MESOSCALE OCEANIC RESPONSE TO WIND EVENTS OFF CENTRAL CALIFORNIA IN SPRING 1989: CTD SURVEYS AND AVHRR IMAGERY

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ABSTRACT

Analysis of hydrographic data obtained during juvenile groundfish surveys, in relation to local wind forcing and AVHRR sea-surface temperature imagery, reveals that the oceanic region off central California between Point Reyes and Point Sur in spring 1989 was characterized by complex circulation patterns and considerable temporal and mesoscale variability. The "spring transition" to upwelling-favorable winds is most clearly evidenced by rapid, large decreases in SST (up to 4°–5°C) measured at four meteorological buoys. Daily-averaged winds are spatially coherent and oscillate between upwelling-favorable and relaxation conditions at 3–10-day intervals.

Persistent upwelling centers near Point Reyes and Point Año Nuevo were characterized by relatively cool, salty (8°–10°C, 33.6–34.0 psu) water in the upper 50 m, which is derived from offshore water at depths of 50–100 m. Water-mass analysis reveals that upwelled water is advected equatorward from its source. Some upwelled water is transported into shallow coastal areas and warmed. Alongshelf fronts between relatively warm, low-salinity (>13°C, <33.5 psu) offshore water and cool, higher-salinity upwelled water are advected onshore in response to wind relaxation or reversal events; frontal gradients intensify at these times. AVHRR imagery verifies the spatial patterns and complex mesoscale variability of the near-surface patterns observed in the CTD survey data. Eddylike hydrographic features are noted with horizontal scales on the order of the station spacing (10 km). How the complex circulation patterns and intense mesoscale spatial and temporal variability affect the survival and subsequent recruitment of juvenile groundfish is discussed.

RESUMEN

Análisis de datos hidrográficos con relación a la fuerza del viento local y a imágenes infrarrojas de satélite (AVHRR SST), obtenidos durante las campañas de investigación de juveniles de peces de fondo, muestra que la región oceánica de la parte central de California, entre Punta Reyes y Punta Sur, en la primavera de 1989, estaba caracterizada por patrones de circulación complejos y una considerable variabilidad temporal y espacial de mediana escala. La "transición de primavera" hacia vientos favorables a la surgencia de aguas es claramente evidente en las grandes y rápidas reducciones en salinidades y temperaturas superficiales (SST), de hasta 4°–5°C, medidas entre cuatro boyas meteorológicas. Los promedios diarios de los vientos son coeherentes en el espacio y varían entre condiciones favorables a la surgencia y períodos de relajamiento en intervalos de 3 a 10 dias.

Centros de surgencia persistentes cerca de Punta Reyes y Punta Año Nuevo estaban caracterizados por aguas relativamente frías y saladas (8°–10°C, 33.6–34.0‰) en los 50-m superficiales. Esta agua se deriva del mar abierto a profundidades de 50–100 m. Análisis de masas de aguas muestran que el agua de surgencia se desplaza hacia el ecuador desde su punto de origen. Algo de agua de surgencia es transportada hacia zonas costeras poco profundas donde se calienta. Frentes a lo largo de la plataforma continental, que separan aguas de mar abierto relativamente cálidas y de baja salinidad (>13°C, <33.5‰) y aguas de surgencia frías y de más alta salinidad, son desplazados hacia la costa en respuesta al relajamiento de los vientos (o sucesos revertidos); los gradientes a través del frente se intensifican en estos momentos. Imágenes de satélite infrarrojas verifican los patrones espaciales y la compleja variabilidad de las aguas superficiales observada en escalas intermedias con sonda de temperatura, salinidad, y profundidad (CTD) durante las campañas. Se observaron rasgos hidrográficos parecidos a remolinos con escalas horizontales del orden de la distancia entre estaciones (10 km). Se discute la influencia de los patrones complejos de circulación y la intensa variabilidad temporal y espacial a escalas intermedias con relación a la supervivencia y reclutamiento de los juveniles de los peces de fondo.

INTRODUCTION

The oceanic region off central California between Point Reyes (38°N) and Point Sur (36.3°N) (figure 1) is characterized by several important dynamic processes and features that contribute to an ap-

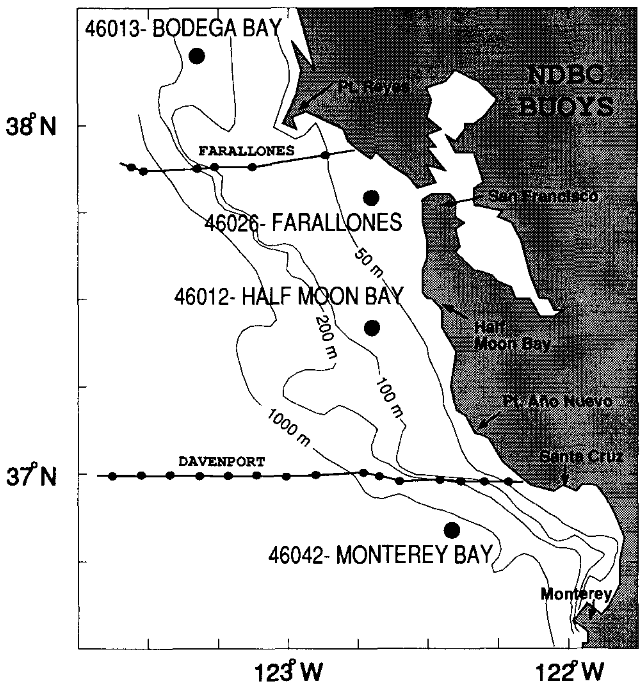

Figure 1. Area map of the juvenile rockfish recruitment survey region, showing location of NDBC meteorological data buoys (*large solid circles*) and cross-shelf CTD sections.

parently complex circulation. Significant physical processes include wind-forced motions (e.g., upwelling, horizontal advection, vertical mixing), tides, the circulation of the large-scale California Current system, flow/bathymetry interactions, and buoyancy effects (e.g., heat exchange with the atmosphere, freshwater inflow). Bathymetric features on a range of scales that could profoundly influence the circulation appear throughout the region. These include submarine canyons, banks, seamounts, headlands and embayments of various dimensions, and a wide range of continental shelf and slope widths. Water masses of unique characteristics may enter the region via local upwelling, advection onshelf or alongshelf due to changes in wind stress, and freshwater discharge, primarily from San Francisco Bay. Given this complex arrangement of forces and processes, a circulation that varies greatly in time and space should be expected over this portion of the California shelf.

This coastal environment is also a transition zone between two major biogeographical provinces, resulting in the presence of more species than are found either in the cold-temperate north (Oregonian Province, 35°–55°N) or in the warm-temperate south (California Province, 25°–35°N) (Briggs 1974). The area around Monterey Bay is believed to be a distributional barrier for a variety of marine organisms, including algae (Murray et al. 1980), molluscs (Valentine 1966), and fish (Horn and Allen 1978). The rich biological diversity may be enhanced further by the complex circulation patterns and by the diverse physical processes and variety of water types and ocean conditions in the region. At least, the flow regime must greatly influence the location, temporal variability, and ultimate success of larval and juvenile dispersal and recruitment into the adult groundfish population.

The region features numerous commercially and recreationally important species of groundfish, including the *Sebastes* complex — a major component of the West Coast groundfish fishery (Gunderson and Sample 1980), with annual landings from 1981–88 averaging over 45,000 MT/yr (PFMC 1989). Since 1983, the Southwest Fisheries Science Center (SWFSC) of NOAA NMFS has conducted a systematic midwater trawl field survey of the coastal ocean between Point Reyes and Point Sur each spring. The goals of the survey are to describe variations in groundfish recruitment, and to define the environmental conditions that lead to variability within the fishery. Data obtained during these annual surveys provide information on distribution and abundance patterns of young-of-the-year pelagic juveniles in this area (Wyllie-Echeverria et al. 1990). The Groundfish Analysis Group of SWFSC Tiburon Laboratory, under the direction of William Lenarz, is developing a recruitment index for rockfish based on this information.

The physical oceanographic component of these annual studies includes repeated surveying of the central California coastal region's hydrography via conductivity/temperature/depth (CTD) vertical casts and continuous surface mapping of temperature and salinity. CTD data from three spring 1989 sweeps (NOAA R/V *David Starr Jordan* cruise DS89-04) are used to define and describe the predominant hydrographic features present in the near-surface coastal ocean off central California following the spring transition. Selected Advanced Very High Resolution Radiometer (AVHRR) satellite sea-surface temperature (SST) images are used to verify and test the synopticity of the maps constructed from near-surface ship observations and to detail surface hydrographic features occurring beyond the sampling region.

We will discuss two key hypotheses. First, hydrographic and circulation features off central California, on scales on the order of 100 km, occur persistently during the upwelling season. Second, substantial spatial (10–50-km) and temporal (1–2-day) variations occur in the position and extent of these features. We focus on defining persistent hydrographic features and their variability on synoptic (<10-day) time scales. These should relate to natural fluctuations within the physical processes (e.g., upwelling) that control the circulation and, ultimately, the distribution and eventual settlement of larval and juvenile groundfish.

METHODS

Juvenile Rockfish Survey Design

Annual 30-day cruises aboard the NOAA R/V *David Starr Jordan* began in 1983 and have been conducted annually during late spring (May–June), a time when most pelagic stage juvenile rockfishes are identifiable to species, but before they settle to nearshore and benthic habitats. The sampling design presently permits three consecutive sweeps through a study area from 38°10′N (near Point Reyes) and 36°35′N (near Monterey), and from the coast to about 75 km offshore (figure 1). A CTD cast is made at each trawl station. Beginning in 1987, daytime activities were restructured to permit sampling of a more extensive grid of CTD stations. Each sweep is sampled south to north, and takes approximately ten days (seven nights of scheduled work plus three nights of additional discretionary sampling).

Collection and Processing of CTD Data

All CTD data obtained during the 1989 juvenile rockfish surveys were collected with a Sea-Bird Electronics SEACAT-SBE-19 profiler. At each CTD station, the profiler was lowered to its maximum rated depth (200 m), or to a depth 10 m off the bottom if water was less than 200 m deep. Only data collected on the downcast were ultimately preserved for analysis. A total of 380 acceptable CTD casts were obtained during the 1989 survey. One hundred thirty-five acceptable casts were obtained during sweep 1 (14–22 May); 153 casts during sweep 2 (23 May–3 June); and 92 casts during sweep 3 (4–13 June). Schwing et al. (1990b) provide a detailed description of the data collection and the reduction and processing procedures for this cruise, together with a full suite of data.

Meteorological Time Series

Meteorological data were obtained for selected sites in the survey region (figure 1). These sites include the region's four National Data Buoy Center (NDBC) moored buoys — 46013 (Bodega Bay: 38.2°N, 123.3°W); 46026 (Farallones: 37.8°N, 122.7°W); 46012 (Half Moon Bay: 37.4°N, 122.7°W); and 46042 (Monterey Bay: 36.8°N, 122.4°W) — and a land station at Monterey (Monterey Bay Aquarium; 36.6°N, 121.9°W). Daily averages of several surface meteorological characteristics, including air and sea temperature, wind speed and direction, and barometric pressure, were calculated for the period that includes the 1989 *Jordan* rockfish survey. The principal axis components of each buoy's wind, which is the compass heading along which variance is maximized, were also derived.

AVHRR Imagery

Sea-surface temperature (SST) images for the study region were produced from the data of the AVHRR carried aboard TIROS-N/NOAA polar-orbiting satellites (McClain et al. 1985). The calculated SST values and the blackbody brightness temperatures were registered to the surface temperature at NDBC 46042. Additional processing details are found in Tracy 1990.

RESULTS

Meteorological Conditions Preceding and During the DS89-04 Cruise

Meteorological time series of the daily vector mean wind, the principal axis component of the wind, and SST are presented for the four NDBC buoys (figures 2 and 3). All four NDBC wind series display very similar signals. Daily winds at Monterey Bay Aquarium are included to demonstrate the relative difference in wind speed over land and ocean. Until about 1 May, there were frequent (every 3 to 10 days) reversals or reductions in the principal wind component; however, the mean alongshore wind was about zero. After 1 May, winds at all sites were predominantly southward to southeastward (i.e., upwelling-favorable), until 30 June and beyond. This dramatic change in the region's wind patterns, called the spring transition (Huyer et al. 1979; Lentz 1987; Strub et al. 1987b), marks the onset of the upwelling season. However, numerous wind-relaxation events (reductions in the speed of upwelling-favorable wind) and wind-reversal events occurred during the upwelling season (Send et al. 1987). Two notable reversals occurred near the beginning of sweeps 2 (23 May) and 3 (4 June). Although the principal component at the three southern buoys is nearly alongshore, thus optimal for upwelling, the principal axis at Bodega is nearly normal to the coast (figure 2).

The synoptic variability of the wind field is reflected in SST at the buoys as well (figure 3). Changes in SST were relatively minor before the spring transition, and were associated with wind

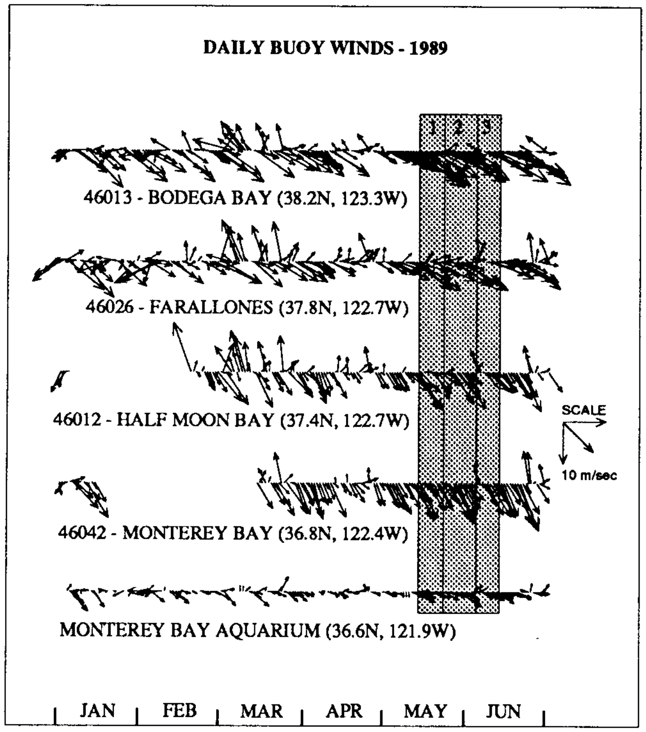

Figure 2. Vector time series of daily average winds from NDBC buoys and Monterey Bay Aquarium, January–June 1989. *Arrows* point in direction to which wind was blowing. *Shaded area* denotes period of groundfish cruise.

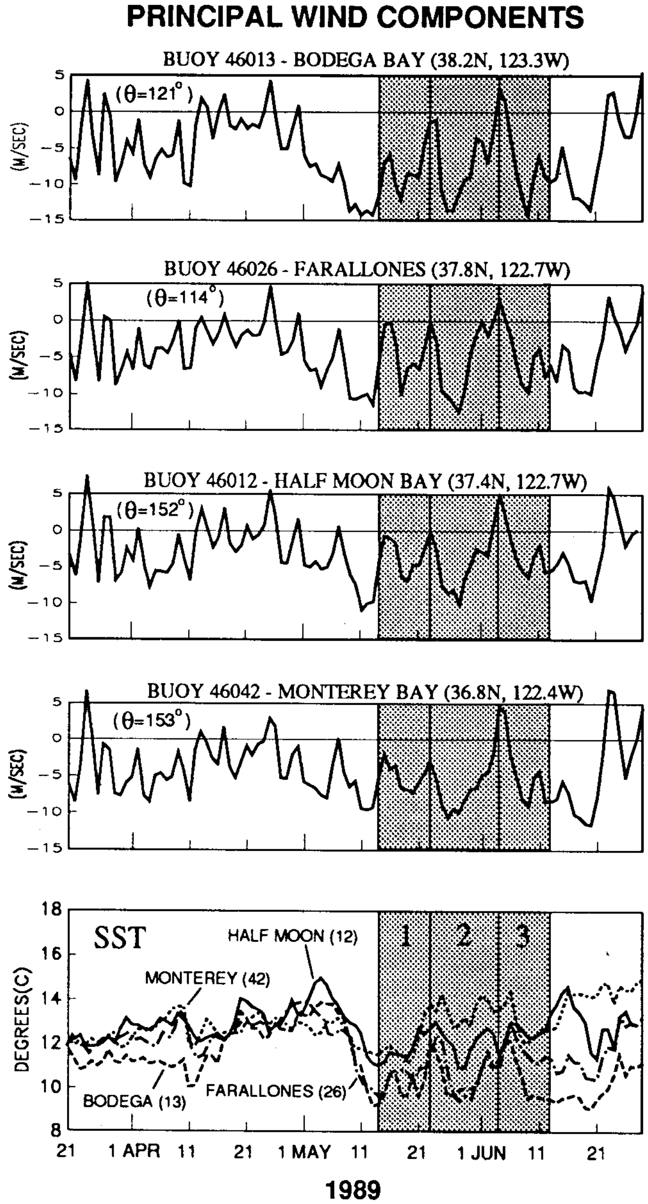

Figure 3. Time series of principal-axis wind component and sea-surface temperature (SST) from NDBC buoys for 21 March–29 June 1989. Negative wind speeds are in the direction of the principal axis, defined by θ at each buoy. *Shaded areas* denote period of groundfish cruise.

reversals. SST was also positively correlated with air temperature (not shown) at each site. The onset of upwelling, however, resulted in a dramatic decrease in SST of up to 4°–5°C at the buoys. Wind reversals and relaxations are reflected as warming events in the SST signals. Although SST at all four buoys responded similarly to wind forcing, the magnitude of the response, as well as the mean temperature for the upwelling season, varied with location. Monterey SST is generally the warmest; Bodega is generally the coolest.

In summary, both wind and SST from NDBC buoy time series varied widely on scales less than 10 days; i.e., less than the period of one sweep. For example, buoy SSTs changed by as much as 3°C during a single sweep. Such variability must be kept in mind for interpretations of the "synoptic" horizontal property maps from a single sweep—especially near-surface conditions, which are most influenced by meteorological forcing.

Horizontal Maps of Temperature, Salinity, and Density

Near-surface (5-m-depth) temperature and salinity throughout the groundfish survey region is summarized, by sweep, in a series of horizontal maps (figures 4–6). These maps were objectively contoured from the CTD cast data. The NDBC SST and principal wind-component time series, shown as inserts in the temperature maps, clearly demonstrate that conditions changed substantially during the course of each sweep. We will consider day-to-day environmental changes when describing the hydrography, rather than interpret the contour maps in a synoptic sense, i.e., as if the entire survey was made instantaneously.

Sweep 1 surface hydrography. Near-surface conditions during sweep 1, 14–22 May (figure 4), reflect

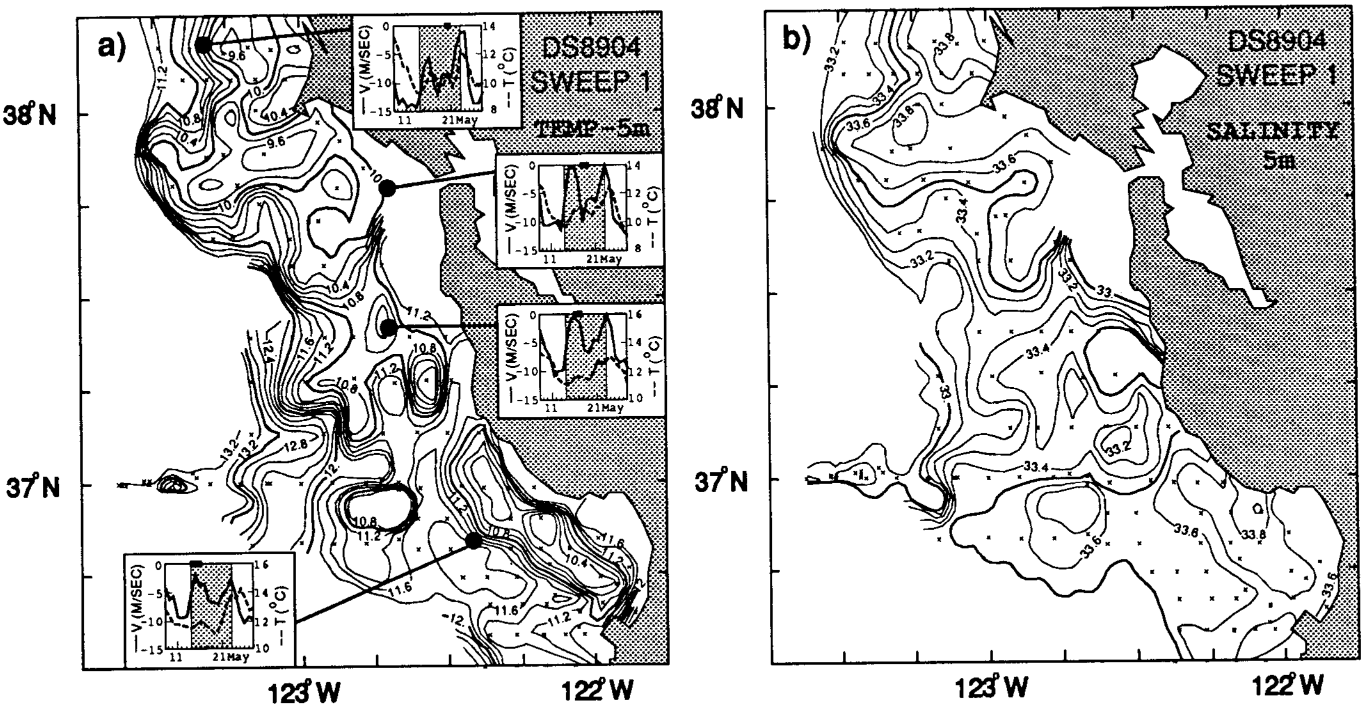

Figure 4. *a*, Temperature at 5-m depth during sweep 1 (14–22 May 1989), from CTD data. Location of CTD stations denoted with an x. Contour interval is 0.2°C; *bold contours* denote 1°C intervals. Time series of principal-axis wind components and SST at the four NDBC buoys, whose positions are denoted by *large solid circles*, are also shown. *Shaded areas of buoy records* define sweep duration; *short bold bars* mark period when stations in the area of each buoy were occupied. *b*, Salinity at 5-m depth during sweep 1. Contour interval is 0.1 psu; *bold contours* denote 0.5-psu intervals.

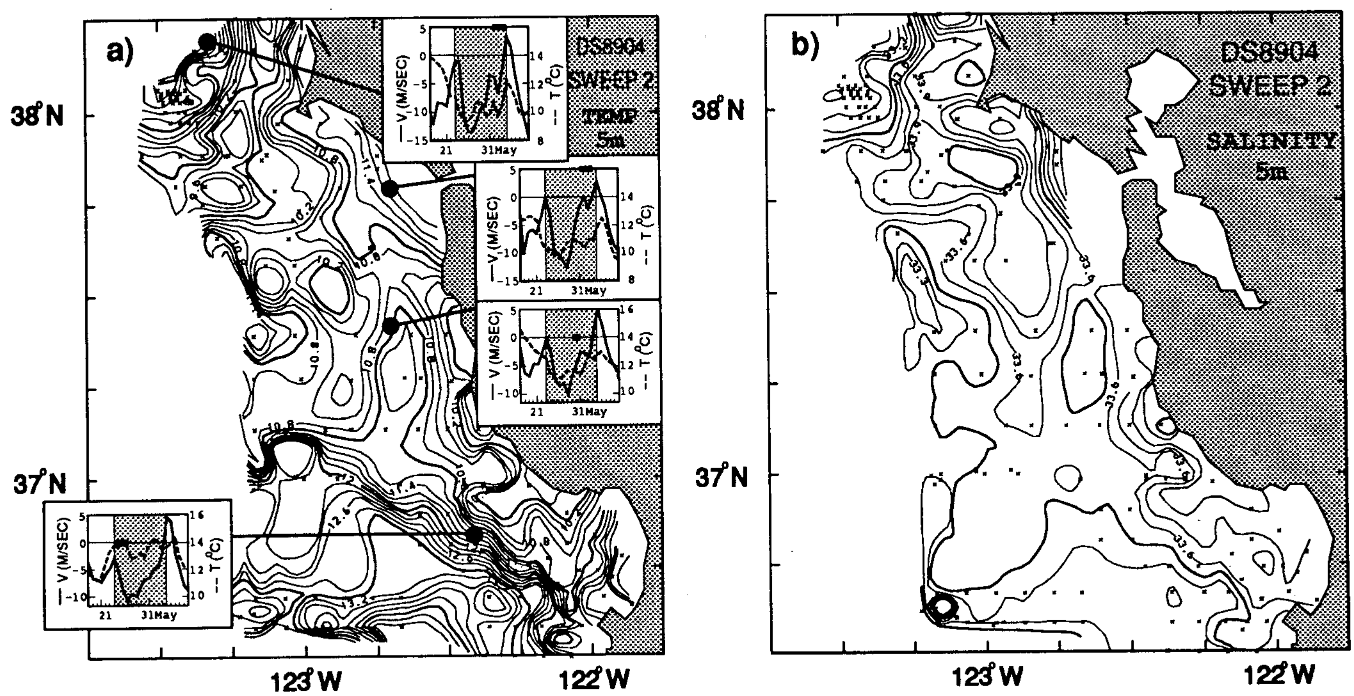

Figure 5. *a*, Temperature at 5-m depth during sweep 2 (23 May–3 June 1989), from CTD data. Contour interval is 0.2°C; *bold contours* denote 1°C intervals. See figure 4a for further details. *b*, Salinity at 5-m depth during sweep 2. Contour interval is 0.1 psu; *bold contours* denote 0.5-psu intervals.

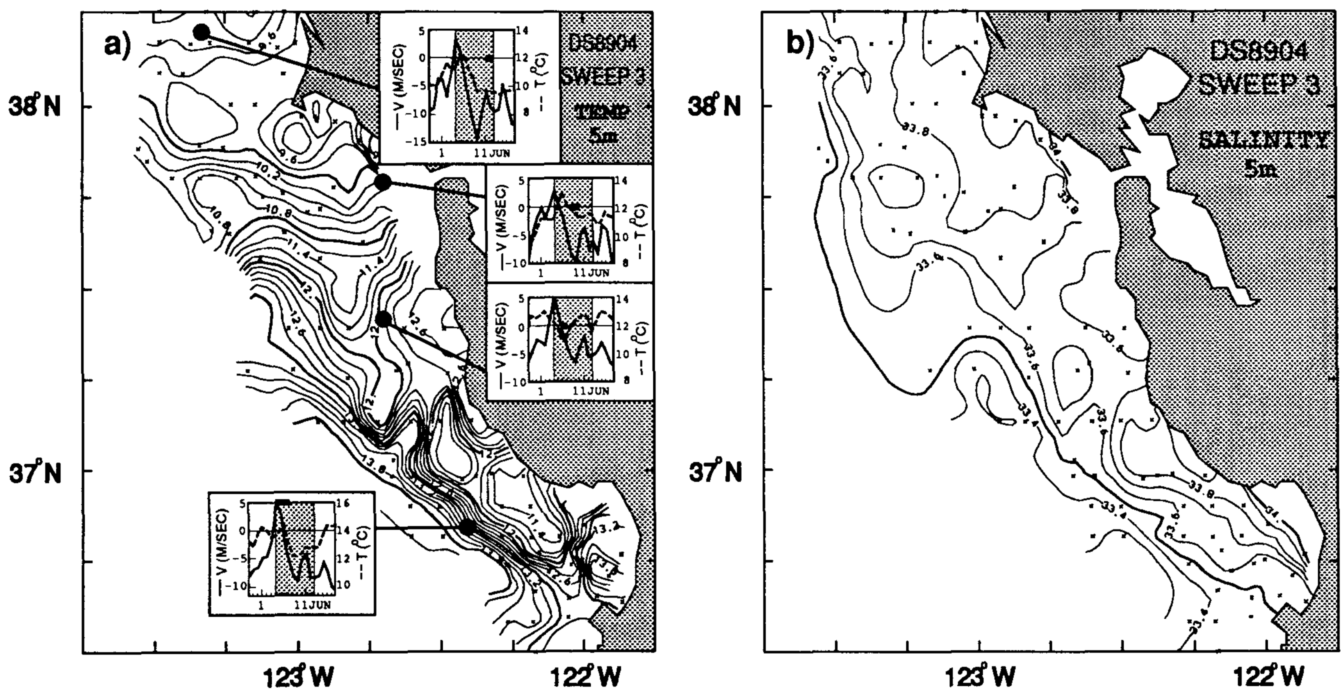

Figure 6. *a*, Temperature at 5-m depth during sweep 3 (4–13 June 1989), from CTD data. Contour interval is 0.2°C; *bold contours* denote 1°C intervals. See figure 4a for further details. *b*, Salinity at 5-m depth during sweep 3. Contour interval is 0.1 psu; *bold contours* denote 0.5-psu intervals.

the presence, position, and extent of several features of water mass and circulation typically seen in this region during spring. Two relatively cool (<10.5°C) and saline (>33.7 psu) areas of recently upwelled surface water appear near Point Reyes (38.0°N) and Point Año Nuevo (37.2°N). These areas of upwelled water contrast with the much warmer (>13°C) and less saline (<33.0 psu) surface water seen offshore. A warm feature that appears persistently west of Monterey Bay in CTD maps and AVHRR SST imagery (Tracy 1990) is composed of this water type. A strong alongshelf front often develops between these two water types. A second source of warm, fresh water appears to be the San Francisco Bay plume; however, CTD coverage is limited in the area where the bay's effluent is most evident. The plume is more apparent in AVHRR imagery.

Situated within these larger water masses are numerous mesoscale eddylike features whose horizontal dimensions are on the order of 10 km. They are much smaller than previous hydrographic sampling in the region (e.g., CalCOFI) could reveal, and are barely resolvable at the station spacing of the rockfish surveys. The existence and size of these features are confirmed with continuous surface mapping (Schwing et al. 1990b) and AVHRR imagery.

The coolest and most saline water was observed during sweep 1 off Point Reyes, and featured a minimum temperature of about 9.5°C and a maximum salinity of over 33.9 psu. This water was bounded offshore by a very strong front. Surface water gradually increased in temperature and decreased in salinity from Point Reyes to Half Moon Bay. A second relatively cool, saline feature extended along the shelf from Point Año Nuevo to near Monterey, crossing the mouth of Monterey Bay. Tracy (1990) demonstrated the existence of a persistent upwelling center off Point Año Nuevo with AVHRR imagery. His results imply that upwelled water is subsequently advected south in a relatively shallow (<50 m) surface layer toward Monterey Bay. The position and extent of the elongated cool, salty feature seen in figure 4 is consistent with those findings. A similar process, associated with an upwelling center north of the survey region, is probably responsible for the cool, saline water seen near Point Reyes.

Although the highest salinities within these recently upwelled features were observed at sites nearest the coast, the coolest water was actually found about 20–25 km offshore. Thus the shallowest portions of the shelf adjacent to these upwelling sources feature relatively warm and saline water at the surface. The discrepancy is more extreme off Point Año Nuevo and in Monterey Bay. In contrast, temperatures at 30 m (not shown) were coolest at the most nearshore sites, corresponding to the salinity maximum at this depth. The character of this coastal water suggests that it was upwelled, then warmed over the shallow (<50 m) areas of the shelf. Aside from this difference in shallow shelf regions, the surface hydrographic features seen in all three sweeps extended to 50 m and deeper.

Sweep 2 surface hydrography. Near-surface temperature and salinity patterns during sweep 2, 23 May–3 June (figure 5) are similar to those seen during sweep 1. The coolest and most saline water masses were located off Point Reyes and Point Año Nuevo; warmer, fresher water was noted again in the offshore and southern portions of the region and immediately seaward of San Francisco Bay. Again the fine scale of the sampling design reveals several mesoscale hydrographic features. However, temperature, salinity, the position and extent of these water types, and the location and intensity of the fronts that separate them all vary substantially from sweep 1. For example, the offshore front during sweep 1 was sharper north of 37°N than to the south. During sweep 2 this front was much more distinct south of 37°N. The Point Año Nuevo upwelling center featured a cooler minimum temperature (<10°C) during sweep 2, and was constrained to the shallowest stations along the coast. The maximum salinity near Point Año Nuevo was also higher (>34 psu) during sweep 2.

Stations off Point Año Nuevo and Half Moon Bay were occupied after a significant wind-relaxation event during sweep 1, but after relatively strong upwelling-favorable winds during sweep 2. Stations off Monterey, on the other hand, were surveyed after the upwelling-favorable conditions that preceded the first survey, but immediately following the significant wind-relaxation event of 23 May. Thus it appears that a stronger offshore front develops during relaxation events, in contrast with the findings north of Point Reyes (Send et al. 1987).

Sweep 3 surface hydrography. Conditions during sweep 3, 4–13 June (figure 6), display even more dramatic differences from the first two sweeps, although the same water masses and eddylike features are again apparent. The alongshelf front separating upwelled and offshore water masses is sharpest off Monterey Bay; essentially no cross-shelf gradient is seen north of 37.5°N. Surface water south of 37°N was 1°–2°C warmer during sweep 3, with the coolest water (11.5°C) away from the coast once again. Stations in the southern half of the survey were occupied after a strong wind reversal; northward wind components up to 5 m/s were observed at all buoys on 4 June. As a result, the offshore front was most distinct during this sweep.

Temperature-Salinity Relationships

A temperature-salinity diagram composed of CTD observations taken south of 37.25°N during sweep 2 clearly defines the differences between the offshore, upwelled, and nearshore water masses, and reveals some of the region's vertical structure (figure 7). Surface offshore water (*triangles*; >13°C, 33.2–33.4 psu) contrasts with water at upwelling centers north of Monterey Bay (*circles*; <10.5°C, 33.6–33.9 psu). These two masses are separated by an alongshore front, represented by *diamonds*. Frontal water comprises a linear mixture of offshore and upwelled water. Upwelled water at the surface displays the characteristics of offshore water at 50-m depth. In addition, upwelled water at 50 m is similar to the 100-m offshore water; i.e., water is vertically advected by about 50 m near the coast. Nearshore water, confined to Monterey Bay in this area, features salinities identical to those measured at upwelling centers, but is 1°–2°C warmer. The range of temperature and salinity, defined at the surface, 50 m, 100 m, and 200 m within dashed lines, decreases with depth. The large temperature range observed at the surface is probably due to greater short-term variability in surface heating.

Individual profiles of temperature, salinity, and density from stations representing offshore, upwelled, nearshore, and frontal locations (figure 8) further reveal the distinct characteristics of these water masses. Although the temperature of nearshore water to about 60 m was between that at offshore and upwelling sites, its salinity was clearly that of the upwelling centers. At greater depths, the salinity in Monterey Bay is increasingly that of an offshore source. Frontal water, in contrast, is some mixture of offshore and upwelled water to at least 150 m.

AVHHR SST

Four SST images (figure 9) collected during the survey period provide an excellent illustration of how quickly the position, extent, and intensity of surface water masses can change. Both the persistence of features and the variability of their relative locations are demonstrated in these data. The observed patterns correspond closely with those described from the hydrography. All are presented with the same grey scale, which is linear between 8° and 13°C. Waters cooler than 8°C are uniformly light; waters warmer than 13°C are uniformly dark.

The first image, from 11 May, shows the SST pattern three days before the beginning of sweep 1. This image was collected just before the peak of a fairly strong period of upwelling-favorable winds. Cool

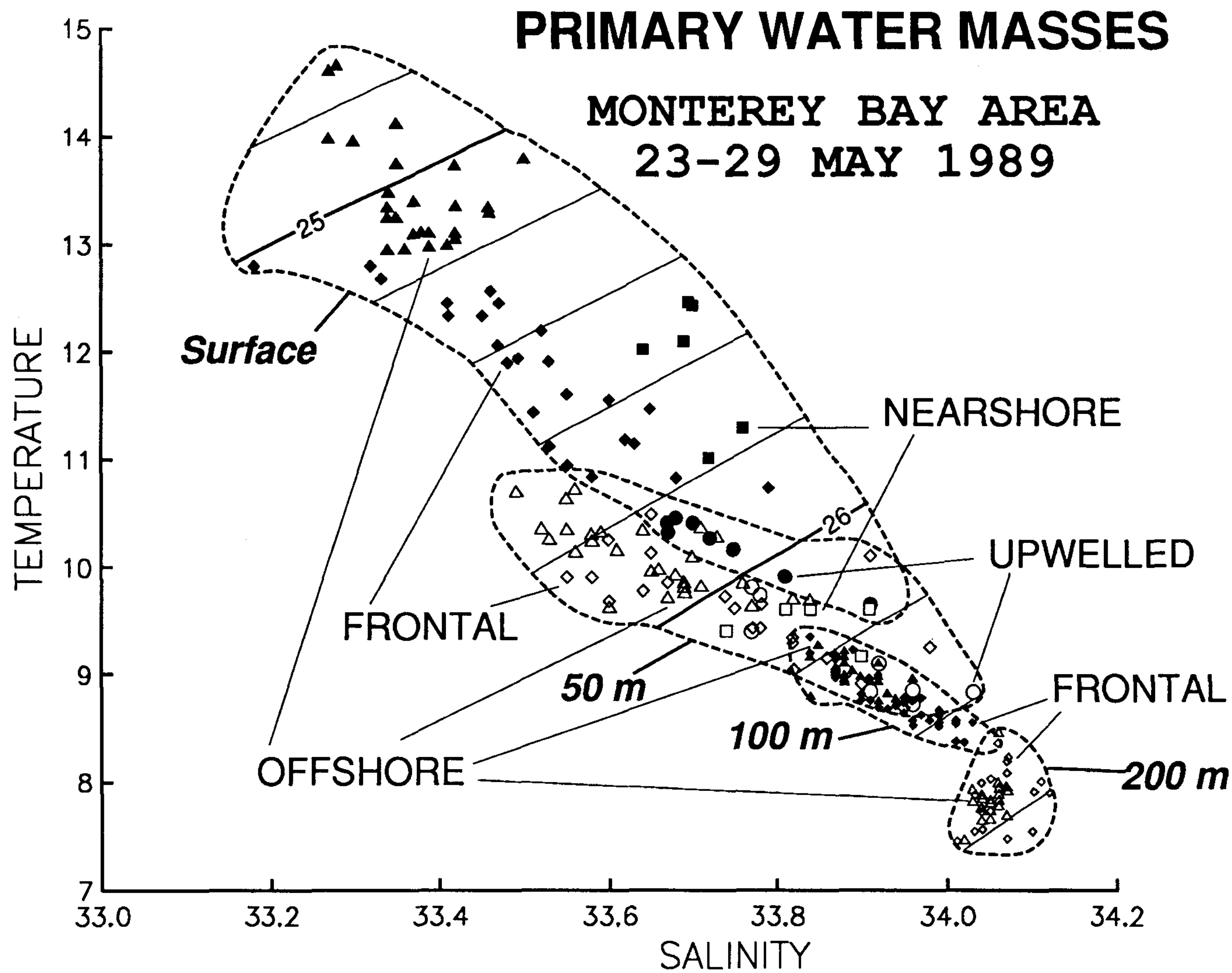

Figure 7. Temperature-salinity (T-S) diagram from CTD observations taken south of 37.25°N during sweep 2. *Dashed lines* enclose T-S ranges at surface (*large solid symbols*), 50-m depth (*large open symbols*), 100-m depth (*small solid symbols*), and 200-m depth (*small open symbols*). *Triangles* represent T-S pairs at offshore stations; *circles* represent stations in upwelling centers; *squares* represent nearshore (Monterey Bay) stations; and *diamonds* represent frontal stations. Sigma-t isolines are shown at 0.2 kg/m³ intervals.

water (lighter shade) extends south past Point Reyes to about 37.25°N. It appears that this streamer comprises cool water upwelled from two sources. The majority is an extension of cool water from the north, flowing past Point Reyes, and augmented by water upwelled locally near the point. South of 37.5°N, the streamer separates, one portion going approximately alongshelf southeast of 123°W, the other passing offshore to the southwest. Warmer water (darker shade) is located between these streamers.

A warm streamer, with maximum temperature offshore of the Golden Gate, extends to the south, leaving the coast around Half Moon Bay. Cool water, suggestive of coastal upwelling, appears along the coast from Half Moon Bay to Santa Cruz and again to the south of Monterey Bay. This cool water band appears separated from the Point Reyes cool water by the Golden Gate warm band.

The cool upwelling streamer near Point Año Nuevo has offshore and alongshore components and the suggestion of a warm feature between them, similar to the streamer off Point Reyes. The alongshore streamer extends south from Santa Cruz about halfway across Monterey Bay. Surface temperature inside the bay is fairly uniform, with the suggestion of some warm water right along the coast. Clouds obscure the southwest corner of the image.

This image corresponds well with the sweep 1 surface map (figure 4a). The Point Reyes streamer and the downstream split are clearly seen, as well as

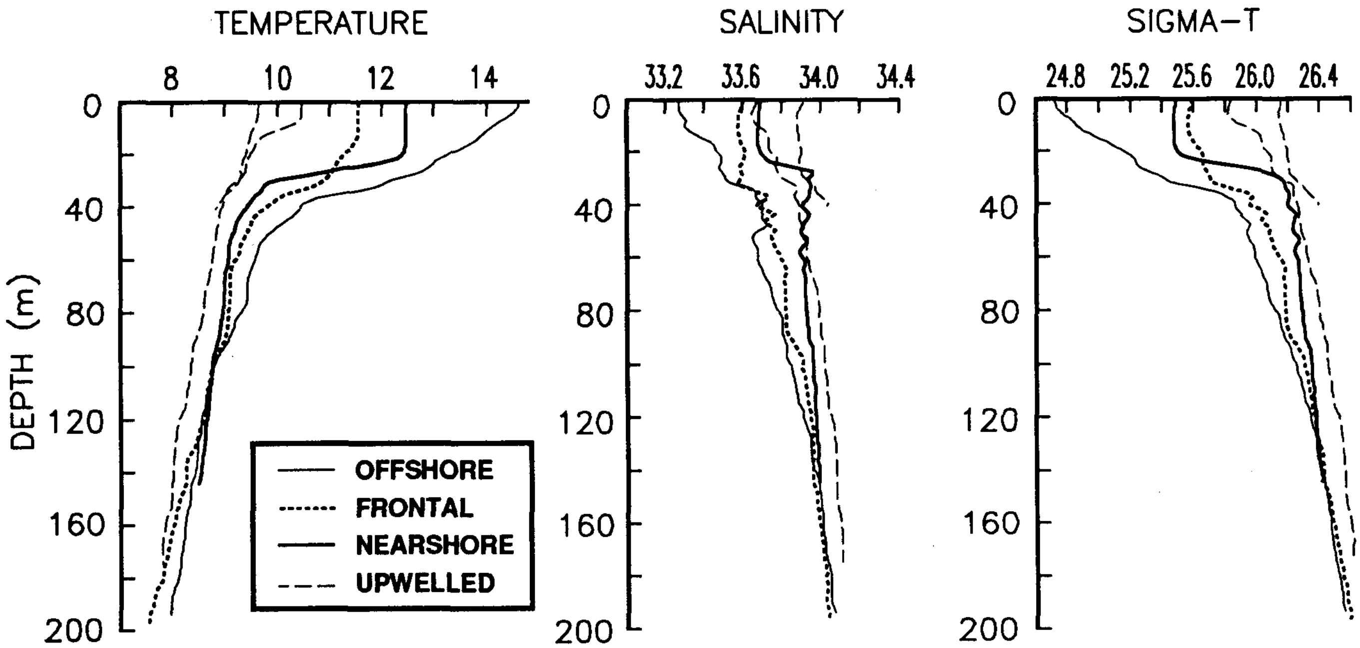

Figure 8. Individual profiles of temperature, salinity, and sigma-t at CTD stations representative of offshore, upwelled, nearshore, and frontal locations during sweep 2.

the Point Año Nuevo streamer extending across Monterey Bay, and the relatively warm water inside the bay. The position of the alongshelf front separating upwelled and offshore water is also approximated. Although the eddylike features seen in the CTD near-surface maps appear in the AVHRR imagery as complex but connected flow features, the small spatial scales of variability noted in the hydrographic data are reflected in the satellite observations.

The date of the second image, 25 May, is closer to the time of the northern sampling during sweep 1 (19–21 May) than sweep 2 (1–3 June). The southern portion of the study area was surveyed during sweep 2 at the time of this image, thus that portion of figure 5a has a slightly stronger correspondence to figure 9b. Upwelling-favorable winds began blowing on 24 May, following a significant wind reversal. Although the general pattern is the same, the SST field on 25 May differs from that on 11 May (figure 9a) in two significant ways. The most noticeable change from sweep 1 is the presence of a distinct warm feature just west of Monterey Bay. Although this feature looks like a meander or eddy at this scale, the full-scale image (not shown) suggests that it is best described as a warm segment of the variegated eastern boundary of the California Current. In addition, the whole region appears slightly warmer relative to two weeks earlier.

The Point Reyes streamer is still well defined on 25 May, extending south to the edge of the warm feature off Monterey Bay (figure 9b). However, it is not as cool as that seen after several days of upwelling-favorable wind (cf. figure 9a). The streamer is no longer divided, although the offshore edge shows evidence of complex small-scale interaction with the warmer oceanic water to the west. The Golden Gate warm streamer again extends south, separating the Point Reyes streamer from the cool coastal water present from Half Moon Bay to Santa Cruz. Distinct cool water centers are seen along this portion of the coast. Cool water extends across Monterey Bay; the separation of warm coastal (Monterey Bay) water from the warm offshore feature is more distinct than noted previously. As in the sweep 2 surface-temperature map (figure 5a), the strongest front is associated with the north-to-southeast edge of this feature. There are no strong fronts in the northern part of the study area, although remnants of the different water masses are seen.

By 28 May (figure 9c) the coastal oceanic response to the upwelling event that began about 24 May is well established. There is strong upwelling both north and south of Point Reyes, near Point Año Nuevo, and near Point Sur. Water from these upwelling centers has spread both offshore and generally southward. The coastal-oceanic boundary has retreated offshore. This is demonstrated by the

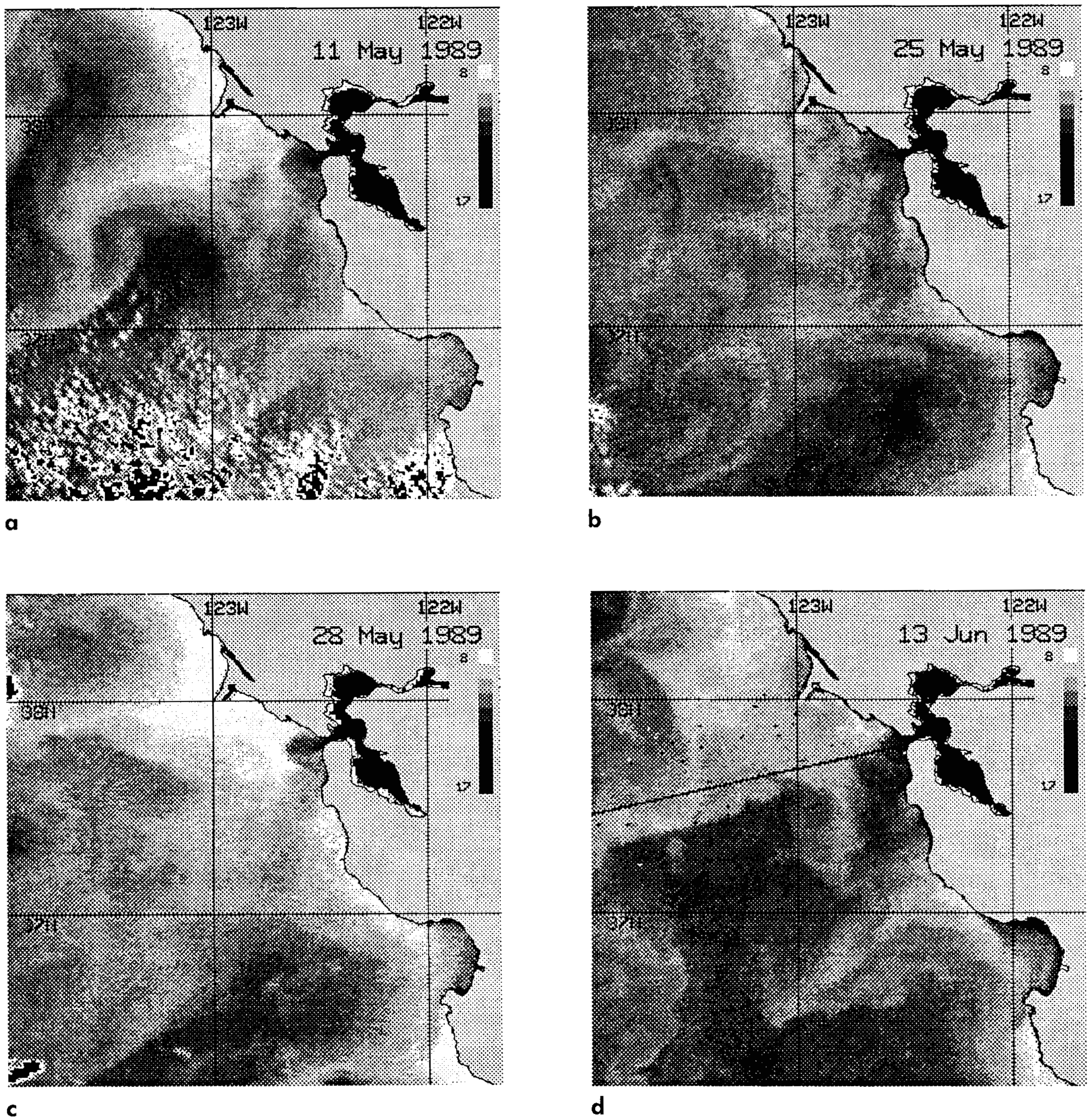

Figure 9. AVHRR sea-surface temperature (SST) images of the survey region from 11 May, 25 May, 28 May, and 13 June 1989. Linear grey scale for SST is shown. Lighter shades denote cooler temperatures. Speckled pattern at bottom of image from 11 May is scattered cloud. Latitude and longitude are shown at 1° intervals.

westward displacement of the warm water off Monterey Bay. A comparison of the images in figures 9b and c, taken only three days apart, clearly shows how suddenly and dramatically coastal ocean conditions can change during the upwelling season.

About two weeks later, 13 June, the imagery reveals more warm water closer to shore, with coincident warming and possible constriction of the southward-flowing Point Reyes cool streamer (figure 9d). Winds at this time were light and upwelling-favorable, but varied substantially from north to south (figures 2 and 3). There is again an offshore streamer of cool water west of Point Año Nuevo, possibly comprising both Point Año Nuevo and

Point Reyes cool waters. But the offshore extent of this cool water is limited, relative to that during upwelling periods. During strong wind reversals, such as on 29 June (figures 2 and 3), surface evidence of upwelling is hidden as the entire coastal region warms to greater than 13°C (Tracy 1990).

The Point Reyes streamer appears ~2°C warmer than the Point Año Nuevo coastal upwelling streamer on 13 June, probably because the northern portion of the survey region was under wind-relaxation conditions while the southern part was experiencing stronger southward wind (figure 2). The warm feature off Monterey Bay is still present, and is connected with a region of warm water extending northward, west of 123°W. This image further indicates the complexity of the boundary between the coastal and offshore water masses. The warmest water is seen again off the Golden Gate and in Monterey Bay. Figure 9d corresponds well with the CTD temperature map from sweep 3 (figure 6a), even though the image was taken on the last day of the sweep.

The impression gained from a series of satellite images of the study area is that several general water masses, indicated by surface temperature, are present at all times, but their relative and absolute location can change on short subsynoptic time scales not detected by traditional ship-survey methods. These changes could profoundly affect the biota in the region, as discussed below.

Both the persistence of these water masses during the upwelling season, and their variability on synoptic time scales is reflected in the CTD surface maps (figures 4–6) as well as the NDBC SST time series (figures 2 and 3). The consistently coolest buoy site, off Bodega, is located near the core of the southward-flowing upwelling streamer off Point Reyes. Buoy SST increases to the south, as this streamer mixes with warmer surrounding water. The warmest buoy, off Monterey, lies in the warm feature that separates the two Point Año Nuevo upwelling streamers.

Vertical Cross-Shelf Sections

The vertical distribution of density along two representative cross-shelf sections (figure 1), extending offshore from Davenport (37°00′N) and through the Farallones (37°53′N), are presented for each sweep in figures 10 and 11. These figures display the vertical structure and extent of the features defined previously from the near-surface CTD and AVHRR data. They also show the pronounced spatial and temporal variability of the coastal ocean associated with upwelling/relaxation events. The time series of the principal-axis wind component from the NDBC buoy nearest each section is included.

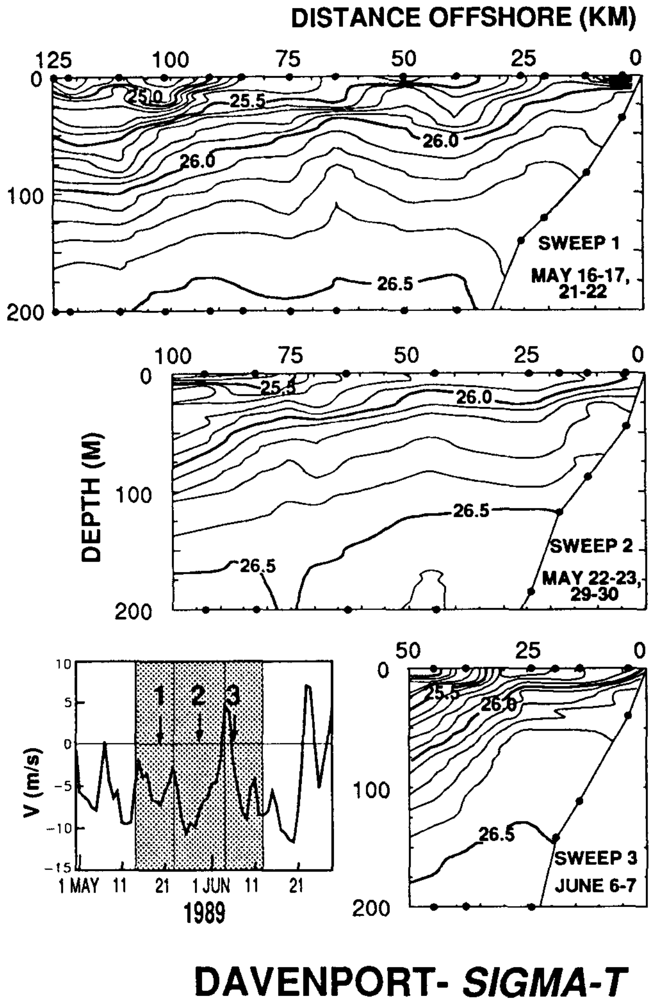

Figure 10. Vertical distribution of density along Davenport cross-shelf section (37°00′N), by sweep. Time series of the principal-axis wind component at NDBC buoy 46042 is included. *Bold arrows above the wind records* indicate the start of each survey.

Changes in the density structure off Davenport (figure 10) are representative of the temporal variability that existed during the survey period, and show the close relationship between ocean structure and coastal wind conditions. Wind during sweeps 1 and 2 was upwelling-favorable. The hydrographic structure appears similar during these sweeps as well.

Isopycnal doming near the coast, to depths as great as 100 m, defines the local upwelling center seen in the horizonal maps (figures 4–6) and AVHRR images (figure 9), and affirms the idea, based on the temperature-salinity relationship (figure 7), that water upwells from about 50 m to the surface. Doming off Davenport is confined to within 10–20 km of the coast (figure 10), consistent with estimates of the Rossby baroclinic radius of deformation based on these CTD data.

Between sweeps 1 and 2, all isopycnals to depths of at least 200 m, the maximum depth of the CTD casts, shoaled in response to increasing southward wind. The 26.0 isopycnal actually surfaced during sweep 2. Over the same interval, the outcropping of the 25.5 isopycnal moved from 35 km to 75 km offshore. The generally higher densities during sweep 2 indicate more recently upwelled water, in agreement with the stronger southward wind.

Possibly the most striking temporal variability is associated with the position, strength, and slope of the offshore front that separates less dense (warm, fresh) offshore water from denser (cool, salty) water nearer the coast. The front was located about 90 km offshore during sweep 1. Following the strong wind reversal at the onset of sweep 3, this front intensified, steepened, and moved to within about 35 km of the coast. The ocean response was rapid, within a few days of the wind reversal. Near-surface stratification also increased after the reversal (i.e., the mixed-layer depth decreased). The pattern of increased near-surface stratification during periods of weak wind was also noted elsewhere in the survey region.

It is thought that low wind speed results in reduced vertical mixing, which allows heat entering the ocean from the atmosphere to be trapped in a relatively thin surface layer. Reversals also bring warmer air into the region: the air temperature at NDBC buoy 46042, off Monterey, increased by 3°C during the reversal at the beginning of sweep 2 (figure 3). The large excursions in the position and strength of the offshore front, and the general change in the region's surface temperature are evident in the SST images (figure 9).

The position of the offshore front near the Gulf of the Farallones (figure 11) also moved between sweeps, suggesting that the relative contribution of upwelling varies on time scales of 10 days or less. However, the source of upwelled water over this portion of the shelf does not appear to be "local." Although isopycnal doming is again evident over the continental shelf break and slope (>50 km offshore), isopycnals are relatively flat over the shelf. No upwelling within a Rossby radius of the coast is apparent. Thus most of the upwelled water in the gulf is probably advected from the north, as implied from the near-surface hydrographic maps (figures 4 and 5) and satellite SST images (figure 9). Contrast this with the Davenport section (figure 10), where there is significant isopycnal tilting up to the coast.

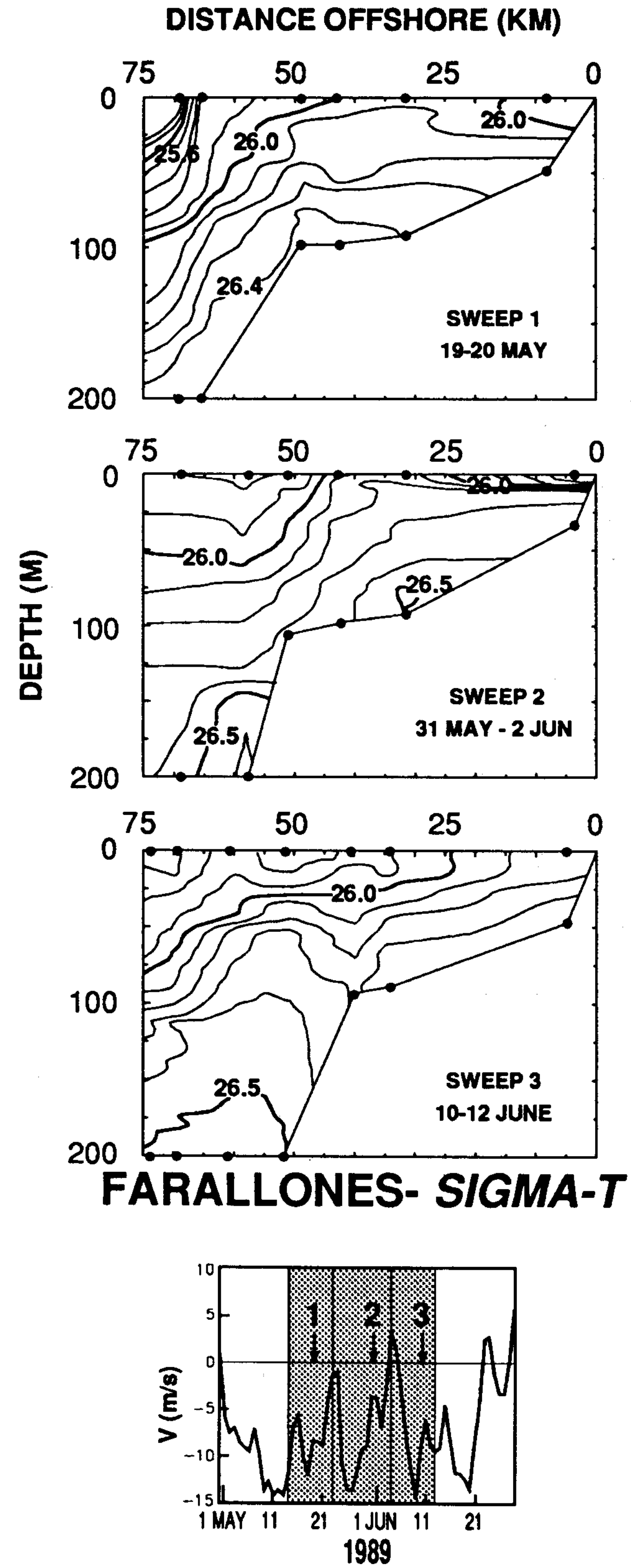

Figure 11. Vertical distribution of density along Farallones cross-shelf section (37°53′N), by sweep. Time series of the principal axis wind component at NDBC buoy 46026 is included. *Bold arrows above the wind records* indicate the start of each survey.

Although some of the isopycnal tilting over the slope off the Farallones may have been due to true upwelling, the structure is probably an artifact of the front that separates warm, fresh, offshore water from cool, saline, upwelled water. A density maximum is seen about 30–40 km offshore at this latitude, corresponding to the core of the cool water advecting south past Point Reyes. This mass of dense water appears even more distinct in contrast to the less-dense lens of water over the inner 20 km of the section, the source of which was probably San Francisco Bay outflow.

DISCUSSION

The hydrographic observations from the spring 1989 rockfish survey define a physical environment off central California that comprises several persistent and distinct water masses. The general locations of these masses are consistent throughout the 30-day survey period, and during the spring of other years as well (Schwing et al. 1990a). Most notable are two recently upwelled water masses off Point Reyes and Point Año Nuevo, which are separated from warmer and less saline offshore water by a distinct alongshelf front. Other distinct masses include the outflow from San Francisco Bay, and nearshore water, which is upwelled, advected onto the shallow portions of the shelf, and then warmed. Because much of this nearshore area is fairly sheltered from the wind, vertical mixing is reduced, and heat accumulates rapidly in the surface mixed layer. Nearshore areas also receive greater radiation because they are less susceptible to fog.

The location of each water mass, and of other circulation features described here, is linked to the physical processes characteristic of the site (e.g., wind forcing, flow/bathymetry interaction). The forces that contribute to the region's dynamics are the same everywhere; it is the *relative balance* of these forces — which varies (possibly greatly) with position — that leads to the seemingly incoherent arrangement of upwelling centers, fronts, and other dynamic features. For example, the proper combination of wind forcing and bathymetry is needed for upwelling to occur at a specific site. Given the rich environmental complexity off central California, it is not surprising that the coastal ocean displays such high mesoscale variability.

Despite their persistence, these water types vary substantially in extent and relative importance from sweep to sweep. Although wind direction during late spring is predominantly equatorward, or upwelling-favorable, the wind typically weakens or reverses direction at 3–10-day intervals (figures 2 and 3). The coastal ocean responds to such meteorological changes within 1–2 days. The strength of the offshore front that separates cool, salty shelf water from warmer, less saline offshore water seems directly linked to wind-relaxation events. Sharper fronts are observed immediately after relaxations or reversals of upwelling-favorable wind. The fronts also migrate closer to the coast after wind-relaxation events.

The dynamics behind this pattern may be relatively straightforward. During upwelling, an offshore flow in the surface Ekman layer sets up a cross-shelf pressure gradient and isopycnal doming within a Rossby radius of the coast. These gradients are balanced by an equatorward geostrophic current. Under steady upwelling conditions, the offshore surface flow is mass balanced by along-isopycnal flow toward the coast at depth. The resulting counterclockwise vertical cell (looking north) is confined inshore of the upwelling front.

A decrease or reversal in wind stress creates an unbalanced situation. An onshore flow develops to adjust the cross-shelf gradient. This flow is revealed by the rapid onshore movement of the offshore front. The circulation of the inshore cross-shelf cell is opposite the circulation during upwelling. Whereas the seasonal upwelling flow is controlled primarily by the density field, the 3–10-day variations in upwelling are largely barotropic (Mooers et al. 1978). Another effect of episodic upwelling periods separated by relaxation events is a long-term circulation that is a hybrid of these two regimes (Smith et al. 1971; Send et al. 1987). This highly complex residual circulation may maintain larvae and their prey near the highly productive upwelling centers. Direct velocity measurements are needed to confirm this conceptual model of the upwelling/relaxation circulation based on hydrographic and satellite data.

Our observations reveal that recently upwelled water flows offshore and equatorward as two distinct streamers separated by a warm, less saline water mass. Some unknown dynamic process exists that either (1) forces warm offshore meanders near the shelf or (2) forces separate upwelling streamers to the west and south, and causes the subsequent complex frontal interaction between these masses. We are examining this phenomenon in more detail. Some recent studies describing the behavior of filaments as they flow offshore, and in some cases retroflect (Strub et al. 1991) may shed light on this problem. The mechanism responsible for the variegated offshore front is also not known. Several possibilities exist: barotropic or baroclinic instabilities, spatial wind variability (wind curl), or variations in bathymetry.

Of particular interest to fisheries oceanographers is how the important coastal processes, water masses, and features off central California affect fisheries recruitment in the region. In the paragraphs below, we discuss some of the key physical processes associated with the rockfish survey results, and speculate on their biological implications. Larval and juvenile groundfish may take advantage of these oceanographic processes to enhance development, avoid predators, and position themselves for favorable settlement as preadults.

1. *General transport patterns.* Consider first the typical, persistent circulation of the region during spring. The mean flow generally parallels the near-surface isotherms, with cooler water on the left when looking downstream. The hydrographic structure in the upper 200 m implies a predominantly equatorward surface current over the entire region. Previous current-meter studies between the Farallones and Monterey Bay have measured predominantly southward velocities, typically 20–30 cm/s, during the upwelling season (Strub et al. 1987a; Chelton et al. 1988). Superimposed on this pattern are numerous eddylike features, whose horizontal scales are typically 10 km, that extend as deep as 100 m. The circulation is typically clockwise around a warm feature, and counterclockwise around a cool-water mass.

Species with long larval stages are likely to be transported a substantial distance southward by the mean flow. In the absence of any other transport mechanism or behavioral strategy that precludes long-distance transport, recruitment within a central California population will probably be provided by a stock to the north. Mesoscale features, which appear to be somewhat persistent, may be one mechanism for maintaining larvae near their source, or at least aggregating them before settlement. These features may also concentrate and enhance primary and secondary production, which could attract larvae and promote their development (Hayward and Mantyla 1990). Finally, the well-defined and persistent alongshelf front that separates offshore and shelf water may also separate areas of high and low biological productivity (Hood et al. 1990).

2. *Discrete, persistent upwelling centers.* Our observations suggest that upwelling does not occur uniformly along the central California coast, but is confined to several discrete upwelling centers. The dominant centers in this region appear to be somewhere north of Point Reyes, near Point Año Nuevo, and at Point Sur, to the south of the survey region. The three-dimensional structure of these centers is associated with variations in alongshelf and vertical flow, which are due to spatial differences in the wind field, bathymetric irregularities, and coastline irregularities (Smith 1983). Variable coastal upwelling and advection produces a complex hydrography and circulation near the coast, and numerous cross-shelf as well as alongshelf fronts. Thus certain locations along the coast associated with this variability may be more favorable for the aggregation and development of groundfish larvae and their prey. Closely spaced physical and biological sampling is required to properly resolve this complexity *in situ*.

Frequency of wind reversals. Wind forcing is not continuously upwelling-favorable in time, but relaxes or reverses direction every three to ten days. As our results demonstrate, an onshore surface flow develops in response to each relaxation event. This flow, which is evidenced by the rapid onshore movement of the offshore front, may also transport nutrient-rich water, plankton, and larval fish back toward the coast, or at least maintain their position fairly close to the coast. A poleward component of flow also develops during relaxation (Send et al. 1987) and may limit the extent that larvae are transported alongshore before settlement. At least, the absence of continuous upwelling precludes upwelled water and its contents from being transported far offshore, and into the southward-flowing California Current. Episodic upwelling regularly provides nutrients to the coastal environment while it maintains material, including larval and juvenile fish, relatively close to the source of high productivity.

4. *Frontal position, strength, and variability.* The offshore front moves rapidly onshore and strengthens during wind reversals. As it moves onshore, it probably transports and accumulates material in the frontal zone. Preliminary analysis suggests that the largest hydrographic variability in this region is along fronts (Schwing et al. 1990a). This variability probably is associated with the 3–10-day wind variability described in this paper. Evidence suggests that plankton biomass is maximized relative to offshore filaments (Abbott and Zion 1987; Hood et al. 1990). Larger organisms may be able to detect these variations and position themselves in productive frontal zones. Future analyses will correlate larval and juvenile abundance with frontal position, to test the hypothesis that fronts aggregate fish. Aggregation may be either active (fish are transported with the front) or passive (higher prey concentrations within the front attract larvae and juveniles).

5. *Aging of upwelled water.* Some time lag exists between the initial upwelling of nutrient-rich water, the peak in primary production, and the peak in secondary production. "Aged" upwelled water may

be a more productive trophic environment for larval and juvenile groundfish. Episodic upwelling events bring pulses of productive water to the surface, where — under the right environmental conditions — energy is sequentially passed up trophic levels to the groundfish. Again the importance of the offshore front as a mechanism for concentrating nutrients and plankters is evident. If offshore flow is continuous or too strong, these materials will disperse rapidly, creating a relatively unproductive environment for larval growth. Another potentially productive environment is upwelled water trapped in cyclonic eddies (Hayward and Mantyla 1990).

It is still not known how, and to what degree, larval and juvenile groundfish respond to these physical factors to maintain a position that best helps them grow rapidly, avoid predators, and settle in optimal sites. The complexity of the region's physical oceanography is reflected in the temporal and spatial variability of phytoplankton (Hayward and Mantyla 1990; Hood et al. 1990) and zooplankton (Abbott and Zion 1987). This complexity may selectively fractionate biological organisms by size or taxonomic group as well (Hood et al. 1990). For example, a phytoplankter's position is totally controlled by the current regime, whereas zooplankton can modify their position with their behavior to abet or minimize their transport. Smaller groundfish larvae are much more at the mercy of the flow than are juveniles and preadults. Thus when considering how the processes and features of circulation affect a region's biological variability, the behavioral capabilities of the organism in question must be addressed specific to its life history and trophic level. One intriguing prospect is that dynamic features act as "trophic traps" for fish; i.e., eddies and fronts that concentrate plankton ultimately may attract fish, concentrating them as well.

We have provided a conceptual model of the spring circulation off central California, and speculated how it may directly and indirectly affect fish distribution and abundance. But there is still much to be learned about this coastal environment. This will require more detailed synoptic field measurements that combine physical and biological sampling; the development of refined process models; and, ultimately, coupled physical-biological models that realistically account for behavioral effects.

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