Oceanographic observations in Chilean coastal waters between Valdivia and Concepción

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[1] The physical oceanography of the biologically productive coastal waters of central Chile (36° to 40°S) is relatively unknown. In December 1998 we made a short exploratory cruise between Valdivia (40°S) and Concepción (37.8°S) taking temperature, salinity, oxygen, and current velocity profiles. Coincident sea surface temperature and color measurements were obtained by satellite. The results showed an area dominated by wind-induced coastal upwelling, river runoff, intrusion of offshore eddies, mixing, and heating. Upwelling centers were found over the shelf at three locations: inshore of Mocha Island, off Valdivia, and off Lavapie Point. At these centers, equatorial subsurface water (ESSW) intrudes into the coastal waters, sometimes affecting the surface waters. Since ESSW has characteristically low-oxygen and high-salinity values, it is easily detected. Off Valdivia, runoff imparts stratification, while farther north, solar heating and reduced mixing may facilitate stratification. In some areas, even strong winds would not destroy the stratification imparted by the advection of buoyancy that occurs during the upwelling process. Strong equatorward currents (>1 m s^{-1}) in the form of an upwelling jet were found off Lavapie Point. This is also the location of an intruding anticyclone. Elsewhere, currents were mainly northward but highly variable because of intrusions from offshore eddies. The sea surface temperature and ocean color images show a complex field of onshore and offshore intrusions combined with the effects of mixing on chlorophyll concentrations. The residence time of upwelled water on the shelf is estimated to be less than 1 week. *INDEX TERMS:* 4279 Oceanography: General: Upwelling and convergences; 4516 Oceanography: Physical: Eastern boundary currents; 4528 Oceanography: Physical: Fronts and jets; *KEYWORDS:* Upwelling; wind; water circulation; eddies; central Chile coast

1. Introduction

[2] The coastal waters of Chile are unique because a combination of meteorological and oceanographic processes and geography has created one of the world's most biologically productive ocean areas. The coast extends in a nearly north/south direction over 40° of latitude (not including the Antarctic) bordered by the Andes to the east and the Peru-Chile Trench to the west. Thus Chilean coastal waters lie between two of the highest relief features on Earth. Over this vast latitudinal range, climatic conditions vary from arid to subantarctic with upwelling winds off northern Chile, downwelling winds off southern Chile, and strong westerlies and considerable variability between. Rainfall toward the north is in some places nonexistent, while farther south it is quite high. The extremely high productivity of the Chilean coastal waters is attributable to upwelling of nutrient rich Peru-Chile Undercurrent water [*Strub et al.*, 1998] and processes that maintain biological populations in the shallow coastal waters.

[3] In December 1998 we made an exploratory cruise along the coast between Valdivia (40°S) and Concepción (37.8°S). This region is noted for its extremely high biological productivity that sometimes provides 4% of the world's fish catch. Our preliminary results, based on a unique but sparse data set, show the structure of currents, upwelling centers, and low-salinity water along the coast and the relationship to satellite-derived SST and chlorophyll.

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2. Regional Setting

[4] The region studied has a broad shelf that gradually narrows to the north at Lavapie Point (Figure 1). The shelf is about 50 km wide south of Tucapel Point with Mocha Island lying on the outer shelf marking the widest and shallowest part of the shelf. North of Tucapel Point the shelf narrows to about 10 km then starts to widen again at Lavapie Point. The broad and shallow Gulf of Arauco lies northeast of Lavapie Point. The Gulf of Arauco is a large embayment with Santa Maria Island lying offshore inline with the coast to the south. The Bio Bio River flows into the northern end of the Gulf, and the submarine canyon associated with the Bio Bio River crosses the shelf west of its present mouth.

[5] It is important to note two geographic features that affect the wind field. The first feature is change in coastline direction at Lavapie Point. South of Lavapie Point the coastline trends toward 355°T, while north of Lavapie Point

the shore trends toward 20°T. The Gulf of Arauco itself represents a large-scale equatorward facing embayment in the 20°T trending coast. Response to upwelling winds depends on the changing trends of the general bathymetry that follows the shoreline. The changing shoreline direction and diverging isobaths at Lavapie Point would induce upwelling in a northward flowing current [*Arthur*, 1965; *Blanton et al.*, 1981].

[6] The coastal wind field may also be affected by the presence of a coastal range of mountains extending from Concepción southward to the latitude of Mocha Island: the Cordillera de Nahuelbuta. North and south of the Cordillera de Nahuelbuta the coastal range is relatively low in relief. However, maximum heights in the range reach over 1000 m. These heights may cause intensified winds in the adjacent coastal waters.

[7] River flow into the region consists of the Bio Bio River (36.8°S) to the north and the Imperial River (38.8°S), Tolten River (39.2°S), Queule River (39.6°S), and the Calle Calle River (39.8°S) to the south. The previously mentioned cordillera blocks westward flowing rivers in the central part of the region. The total flow in the region from 37° to 40°S is about 3100 m^3 s^{-1} or 100 km^3 yr^{-1} [*Davila et al.*, 2000]. This amount of flow is not large but would be expected to produce areas of low salinity and coastal currents for a few tens of kilometers around the river mouths during the rainy winter season and early summer when the snow melts. South of 40°S the river flow increases significantly relative to flow to the north.

[8] The water mass and general circulation characteristics off central Chile were recently summarized [*Strub et al.*, 1998], so we will keep the review here to a minimum. Wind-driven coastal upwelling is the dominant process in the area during the summer. The cold, salty, nutrient-rich, oxygen-poor equatorial subsurface water (ESSW) flowing southward in the Peru-Chile Undercurrent upwells across the shelf and often intrudes to the coast [*Gunther*, 1936; *Silva and Neshyba*, 1979].

[9] Satellite-derived sea surface temperature imagery [*Cáceres*, 1992] shows filaments and offshore eddies in the region. Offshore anticyclonic eddies are most often found north of Lavapie Point. Offshore-flowing filaments are concentrated in the region just north of Mocha Island and off the Gulf of Arauco. Our data show that offshore and onshore flow affects the inshore waters that we sampled.

3. Methods

[10] In this section we review the methods used and sources of data. The observations were made from the R/V *Kay Kay* operated by the Universidad de Concepción. Between 8 and 11 December 1998 the ship was taken along a path up the coast in a pattern dictated by the schedule and weather (Figure 1). Courses were laid out to sample the coastal current, upwelling centers, and other features of the region. Along the route, continuous current profiles were made with acoustic Doppler current profiler (ADCP) and conductivity-temperature-depth (CTD) casts were made at the end points of each zigzag leg.

[11] Mean monthly upwelling winds were obtained from the NOAA Pacific Fisheries Environmental Laboratory in Monterey, California. We used data from the 36°S node. Coastal winds were obtained from a station at Lavapie Point maintained by the Department of Physics of the Atmosphere and Ocean at the University of Concepción. There are no other wind observations in the region's coastal waters for this time period. Sea surface temperature data were from advanced very high resolution radiometer for 9 December 1998. Images for 10 and 11 December were contaminated with clouds but suggested surface warming consistent with the decreasing upwelling wind speeds. A SeaWifs image from 9 December 1998 was processed using the most recent algorithms for coastal waters.

[12] An RD Instruments Workhorse (300 kHz) ADCP was used to make the current velocity profiles. The ADCP was mounted on a 1.2-m-long catamaran towed several meters to the side of the ship. Raw data were averaged over 90 s and 1-m bins. Bottom tracking was always on, and navigation was by GPS. The data were not detided as the onshore offshore cruise track created nodes similar to tidal nodes if any were present. This was the first time an ADCP was used in this region of Chile.

[13] Temperature, oxygen and salinity profiles were made with a SeaBird 19 CTD. All data where processed using SeaBird software.

4. Results

[14] In this section the results of the observations and other ancillary data are described. First the winds and remotely sensed data are presented, followed by the subsurface observations.

[15] The mean monthly upwelling index (Figure 2a) was very high in late 1998 relative to other years. The short-term record (Figure 2b) shows that the upwelling during the year started in July 1998 and had reached very high values by December. It is clear that our sampling took place during a period of steadily increasing upwelling on the monthly scale. Data from Lavapie Point (Figure 3) indicate a pulse of strong upwelling winds late on 9 December then two smaller events on 10–11 December. The consistent wind stresses over 0.1 N m^{-2} no doubt led to the upwelling we observed, and the decreasing stress on the 10 and 11 December would have caused a decrease in wind-induced upwelling. It should be noted that the cruise was toward the end of an El Niño period and at the beginning of a La Niña.

6. Conclusions

[45] Our limited observations between Valdivia and Concepción during upwelling wind conditions suggest a coastal area strongly influenced by both local upwelling centers and the presence of offshore eddies. That, combined with the influx of runoff into some parts of the region and variations in heating and mixing, creates variations in stratification.

[46] This unique combination of forces and geography result in a complex physical oceanographic situation that apparently results in extremely high biological productivity. Regions such as this one are excellent examples of how carbon, fixed in a coastal upwelling system, is exported offshore. The highly productive fisheries suggest that much of the primary production makes its way to higher trophic levels, but it eventually must be deposited in slope and trench sediments. Examination of those sediments might yield new insights into coastal upwelling and carbon sequestration processes.

[47] The similarities and differences between this region and the California upwelling regions are striking. It seems that comparative studies would be enlightening.