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Climate and upper ocean variability off Baja California, Mexico: 1997–2008

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ABSTRACT

Temperature and salinity anomalies derived from observations obtained in the period 1997–2008 are used to study the changes in physical properties off the Baja California west coast (24–31 N). Near surface anomalies were used to characterize four periods of distinctive variability: (1) a warm and saline phase of El Niño 1997–1998, (2) a saline period from 1999 to 2002, (3) fresh subarctic water in 2002–2006, and (4) a saline-fresh (El Niño-La Niña) phase in late 2006 to early 2008. Subsurface (200 m) salinity anomalies depicted a trend towards saltier conditions ($\Delta S \sim 0.1$) from 2001 onwards, and did not show the four periods discernible near surface. EOF analysis of sea surface wind stress and wind stress curl suggested that after the intense westerly winds in late 2001, freshening during late 2002–2006 was due to the weakening (strengthening) of the North Pacific Current (Aleutian Low), and to a decrease of wind stress curl produced upwelling. Data also showed differences in the timing and magnitude of anomalies observed between the north (poleward of 28 N) and the south (equatorward of 28 N). Subsurface geostrophic currents demonstrated the existence of two large scale cyclonic gyres, one associated with a subarctic domain in the northern region, and another having tropical characteristics. The likely role of subsurface cyclonic pairs in the definition of a provincial boundary, and the importance in influencing the CCS ecosystem, are discussed.

1. Introduction

The region off the western Baja California (BC) coast is the southern limit of the California Current System (CCS). It exhibits many of the typical features common to eastern boundary upwelling systems (EBUS), namely, an alongshore near surface equatorward flow carrying cold and fresh modified subarctic water, a subsurface poleward current flowing along the edge of the continental slope, and coastal upwelling due to northerly winds most of the year. The area is considered a transition region where the relatively cold and fresh equatorward flow of the California Current (CC), meets with saltier and warmer tropical and subtropical waters (Durazo and Baumgartner, 2002). The boundary between these water masses exhibits latitudinal shifting at seasonal and larger scales (Lynn and Simpson, 1987). At the seasonal scale, subarctic waters dominate during the peak of the upwelling season in spring and summer, while tropical and subtropical influences are commonly observed during summer and fall. At longer time scales, the shifting of boundaries may be more pronounced as a response to the scales of variability of large events.

Over the last decade, a series of changes in physical conditions has taken place within the limits of the CCS. These regional changes have been commonly associated with basin-wide events like the warming triggered by the El Niño (EN) in 1997–1998, followed by the cooling during the La Niña (LN) event that lasted until at least the year 2000 (Schwing et al., 2000; Durazo et al., 2001; Goericke et al., 2007). Noticeable changes also include the limited influence of a weak EN in 2002–2003 (Venrick et al., 2003; Durazo et al., 2005), and the freshening of the upper 100 m during 2002–2006 (Freeland et al., 2003; Bograd and Lynn, 2003; Goericke et al., 2005). Whereas the effects of these basin-wide forcings have been thoroughly discussed for the regions off California and Oregon (Durazo et al., 2001; Venrick et al., 2003; Freeland et al., 2003; Goericke et al., 2005, 2007), little research has been done regarding the physical settings at latitudes south of 31 N. Among other aspects of variability, the fresh subarctic waters that dominated the CCS in 2002 (Freeland et al., 2003; Bograd and Lynn, 2003) were waning off Oregon by 2004, but were still noticeable in southern California (Goericke et al., 2005). Although their presence has been documented for waters off BC (Durazo et al., 2005), the latitudinal influence they exhibit to the south is not yet known.

Being the southern limit of the CCS, much of the variability first observed in the ocean region off BC may be propagated poleward and observed at northern latitudes. The biological consequences of these signal propagations are numerous, from the shifting in zooplankton species according to their water masses affinity (Brodeur, 1986; Lavaniegos and Ohman, 2003; Keister et al., 2005), to the shifting and replacement of commercial fisheries such as the California sardine (*Sardinops sagax*) and many others

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(Logerwell and Smith, 2001). Thus, an analysis of the regional, southern CCS time–space variability, will help to recognize the differences and similarities between northern and southern domains of the CCS, and will aid better understanding of the patterns and processes that cause ecosystem changes in the northeastern Pacific (NEP).

This paper uses almost 11 years of recent temperature and salinity records (October 1997 to April 2008) to investigate the time–space variability of upper ocean anomalies for the oceanic region off the BC coast, between latitudes 24 N and 31 N, and to analyze the effects that local and basin-wide events have on the hydrographic properties at the southern extension of the CC.

2. Data and methods

Since October 1997, the Investigaciones MExicanas de la COrriente de CALifornia (IMECOCAL) program has conducted quarterly cruises (usually January, April, July and October) to monitor the oceanographic conditions off the BC coast in Mexico, between 24 N and 31 N. Sampling is carried out along 90 hydrographic stations which are a subgrid of the California Cooperative Fisheries Investigation (CalCOFI, www.calcofi.org) program station plan (Fig. 1). Distance between stations is 35 km (20 nm.) and distance between transects doubles that amount. At each station, temperature and salinity are measured using vertical casts down to 1000 m (depth permitting) using in most cases a Seabird 911plus CTD, armed with factory calibrated, dual temperature and conductivity sensors. To date, a total of 40 cruises have been conducted. Supplementary Table 1 of the Supplement e-material gives a list of cruises conducted.

Data collected by the IMECOCAL program are complemented with the CalCOFI historical data set which sampled the region off BC in the period 1950–1978, along the stations depicted in Fig. 1. Climatological seasonal means were obtained by fitting annual harmonics to all data. It was found that for upper layer waters (~100 m), curve fits for temperature at any certain depths usually explained between 40% and 80% of the total variance, while salinity curves only account for about 20%. The percent of explained variance obtained by fitting two harmonics was not statistically different from that obtained using only the annual signal. Therefore, results presented below correspond to anomalies computed by contrasting measured data to climatological means obtained using the annual curve only. Salinity showed small seasonality since most of the variability is due to non-seasonal changes. Due to the large amount of data (38 years), arithmetic means of seasonal cruises are robust and gave essentially the same results as the harmonic analysis. An example of results from the annual harmonic analysis fit to temperature and salinity time series is given in Supplementary Figs. 1 and 2 of electronic supplements, respectively, for one of the sampled sections.

Hydrographic casts are used to compute the dynamic height anomaly at 200 dbar over the 500 dbar reference level. The reference level is chosen to provide comparative results with the historical CalCOFI data set, and also to be able to use data from critical near coastal stations. For the period July 1999 to August 2008, monthly averaged sea surface wind stresses were obtained from the QuikSCAT satellite for the northeastern Pacific in a $0.5^\circ \times 0.5^\circ$ spatial resolution grid. A description of the processing and validation of these data, distributed by the *French ERS Processing and Archiving Facility*, Institut Francais de Recherche pour l'Exploitation de la Mer, Brest, France, can be found at http://www.ifremer.fr/cersat. At each grid cell, wind stress vector time series were rotated along the principal axis of variability. Wind stress anomalies were derived by subtracting satellite measured values from the monthly climatology computed for each grid cell.

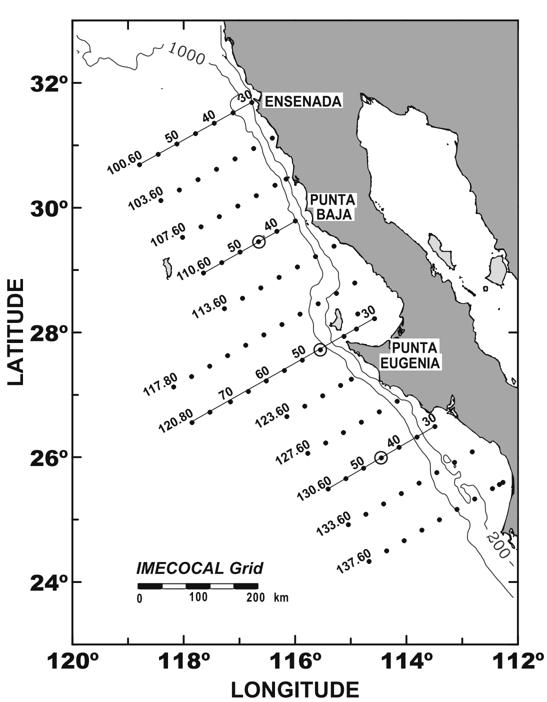

Fig. 1. IMECOCAL grid. Transects where detailed time–space variability is analyzed are shown with solid lines. Numbers refer to line and station number. Open circles in lines 110, 120 and 130 indicate stations where detailed time–depth variability is analyzed. The 200 and 1000 m depth contours are included.

3. Results

The time–space variability of anomalous conditions at 10 m depth on each of the cardinal sections (marked with solid lines in Fig. 1), are shown in Fig. 2 as Hovmöller diagrams of temperature (T) and salinity (S) departures from the climatological seasonal mean. The evolution of near surface property anomalies identifies the four major events of the last decade, namely: (1) the El Niño 1997–1998 as indicated by the warmer and saltier than usual conditions between 1997 and 1998, (2) La Niña between late 1998 until mid to late 2002, with slightly cool (~−1 °C) to normal temperatures and increased salinity (~0.1 to 0.2), (3) a freshening period between 2002 and 2006 and (4) EL Niño-La Niña conditions during late 2006–2007, and 2007–2008, respectively, depicted by a transition from moderately positive temperature and salinity anomalies during the winter 2006–2007 to slightly cool and fresh conditions in late 2007 and 2008. Temperature anomalies (Fig. 2a) reveal latitudinal differences in the spreading of EN in 1997–1998, with maximum anomalies at the center of the survey region. As indicated by the positive T and S anomalies, EN persisted longer in southern latitudes. Near surface warmest waters ($\Delta T \sim 5$ °C) were observed eastward of line 120, off Punta Eugenia, although peak T anomalies ($\Delta T \sim 8$ °C, not shown) were observed at 50 m depth at the same location (see Durazo and Baumgartner, 2002). During EN 1997–1998, positive T and S anomalies occupied most of the section in central lines, but were restricted to near shore areas in northern latitudes. This is consistent with narrow poleward flows reported for the region (Durazo and Baumgartner, 2002), and for southern and central California (Lynn and Bograd, 2002; Collins et al., 2002).

La Niña conditions persisted from 1998 until 2002, coincident with the strengthening of the atmospheric North Pacific High and the resulting more intense alongshore winds over the whole CCS. During this time period, two short-term cooling events (~−2 °C) were evident, one in summer 2002 and another in late 2005–early

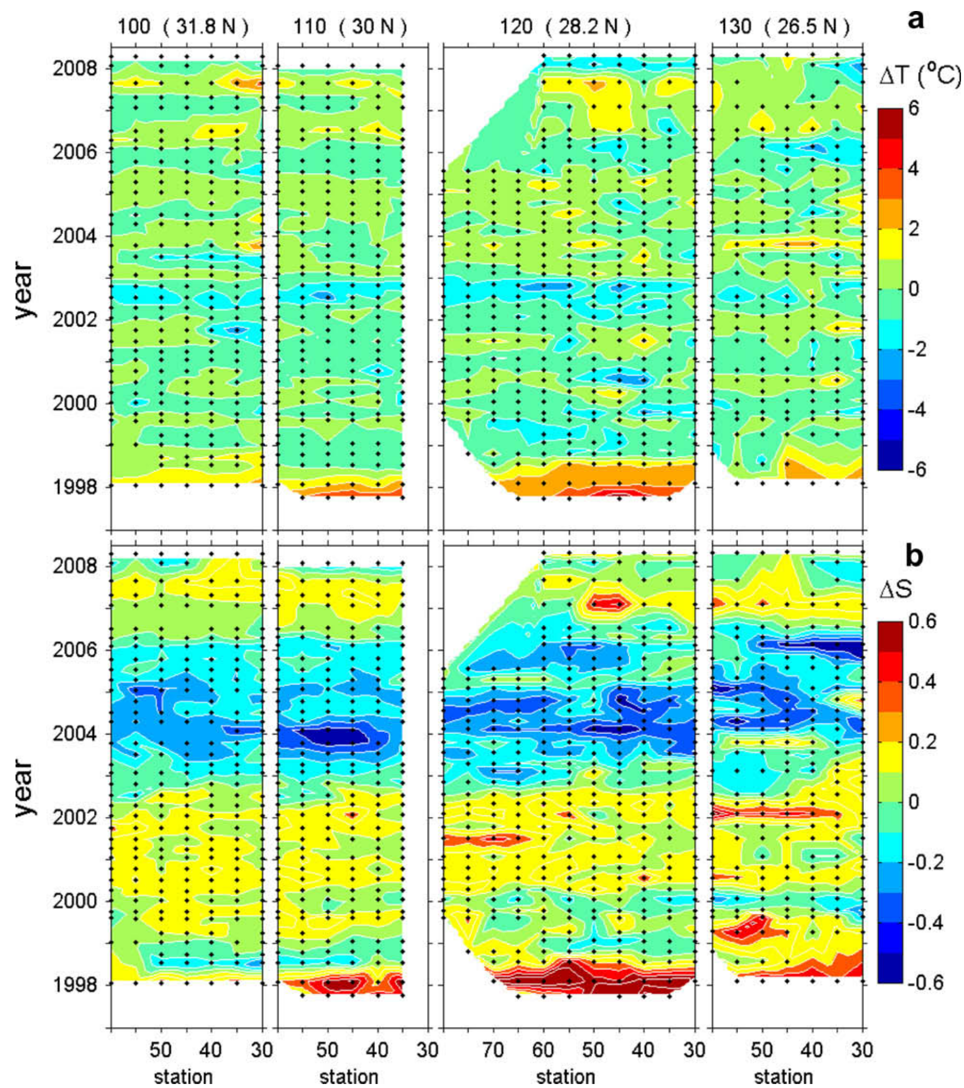

Fig. 2. Time–space variability of (a) temperature (upper row) and (b) salinity (lower row) anomalies at 10 m depth off Baja California, Mexico. Line numbers and latitudes are indicated at top.

2006. The cool event in 2002 was recorded in most of the survey area, while in 2005, cooling was mostly restricted to the central and southern survey transects. The first (second) of these events coincided with the arrival (retreat) of an excess of subarctic waters to the CCS, as indicated by the transition to fresher (saltier) waters in the salinity anomaly series (Fig. 2b). Prior to the first cooling event, LN conditions that prevailed since mid 1998 gave place to upper layer cooler waters over that period, conditions that lingered until winter 2002–2003 (Fig. 2a). The multivariate ENSO index (MEI, Wolter and Timlin, 1998) became positive by summer 2002 reflecting a moderate EN that peaked in December 2002–January 2003. However, the event did not evolve as a typical canonical EN characterized by the poleward advection of tropical and subtropical warmer waters. EN 2002–2003 rapidly decayed by spring 2003, and warm and salty anomalies did not fully develop over the NEP (Venrick et al., 2003). This could explain the lack of warmer waters within the sampling region during this weak EN. It also suggests that cooling during summer–fall 2002 may have been controlled by local wind processes rather than a response to basin-wide forcings. Prior to the second cooling event, during spring–summer 2005, a weak LN state led to sustained coastal upwelling in central California and Baja California (Supplementary Fig. 3), conditions that prevailed until winter 2005–2006 when the MEI returned to neutral values. It is likely that cooler waters were also a product of local coastal upwelling and mixing processes that modified upper layer temperatures.

Given its non-seasonal variability, salinity may function as a better indicator of the time–space transitions between interannual events. Besides displaying the 10 m time–space variability (Fig. 2b), the depth–time evolution of S anomalies at three selected coastal stations that underwent large fluctuations (110.45, 120.45, 130.45), are shown in Fig. 3. Furthermore, bar plots of 10 m and 200 m regional averages of salinity anomalies are presented in Fig. 4. Upper frames in this figure depict the evolution of salinity anomalies for all stations occupied over the four northernmost lines (100–113), while lower frames include the corresponding anomalies for stations south of Punta Eugenia (lines 123 to 133). In all Figs. 2–4, the four periods of variability mentioned above are clearly differentiated.

During EN 1997–1998, surface positive salinity anomalies were maximum ($\sim$0.5) near the peninsula central region, between lines 110 and 130, and reached depths of 125 m (Fig. 3). The large positive S anomalies created by the poleward intrusion of tropical and subtropical waters (Durazo and Baumgartner, 2002) remained for several months longer in the southernmost sections. Southern origin waters quickly retreated and were replaced by slightly up-

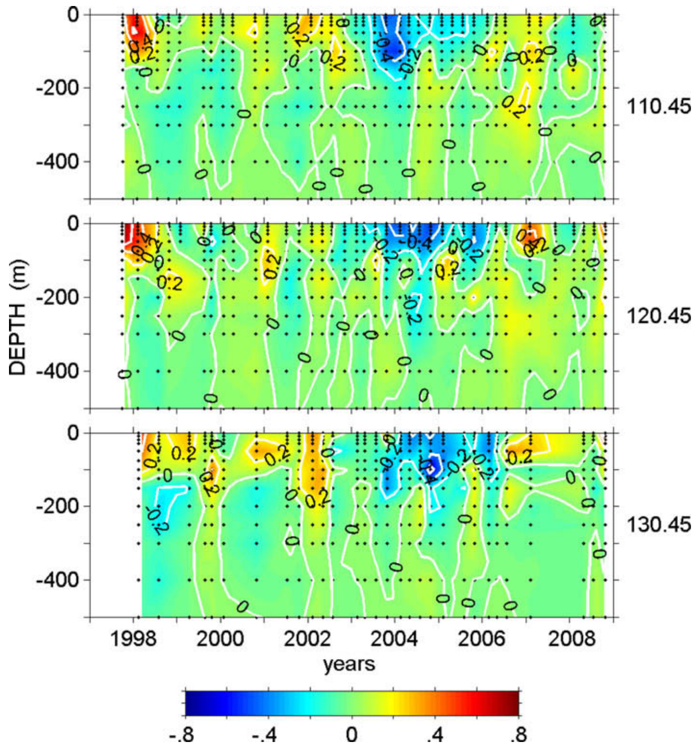

Fig. 3. Time–depth variability of salinity anomalies for three selected stations, 110.45, 120.45 and 130.45 indicated in Fig. 1 as open circles.

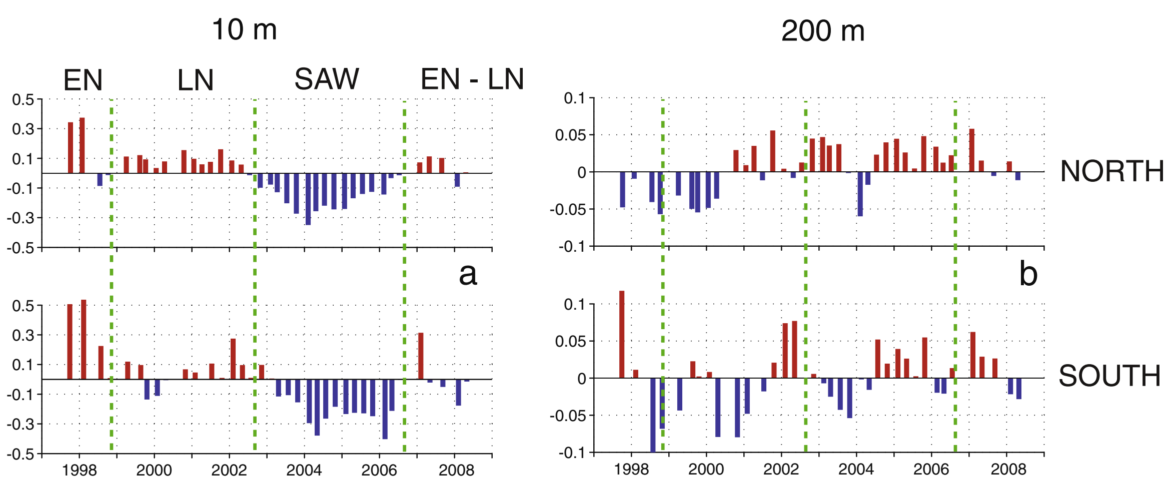

Fig. 4. Regional averages of salinity anomalies at depths of (a) 10 m, and (b) 200 m. Upper row corresponds to averages derived for the northern region, lines 100, 103, 107 and 110. Lower row are averages for the southern region, lines 123, 127, 130 and 133. Vertical dashed lines denote the approximate times of major changes in salinity anomalies. EN – El Niño, LN – La Niña, SAW – subarctic water, EN-LN – El Niño, La Niña.

welled salty waters brought up by the strong alongshore winds in 1998–1999 over most of the CCS (see Supplementary Fig. 3). Near surface S anomalies lingered positive until summer–fall 2002 in the northern region (Figs. 2b, 3, 4a; lines 100–120), and displayed a more heterogeneous pattern in the central and southern portions of the sampling grid, although with a dominance towards salty conditions. The different response of both north and south regions during this 1998–2002 LN period may be accounted for by the different intensities of alongshore winds. While upwelling positive anomalies persisted in central California during the LN period 1998–2002 (see Supplementary Fig. 3), they were only positive during the peak of LN in 1998–1999, and mostly negative afterwards and until mid 2005 in the region off northern BC (30 N). Further south, coastal upwelling was stronger than usual and in phase with forcings in central California. The increased salinity in the northern region may be a result of mixing of recently upwelled relatively salty waters with the CC flow, being advected towards northern BC. Reduced upwelling and reduced coastal Ekman transport in northern BC could led to near normal to lower salinities south of Punta Eugenia. Also, sustained upwelling winds might inhibit the onshore and poleward advection of tropical and subtropical waters in the southern region that takes place during summer–fall each year, hence favoring the freshening of southern waters during LN period (Figs. 2,3,4a).

The subarctic water enhancement was clearly distinguished in 2002 by the fresher than normal waters entering the survey region and influencing both coastal and oceanic waters. Negative salinity anomalies were restricted to the upper 100 m and filled the whole of the survey region by mid 2002 (Fig. 2b), except in 2004 when fresher waters were observed down to 500 m depth in central BC (Fig. 3). The arrival of the signal occurred in October 2002 in the northern sections while it was January–April 2003 when low salinity waters were evident in the southern region (line 130 in Fig. 2b). This time lag in approximately 2–3° latitude (2–4 cm/s) is consistent with a continuous southward movement of the cold and fresh water, and is analogous to the findings of Bograd and Lynn (2003) and Strub and James (2003) off California and Oregon, respectively. Departures from the mean were larger in the south. The peak of the freshening in the north occurred during early 2004 and slowly decreased to zero by early-mid 2006 (Fig. 4a). In central and south BC, two peaks of freshening were observed, one coincident with the northern freshening and another in late 2005 – early 2006 (Figs. 3 and 4a). In contrast, southern salinities quickly returned to normal in early-mid 2006. The larger negative anomalies recorded in the southern section could have been related to the dominant water masses of this region. South of 28 N, relatively salty ($S \sim 34.6$–34.8) tropical and subtropical waters mix with the fresh ($S \sim 33.7$) flow of the CC, mainly during summer and fall. Thus, either an excess of subarctic waters as the one observed, or reduced poleward transport of salty waters common over this region, or both, would have produced the larger anomalies observed.

In the winter 2006–2007, warmer and saltier EN-like conditions (Figs. 2,3,4a), dominated in the IMECOCAL region. Durazo and Baumgartner (2002) suggested that off BC, the poleward advection of tropical and subtropical waters might be the reason for anomalously high T and S during canonical EN events. The rapid change of fresher (SAW) to warm and salty conditions in both the northern and southern regions in 2006–2007 was apparently caused by anomalous advection of southern waters. Spatial distributions of near surface salinity and geostrophic flows in the winter 2006–2007 presented by Goericke et al. (2007), indicate poleward surface flows as a tongue of relatively salty water. The tongue only reached to latitudes near line 110 (29 N) and quickly vanished due to the unseasonably strong upwelling that began early in 2007, giving place to La Niña conditions that continued until spring 2008 (Figs. 2,3,4a).

It is interesting to note that regional differences observed in the upper layer are also noticeable at larger depths. The regional average salinity anomalies at 200 m, approximately the depth of the California Undercurrent (CU) poleward flow core, are shown in Fig. 4b. Periods of variability discussed in detail above are marked for reference. Striking regional differences can be distinguished as anomalies develop, which unlike near surface events, are out of phase in both regions. Except for the negative salinity anomalies in the southern region during 1998–1999, none of the four events discussed above is reflected in the time variability at depth. In the north, two stages are clear: a "fresh" period ($\Delta S \sim -0.1$) from 1998 to mid 2000, and a "salty" period ($\Delta S \sim 0.05$) onwards. In the southern region, S negative anomalies were larger ($\Delta S \sim -0.1$ to -0.2, see also Fig. 3) and the scale of time variability is shorter. Both northern and southern regions coincide in a trend towards saltier than usual conditions from mid 2004 to the present day, a trend that would imply more poleward transport of subsurface equatorial waters by the CU.

4. Discussion

4.1. Dynamics of climate variability

An increase in upper layer salinity in the CCS may be generated by a poleward advection of tropical and subtropical waters during El Niño warming events (Durazo and Baumgartner, 2002; Collins et al., 2002) or through an increased volume of subsurface water brought up from the bottom of the Ekman layer, either through westward advection during enhanced coastal upwelling, or through the upward entrainment of subsurface water due to thinning of the mixed layer by mesoscale cyclonic features. Freshening can be generated by river runoff near the coast and by the anomalous strong southward Ekman transport of subarctic water into the North Pacific Current (NPC). It has been suggested (c.f. Murphree et al., 2003) that the anomalously cool and fresh water that occupied most of the CCS domain in summer–fall 2002 was the result of larger scale atmosphere–ocean anomalies in the northeastern Pacific that triggered an increased advection of the North Pacific Current (NPC) which carried an excess of entrained subarctic water from the north, as well as an increase of coastal upwelling that favored the spreading of these fresh waters equatorward. Given the large interannual variability of atmospheric forcings over the NEP, it is interesting to investigate the likely effect of winds on the variability of upper layer properties in recent years.

To further analyze the role of sea surface winds on the anomalous advection of fresher waters, EOF analyzes on the wind stress (WS) and wind stress curl (WSC) anomalies time series were performed and are shown in Fig. 5. Only EOF modes that clearly show a temporal signal related to the presence of fresher waters, namely mode 2 of WS and mode 3 of WSC, are shown. For reference, mean wind stress vectors superimposed to contours of spatial amplitude for each mode are included. On each figure, besides indicating a measure of the importance of each corresponding mode (percent), a spatial representation of the local variance, that is, the fraction of the total variability explained within the mode, is included. This is of particular importance since it indicates the regions where a particular EOF mode is more relevant.

The second mode of variability of wind stress monthly anomalies accounts for 25% of the total variability. It depicts largest positive values associated with the region dominated by eastward flow of the NPC, west of 140 W and between latitudes 45 and 55 N (Fig. 5a). Local variance (Fig. 5b) shows that most of the local variability for this mode (~80%) occurs in the same region, around 48 °N, which suggests that this can be distinguished as the NPC mode. Smaller values (~20%) near the coasts of Oregon and northern California suggest that alongshore WS variability may also be important there. Mode 2 wind stress time series (Fig. 5e) shows a strengthening of NPC and alongshore winds during late 2001, consistent with findings of Murphree et al. (2003) and Strub and James (2003). It also intensified during late 2005 to mid 2006. In the period 2002–2005, the SAW event, negative values in the time series are consistent with weaker wind stress over the NPC, northern California and Baja California regions. Although this might seem contradictory and does not fully explain the freshening of the upper ocean, we must bear in mind other sources for fresher waters at the northernmost limit of the CCS. The period of freshening and NPC weakening coincides with unusually large values of the Aleutian low index (Beamish et al., 1997) which resulted in large cyclonic wind anomalies over most of the northeastern Pacific (Venrick et al., 2003). Accordingly, once the NPC weakened and coastal upwelling decreased, the continuing source of fresh waters from late 2002 until early 2006 was due to the strengthening of the Aleutian Low.

Besides upwelling induced by the alongshore wind stress, curl-driven upwelling due to WSC near the coast is an important mechanism for supplying salty (nutrient rich) waters to the surface. Its time variability has been linked to the variability of pelagic fishes at interannual and decadal scales (Rykaczewski and Checkley, 2008). Increased positive WSC would imply an increase in clockwise atmospheric circulation, strengthening of the NPC and a reduced upward entrainment due to the deepening of the thermocline. For the northeastern Pacific, WSC was computed from Quikscat winds, and mode 3 of EOFs obtained from the monthly

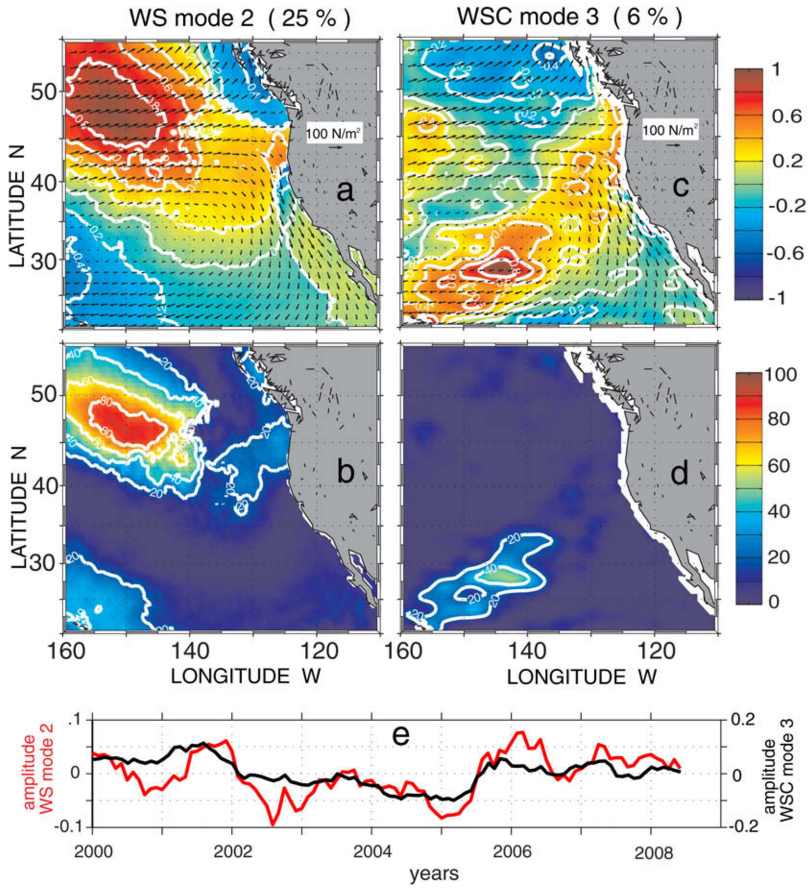

Fig. 5. Spatial patterns and temporal variability of selected EOF analysis results of wind stress and wind stress curl for the northeastern Pacific. (a) wind stress mode 2, (b) local variance of wind stress mode 2, (c) wind stress curl mode 3, (d) wind stress curl local variance, (e) temporal evolution of wind stress mode 2 (red) and wind stress curl mode 3 (black). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

anomalies is shown in Fig. 5. The mode accounts for ~6% of the total variability. The largest values are associated with regions dominated by the NPC and the center of the atmospheric NEP gyre (30 N, 145 W), while negative values occur in the coastal region north of 50 N (Fig. 5c). Local variance for this WSC mode (Fig. 5d) is mostly confined to the center of the large scale eddy. During the period of upper layer freshening (Fig. 5e), the negative phase of the mode is associated with changes in salinity. This would imply that a decrease of Ekman divergence due to WSC occurred during the freshening period in the CCS. This results suggest that the 2002–2006 upper layer freshening was also due to a decrease in WSC produced upwelling.

4.2. Regional differences

Time series of near surface salinity anomalies (Figs. 2b, 3, 4 a) provided evidence that both the latitudinal extension and the duration of interannual events over the last decade were different between north and central-south BC. Regional differences are further substantiated by the contrasting salinity variability at depth, where the northern region exhibited larger temporal scales compared to the south. Spatial and temporal north–south differences in the anomalies presented suggest that the IMECOCAL region is separated into two distinctive dynamic regions with dissimilar responses to physical forcings. The all-time mean of surface dynamic heights obtained using all available data (not shown) resembles the mean equatorward flow of the CC illustrated by Lynn and Simpson (1987), and do not fully reveal two dynamic regimes that may help to explain the noted differences. However, the all-time

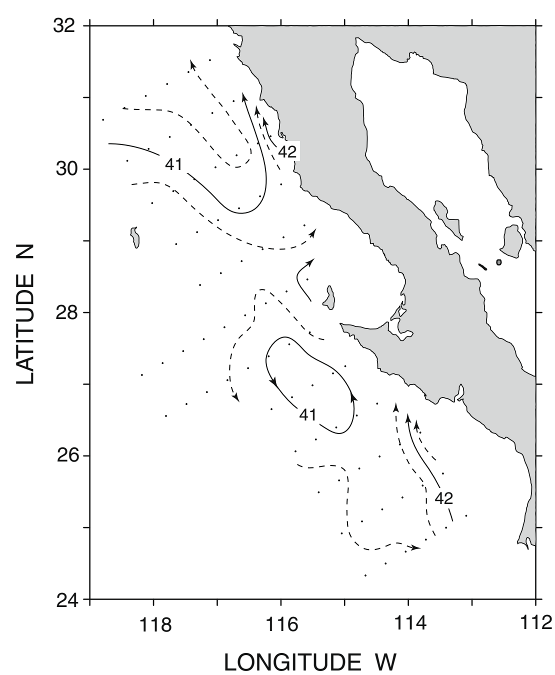

Fig. 6. Dynamic height at 200 dbar relative to 500 dbar (dyn cm, 1 dyn cm equal to 0.01 J/kg). Contour interval is 0.5 dyn cm. Current direction is indicated by arrows. Means at each station were computed using all available data from CalCOFI (1950–1978) and IMECOCAL (1997–2008).

mean of dynamic height mapped at 200 dbar (Fig. 6), the approximate depth of the CU, allows us to clearly identify two distinctive dynamic regimes delineated by two large scale subsurface cyclonic eddies off BC. As the all-time mean geostrophic flows show, cyclonic eddies clearly become detached near the vicinity of Punta Eugenia (28 N), the major prominence along the Pacific coast. The 200 m northern cyclonic circulation is a deeper expression of the Southern California Bight Eddy. The southern gyre represents the northernmost expression of the circulation of subsurface equatorial waters. Both the position and size of these cyclonic features exhibit seasonal variability (not shown), being absent or diffuse during spring and better defined during summer and fall. The eastern limbs of these large scale features confirm the existence of the poleward flow of the CU at this depth. Typical of an EBUS, the poleward nearshore CU flow occurs above the shelf break. In the vicinity of Punta Eugenia, the CU is diverted towards the west. A portion of the westward flow returns south, but a portion becomes entrained into the northern cyclonic circulation to continue its path along the shelf break into northern BC and California. Since basin-wide interannual events may influence the size and strength of these circulation features north and south of Punta Eugenia, some of the variability observed at this depth may reveal its signature at the surface. It has been suggested, for instance, that warm events like El Niño 1997–1998 could have increased the volume of waters carried by the CU (Durazo and Baumgartner, 2002) which could have largely modified the termohaline characteristics of surface waters in higher latitudes. Results presented here bring new questions about the role of interannual variability on the strengthening and weakening, growth and shrinking of this cyclonic pair, and their role in water mass exchanges between the subarctic and tropical domains.

Results from biological indicators suggest that 28 N, the latitude of Punta Eugenia, may act as a provincial boundary for several fish species such as northern anchovy, Pacific sardine and Pacific hake, organisms that display a population break between both regions (Hewitt, 1981). Such differentiation has also been reported in faunal associations with oceanographic variability (Lavaniegos et al., 2002; Lavaniegos, this issue). Latitudinal differences in the abundances, life cycles and taxonomic composition of plankton communities have also been documented between these two regions (Lavaniegos and Ohman, 2003; Goericke et al., 2007). It is thus likely that a shallower expression of the cyclonic pair subsurface dynamics determines the existence of such a provincial boundary by providing a physical mechanism through which larval recruitment to the adult populations is favored. At longer time scales, subsurface water mass exchanges between the two regions play a key role in the nutrient enrichment of the coastal ocean. Subsurface waters reach the surface during upwelling events and become available at the photic layer, and may influence changes in ecosystem structure and biotas within the CCS (Lavaniegos and Ohman, 2003). Recent results (Feely et al., 2008) have shown the North American continental shelf is affected by ocean acidification. Thus, the exchange between the two regions is of particular importance since the CU may act as a conveyor belt that carries low pH waters along the shelf break, and eventually to the near surface layers through coastal upwelling. Thus, a better understanding of deep circulation variability will help us to obtain a better understanding of the physical–biological interactions within the IMECOCAL region, and will also help to better understand why ecosystem processes and responses are different within the domain of the CCS, from Oregon to the southern tip of the BC peninsula.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.pocean.2009.07.043.

References

Beamish, R.J., Neville, C.E., Cass, A.J., 1997. Production of Fraser River sockeye salmon (*Oncorhynchus nerka*) in relation to decadal-scale changes in the climate and the ocean. Canadian Journal of Fisheries and Aquatic Sciences 54, 543–554.

Bograd, S.J., Lynn, R.J., 2003. Anomalous subarctic influence in the southern California Current during 2002. Geophysical Research Letters 30, 8020. doi:10.1029/2003GL017446.

Brodeur, R.D., 1986. Northward displacement of the euphausiid Nyctiphanes simplex Hansen to Oregon and Washington waters following the El Niño event of 1982–1983. Journal of Crustacean Biology 6, 686–692.

Collins, C.A., Castro, C.G., Asanuma, H., Rago, T.A., Han, S.-K., Durazo, R., Chavez, F.P., 2002. Changes in the hydrography of Central California waters associated with the 1997–1998 El Niño. Progress in Oceanography 54, 129–147.

Durazo, R., Baumgartner, T., 2002. Evolution of oceanographic conditions off Baja California: 1997–1999. Progress in Oceanography 54, 7–31.

Durazo, R., Baumgartner, T.R., Bograd, S.J., Collins, C.A., de la Campa, S., García, J., Gaxiola-Castro, G., Huyer, A., Hyrenbach, D., Loya, D., Lynn, R.J., Schwing, F.B., Smith, R.L., Sydeman, W.J., Wheeler, P., 2001. The state of the California Current 2000–2001: a third straight La Niña year. CalCOFI Reports 42, 29–60.

Durazo, R., Gaxiola-Castro, G., Lavaniegos, B., Castro-Valdez, R., Gomez-Valdes, J. Mascarenhas Jr., A.S. 2005. Oceanographic Conditions west of Baja California, 2002–2003: A weak El Niño and Subartic Water Enhancement., vol. 31, pp. 537–552.

Feely, R.A., Sabine, C.L., Hernandez-Ayon, J.M., Ianson, D., Hales, B., 2008. Evidence for upwelling of corrosive "acidified" water onto the continental shelf. Science 320, 1490. doi:10.1126/science.1155676.

Freeland, H.J., Gatien, G., Huyer, A., Smith, R.L., 2003. Cold halocline in the northern California Current: an invasion of subarctic water. Geophysical Research Letters 30, 1141. doi:10.1029/2002GL016663.

Goericke, R., Venrick, E., Mantyla, A., Bograd, S.J., Schwing, F.B., Huyer, A., Smith, R.L., Wheeler, P.A., Hoof, R., Peterson, W.T., Chavez, F., Collins, C., Marinovic, B., Lo, N., Gaxiola-Castro, G., Durazo, R., Hyrenbach, K., Sydeman, W.J., 2005. The state of the California Current, 2004–2005: still cool? CalCOFI Reports 46, 32–71.

Goericke, R., Venrick, E., Koslow, T., Sydeman, W.J., Schwing, F.B., Bograd, S.J., Peterson, W.T., Emmett, R., Lara Lara, J.R., Gaxiola Castro, G., Gómez Valdez, J., Hyrenbach, K.D., Bradley, R.W., Weise, M.J., Harvey, J.T., Collins, C., Lo, N.C.H., 2007. The state of the California Current, 2006–2007: regional and local processes dominate. CalCOFI Reports 48, 33–66.

Hewitt, R., 1981. Eddies and speciation in the California Current. CalCOFI Reports 22, 96–98.

Keister, J.E., Johnson, T.B., Morgan, C.A., Peterson, W.T., 2005. Biological indicators of the timing and direction of warm-water advection during the 1997/1998 El Niño off the central Oregon coast, USA. Marine Ecology Progress Series 295, 43–48.

Lavaniegos, B.E., this issue. Influence of a multiyear event of low salinity on the zooplankton from Mexican eco-regions of the California Current. Progress in Oceanography.

Lavaniegos, B.E., Ohman, M.D., 2003. Long-term changes in pelagic tunicates of the California Current. Deep Sea Research 50, 2473–2498.

Lavaniegos, B.E., Jimenez-Perez, L.C., Gaxiola-Castro, G., 2002. Plankton response to El Niño 1997–1998 and La Niña 1999 in the southern region of the California Current. Progress in Oceanography 54, 33–58.

Logerwell, E.A., Smith, P.E., 2001. Mesoscale eddies and survival of late stage Pacific sardine (*Sardinops sagax*) larvae. Fisheries Oceanography 10, 13–25.

Lynn, R.J., Bograd, S.J., 2002. Dynamic evolution of the 1997–1998 El Niño-La Niña cycle in the southern California Current System. Progress in Oceanography 54, 59–75.

Lynn, R.J., Simpson, J.J., 1987. The California Current system: the seasonal variability of its physical characteristics. Journal of Geophysical Research 92, 12947–12966.

Murphree, T., Bograd, S.J., Schwing, F.B., Ford, B., 2003. Large scale atmosphere–ocean anomalies in the northeast Pacific during 2002. Geophysical Research Letters 30, 8026. doi:10.1029/2003GL017303.

Rykaczewski, R.R., Checkley, D.M., 2008. Influence of ocean winds on the pelagic ecosystem in upwelling regions. PNAS 1, 7–9. doi: 10.1073pnas.0711777105.

Schwing, F.B., Moore, C.S., Kalston, S., Sakuma, K.M., 2000. Record coastal upwelling in the California Current in 1999. CalCOFI Reports 31, 148–160.

Strub, P.T., James, C., 2003. Altimeter estimates of anomalous transports into the northern California Current during 2000–2002. Geophysical Research Letters 30, 8025. doi:10.1029/2003GL017513.

Venrick, E., Bograd, S., Checkley, D., Cummings, S., Durazo, R., Gaxiola-Castro, G., Hunter, J., Huyer, A., Hyrenbach, K.D., Lavaniegos, B.E., Mantyla, A., Schwing, F.B., Smith, R.L., Sydeman, W.J., Wheeler, P.A., 2003. The State of the California Current, 2002–2003: Tropical and Subarctic influences vie for dominance. CalCOFI Reports 44, 28–60.

Wolter, K., Timlin, M.S., 1998. Measuring the strength of ENSO events—how does 1997/98 rank? Weather 53, 315–324.