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Seasonal and spatial variation of nearshore hydrographic conditions in central Chile

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Abstract

Numerous oceanographic processes involved in the transport and survival of larval stages of marine organisms, as well as, in nutrient and phytoplankton delivery, occur in nearshore waters. Yet, while large-scale oceanographic patterns are relatively well known for central Chile, little information exists on temporal and spatial variation in the nearshore environment. In this study, we examined the inner shelf hydrography of two sites in central Chile separated by 15 km and with slightly different coastline orientation. Our results show that both sites follow the general oceanographic patterns described for the region, with a well mixed water column and spatial homogeneity in winter months and the onset of a thermocline in spring and through the summer, when upwelling favorable winds intensified. However, despite the proximity of the sites, persistent differences in surface temperature, salinity, stratification, and chlorophyll-*a* concentration, as well as in the intensity of wind forcing were detected. Time series and cross-correlation analyses between wind and temperature, as well as satellite images, suggest that the intensity and frequency of upwelling varies between these sites, probably due to differences in coastline orientation. The potential existence of a localized upwelling shadow at one site and the influence of riverine input are discussed. The meso-scale oceanographic differences described in this study can have important consequences on the dynamics of nearshore ecosystems and should be born in mind when designing conservation or management strategies.

Keywords: Nearshore oceanography; Upwelling shadow; Chile; Surface temperature; Topographic effects; Wind forcing

1. Introduction

The coastal ocean, located between the coastline and the edge of the continental shelf, sustains the majority of the commercially exploited benthic and pelagic species (Bakun, 1996). Consequently, many biological and oceanographic studies have been conducted in coastal oceans to help understand their dynamics and to improve the sustainable management of renewable resources (Mann and Lazier, 1996). However, within this vast area, the nearshore waters, those within the first few kilometers from the shore and less than 100 m

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deep, have received much less attention than waters further offshore, especially in high-energy environments. Logistic difficulties (e.g. inaccessibility to large vessels, difficulty to deploy instruments in wavy areas), together with the physical complexity of this margin system, have probably slowed the pace of oceanographic studies in the nearshore. Yet, this zone is of special socio-economic importance since it is here where the vast majority of artisanal fishery extraction occurs and where human activities have had the most intense and persistent impacts (Lubchenco et al., 1995; Botsford et al., 1997; Castilla and Defeo, 2001). In addition, variability in physical conditions impinge on adult stages of benthic organisms and play a key role in the retention, dispersion and/or supply of larvae to areas suitable for settlement (Shanks and Wright, 1987; Shanks, 1995; Pineda, 1994; Poulin et al., 2002a). Therefore, information on the spatial and temporal variability of predominant oceanographic conditions over scales of a few to tens of kilometers along the coast are sorely needed to understand, for instance, spatial variation in population dynamics of many benthic species and suggest the siting of marine protected areas.

In addition to terrestrial inputs (freshwater, nutrients and sediments), the coastline represents a barrier to the flows of water and air, causing convergences and divergences in currents of greater intensity than in the open sea, sometimes neutralizing the effects of wind forcing (Tomczak and Godfrey, 1994). Also, the shallower depth of nearshore waters increases the importance of bottom layer friction (Lentz and Trowbridge, 1991) and generally intensifies tidal currents (Tomczak and Godfrey, 1994). The interaction of these factors makes nearshore waters a complex system that presents important variability at smaller spatial scales than in open seas.

Previous studies on coastal dynamics of the eastern South Pacific have demonstrated that the region is characterized by strong coastal upwelling and high biological productivity (Avaria et al., 1989; Strub et al., 1998; Barbieri et al., 1995; Letelier, 1998). Large-scale circulation has been relatively well studied, identifying a series of currents and countercurrents along the coast (see Strub et al., 1998, for review). The anticyclonic subtropical Pacific Gyre significantly contributes to the control of the large-scale atmospheric circulation in northern and central Chile (Bakun and Nelson, 1991), generating strong south–southwesterly winds primarily during the austral spring and summer, which produce upwelling of subsurface waters along the coast (Pizarro et al., 1994; Shaffer et al., 1997, 1999). These conditions are relatively persistent year after year, but can be drastically modified during El Niño events, when coastal waters warm up causing changes in the coastal ocean and climate (e.g. Blanco and Díaz, 1985; Fonseca, 1985; Shaffer et al., 1997, 1999; Thomas et al., 2001; Hormazábal et al., 2001; Navarrete et al., 2002). These studies have provided a general understanding of the coastal ocean over scales of hundreds of kilometers. However, variability at scales of a few to tens of kilometers from the coast has been poorly studied along the exposed coast of Chile.

The objectives of this study are to describe general hydrographic characteristics of nearshore waters at two coastal sites in central Chile ($\sim$33.5°S) separated by 15 km, with the purpose to determine whether the sites exhibit similar variability. The study was undertaken during a period without strong El Niño events, to describe: (1) seasonal variation in physical characteristics of surface waters (0–20 m), (2) high and low frequency temporal variation in winds and sea surface temperature, and (3) the occurrence and spatial variability in coastal upwelling events.

2. Materials and methods

2.1. Study area

Two sites located in central Chile, Las Cruces (33.5°S–71.63°W; hereafter LC) and El Quisco (33.4°S–71.7°W; hereafter EQ) were selected. These sites, separated by 15 km, are protected from human exploitation to different degrees. At Las Cruces there is a 20 year-old small marine reserve where no human activities, other than research are allowed (Castilla, 1999) and at El Quisco there is a 10 year-old Management and

Exploitation Area (Castilla, 1996), to which only one fisher's association has exploitation rights on benthic resources (Castilla et al., 1998). The scale of our study is thus comparable to the scale and spacing at which management and conservation policies are being applied along the Chilean coast. Las Cruces and El Quisco are located between two important upwelling centers: Punta Curaumilla to the North and Punta Toro to the South (Fig. 1a). To the south of LC the presence of the submarine canyon of San Antonio (Atlas Hidrográfico de Chile, Servicio Hidrográfico y Oceanográfico de la Armada, 1997), is associated with the Maipo River. The two sites present moderately different coastal topographic characteristics. At LC, the coastline is oriented to the northwest, while at EQ the coastline is oriented to the north. Bathymetrically, the two sites are similar, with the shelf slope more pronounced in EQ than in LC (Fig. 1b). At a large-scale, however, the break in the continental shelf (200 m) produced by the San Antonio submarine canyon can be identified to the south of LC (Fig. 1a).

2.2. Data collection and analysis

The data compiled for the study area were obtained through: (1) monthly nearshore cruises, (2) high frequency measurements of winds, temperature at the sea surface and in the water column, and (3) inspection and analyses of satellite images.

Nearshore cruises. A total of 12 cruises were made between July 1999 and July 2000 on the F/V *Barracuda* (a long-line albacore vessel). One cruise per month per site was conducted on consecutive days at LC and EQ. At each site, a grid was sampled consisting in six 1.8 km long transects parallel to the coast at distances of 0.15, 0.35, 0.5, 1, 2 and 4 km from the coast (Fig. 1b). Data were

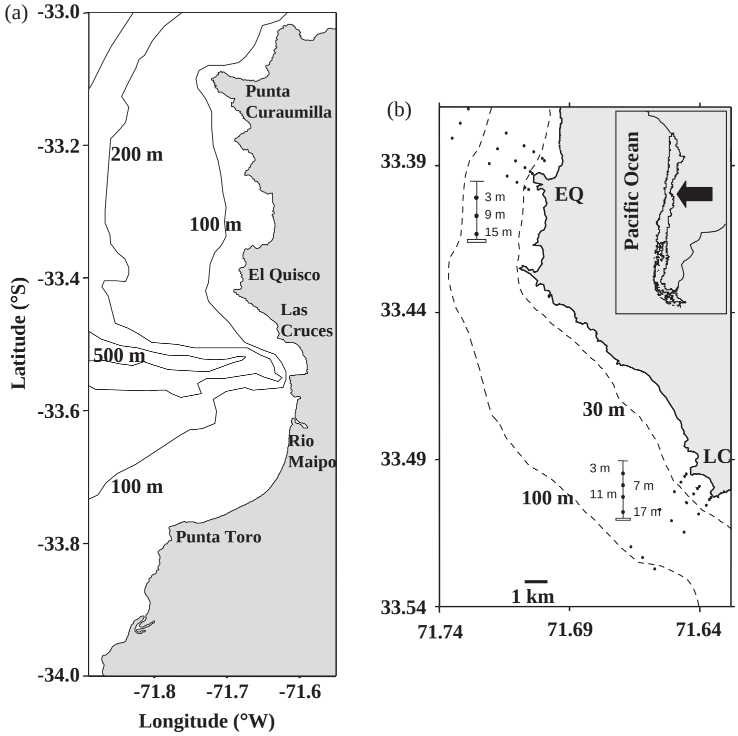

Fig. 1. Map of the study area along the coast of central Chile showing (a) the location of the study sites and known upwelling centers, (b) the spatial grid of CTD casts and the depths at which the temperature loggers were anchored at Las Cruces (LC) and El Quisco (EQ).

collected between 9:00 a.m. and 3:00 p.m. on the consecutive days, so the tidal cycle was nearly the same for the paired cruises. Additional cruises were conducted during periods of intense southerly winds on August 31, 2000, and September 25, 2000, at LC and EQ, respectively. Hydrographic properties of the upper water layer (0–20 m depth) were obtained with a conductivity, temperature, depth recorder Seabird 19 CTD at the extremes and center of each transect. The CTDs were acquired and calibrated in January 1999. The CTDs were also equipped with a SBE 23Y dissolved oxygen sensor and a WETStar fluorometer. Oxygen and chlorophyll-*a* were also measured at one to four stations during each cruise in water samples collected with a Niskin bottle at 10, 15 and 20 m depths, following the method described by Wieters et al. (2003) for total extracted chlorophyll-*a* and using titrimetric oxygen test (Aquamerck®) for dissolved oxygen. In all cases, linear correlation between oxygen measured by the CTD and water samples was high ($r > 0.87$), as well as the correlations between fluorescence measured by CTD and extracted chlorophyll-*a* ($r > 0.89$). Therefore, CTD values provide proper estimates of variability in chlorophyll-*a* concentration.

To characterize the monthly and seasonal variations of the water column and to eliminate the influence of variation in tidal cycle during each cruise, an average monthly profile was calculated from all the casts made in a given month for each site. This resulted in mean monthly estimates of temperature, salinity, chlorophyll and dissolved oxygen at depths of 1, 5, 10 and 20 m.

Sea temperature and wind time series. Seawater temperature time series were obtained from: (a) temperature loggers (Stow Away® Tidbits, Onset Computers Corp., with ±0.3°C precision) mounted subtidally on rocks 1 m below the lowest low tide mark at each site (rock loggers), (b) from a series of loggers suspended from buoyant lines moored approximately 150 m from the shore and 25 m bottom depth at each site (moored loggers). Loggers were suspended from the moorings at 3, 7, 11 and 17 m depth at LC and 3, 9 and 15 m at EQ. Loggers on the rocks were programmed to record temperature every 5 min at LC and every 30 min at EQ, from January 1999 to December 2000. Moored loggers were programmed to record temperature every 30 min from February 1999 to July 1999, and from November 1999 through May 2000. Storms during the austral winter of 1999 destroyed the mooring lines causing a discontinuity in the mooring time series. Wind direction and velocity were recorded every 20 min, from April 1999 to December 2000, by a Campbell meteorological station located at the Estación Costera de Investigaciones Marinas (ECIM) at Las Cruces.

Mean daily temperature cycles at each site and depth were calculated from the mooring loggers separately for austral spring (October–December) and summer (January–March), corresponding to the periods of greatest stratification of the water column and greatest daily differences in temperature (see Results). Daily cycles were obtained by calculating hourly averages of temperature using records from all days within the season. The average daily wind cycle was calculated for each hourly segment of the day from the entire time series, separately for fall–winter (April–September) and spring–summer (October–March). To detect possible effects of wind on sea surface temperature, we performed cross-correlation analyses following Emery and Thomson (1998). We used the north–south component of wind stress registered at LC and the surface temperature registered by rock loggers at each site during austral spring (upwelling-favorable) and winter. Wind stress was calculated using a coefficient of drag and air density of 1.3×10^{-3} and $1.2\,\mathrm{kg\,m^{-3}}$, respectively (Bakun and Nelson, 1991).

Satellite images. To obtain a large-scale perspective of spatial variation in the sea surface temperature across the study region, 62 Advanced Very High Resolution Radar (AVHRR) satellite images (resolution $1.1\,\mathrm{km}^2$) were analyzed for 4 spring–summer period, (1992–1993; 1997–1998; 1999–2000 and 2000–2001). From these images, we calculated an average sea surface temperature to represent the surface thermal structure predominant during the spring–summer season. Images were obtained from the Centro de Estudios Espaciales of the Universidad de Chile, Santiago, Chile.

To better characterize the dynamics of upwelling events, temperature data about 2 km from the coastline, offshore from Punta Curaumilla (PC), EQ, LC, and Punta Toro (PT), were also extracted from a sequence of AVHRR images during the evolution of an upwelling event that occurred between November 1 and 8, 1999. Missing data from this time series correspond to clouds in the images. Some of these images have been presented by Poulin et al. (2002b).

3. Results

3.1. Seasonal variability and between site differences

During austral winter (July–September 1999) and fall (March–July 2000) inner shelf surface temperatures differed between Las Cruces and El Quisco by no more than 0.5°C. At both sites, weak thermal gradients, less than 0.1°C/m, were present and the mean temperature between 0 and 20 m was 12.7°C (Figs. 2a and e). During October, sea surface temperature gradually increased, especially at LC, where temperature peaked at 16.6°C in January and a difference of as much as 5°C was observed between the surface and 20 m depth. At EQ, the temperature also began to increase in October, but decreased around 1°C in December 1999, to then reach a maximum of 15°C in February 2000. In both locations, the seasonal increase in temperature was apparent down to 5 m depth. Below that depth the temperature varied by no more than 2°C throughout the study period (Figs. 2a and e).

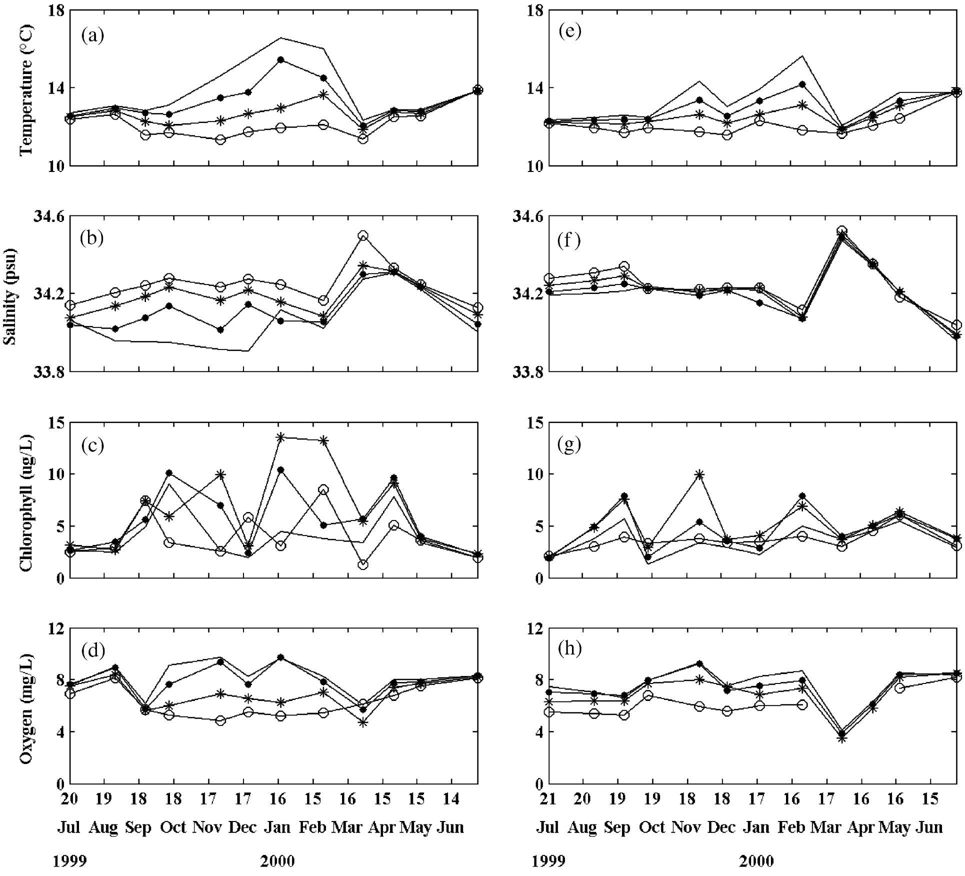

Fig. 2. Annual variability in physical variables of the water column at Las Cruces (a–d) and El Quisco (e–h), at 1 (solid line), 5 (dot line), 10 (asterisk line) and 20 (circle line) meter depth.

Between August and December 1999, LC also presented a strong vertical gradient in salinity (~0.02 psu/m), produced by a minimum surface salinity of ~33.9 psu (Fig. 2b). The maximum salinity was 34.5 psu at 20 m deep in March 2000. At EQ, salinity was more homogeneous throughout the water column with a mean value on the order of 34.2 psu (vertical gradient <0.005 psu/m) from July 1999 to January 2000. The maximum salinity at EQ was 34.5 psu at 20 m in March 2000 (Fig. 2f).

Overall, chlorophyll concentration at LC was more variable and reached higher values than those registered at EQ. Maximum chlorophyll concentration at LC (~13.5 μg/l) was registered between January and February 2000 at 10 m depth, and minimum values of approximately 2 μg/l a 20 m depth in March 2000 (Fig. 2c). At EQ, chlorophyll presented a maximum of 10 μg/l in November 1999 at 10 m depth (Fig. 2g). Dissolved oxygen was fairly homogeneous in the water column at LC during winter of 1999 (July–September) and fall of 2000 (March–July), with a vertical gradient of less than 1 mg/l from the surface to 20 m depth. Between October 1999 and February 2000, a vertical gradient in dissolved oxygen was clearer at LC, with highest mean values of 8.5 mg/l at the surface and lowest of 5.4 mg/l at 20 m (Fig. 2d). A stronger vertical gradient of about 1.5 mg/l characterized EQ throughout the study period, with mean surface values of 7.5 mg/l and a mean of 6 mg/l at 20 m depth (Fig. 2h).

Temporal variability in sea surface temperature registered with rock loggers was governed by a seasonal cycle, with maximum values during summer months (~18°C) and minimum values in winter (~11°C, Figs. 3a and b). At LC, the annual cycle explained 45% of the total variance in surface temperature, while at EQ it only explained 16% of the total variance. On average, throughout the year, LC presented slightly warmer temperatures at the surface than EQ as well as greater variability. These between-site differences were stronger in summer months, when the temperature at LC was on average 1°C higher than at EQ (15.2 v/s 14.2°C). At both locations, surface temperature presented higher variability at high-frequencies (days and hours) during spring and summer months than during fall–winter (Figs. 3a and b).

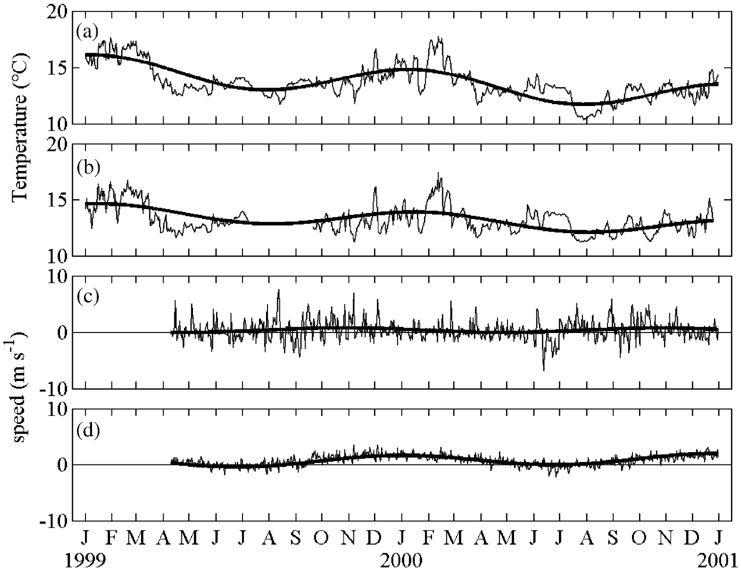

Fig. 3. Daily means of temperature recorded in the coastal border at Las Cruces (a) and El Quisco (b). The mean daily north–south (c) and east–west (d) wind components are also shown. Positive values in wind components refer to winds coming from the south (c) and west (d). The thick line represents the annual signal of the series.

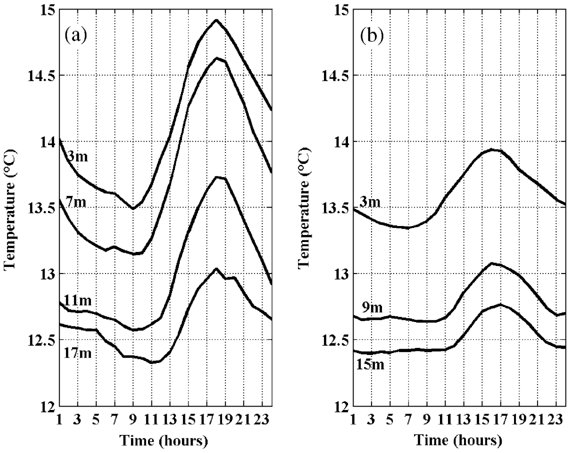

Fig. 4. Mean daily water temperature cycle at Las Cruces (a) and El Quisco (b), based on hourly records from loggers suspend from moorings during spring and summer.

The daily mean temperature cycles, calculated from the temperature records from the moorings at LC and EQ, showed a similar tendency at both sites, however the range of variations was greater at LC than EQ (Figs. 4a and b). In the morning, temperature reached minimum values between 6:00 and 8:00 (~13.6°C and 13.4°C at 3 m depth at LC and EQ, respectively). Throughout the day, the temperature rose, reaching a maximum between 17:00 and 19:00 (~14.9°C and 13.9°C at 3 m depth in LC and EQ, respectively). These daily variations were observed in the entire water column (0–20 m), but with decreasing amplitude at greater depths (Figs. 4a and b).

3.2. *Local wind*

The wind records presented a strong seasonal signal, marked mostly by the east–west component during spring and summer months. However, amplitudes of the daily variations in the north–south component were much greater than those in the east–west component (Figs. 3c and d). Variation in the north–south component explained 79% of the total variance in winds throughout the study period, and the east–west component explained 21%. The wind speed was higher during spring and summer month. The wind direction was predominantly from the west-southwest, especially during the austral spring and summer. Northerly winds were observed in July 1999 and May–June 2000, which can be attributed to storm conditions during this period (Fig. 3c and d).

The mean daily cycle of winds was similar throughout the year (Figs. 5a and b), with strong daily signals both in magnitude and direction. Weak winds ($<1\,\mathrm{m/s}$) were observed in the early morning (between 0:00 and 9:00 h), with increasing magnitudes throughout the day, reaching maxima between 13:00 and 16:00 h (approx. 3 m/s in fall–winter and 4m/s in spring–summer; Figs. 5a and b). During fall, winds were primarily from the east-northeast during the late night, and primarily from the southwest-west between 11:00 and 20:00 h (Fig. 5a). During spring–summer and between 1:00 and 8:00 h, weak winds were primarily from the north (between northwest, north or northeast), changing to strong winds from the southwest-west later in the day, between 10:00 and 23:00 h (Fig. 5b).

3.3. *Wind forcing influence on sea surface temperature*

Cross-correlation between the north–south component of wind stress and surface temperature showed relatively weak correlations at both sites, especially during austral winter. During the upwelling favorable months of the year (especially spring), correlations were significantly negative and greater in magnitude ($R = 0.3$; time lag of 1 day at maximum correlation value), suggesting an increase in wind stress parallel to the coast followed by a drop in the sea surface temperature.

The cross-shore vertical sigma-t sections under conditions of ‘normal’ winds (weak southerly winds, Fig. 6), showed that at LC and EQ the water column presents a stable condition and offshore gradients are weak (Figs. 6a and b). When the southerly winds intensify and exceed $5\,\mathrm{m\,s^{-1}}$, the presence of cold, denser water is observed on the coast, especially at EQ (Figs. 6c and d).

Sea surface temperature averaged from the 62 AVHRR satellite images supports the existence of two main upwelling centers in Punta Curaumilla

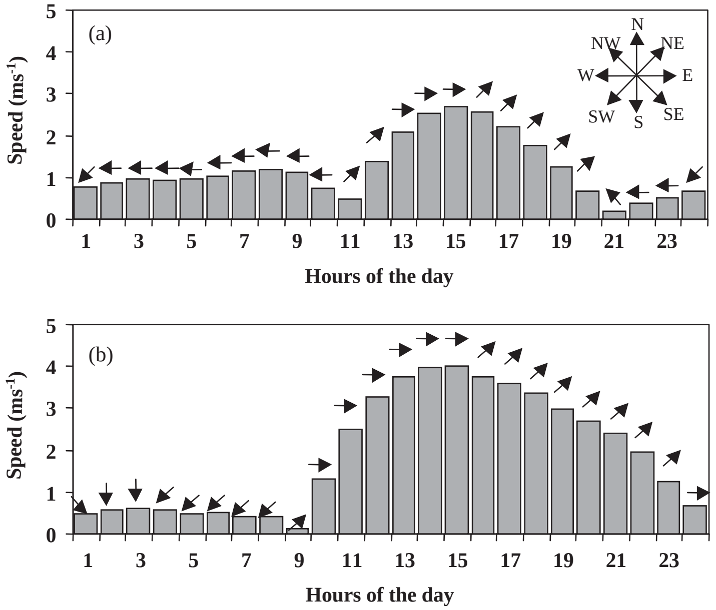

Fig. 5. Daily wind cycle in fall–winter (a) and spring–summer (b). Arrows above bars indicate the mean direction of the wind.

and Punta Toro, and shows another, weaker upwelling center near EQ. The images also show that the coastal area of Las Cruces is characterized by waters warmer than the waters up or down the coast. A similar situation occurs in the Bay of Valparaiso, north of Punta Curaumilla (Fig. 7).

During the intense upwelling event occurring between 1 and 8 November 1999 (Fig. 8), winds were predominantly from the south west and exceeded 5 m s^{-1} during the afternoons of 3 consecutive days. Toward the end of the event (8 November), winds were less intense and changed to primarily from the north west. As the wind increased, the surface temperature measured from satellite images began to drop rapidly at Punta Curaumilla and Punta Toro, while at EQ and LC surface temperature remained constant or even increased slightly at LC ($\sim$0.3°C). After the first two to three days of southerly winds, surface temperature dropped at all sites, reaching minimum values by November 7. Temperature at LC was on average the highest ($\sim$14°C) of all sites and PT was the lowest ($\sim$13°C). After November 7, surface temperature began to increase at all sites (Fig. 8).

4. Discussion

The winds and hydrographic conditions described during our study conform well to the regional patterns previously reported for central Chile for years of nearly normal conditions (non El Niño years) (e.g. Shaffer et al., 1997, 1999; Strub et al., 1998). However, we detected and quantified important variability in predominant hydrographic conditions and intensity of upwelling between coastal sites separated by not more than 15 km. Although monthly cruises provide only a limited representation of the dynamics of the system, we observed at both study sites clear patterns of seasonality in physical and chemical variables in the upper layer of the water column. During fall and winter months, the water column was homogeneous from surface down to 20 m deep and there were no appreciable differences between locations. In contrast, during most of spring and throughout summer, there was a sharp thermocline at about 10 m depth, produced by the increase in solar radiation at mid latitudes during summer (Pickard and Emery, 1982). Onset of the thermocline occurred by mid October at both sites,

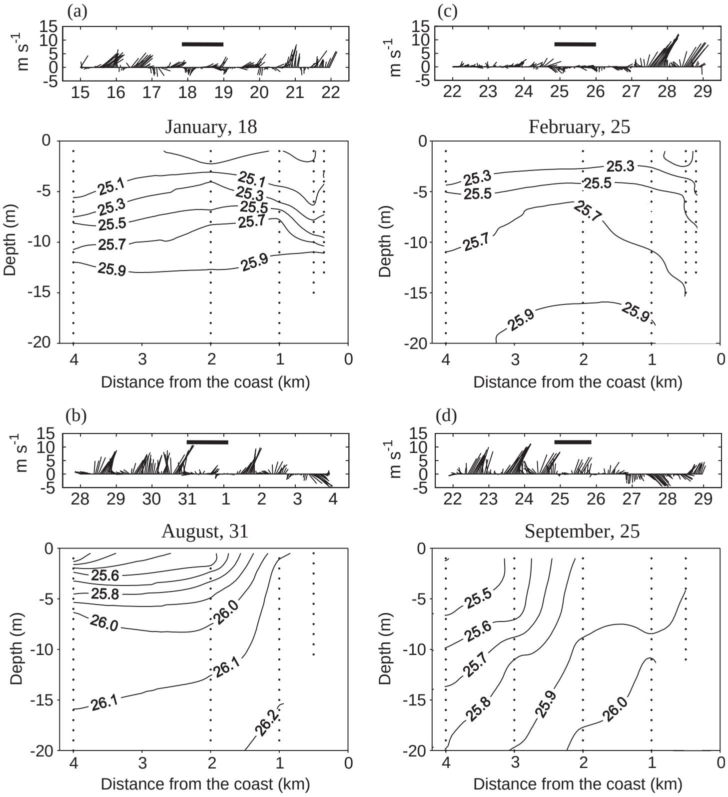

Fig. 6. Vertical sigma-*t* structure during non-upwelling favorable wind conditions at Las Cruces (a) and El Quisco (c) and during upwelling favorable winds at Las Cruces (b) and El Quisco (d). The panels above the sigma-*t* sections show stick diagrams of winds for three days before and 3 days after the cruise. The horizontal bar indicates the cruise day, when CTD casts were done.

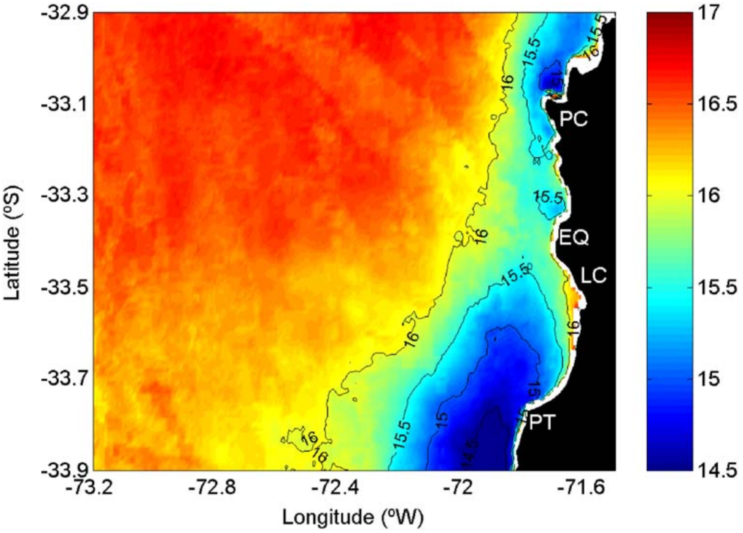

Fig. 7. Mean spatial pattern of the sea surface temperature derived from 62 AVHRR images taken during 4 upwelling season (1992–1993; 1997–1998; 1999–2000 and 2000–2001).

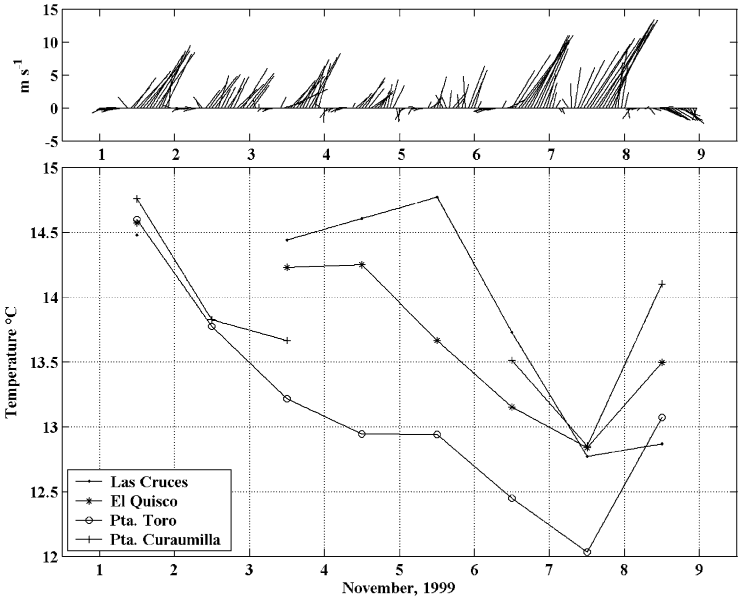

Fig. 8. SST obtained from the pixels closest to the shore from AVHRR satellite images spanning November 1–8, 1999. Dotted line: Curaumilla, starred line: El Quisco, line and circles: Las Cruces, line and plus signs: Punta Toro (see Fig. 1 for locations) The upper panel shows the stick diagram of winds for the same time period recorded in Las Cruces.

but the intensity and stability of the temperature gradient varied markedly between sites (see below).

The coastal wind regime presented a well-defined seasonal variation, driven principally by the sea breeze component (winds from the west). The sea breeze occurs regularly in spring and summer and is virtually absent in winter months. This sea breeze is produced by the greater thermal difference between land and ocean in summer and therefore it nearly disappears in winter (Simpson, 1994; Urrutia et al., 1996). The upwelling-favorable west-southwest winds were present throughout the year, but intensified in spring and early summer. Short-term pulses of north-northeast winds, associated with frontal systems and storms, were observed in winter months (e.g. June 2000). Within seasons, the north–south component of the wind presented an intermittent pattern, characterized by alternating periods of 3–7 days of strong upwelling-favorable south winds followed by 1–2 days of calm or weakly northerly winds (see Fig. 3).

At even smaller temporal scales, a clear daily wind cycle was observed throughout spring and summer, with stronger winds during the day and weak, nearly null winds during night hours (see also Kaplan et al., 2003). This daily cycle was actually magnified during periods of strong upwelling-favorable winds, which is related to resonance of inertial periods of atmospheric forcing in the region (Vergara, 1992). Density structures showed that both locations were affected by the upwelling of cold water, particularly in spring. Closer examination of upwelling events showed that, on average, daytime west-southwest winds of constant intensity greater than $5\,\mathrm{m\,s^{-1}}$ for at least 2–3 days, interrupted only by weak winds at night, are necessary to produce a drop in surface temperature. However, the time lag between the onset of southerly winds and the drop in surface temperature was longer at LC, 1–2 days, than at EQ, 1 day. Inspection of temperature time series showed not only that surface waters at LC were usually warmer, but that many temperature drops at EQ were not accompanied by similar drops at LC, especially when temperature changes were small (see Fig. 3).

The analyses of temperature time series extracted from satellite images during the upwelling event of November 1–8, 1999, provided information about the dynamics of upwelling in the region and about spatial, among-site differences in upwelling intensity and frequency (see also Broitman et al., 2001). Rapid cooling of the superficial layer of water was observed at the beginning of the upwelling-favorable wind episode at two well known upwelling centers: Punta Curaumilla (Fonseca and Farías, 1987; Sievers and Silva, 1979) and Punta Toro (Fonseca and Farías, 1987). At EQ, the temperature drop in SST began three days after the drop observed at PC and PT, while at LC it began after the fourth day (see Fig. 8). This general pattern of between-site differences in the dynamics of upwelling events seems consistent with our observations of satellite images for other periods of spring in different years (Fig. 7). Moreover, as shown by Broitman et al. (2001) and Wieters et al. (2003), also for central Chile, these temporal differences in upwelling dynamics are reflected in important and persistent differences in the frequency of upwelling events among sites.

In theory, coastal upwelling develops over the entire north and central coast of Chile as a result of wind forcing (Fonseca and Farías, 1987), but it is intensified at specific points along the coast, such as headlands, capes and outer sections of bays (Barbieri et al., 1995; Letelier, 1998; Strub et al., 1998). At the scale of kilometers, the coastline at EQ appears oriented in a roughly north–south direction (~355°), while at LC it is oriented in a southeast–northwest direction (~300°). This means that the predominant west-southwest winds causing upwelling in the region, push water mostly onshore at LC and alongshore at EQ, which can explain differences in how rapid sub-superficial waters are upwelled. Under this scenario, one would expect that only the most intense winds (in terms of velocity and duration of south west winds) would have effect on LC temperature, while the occurrence of upwelling events would be more frequent and stronger at EQ. Greater frequency of upwelling events at EQ, and the consequent mixing of the water column, could explain the greater homogeneity in physical and chemical variables at this locality. These differences are also reflected in the average pattern of daily warming of surface waters, which was larger at LC than EQ. The fact that the annual cycle at EQ explained only 16% of the total variance in the continuous temperature records (in contrast to 45% at LC), also suggests a greater frequency of short-term (few days) changes in the water temperature.

In summary, the smaller influence of the annual temperature cycle, less stratification of the water column, and more rapid response to upwelling-favorable winds, suggest a greater impact of upwelling events at EQ than LC. These differences appear related to meso-scale (kilometers) differences in coastline orientation. It is also possible that, in addition to coastline orientation, the oceanographic differences between sites summarized above could be the result of warm water features like an ‘upwelling shadow’ or ‘upwelling trap’ (see Castilla et al., 2002) at LC and not at EQ. These warm water features have been described as a region inshore and usually downstream from an active upwelling center, where upwelling of cold waters is significantly reduced, producing warmer superficial pockets of water (Graham and Largier 1997). Upwelling plumes originating upstream would produce a front and a retention zone at the upwelling shadow region, which may influence the dynamics of the ecosystem in the area (Graham et al., 1992; Graham and Largier, 1997; Wing et al., 1998; Castilla et al., 2002). Upwelling shadows usually are contained by convex coastlines (such as LC), downstream of capes or headlands (Graham and Largier, 1997). Indeed, sea water temperature averaged from satellite images show that the upwelling plume that originates south of LC, at Punta Toro, usually extends north and slightly offshore past San Antonio. The plume appears to entrain a body of warmer waters off Las Cruces (Fig. 7). This is similar to the pattern described for warm water features in the Northern Hemisphere (Graham and Largier, 1997; Wing et al., 1998) and for the bay of Antofagasta in Northern Chile (Castilla et al., 2002). Observed between-site differences in chlorophyll-*a* concentration could be due in part to higher residence of waters at LC and nutrients subsidies from upstream upwelling centers, as discussed by Wieters et al. (2003) based on long-term daily chlorophyll measurements. Although the Maipo River output is medium to low for most of the year ($<150\,\mathrm{m}^3\,\mathrm{s}^{-1}$), its presence only 11 km south of LC affects this site during southerly wind periods (Kaplan et al., 2003 and author's pers. obs.). The river probably intensifies the differences in the structure of the water column between sites, producing a greater stability of nearshore water stratification at LC. Indeed, the low salinities observed at LC at 1 and 5 m depths during winter and spring months, when runoff produced by rains and melting snow is higher, probably favor greater stratification during this time of year.

While the characteristics of the coastal zones of El Quisco and Las Cruces follow the general patterns described for the coast of central Chile (e.g. the occurrence of upwelling, seasonality of the wind and temperature regimes), differences in coastline orientation and probably the presence of a river discharge, appear to significantly affect hydrographic conditions and upwelling dynamics over scales of a few kilometers. These differences might be responsible for the observed differences in phytoplankton biomass, larval abundance and invertebrate recruitment observed between these sites (Navarrete et al., 2002; Martínez and Navarrete, 2002; Poulin et al., 2002a; Wieters et al., 2003). Further studies should more precisely quantify riverine influence in coastal waters and determine to what extent they contribute to the among site differences described here. Moreover, the addition of data about local circulation by means of drifters and current meters are needed to evaluate our suggestions and improve understanding of the dynamics of this coastal system.

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