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Seasonal renewal of the California Current: The spring transition off California

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[1] A pair of high-resolution oceanographic surveys in March and April 1995 revealed a large and rapid transition from late winter to spring conditions in the coastal zone off central and southern California. These data are unique in capturing the detailed three-dimensional physical structure of and biological response to the spring transition in the southern California Current System (CCS). Changes associated with the transition included a strong tilting of isopycnals, which lifted by up to 60 m near the coast and dropped 20–40 m offshore, a subsequent increase in cross-shore density gradients, the development of a strong nearshore equatorward jet, and an increase in net equatorward transport from the shelf break out to 300 km offshore. The most dramatic physical changes were confined to the shoreward 150 km and extended at least to the depth of the core of the California Undercurrent (~300 m). In response to these physical changes, there was an apparent strong increase in primary productivity, as indicated by changes in nearshore vertically integrated fluorescence and beam attenuation coefficient. Atmospheric and oceanic conditions in the CCS were near seasonal norms in the winter and spring of 1995, implying that a transition of the magnitude and rapidity observed here may be an annual event. Furthermore, the development of the coastal upwelling jet was independent of the winter manifestation of the main core of the California Current, which was maintained well off shore. This suggests that the California Current is regenerated seasonally through the development and offshore evolution of the coastal upwelling jet. It is not known whether the new jet joins and strengthens or replaces the offshore core of the previous winter. *INDEX TERMS:* 4516 Oceanography: Physical: Eastern boundary currents; 4227 Oceanography: General: Diurnal, seasonal, and annual cycles; 4219 Oceanography: General: Continental shelf processes; 4572 Oceanography: Physical: Upper ocean processes; *KEYWORDS:* California Current, spring transition, upwelling, eastern boundary current

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1. Introduction

[2] The transition from winter to spring conditions (the "spring transition") in the coastal ocean off the U.S. west coast is remarkable in its magnitude and rapidity, with dramatic changes in stratification and circulation often occurring within a week. Coastal sea level decreases significantly, coastal currents reverse from poleward to equatorward, vertical current shear changes from weak to strong, and cross-shelf density gradients increase. Previous studies have reported on the nature of the spring transition off Oregon [*Huyer et al.*, 1975, 1979; *Bilbao*, 1999; *Barth et al.*, 2000] and northern California [*Lentz*, 1987], and on the large-scale structure and forcing mechanisms of the spring transition off western North America [*Strub et al.*, 1987a, 1987b; *Strub and James*, 1988]. Few studies, however, have reported on the three-dimensional structure and biological response of the spring transition within the southern California Current System.

[3] Large-scale oceanographic surveys that repeated the same dense grid of stations off central and southern California in March and April 1995 captured the detailed physical and biological response of the coastal ocean to that year's spring transition. These data provide a unique view of the amplitude and timing of the spring transition off California, as well as the alongshore, cross-shore, and vertical extent of the changes. The objectives of this study are to describe the three-dimensional physical structure of the spring transition off California in 1995 as well as the lower trophic biological response to the transition. We also use these data to clarify aspects of the seasonal evolution of the California Current.

2. Data

[4] Two surveys were conducted by the Southwest Fisheries Science Center (SWFSC) on NOAA RV MacArthur in

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late winter and early spring 1995: an 18-day CTD survey from 9 to 27 March and a 16-day CTD survey from 19 April to 5 May. These bracketed the regular seasonal surveys of the California Cooperative Oceanic Fisheries Investigations (CalCOFI), which occupied nominal stations off southern California in January and April–May [*Scripps Institution of Oceanography*, 1995]. The SWFSC surveys are identified by a year/month code: 9503 and 9504. The station grid, common to both surveys, extends from Pt. Reyes (north of San Francisco) to the middle of the Southern California Bight, to 300 km offshore, and shoreward to the 500 m isobath (Figure 1). Station spacing is 37 km between stations and between lines in groups of three, which is approximately twice the station density of the nominal CalCOFI grid. Both surveys progressed from south to north. Of the 128 stations occupied during 9503, 117 were reoccupied during 9504 (126 total stations) after a nominal 40-day interval.

[5] Stations consisted of casts to 1000 dbar, bottom depth permitting, using a SeaBird Electronics, Inc. 9/11 CTDO2. CTD data were processed using SeaBird software. Each cast included a Sea Tech 25 cm transmissometer and a Chelsea Instruments Ltd. Aquatracka III Fluorometer. Water samples were collected every fourth cast with a General Oceanics, Inc. 12-bottle rosette. Oxygen titrations and salinity determinations were conducted on all samples and used to correct any offset of the sensors. Oxygen was measured by a Beckman-style probe and a YSI probe in series, with the Beckman-style probe providing the better results. Specially designed software was used to greatly reduce the characteristic hysterisis in oxygen between up and down casts prior to applying bottle offset corrections. The transmissometer was calibrated using procedures recommended by the manufacturer. A faulty connector on the unit caused sporadic loss of signal at pressures greater than 80 dbar during 9503; transmissometer data below this level were eliminated. The fluorometer manufacturer's original (1991) calibration factors for chlorophyll were used in processing the data (no in situ chlorophyll measurements were made during the surveys). The fluorometer data are presented as "uncalibrated" because of the lack of a more timely calibration. The results can be used to track survey-to-survey differences in relative chlorophyll. Dynamic height was interpolated or extrapolated where cast depth failed to reach 1000 dbar [*Reid and Mantyla*, 1976].

3. Results

3.1. Anatomy of the 1995 Spring Transition

3.1.1. Surface Patterns

[6] The March and April 1995 cruises captured a dramatic transition in surface circulation and water properties off the California coast (Figure 2). There was a 1.5–4°C decrease in temperatures near the coast (Figures 2c and 2d). The March distribution resembles the long-term mean winter pattern of isotherms perpendicular to the coast, while the April distribution resembles the mean summer pattern of isotherms predominantly parallel to the coast [*Robinson*, 1976]. The seasonal establishment of upwelling favorable winds between March and April led to a pattern that is typical of a spring coastal upwelling phase.

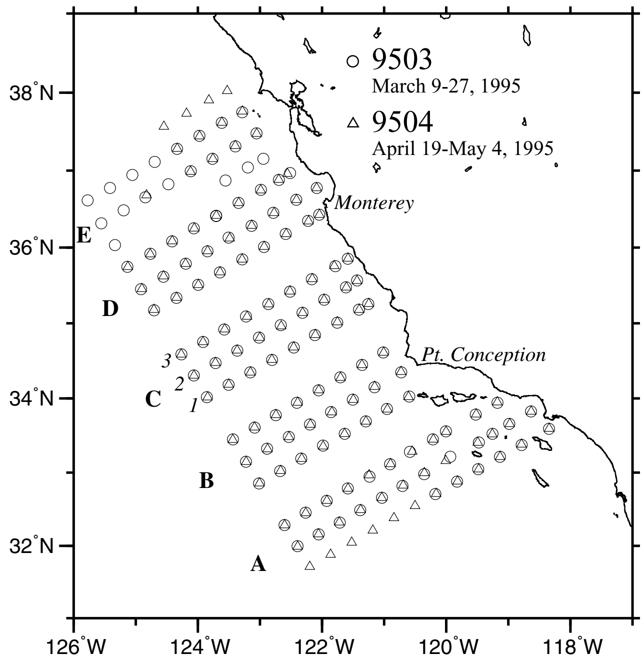

Figure 1. Station positions for CTD surveys in 9–27 March (9503, open circles) and 19 April to 4 May 1995 (9504, open triangles). Groups of sections are labeled.

[7] The patterns of dynamic height (Figures 2a and 2b) show a change from a weak, eddying flow in the coastal zone during March to the development of a strong coastal upwelling jet extending the length of the coastline by April. We identify the flow in the northwest corner of the grid in March to be the eastern edge of the California Current, which flows to the west of the grid, loops eastward at the latitude of Pt. Conception, then continues south. Typical speeds are 15 cm s^{-1}, with a maximum of 40 cm s^{-1} at the southwest corner of the grid. By April, the meandering equatorward flow of the main California Current remained largely unchanged on the southwest corner of the grid, while the eddy field nearer to shore was overridden by the newly developed coastal current, which had surface speeds of 20–30 cm s^{-1} near the coast. This compares with speeds of ~50 cm s^{-1} in the core of the inshore coastal upwelling jet observed by shipborne Acoustic Doppler Current Profiler in the Coastal Ocean Dynamics Experiment (CODE) surveys of 1982, between Point Arenas and Point Reyes [*Huyer and Kosro*, 1987]. The cyclonic feature observed at the southern end of the grid in March appears to have translated westward by April, pushing the California Current core further offshore. Coolest temperatures and highest salinities in April were found just downstream of Big Sur (36.4°N) and Point Conception (34.5°N), which are known to be regions of strong topographically induced coastal upwelling [*Brink et al.*, 1984].

[8] An identifying characteristic of the California Current is its southward penetrating tongue of low-salinity water (Figures 2e and 2f). Typically, the minimum salinity is found west of the velocity maximum [*Lynn and Simpson*, 1987; *Huyer et al.*, 1991]. In March, there is a weak but identifiable tongue of relatively low-salinity water in an

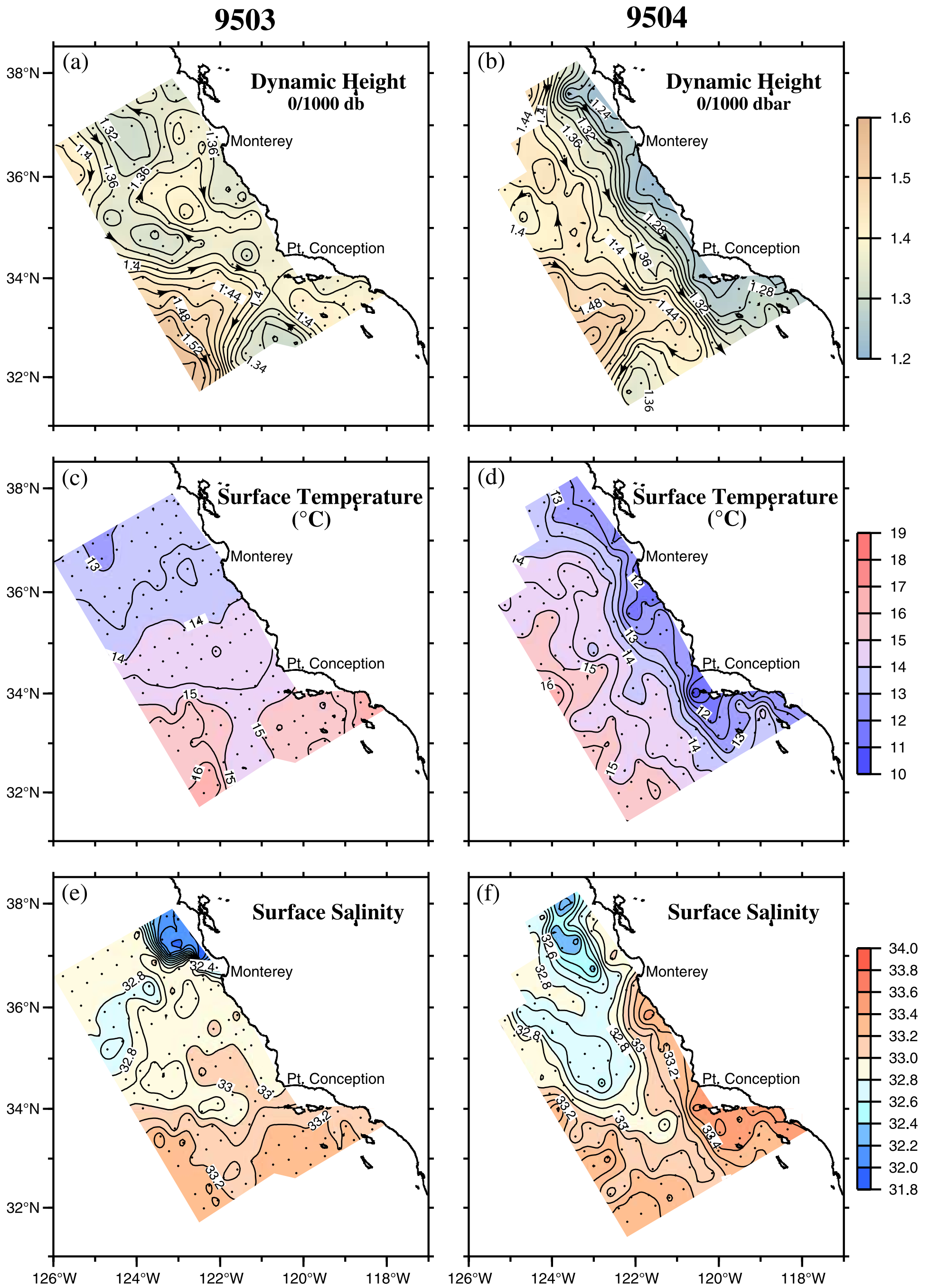

Figure 2. (a) and (b) Dynamic height (0/1000 dbar) (m^2s^{-2}), (c) and (d) surface temperature (°C), and (e) and (f) surface salinity for surveys (left) 9503 and (right) 9504.

arch that mimics the California Current core identified from gradients in dynamic height (southwest edge of the grid; Figure 2e). The low-salinity tongue was still present in April, although the dominant salinity pattern was caused by the transport of even lower salinity waters from the north coupled with upwelling of higher salinity along the coast (Figure 2f). The pool of very low-salinity water seen in March at the northeast corner of the grid, and diluted downstream in April, is most likely winter runoff from San Francisco Bay, a feature that was also observed in the CODE surveys [*Send et al.*, 1987].

[9] Thus the offshore jet was still present in April with only modest changes, while the coastal upwelling jet appears to exist independently of the offshore core. These observations suggest that the California Current is regenerated each spring through the development of the coastal upwelling jet, rather than the main California Current core moving onshore from its winter position, as has often been supposed [e.g., *Bray et al.*, 1999].

3.1.2. Vertical Structure

[10] The physical changes associated with the spring transition were deeper than the surface layer. Velocity and

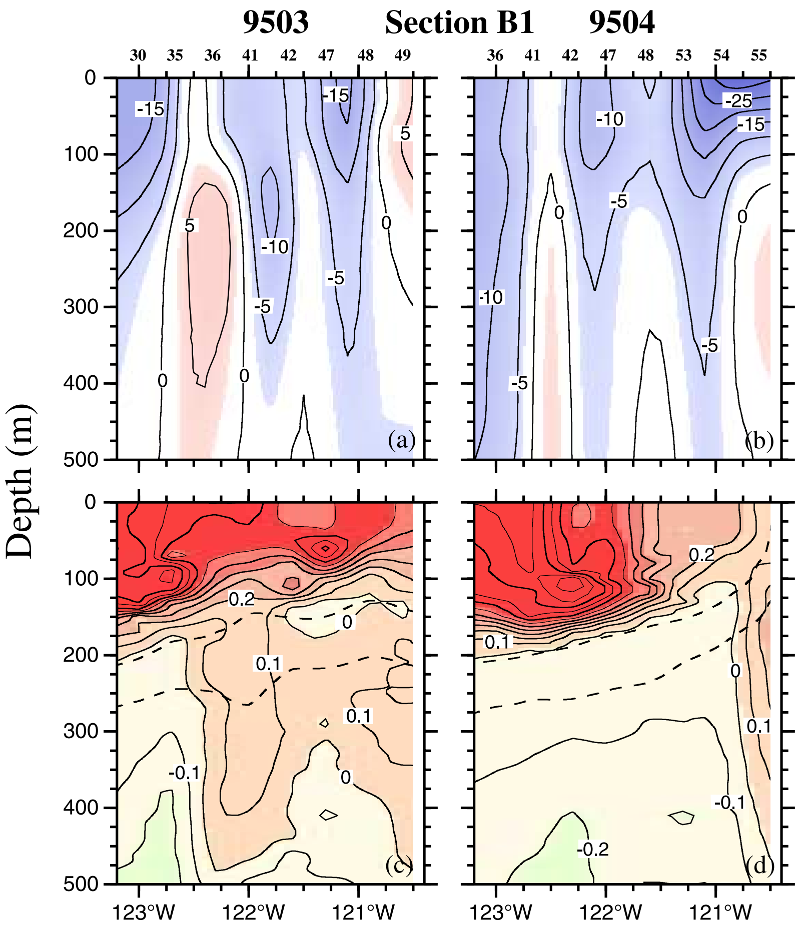

Figure 3. (a) and (b) Cross section (B1) of geostrophic velocity (cm s^{-1}; relative to 1000 dbars) and (c) and (d) spiciness (kg m^{-3}) for surveys (left) 9503 and (right) 9504. Position of section B1 is identified in Figure 1. The σ_θ = 26.0 and σ_θ = 26.4 kg m^{-3} isopycnal surfaces are shown with dashed lines.

property sections through line B1 (see Figure 1 for position of section), which cuts through the shoreward-looping California Current offshore as well as some of the strongest surface water property changes inshore, present a good example of the vertical structure of the spring transition (Figure 3). In March, a subsurface anticyclonic feature was evident between stations 35–42, while a weak countercurrent was seen at the inshore stations. The corresponding spiciness section shows the subsurface eddy to be composed of relatively warm and salty water, indicating its source as the California Undercurrent [*Lynn and Simpson*, 1990; *Simpson and Lynn*, 1990]. (For a description of spiciness, please refer to *Flament* [2002].)

[11] By April, the coastal surface flow had reversed, with a shallow (upper 150 m) 30 cm s^{-1} equatorward jet on the inner 60 km of the grid. The California Undercurrent had also become organized on this section, as evidenced by the poleward nearshore flow at depth and the corresponding increase in spiciness, although it had weakened on some other sections. The anticyclonic eddy observed in March had been destroyed or had moved off of this section. Upper level spiciness had been reduced on the inshore half of the grid, primarily as a result of the cooler waters advected into the region within the coastal jet.

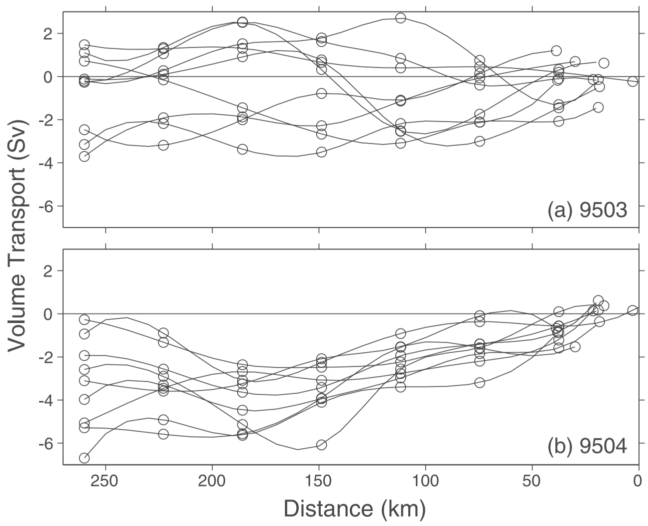

Figure 4. Accumulated volume transport (10^6 m^3s^{-1}; relative to 1000 dbars) starting at the nearshore station pairs for the nine central lines of surveys (a) 9503 and (b) 9504.

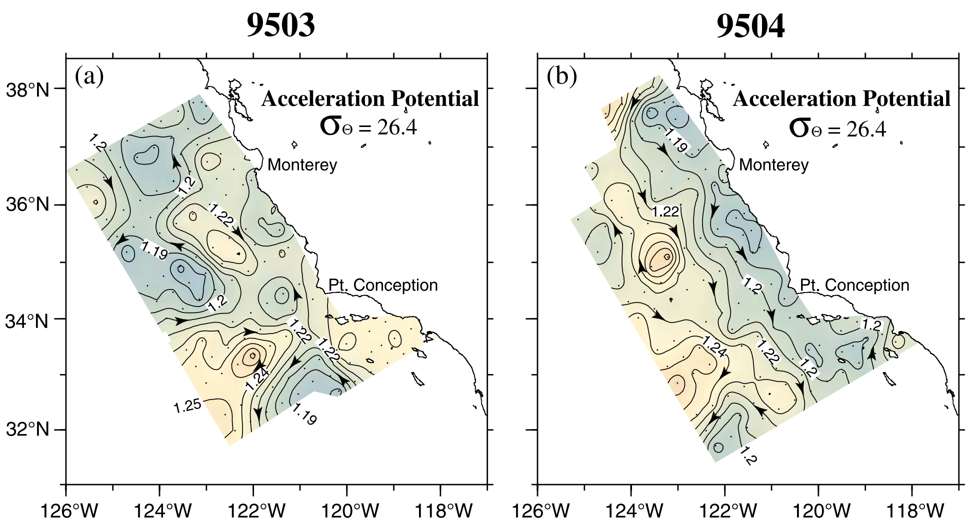

Figure 5. Acceleration potential (m^2s^{-2}) on isopycnal surface σ_θ = 26.4 kg m^{-3} for surveys (a) 9503 and (b) 9504.

[12] Accumulated volume transports for the 9 central lines of the grid (sections B, C, and D; see Figure 1) demonstrate the modified flow structure over the transition (Figure 4). While there was variation among the lines in the March survey, there was very little net equatorward transport (~1 Sv). The strong eddy field was responsible for this variable but weak net flow. In contrast, the April survey revealed a net equatorward transport of 2–6 Sv, most of which was confined to the shoreward 150 km. These April transport estimates are similar to (slightly smaller) than those measured in a series of five mesoscale surveys spanning the coastal jet at 38°N in the summer of 1988 [*Huyer et al.*, 1991].

[13] Acceleration potential [*Montgomery*, 1937; *Reid*, 1965] on the σ_θ = 26.4 isopycnal surface reveals the magnitude of the transition at the depth of the spiciness maximum associated with the California Undercurrent (Figure 5). Large changes in flow structure are still seen at this level, which lies at ~200 m depth near the coast and at ~300 m depth offshore (Figure 3). The coastal jet is still clearly evident and continuous along the grid in April. Changes in the California Undercurrent varied alongshore, with an apparent strengthening or reorganization occurring between Monterey and Point Conception (sections B and C) and within the Southern California Bight (section A). Since large eddies tend to persist over months, we can conjecture that some of the features seen in March were still present in April. The large cyclonic eddy at the southern end of the grid in March appears to have moved offshore by April, while the eddy dipole in midpattern appears to have rotated 60° and also shifted westward. The anticyclonic feature of this dipole pair spun up over the interval, perhaps through energy fed on its eastern flank by the coastal jet.

[14] We also look at water property changes on the σ_θ = 26.0 isopycnal surface (Figure 6), which lies within an intermediate spiciness minimum in the lower portion of

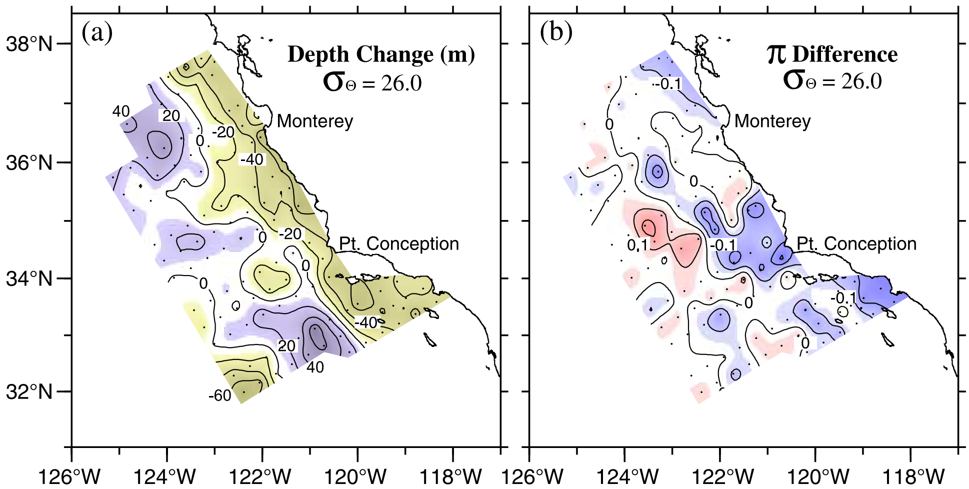

Figure 6. Change in (a) depth (m) and (b) spiciness (kg m^{-3}) on isopycnal surface σ_θ = 26.0 kg m^{-3}; 9504 values minus 9503 values.

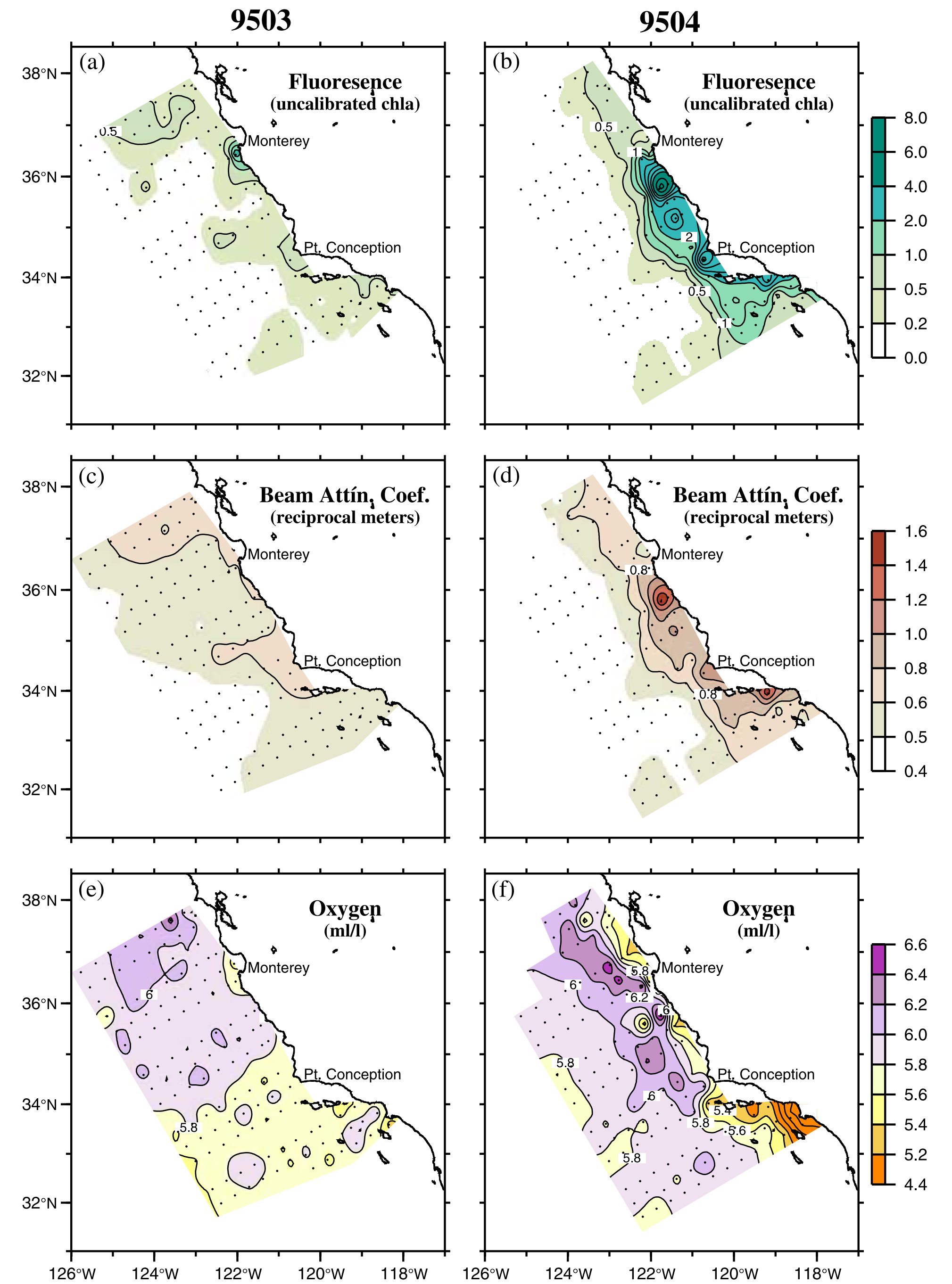

Figure 7. (a) and (b) Fluorescence (relative (uncalibrated) units of chlorophyll *a*, μg m^{-3}), (c) and (d) beam attenuation coefficient (m^{-1}), and (e) and (f) oxygen concentration (mL l^{-1}) for surveys (left) 9503 and (right) 9504.

the pycnocline, below the warm surface waters and above the spiciness maximum associated with the California Undercurrent (see Figure 3). During the transition, this surface lifted more than 60 m along the central California coast, while dropping 20–40 m at most offshore locations (Figure 6a). The 40-day spiciness difference at this density level shows the large transition near the coast and patchy changes in the middle of the pattern where mesoscale features moved. The offshore region had insignificant changes at this level. This is consistent with the idea that a new California Current jet was created, rather than there being a shoreward shift of the winter manifestation of the core.

3.2. Biological Response to the 1995 Spring Transition

[15] Changes in productivity resulting from the physical transition are revealed in maps of fluorescence (chlorophyll *a*, μg m^{-3}), beam attenuation coefficient (BAC; m^{-1}), and

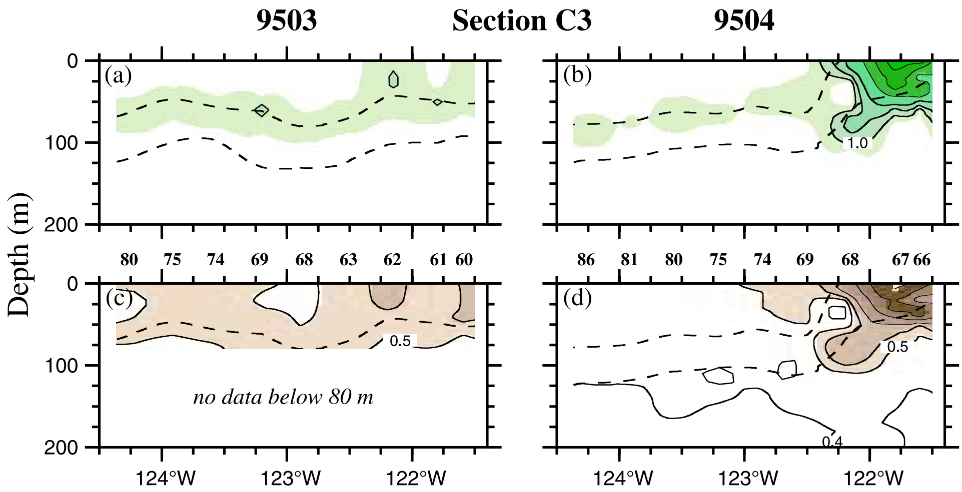

Figure 8. (a) and (b) Cross section (C3) of fluorescence (uncalibrated chlorophyll *a*, μg m^{-3}), and (c) and (d) beam attenuation coefficient (m^{-1}) for surveys (left) 9503 and (right) 9504. Position of section C3 is identified in Figure 1. The $\sigma_\theta = 25.0$ and $\sigma_\theta = 25.8$ kg m^{-3} isopycnal surfaces are shown with dashed lines.

oxygen (mL l^{-1}), each averaged over the upper 50 m (Figure 7). Both fluorescence and BAC show large increases in the near-coastal zone and small decreases in the offshore half of the grid between 9503 and 9504 (Figures 7a, 7b, 7c, and 7d). Maximum values of chlorophyll *a* (50-m average: 4.89 μg m^{-3}; surface value: 8.98 μg m^{-3}) and BAC (50-m average: 1.38 m^{-1}; surface value: 1.83 m^{-1}) occur at a coastal station off central California near 36°N. Secondary peaks are found off Point Conception and at the northern end of the Southern California Bight (SCB). An exception to this pattern is the offshore shift of modest values of fluorescence and BAC with the west-southwestward translation of the cyclonic eddy in the southwest corner of the grid.

[16] Cross sections of fluorescence and BAC along section C3 (see Figure 1), which includes the peak values, shows the uplifting of density surfaces and stripping away of low-density surface waters within 100 km of the continental slope (Figure 8). The largest increases in 9504 were at the surface, and there is evidence of some subduction of the high values within a density stratum around 25.8 kg m^{-3}.

[17] The simple pattern of surface layer oxygen seen in 9503 suggests equilibrium saturation (Figure 7e). The mean surface oxygen saturation for 9503 was 101% with a range of 92% to 107% (with the exception of six inshore stations within the SCB; oxygen profiles for these six stations had unusually high values in apparent

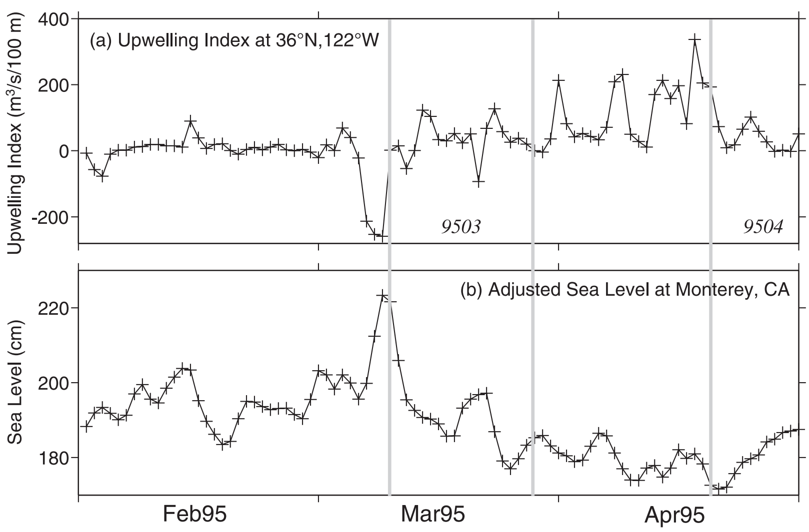

Figure 9. Time series (February–April 1995) of (a) daily upwelling index (m^3 s^{-1} per 100 m coastline) from 36°N, 122°W and (b) daily adjusted sea level (cm) from Monterey, California. Periods of the surveys are marked with gray lines.

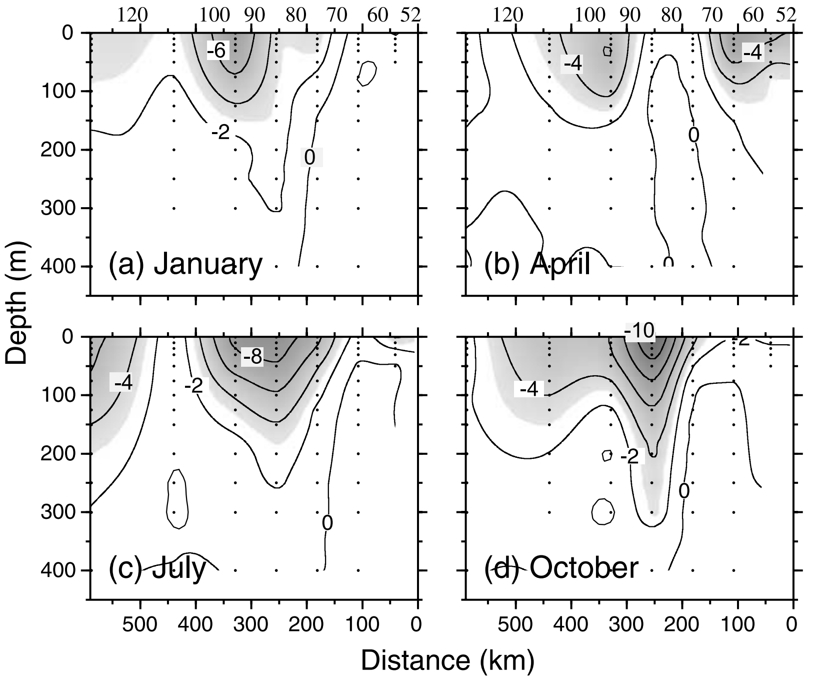

Figure 10. Long-term mean geostrophic velocity across CalCOFI line 60 (off Pt. Reyes, 240°T) for four seasons. Replotted from CalCOFI Atlas 30 [*Lynn et al.*, 1982]. Data were typically drawn from 55 calendar day periods to derive the mean; label indicates the dominant month. The number of observations used to compute these climatological fields range from (a) 6 to 13 for January, (b) 6 to 19 for April, (c) 6 to 16 for July, and (d) 3 to 19 for October; the offshore stations have fewer observations.

response to a local and unknown event). The distribution of oxygen is much more complex following the transition (Figure 7f). The mean surface oxygen saturation for 9504 was 103% with a range of 86% to 140%. Fresh upwelling, combined with poleward advection within the Inshore Countercurrent and California Undercurrent, brings low-oxygen waters to the surface layer, while high productivity fuelled by nutrient enrichment creates regions of oxygen supersaturation. This complexity suggests that considerable changes occurred at spatial scales smaller than the sampling resolution.

4. Discussion

[18] A key question is whether the rapid and dramatic transition in the physics and biology of the CCS observed in 1995 is a typical annual phenomenon. The coastal upwelling index at 36°N, 122°W and the adjusted sea level at Monterey, California, show conditions in winter-spring 1995 to be near seasonal norms (Figure 9). After a month of no upwelling (February), a strong 4-day downwelling event occurred along the central coast as the first survey occupied the initial stations on the southern lines of the grid. This was followed by two brief, small upwelling events during the survey. Several moderate upwelling events occurred in the 23-day period between the surveys, with the largest and longest just prior to the beginning of the second survey. The sea level responded to the winds as expected, with a low point reached as the second survey started (around 20 April; Figure 9b). Thus the major changes associated with the 1995 spring transition developed over a period of several weeks with average upwelling conditions.

[19] Historical hydrographic data of sufficient spatial and temporal resolution to capture the spring transition, and to define its climatological impacts, are not available for most of the CCS. However, we can use historical CalCOFI data to provide a view of the region's seasonal mean flow patterns (Figure 10). Cross sections of geostrophic velocity along CalCOFI line 60 (off Point Reyes; 38°N, 123°W) show a seasonal progression from a single dominant current core positioned ~300 km offshore in winter (Figure 10a) to two current cores of nearly equal strength ~300 km and <100 km offshore in spring (Figure 10b). (The remaining panels of Figure 10 show the climatological California Current to strengthen in summer and fall.) Thus the expected position of the winter core is at the outer edge of the March 1995 survey grid, where it was observed. Although averaging the velocity of a meandering jet will result in a broad, slow mean flow, it does reveal the central positions of the main California Current cores. A detailed hydrographic survey in March 1992 [*Lynn et al.*, 1995, Figure 1] shows the California Current jet approximately 360 km offshore of northern California, matching the climatological picture and the data from the 1995 surveys. Low-resolution, large-scale CalCOFI surveys in March, April, and May 1950 [*Wyllie*, 1966] (see charts 37–40) also show an offshore core of the California Current persisting from February through May, and an inshore jet developing by April; thus these data are also consistent with the evolution observed in 1995.

[20] *Strub and James* [2000] present a sequence of large-scale altimeter-derived sea surface height fields for the northeast Pacific that depict the seasonal cycle of the

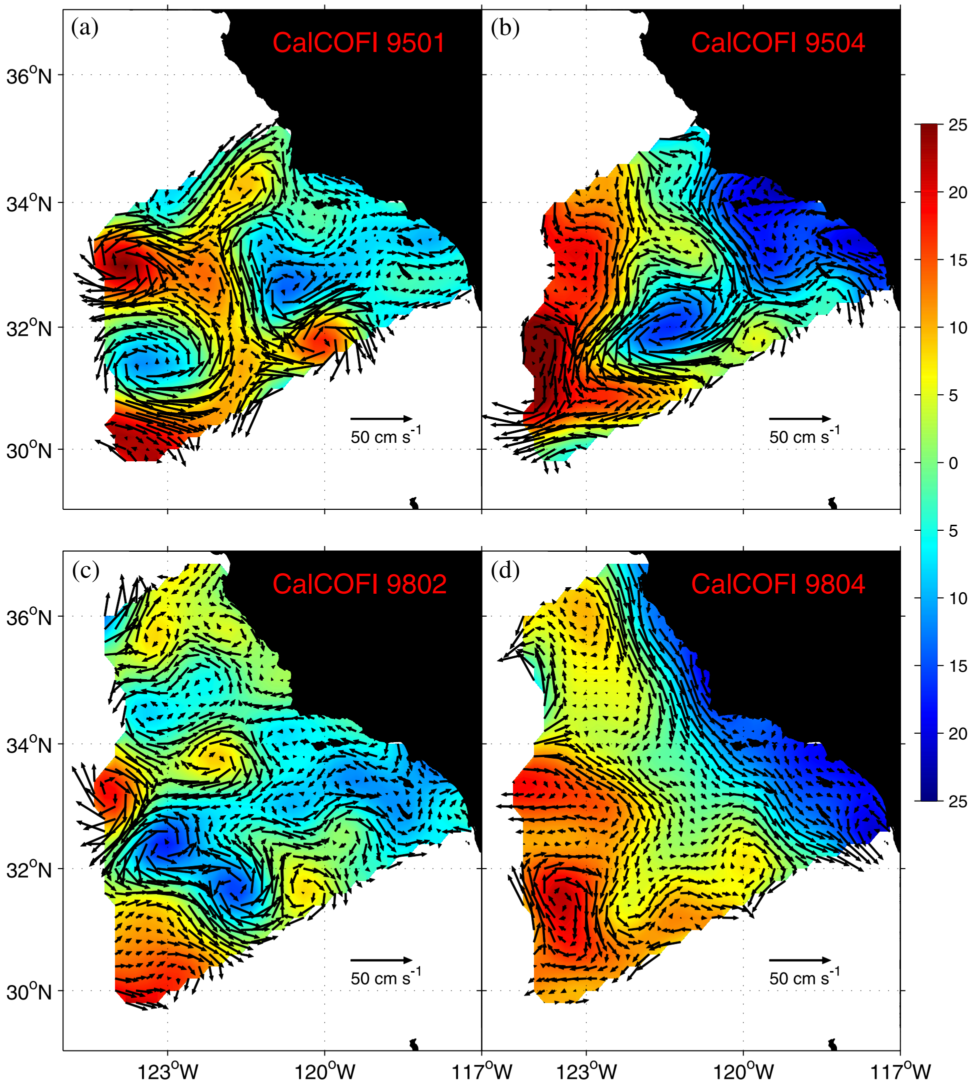

Figure 11. Vector velocities and velocity stream function at 50 m from the shipboard ADCP observations made on CalCOFI surveys on (a) 4–21 January 1995, (b) 6–22 April 1995, (c) 28 January to 14 February 1998, and (d) 2–23 April 1998.

California Current System [*Strub and James*, 2000, Figure 3]. Their bimonthly mean maps show the winter California Current jet, the addition of the coastal jet in March–April, and the strengthening of the coastal jet in late spring and summer and its subsequent translation offshore. Throughout the period of the coastal jet evolution, a weak to moderate current core remains approximately 500 km offshore. Maximums in SSH gradients and eddy kinetic energy occur in summer-fall, and their offshore progression is indicative of Rossby wave dynamics. Thus the altimetric view of the CCS supports our interpretation of the hydrographic data.

[21] To observe the transition from quiescent to highly energetic conditions in the CCS, such as in March–April 1995, requires fortuitous timing of surveys. Although CalCOFI has been regularly sampling this part of the ocean for many years [*Bograd and Lynn*, 2003], both its temporal and spatial resolution have generally been too coarse to capture the spring transition. Thus the data described here sets a limit on the duration of the transition, much of which apparently occurs in less than a month. Winter and spring CalCOFI cruises often reveal very different dynamics, however, as seen in the ADCP-derived near circulation patterns for 1995 and 1998 (Figure 11). Moderate to strong eddies dominate a complex circulation pattern in January 1995 (Figure 11a), which represents typical winter conditions. By April 1995 (this cruise overlapped our 9504 survey), a strong equatorward jet is evident at the outer edge of the Southern California Bight (Figure 11b), which is the southern portion of our grid. Maps of temperature, salinity and dynamic height for these two cruises assist in defining the evolution of the CCS during this period [*Scripps Institution of Oceanography*, 1995; *Hayward et al.*, 1995, 1996]. A similar transition is seen between February and April 1998, even though El Niño-dominated conditions [*Lynn and Bograd*, 2002] complicated the seasonal evolution (Figures 11c and 11d). During February, at the peak of the El Niño influence, the poleward

Inshore Countercurrent and California Undercurrent were sufficiently strong to result in net poleward transport across the CalCOFI lines. By April 1998, a strong coastal jet had formed, initiating an extended period of strong equatorward transport [*Lynn and Bograd*, 2002].

5. Conclusions

[22] A pair of high-resolution oceanographic surveys in March and April 1995 revealed a large and relatively rapid transition from late winter to spring conditions in the coastal zone off central and southern California. These data are unique in capturing the detailed three-dimensional physical structure of and biological response to the spring transition in the southern California Current System. Changes associated with the transition include: (1) a strong tilting of isopycnals, which lifted by up to 60 m near the coast and dropped 20–40 m offshore, and a subsequent increase in cross-shore density gradients along the extent of the California coast; (2) a reversal of the nearshore flow from weak poleward to strong equatorward, as a strong coastal upwelling jet developed independently of the winter manifestation of the California Current core; (3) an increase to a net equatorward transport of 2–6 Sv between the shelf break out to 300 km offshore; and (4) an apparent strong increase in primary productivity, as indicated by changes in vertically integrated fluorescence and beam attenuation coefficient. The most dramatic physical changes were confined to the shoreward 150 km, and extended at least to the depth of the core of the California Undercurrent, ~300 m depth near the coast.

[23] The spring transition in the coastal ocean was preceded by a fairly rapid change from weak or poleward wind stress to stronger, sustained equatorward wind stress. This is consistent with the atmospheric forcing of the spring transition observed off the northern CCS in the early 1980s [*Strub et al.*, 1987a, 1987b; *Lentz*, 1987; *Strub and James*, 1988]. Atmospheric and oceanic conditions in the CCS were near seasonal norms in the winter and spring of 1995, implying that a transition of the magnitude and rapidity observed here may be an annual event. Furthermore, the development of the coastal upwelling jet appears to be independent of the winter manifestation of the main core of the California Current, which typically lies some 300 km offshore. The implication is that the California Current is regenerated seasonally through the development of this coastal upwelling jet, which has physical characteristics traditionally associated with the main core of the California Current. Earlier studies [e.g., *Strub and James*, 2000] have shown that in subsequent seasons this jet broadens, moves further offshore, and a (poleward) countercurrent develops within the coastal zone. It is not known whether the new jet joins and strengthens or replaces the offshore core of the previous winter. Further observational and modeling studies are needed to understand the triggering mechanism of the spring transition, to better quantify the magnitude and duration of the physical and biological changes, and to explore the range of interannual variability in the timing and strength of the spring transition in the CCS.

[24] **Acknowledgments.** Huyer was supported by NSF grant OCE-0000733; Chereskin was supported by NASA grant NAG5-6497. Upwelling index data were obtained from the Pacific Fisheries Environmental Laboratory; sea level data were obtained from the University of Hawaii Sea Level Center. We thank two anonymous reviewers for helpful comments.

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