Lafferty, K. D., and A. M. Kuris. 1993. Mass mortality of abalone *Haliotis cracherodii* on the California Channel Islands: tests of epidemiological hypotheses. Marine Ecology Progressive Series 96:239–248.

Leet, W. S., C. M. Dewees, and C. W. Haugen (editors). 1992. California's living marine resources and their utilization. California Sea Grant Extension Publication UCSGEP-92-12. University of California, Davis. 257 pp.

Lessios, H. A. 1988. Mass mortality of *Diadema antillarum* in the Caribbean: what have we learned? Annual Review of Ecology and Systematics 19:371–393.

Lewis, D. B., F. Gress, T. Ingram, G. L. Hunt, and D. W. Anderson. 1988. Seabird monitoring handbook. Channel Islands National Park, California, National Park Service, Ventura, California. 78 pp.

List, E. J., and R. C. Y. Koh. 1976. Variations in coastal temperatures on the southern and central California coast. Journal of Geophysical Research 81:1971–1979.

Littler, M. M. 1980. Overview of the rocky intertidal systems of Southern California. In: The California Islands: Proceedings of a Multidisciplinary Symposium (edited by D.M. Power), Santa Barbara Museum of Natural History, Santa Barbara, pp. 265–306.

Littler, M. M., and D.S. Littler. 1979. Rocky intertidal island survey. Technical Report II-5.0. Bureau of Land Management, U.S. Department of the Interior, Washington D.C. 9 pp.

Murray, S. N., M. M. Littler, and I. A. Abbott. 1980. Biogeography of the California marine algae with emphasis on the Southern California Islands. In: The California Islands: Proceedings of a Multidisciplinary Symposium (edited by D. M. Power), Santa Barbara Museum of Natural History, Santa Barbara, pp. 325–339.

Neushul, M., W. D. Clarke, and D. W. Brown. 1967. Subtidal plant and animal communities of the Southern California Islands. In: Proceedings of the Symposium on the Biology of the California Islands (edited by R. N. Philbrick), Santa Barbara Botanic Garden, Santa Barbara, pp. 37–55.

Philbrick, R. N. (editor). 1967. Proceedings of the Symposium on the Biology of the California Islands. Santa Barbara Botanic Garden, Santa Barbara. 363 pp.

Power, D. M. (editor). 1980. The California Islands: proceedings of a multidisciplinary symposium. Santa Barbara Museum of Natural History, Santa Barbara. 787 pp.

Richards, D. V., and G. E. Davis. 1988. Rocky intertidal communities monitoring handbook. Channel Islands National Park, California. 78 pp.

Richards, D. V., and G. E. Davis. In press. Early warnings of modern population collapse in black abalone *Haliotis cracherodii*, Leach, 1814 at the California Channel Islands. Journal of Shellfish Research.

Richards, D. V., C. Gramlich, and G. E. Davis. in press. Kelp forest monitoring—Channel Islands National Park 1982–1989. Channel Islands National Park Natural Science Reports. Ventura, California.

Richards, D. V., D. Kushner, and W. Avery. 1993a. Kelp forest monitoring—Channel Islands National Park (1990 Annual Report). Technical Report NPS/ERUC/NRTR-93/05. National Park Service, University of California, Davis. 195 pp.

Richards, D. V., D. Kushner, and W. Avery. 1993b. Kelp forest monitoring—Channel Islands National Park (1991 Annual Report). Technical Report NPS/ERUC/NRTR-93/06. National Park Service, University of California, Davis. 180 pp.

Seapy, R. R, and M. M. Littler. 1980. Biogeography of rocky intertidal macroinvertebrates of the Southern California Islands. In: The California Islands: Proceedings of a Multidisciplinary Symposium (edited by D.M. Power), Santa Barbara Museum of Natural History, Santa Barbara, pp. 307–323.

Seymour, R. J., M. J. Tegner, P. K. Dayton, and P. E. Parnell. 1989. Storm wave induced mortality of giant kelp, *Macrocystis pyrifera*, in Southern California. Estuarine, Coastal and Shelf Science 28:277–292.

Straughan, D., and D. Hadley. 1980. Ecology of Southern California Island sandy beaches. In: The California Islands: Proceedings of a Multidisciplinary Symposium (edited by D.M. Power), Santa Barbara Museum of Natural History, Santa Barbara, pp. 369–393.

Tegner, M. J., and P. K. Dayton. 1981. Population structure, recruitment and mortality of two sea urchins (*Strongylocentrotus franciscanus* and *S. purpuratus*) in a kelp forest. Marine Ecology Progress Series 5:255–268.

Tegner, M. J., and P. K. Dayton. 1987. El Niño effects on Southern California kelp forest communities. Advances in ecological research 17:243–279.

Tegner, M. J., and P. K. Dayton. 1991. Sea urchins, El Niños, and the long term stability of Southern California kelp forest communities. Marine Ecology Progress Series 77:49–63.

Tegner, M. J., and L. A. Levin. 1983. Spiny lobsters and sea urchins: analysis of a predator-prey interaction. Journal of Experimental Marine Biology and Ecology 73:125–150.

Tissot, B. N. 1991. Geographic variation and mass mortality in the black abalone: the roles of development and ecology. Ph.D. Dissertation, Oregon State University. 271 pp.

VanBlaricom, G. R., and J. A. Estes (editors). 1988. The community ecology of sea otters. Ecology Series 65. Springer-Verlag, New York. 247 pp.

The Fourth California Islands Symposium: Update on the Status of Resources
Edited by W. L. Halvorson and G. J. Maender. 1994. Santa Barbara Museum of Natural History, Santa Barbara, CA.

Understanding the Oceanic Circulation in and around the Santa Barbara Channel

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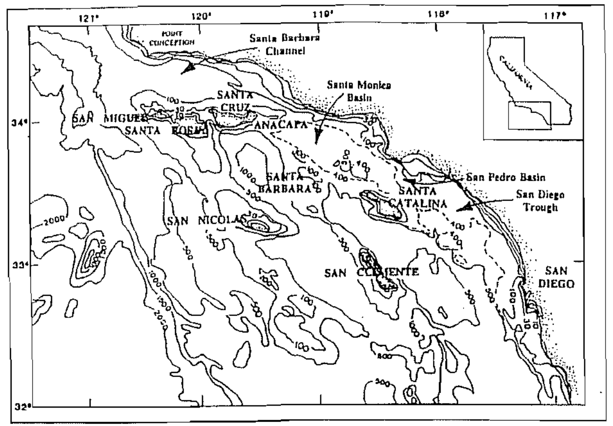
Abstract. The major oceanic circulation patterns characteristic to the Santa Barbara Channel and the greater Southern California Bight are discussed. The bathymetry, sources of water and their physical properties, wind regime (interior and exterior to the bight), geostrophy, and externally driven coastally trapped waves are presented, giving their relative importance in driving the circulation in the region. Characteristics of prominent meso-scale circulation features such as eddies, temperature fronts, and geostrophically induced fluctuations in the coastal currents in the bight and the channel are explained. A new synoptic approach for determining surface currents and surface wind stress in the Santa Barbara Channel is presented as the most plausible way to estimate surface pollutant trajectory. Research supporting this new approach to determining ocean surface trajectories is one of the major objectives of the presently ongoing Minerals Management Service (MMS) study, entitled the Santa Barbara Channel-Santa Maria Basin Circulation Study. Another objective is to use the knowledge gained from the study plus real time data from monitoring stations in the channel for accurate and timely prediction of oil spill trajectory in support of local response to an actual oil spill; a full list of objectives and general field plan are summarized.

Keywords: Oceanic circulation; oceanographic forecaster; California Current; California Undercurrent; California Countercurrent; eddy or eddies; upwelling; thermal front; recirculation; coastally-trapped waves; oil spill trajectory; bi-directional flow; geostrophic currents; upwelling favorable winds.



NOTE: Measurements in fathoms.

Figure 1. Southern California Bight bathymetry (Hickey 1992).

Circulation in the Southern California Bight

One cannot understand the circulation in the Santa Barbara Channel without first having a basic understanding of the circulation in the Southern California Bight, of which the Santa Barbara Channel is a part. The Southern California Bight (Fig. 1) is bounded to the north and east by the California coast, from Point Arguello to the U.S./Mexican international border. It is bounded offshore to the west by the Santa Rosa-Cortes Ridge. Within the bight are submarine valleys and mountains, the peaks of which form the various offshore islands. The ridges and troughs generally run northwest to southeast, with the exception of the Santa Barbara Channel, which runs east to west. The oceanic circulation in the Southern California Bight owes its complexity principally to the bight's composite bottom topography. Any flow entering the 14 basins making up the Southern California Bight at depths below 250 m must do so from the southeast along the San Diego Trough and into the Santa Monica-San Pedro basins. The Santa Monica-San Pedro basins act as a conduit for water flow into the rest of the bight, opening up to the southeast at 737 m, to the northwest into the Santa Barbara Basin at 250 m, and to the west into the Santa Cruz Basin at 650 m. Together, the Santa Monica-San Pedro basins are 100 km long, 40 km wide, and 900 m deep at the deepest point.

The sources of water in the Southern California Bight are (1) the cold, low salinity, highly oxygenated sub-arctic water brought in by the California Current; (2) the warm, saline, central north Pacific water that advects in from the west; and (3) the warm, highly saline, low oxygen content (Equatorial) water entering the bight from the south, principally by way of the California Undercurrent (at 300 m depth), and secondarily by the California Counter-Current closer to the surface (Fig. 2). The distribution of these waters in the bight is such that the top 200 m is typically low in salinity and high in oxygen content, which identi-

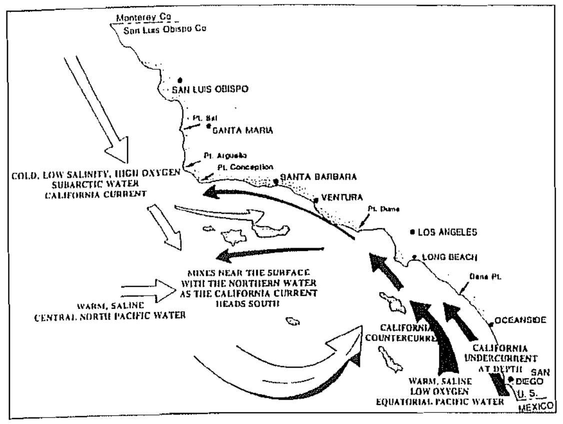


Figure 2. Characteristic oceanic circulation pattern in the Southern California Bight.

fies this water mass as principally sub-arctic, even though the temperatures range between 9 and 18° C. The next 300 m are consistently high in salinity and low in dissolved oxygen, identifying it as equatorial Pacific water. The temperature range for this water mass is 9–5° C (Jackson 1986).

The wind pattern along the west coast of the United States is typically strong, alternating in direction between the northwest and the southeast in the northern part of the coast and becoming more polarized toward the southeast in the southern region, especially off the California coast around Points Sal, Arguello, and Conception. This polarization of the winds toward the southeast off the entire coast of California is most prominent during the late spring to early fall. These winds are called upwelling favorable winds because their consistent southeast direction moves surface waters off-shore. This gives rise to upwelling of cold, nutrient-rich, bottom water at the coast that, in turn, moves this water mass offshore in a continual cycle. The Santa Ynez mountains at the northern part of the Southern California Bight shield bight waters from this strong wind pattern, causing the winds inside the bight to be moderate and directed east to southeast throughout the year.

The circulation patterns in the Southern California Bight were successfully approximated by geostrophic (resultant movement from balance between forces caused by pressure gradients and the earth's rotation) calculations using temperature and salinity data obtained in the now-40-yr-old California Cooperative Oceanic Fisheries Investigations. These patterns were later verified by Barbara Hickey of the University of Washington (Hickey 1992). It is her investigations of the currents in the Santa Monica and San Pedro basins from 1987 to 1990 that give us the detail of the poleward flow in the Southern California Bight, and also some surprising revelations concerning flows associated with this main poleward movement of water.

In Figure 2, we see that the California Current brings in cold, low-salinity, highly oxygenated water from the Subarctic region. It flows from the north, in a southerly direction past Point Conception, where some of the flow is actually pulled into the Santa Barbara Channel. The California Current continues in its southerly direction, mixing along the way with the warm, saline, north-central Pacific water coming in from the west. South of San Diego, part of the California Current spins back up into the Southern California Bight, where it joins the poleward moving California Undercurrent and the California Counter-Current. The California Undercurrent and, secondarily, the California Counter-Current bring warm, highly saline, low-oxygenated Equatorial Pacific water from the south. This poleward flow continues toward the Santa Barbara Channel where it bifurcates, flowing northwest into the Santa Barbara Channel along its northern coast and in a westerly direction just south of the Channel Islands.

Hickey's investigations (Hickey 1992) showed that the currents at the top 200 m over the basins were poleward year-round, with their speed ranging from 15 cm/sec to 20 cm/sec from late spring to winter and approximately 5 cm/sec from late winter to early spring. There also exist 50 cm/sec fluctuations throughout the year. In the spring, these fluctuations are only locally correlated and indicate a counter-clockwise eddy over the basins. The rest of the year, these current fluctuations are correlated with sea-level fluctuations observed as far south as Cape San Lazaro on the Pacific side of the Baja Peninsula, 1,029 km south of the Southern California Bight. These fluctuations turn out to be coastally trapped waves that travel up the west coast of Mexico and the United States at speeds of 500 cm/sec. These are long-period waves with periods of 25 to 30 days. When these coastally trapped waves reach the Southern California Bight, their speeds attenuate to 50 cm/sec. As they pinch into the bight, these waves follow along the coast in a counter-clockwise fashion, where they then exit the bight and continue their trek northward up the coast.

The importance of both of these types of fluctuations is that they are the dominant reason for the way coastal or shelf currents behave in the bight. Through analysis, it was shown that the subtidal coastal currents are driven geostrophically by these fluctuations, and not by the local winds. These processes will have to be investigated further if we hope to be able to perform adequate oil-spill risk analysis along the shelf of the Southern California Bight.

Previously, biologists have thought that benthic (sea bottom) sediments were depleting the oxygen content from the waters in the deep basins (700–900 m depth). This may be true, but they reasoned that this apparent consistent lack of oxygen was due to a very slow overturning of basin water and 6–18 mo for complete overturning. Hickey's measurements indicated that complete overturning in the basins occured in only 3–5 months. The lack of oxygen content in the basins results from a good part of the basin waters coming from the California Undercurrent, bringing in highly saline, low-oxygenated, equatorial Pacific water.

Hickey also discovered that during the fall, a rather large mass of water over the Santa Monica-San Pedro basins (between the depths of 300 and 600 m) actually flows at the top 200 m in the opposite direction of the poleward current, toward the equator (south).

Finally, Hickey presented evidence as to why the poleward flow switches from bifurcating around the Santa Barbara Channel islands (flowing in the channel and south of the channel) to a single flow diverted south and west of the channel's eastern entrance. When there are strong northwest winds causing strong upwelling along the coast and a net eastern flow coming out of the eastern entrance of the channel, virtually no flow can enter the channel from the east. In this case, the coastal upwelling and the eastern-directed flow coming out of the channel at its eastern entrance diverts the poleward flow in the Southern California Bight to a westerly direction just south of the Channel Islands.

Circulation in the Santa Barbara Channel

Information is taken from the results of the MMS 1983–1987 Santa Barbara Channel Model and Field Study (Gunn et al. 1987) and (Lagerloef 1991) and interim results from the Santa Barbara Channel-Santa Maria Basin Circulation Study, Phase I. Current measurements have been taken no closer than 30 m from the surface except for passes between San Miguel and Santa Rosa and between Santa Rosa and Santa Cruz islands, where measurements were taken at 25 m., i.e., mean flows below the mixed surface layer. This limitation was one of the major reasons MMS was prompted to sign a Cooperative Agreement in July 1991 with the Scripps Institution of Oceanography (SIO) to conduct the Santa Barbara Channel-Santa Maria Basin Circulation Study, Phases I and II (1991–1998).

The Santa Barbara Channel is a semi-enclosed basin approximately 100 km long, 50 km wide, and with a central basin depth of approximately 500 m. It occupies the transition region between cold, subarctic coastal water masses to the north and the warm, equatorial waters that have entered the Southern California Bight to the south.

North and west of the western entrance to the channel, water temperatures range from 12° C in the spring to 15° C in the autumn, whereas south and east of the Channel Islands in the Southern California Bight, warmer water temperatures range from 14° C in spring to 17° C in autumn.

There are 4 major circulation patterns seen in the Santa Barbara Channel: (1) bi-directional flow regime with cyclonic (counter-clock-wise) recirculation; (2) western-directed, warm flow circulation regime; (3) eastern-directed, cool flow circulation regime; and (4) cyclonic, eddy-dominated circulation regime (M. Hendershott 1993, pers. comm.).

Bi-directional flow regime with cyclonic recirculation

Approximately 50% of the time, the mean circulation pattern in the channel is bi-directional with cyclonic recirculation, as depicted in Figure 3. Warmer waters from the Southern California Bight flow into the Santa Barbara Channel through its eastern entrance and continue to flow west along the northern coast of the channel to Point Conception. This westbound flow turns north past Point Conception to form the Davidson current, or recirculates by turning south towards San Miguel Island, and then east back into the channel. This northern westbound flow on occasion bifurcates, flowing north around Point Conception and recirculating into the channel. The recirculation of the westbound flow into the channel actually acts to pump cool water in from the west, forming an eastbound current along the northern coasts of the Channel Islands. The west-bound flow at the eastern entrance has its maximum of 20 cm/sec at 80 m depth. At the western entrance, this west-bound jet is displaced upward and toward the northern coast to form a near-surface jet, fluctuating between 25–40 cm/sec.

In the southern half of the channel, a narrow eastbound current of cold water enters through its western entrance and dominates the flow along the Channel Islands. This eastbound current averages a maximum of 10 cm/sec at 100 m depth. The eastbound flow is traceable to the eastern end of Santa Cruz Island, but does not exit through the channel's eastern opening. It therefore must recirculate in the eastern central part of the Santa Barbara Basin or become entrained in the swifter westbound current to the north. The opposing currents along the perimeter of the channel and monotonic mean inflow through the eastern entrance suggest a closed-end cyclonic gyre dominating the eastern central basin. The current meter stations at the western end of the channel showed no similarity in fluctuations to those at the eastern end of the channel.

Moorings 6, 2, 3, 5, 20, and 21 at the western end of the channel (Fig. 4) indicate that the westbound current is broader than the eastbound current along the Channel

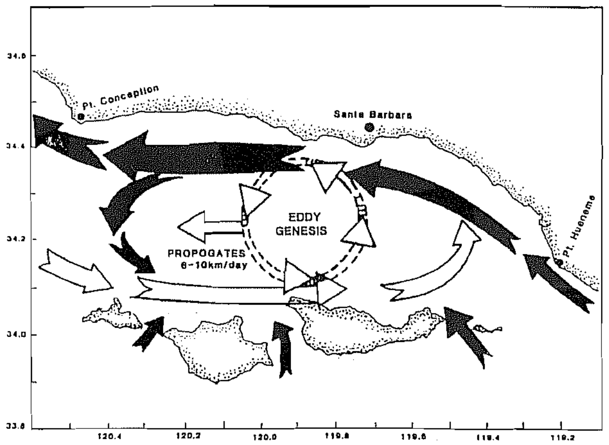


Figure 3. Two-directional flow regime with cyclonic recirculation in the Santa Barbara Channel.

Islands. These data also indicate cyclonic gyre recirculation at that location. Current fluctuations at stations 2 and 3 were inversely coherent with fluctuations at station 5. Fluctuations at station 6 were inversely coherent with fluctuations at station 20. Stations 2 and 3 indicated a southward flow component along the western entrance of the channel. As stated above, it is this cyclonic gyre that is now thought to be a major mechanism that pulls in the colder water from the northwest to form the eastbound current in the southern part of the channel. This current data, and a succession of satellite data, indicate the genesis of counter-clockwise, eddy-like structures in the western central basin, followed by their westward transit at a propagation speed of 7–12 cm/sec or 6–10 km/dy.

Data obtained in the 1983–1987 Santa Barbara Channel Model and Field Study (Fig. 4) also show that inter-island passes act as conduits for inflow, but no known out-flow has been observed. It seems as though the northwest corner of this channel is the only egress for water parcels at 30 m or deeper. There are, however, reversing tidal flows through these inter-island passes. Analysis of the data (Auad et al. 1993) indicates that there is a net influx through these passes of approximately 4% of the total influx into the channel.

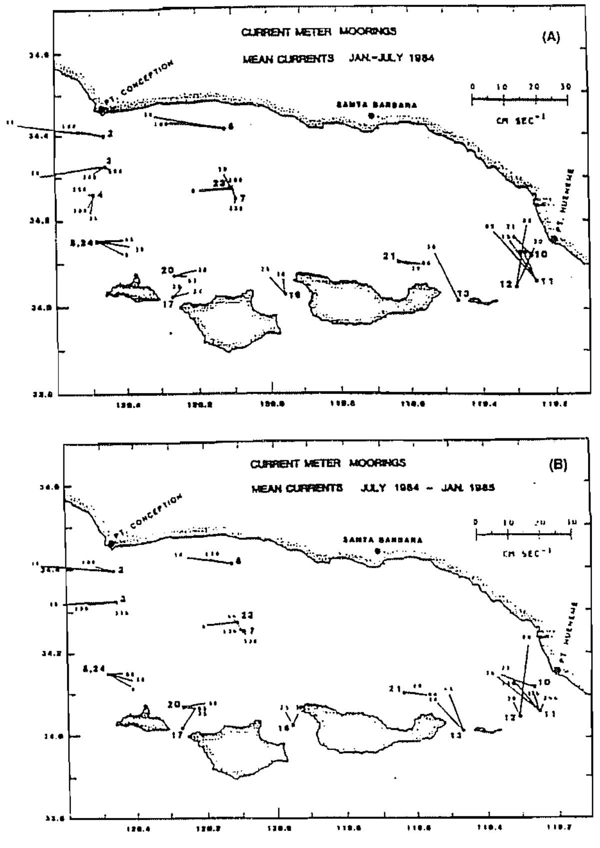


Figure 4. Six-month vector averaged currents from the deployment (A) January–July 1984, and (B) July 1984–January 1985. Numbers at ends of stick vectors indicate measurement depth in meters. Boldfaced numbers indicate mooring I.D. (Gunn 1987).

In this bi-directional flow regime a thermal front forms, which typically runs northwest to southeast (sometimes north to south) across the channel separating the cooler water to the south that flows into the channel from the west along the islands, and the warmer water to the north that flows from the Southern California Bight along the channel's northern perimeter. This thermal front moves back and forth along the channel axis. It has been observed to translate 40 km from the western entrance to the mid-channel position in 3–5 dy.

In general, summer conditions show a 15–30% increase in flow speeds over those in the winter. I believe this occurs for 2 reasons: (1) the maximum poleward flow through the Southern California Bight occurs in the summer and early fall; and (2) the temperature difference between the cold water in the southern part and the warm water in the northern part (of the Santa Barbara Channel) is increased due to seasonal warming of the waters of the Southern California Bight entering the channel from the east, and the pulling in of the colder upwelled water off the Point Arguello region during the season of increased upwelling. This increased difference in temperatures between the 2 water masses intensifies the geostrophic component of flows in the channel.

Western-directed, warm flow circulation regime

There are times when the Santa Barbara Channel undergoes a transition to a monotonic influx of warm water from the Southern California Bight. The channel itself acts as little more than a conduit for the warm water that ultimately flows out the western entrance to the west and, if there is no upwelling at the time, north along the California coast.

Eastern-directed, cold flow circulation regime

This third flow regime occurs less frequently than the others summarized, but does so enough to be considered a characteristic flow regime of the Santa Barbara Channel. Again, the channel acts as a conduit, this time for the California Current flows and coastal bottom waters that experience upwelling and are advected south and east through the channel in the Southern California Bight.

Little is known yet about what upsets the dynamic balance of one circulation pattern causing a transition to another. However, the fourth characteristic flow regime, the cyclonic, eddy-dominated circulation regime, is the second most prevalent regime and is thought to be responsible for generating the bi-directional flow regime discussed first.

Cyclonic, eddy-dominated circulation regime

Satellite images indicate that eddies are frequently formed either in the eastern half or central part of the Santa Barbara Channel. There can be more than a single eddy formed in the channel at one time. Occasionally, a single cyclonic eddy will fill most, if not all, of the channel. Once formed, it migrates toward the western entrance at a speed of 6–7 km/dy. At the western entrance, the eddy intensifies the recirculation there, which pumps cold water from the northwest (offshore Point Arguello).

This possibly initiates our first and most common situation, a thermal front separating warmer Santa Barbara Channel water on the northern part of the channel and colder water along the islands to the south. Preliminary satellite data seem to show a strong tendency for the bi-directional flow regime to be in place a few weeks later.

Effect of winds in the Santa Barbara Channel

Consistent westerly winds over the channel throughout the year opposing the dominant coastal jet suggest that the channel currents at 30 m and below are not wind forced. Fluctuations in wind did not correlate with fluctuations in the current (Lagerloef 1991). This lack of correlation between the Santa Barbara Channel winds and the dominant currents at 30 m in the channel leads one to believe that the mean flow appears to be maintained by the larger circulation patterns of the California Current system in the Southern California Bight, as well as by the physical properties of the water masses converging within the channel.

Unfortunately, one of the shortcomings of the 1983 Santa Barbara Channel Model and Field Study was that there were no near-surface current measurements (5 m or less). Since we have had occasion to track minor oil spills in the channel, we have seen that their trajectories have not necessarily followed the net circulation, but probably the wind and the mixed surface layer circulation. The 1969 Santa Barbara Channel oil spill, however, is one example of a spill that followed the net circulation, which happened to be the bi-directional flow regime with cyclonic recirculation, and eddy formation in the eastern part of the channel.

Santa Barbara Channel-Santa Maria Basin Circulation Study

The Santa Barbara Channel-Santa Maria Basin Circulation Study was designed, in part, to rectify the deficiencies in the data set acquired in the 1983–1987 Santa Barbara Channel Model and Field Study. The 1983–1987 Santa Barbara Channel Model and Field Study simply did not acquire enough information about the area to support further leasing activity. The spatial coverage of the previous study in the Santa Barbara Channel was too sparse along the perimeter of the channel and virtually nonexistent in the center of the channel. There were no near-surface current measurements obtained at all, which, along with meteorological measurements, are the most important for understanding transport and forcing mechanisms that act on a pollutant floating on the ocean surface. The field program was conducted to support numerical modeling of the circulation in the Santa Barbara Channel. This numerical model was ultimately going to provide simulated currents at several depth levels (including the surface) of the Santa Barbara Channel waters that would serve as input to MMS's Oil Spill Risk Analysis (OSRA) model. The OSRA model estimates oil-spill trajectories should an oil spill occur under specified oceanic conditions. Unfortunately, the resulting data set was not adequate for thorough model verification, and the model itself did not produce results that were even close to adequate for an oil-spill risk analysis.

After looking at past studies conducted on the Pacific Coast in support of pre- and post- leasing activities, the National Research Council (NRC) made a number of recommendations (NRC 1989 and 1990). Those recommendations concerned with the status of MMS oceanographic programs are summarized in Table 1. Recommendations 1–4 state that the use of observations, rather than numerical modeling, should play the dominant role in impact assessment, but numerical modeling is still needed to temper statistical estimates with the dynamic picture of the circulation. Recommendation 5 states that substantial field work needs to be undertaken in the Southern California Bight. Recommendations 6–9 state what needs to be measured in a field program conducted in the Southern California Bight.

The Santa Barbara Channel-Santa Maria Basin Circulation Study was designed to make a thorough investigation of the 3-dimensional circulation within the Santa Barbara Channel, with a strong emphasis on understanding the forcing and resultant circulation of the mixed surface layer. Phase I of this circulation study is presently underway, and has provided the most recent information presented above. Phase II is an expansion of Phase I; and together they will provide the information deemed necessary by NRC to make prudent decisions about further pre- and post-leasing decisions in currently active leases (Santa Barbara Channel), and also in possible future leasing (Santa Maria Basin Shelf). The purpose of the Santa Barbara Channel-Santa Maria Basin Circulation Study is to (1) make predictions of oil-spill/pollutant trajectory based on previous and real time observations, (2) supply data to oil spill trajectory models such as OSRA and National Oceanic and Atmospheric Administration's oil-spill trajectory model, (3) provide adequate oceanographic data for post-lease exploration and development, and (4) provide adequate oceanographic and meteorological data for numerical model development.

Table 1. National Research Council recommendations.

1. The Mineral Management Service should rely less on numerical models of oceanic circulation and much more on an adequate observational data base for impact assessment.
2. To make adequate predictions of trajectories for water parcels and materials, a representation is needed of the current field that is in quantitative agreement with the existing observations is needed. The observed currents must involve the latest database of drifter (Lagrangian) and moored (Eulerian) measurements.
3. Error estimates must be computed for trajectory predictions.
4. Studies should be conducted in consideration of the sensitivity of model results to initial and boundary conditions, and to the sensitivity of Lagrangian trajectories.
5. Substantial field work to provide a better observational picture of circulation in the Southern California Bight needs to be undertaken.
6. An adequate observational data base and resulting depiction of the circulation should include:
   a. the seasonal mean circulation, including known contributions from the local density field, nonlinear tidal current interactions, and larger-scale regional circulation;
   b. low-frequency currents induced by winds and major current excursions;
   c. tidal currents including internal tides; and
   d. currents associated with fronts and eddies.

   The information should include vertical structure in the currents and appropriate vertical mixing rates.
7. The MMS should develop a long-term observational program to include primarily near-surface currents, but also currents at depth.
8. The MMS should vigorously pursue understanding the overlying atmospheric boundary layer (marine boundary layer), especially as it relates to oceanic cross-shelf exchange.
9. Field work should include a measurement program that will identify mechanisms responsible for cross-shelf exchange in areas where the alongshore circulation is known to converge. "Is this cross-shelf exchange primarily a result of local wind forcing or from internal ocean processes?" is an important question to answer.

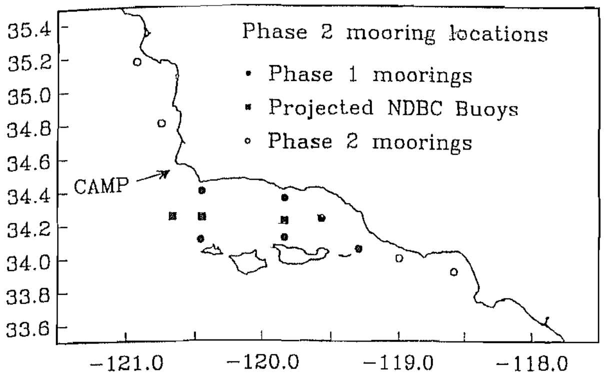


Figure 5. Phase II mooring locations of the Santa Barbara Channel-Santa Maria Basin Circulation Study.

The field program (Fig. 5) consists of mooring observations from 10 surface moorings and 4 subsurface moorings, 225 surface drifters giving 450 drifter trajectories, 3–4 satellite images per day, hydrographic surveys consisting of 1,300 XBT (expendable bathy-thermograph) launches, and the procurement and analysis of meteorological data from program-deployed instrumentation as well as concurrent measurements taken by other organizations over a 3-yr period.

The observations obtained in this study and their ensuing analysis will give us a predictive capability that will allow us to (1) establish refined characteristic circulation patterns inferred by satellite imagery and verified by observations; and (2) derive real-time intuitive, descriptive, and numerical forecast ability using past observations and real-time data in the channel.

New Approach to Oil-Spill Trajectory Analysis

As just discussed, MMS has attempted in the past to rely on numerical model-generated surface currents as input to its OSRA model that would yield estimated oil-spill trajectories based on this simulated input. These models frequently have not been constructed or verified by an adequate data set, and therefore have not performed well. The NRC has stated that MMS needs to rely much more on real observations and numerical models constructed from adequate observations to predict oil-spill trajectories in the future.

The new approach to predicting the circulation in the Santa Barbara Channel area that SIO and MMS scientists are now exploring is similar to the way a meteorologist approaches predicting the weather for a region. By assessing pressure maps, temperature data, satellite images, and consulting the results of a numerical model, a meteorologist can determine if the Southern California Bight will experience a Santa Ana Wind condition, a Catalina Eddy, or a major trough moving through the area. The meteorologist's basic knowledge of meteorology and the characteristic weather patterns of the area enables this.

The MMS/SIO approach to predicting the circulation patterns in the Santa Barbara Channel area will be the same as that of the meteorologist. We will first identify and understand the dynamics behind the 4 basic characteristic flows and their refined variations by comparing and analyzing results from Lagrangian current measurements, moored current and pressure measurements, towed acoustic doppler current profiler (ADCP) current measurements, hydrographic measurements, meteorological measurements, and the satellite imagery. From this analysis, oceanographers will develop an intuitive knowledge concerning the spatial and temporal dynamics behind the satellite imagery, much like synoptic weather forecasters develop this ability after studying atmospheric data.

Along with this background knowledge, statistical and numerical models of these circulation patterns and processes will also be constructed as aids to the oceanographic forecaster. All this, together with the input of real-time data from the monitoring stations that will remain in the channel after the Santa Barbara Channel-Santa Maria Basin Circulation Study is completed, will enable the oceanographic forecaster, located at a currently proposed MMS Camarillo Oil Spill Response Advisory Center (Fig. 6), to make accurate predictions of the surface current flow and surface wind stress acting on a real or imaginary oil spill. From these predictions, much more accurate and timely oil-spill trajectories can be made.

Since MMS is one of the first agencies to be alerted of an oil spill in the channel, reasonably good predictions of oil-spill trajectory could be made within the first 3 hr after spill occurrence. Three hours is a typical response time for field crews to be at the scene with their vessels, containment booms, and deflection booms. Unfortunately, 3 hr from spill occurrence is typically too soon for NOAA HAZMET to be able to respond with predicted oil-spill trajectories. A trained MMS oceanographic forecaster, with the proper real-time data and tools, which could be provided at the proposed oil spill response advisory center

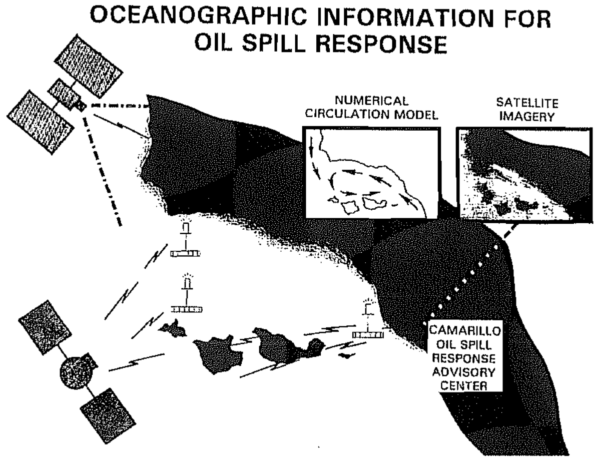


Figure 6. Currently proposed MMS Camarillo Oil Spill Response Advisory Center.

(Fig. 6), would provide valuable and timely information for a multi-agency oil-spill response effort until the NOAA HAZMET team could respond effectively.

When faced with an actual oil spill, or oil spill alert, the trained oceanographic forecaster will then use (1) the basic knowledge learned from the Santa Barbara Channel-Santa Maria Basin Circulation Study, (2) the latest satellite imagery of the area, (3) real-time oceanographic and meteorological data obtained from monitoring stations, (4) statistical models of Lagrangian trajectories (statistics from drifter trajectories), (5) results from the latest numerical circulation and oil-spill trajectory model runs, and (6) personal ability to synthesize the results into accurate estimates of surface trajectories of water/pollutant particles.

The oceanographic forecaster will then alert authorized field crews and appropriate government agencies to the land areas most vulnerable to oil contact within 3 hr of notification of the spill, and then will supply prediction updates to field crews and agencies as the climate changes.

When writing an environmental impact statement, real-time data would not be required to make a good statistical estimate for any particular shoreline to experience oil contact.

Literature Cited

Auad, G., M. Hendershott, and C. Winant. 1993. Subtidal circulation in the Santa Barbara Channel in 1984. Draft manuscript in progress in support of the MMS/SIO Santa Barbara Channel-Santa Maria Basin Circulation Study (1991–1998).

Gunn, J. T., P. Hamilton, H. J. Herring, L. H. Kantha, G.S.E. Lagerloef, G. L. Mellor, R. D. Muench, and G. R. Stegen. 1987. Santa Barbara Channel circulation model and field study, Vol. 1. Prepared by Dynalysis of Princeton, Princeton, New Jersey. MMS Final Report No. 87-0089, Minerals Management Service, Department of the Interior, pp. 175, 1987.

Hickey, B. M. 1992. Circulation over the Santa Monica-San Pedro Basin and Shelf. Progress in Oceanography 30:37–115.

Jackson, G. A. 1986. Physical oceanography of the Southern California Bight, plankton dynamics of the Southern California Bight. In: Lecture Notes on Coastal and Estuarine Studies Series, Vol. 15 (edited by R. W. Eppley), Springer-Verlag, New York, Chapter 2, pp. 13–52.

Lagerloef, G. S. E. 1991. MMS Studies in the Santa Barbara Channel, Southern California Bight Physical Oceanography, Proceedings, pp. 69–90.

National Research Council. 1989. The adequacy of environmental information for outer continental shelf oil and gas decisions: Florida and California. National Academy Press.

National Research Council. 1990. Assessment of the U.S. outer continental shelf environ-mental studies program, I. Physical Oceanography, National Academy Press.

The Fourth California Islands Symposium: Update on the Status of Resources
Edited by W. L. Halvorson and G. J. Maender. 1994. Santa Barbara Museum of Natural History, Santa Barbara, CA.

Catalina Island Kelp Forests: 1992–1993

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Abstract. A monitoring project initiated in the spring of 1992 at the Catalina Marine Life Refuge focused on giant kelp (*Macrocystis pyrifera*), sea urchins (*Strongylocentrotus* and *Centrostephanus*), and water temperatures along 60-m longshore transects at depths of 4, 10, and 20 m. Quarterly assessment of plant size and density tracked a continuing decline in kelp abundance at the site coincident with elevated sea temperatures. Frond elongation fell precipitously through the summer of 1992 and reached a low in the winter of 1993. Growth remained depressed through the spring and summer of 1993. This contrasts with previously measured temporal patterns of growth at this site when rates were highest in winter and spring. Population densities of sea urchins were relatively constant. Diminishment of the kelp forest together with the appearance of pelagic red crabs, a juvenile green turtle, and several species of tropical fish at Catalina portrays effects of lingering worldwide "El Niño" conditions.

Keywords: Kelp forest; *Macrocystis pyrifera;* monitoring; temperature; sea urchin; El Niño; Catalina Island; nitrate.

Introduction

Forests of giant kelp (*Macrocystis pyrifera*) in southern California exhibit localized, often dramatic density changes. While many factors influencing the population biology of *Macrocystis* are known, information is lacking to explain their integrated effects over broad ranges of spatial and temporal variability. (For review see North 1971, 1994; Foster and Schiel 1985; and recent studies: Tegner and Dayton 1991; Dayton et al. 1992.) In southern California, the location of the Channel Islands-between northern cold-temperate and southern warm-temperate biogeographic provinces-provides a natural laboratory for kelp forest investigations. Monitoring projects, underway since the early 1980s, document kelp forest dynamics at specific locations around the northern (cold) and central (thermally intermediate) Channel Islands (Harold and Reed 1985; Davis 1989; Richards et al. 1993a, 1993b). A comparable database describing the typically warmer southern islands of San Clemente and Santa Catalina, which have higher percentages of species with tropical affinities (Murray et al. 1980; Seapy and Littler 1980; Engle 1994), is lacking.

The recurrence of anomalous hydrographic conditions over the past 10–15 yr and the possibility of long-term central pacific warming emphasize the importance of expanding databases to include a broad range of climates and species assemblages. Our objective was to initiate a database for kelp forest dynamics in the southern islands.

Methods and Materials

Study sites

To monitor populations of *Macrocystis* and urchins, 3 60-m permanent longshore transects were established at depths of 4, 10, and 20 m in the Catalina Marine Life Refuge in the winter of 1991–1992 (Fig. 1). In August 1993, a second study site was selected on the windward side of the island just west of Little Harbor (Fig. 1).

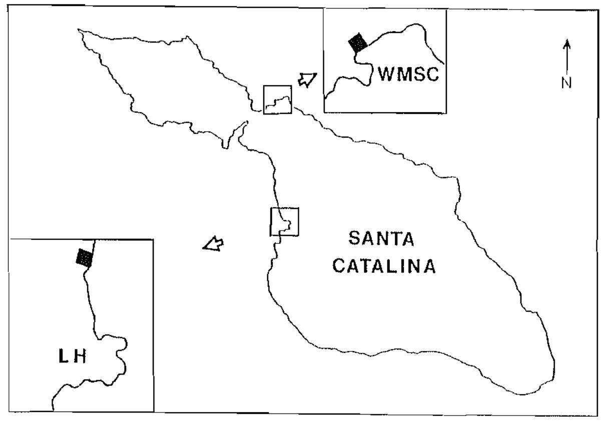

Figure 1. The Marine Life Refuge and Little Harbor study sites at Catalina Island. Black rectangles indicate transect locations. The refuge, including Big Fisherman Cove, is located adjacent to the Wrigley Marine Science Center (WMSC). Upper inset: Marine Life Refuge site; lower inset: Little Harbor site (LH).