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Final Report: The Santa Barbara Channel - Santa Maria Basin Circulation Study

Cooperative Agreement No. 14-35-0001-30571

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I. INTRODUCTION

I.A. Background

In section 20 of the 1978 Outer Continental Shelf (OCS) Lands Act Amendments, the Congress spelled out a number of the requirements for environmental studies to help guide OCS leasing and management decisions. The types of environmental studies that must be conducted and how they should be used are described as follows:

. Each OCS area or region is to be studied to establish the environmental information needed for assessment and management of environmental impacts - including those to the human environment - resulting from oil and gas development.

. This information must be used in decisions concerning post-lease operations, management, and leasing.

. Studies must predict impacts on marine biota and on affected onshore and coastal areas from chronic low-level pollution, large spills, drilling muds and cuttings, and pipeline construction, and on affected onshore and coastal areas from offshore development.

. Post-lease monitoring and studies are required to identify changes and trends in the environment.

In 1989, the National Research Council (NRC) was requested by President Bush, and by the Minerals Management Service (MMS), to review the adequacy of information available to assess the impact of oil and gas development on the OCS. That review was conducted and the results are described in two reports (NRC, 1989;NRC, 1990). In summary the main recommendation made in these reports are as follows:

. The MMS should rely less on numerical models of ocean circulation and much more on an adequate observational database for impact assessment.

. To make adequate predictions of trajectories for water parcels and materials, a representation of the current field that is in quantitative agreement with the existing observations is needed. The observed currents must include the latest database of drifter (Lagrangian) and moored (Eulerian) measurements.

. Error estimates must be computed for trajectory predictions.

. Studies should be conducted to determine the sensitivity of the model results to initial and boundary conditions, and to the variability of Lagrangian trajectories.

. Substantial field work to provide a better observational picture of the circulation in the Southern California Bight needs to be undertaken.

. An adequate observational database 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 large-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.

This information should include vertical structure in the currents and appropriate vertical mixing rates.

. The MMS should develop a long-term observational program to include primarily near-surface currents, but also currents at depth.

. The MMS should vigorously pursue understanding the overlying atmospheric boundary layer (marine boundary layer), especially as it relates to oceanic cross-shelf exchange.

. 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 a result primarily of local wind forcing or from internal ocean processes?

In response to the concerns raised in the NRC reviews, the MMS developed a Cooperative Agreement (CA) with the Scripps Institution of Oceanography (SIO) at the University of California, San Diego (UCSD). The study, named The Santa Barbara Channel - Santa Maria Basin Circulation study, was originally funded in 1989 and extended until 2005. It principally consisted of two components, one observational and the other a numerical modeling study that are described in the following. This reports presents all of the scientific papers published to date in the peer reviewed scientific literature, that comprehensively describe the work performed by SIO UCSD and its partners at Princeton University, SUNY-Stony Brook and the Desert Research Institute as part of the CA.

I.B. Components of the study

Following the recommendation of the NRC, MMS and SIO undertook a combination of observational and numerical modeling studies. Each of these components, and the subcomponents are described summarily in the following. A more comprehensive description is to be found in the scientific publications that comprise the main body of this report.

I.B.1. Observations

The NRC studies require an observational program that describes the atmospheric forcing, as well as Drifter Moored and Survey observation of the response of the coastal ocean to that and other relevant forcing mechanisms.

I.B.1.a. Atmospheric Forcing

The general objective of this component has been to provide a description of the atmospheric flow over the SBC-SMB area with greater emphasis on sea level variables, and variables such as the wind stress that force the oceanic circulation. Wind variations that influence the ocean circulation at the space and time scales resolved by the ocean measurements were resolved by the meteorological network from interannual time scales down to time scales corresponding to the diurnal period. Observations were collected from the following sources:

. Surface meteorological observations from stations maintained by federal and state agencies, air pollution control districts and electrical utilities throughout the region of interest. These consisted of about 25 stations located along the coast between San Diego and Morro Bay, and at a few island stations. Observations always included winds and air temperature with many including moisture and atmospheric pressure.

The National Data Buoy Center (NDBC) was sponsored by MMS to maintain up to 5 meteorological buoys in the region, beginning in August 1993. These buoys were equipped to observe winds, air temperature and water temperature and atmospheric pressure once each hour. In addition half the NDBC buoys were equipped with ADCPs to measure the current at different depths beneath the buoy

. Surface meteorological observations from stations deployed on two offshore islands (Santa Cruz and Santa Rosa) and four oil platforms (Grace, Harvest, Hondo and Inez).

I.B.1.b. Moored Observations

Moored observations, spanning up to 12 years in some cases, were used to describe the annual average and seasonal cycle of the flow in this complex area, and to show that the seasonal cycle can be described in terms of three characteristic circulation patterns (Winant et al.,2003). A total of 17 mooring sites were occupied for periods longer than one year. Locations are described in Winant et al. (2003). The mooring nomenclature is as follows: the first two letters correspond to the transect on which the mooring is deployed (AN for Anacapa, SM for San Miguel, etc...), and the following two letters (IN, MI or OF) indicate the location relative to the coast. Thus, the inshore mooring on the Point Sal transect is SAIN. With the exception of a single mooring (ANMI), deployed on the sill at the eastern entrance to the SBC in 200 m depth, all other moorings in the SBC were deployed on the 100 m isobath. Poleward of Point Conception, moorings were deployed on three transects perpendicular to the local isobaths, in depths of 35, 100 and

350 m. Instruments deployed on each mooring included current meters, temperature, conductivity and, except for the 350 moorings, bottom pressure sensors. Four moorings (ANMI, SMIN, SMOF and SAMI) were deployed for over ten years. Three of the meteorological buoys maintained by the National Data Buoy Center in support of this program were equipped with downward looking 75 kHz Acoustic Doppler Current Profilers (ADCP). Two of these buoys (NDBC 23 and NDBC 53) occupied two different sites at different times. ADCP observations are thus available from a total of five sites.

I.B.1.c. Drifter Observations

The drifters used in this study are described by Winant et al. (1999). Up to 24 release sites were used, half in the SBC, and the other half north of Point Conception. Including a test release conducted in 1996, Drifters were released a total of 30 times. For the first 18 releases, drifters were deployed in the SBC only. Drifters were deployed at all 24 locations for most, but not all, of the subsequent releases. Details of the first 20 releases are summarized by Winant et al. (1999). Details of the remaining releases are described in Winant et al. (2003).

I.B.1.d. Surveys

Surveys of currents (using an ADCP) and of water mass properties (using expendable bathythermographs and in a limited number of cases a CTD) have been conducted on each research cruise in the area, extending from Port San Luis to Port Hueneme. These observations were focused on eight cross-shelf transects: five in the Santa Barbara Channel and three in the Santa Maria Basin. During each of these transects, an ADCP was used to measure currents relative to the ground beneath the ship at selected depths. Expendable bathythermographs (XBTs) were cast while the ship was moving to determine the vertical profile of temperature along each transect. The emphasis of these surveys was to acquire observations in as synoptic a way as possible, and to avoid stopping the vessel during the survey. CTD profiles of water mass properties as a function of depth, which require stopping the vessel, were acquired along three transects only: two in the SBC and one in the Santa Maria Basin.

I.B.1.e. Ancillary Observations

During the entire duration of the field effort, NOAA AVHRR sea surface temperature imagery was acquired and catalogued. In addition regular GOES imagery was acquired as well.

I.B.2. Numerical Models

The effort to develop a numerical model of the circulation in the entire region of interest began in 1995, when SIO-UCSD awarded sub-contracts at MMS' request to Princeton and SUNY-Stony Brook. A further effort to model the marine atmospheric boundary layer was implemented in 2002, with the award of a subcontract to the Desert Research Institute.

I.B.2.a. Process and Data Assimilation Studies

A number of model process studies were conducted by Princeton and SUNY-Stony Brook to test hypotheses relating specific features of the observed circulation (notably the cyclonic gyre that occupies the western portion of the Santa Barbara Channel) to different forcing mechanisms. At the same time different methods of assimilating actual observations into the model were implemented and evaluated.

I.B.2.b. Nowcast and Hindcast Models

The central synthesis of all observational and modeling studies was achieved through hindcast modeling runs performed by Princeton. This work is described in detail in the scientific publications included in this volume.

I.B.2.c. Atmospheric Modeling

A collaboration between SIO and the Desert Research Institute was formed to develop a three-dimensional meteorological mesoscale model of the MABL.

II. Scientific Results

II.A. Antecedent (Pre-MMS Project) Studies

The earliest surveys (Sverdrup and Fleming, 1941) of circulation in the Southern California Bight outlined the general circulation pattern in the upper 500 m. California Cooperative Fisheries Investigation (CalCOFI) cruises added spatial and seasonal detail but did not resolve flow structure within the SBC. Kolpack (1971) carried out a hydrographic and drifter-card study in the SBC that resolved strong cyclonic flow in the western SBC as well as a generally northwesterly flow along the California Coast. The 1983 Organization of Persistent Upwelling (OPUS) study documented new detail in both the winds and currents in the vicinity of Point Conception (Brink and Muench, 1986). In 1984, the MMS carried out an extensive observational and modeling study of the circulation in the SBC reported in Gunn et al. (1987).

II.A.1. OPUS results

The most noteworthy OPUS (Brink and Muench, 1986) results were (a) that flow along the California coast of the SBC in the vicinity of Pt. Conception during a 57 day spring and summer observing period was almost always westward, against the local (eastward) wind stress while (b) at the beginning of the observation period, currents in the vicinity of Pt. Conception were strongly correlated with local winds but this correspondence abruptly vanished about midway through the observing period. These mysterious results were not dynamically understood until the PhD research of graduate student S. Harms (Harms, 1996 PhD thesis and publication, 20).

II.A.2. New Results from the 1984 MMS SBC Experiment

relevant publications: 17, 18, 22 - The 1984 MMS SNC dataset was further analyzed by PhD student G. Auad for his thesis research. A particular feature of the 1984 data set was that both the eastern and western mouths of the SBC were sufficiently densely instrumented that the time varying total (laterally and vertically integrated) mass and heat transports through each could be resolved. For the period January-July 1984, the net mass transport in the SBC was 0.28 Sv westward; this was partitioned into 0.46 Sv of westward transport in the northern part of the western mouth and 0.16 Sv of eastward transport in the southern part. Winds and mass transport were significantly coherent in the 2.5-3.0 and 4.7-5.2 day bands (publication 22). About 62% of the variance of Eastern mouth transport fluctuations in the 6-18 day bands was captured by linear regression on local wind stress and distant sea level as determined using tide gauges from San Quintin (BCN, Mexico) to Port San Luis in the SMB (publication 17). Energetic high frequency (about 3 day period) currents were found both in the shallow passes between the Channel Islands and at the deepest instruments (e.g. 25 m above the bottom in the western central SBC where the total depth is 563 m). The deep high frequency currents increased in amplitude with depth, were not significantly correlated with currents immediately overhead near the surface, but were significantly correlated both with local winds and with the high frequency currents in the passes. Publication 18 interpreted these as bottom trapped Rossby waves.

II.B. Instrument Development

II.B.1. Moored ADCP Verification

relevant publication: 8 - In December 1991, the National Data Buoy Center (NDBC) deployed downward looking Acoustic Doppler Current Profilers on two NDBC buoys in the Southern California Bight, and shortly thereafter SIO deployed a vertical array of seven Vector Measuring Current Meters near each of these in order to obtain simultaneous ADCP and VMCM records about four months in length for the purpose of determining the quality of currents derived from ADCPs mounted on surface moorings subject to pitch and roll. It was found that the buoy mounted ADCPs produced reliable estimates of horizontal velocities in the upper 200 m of the ocean unless the waves were too strong. ADCP vertical velocities were however deemed unreliable on account of mooring motion. This fieldwork began the development of the mooring system subsequently used for the entire SBC-SMB experiment. The results are reported in publication 8.

II.B.2. Towed ADCP Development

relevant publication: 10 - Vessel mounted ADCPs are now common, but at the beginning of the SBC-SMB experiment, an alternate method of making underway ADCP current sections had to be devised. Publication 10 reports the design and early deployment of a towed ADCP platform deployable from ships of opportunity. With navigation information sufficiently good to correct the ADCP compass for the effects of the ship and the towed body, the towed ADCP profiles are comparable in quality to those obtained using vessel mounted ADCPs. This towed platform was used for several years from the beginning of the SBC-SMB experiment, until the RV Sproul and the RV New Horizon were outfitted with vessel mounted ADCP's.

II.B.3. ARGOS Tracked Drifters

The drifter developed by Davis (1985) was slightly modified and outfitted to be tracked by the ARGOS satellite system. The drifter consists of a submerged vertical tube which houses the electronics and battery. An antenna protrudes from the top of the tube and extends upward through the surface of the water. Four cloth vanes of total area 1.8 square meters are supported on rods that extend radially from the top and bottom of the tube. Four flotation elements are attached at the end of each rod by short lengths of nylon line. The electronics consist of a controller with temperature circuit and transmitter. The transmitter allows the drifters to be located by orbiting satellites using the Argos system. This system locates the drifters several times each day, with positional accuracy varying between 150 m and 1000 m. The temperature circuit measures hourly averages of sea surface temperature accurate to 0.01 deg C. The drifters were programmed to run for 40 days after deployment. A total of 572 drifters were set out in 30 deployments made over the course of the SBC-SMB experiment (from January 1993 to November 1999; see also Section I.B.1.c above).

II.B.4. Bottom-Mounted Pressure Sensors

relevant publications: 8, C. English Thesis - All of the moorings of the SBC-SMB experiment except those in water deeper than 100 m. were outfitted with anchor-mounted bottom pressure sensors. Publication 8 reported early bottom pressure sensor records, and developed the procedure for combining them with simultaneous water column temperature records to produce synthetic subsurface pressure (SSP) series. SSP series are less noisy than tide gauge sealevel series, but at low frequencies may be contaminated by unknown slow motions of the anchor.

In his PhD thesis "The Role Of The Pressure Field In Wind Driven Coastal Circulation", PhD student Chad English (2005) re-examined the bottom pressure data set and the comparison between SSP and sea level in a low frequency band (frequencies less than 2 cpy), and a synoptic band (frequencies between 1/45 cpd and 1/2 cpd). There was no clear relationship between local wind stress and the low frequency pressure. The synoptic band includes less of the total variance than does the low frequency band, but the amplitude is more spatially variable across the domain so that dynamically significant horizontal pressure gradients are associated with synoptic band pressure variability. The dominant synoptic band pressure EOF (spatial mean removed) amplitude time series is well correlated with the wind; in the sense that pressure increases poleward and onshore following an episode of poleward wind stress.

II.C. Winds and Meteorology

II.C.1. Studies of Historical Data

relevant publications: 11, 15 - Early in the course of the project, the statistical properties of the sea surface wind field and sea level atmospheric pressure along the west coast of the US were documented from ten years of time series at the National Data Buoy Center (NDBC) buoys along the US West Coast (publication 11). About half of the wind speed variability is synoptic and half associated with the annual cycle. In both the annual cycle is strong: off the coast of California highest pressures are found in winter whereas the most rapid along shore (equatorward) winds occur in summer. There are two West Coast US summer mean monthly wind speed maxima: one is in the western mouth of the SBC. Sea surface temperature (also measured by the NDBC buoys) is highly correlated with along shore winds; annual cycle temperatures are minimal when annual cycle winds are fastest.

The NDBC buoy array is not sufficiently dense to estimate wind stress curl or to attempt to map the air-sea heat flux using bulk methods. The seasonal patterns of these quantities were however estimated for the Southern California Bight (publication 15) using wind and sea surface temperature time series from 1945 to 1994 at the California Cooperative Fisheries Investigation (CalCOFI) grid. During winter the wind stress is spatially homogeneous but varies as large storms sweep through the region whereas in summer the winds offshore of the Pt. Conception-Ensenada line are much greater than those closer to shore. A strong cyclonic wind stress curl is found in the western SBC and south of the Channel Islands in spring and summer. Atmosphere mesoscale modeling of the wind stress curl will be discussed in the following section.

II.C.2. SBC-SMB and US West Coast Winds

relevant publications: 27, 30, 41 42, K. Edwards Thesis - The extensive wind and meteorological station network of the SBC-SMB experiment (section I.B.1.a, above) was exploited to produce a detailed description of the geographical and time variability of the marine atmosphere in the vicinity of the SBC (publication 27). In summer there is a well-defined marine atmospheric boundary layer (MABL). Maximum surface winds extend south and east from Pt. Conception. Along the coast east of Pt. Conception winds are generally weaker, sometimes reversing at night. In winter traveling cyclones are generally preceded by strong southeast winds and followed by strong northwest winds. Summer spatial variations in the wind field are consistent with a hydraulic model of the MABL.

Although dense by the standards of most comparable coastal oceanographic studies, the network of wind stations in the SBC-SMB experiment was not sufficiently dense to resolve the wind stress curl field in the SBC-SMB. A generation of very detailed atmospheric model studies of the wind field in this region began with publication 41. The fifth-generation Pennsylvania State University-NCAR Research Mesoscale Model MM5 was run at 9 km resolution over a domain spanning the California coast from north of

Cape Mendocino to Bahia Vizcaíno for the month of June (when winds are strongly upwelling favorable), 1999; 12 hour boundary conditions were obtained from a contemporaneous NCEP analysis and all available surface and upper air data were assimilated into first guess synoptic fields. The spatial structure of the wind stress curl is a consequence of the nearshore wind stress maximum and the downwind variation of coastal alignment. Cyclonic wind stress curl generally occurs near the coast, with weak anticyclonic curl further offshore. The largest (cyclonic) wind stress curl is found in the lee of Pt. Conception. The very good agreement between observed and model-predicted surface winds at the NDBC buoys give confidence that the resolution is approaching that required to provide wind stress curl at the detail needed in numerical models of the ocean circulation in this region.

The consistency of spatial variations in the SBC-SMB wind field in the summer in the vicinity of Pt. Conception with a hydraulic model of the marine atmospheric boundary layer (MABL) corresponds to a particular instance of the hydraulic nature (Dorman 1985) of flow in the MABL along the entire California Coast. In fact, the marine layer is near supercritical (Winant et al. 1988, Samelson 1992) or transcritical (Rogerson 1998).along much of the California Coast during the summer. The marine layer slows and thickens upwind of Capes forming a compression bulge. Rounding the cape, the marine layer accelerates and thins in the lee, forming an expansion fan. In summer, significant changes in the MABL speed and depth occur over small spatial scales (less than 100km) downstream of coastline variations (publications 27, 30, 32, 34 and 42).

The most dramatic and important hydraulic atmospheric feature to the coastal oceans are the high-speed wind zones which correspond to the high wind stress zones. These are supercrital flows (Winant et al. 1988, Samelson 1992) if the inbound surface winds are above 8-10 m/s and transcritical if the surface wind speeds are in the range of 4-8/10 m/s (Rogerson 1998). In the lee of coastline bends or capes, the winds accelerate into a high wind and wind stress expansion fan. The marine layer has two major along-coast scales: one is on the California scale and the other is on the Cape scale. The large-scale coastal bend in California between extreme N. California and the remainder of California, is responsible for the general high-speed surface winds that extend from S. Oregon to past Pt Conception California, and extends hundreds of kilometers offshore. Nested within this California scale expansion fan, there are smaller, Cape scale expansion fans that cause additional accelerations in the lee of each major cape, with the area of the expansion fan related to that of the cape that caused it. There are four major, California cape scale expansion fans: Cape Mendocino, Pt. Arena, Pt. Sur and the southernmost is Point Conception. The acceleration and thinning of the MABL are reproduced in the California scale and the cape scale when the flow is modeled as a shallow transcritical layer of fluid impinging on the coastal features (Edwards, PhD Thesis).

II.D. SBC-SMB Circulation: Description and Dynamics

II.D.1. Early Reviews

relevant publications: 6, 13 - Under the CA, SIO maintained 9-12 moorings from November 1992 to November 1999 in the region. From 1992 to the end of 1995, the field program focused on the Santa Barbara Channel. Each mooring included a Vector Measuring Current Meter (VMCM) at 5 and 45 m depth as well as temperature sensors at these and several other depths. From 1996 to 1999 a similar array of 12 current meters was focused on the Santa Maria Basin. Four of the moorings were maintained over both phases of the study, one at the eastern entrance to the Santa Barbara Channel, two at the western entrance to the channel and one in the Santa Maria Basin (this one began in December 1993). These four long-term moorings were maintained until September 2004. Some additional near-surface current meter data is available from the California Monitoring program (CAMP) and on several NDBC buoys in the region. The CAMP data is available from 1992 to 1994 near Pt. Arguello. NDBC buoys with ADCPs were initially placed in the Santa Barbara Channel (NDBC 46023a, 46053 and 46054). Later moorings with ADCPs were placed in the Santa Maria Basin (46023b and 46062). In most cases the shallowest ADCP data from these moorings is at 24 m, hence needs to be considered carefully.

Preliminary results were reported prior to the first major publication (20). Publication 6 summarized the project and introduced, by analogy with meteorological usage, the idea of synoptic states of the circulation (explained below, Section II.D.2). Publication 13 showed corresponding examples of drifter trajectories superposed on AVHRR images of sea surface temperature.

II.D.2. SBC-SMB Circulation and Dynamics

relevant publications: 20, 37 - The PhD thesis of Harms was the basis of publication 20, hereafter HW98. This work both described the upper ocean circulation in the SBC on the basis of the data gathered there 1993-5, and drew important conclusions about the dynamics.

Except along the California coast just East of Pt. Conception, the 5 m and 45 m flow in the SBC had a strong along-coast equatorward component during upwelling favorable winds. The winds relax between upwelling periods but usually do not actually reverse to blow poleward for more than a few days, yet during such relaxation intervals the 5 m and 45 m flow in the SBC had a strong along-coast poleward component. This reflects the existence of a large-scale pressure gradient force that is generally poleward against the mean wind stress; the wind stress is dominant under upwelling winds but the pressure gradient force dominates when the winds relax. In addition to this overall alternation of flow direction, there is a persistent cyclonic eddy in the western half of the SBC so that flow along the California coast East of Pt. Conception is nearly always along-coast poleward.

HW98 found that the upper ocean circulation could be qualitatively described as a series of synoptic states. These provide a compact way of describing the surface circulation based on wind measurements and current measurements at several key locations. In the first and second phases of the SBC-SMB experiment, when moored time series were acquired primarily within the SBC, six synoptic states were identified (HW98). These were: upwelling, cyclonic, relaxation, flood east, flood west, and propagating cyclones. Upwelling consists of flow to the east along the north side of the Channel Islands and out the eastern entrance to the SBC. A weak westward flow may exist along the mainland coast during upwelling. Cyclonic flow consists of a well-developed cyclonic circulation in the western SBC with westward flow at the eastern entrance to the SBC. Relaxation consists of westward (poleward) flow from the eastern entrance to the SBC, continuing along the mainland coast and exiting at the western entrance to the SBC. A weak eastward recirculation may be found along the north side of the Channel Islands.

The synoptic states were found to be closely related to the observed wind field and pressure gradient. Strong equatorward wind forcing accompanied by a weak pressure gradient was associated with upwelling. Conversely, a strong poleward pressure gradient accompanied by weak wind forcing was associated with relaxation. Strong winds and a strong poleward pressure gradient resulted in the cyclonic synoptic state. Upwelling conditions were found most commonly in spring (March and April). Relaxation conditions were found most commonly in fall and early winter (October through December). The cyclonic state was found most often in summer (July through September). The propagating cyclones state reflects the fact the mean cyclonic circulation is in part the result of cyclones that propagate west from near San Miguel Island past San Miguel to the western entrance to the SBC. When both winds and pressure gradient were weak, conditions such as flood east or flood west could take place. Flood east and flood west are weak, essentially uniform, eastward or westward flow along the SBC.

The synoptic states could also be constructed as superpositions of Empirical Orthogonal Functions (EOF) resulting from EOF analysis of the observations, but the relationship of the EOFs to wind and pressure gradient driving was not as clear as that for the synoptic states.

Later, in phase 3 of the SBC-SMB experiment, when moored time series were acquired primarily in the SMB, the synoptic states were simplified to three: upwelling, relaxation, and surface convergence (publication 37). Upwelling now includes flood east as defined by HW98. Relaxation state now includes flood west as defined by HW98. The cyclonic and propagating cyclones states defined by HW98 are subsumed by the surface convergence state. The definition of these states and their use in velocity maps produced for MMS is further described in section III.C, below.

II.D.3. Drifter Results

relevant publications: 23, 26 - Concurrent with the moored program, thirty drifter releases were made, separated by about 3-4 months. Releases took place in all seasons and deliberate attempts were made to sample a variety of flow states. Each release consisted of 15-24 drifters released over a grid pattern in the study region of interest. Again from 1992-1995, most drifters were released in the Santa Barbara Channel. From 1996-1999, most drifters were released in the Santa Maria Basin, although several releases were made of drifters throughout the SBC and SMB.

Although the synoptic states provide a compact way of describing the near surface circulation based on a limited number of time series, this description is necessarily incomplete. The Santa Barbara Channel (SBC) and Santa Maria Basin exhibit relatively complicated and energetic circulation features, which can strongly affect surface parcel trajectories. Comparisons of actual drifter trajectories with estimates from wind forcing and seasonal circulation patterns indicate these features are not adequately accounted for by wind forcing alone (the 3% wind rule) or by seasonally averaged circulation patterns (publication 23).

The trajectories of drifters released at the same time from sites only 20 km apart can be remarkably different. Once the drifters leave the SBC, their trajectories may be grouped into a few patterns. In spring and summer, drifters tend to enter the Southern California Bight and their trajectories often remain close over extended periods. In the fall the drifters often go poleward into the SMB and beyond along the central California coast. About 1/3 of the 235 drifters released during this study ran aground, mostly in the SBC along the California coast or the Channel Islands. Drifters that escaped the SBC and moved poleward often reached Point Sur, and one was ultimately recovered off Astoria, Oregon.

Drifter coverage can be biased towards different flow states. For example, flow states which tend to leave drifters close to the coast (i.e., relaxation in the Santa Maria Basin) or weak flow in which drifters can be retained in the Santa Barbara Channel will lead to more drifter data being acquired under these conditions and hence to a bias in averages of this drifter data.

Publication 23 studies the statistical aspects of the drifter data. Current meter and drifter velocity mean are generally in good agreement, although drifter means tend to be somewhat higher. The difference may be real as the current meters are at 5 m depth below the surface while the drifter sample the upper meter. The drifter velocities provide estimates of the horizontal and total eddy stress divergence. In the western cyclonic region, the horizontal rather than vertical divergence dominates, this is in contrast with the CODE region where horizontal and total eddy stress divergence were quite different.

The eddy stress divergence is largest in the western SBC, but even in this region it is a good deal smaller than the Coriolis acceleration, indicating that models emphasizing linear dynamics should provide insight into the mean circulation. The drifter velocities allow estimates of single particle diffusivities. The along-channel single particle diffusivity is substantially greater than the across-channel single particle diffusivity.

The drifter trajectories are our best estimates of surface parcel paths, and hence were vital in applying the results of this study to the oil spill risk analysis problem; section III below explains the manner in which this was done.

II.D.4. SBC in Larger Setting

relevant publications: 24, 35 - Circulation in the SBC is described by the synoptic states discussed above. Of these the relaxation state, seasonally dominant in fall and early winter (October through December) and on shorter time scales when the wind relaxes, is closely related to the larger scale flow of the southern California Bight (publication 24).

The 1997-8 El Nino was clearly visible in the SBC-SMB data of this study (publication 35). Local sea level and surface temperature showed three distinct peaks, the first two clearly associated with regional response to the El Nino. The initial El Nino peak in temperature was surface intensified and barely detectable at 45 m. The subsequent (main) peak was visible down to 200 m. Stronger than average poleward flow was observed at the eastern entrance of the SBC at depths between 5 m and 100 m in 1997, and both current meter and drifter data suggest stronger than average poleward flow in the SMB for fall of that year.

II.D.5. Model Results

relevant publications: 25, 33 - Section III.D below outlines model results directly useful in mapping the flow for Oil Spill Risk Analysis. But a number of earlier model results were important in understanding the dynamics of the flow in the SBC-SMB.

In his PhD thesis, Auad had found that some part of the flow in the eastern SBC is coherent with the along-coastal sea level gradient as determined using tide gauges from San Quintin (BCN, Mexico) to Port San Luis in the SMB (publication 17). Oey (publication 25) found that if the wind distribution along the coast is characterized by a cross-shore scale small relative to the along-shore scale, then coastal Kelvin waves are forced not only by the coastal wind stress but also by the time-integral of the along-shore gradient of the wind stress curl. Numerical experiments suggested that the dominant term for the SBC is the equatorward weakening of the wind-stress curl.

In a very different study Chen and Wang (publication 33) showed that a three dimensional model that continuously assimilated monthly mean temperature data from the SBC array but did not explicitly allow wind forcing nonetheless faithfully reproduced the cyclonic eddy and poleward flow along the California coast in the western SBC, but failed to predict currents at the channel exits. In particular the calculation highlighted the as yet not fully understood question of what drives the local flow in the eastern mouth of the SBC.

II.E. Tidal Currents

relevant publications: 21, 40 - Publication 21 combined semidiurnal and diurnal current fluctuations in the SBC, and found that while tidal elevations there are consistent with a poleward propagating barotropic Kelvin wave, the current fluctuations are not. The strength of tidal band currents depends strongly on location, with greatest strengths in the eastern mouth of the SBC and in the passes between the Channel Islands.

Publication 40 analyzed the diurnal band variability of temperatures and currents in the SBC-SMB. The diurnal band temperature field consisted of two distinct modes: a surface enhanced mode coherent with meteorological (surface wind and heating) forcing and a second mode whose amplitude is greatest at mid depths and whose amplitude spectrum exhibits peaks at the astronomically determined tidal frequencies of the diurnal band. This latter mode is presumably a localized baroclinic response to tidal forcing. The diurnal band currents consist of a clockwise component coherent with the wind stress and with the surface enhanced temperature mode, and a barotropic and counterclockwise mode whose amplitude spectrum exhibits peaks at the astronomically determined tidal frequencies of the diurnal band and whose phase relative to local surface elevation varies but little over the SBC-SMB.

III. APPLICATION TO MMS OIL SPILL RISK ASSESSMENT

III.A. Introduction

The major goal of the Cooperative Agreement (CA) between the Minerals Management Service (MMS) and Scripps Institution of Oceanography (SIO) was to interpret the results of the field program and modeling effort in a way that would aid MMS oil spill risk assessment. Several different deliverables were developed by SIO investigators and by Leo Oey et al. at Princeton University and Dong-Ping Wang et al. at the State University of New York at Stony Brook. These deliverables include the development of synoptic states that describe the large scale circulation in the Santa Barbara Channel (SBC) and Santa Maria Basin (SMB), mapped velocity data for the prediction of oil spill trajectories, and a data-assimilating numerical model forced by realistic winds. The products are described in further detail below. All references are to publications that can be found in the list of CA publications included in this report.

III.B. Synoptic States

The three synoptic states discussed above (Section II.D.2) were used to interpret the fate of drifters released in the SBC and SMB (Winant et al., 2003), and produce maps of surface circulation based on drifters and moored time series (Dever, 2004). The occurrence of synoptic states has a seasonal variation. Upwelling events have the highest probability of occurring in February-June, surface convergence from July-October, and relaxation from November-January. The synoptic states also provide an estimate of surface circulation that can be used for familiarization with NOAA's GNOME model or ASA's Oilmap model. Maps of the large-scale circulation similar to those described in Dever (2004) were provided to MMS, NOAA/HazMat, and Applied Science Associates (ASA). These maps were produced using the methods outlined in section III.C. below.

III.C. Time Varying Mapped Velocity Fields

To provide an improved estimate of drifter trajectories based on the observations, we adopted an objective analysis (OA) approach in which near surface current meter and drifter data acquired during the CA as well as regional National Data Buoy Center (NDBC) data were incorporated. This method took advantage of the spatial distribution of drifter data and the temporal sampling of the current meters available at any given time. We used the OA to produce time series of interpolated fields. Velocity fields derived from the OA streamfunctions are provided for the MMS Oil Spill Risk Analysis (OSRA), ASA OILMAP and National Oceanic and Atmospheric Administration (NOAA) GNOME/TAP trajectory models.

The OA approach was designed to merge the two methods used to observe the near-surface circulation: moorings and drifter deployments. Each method had its particular strengths and the methods were designed to complement one another. The moored data has good temporal coverage, but coarse spatial coverage. The drifters have very good spatial coverage, but limited temporal coverage and the potential to be biased towards flow states that retained drifters in the SBC-SMB region (convergence and relaxation).

To take advantage of the complementary nature of mooring and drifter data we employed the combined spatial coverage of drifters and current meters using the large-scale flow states identified in section III.B (see also Winant et al., 2003; Dever 2004). However the large-scale states do not account for all the variability (about 50%), nor do they include high frequency (tidal) variability. Our solution is to use objective streamfunction mapping at two scales, the large-scale state and the departure from the large-scale state. The mapping procedure determines best fit of available data to one of three large-scale states, then maps the remaining small-scale field.

For the present application a curvilinear coordinate system of along-shelf and cross-shelf coordinates is adopted. This takes advantage of the natural polarization of flow in the along-shelf direction and makes the specification of covariances more natural. The domain extends from the eastern Santa Barbara Channel to Morro Bay, from the easternmost current meter to the northernmost drifter deployment line. Objective analysis requires the spatial correlation function be specified. Here the covariance function is specified to be anisotropic in the curvilinear coordinate system with differing correlation scales in the along-shelf and cross-shelf directions. Use of an anisotropic correlation function with longer decorrelation distances in the along-shelf direction is consistent with characteristics of shelf flow observed in historical observational studies. The along-shelf decorrelation scale specified is approximately 35 km and the cross-shelf decorrelation scale is 25 km. This scale roughly matches that provided by the moored array. It is capable of reproducing features such as the cyclone in the western Santa Barbara Channel, but cannot reproduce smaller-scale features such as flow through the inter-island passes often seen in drifter trajectories (Winant et al., 1999).

As mentioned previously, the objective mapping is made on 2 scales, a large-scale synoptic state and a shorter scale remainder. Determining the appropriate large-scale state first and subtracting it from the data allows better interpolation between widely spaced velocity measurements. Fitting the remaining small-scale data allows high frequency (tidal), small scale, and atypical large-scale spatial patterns to be taken into.

The large-scale states are first determined as follows: (1) the days for which upwelling, relaxation, or convergent states occur in the Santa Barbara Channel/Santa Maria Basin are identified, (2) average velocities for each state are calculated, and (3) average synoptic state streamfunctions are estimated from available data.

Each of these steps are explained in more detail below:

Mooring data acquired over the course of the SBC/SMB study are first quality-controlled and averaged over 6 hr periods. Available National Data Buoy Center (NDBC) Acoustic Doppler Current Profiler (ADCP) and CAMP S4 current data are also used. Data from December 1993 to November 1999 are used to characterize the synoptic state into one of 3 states, upwelling, convergence or relaxation using the following criteria:

> **Upwelling** is defined to occur when (subtidal) flow in the Santa Maria Basin (SAMI) included a southward component (flow direction 90 to 270 T) and flow at the eastern entrance to the Santa Barbara Channel (ANMI) included a southeastward component (flow direction 45 to 225 T).
>
> **Convergence** is defined to occur when (subtidal) flow in the Santa Maria Basin was southward (90 to 270 T), flow at the eastern entrance to the Santa Barbara Channel was northwestward (225 to 45 T), and flow at Pt. Conception (SMIN) was westward (180 to 360 T).
>
> **Relaxation** is defined to occur when (subtidal) flow in the Santa Maria Basin was northward (270 to 90 T), flow at the eastern entrance to the Santa Barbara Channel was northwestward (225 to 45 T), and flow at Pt. Conception (SMIN) was westward (180 to 360 T).

For each time step, the best fit (in a least squares sense) large-scale state is determined with a variable positive amplitude. This is subtracted from the available data to determine a small-scale remainder field. The remainder field is then fit to a streamfunction and added back to the large-scale field to get a total field.

For the large-scale state, the decorrelation distance isn't very important as data from all current meters as well as the spatially rich drifters are used. For the small-scale state, the correlation scales allow interpolation between current meters in each of the arrays and make sense based on the observed correlation scales.

The streamfunction is determined from objective mapping on the along-shelf and cross-shelf coordinates. To get velocities for OILMAP and OSRA, the velocities are calculated at the OA gridpoints from the streamfunction using centered differences except on the boundaries where forward and backward differences are used. To get velocities on the verdat coordinates used by GNOME and TAP, simple linear interpolation is used. Because the distance interpolated over is much smaller than the decorrelation scale specified in the OA mapping, this should not cause problems.

We mapped the streamfunction from November 1992 to November 1999. These times correspond to the beginning of the Santa Barbara Channel array and the ending of the Santa Maria Basin array. Time series of mapped velocities with actual current meter velocities show very good agreement with the along-shelf component, including tides, and reasonable agreement with the cross-shelf component.

Our overall assessment is that the interpolations are broadly accurate. They reproduce features such as the western cyclone in the Santa Barbara Channel, poleward and equatorward flow in the Santa Maria Basin, the offshore jet at Pt. Conception, and eastward flow at the eastern entrance to the Santa Barbara Channel during upwelling. Although the mapped fields incorporate the large-scale synoptic states discussed in section III.B., they include atypical flow states by representing the total flow at any one time as the best fit synoptic state plus a remainder field. The best accuracy for small-scale flow and for flow over the Pt. Hueneme shelf, extreme southwest SMB area, and inter-island passes is achieved during drifter releases. Broader-scale accuracy is highest in the Santa Barbara Channel from 1992-1995 and in the Santa Maria Basin from 1996 to 1999. It coincides with the positioning of the moored array. Beginning in 1995, there are 2 moorings in the Santa Maria Basin, allowing slightly better accuracy there. The adoption of large-scale states does allow a sensible interpolation beyond the coverage range of mooring data. This gives the mapping some skill in the Santa Maria Basin from 1992-1995 and likewise gives the mapping some skill in the Santa Barbara Channel from 1996-1999.

III.D. Modeled Circulation

The mapped velocity fields provide a reasonably accurate, data-based, kinematic interpolation of moored and drifter velocity estimates from 1992-1999. However, the mapped fields have an important shortcoming. Because the data is only acquired in the SBC-SMB region, the fate of parcels that exit the region is unknown. To provide estimates of near surface velocities and parcel trajectories over a wider region, Leo Oey et al. at Princeton and developed a numerical model incorporating data assimilation procedures developed by Dong Ping Wang et al. at SUNY - Stony Brook. Their data assimilating models provide a dynamic rather than kinematic based interpolation and extrapolation of data.

The model domain and topography are the same as those used in Oey (1996; Fig. 1), except that the present application employs the coarse grid only (i.e., the nested grid option is turned off), with grid sizes of 5 by 5 km and 30 equally spaced sigma layers in the vertical direction. The model used is the Princeton Ocean Model (POM), an open source numerical ocean model. The model domain extends from near San Diego to Pt. Sur and from the coast to about 350 km offshore. The model was run from January 1992 to December 1999 although the data assimilation begins in 1993. Modeled fields were provided to Walter Johnson of MMS.

The circulation in the SBC-SMB area is sensitive to details of the wind forcing. Moreover the wind fields are an important component of forcing of oil spill trajectories in their own right. In an attempt to produce an accurate wind field, satellite measurements, modeled wind products, NDBC winds and wind measurements acquired as part of the CA were combined into a single product using optimal interpolation (OI). The NDBC winds and the other wind data points from land, island, and platform stations provide descriptions of the fine-scale wind structures in the vicinity of the SBC. To use these synoptic (hourly) data in the model, we merge them with six-hourly European Centre for Medium-Range Weather Forecasts (ECMWF) wind direction (resolution is approximately $1° \times 1°$) in combination with satellite wind speed estimates derived from the Special Sensor Microwave Imager (SSM/I). The final products are hourly wind maps that include detailed wind station values in the SBC vicinity and larger-scale SSM/I and ECMWF information farther away.

Monthly temperature-salinity (T/S) climatological data are used to specify initial and open-boundary conditions. The open-boundary conditions are a mix of advections, radiations, and specifications as described in Oey (1996). At the coast, the normal fluxes are nil, and a no-slip condition is imposed on the tangential velocity component. At the sea surface, wind stresses are specified and T/S are relaxed to their monthly climatological sea surface values. At the seafloor, all normal fluxes are nil, and a quadratic bottom stress formula is used that uses the velocity at the lowest grid. Along open boundaries, the monthly climatological values are then used to specify the T/S profiles when there are inflows into the modeled region.

The near-surface circulation adjusts rapidly to assimilated temperature in the channel's vicinity, and the solution there is not sensitive to the use of monthly climatological T/S as initial and boundary conditions. We briefly describe here the data assimilation; details are given in Chen and Wang (1999) and Chen and Wang (2000). Data at 10 moorings in the SBC-SMB are used. Temperature and velocity at the moorings described in section III.C. are used. The hourly observations contain some gaps in time. We first optimally interpolate (OI) in space every hour and use the OI values to fill the gaps. Then at each model grid, the modeled parameters are replaced by an analyzed (or assimilated) parameter. The measured parameter is given a predetermined statistical weighting coefficient matrix that is a function of the separation distance between the model grid and mooring station. The error correlation scale is taken to be 10 km. This value confines the injection of the observed mooring information to the immediate vicinity of the mooring. Unlike the commonly used assimilation procedure based on optimal interpolation, which generally works well in the open oceans, the coastal circulation contains various anisotropic scales, and one cannot presume to know more than what is observed (at each mooring). In essence, the model seeks its own decorrelation scales through dynamic readjustment of the modeled currents, which then would become consistent with the observed fields.

The data-assimilated model fields capture the spatial and seasonal variation of the circulation in the SBC-SMB region. Momentum analysis (Oey et al., 2004) suggests that the along-channel pressure gradient (PG) serves as a dynamic index of the seasonal circulation. The PG is equatorward with the onset of spring from about late February through early May. The cause in the model is erosion and reversal of the poleward PG from the previous winter by a series of equatorward wind bursts east and south of the channel. The PG becomes poleward and strong in summer and autumn and then weakens in winter. The cause in the model is the large-scale differential wind curl as detailed in Oey (1999).

Modeled fields are realistic within the SBC-SMB region with high correlation coefficients between the observations and the data-assimilated model. Outside of this region, there is not enough data for a quantitative comparison to the model. However, the modeled drifter trajectories outside the SBC-SMB region are qualitatively similar to the large-scale drifter trajectories described by Winant et al. (1999) and Winant et al. (2003).

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