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The Coastal Ocean Dynamics Experiment Collection: An Introduction

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The Coastal Ocean Dynamics Experiment (CODE) was designed to identify and study those dynamical processes which govern the wind-driven motion of water over the continental shelf. The initial effort in this multiyear, multi-institutional research program was to obtain high-quality data sets of all the relevant physical variables needed to construct accurate kinematic and dynamic descriptions of the response of continental shelf waters to strong wind forcing in the synoptic band covering 2- to 20-day variability. Two small-scale, densely instrumented field experiments, each approximately 4 months long, were conducted in spring and summer 1981 (CODE 1) and 1982 (CODE 2). A more sparsely instrumented, long-term, large-scale component was also conducted in conjunction with a separate but related Large-Scale West Coast Shelf Experiment (informally called "SuperCODE") to help separate the local wind-driven response in the region of the small-scale experiments from motions generated in some distant region along the coast and to investigate the seasonal cycles of atmospheric forcing, water structure, and coastal currents between 35° and 48°N.

The site selected for CODE is a region of the continental shelf north of San Francisco extending from Point Reyes north to Point Arena (see Figure 1). Relative to the rest of the California shelf, this location is characterized by both simple bottom topography and large wind stress fluctuations during both winter and summer. The monthly mean wind stresses in the CODE region are the largest along the U.S. west coast. More importantly, the fluctuating wind stress exhibits large variability on time scales of several days, superposed on a strong annual cycle which consists of generally southward (upwelling-favorable) winds in the spring and summer and strong variable winds in the winter. The middle and outer shelf in this region has a mud–silty sand bottom and is generally characterized by an absence of large-scale bedforms [*Cacchione et al.*, 1983]; hence relatively well behaved near-bottom flow was expected and found in CODE [*Grant et al.*, 1983].

The major observational elements in CODE were (1) moored arrays instrumented to measure wind velocity, air temperature, solar radiation, current velocity, water temperature, conductivity, and bottom pressure; (2) shipboard observations of water temperature, conductivity and current, and velocity as a function of depth; and (3) aircraft observations of wind velocity, wind stress, temperature, humidity, and sea surface temperature. In addition, surface drifters were tracked from shore and by aircraft; satellite-derived sea surface temperature data and coastal zone color scanner (CZCS) data were collected; and auxiliary measurements of wind, atmospheric pressure, and sea level at appropriate coastal stations and environmental buoys were obtained.

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The first small-scale experiment (CODE 1) was conducted as a pilot study in which primary emphasis was placed on characterizing both the wind-driven "signal" and the "noise" from which this signal must be extracted. In particular, CODE 1 was designed to identify the key features of the circulation

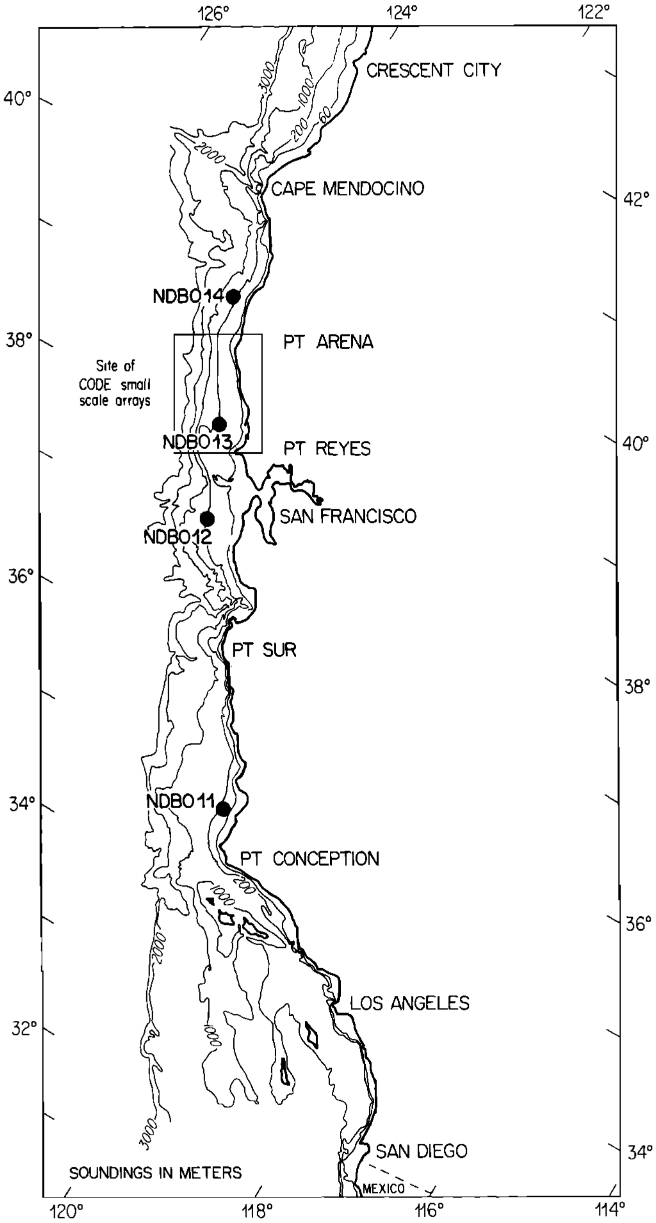

Fig. 1. The region of the CODE small-scale experiment shown in relationship to the rest of the California coast and adjacent continental shelf. The locations of NOAA Data Buoy Office (NDBO) meteorological buoys deployed along the California shelf are also shown.

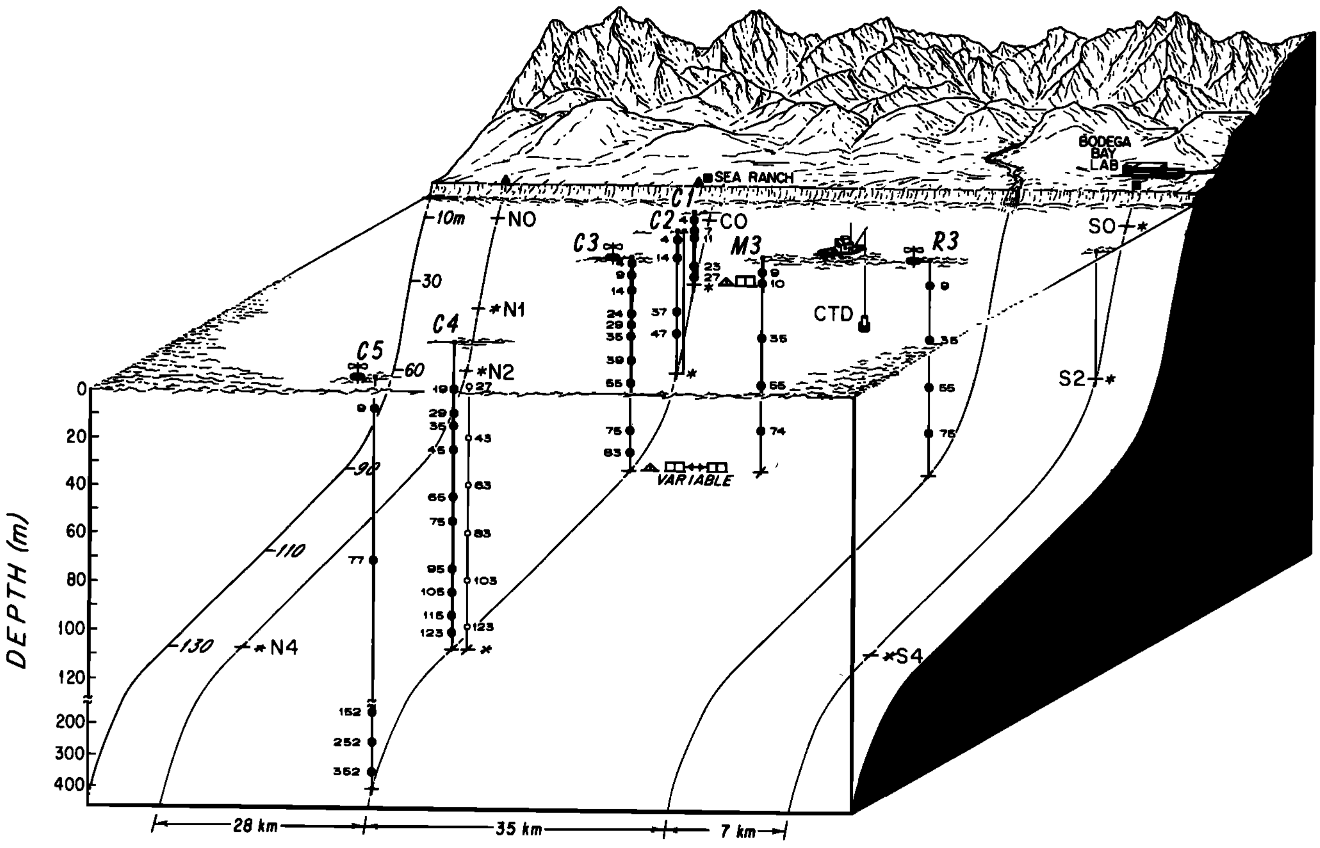

Fig. 2. A three-dimensional schematic of the final CODE 1 moored array which returned usable data. Current meter locations are identified by solid circles, meteorological buoys are shown by buoys, the temperature-conductivity chain is shown by open circles, the bottom stress instrumentation is shown by bisected triangles and rectangles, bottom pressure and temperature recorders are shown by asterisks, coastal sea level stations are shown by triangles, and coastal meteorological stations are shown by solid squares. Thermistor chains are shown at C2 and S2. The shelf width in this region is about 20 km. One of the bottom stress instruments was moved during both CODE 1 and CODE 2 to sample various locations near C3.

and its variability over the northern California shelf and to determine the important time and length scales of the surface forcing and wind-driven response. Accordingly, a T-shaped array of instrumented moorings was deployed, consisting of a five-element cross-shelf transect and a three-element subarray deployed along a midshelf isobath. A schematic of the CODE 1 moored array is shown in Figure 2. Previous observations had suggested that the vertical structure of currents was likely to change most rapidly in a cross-shelf rather than alongshelf direction, and thus the Central line located near Sea Ranch was most heavily instrumented.

The CODE 1 results showed that the current field was highly coherent in the vertical but exhibited larger than expected horizontal mesoscale variability over the shelf and suggested that the flow over both shelf and slope may be strongly influenced by offshore eddy features, distant and local wind forcing, and local topographic features like Point Arena and Point Reyes. As a result, the moored array for the second small-scale experiment, CODE 2, was designed with reduced vertical but increased horizontal sampling to study the mesoscale variability in all parameters. The CODE 2 moored array consisted of three main cross-shelf subarrays and a lightly instrumented cross-shelf subarray just north of Point Arena to examine flow continuity around Point Arena. A schematic of the CODE 2 moored array is shown in Figure 3. The three main cross-shelf subarrays were labeled the North (N), Central (C), and Ross (R) lines and consisted of moorings deployed at the 60-m, 90-m, and 130-m isobaths which characterize the inner, middle, and outer shelf, respectively. In addition, the ship and aircraft survey areas were enlarged to investigate better the influence of Point Arena and slope flow phenomena.

The CODE field program ended in early 1983, and some results have been published prior to this special issue. An initial description of the CODE 1 results presented in *Eos* [*CODE Group*, 1983] focused on the spatial structure and variability of the various fields and the need for expanded horizontal sampling in CODE 2. Other early results included an analysis of the large-scale sea surface temperature (SST) field from advanced very high resolution radiometer (AVHRR) imagery and its relationship to the large-scale wind field and coastal topography [*Kelly*, 1985], the existence of atmospheric internal Kelvin waves propagating northward in the coastal marine layer off northern California [*Dorman*, 1985], a description of water structure over the shelf and slope in CODE 1 and the relationship between atmospheric forcing and variability in shelf water properties [*Huyer*, 1984], nonlinear internal waves propagating across the outer shelf [*Howell and Brown*, 1985], event and statistical descriptions of the Lagrangian flow field and the heat budget as determined by near-surface drifters [*Davis*, 1985*a*, *b*], the existence of large horizontal current shear over the shelf inferred from a remotely sensed surface wave refraction pattern [*Sheres et al.*, 1985],

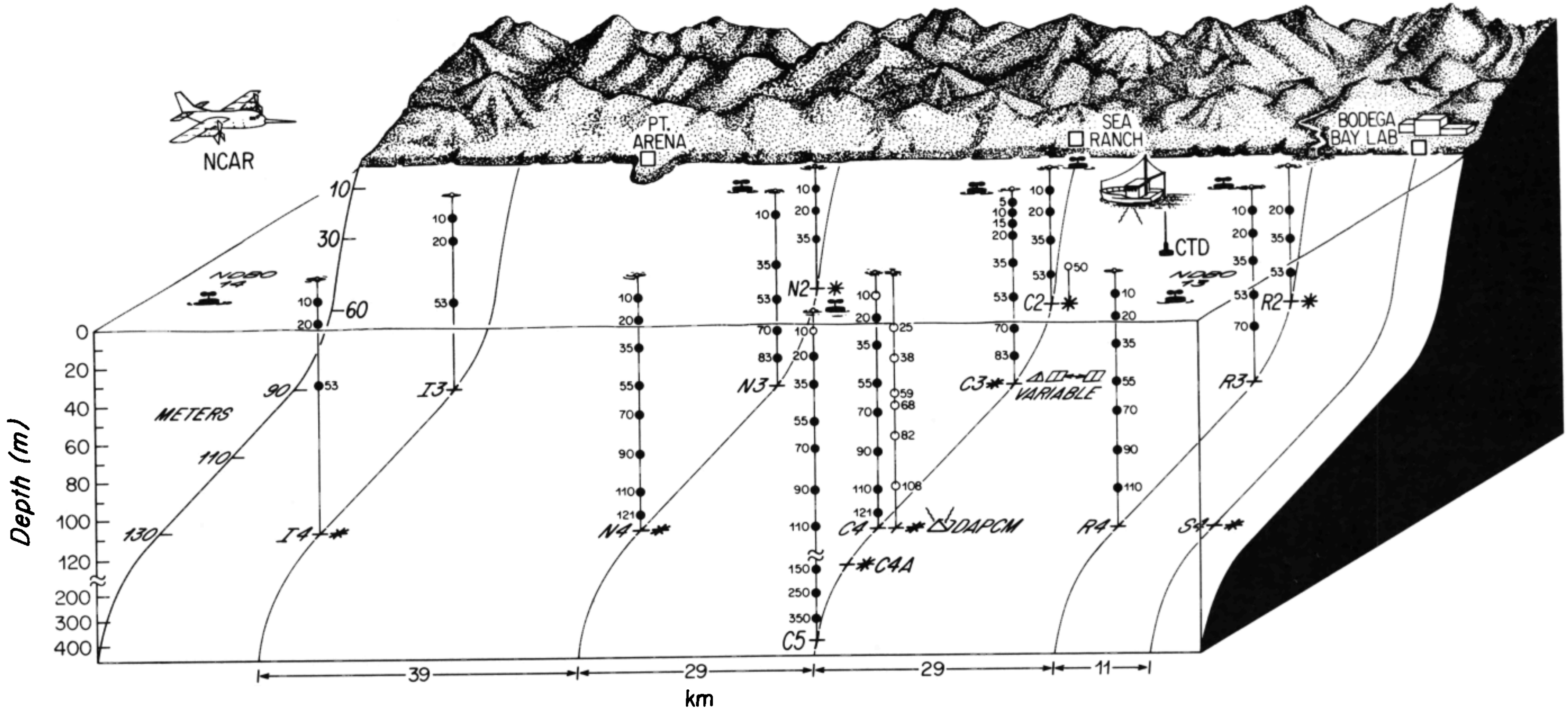

Fig. 3. A three-dimensional schematic of the final CODE 2 moored array which returned usable data. Current meter locations are identified by solid circles, meteorological buoys are shown by buoys, the temperature-conductivity chain is shown by open circles, the bottom stress instrumentation is shown by bisected triangles and rectangles, bottom pressure and temperature recorders are shown by asterisks and coastal meteorological stations are shown by open squares. A bottom-moored Doppler acoustic profiling current meter (DAPCM) was deployed at C4. The NCAR Queen Air and R/V *Wecoma* were used for all aircraft and most shipboard survey work respectively, in CODE 1 and 2.

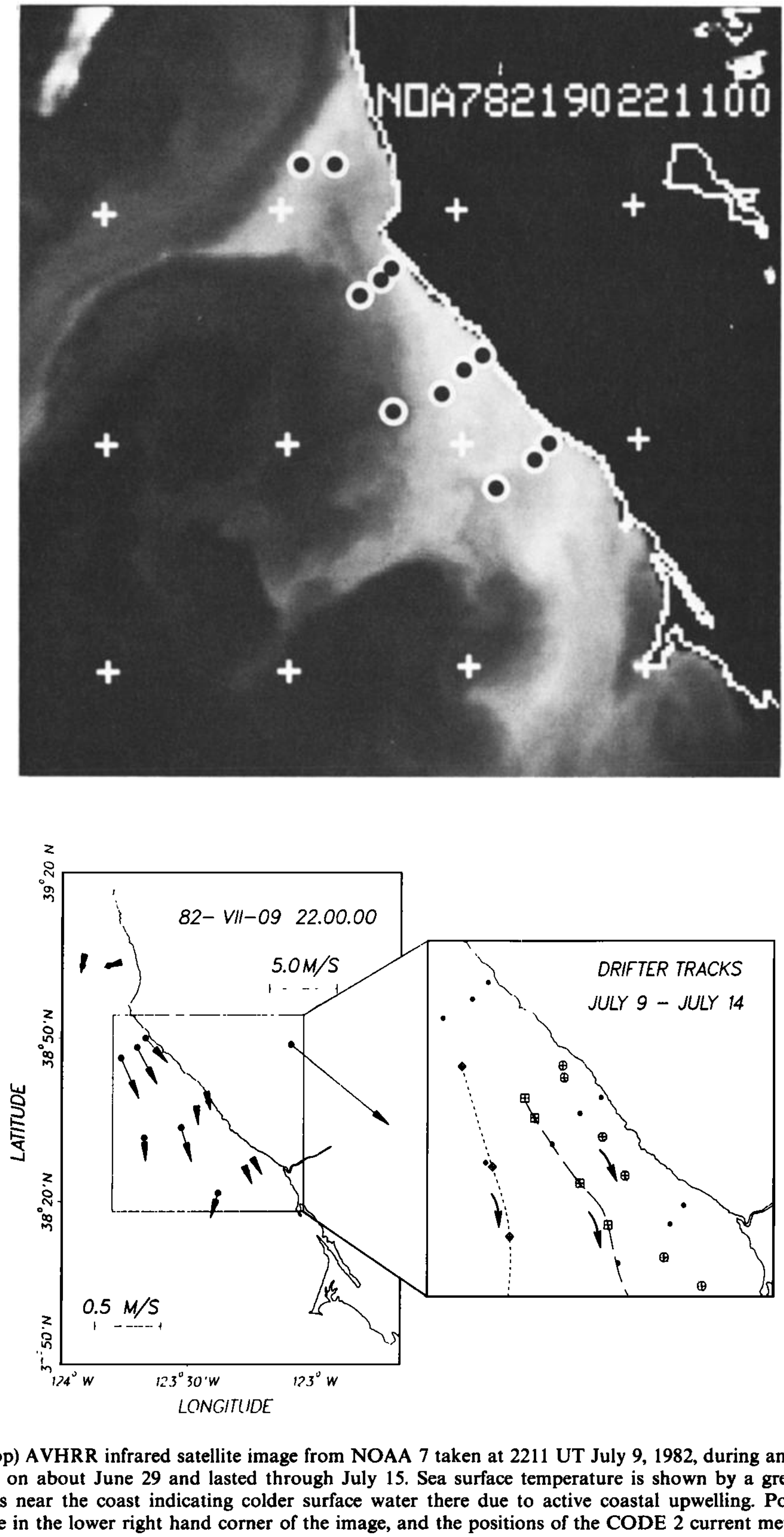

Fig. 4. (top) AVHRR infrared satellite image from NOAA 7 taken at 2211 UT July 9, 1982, during an upwelling event which started on about June 29 and lasted through July 15. Sea surface temperature is shown by a grey scale with the lighter regions near the coast indicating colder surface water there due to active coastal upwelling. Point Reyes is the coastal feature in the lower right hand corner of the image, and the positions of the CODE 2 current meter moorings are noted by circles. (bottom) On the left are the low-passed current vectors at 10-m depth on each of the current meter moorings and the wind vector from the C3 meteorological buoy (displayed in the upper right of this panel) at the same time as the satellite image. Scales for the current and wind vectors are given in the lower left and upper right respectively. The right panel shows selected surface drifter tracks through the CODE array over a 5-day period beginning July 9. Symbols represent actual drifter fixes; lines connecting symbols are subjective representations of the drifter tracks. Note that wind and current vectors and drifter tracks are all southeastward and a band of cold water is evident near the coast.

the influence of the combined wave and current near-bottom flow field on bottom stress [*Grant et al.*, 1984], sediment transport over the inner shelf [*Cacchione et al.*, 1984], and a description of several offshore jets or "squirts" of upwelled shelf water based on shipboard acoustic Doppler current and hydrographic observations [*Kosro and Huyer*, 1986]. In addition, over 40 CODE technical and data reports have been published by the various CODE investigators. Listings of these and other published papers, plus copies of data reports summarizing the CODE 1 [*Rosenfeld*, 1983] and CODE 2 [*Limeburner*, 1985] moored array and large-scale observations are available and can be obtained by writing to us at the Woods Hole Oceanographic Institution.

Because CODE involved investigators from both coasts, informal workshops have been held at the fall meetings of the American Geophysical Union to discuss results and coordinate analyses, and the idea of a dedicated issue of the *Journal of Geophysical Research* arose as a vehicle for presentation of other initial analyses of the various CODE observations. The collection of papers that follows is the result of that effort. Some papers focus on one or several phenomena or processes and use various parts of the combined CODE data set in their analyses, while other papers describe specific measurements or present modeling results. While the primary objective of CODE was to examine the subtidal shelf response to strong synoptic scale wind forcing, the CODE and CODE-related studies presented in this collection investigate many different processes which cover a wide range of spatial and temporal scales, from thousands of kilometers to centimeters and from months to seconds, respectively.

An important goal of the CODE program is to characterize atmospheric forcing over the California shelf. The first four papers in this volume examine various aspects of the wind forcing. *Halliwell and Allen* [this issue] use both observed and geostrophic winds derived from surface pressure maps to characterize the structure and variability of the large-scale surface wind field along the west coast of the United States and Canada during both winter and summer seasons. An overview of the marine boundary layer structure and the associated surface wind field over the northern California shelf during the upwelling season is given by *Beardsley et al.* [this issue]. The marine layer in this region during the upwelling season is capped by a sharp inversion during periods of persistent upwelling-favorable winds, and *Zemba and Friehe* [this issue] use aircraft measurements to describe the low-level jet in the alongshelf wind profile which occurs near the inversion height over the shelf. During the spring and summer upwelling season, the surface winds over the shelf off northern California are strongly polarized in the alongshelf direction and are generally upwelling favorable; however, the winds occasionally weaken or reverse. *Dorman* [this issue] shows that some of these wind relaxations or reversals may be associated with northward propagating coastally trapped gravity currents in the marine boundary layer.

The two CODE small-scale experiments were conducted during the upwelling season which occurs in late spring and summer over the northern California shelf. *Strub et al.* [this issue (*a*)] use the long-term CODE and SuperCODE coastal wind, sea level, and moored current measurements to describe the annual variations in atmospheric forcing, current, water temperature, and sea level along the west coast of the United States between 35° and 48°N. The "spring transition" is a sudden, large-scale event, with an alongshelf scale exceeding 1000 km, which marks the establishment of the North Pacific high and the onset of persistent upwelling-favorable winds along the Oregon and northern California coast. The atmospheric spring transition usually occurs over a 1- to 2-day time span in late March or April and is followed by a more gradual fall transition (occurring in September and October) back to winter conditions. The CODE small-scale arrays were deployed in March or early April (thus capturing the spring transition) and continued through the spring and summer upwelling season. *Strub et al.* [this issue (*b*)] describe the large-scale characteristics of the oceanic spring transition along the California and Oregon shelf, while *Lentz* [this issue] gives a more detailed description of the shelf response in the CODE region to this sudden atmospheric transition.

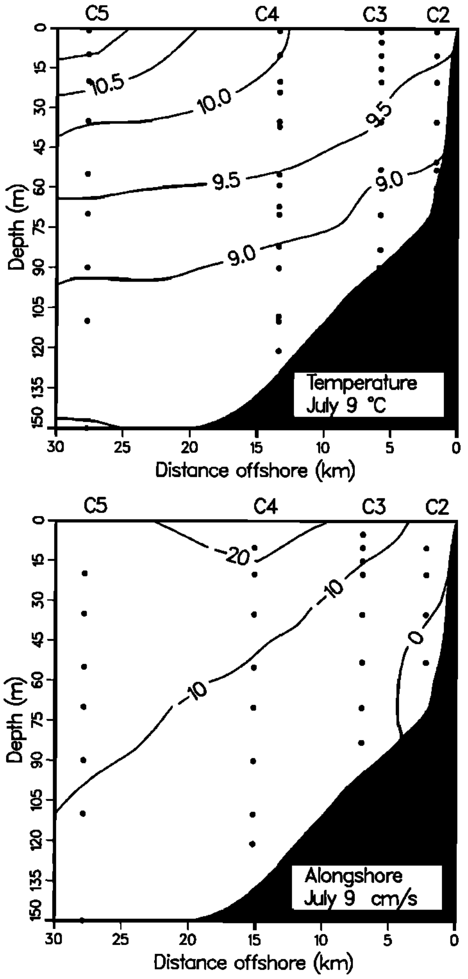

Fig. 5. Cross sections of the low-passed alongshelf current and temperature along the C line at 2200 UT July 9, 1982 (same time as Figure 4). The current meter measurements used to infer the isotachs and isotherms were made at the locations identified by dots. Note that the isotherms slope upward toward the coast. The alongshelf current is equatorward, with the maximum velocity at midshelf.

An overview and comparison of the spatial structure and temporal variability of the post-spring transition surface wind stress, current, and temperature fields during CODE 1 and 2, based primarily on the moored observations, is presented by *Winant et al.* [this issue]. This and some of the subsequent papers focus on the shelf response to the two basic wind states during CODE: periods of strong, persistent upwelling-

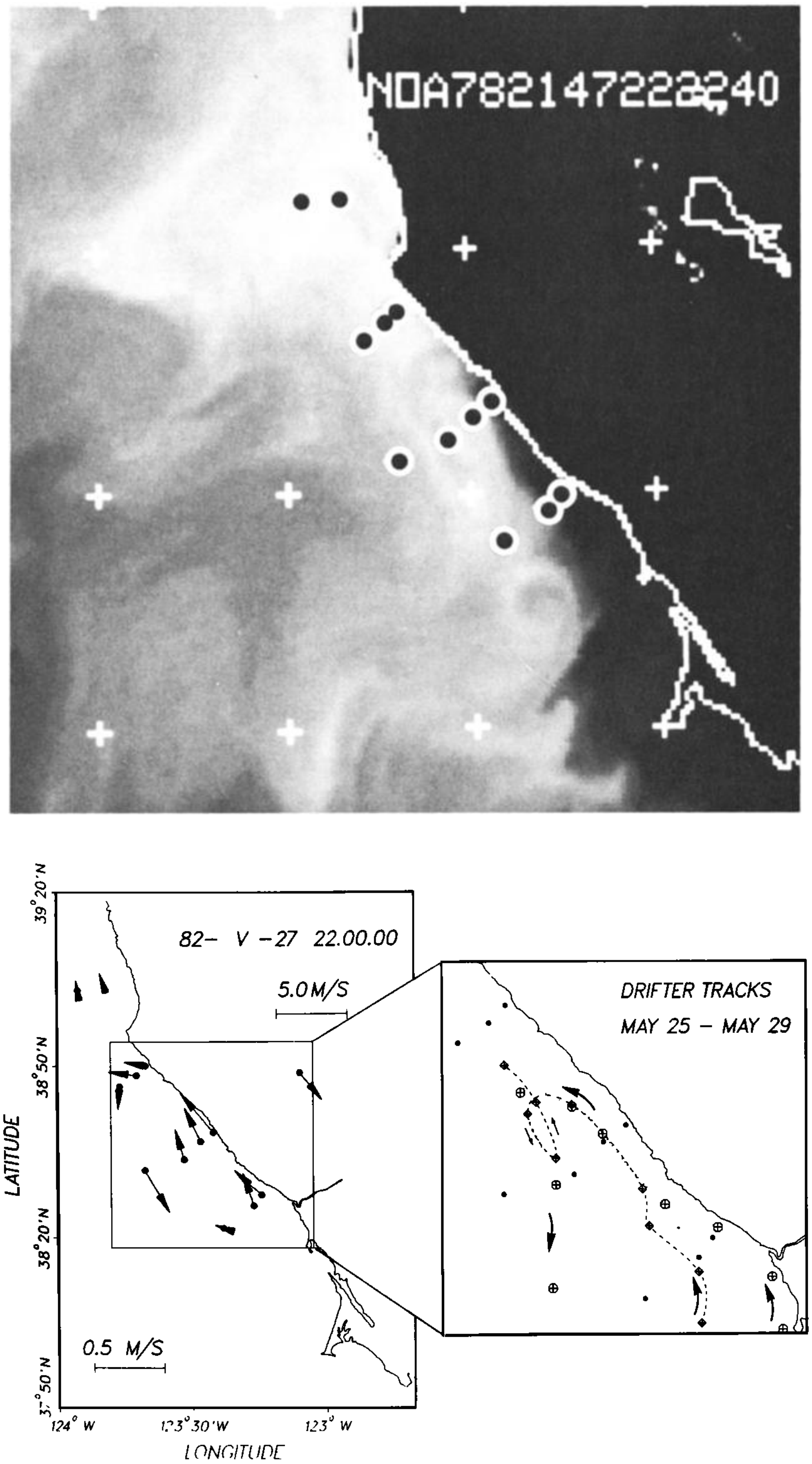

Fig. 6. Same as Figure 4 for a relaxation event during CODE 2. The satellite image was taken at 2222 UT May 27, 1982, and the low-passed wind and 10-m current vectors correspond to the same time. This wind relaxation event started on May 23 and lasted until June 1. The drifter tracks cover the time period from May 25 to 29. Note that the wind is weak and there is a more complicated current pattern relative to the upwelling event in Figure 4. Both the current meters and the drifters show a poleward flow nearshore, with a band of warm water extending poleward from Point Reyes.

favorable winds, and periods of weak and/or reversed winds called wind relaxation events. Examples of the two resulting flow regimes and the complex three-dimensional structure of the shelf response are illustrated in Figures 4–7. SST and near-surface flow fields and cross-shelf sections of temperature and alongshelf current observed during CODE 2 are shown in Figures 4 and 5 for one upwelling period and in Figures 6 and 7 for one wind relaxation event. These figures, which display satellite infrared images, moored current and temperature observations, and drifter tracks, also give a flavor for the variety of observational techniques used to characterize the shelf response in CODE. An equatorward near-surface jet occurs over the shelf during the upwelling period, with the coldest water near the coast and isotherms sloping upward toward the coast. During the relaxation event, the flow pattern is three dimensional and includes a poleward flow near the coast. A tongue of warm water trapped to the coast extends northward from Point Reyes, and isotherms slope downward toward the coast over the inner shelf and upward over the outer shelf where previously upwelled water is continuing to flow offshore. The overall water temperatures are warmer during the upwelling period shown here because this event occurred later in the summer and there is a general tendency for the shelf water temperatures to rise through the summer [*Huyer*, 1984]. A complementary overview of the spatial structure and temporal variability of the pressure field using observations from moored bottom pressure, temperature, and conductivity sensors and coastal pressure and buoy wind observations is given by *Brown et al.* [this issue]. A description of the spatial structure of the shelf current field during CODE 1 and 2 using shipboard acoustic Doppler current measurements is given by *Kosro* [this issue], while *Huyer and Kosro* [this issue] describe the spatial structure of the temperature, salinity, and density fields in the CODE region based on three mesoscale hydrographic surveys made during each small-scale experiment. While the coldest surface water is generally found over the inner shelf near the coast during active upwelling in the CODE area, a band of warm water is frequently observed nearshore during wind relaxation events (see Figures 6 and 7). *Send et al.* [this issue] propose a simple conceptual model to explain the near-surface, nearshore temperature evolution during wind relaxation events. The cross-shelf structure of temperature, salinity, and light transmission during upwelling and wind relaxation events is examined by *Drake and Cacchione* [this issue].

The CODE moored array included one mooring deployed on the upper slope (C5, Figure 3) for a 16-month period. *Noble et al.* [this issue (*a*)] use observations from this mooring in conjunction with simultaneous observations made over the midslope and adjacent deep-sea basin to examine the structure and variability of the deeper subtidal flow field. They find some evidence for local wind forcing. The structure and nature of the barotropic semidiurnal tidal currents over the northern California shelf and deeper continental margin are described by *Rosenfeld and Beardsley* [this issue] and *Noble et al.* [this issue (*b*)], respectively.

The wave guide nature of the continental margin is well recognized now, and wind-driven coastal-trapped wave theory describes how subinertial currents in a particular shelf region can, in principle, be driven by distant (i.e., nonlocal) wind forcing. *Denbo and Allen* [this issue] describe and contrast the response of alongshelf current and coastal sea level along the U.S. Pacific coast to large-scale atmospheric forcing during CODE 1 and 2 using the combined CODE and SuperCODE data sets. *Brink et al.* [this issue] force a linear model with a realistic frequency-wave number spectrum of the shelf wind stress field to predict the statistical relationship of current, pressure, and density fluctuations over the shelf and slope to wind stress in CODE 2. *Chapman* [this issue] uses observed coastal winds and long, coastal-trapped wave theory to predict the temporal behavior of current, pressure, and density fluctuations over the shelf in the CODE region during CODE 2. Both approaches demonstrate the importance of including realistic specifications of the wind stress and bottom stress fields and are more successful with predictions involving bottom pressure and alongshelf current than density and cross-shelf current.

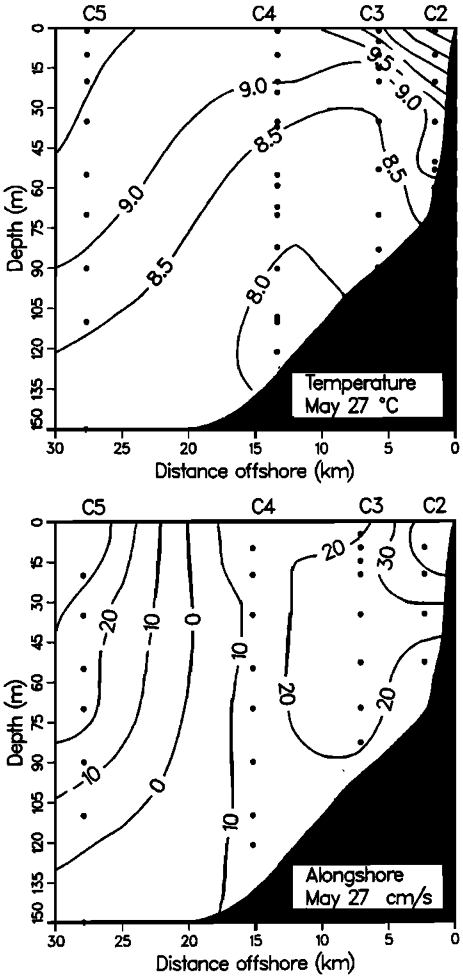

Fig. 7. Same as Figure 5 for the relaxation event shown in Figure 6. Note that the isotherms slope upward toward the coast over the outer shelf and downward over the inner shelf, and relatively warm water is evident very near shore near the surface (the maximum temperature is about 11.5°C at the surface at C2). The alongshore flow is equatorward over the outer shelf and poleward over the inner shelf.

CODE included near-bottom flow measurements made with two types of instrumented bottom tripods. *Cacchione et al.* [this issue] use data from a previous winter deployment of the Geoprobe off Bodega Bay to compare profile estimates of the bottom shear stress with predictions of a simple combined wave-current model that includes moveable bed effects. *Sanford and Grant* [this issue] propose a model to account for dissipation of internal wave energy through the bottom boundary layer which incorporates wave-current interaction theories.

One of the first major deployments of the commercial version of the vector-measuring current meter (VMCM) was made in CODE, and a comparison of this instrument with a vector-averaging current meter (VACM) on a surface mooring in the CODE environment is presented by *Beardsley* [this issue]. A prototype bottom-mounted acoustic Doppler profiling current meter was also deployed at one of the mooring sites in CODE 2 (C4, Figure 3), and a preliminary comparison of the performance of this instrument with both VACMs and VMCMs has been made by *Pettigrew et al.* [1986].

While CODE was originally designed as a physical oceanographic experiment, its results have not been entirely limited to physical aspects of the coastal ocean. In an earlier paper, *Abbott and Zion* [1984] show how sea surface temperature and near-surface phytoplankton pigment concentrations based on coastal zone color scanner (CZCS) imagery evolved during one upwelling event in CODE 1. This analysis has been extended here [*Abbott and Zion*, this issue] to a time series of CZCS imagery spanning much of CODE 1 which shows how spatial patterns of phytoplankton pigment concentration are related to persistent patterns of wind forcing over the northern California shelf. Side-scan sonar records obtained in CODE showing systematic gouges over the central shelf have also provided the first evidence that the California grey whales feed along the bottom during their annual migration along the California shelf to their winter breeding grounds off Baja California [*Cacchione et al.*, 1986].

The papers presented in this volume represent part of the initial analysis effort on the CODE observations. Many CODE investigators are working on follow-up studies which will appear later, hopefully to be followed by a comprehensive review or summary of the entire program.

Acknowledgments. The very successful execution of the CODE field program was made possible through the efforts of a great many people, and the CODE investigators who have been and are now working with the combined CODE data set would like to take this opportunity to express their deep appreciation for the excellent scientific, engineering, and technical support given throughout the entire program. The skill and cooperation of the crews of the Oregon State University research vessel *Wecoma*, the U.S. Gelogical Survey (USGS) research vessel *S. P. Lee*, and the National Center for Atmospheric Research Queen Air research aircraft contributed significantly to the success of the field operations, and the officers and crew of the U.S. Coast Guard Base at Yerba Buena Island in San Francisco Bay and the staffs at the USGS Marine Facility in Redwood City and the University of California, Davis, Bodega Bay Marine Laboratory, all helped make those facilities ideal for staging the field program. The Coastal Ocean Dynamics Experiment has been supported by grants to the individual institutions from the Ocean Sciences Division of the National Science Foundation.

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