as well as the effects of the 1997–1998 El Niño and 1998–2000 La Niñas on coastal upwelling and nearshore water properties.

2. Wind Forcing and Hydrography

2.1. Large-Scale Atmospheric Circulation

[7] Northeast Pacific spring and summer (March–September) atmospheric circulation is dominated by the North Pacific High (NPH) pressure center, which is bounded to the north by the West Wind Drift (50°N) and to the south by the Intertropical Convergence Zone (ITCZ, 5°–10°N). In February, the NPH intensifies and migrates from 28°N, 130°W off Baja California to 38°N, 150°W off northern California, resulting in maximum equatorward upwelling favorable winds for seven months of the year at the northern California coast [*Strub et al.*, 1987]. With decreasing latitude, spring/summer equatorward winds grow progressively weaker and persist for fewer months of the year [*Strub et al.*, 1987]. In fall, the strengthening Aleutian Low pressure center displaces the NPH to its southerly position, and poleward downwelling favorable winds are present at the northwest U.S. coast through winter [*Huyer*, 1983]. The NPH influences coastal winds during both winter and summer off southern California (south of 33°N) and Baja California, resulting in year-round equatorward winds with weak seasonality [*Strub et al.*, 1987].

[8] Atmospheric forcing over the southeast Pacific is dominated by the South Pacific High (SPH), which is bounded to the north by the ITCZ and to the south by the West Wind Drift (~45°S). Unlike the northeast Pacific, there is no dominant low-pressure center over the southeast Pacific in winter and the SPH migrates poleward only a few degrees in austral summer, from 28°S, 85°W to 31°S, 95°W [*Strub et al.*, 1998]. As a result equatorward upwelling favorable winds prevail year-round over a wide latitudinal range (4°–35°S), while seasonally reversing alongshore winds are limited to ~35°–45°S [*Strub et al.*, 1998].

2.2. Large-Scale Oceanic Circulation

[9] Three principal currents comprise the California Current System off western North America: the surface-flowing California Current (CC) which transports relatively fresh (>32.7), nutrient- and oxygen-rich Pacific Subarctic Water (SAW) equatorward, the subsurface (200–500 m) California Undercurrent (CU) which transports relatively saline (34.7), nutrient-rich, oxygen-deficient Equatorial Subsurface Water (ESsW) poleward, and the seasonal Davidson Current (called the Inshore Countercurrent south of Point Conception) which is present as a fall/winter poleward surface flow within 200 m of the coast [*Lynn and Simpson*, 1987]. In spring and summer cold, salty, nutrient- and Cd-rich coastal upwelled water is present adjacent to the North American coast in a narrow ~50-km-wide band [*Huyer*, 1983].

[10] Off Baja California, the CC appears as a shallow salinity minimum (<33.7) at 50–150 m depth overlain by Transition Water, which is formed by lateral mixing of SAW with very saline (>34.4) nutrient-depleted Subtropical Surface Water (StSW) at the western boundary of the CC [*Roden*, 1971; *Durazo and Baumgartner*, 2002]. Southern

Table 1. Locations, Durations, and Coordinates for Sampling Sites; Hydrographic and Surface Pressure Grid Points

Station	Monitoring Period	Location	CUI/WOA Grid Points
Northern Hemisphere			
Pillar Point, N. Calif. (coast)	Jan. 1991 to Dec. 2000	37.50°N, 122.50°W	36°N, 122°W/37.5°N, 122.5°W
Arbolitos, N. Baja Calif. (coast)	Dec. 1996 to Dec. 1999	31.70°N, 116.68°W	31°N, 118°W/31.5°N, 116.5°W
Tres Hermanas, N. Baja Calif. (bay)	Dec. 1996 to Dec. 1999	31.74°N, 116.71°W	"
Los Cerritos, S. Baja Calif. (coast)	Dec. 1996 to Dec. 1999	23.33°N, 110.18°W	21°N, 107°W/21.5°N, 111.5°W
El Tecolote, S. Baja Calif. (gulf)	Dec. 1996 to Dec. 1999	24.35°N, 110.27°W	"
Southern Hemisphere			
Santa Maria, N. Chile (coast)	Nov. 1996 to Aug. 2000	23.42°S, 70.58°W	23°S, 72°W/23.5°S, 70.5°W
Las Lozas, N. Chile (bay)	Nov. 1996 to Oct. 1998	23.46°S, 70.49°W	"
El Quisco, C. Chile (coast)	Nov. 1996 to Oct. 1998	33.40°S, 71.70°W	33°S, 73°W/33.5°S, 72.5°W
Las Cruces, C. Chile (bay)	Nov. 1996 to May 2000	33.50°S, 71.63°W	"
Coliumo, C.-S. Chile (coast)	Nov. 1996 to Dec. 1998	36.52°S, 72.90°W	36°S, 74°W/36.5°S, 73.5°W
Bio-Bio, C.-S. Chile (bay)	Nov. 1996 to Dec. 1998	36.81°S, 73.18°W	"

Baja California lies in an oceanographic transition zone where northward flowing Tropical Surface Water (TSW, <34; at the surface) and ESsW (at depth) converge with southward flowing waters in the CC [*Wyrtki*, 1967; *Roden*, 1971].

[11] Unlike other eastern boundary current systems, the Peru-Chile Current System off western South America is dominated by poleward surface flow in the nearshore region [*Strub et al.*, 1998]. High salinity (>34.9) poleward flowing Subtropical Water (STW) is present from the surface to 50 m depth, underlain by relatively fresh (<34.8) equatorward flowing Subantarctic (SAAW) at 50–100 m depth. Between 100–500 m depth the Poleward Undercurrent (PU) transports oxygen-depleted nutrient-rich Equatorial Subsurface Water (ESsW, which has the same origin as ESsW in the northeast Pacific) of intermediate salinity (34.7–34.9) [*Strub et al.*, 1998; *Morales et al.*, 2001; *Ahumada*, 2002]. A narrow ~40-km-wide coastal upwelling zone occurs adjacent to the coast [*Strub et al.*, 1998; *Morales et al.*, 2001].

2.3. Upwelled Water Characteristics

[12] Comparisons of upwelling tracers in newly upwelled waters with those in offshore water column profiles suggest that in the northern California Current System upwelled waters originate below 200 m depth [*van Geen and Husby*, 1996; *Takesue and van Geen*, 2002]. Off California, Cd, nutrients, and salinity increase with depth, so upwelled waters are enriched relative to surface waters. Generalized descriptions of upwelling source water properties for the northeast Pacific can be inferred from 1994 World Ocean Atlas (WOA94; data available at http://ingrid.ldeo.columbia.edu) annual averages at grid points nearest to the coast (coordinates given in Table 1, profiles shown in the auxiliary material (Figure A1)[1]). At 37.5°N (northern California), waters below 200 m are characterized by temperature <8°C, salinity >34, phosphate >2.3 μmol kg^{-1}, and O_2 <2.2 mL L^{-1}. With decreasing latitude the influence of equatorial water masses becomes stronger, such that at 200 m depth off southern Baja California (23.5°N) temperatures have increased by 4°C, salinity by 0.7, and phosphate by 0.5 μmol kg^{-1}. Off Baja California the California Current becomes a subsurface flow creating a shallow salinity minimum. As a result, upwelling from shallow depths may result in a salinity decrease. The northern limit of a strong oxygen minimum zone (OMZ; <0.2 mL L^{-1}) occurs off central Baja California between 100–1000 m depth [*Brandhorst*, 1959].

[13] Off the western coast of South America, waters typically upwell from the PU [*Blanco et al.*, 2001; *Morales et al.*, 2001; *Sobarzo and Figueroa*, 2001; *Ahumada*, 2002], which has a core depth ~150 m off northern Chile and 200–300 m off central Chile [*Strub et al.*, 1998]. ESsW in the PU is characterized by local salinity and P maxima (34.5–34.8, and 2.2–2.6 μmol kg^{-1}) and a minima in O_2 (0.2–0.7 mL L^{-1}) (Figure A1). Upwelling of oxygen deficient waters can lead to water column denitrification [*Morales et al.*, 1999, 2001] and fish kills [*Strub et al.*, 1998]. The OMZ off western South America extends from the equator to about 40°S, and is a much larger feature than the OMZ off western North America [*Wyrtki*, 1967]. When alongshore winds are upwelling favorable but weak, relatively fresh, nutrient-depleted SAAW at 50–100 m depth can be upwelled to the coastal ocean [*Morales et al.*, 2001; *Sobarzo and Figueroa*, 2001].

3. Methods

[14] In November–December 1996 paired monitoring stations were established at five latitudes along the Baja California and Chile coasts: one on the open coast and one inside a nearby semienclosed embayment (Figure 1 and Table 1). Station pairs were separated by less than 30 km, except for the station at El Tecolote (24.4°N) inside the Gulf of California, which was 110 km north of its corresponding Pacific coastal station, Los Cerritos (23.3°N). After the initial 2-year pilot study, sampling continued at one station per latitude, except at 36.5°S.

3.1. Surf Zone Monitoring

[15] Surf zone water samples were collected for Cd, nutrient, and salinity analyses at 2-week intervals throughout the year, except at Pillar Point where winter sampling was monthly (September–February). At each site, two replicate 250-mL water samples for trace metal analyses were collected within a few minutes of each other in acid-cleaned polyethylene bottles attached to the end of a 3-m-long nonmetallic sampling pole. One liter of water was collected for salinity and nutrient analyses. Water samples were stored in an insulated cooler until processing the same day.

[1]Supporting materials are available at ftp://ftp.agu.org/apend/jc/2003JC001856.

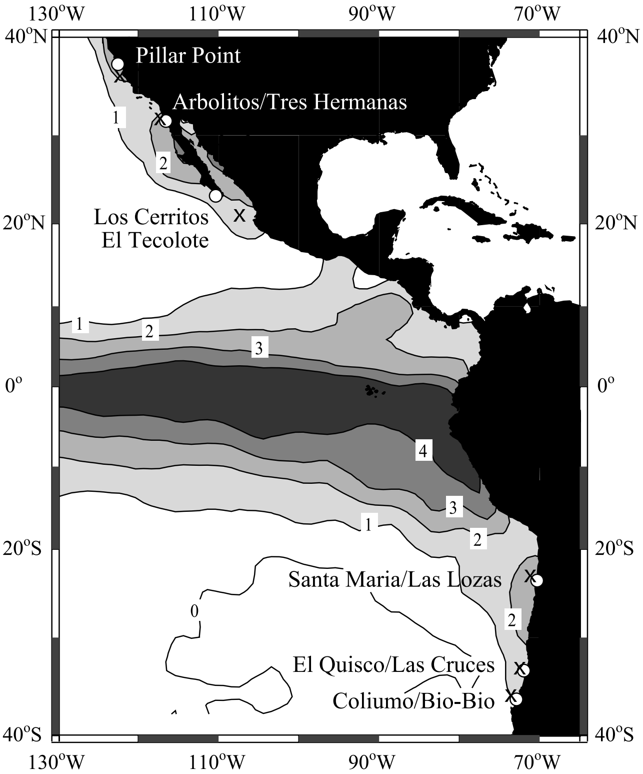

Figure 1. Locations of coastal upwelling monitoring sites (open circles). Two sampling stations were maintained at each latitude, except at 37.5°N. Crosses show the center point of a 3° × 3° box where the coastal upwelling index (CUI), a surface pressure-derived estimate of offshore Ekman transport, was calculated. Contours show Integrated Global Ocean Services System (IGOSS) monthly mean sea surface temperature anomalies during peak El Niño conditions in December 1997. The contour interval is 1°C. (data available at http://www.ingrid.ldeo.columbia.edu).

[16] Trace metal samples were filtered through acid-cleaned 0.4 μm polycarbonate membrane filters (Nuclepore®) under a Class-100 laminar flow bench. Unacidified trace metal samples were stored in the dark at room temperature for up to a year. Upon return to Lamont-Doherty Earth Observatory, samples were acidified to 0.1% by volume 12N Optima Grade (Fisher Scientific) hydrochloric acid, agitated, and allowed to sit at least overnight before analysis. Coastal water samples analyzed one day after acidification and again almost one year later had indistinguishable Cd concentrations (n = 5), indicating that the acidification procedure effectively returned all dissolved Cd to solution.

[17] Nutrient samples were filtered through 0.45 μm polypropylene syringe tip filters and acidified to pH ~ 2 with 12 N Reagent Grade (Fisher Scientific) hydrochloric acid a few hours after collection. Salinity samples were stored in glass salinity bottles with Poly-Seal®-lined caps. Bottles and caps were rinsed three times before filling.

3.2. Analyses

[18] Dissolved Cd was measured by graphite furnace atomic absorbtion (GFAA) using the automated in-line preconcentration method described by *Takesue and van Geen* [2002]. The preconcentration uses a transition metal cation-specific resin, 8-hydroxyquinoline (8-HQ), to extract dissolved Cd from a seawater sample buffered to pH ~ 8. A 7 minute preconcentration step was followed by a 10 minute analysis in the graphite furnace. Analytical detection limits, calculated as three times the standard deviation of a seawater blank, were 0.05 nmol kg^{-1} Cd *Takesue and van Geen* [2002]. Under optimal conditions, analytical precision, defined as the 1 σ error of a high standard repeated throughout a 24 hour sample run, was 0.003 nmol kg^{-1} Cd (n = 11); day-to-day reproducibility, calculated from a high standard run over five days, was 0.03 nmol kg^{-1} Cd (1 σ).

[19] Nutrients (phosphate, silicate, and nitrate+nitrite) were measured on a flow injection autoanalyzer (QuikChem 8000, Lachat Instruments) using standard colorimetric methods [*Strickland and Parsons*, 1968]. Detection limits were 0.1, 0.2, and 0.1 μmol kg^{-1} for P, Si, and N, respectively [*van Geen et al.*, 2000]. Salinity was measured on a Guildline salinometer calibrated with IAPSO (International Association for Physical Science of the Ocean) standard seawater.

3.3. Large-Scale Wind Estimates

[20] The Coastal Upwelling Index (CUI), available from the Pacific Fisheries Environmental Laboratory (PFEL) at http://www.pfeg.noaa.gov, was used as an estimate of large-scale alongshore winds. To derive daily CUI values, 6-hourly surface pressure is used to calculate the alongshore component of the geostrophic wind and offshore Ekman mass transport, which is then converted to units of the upwelling index and averaged. Daily CUIs were calculated at grid points ~100 km offshore of the six coastal sites (Table 1 and Figure 1). The CUIs used for two North American sites: 36°N, 122°W (northern California) and 21°N, 107°W (southern Baja California) are standard PFEL products and were calculated using pressures interpolated over a 3° × 3° latitude grid and a constant drag coefficient [*Bakun*, 1975]. Daily CUIs for the northern Baja California and Chilean sites were derived upon request and were calculated using pressures interpolated over a 1° × 1° latitude grid and a nonlinear drag coefficient that varied as a function of wind speed. Because the CUI is derived from surface pressures at surrounding grid points 100 km away, CUI values near the coast may be influenced by processes over land, which may lead to spatial distortions [*Bakun*, 1975; *Halliwell and Allen*, 1987], however temporal variations at a particular site should be adequately represented [*Bakun*, 1975].

4. Results

[21] A 9 year-long upwelling tracer time series at Pillar Point provides a long-term perspective on typical seasonal coastal upwelling patterns. During spring and summer (March–August) when winds are persistently equatorward (offshore transport, positive CUI; Figure 2a), Cd- (and nutrient-) rich water is upwelled at the coast (Figure 2b). As alongshore winds become poleward in fall and winter (onshore transport, negative CUI), Cd- and nutrient-depleted CC surface waters are advected onshore to the coast. *van*

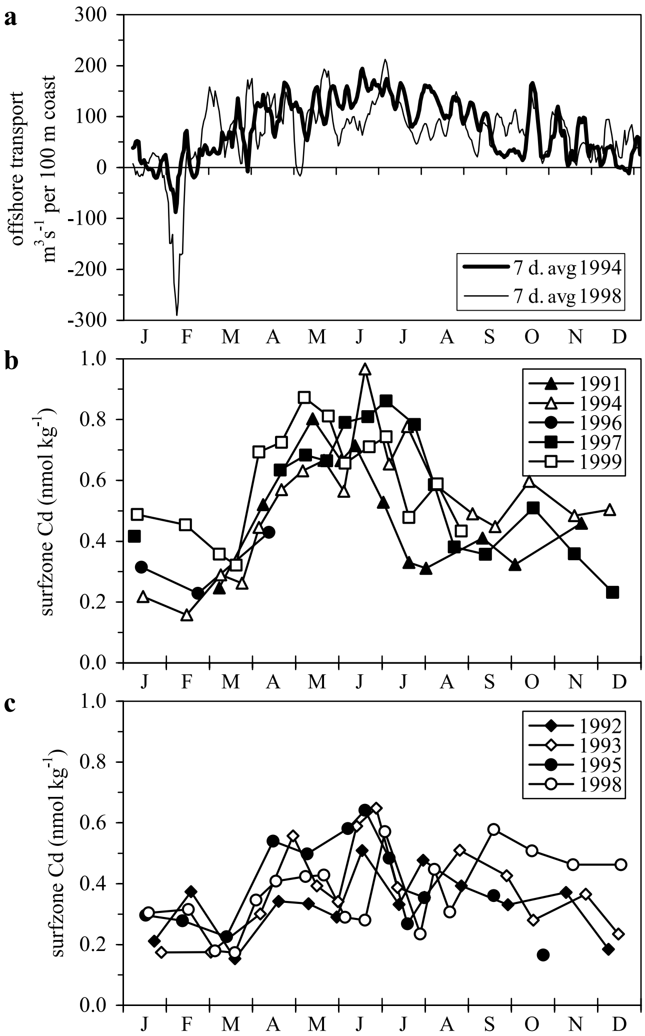

Figure 2. (a) The 7-day running average of the daily CUI at 36°N during a non-El Niño year (1994, bold line) and following an El Niño winter (1998, fine line). Seasonal patterns of nearshore dissolved Cd at Pillar Point, northern California (37.5°N), following (b) non-El Niño winters and (c) El Niño winters.

Geen and Husby [1996] showed that seasonal Cd enrichments were best correlated with 30-day smoothed CUIs at a lag of 14 days. Upwelling seasons following El Niño events were characterized by depressed spring/summer Cd (and nutrient) enrichments (Figure 2c).

[22] In general, upwelling tracers at coastal sites were higher and more closely related to alongshore wind forcing than at embayment sites (Figures 3 and 4). The longer residence times of waters in coastal embayments probably led to more intense biological productivity [*Castilla et al.*, 2002] and nutrient draw down. For example, Tres Hermanas (31.7°N) and Las Lozas (23.5°S) had N (NO_3^-+NO_2^-) concentrations 31% and 91% lower, respectively, than neighboring coastal sites. Here we discuss results primarily from the six coastal sites. Ranges of upwelling tracer concentrations, excluding high values that appear to be of nonupwelling origin, are given in Table 2. The mean Cd concentration of replicate surf zone samples is used in figures, text, and tables. 85% of replicate Cd samples were within ±5% of their mean value. Thirteen replicate samples had Cd concentrations that differed by 20% or more of their mean value. All data are given in the auxiliary material.

4.1. Pillar Point, Northern California (37.5°N)

[23] In spring and summer 1997 and 1999, upwelling favorable wind forcing resulted in expected upwelling tracer enrichments (Figure 3a). In both years Cd and P peaked at 0.8 nmol kg^{-1} and at least 2.2 μmol kg^{-1}, respectively. Declining equatorward winds in fall 1997 corresponded with decreasing nearshore Cd and P concentrations. The 1998 upwelling season lacked a clearly defined upwelling tracer peak, despite upwelling favorable wind forcing. From April to August, Cd and P enrichments were almost 50% lower than in 1997 and 1999. Nearshore waters were 0.6 salinity units fresher than during the same period in 1999. Unlike typical years, positive (upwelling favorable) CUI values persisted into fall and winter 1998, with a corresponding winter elevation in Cd, P, and salinity. This was also the case during winter 1999, a strong La Niña year. The 2000 upwelling season began as expected with an abrupt increase in Cd and P in late March and elevated nearshore concentrations through May, but was interrupted in June and September by the appearance of waters with low Cd and salinity <30. These low-salinity waters were not associated with elevated nutrients (Figure 5a; Figure A2) and did not correspond to local precipitation events. Coastal upwelling tracer enrichments were inconsistent throughout 2000, persisting for only a few weeks at a time. In 2000, four surf zone samples (14 May, 11 June, 13 July, and 23 September) had replicate Cd concentrations that differed from their means by at least 20%, suggesting that one or both of the replicates were contaminated for Cd. The lower value is plotted in Figure 3a.

4.2. Arbolitos, Northern Baja California (31.7°N)

[24] The CUI off northern Baja California indicated year-round upwelling that peaked in spring and declined through summer and fall. Upwelling tracers off northern Baja California showed only a weak response to alongshore wind forcing. Moderate Cd and P enrichments occurred each year in spring or summer coupled with coastal salinity >33.6 (Figure 3b), characteristic of waters in the subsurface CC. In 1997 and 1999 upwelling tracer enrichments lasted a few weeks or less, while in spring 1998 enrichments persisted for two months. The winter 1997–1998 El Niño event coincided with a period of unusually high salinity (>33.7). In late December 1997, salinity increased abruptly, peaked at 34.1 in early January 1998, then gradually declined over the next two months. During this period nearshore waters were depleted in Cd and P (<0.2 nmol kg^{-1} and <0.7 μmol kg^{-1}, respectively). It is not certain whether the high Cd enrichment (0.85 nmol kg^{-1}) observed on 14 October 1997 was of upwelling origin, since the sample collected two weeks earlier was contaminated for Cd (3.6 nmol kg^{-1}) and neither nutrients nor salinity were similarly elevated. Three Cd enrichment events were also observed during September–December 1997 at the nearby embayment site (Figure 3b).

4.3. Los Cerritos, Southern Baja California (23.3°N)

[25] CUI values at the southern tip of Baja California were equatorward from approximately February to June and poleward or weakly equatorward from July to January

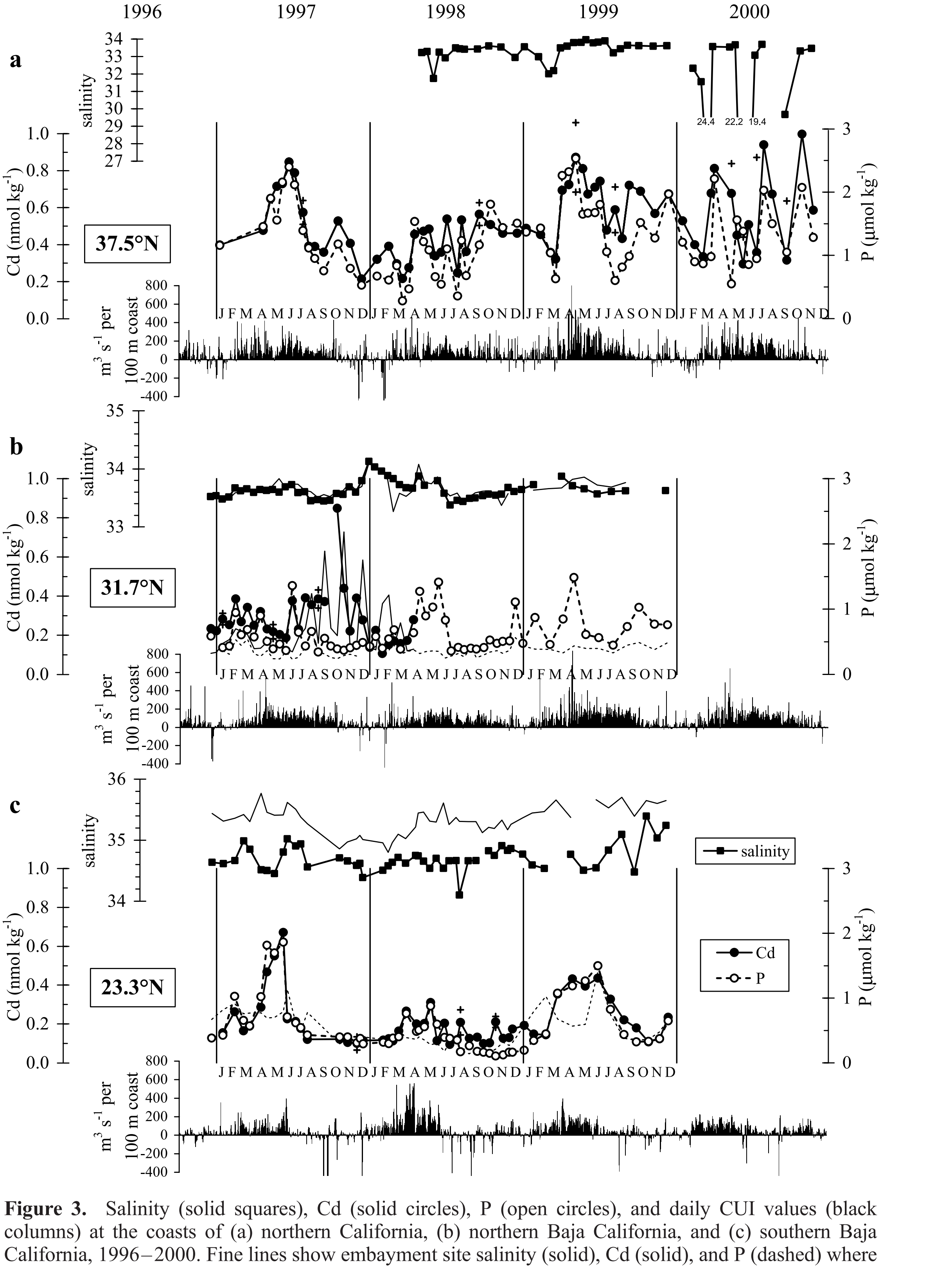

Figure 3. Salinity (solid squares), Cd (solid circles), P (open circles), and daily CUI values (black columns) at the coasts of (a) northern California, (b) northern Baja California, and (c) southern Baja California, 1996–2000. Fine lines show embayment site salinity (solid), Cd (solid), and P (dashed) where available. Crosses indicate Cd replicates that differ by over 20%.

(Figure 3c). Cd and nutrients were closely coupled to each other and to upwelling favorable wind forcing. Dynamic ranges of Cd, P, and salinity were 0.1–0.7 nmol kg^{-1} Cd, 0.1–1.9 μmol kg^{-1} P, and 34.1–35.4 (Table 2). In 1997, upwelling resulted in an initial increase in coastal salinity, followed by a 2 month-long decrease, then another increase before upwelling ceased in mid-June. Throughout this period Cd and nutrients progressively increased. Together these patterns are consistent with upwelling from increasing depths, causing first thermocline water, then CC

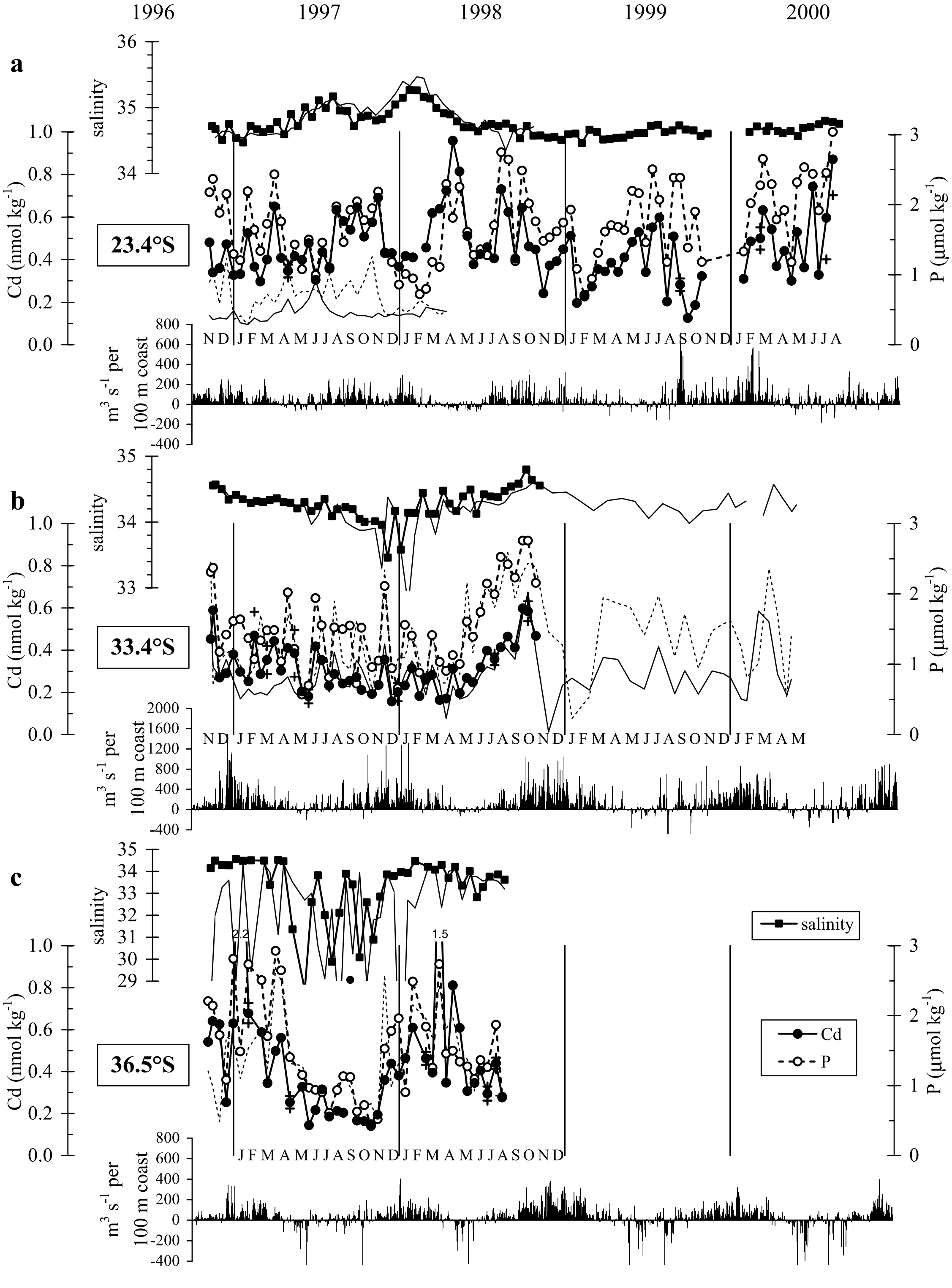

Figure 4. Salinity (solid squares), Cd (solid circles), P (open circles), and daily CUI values (black columns) at the coasts of (a) northern Chile, (b) central Chile, and (c) central-southern Chile, 1996–2000. Fine lines show embayment salinity (solid), Cd (solid), and P (dashed) where available. Crosses indicate Cd replicates that differ by over 20%.

water (in the shallow salinity minimum at 50–150 m depth), then ESsW (from the CU below 200 m depth) to be upwelled at the coast. During nonupwelling months, surface salinities between 34.4–35 indicated onshore advection of StSW. The short-lived salinity decrease (to 34.1) on 6 August 1998 occurred when CUI values were strongly negative, which could indicate northward transport of TSW (salinity <34). The 1997–1998 El Niño had a dramatic effect on spring 1998 upwelling tracers. Despite strongly upwelling favorable CUI values, Cd and P enrich-

Table 2. Range of Upwelling Tracer Variations Observed at the Six Monitoring Sites

Station	Salinity	Cd, nmol kg^{-1}	P, μmol kg^{-1}	Si, μmol kg^{-1}	N, μmol kg^{-1}
Northern Hemisphere					
Pillar Point, 37.5°N	19.4–34.0	0.2–1.0	0.3–2.5	2.1–50.8	<0.1–29.6
Arbolitos, 31.7°N	33.4–34.1	0.1–0.9	0.3–1.5	1.6–18.9	<0.1–15.6
Los Cerritos, 23.3°N	34.1–35.4	0.1–0.7[a]	0.1–1.9	0.4–19.8	<0.1–16.6
Southern Hemisphere					
Santa Maria, 23.4°S	34.5–35.3	0.1–1.0	0.7–3.0	0.5–24.3	0.2–23.0
El Quisco, 33.4°S	33.5–34.8	0.2–0.6	0.6–2.8	<0.2–25.8	1.5–21.5
Coliumo, 36.5°S	28.6–34.6	0.1–0.8[a]	0.4–2.9	3.0–54.0	0.2–22.8

[a]Does not include values of nonupwelling origin.

ments averaged 60% lower than in 1997 and 33% lower than in 1999.

4.4. Santa Maria, Northern Chile (23.4°S)

[26] Daily CUI values ~140 km offshore suggest that alongshore winds were persistently equatorward from June to February with occurrences of near-zero or poleward winds from February to May (Figure 4a). However, land-based [*Blanco et al.*, 2001] and satellite-based [*Shaffer et al.*, 1999] estimates of wind forcing indicate year-round equatorward winds at the northern Chile coast.

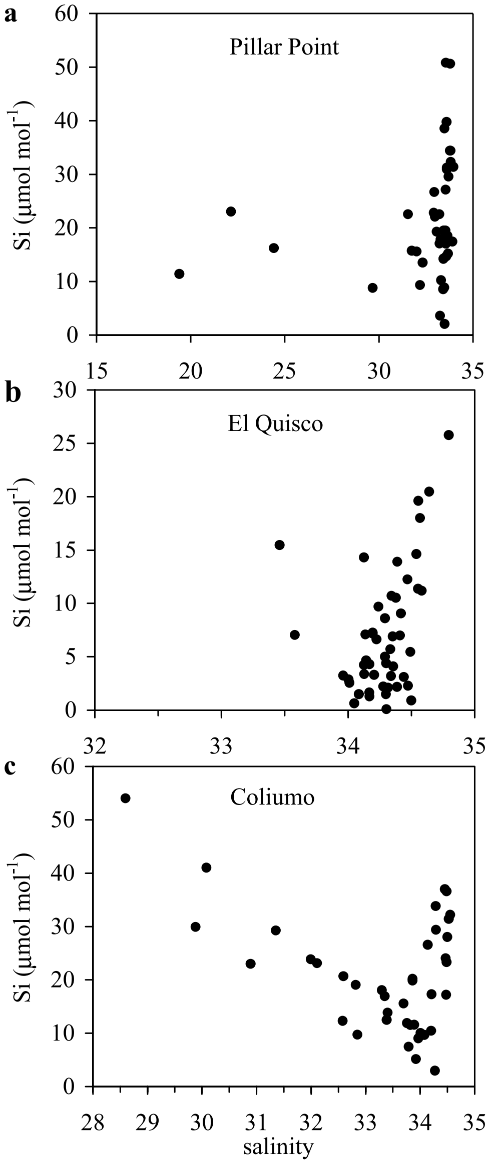

Figure 5. Silicate versus salinity regressions for sites at the coasts of (a) northern California, (b) central Chile, and (c) central-southern Chile, 1996–2000.

[27] Upwelling tracers at Santa Maria varied at 3–4 month timescales from the beginning of the monitoring period through July 1998, then shifted to a seasonal but highly variable pattern (Figure 4a). Dynamic ranges of Cd and P were quite large at Santa Maria: 0.1–1.0 nmol kg^{-1} Cd and 0.7–3.0 μmol kg^{-1} P (Table 2). Nearshore Cd and P were well correlated with each other but alternated between positive (November 1996 to April 1997; May 1998 to August 2000) and inverse (May 1997 to April 1998) correlations with coastal salinity (Figure 6). Salinity varied over a small range (34.5–34.9) during most of the monitoring period, except during the two El Niño pulses in mid-1997 and December 1997 to January 1998, when values were unusually high. The first period of high salinity began in May 1997 (austral winter) and coincided with an abrupt drop in Cd and nutrients. Salinity increased in a stepwise fashion through July to 35.1 while Cd and P remained low (0.4 ± 0.08 nmol kg^{-1} (1 σ) and 1.2 ± 0.2 μmol kg^{-1} (1 σ), respectively). Coastal salinities during this period were characteristic of offshore STW. A relaxation of El Niño conditions and the occurrence of upwelling favorable wind forcing from August to November 1997 resulted in a brief period of coastal upwelling. Cd and P abruptly doubled and salinity decreased to ~34.8 (Figure 4a), characteristic of ESsW in the PU below 100 m depth. The second period of unusually high coastal salinities began in late December 1997, was again marked by an abrupt drop in Cd and nutrients (Figure 6), and lasted through early April 1998. In the latter half of 1998 nearshore Cd and P appeared to follow variations in upwelling favorable wind forcing but remained elevated in winter 1999 even though CUI values decreased. Cd patterns in 2000 were similar to those in 1998, but depressed winter values occurred two months earlier in the year (April rather than June).

4.5. El Quisco, Central Chile (33.4°S)

[28] Two-fold higher CUI magnitudes offshore of central Chile (compared to all other sites) suggest CUI calculations at this site were affected by proximity to land, despite the use of a grid point ~130 km offshore (Figure 4b). CUI calculations do not account for blocking by coastal mountain ranges (the Andes), leading to an amplified value [*Bakun*, 1975]. Daily CUI values varied seasonally, with upwelling favorable conditions prevailing for most of the

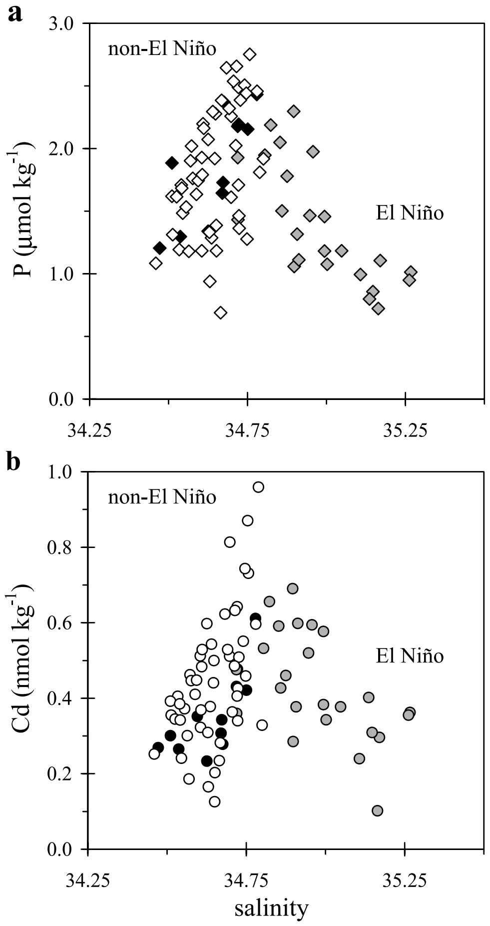

Figure 6. Santa Maria, northern Chile (a) salinity-P and (b) salinity-Cd plots showing positive slopes before May 1997 and after April 1998 (both non-El Niño conditions) and inverse relations during May 1997 to April 1998 (El Niño conditions).

year and occasional poleward wind events in austral fall and winter (May–August).

[29] Upwelling tracer patterns were very different during the two years sampled at El Quisco and only followed upwelling favorable wind forcing in the latter half of 1998 (Figure 4b). The lack of seasonal upwelling tracer enrichments during summer 1997–1998 were likely related to El Niño conditions, which peaked in December 1997. Although Cd and salinity were elevated at the onset of sampling in November 1996 (austral summer), both declined throughout 1997 and reached minimum values in late November (salinity ~33.5) and December (0.2 nmol kg^{-1} Cd; Figure 4b). Low-salinity waters ≤33.6 occurred at El Quisco on two occasions in November and December (Figure 5b). Salinity excursions at Las Cruces were lower than those at El Quisco, suggesting that freshening events were associated with outflow from the Maipo River, 13 km south of Las Cruces [*Kaplan et al.*, 2003]. Beginning in July 1998 (austral winter) alongshore winds became upwelling favorable and Cd and P increased steadily through October (austral spring), peaking at 0.6 nmol kg^{-1} and 2.8 μmol kg^{-1}, respectively. After an initial small decrease in July, salinity increased in parallel with Cd and P, reaching a maximum of 34.8. These upwelling tracer values were consistent with upwelling of ESsW from below 100 m depth. Because sampling decreased to once per month, comparisons between upwelling tracer and CUI time series were more tenuous after November 1998. Nevertheless, it appears that, as was the case off northern Chile, nearshore waters experienced unexpected enrichments of Cd and P in fall and winter 1999. It is not clear why spring 1999 lacked a peak in upwelling tracers, since CUI values were strongly positive. Peak Cd and P values in March 2000 (austral fall) were consistent with upwelling of ESsW.

4.6. Coliumo, Central-Southern Chile, (36.5°S)

[30] Values of the daily CUI calculated ~150 km offshore of central-southern Chile showed a seasonally reversing cycle: alongshore winds were upwelling favorable in early austral spring (September), peaked in early summer (December), declined through the fall (April), and became strongly poleward in winter (June). Among the three Chilean monitoring sites, upwelling tracers at Coliumo were most closely related to seasonal wind forcing. Cd, P, and salinity enrichments occurred during periods of highly positive CUI values (strong equatorward winds) while Cd, P, and salinity were lowest from winter into early spring when CUI values were negative (poleward winds) (Figure 4c). Upwelled waters were characterized by salinity >33.8, Cd > 0.4 nmol kg^{-1}, and P > 1.5 μmol kg^{-1}. Nearshore enrichments of Cd and P varied in parallel and had dynamic ranges of 0.1–0.8 nmol kg^{-1} and 0.4–2.9 μmol kg^{-1}, respectively (excluding the three highest Cd values), and salinity varied from 28.6–34.5 (Table 2). Local river run-off resulting from El Niño-related precipitations events were probably responsible for freshening events at the coast in fall and winter 1997, since low-salinity excursions (<32) were correlated with increases in nearshore Si (Figure 5c; Figure A2). On 12 January 1997 and 31 March 1998 coastal Cd exceeded 1.2 nmol kg^{-1}, the highest Cd value found in natural oceanic waters [*De Baar et al.*, 1994], suggesting a nonoceanic source. On 14 September 1997 high coastal Cd occurred during late winter when the CUI, P, and salinity were low. These Cd data were excluded from our interpretations.

5. Discussion

[31] Wind-driven coastal upwelling occurred at all IAI monitoring sites, however the relative influence of wind forcing on nearshore water properties varied greatly with latitude, as was also shown by *Strub and James* [2002]. At midlatitude sites (northern California, central-southern Chile) as well as at the southern coast of Baja California, seasonally reversing alongshore winds were the dominant influence on coastal water properties, whereas the northern and central Chile coasts were more strongly influenced by propagating signals from the equator, particularly the strong 1997–1998 El Niño event.

5.1. Wind-Forcing and Coastal Upwelling Tracers

5.1.1. Baja California

[32] The monitoring site at the northern Baja California coast (Arbolitos, 31.7°N) was located just south of the Southern California Bight and onshore of the southeastward flowing limb of the Southern California Eddy [*Reid et al.*,

1963; *Chereskin and Niiler*, 1994]. During spring, relatively fresh, nutrient-depleted, recirculated waters from within the SCB may flow southward along the coast to northern Baja California [*Hickey*, 1979; *Lynn and Simpson*, 1987]. During summer, nutrient-depleted SAW flowing onshore in the Southern California Eddy may impinge upon the coast [*Barton and Argote*, 1980]. Such inputs likely contributed to the short-lived and lower than expected upwelling tracer enrichments at Arbolitos. Nevertheless, May–June P and salinity increases indicated that coastal upwelling occurred in each of the three years and that waters upwelled at the northern Baja California coast originated below the low-salinity core of the CC (>50 m depth).

[33] At the southern tip of Baja California coastal salinity was lower during upwelling than at other times of the year. Profiles offshore of northern and central Baja California [*Walsh et al.*, 1974; *Lynn and Simpson*, 1987; *Sañudo-Wilhelmy and Flegal*, 1991] and the WOA94 showed that waters observed at Los Cerritos in April–May 1997 and April–June 1999 had characteristics similar to subsurface CC waters at 50–100 m depth. The presence of StSW during nonupwelling conditions (winds fluctuating between weakly equatorward and poleward) indicated that onshore rather than northward advection is favored. Inside the Gulf of California, salinities often >1 than on the Pacific coast reflected the evaporative nature of the basin [*Delgadillo-Hinojosa et al.*, 2001; *Monreal-Gomez et al.*, 2001].

[34] Nearshore and surface processes such as mixing with coastal water masses [*Martin et al.*, 1976; *Bruland et al.*, 1978; *Bruland*, 1980], phytoplankton growth [*Cullen et al.*, 1999; *Takesue and van Geen*, 2002], or exchange with shelf sediments [*Sundby et al.*, 1986; *Westerlund et al.*, 1986] can cause deviations in upwelling Cd:P ratios relative to source water values. Perhaps the most surprising result of this study was that these secondary processes did not appear to be important in the coastal upwelling system at the southern tip of Baja California. Variations in nearshore Cd and P throughout the upwelling season were maintained at a near-constant ratio ($0.31 \times 10^{-3} \pm 0.01$ mmol mol^{-1}) that closely matched the northeast Pacific source water Cd:P ratio found by *Bruland et al.* [1978] off central California. Furthermore, Cd and P in the upwelling system at Los Cerritos showed the most sensitive response to El Niño. These characteristics make southern Baja California a promising site for paleoupwelling and paleo-ENSO studies.

5.1.2. Chile

[35] The straight, continuous coastline and lower latitude of northern Chile contribute to the strong influence of equatorially forced variability in this region [*Strub et al.*, 1998; *Shaffer et al.*, 1999; *Blanco et al.*, 2001; *Thomas et al.*, 2001]. The appearance of Cd- and nutrient-enriched waters in austral spring 1997 during a relaxation of El Niño conditions [*Thomas et al.*, 2001; *Blanco et al.*, 2002; *Carr et al.*, 2002] and in austral spring 1998 during periods of strong equatorward winds showed that wind-driven coastal upwelling was a significant source of nutrients, and thus important for biological productivity in this region.

[36] At the central Chile coast, coastal upwelling tracer enrichments were correlated with equatorward wind forcing in spring 1998, but not in summer. It seems unlikely that summer Cd and nutrient depletions were due entirely to biological uptake, since *Wieters et al.* [2003] showed that productivity events at El Quisco were of short duration (weeks). It may be that a change in the depth from which water upwelled at the central Chile coast resulted in inconsistent seasonal patterns in upwelling tracers. *Poulin et al.* [2002] found that upwelling occurred from around 25 m depth in November 1999. In contrast, El Quisco upwelling tracers indicated upwelling from depths greater than 100 m. Similarly, *Sobarzo and Figueroa* [2001] showed that moderate equatorward winds could result in upwelling of SAAW (<100 m depth) while strong equatorward winds resulted in upwelling of ESsW (>100 m depth).

[37] At the central-southern coast of Chile, nearshore Cd, P, and salinity peaked during the upwelling season. Profiles of salinity and nutrients 60 km offshore (WOA94) and at the mouth of Coliumo Bay [*Ahumada*, 2002; *Atkinson et al.*, 2002] showed that upwelled waters had similar values as waters in the subsurface salinity maximum between 100–300 m depth, suggesting that the oxygen-depleted PU (ESsW) was the source of upwelled water at the central-southern Chile coast. The dominance of seasonal variability and the magnitude of upwelling tracer enrichments at 36.5°S suggest that the coastal upwelling system at the central-southern Chile coast is analogous to that off northern California (37.5°N). In winter, increased run-off from the nearby Andalien and/or Bio Bio Rivers [*Ahumada*, 2002] resulted in fresher salinities at the coast.

5.1.3. Low Cd:P Ratios at the Chilean Coast

[38] Newly upwelled waters off northern California and Baja California had Cd:P ratios close to 0.35×10^{-3} mmol mol^{-1}, characteristic of the deep North Pacific [*Bruland*, 1980]. Off northern, central, and central-southern Chile, coastal waters had Cd:P ratios averaging: $0.27 \pm 0.09 \times 10^{-3}$ mmol mol^{-1} at Santa Maria, $0.22 \pm 0.06 \times 10^{-3}$ mmol mol^{-1} at El Quisco, and $0.27 \pm 0.09 \times 10^{-3}$ mmol mol^{-1} at Coliumo. Lower than expected Cd:P ratios could result from a difference in source water composition in the southeast Pacific relative to the northeast Pacific, from redox-driven Cd and P sediment-water interactions during cross-shelf advection, or both. Existing data do not allow us to distinguish these possibilities.

[39] Although Cd and P distributions are strongly correlated in the water column, the two elements behave very differently at the sediment-water interface under suboxic conditions. P is generally released to anoxic pore waters and overlying bottom waters if they are sufficiently low in oxygen [*Sundby et al.*, 1986; *Ingall and Jahnke*, 1994; *McManus et al.*, 1997]. In contrast, it has been shown that Cd concentrations are lowered in pore waters by reducing conditions [*Westerlund et al.*, 1986; *Rosenthal et al.*, 1995; *van Geen et al.*, 1995]. These processes could have modified the proportion of P and Cd in upwelling waters since the OMZ off the coast of Chile is particularly pronounced and bottom waters over the continental shelf periodically become anoxic [*Morales et al.*, 1999; *Blanco et al.*, 2001]. *Westerlund et al.* [1986] showed that Cd taken up by shelf sediments during a period of temporary (<10 days) bottom water anoxia was released back into the water column when oxygenated conditions returned. P, on the other hand, which was released from shelf sediments under low-oxygen conditions, remained significantly enriched in bottom waters [*Sundby et al.*, 1986]. If conditions at the sediment-water interface off Chile can be compared to those observed by

Westerlund et al. [1986] and *Sundby et al.* [1986] off Sweden, then it seems more likely that low Cd:P ratios off Chile resulted from P enrichment rather than Cd depletion.

5.2. Effects of ENSO on Coastal Water Properties

[40] The period of our coastal upwelling monitoring program coincided with the strong 1997–1998 El Niño and the 1998–1999, 1999–2000 La Niña events. ENSO affects surface and upper ocean properties along western north and south America through oceanic (poleward propagating coastal Kelvin waves) and atmospheric (sea level pressure) linkages to the tropical Pacific [*Horel and Wallace*, 1981; *Emery and Hamilton*, 1985; *Shaffer et al.*, 1999; *Hormazabal et al.*, 2002; *Schwing et al.*, 2002; *Strub and James*, 2002]. ENSO-related processes result in anomalous sea surface temperature (SST), sea level (SL), and surface and subsurface current flows along the North and South American west coasts.

5.2.1. Coastal Response to El Niño

[41] In the eastern tropical Pacific, the 1997–1998 El Niño event was characterized by two periods of anomalously high SST and increased thermocline depth centered around June and November 1997 [*McPhaden*, 1999; *Carr et al.*, 2002; *Schwing et al.*, 2002]. Positive SST and SL anomalies first appeared at the northern Chile (20°S) coast in May 1997 [*Thomas et al.*, 2001; *Blanco et al.*, 2002; *Carr et al.*, 2002], at the Gulf of California (23°N) in June 1997 [*Strub and James*, 2002], then propagated poleward [*Strub and James*, 2002]. Surface anomalies were accompanied by intensified subsurface flow in the poleward undercurrents of each hemisphere [*Shaffer et al.*, 1999; *Blanco et al.*, 2002; *Durazo and Baumgartner*, 2002; *Lynn and Bograd*, 2002] and a deepened thermocline/nutricline [*Blanco et al.*, 2002; *Castro et al.*, 2002; *Chavez et al.*, 2002]. El Niño ended abruptly in May 1998 with the return of the trade winds and onset of seasonal equatorial upwelling in the eastern Pacific [*McPhaden*, 1999]. By this time water properties along the northern Chile coast were near seasonal averages [*Blanco et al.*, 2002; *Carr et al.*, 2002; *Strub and James*, 2002], but along the North American coast anomalous upper ocean conditions persisted throughout 1998 [*Schwing et al.*, 2002]. The spatial expression of the strong El Niño on eastern Pacific sea surface temperature can be seen in Figure 1.

[42] Nearshore regions off the northern, central, and central-southern Chile coast were affected in very different manners by El Niño. During periods of peak El Niño anomalies in austral winter 1997 and summer 1997–1998, coastal salinities indicated that STW, which usually resides over 100 km offshore and originates northwest of Peru [*Blanco et al.*, 2001], impinged on the northern Chile coast. This is consistent with IFOP hydrographic surveys off Mejillones Peninsula (23°S) which showed onshore or poleward flow at the surface during August 1997 and March 1998 [*Blanco et al.*, 2002]. Ten degrees to the south at the central Chile coast, little, if any, change in winter 1997 coastal circulation was apparent from upwelling tracers. During austral spring, however, 33% lower Cd and nutrient enrichments (relative to the same period in 1998) probably resulted from upwelling from within a depressed thermocline/nutricline. In austral summer, coastal salinity at El Quisco fell below oceanic values, indicating that run-off from the nearby Maipo River [*Kaplan et al.*, 2003; *Wieters et al.*, 2003] influenced coastal water properties. At the central-southern Chile coast El Niño was associated with unusually low winter salinity, likely resulting from increased precipitation events [*Rutllant and Fuenzalida*, 1991], but did not have an affect on summer coastal upwelling.

[43] In the northern hemisphere, the height of the El Niño event occurred during winter and had a strong effect on winter coastal salinity off Baja California. At the northern Baja California coast salinity increased by 0.3 (equivalent to the 1997 seasonal range) within a period of two weeks. The appearance of unusually high salinity waters at Arbolitos is consistent with poleward advection of StSW in a narrow band along the northern Baja California coast as proposed by *Durazo and Baumgartner* [2002]. *Ladah* [2003], in addition, showed that co-occurring salinity and nutrient enrichments during El Niño winters could be attributed to periodic shoaling of the intensified CU, bringing high-salinity nutrient-rich ESsW to the coastal ocean. Nitrate at Arbolitos was intermediate between depleted StSW values and enriched ESsW values [*Ladah*, 2003], suggesting that the high-salinity water present off northern Baja California during the El Niño winter was a mixture of StSW and ESsW. At the same time that salinity was unusually high off northern Baja California, coastal salinity was relatively low at the Pacific and Gulf coasts of southern Baja California. This would seem to indicate that TSW surrounded the southern Baja California peninsula during the El Niño winter, as has been suggested by *Durazo and Baumgartner* [2002] and *Roden* [1971]. However, since salinities at Los Cerritos were near the upper bound (34.4) of TSW [*Roden*, 1971], waters present off southern Baja California during El Niño could have been a mixture of StSW and TSW.

[44] Spring and summer 1998 Cd (and P) concentrations at the northern California and southern Baja California coasts were 50% and 60% lower, respectively, following the El Niño winter than during the previous year. Contrasting nutrient enrichments off northern Baja California were consistent with elevated chlorophyll *a* concentrations observed during IMECOCAL surveys [*Lavaniegos et al.*, 2002]. Changes in spring/summer wind forcing alone could not account for upwelling tracer patterns at Pillar Point and Los Cerritos, since monthly averaged large-scale upwelling favorable winds were anomalously weak offshore of northern California and anomalously strong offshore of southern Baja California [*Lynn et al.*, 1998; *Schwing et al.*, 2002], while upwelling tracer (Cd and P) enrichments were low at both sites. Rather, depressed Cd and nutrient values during spring and summer 1998 were likely the result of upwelling from a deepened thermocline/nutricline [*Castro et al.*, 2002; *Chavez et al.*, 2002], as was also the case during the 1991–1992 El Niño event [*Chavez*, 1996]. SSTA, upper ocean temperature anomalies [*Schwing et al.*, 2002], and adjusted sea level anomalies [*Smith et al.*, 2001] were consistent with a deepened thermocline throughout the 1998 upwelling season.

5.2.2. Coastal Response to La Niña

[45] The strong 1997–1998 El Niño was immediately followed by La Niña conditions: a weak event in 1998–1999 and a strong event in 1999–2000. Cold La Niña sea surface temperature anomalies first appeared off the coast of northern Chile in August 1998 [*Blanco et al.*, 2002; *Carr*

et al., 2002], off the western U.S. coast in winter 1998 [*Hayward et al.*, 1999; *Bograd et al.*, 2000; *Schwing et al.*, 2002], and persisted through at least 2000 [*Smith et al.*, 2001; *Schwing et al.*, 2002].

[46] During La Niña, anomalously high pressure (upwelling favorable wind forcing) persists over the North Pacific [*Horel and Wallace*, 1981; *Emery and Hamilton*, 1985; *Hoerling and Kumar*, 2000; *Schwing et al.*, 2002]. Unusually high winter Cd and nutrient concentrations at the three northern hemisphere sites (although at Arbolitos this appears only as two P peaks) and at Santa Maria during 1998–1999 and 1999–2000 were consistent with winter upwelling. This process may have implications for nearshore productivity and ecosystems since it represents an increase in the amount of nutrients available for primary productivity.

6. Conclusions

[47] A shore-based approach allowed biweekly monitoring of coastal upwelling tracers (salinity, Cd, and nutrients) in surf zone waters at six latitudes along the coasts of northern California, Baja California, and Chile throughout 1997–2000. Our initial expectation, based on previous studies in the northeast Pacific, that seasonal variations in P and Cd would be coupled to the intensity of coastal upwelling was fulfilled at two new sites, the southern tip of Baja California (23.3°N) and at the central Chile coast (36.5°S). During periods of strong upwelling Cd enrichments were four times higher than during winter.

[48] As has been found in other studies, coastal water properties at the northern Chile coast responded primarily to remote equatorial forcing rather than local wind forcing. El Niño resulted in reductions of at least one third in summer Cd and nutrient concentrations at three coastal sites in northern California, southern Baja California, and central Chile. La Niña resulted in wintertime elevations of Cd and nutrients. ENSO-induced changes in the availability of nutrients and essential trace elements for primary productivity may have significant implications for the productivity of coastal upwelling regions, since future changes in climate may result in decadal or longer shifts in the phase, intensity, and frequency of ENSO events [*Fedorov and Philander*, 2000; *Smith et al.*, 2001].

[49] **Acknowledgments.** R. Takesue and A. van Geen thank Isaac Kaplan, Darcy Gordon, and Aradhna Tripati for assistance with sample collection and processing; Lynn deWitt at PFEL for providing daily upwelling indices for Baja California and Chile, and the U.S. Geological Survey, Menlo Park and UC Santa Cruz for providing clean lab space. JCC received financial support from the Center for Advanced Studies in Ecology and Biodiversity (FONDECYT, Program 15001-0001). This work was supported by IAI ISP Grant 2-085, NSF grant OCE96-33173, and funding from the LDEO Climate Center. This is LDEO Contribution number 6494.

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