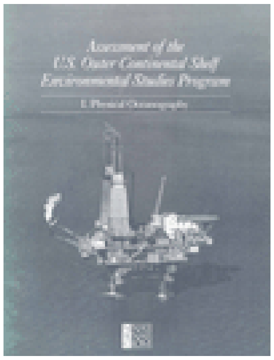

Assessment of the U.S. Outer Continental Shelf Environmental Studies Program: I. Physical Oceanography

Committee to Review the Outer Continental Shelf Environmental Studies Program

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Assessment of the U.S. Outer Continental Shelf Environmental Studies Program

I. Physical Oceanography

Physical Oceanography Panel
Committee to Review the Outer Continental Shelf Environmental Studies Program
Board on Environmental Studies and Toxicology
Commission on Geosciences, Environment, and Resources

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Preface

The review leading to this report was initiated in May 1986 by the National Research Council (NRC) at the request of the Minerals Management Service (MMS) of the U.S. Department of the Interior. Under the auspices of the NRC Board on Environmental Studies and Toxicology, the Committee to Review the Outer Continental Shelf Environmental Studies Program was formed to carry out the overall assignment. Three panels were established, one of which, the Physical Oceanography Panel, investigated the physical oceanographic aspects of the Environmental Studies Program (ESP), the subject of this report, which is the first of three in a series.

It has been 12 years since a previous review by the National Research Council (*OCS Oil and Gas: An Assessment of the Department of the Interior Environmental Studies Program*, National Academy of Sciences, 1978) recommended a change from the previous program of supporting descriptive baseline studies to one of carrying out studies that focus on the prediction of impacts from OCS operations and provide information more directly applicable to leasing and management decisions. To date, the ESP has expended nearly $500 million over its 17-year history for environmental studies applicable to lease sales covering most of the outer continental shelf. It appeared to MMS in 1986 that the time was ripe to assess the status of the present program and to explore the needs for future studies. Thus, MMS requested an evaluation of the adequacy and applicability of ESP studies, a review of the general state of knowledge in the appropriate disciplines, and recommendations for future studies.

The Physical Oceanography Panel based its report on several sources, including presentations from staff members of the Environmental Studies and Environmental Modeling Branches of MMS; briefings by other, independent scientists familiar with the work carried out in the different regions under the support of the Environmental Studies Branch; results of a workshop on numerical modeling held by the panel; and a review of the relevant scientific literature and documentation of MMS's planning and implementation processes leading to various lease sales.

Reviewing the ESP and making recommendations for future studies required the committee and its panels to consider certain interactions between the ESP and other parts of MMS, especially the Branch of Environmental Modeling (BEM) and the producers of environmental impact statements (EISs) for lease sales, the four regional offices of the Branch of Environmental Evaluation (BEE). It was necessary to consider these interactions in order to evaluate the "applicability" of ESP studies to MMS needs. Thus, some parts of this report include particular reference to BEM and to EISs.

Midway through its deliberations, the committee was asked to undertake two additional tasks. First, MMS requested a review of the adequacy of scientific and technical information pertaining to environmental concerns for outer continental shelf (OCS) decisions on the Georges Bank area in the north Atlantic (lease sale 96). Second, President Bush's Task Force on OCS oil and gas leasing requested a review of the adequacy of available scientific and technical information pertaining to environmental concerns for lease sales 116, Part 2 (southwestern

Florida); 91 (northern California); and 95 (southern California). The report to President Bush's Task Force has been completed (NRC, 1989a), and the Georges Bank report is near completion.

The additional studies depended for their success on the work done on the original study, *but* their focus is *not* identical. The original charge was broader in that it covered the entire U.S. OCS and narrower in that it concerned only MMS's ESP; that is why this report does not directly evaluate the adequacy of information for making leasing and other OCS decisions, as the reports on California and Florida and on the North Atlantic do.

The panel benefited greatly from the workshop on numerical modeling, in which J. Herring, J. Galt, J. Leendertse, S. K. Liu, M. Reed, and A. Wallcraft discussed their use of numerical modeling to obtain oil-spill-trajectory information. Their presentations were the initial input for the workshop recommendations formulated by all workshop participants, who also included K. Brink, Z. Kowalik, M. Luther, A. Okubo, R. Pritchard, A. Robinson, R. Smith, D.P. Wang, and the panel. Those recommendations helped clarify the panel's deliberations and the formulation of its own recommendations.

The panel also learned much from presentations describing the physical oceanography of the different geographic regions and the MMS contributions thereto by the following experts: L. Atkinson, B. Butman, L. Pietrafesa, T. Royer, R. Smith, and T. Sturges. R. Sternberg summarized benthic processes for the panel.

The help and cooperation of the MMS staff, particularly D. Aurand, R. Cohen, B. Drucker, R. LaBelle, and T. Paluszkiewicz, were crucial. The panel's work was carefully guided and supported by the National Research Council staff directed by D. Policansky. L. Sanford, who did a superior job of assembling the drafts prepared by individual panel members, improved the report substantially. The reviewers' many helpful comments led to an appreciably better final report.

To all of the above the panel members express their appreciation.

MAURICE RATTRAY, JR.

CHAIRMAN, PHYSICAL OCEANOGRAPHY PANEL

Contents

Executive Summary

Federal responsibility for oil and gas development on the U.S. outer continental shelf (OCS) resides with the Minerals Management Service (MMS) of the U.S. Department of the Interior (DOI). From 1954 through 1988, the last year for which statistics have been published, OCS oil and gas development provided about 7% of total domestic oil production, about 13% of domestic natural gas, and more than $90 billion in revenue from cash bonuses, lease rental payments, and royalties on produced oil and gas (U.S. DOI, 1989).

The DOI's Environmental Studies Program (ESP) is the program through which MMS conducts environmental studies on the OCS and collects information to prepare environmental impact statements (EISs). The ESP began in 1973 under the Bureau of Land Management (BLM). Through 1989, the ESP had invested more than $478 million in a wide variety of studies, most of them performed by contractors. Physical oceanographic studies have amounted to approximately 22% of the ESP budget—on average, more than $7 million a year, for a total expenditure through 1988 of over $105 million for physical oceanography studies.

THE PRESENT STUDY

It appeared to MMS in 1986 that the time was ripe to assess the status of the present program and to explore the needs for future studies. Thus, MMS requested an evaluation of the adequacy and applicability of ESP studies, a review of the general state of knowledge in the appropriate disciplines, and recommendations for future studies. Under the auspices of the NRC Board on Environmental Studies and Toxicology, the Committee to Review the Outer Continental Shelf Environmental Studies Program was formed to carry out the overall assignment. Three panels were established, one of which, the Physical Oceanography Panel, investigated the physical oceanographic aspects of the ESP, the subject of this report, which is the first of three in a series.

The panel based its report on several sources, including presentations from staff members of the Environmental Studies and Environmental Modeling Branches of MMS; briefings by other, independent scientists familiar with the work carried out in the different regions under the support of the Environmental Studies Branch; results of a workshop on numerical modeling held by the panel; and a review of the relevant scientific literature and documentation of MMS's planning and implementation processes leading to various lease sales.

In reviewing the ESP's physical oceanography program, the panel evaluated the quality and relevance of studies carried out in waters under federal control, which extend from the limits of state jurisdictions (3-12 miles offshore) and include the central and outer continental shelf waters and the continental slope. The panel also emphasized features and processes that control the motion and fate of surface and near-surface oil in oceanic waters. Although the effects of oil exploration and resource development are not constrained by political boundaries, most MMS studies have dealt with U.S.-controlled waters and with the features, processes, and models that are of primary importance to the movement of near-surface oil spills in these waters. This does not imply that energy-related impacts in the coastal zone and in the lower water column and benthic boundary layer are unimportant—indeed, the panel recommends that MMS devote more study to nearshore areas—but rather that the panel concentrated on questions that have driven the major physical oceanographic study efforts of MMS. For this reason, the panel also did not specifically consider the effects of gas blowouts.

In completing its evaluation, the panel considered four major topics:

1. The acquisition and use of physical oceanographic information by the ESP;
2. The state of knowledge of general physical oceanographic processes that are most important for understanding and modeling the motion and fate of oil spills in the ocean;
3. The state of knowledge of the physical oceanography for each of the ESP regions, based on all available sources; and
4. The adequacy and applicability of each of the ESP regional physical oceanography programs, as well as the generic studies managed by the MMS headquarters office, as measured by (a) the success of the field programs and modeling efforts in meeting ESP needs; (b) contributions to the general state of physical oceanographic knowledge; and (c) interactions with other agencies and the rest of the scientific community.

Chapter 1 of this report describes the history of the ESP and the structure of MMS; it also discusses how MMS uses physical oceanographic information. Chapter 2 presents an in-depth analysis of topics in physical oceanography that have general relevance to the ESP; it includes information generated by MMS-funded studies as well as by non-MMS studies. Chapter 3 describes the physical oceanography and meteorology of each region and evaluates the regional studies programs. It also evaluates work supported by the Washington Office (WO) of the ESP. Chapter 4 summarizes the panel's conclusions and recommendations for future ESP studies.

ACQUISITION AND USE OF PHYSICAL OCEANOGRAPHIC INFORMATION BY THE ESP

Physical oceanography studies provide an important part of the basis for calculating estimates of the transport and fate of oil spills in the ocean. These calculations are then used to estimate potential effects of oil spills. The Oil Spill Risk Analysis (OSRA) model, developed by the U.S. Geological Survey (USGS) in 1975, is used by MMS's Branch of Environmental Modeling (BEM) to estimate the probability of oil spills in a specific lease area, to calculate oil-spill trajectories from selected spill launch points (i.e., places that a spill is assumed to occur), and to determine the probability that an environmental resource or coastline segment will be affected by oil released from the selected launch points. Physical oceanographic and meteorological data are required to calculate the probable trajectories of oil from spill sites and more generally to provide background information for environmental impact assessment. Some of this information is provided by studies funded by the ESP. Although physical oceanographic information (including model outputs) obtained through the ESP has been used primarily as input to the OSRA model and to prepare associated EISs, it has also been used to support biological and ecological studies and to predict the transport of drilling muds and cuttings and other by products of oil exploration and production.

The primary physical environmental information requirements of the OSRA model are definitions of the circulation and wind fields in a study area (i.e., the output of ocean circulation and meteorological models). BEM calculates trajectories for all OCS waters except those in the Alaska region, where contractors calculate trajectories and provide them to BEM for input to the OSRA model. The OSRA model then calculates the probability of oil-spill occurrence for the selected launch sites using historical data, the number of "hits" (the number of times a spill encounters an environmental resource target or shoreline segment), and the conditional probabilities of impact on the resource within a previously selected time.

CONCLUSIONS

Physical Oceanographic Processes And Models Of Importance To The Esp

MMS-funded studies have contributed to the dramatic increase in knowledge of the coastal marine environment that has occurred during the past decade. These contributions have included the development of circulation models and the observational study of circulation patterns that may be useful for predicting oil-spill trajectories and fate. In general, MMS-funded studies have fit in well with studies funded by other agencies (e.g., USGS, the Department of Energy, the National Oceanic and Atmospheric Administration, and the National Science Foundation).

MMS has relied too heavily on available circulation models. This reliance on numerical circulation models for physical oceanographic input to the OSRA model makes it imperative that the strengths, weaknesses, and limitations of the modeling approach be fully understood. This is true whether the circulation models are used predictively or for spatial and temporal extrapolation of observed data. In addition to considerations of the accuracy of the models used, attention must be paid to the time and space scales of motion that are required for accurate trajectory simulation. The development and incorporation of oil-spill-fate models also are important, requiring an accurate representation of the physical processes that contribute to weathering.

Even where the circulation models used by MMS contractors are the state of the art, as is often the case, this does not justify implicit trust in model results. Verification, intermodel comparison, and sensitivity studies are needed. Areas for possible improvement that are common to most numerical models are identified in Chapter 2. In all cases, it is important to test fully a model's predictive ability against observations and to understand its behavior. Techniques to accomplish these tasks quantitatively are becoming available but are used too seldom.

In spite of the quality of many individual physical oceanography studies, the results of these modeling and field studies have not been effectively integrated. The two types of studies—modeling and field studies—are usually procured separately (either through direct MMS procurements or through cooperation with other agencies), and this seems to have hampered their integration by MMS. Thus, the information that has actually been used by BEM and incorporated into environmental impact assessments in EISs has been less than the information potentially available. The OSRA model, which is used for impact assessment by MMS, relies extensively on the results of ocean-circulation models to estimate the circulation for a given area. However, MMS's use óf circulation-data sets based on field observations (or derived from assimilation of field observations and model results) appears to be minimal. In other words, there is insufficient validation and calibration of the ocean-circulation models with data derived from field observations. Also, field data have not been sufficiently used as independent sources of data to describe the circulation for input to the OSRA model. This problem also was noted in reviewing the regional programs; in general, physical oceanographic field studies have been extensive, but the resulting data have been underutilized. BEM has recently begun to institute changes that the panel believes will improve its use of OSRA (pers. comm., MMS, 1990).

The lack of integration of field-derived information into the models and the impact assessments in EISs contrasts with the summary descriptions of regional ocean circulation in the EISs, where field-derived information is used more extensively than in the impact assessments. Field data from actual spills—particularly large ones, such as the recent spill in Prince William Sound—would also be useful in this regard. A related problem is that the best available circulation models are not always used for the OSRA calculations; this was notable in some OSRA calculations done for the Atlantic region (including the OSRA calculation for the EIS for lease sale 96).

Another difficulty with the OSRA models is that the wind fields used in calculating spill trajectories for the Atlantic, Pacific, and Gulf of Mexico regions have not been the same as the wind fields used to drive the circulation models. Transition-probability matrices (i.e., matrices giving the probabilities that a variable will change from each possible state to every other possible state) have been used to generate wind fields for the OSRA model. The matrices, until recently, have been based on observations at a limited number of stations; since 1989, the transition-probability matrices have been abandoned in favor of wind fields based on meteorological models. The use of only a few stations could have led to inaccuracies in the resultant trajectory calculations, because the true spatial variability of winds is not adequately represented. The potential for such inaccuracies is highlighted by recent detailed analyses of winds observed onshore and offshore, which found large spatial and temporal variability in the structure of the wind field and in the coherence between onshore and offshore stations. This variability is greatest near the coast, where land-sea interaction is an important factor and where spilled oil is more likely to have long-lasting impacts.

The panel identified several processes that must be better understood and included in models that estimate oil-spill motion at or near the surface over the time frame of interest. In most cases, oil spills in the ocean result in surface slicks that drift, spread, and weather in response to environmental conditions. Petroleum spills in the marine environment undergo relatively rapid weathering. Evaporative losses, dispersion, and dissolution into the water column all occur within a few days to a week after a spill (NRC, 1985). After 30 days, most surface slicks are well weathered (Mackay et al., 1983; Koons, 1987; NRC, 1989b). Thus, the physical oceanographic processes that are most important to the ESP from the perspective of the fate and the effects of spilled oil (and the immediate containment and cleanup of spilled oil) are those that most influence the motion of oil at or near the surface within about 30 days of an oil spill. Oil spills might occur at any time during the life of a lease, and so knowledge of the inherent variability of the physical oceanography over seasonal and interannual time scales also is important. Although physical oceanography does not usually consider the behavior of oil and other contaminants per se, oil-spill-fate modeling is important for accurate prediction of oil-spill behavior. This report emphasizes the spreading and dispersion of oil, because they are the most closely tied to near-surface physical oceanographic processes. Spreading is one of the most important processes in oil-spill dynamics, because it determines the areal extent of spilled oil and affects the various weathering processes influenced by surface area. Dispersion is generally assumed to result from wind-generated breaking waves dispersing oil in the water column. Both processes are poorly understood, but both depend critically on the interactions of the wind, the surface-wave field, the response of near-surface waters, and the use of chemical dispersants.

The presence and dynamics of ice clearly are important for modeling oil trajectories in most Alaskan waters (and some nearshore New England waters during especially cold winters); ice conditions are influential in determining the movement and final disposition of spilled oil. In addition, interactions between oil and sea ice are poorly understood. These interactions are extremely complex, depending on the percentage of ice cover, ice motion, temperature, wind, duration of ice cover, and the history and location of ice-oil contact. Few models account for oil-ice interaction.

Regional Oceanography

The U.S. continental margins are divided into four regional jurisdictions covered by the regional offices of ESP: the Alaskan coast, the Pacific coast, the Gulf of Mexico, and the Atlantic coast. In addition, some studies that apply to the entire OCS are funded by the WO. The four regions are distinguished by more than MMS's internal division of responsibility; the regions have fundamental differences in geology, topography, and bathymetry and in the processes that control the circulation of shelf waters and affect the motion of oil in surface waters of the regions. These differences also are apparent between subregions within each region. In general, the physical oceanography of all of the major continental margins is reasonably well known, especially from a basin-wide, descriptive point of view.

Evaluation Of Regional Programs And Washington Office Programs

In contrast to the regional offices' goals of data collection, analysis, and synthesis, the efforts of the WO have focused on supporting regional studies, addressing generic process and modeling issues, and summarizing or documenting previous studies. The number of physical oceanographic studies funded by the WO has been limited, but according to the material available, studies completed by the WO have addressed important areas and have been completed with timely products of generally good quality. Given the importance of generic studies to the overall ESP effort, the WO is small compared to its regional counterparts.

Several important generic research efforts now carried out by the regional offices instead seem appropriate for the WO under the generic studies program. The mandate to complete these overview or generic efforts clearly belongs with the WO, and the management structure of MMS should reflect that.

In evaluating the physical oceanographic components of the ESP in the four regional offices and the WO, the panel noted that although regional efforts vary, too little of the work carried out for MMS has been published in the open, refereed literature. This is particularly true of the modeling and model-data intercomparison studies. Publication in the open literature could improve the quality of MMS-funded efforts through the peer-review process and substantially increase, at little cost, the body of knowledge available to the oceanographic community. MMS's recent efforts in this direction are commendable.

RECOMMENDATIONS

The panel makes three general recommendations for future ESP physical oceanography and oil-spill studies, and for the use of results of these studies by BEM and in EISs. Each general recommendation has several associated specific recommendations. The recommendations (see Chapter 4) are briefly summarized below.

1. **The Minerals Management Service should support continuing studies on relevant physical oceanographic and meteorological processes and features that are poorly understood, poorly parameterized in existing models, or poorly represented by existing modeling methodology. Improvements should continue to be incorporated into the OSRA model**.

a. MMS should support continuing investigations of surface-layer physics, aimed at improving basic understanding and modeling.
b. MMS should continue to support studies that lead to understanding and modeling of oil-spill-fate processes.
c. MMS should support additional observational and modeling studies of sea-ice.
d. MMS's recent moves to adopt consistent methods in calculating oil-spill trajectories at the sea surface and calculating the underlying currents are commended; they should continue.
e. MMS should continue to improve the meteorological input to oil-spill-trajectory simulations to account correctly for the spatial and temporal structure of the wind field.
f. MMS should give more consideration to extreme events (e.g., hurricanes) that might lead to higher spill probability and more rapid water and oil motion.
g. In future trajectory simulations, MMS should incorporate a methodology to address the inherent variability in the wind field and the current field at small (i.e., subgrid) space and time scales.
h. MMS's use of drifters to represent oil spills should be extended to actual field trials in varied areas of the OCS, and in similar regions worldwide as the opportunities occur.

2. **The Minerals Management Service should reduce its present overreliance on model results until the models can be more fully tested and verified; such testing will require sensitivity analyses and model intercomparisons. Instead, MMS should use its extensive field observational data base more fully. Verification will require close cooperation between field scientists and modelers**.

a. MMS should seek a more balanced integration of model and field-data products for future trajectory calculations.
b. For scientific credibility, it is imperative that MMS carry out detailed sensitivity studies for all modeling work.

c. It is also imperative for scientific credibility that MMS perform systematic model intercomparison and verification against field data.
d. MMS should require closer cooperation between field scientists and modelers in future MMS-sponsored physical oceanographic field programs. More input from field scientists is also needed in model design, application, and verification.
e. Given the present level of understanding for most shelf regions of interest to the OCS leasing program, a carefully integrated program using field observations and numerical hydrodynamic modeling is suggested to provide a description of the circulation needed for input to the OSRA model.
f. MMS should strengthen its ability to seize the scientific study opportunities provided by accidental oil spills, such as the recent *Exxon Valdez* spill in Prince William Sound. The *Exxon Valdez* spill also illustrates the importance of analyzing worst-case scenarios.
g. Although technically the ESP's jurisdiction covers the OCS, MMS should consider oil spills occurring shoreward of the OCS. The panel notes that OCS oil can be spilled inshore of the OCS.

3. Program priorities and operating procedures in the ESP should be modified as necessary to ensure that improved scientific input is obtained at all stages of ESP operation in all regions, that available data from cooperating agencies are used, that development of a better-integrated national program continues, and that study results are published more often in the peer-reviewed scientific literature.

a. MMS needs a more appropriate balance between national and regional priorities.
b. MMS should obtain more external scientific input and use it more fully in many aspects of the ESP.
c. MMS's cooperation with other agencies is commended; it should continue.
d. MMS should continue its efforts to develop a better-integrated national program while maintaining the regional office structure.
e. MMS should continue to strengthen its program to have the results of its studies presented at scientific meetings and published in the open, peer-reviewed scientific literature.

1

Introduction

Offshore drilling for oil and gas has been conducted since the beginning of the century, and oil and gas under the seabed continue to be an important part of the energy resources of the United States. The need to balance the value of these resources against the potential for environmental damage has become increasingly recognized in federal laws and national debate over energy.

Until 1969, potential environmental damage from outer continental shelf (OCS) oil and gas activities was mostly a local concern in the affected states. Environmental concerns were brought to national attention by oil-spill damage resulting from a major blowout at a Union Oil platform in the Santa Barbara Channel in January 1969 (Congressional and Administrative News of the U.S. Code, 1978). That oil spill covered 660 square miles, including 150 miles of coastline (Cicin-Sain, 1986). Other accidents involving oil and gas have added to environmental concerns, even though they have not involved the U.S. OCS. Two accidents widely noticed in the United States were the blowout of the Mexican offshore well *IXTOC I* on June 3, 1979, which released over 150 million gallons (500,000 tons) of oil as well as natural gas—the largest accidental oil spill in history (NRC, 1983)—and the grounding of the tanker *Exxon Valdez* on March 24, 1989, which released approximately 11 million gallons of North Slope crude oil into Alaska's Prince William Sound. Even though the *Exxon Valdez* accident did not involve OCS oil, it is clear that it has affected debate on the production of OCS oil.

The value of the petroleum resource is large. From 1954 through 1988, the last year for which statistics have been published, OCS oil and gas development provided about 7% of total domestic oil production, about 13% of domestic natural gas, and more than $90 billion in revenue from cash bonuses, lease rental payments, and royalties on produced oil and gas. In 1988 alone, the OCS provided approximately 10.8% of domestically produced oil, 24.6% of domestic natural gas, and over $3 billion in revenue to the government (U.S. DOI, 1989). Thus, balancing the value of the resource against environmental concerns is an important concern.

OUTER CONTINENTAL SHELF ACTIVITIES

Management Of OCS Activities

OCS leasing is managed by the Minerals Management Service (MMS) of the Department of the Interior (DOI). MMS was formed in 1982 to consolidate responsibility for offshore oil and gas development in one agency. It includes some functions and personnel previously in the Bureau of Land Management (BLM) and the U.S. Geological Survey (USGS). Federal responsibility for development of mineral resources and conservation of natural resources on the OCS was established by the Outer Continental Shelf Lands Act of 1953 as amended in 1978 (OCSLAA) (43 U.S.C. 1331-1356, 1801-1866) and the Submerged Lands Act of 1953 (43 U.S.C. 1301-1315).

In 1974, as part of a strategy to deal with the nation's energy problems following the Arab oil embargo, former President Richard Nixon directed the Secretary of the Interior to increase the amount of acreage leased. Congress was also concerned, however, that federal administration of the leasing program and regulation of OCS development was a closed decision-making process involving the Secretary of the Interior and industry (Congressional and Administrative News of the U.S. Code, 1978). In 1978, when OCSLAA was passed, Congress expected that offshore production would provide the largest domestic source of oil and gas into the 1990s (Congressional and Administrative News of the U.S. Code, 1978). One purpose of the amendments was to provide a statutory mechanism to open decision making to a wide variety of views and to increase public confidence in this government activity (Congressional and Administrative News of the U.S. Code, 1978).

The OCS lease-sale schedule is established in accordance with a 5-year plan indicating the size, timing, and location of proposed leasing activities. The plan is developed in a 2-year process that includes consultation with coastal states and other federal agencies and an opportunity for public comment. Beginning in 1983, lease sales were offered on an area-wide basis instead of for selected tracts so that the number of blocks and leases was increased and more exploratory wells were encouraged in frontier areas, such as areas of deep water. (The area-wide leasing process has been modified in the current five-year plan to a "focused" leasing process that gives primary consideration to promising acreage.) The current plan, effective from mid-1987 to mid-1992, calls for one sale every 3 years in 21 of the 26 OCS planning areas (see Figs. 1 and 2), except in the Gulf of Mexico, where sales are scheduled annually. Sales in several environmentally sensitive subareas have been deferred indefinitely (U.S. DOI, 1987a).

Extent of the Leasing Program

Between 1954 and 1988 there were 100 lease sales offering 127,585 tracts that included 695,936,201 acres in the four OCS regions—Alaska, the Atlantic, the Gulf of Mexico, and the Pacific. Only 10,380 (8.1%) of those tracts, which included 53,270,423 acres (i.e., 7.7% of the acreage offered), were actually leased. Table 1 provides a regional breakdown of lease offerings and sales between 1954 and 1988.

Of 5,818 leases active in 1988, 1,647 (28%, totaling 7,691,964 acres) were producing. To date, all producing leases have been in California and the Gulf of Mexico, although some in Alaska have proven reserves. Production first began in the OCS in the Gulf of Mexico region in 1954. California OCS wells did not begin to produce until 1968. Tracts on federal lands in the Alaska and Atlantic regions were first leased in 1976 but to date have not produced. However, there has been considerable production in state tracts in Alaska as well as in California and the Gulf of Mexico. Table 2 shows, by region, the number of leases active in 1988. Through 1988, 4,235 platforms had been built and 576 had been removed, leaving 3,659 in place (U.S. DOI, 1989).

Environmental Concerns Resulting from OCS Activities

The potential impacts of oil spills resulting from OCS development and production on resources, such as fisheries and endangered species, have caused environmental concern. Other sources of potentially adverse impacts associated with OCS development include the discharge of produced water and drilling muds and chronic loss of oil at the drilling sites. Seismic surveys (conducted in the exploratory phase), platforms, and pipelines may interfere with commercial, recreational, and subsistence fishing activities. In addition, potentially adverse socioeconomic impacts are also associated with the construction of onshore support facilities (NRC, 1978; U.S. DOI, 1987a). The potential for long-term, chronic environmental effects is also a source of concern (Table 3). The effects of oil spills and drilling mud discharges have been the subject of previous NRC reviews (NRC, 1975; 1983; 1985). Oil discharged from OCS operations has been estimated to contribute approximately 1% of oil inputs in the oceans worldwide from all sources (NRC, 1985), but is nevertheless a major source of public concern. Total spillage and seepage for

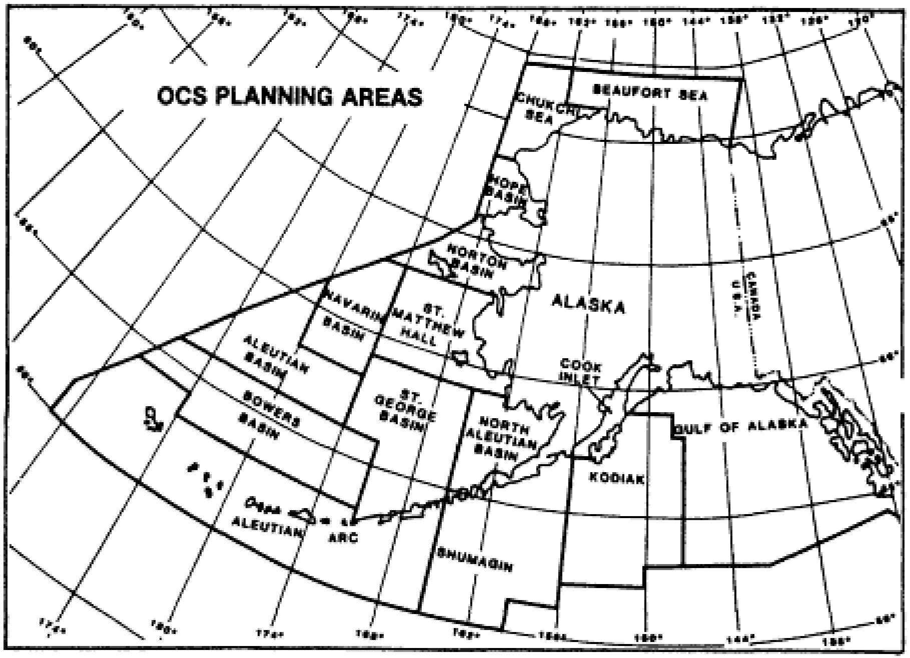

Figure 1
Outer Continental Shelf planning areas (Alaska).
Source: U.S. DOI, 1987a.

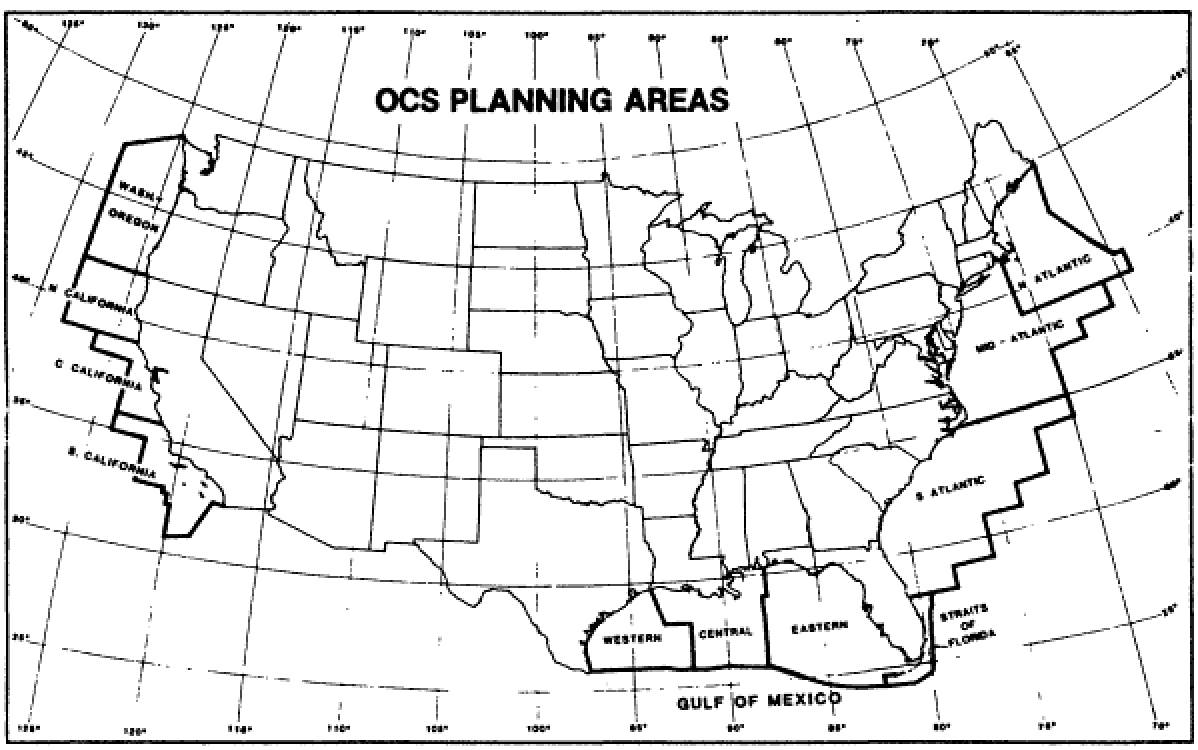

Figure 2
Outer Continental Shelf planning areas (contiguous United States).
Source: U.S. DOI, 1987a

TABLE 1 Lease Offerings and Sales, 1954-1988

		Leases Offered		Leases Issued		Leased Percentage	
Region	Number of Sales	Tracts	Acres	Tracts	Acres	Tracts	Acres
Alaska	15	17,638	98,013,764	1,481	8,181,465	8.4	8.3
Atlantic	8	9,160	51,520,602	410	2,334,205	4.5	4.5
Gulf of Mexico	66	98,885	536,578,440	8,019	40,214,741	8.1	7.5
Pacific	11	1,903	9,823,395	470	2,540,012	24.7	25.9
Total	100	127,586	695,936,201	10,380	53,270,423	8.1	7.7

Source: U.S. DOI, 1989.

TABLE 2 Active Leases, 1988

Region	Active Leases	Percentage of Active Leases	Acres Leased	Percentage of Acres Leased
Alaska	1,000	17.2	5,495,059	18.6
Atlantic	74	1.3	421,296	1.4
Gulf of Mexico	4,609	79.2	22,967,196	77.6
Pacific	135	2.3	700,200	2.4
Total	5,818	100.0	29,583,751	100.0

Source: U.S. DOI, 1989.

the Gulf of Mexico and Pacific regions (1970-1988) was estimated at nearly 205,000 barrels (Table 4) (U.S. DOI, 1989). Table 5 provides the location and type of accident for reported spills of 1,000 barrels or more from 1964 to 1988—all but one were in the Gulf of Mexico.

Other sources of oil in the marine environment include natural sources (e.g., marine seeps and sediment erosion), transportation (including tanker operations, dry-docking, marine terminals, bilge and fuel oils, tanker and nontanker accidents), atmospheric deposition, and municipal wastes (refineries, nonrefining industrial wastes, urban runoff, river runoff, and ocean dumping). In 1985, petroleum inputs to the ocean from all sources were estimated to total between 1.7 and 8.8 million metric tons (12.8 to 65 million barrels). The most likely figure was estimated to be 3.2 metric tons (23.6 million barrels) (NRC, 1985).

MMS'S ENVIRONMENTAL STUDIES PROGRAM

Mandate

Under OCSLAA (43 U.S.C. Sec. 1344), MMS must manage the oil and gas leasing program with consideration for the economic, social, and environmental values of both renewable and nonrenewable resources in the OCS; the marine, coastal, and human environments that could be affected; the laws, goals, and policies of affected states; and the equitable sharing of developmental benefits and environmental risks among the various regions. Timing and location of leasing must be selected, to the maximum extent practicable, to balance the potential for environmental damage and for adverse impact on the coastal environment with the potential for discovery of oil and gas.

TABLE 3 Major Activities in the Development of an Offshore Oil and Gas Field and Their Potential Effects on Marine and Coastal Environments

Activities	Potential Effects
Evaluation	
Seismic surveying	Noise effects on fishes and mammals
Exploration	
Rig fabrication	Dredging and filling of coastal habitats (mostly overseas)
Rig emplacement	Seabed disturbance due to anchoring
Drilling	Discharge of drilling fluids and cuttings; risk of blowouts
Routine rig operations	Deck drainage and sanitary wastes
Rig servicing	Discharges from support vessels and coastal port development
Development and production	
Platform fabrication	Land use conflicts and increased channelization in heavily developed areas
Platform installation	Coastal navigation channels; seabed disturbance resulting from placement and subsequent presence of platform
Drilling	Larger and more heavily concentrated discharges of drilling fluids and cuttings; risk of blowouts
Completion	Increased risk of oil spills
Platform servicing	Dredges and coastal port development; discharges from vessels
Separation of oil and gas from water	Chronic discharges of petroleum and other pollutants
Fabrication of storage facilities and pipelines	Coastal use conflicts
Offshore emplacement of storage and pipelines	Seabed disturbances; effects of structures
Transfer to tankers and barges	Increased risk of oil spills; acute and chronic inputs of petroleum
Construction of on-shore facilities for transportation and storage	Coastal use conflicts; alterations of wetlands in pipeline corridors
Pipeline operations	Oil spills; chronic leaks
Refining	
Construction and expansion	Coastal use conflicts
Operations	Increased pollutant loading; depends on regional demands, imports, etc.

Source: Neff et al., 1987

To balance the benefits of the leasing program with environmental concerns, MMS must conduct studies to develop information needed for "the assessment and management of environmental impacts on the human, marine, and coastal environments of the OCS and the coastal areas that may be affected by oil and gas development" in the proposed leasing area

(43 U.S.C. Sec. 1346 (a)(1)). Specifically, MMS must predict impacts on the marine biota that could result from chronic low-level pollution or large oil spills associated with OCS production or from the introduction of drill cuttings and drilling muds in the area and impacts of offshore development on the affected coastal areas (43 U.S.C. Sec. 1346 (a)(3)). MMS must also conduct studies necessary for monitoring the human, marine, and coastal environments of leased areas "in a manner designed to provide time-series and data-trend information which can be used for comparison with any previously collected data for the purpose of identifying any significant changes in the quality and productivity of such environments, for establishing trends in the areas studied and monitored, and for designing experiments to identify the causes of such changes" (43 U.S.C. Sec. 1346 (b)).

TABLE 4 Crude Oil and Condensate Spills and Seeps of 1 Barrel or More from Offshore Wells on Federal Leases, 1970-1988.

	Gulf of Mexico OCS			Pacific OCS			
	Number of Spills		Total Spillage in Bbls.	Number of Spills		Total Spillage in Bbls.	Total Spillage in Bbls.
Year	1-50 Bbls.	More than 50 Bbls.		1-50 Bbls.	More than 50 Bbls.		
1970	8	5	83,894	0	0	0	83,894
1971	267	7	2,446	0	0	0	2,446
1972	203	1	997	0	0	0	997
1973	178	5	23,125	0	0	0	23,125
1974	80	7	24,453	0	0	0	24,453
1975	109	2	761	0	0	0	761
1976	66	4	5,103	1	0	2	5,105
1977	71	3	1,087	1	0	4	1,091
1978	79	3	1,528	0	0	0	1,528
1979	114	4	2,700	1	0	2	2,702
1980	50	9	2,922	1	0	5	2,927
1981	65	5	5,793	9	0	73	5,866
1982	70	3	1,174	1	0	3	1,177[a]
1983	91	9	2,552	2	0	4	2,556[b]
1984	59	1	380	3	0	36	416[a]
1985	66	5	1,613	1	0	5	1,618[a]
1986	40	2	356	2	0	11	367
1987	34	1	232	2	0	10	242
1988	29	3	15,285	1	0	2	15,287
Total	1679	79	176,401	25	0	157	176,558

NOTE: These figures do not include natural seepage. Natural seepage in the Santa Barbara Channel is estimated at 40-670 barrels daily (14,600-244,500 barrels yearly) from more than 2,000 seeps.
a These totals include spills for the Alaska OCS: 1982, 1 spill of 19 barrels; 1984, I spill of 2 barrels; 1985, 1 spill of 2 barrels; and 1988, 1 spill of 5 barrels.
b This total includes 2 spills totaling 24 barrels on the Atlantic OCS in 1983.
Source: U.S. DOI, 1989.

In addition, the Secretary must "submit to the Congress and make available to the general public an assessment of the cumulative effect of activities conducted under this subchapter on the human, marine, and coastal environments" (43 U.S.C. Sec. 1346 (e)). Although such a report obviously should make use of information generated by the Branch of Environmental Studies (BES), the report is prepared by another branch of MMS. Under the same section, the Secretary must also establish procedures for the conduct of the required studies. OCSLAA (43 U.S.C. 1334 (a)(8)) also requires the Secretary to regulate OCS activities to ensure that they do not prevent the attainment of National Ambient Air Quality Standards.

TABLE 5 Crude Oil and Condensate Spills of 1,000 Barrels or More From Offshore Wells on Federal Leases, 1964-1988

Year	Location	Type of Accident	Number of Barrels Spilled
1964	Eugene Island	Freighter struck platform	2,559
1964	Eugene Island	Platform in hurricane	5,180
1964	Ship Shoal	Platform in hurricane	5,100
1964	Ship Shoal	Platform in hurricane	1,589
1965	Ship Shoal	Well blowout	1,688
1967	West Delta	Anchor damage to pipeline	160,638
1968	South Tirnbalier	Anchor damage to pipeline	6,000
1969	Santa Barbara Channel	Well blowout	77,000
1969	Main Pass	Anchor damage to pipeline	30,000
1969	Ship Shoal	Ship struck platform in storm	2,500
1970	Main Pass	Well blowout	30,000
1970	South Timbalier	Well blowout	53,000
1973	West Delta	Structural failure/tank rupture	9,935
1973	South Pelto	Storage barge sank	7,000
1973	West Delta	Pipeline corrosion	5,000
1974	Eugene Island	Anchor damage to pipeline	19,833
1974	Main Pass	Hurricane damage to pipeline	3,500
1976	Eugene Island	Shrimp trawl damage to pipeline	4,000
1979	Main Pass	Vessel collided with semisubmersible	1,500
1980	High Island	Pump failure, tank spill	1,456
1981	South Pass	Anchor damage to pipeline	5,100
1988	Galveston	Anchor damage to pipeline	14,944

Source: U.S. DOI, 1989.

The Secretary must then use information prepared under these sections to support leasing decisions, promulgate regulations, set lease terms, and establish operating procedures (Congressional and Administrative News of the U.S. Code, 1978; 43 U.S.C. Sec. 1346 (d)). Environmental studies information is used to support permitting decisions as well. Separate permits are required prior to conducting geological and geophysical surveys, exploration, development, and production. Exploration, development, and production plans must be submitted to MMS together with an environmental report and a certificate of consistency with state coastal zone management plans from the affected coastal states.

The information is also used as the basis for ensuring compliance with other applicable environmental laws such as the National Environmental Policy Act (NEPA) (42 U.S.C. 4321-4347). NEPA requires federal agencies to "utilize a systematic and inter-disciplinary approach which will insure the integrated use of natural and social sciences and the environmental design arts in planning and in decision making which may have an impact on man's environment" and to prepare environmental impact statements on the basis of such information prior to major federal actions. Other environmental laws applicable to OCS activities include the Endangered Species Act of 1973 (16 U.S.C. 1531-1543, 50 CFR 17) and the Marine

Mammal Protection Act of 1972 (16 U.S.C. 1361-1407, 50 CFR 216), which require MMS to consult with the Fish and Wildlife Service and the National Marine Fisheries Service to ensure that OCS activities do not cause significant harm to marine mammals and endangered species or destroy their habitat. The Coastal Zone Management Act (16 U.S.C. 1451-1464; P.L. 92-583), the Federal Water Pollution Control Act Amendments of 1972 (33 U.S.C. 1251-1375; P.L. 92-500), the Alaska National Interest Lands Conservation Act (16 U.S.C. 3101-3233; P.L. 96-487), the National Historic Preservation Act (16 U.S.C. 470-470w6; P.L. 89-665), and the Marine Protection, Research and Sanctuaries Act of 1972 (33 U.S.C. 1401-1445; P.L. 92-352) also affect the offshore leasing process.

History of the Environmental Studies Program

The ESP was established in 1973, in large part to comply with the requirements of NEPA. Since its inception, when it was administered by the BLM, through 1989, the ESP has invested over $478 million in a wide variety of studies. Funding for the program has averaged about $30 million per year but has recently declined to approximately $20 million per year. Most studies are performed by contractors to the agency (U.S. DOI, 1988a). MMS's Branch of Environmental Studies (BES) in Washington, D.C., coordinates the environmental studies programs of the four regional offices in Alaska, the Pacific, the Gulf of Mexico, and the Atlantic. The four regional offices (in Anchorage, Los Angeles, New Orleans, and Reston, Virginia) are responsible for defining and contracting most of the studies. MMS's ESP directs and funds one of the largest mission-oriented oceanographic research programs in the federal government (LaBelle and Anderson, 1985). Physical oceanography studies have accounted for approximately 22% of the ESP budget and over $7 million a year for a total of over $105 million through 1988. Table 6 shows the amount of funding for physical oceanographic studies by region. For a regional listing of all physical oceanographic studies, see Appendix C.

TABLE 6 Cumulative Funding for Physical Oceanography Studies by Region, 1973-1988

Region	Funding in Dollars
Alaska	44,856,370
Atlantic	27,493,347
Gulf of Mexico	9,348,651
Pacific	19,394,651
Washington, D.C.	4,202,784
Total	105,295,803

Source: Compiled by the Physical Oceanography Panel from information provided by the ESP.

From 1974 through 1977, descriptive baseline studies were conducted in each OCS region where industry expressed an interest in leasing. According to MMS, these were large-scale, multidisciplinary studies designed to provide decision makers with a baseline of the geological, physical, biological, and chemical characteristics of the proposed leasing areas (U.S. DOI, 1987b). These studies were intended to be used as a reference standard to evaluate the impact of OCS oil and gas operations. An NRC review recommended that the ESP stop supporting descriptive baseline studies, because they did not provide any basis for distinguishing natural variability from changes caused by OCS operations (NRC, 1978). The NRC recommended that the ESP focus on the prediction of impacts from OCS operations and design specific experiments to "establish the vulnerability of key species or communities." That report also questioned "the capacity of the [physical] oceanographic community to use the data being collected to provide descriptions of the environment more useful for regulatory management of OCS oil and gas operations than those using extant data" except in some areas with very limited existing data.

In response to that review, the ESP was restructured in late 1978 to provide more immediately usable results for leasing and management decisions and to provide a framework for establishing study priorities (U.S. DOI, 1987b). Under the mandate to establish procedures for conducting environmental studies, guidance was developed by an OCS ad hoc advisory committee and published in "Study Design for Resource Management Decisions: OCS Oil and Gas Development and the Environment" (U.S. DOI, 1978); it was adopted by the OCS Advisory Board on April 29, 1978. The guidance document requires identification of management decisions and development of studies to provide the information needed for making those decisions.

The national OCS Advisory Board was established by the Secretary of the Interior in 1975 to provide guidance and recommendations on the leasing and development process, to receive comments and recommendations from state officials and other interested parties, and to provide a forum for discussion among the federal agencies involved. The Advisory Board consists of a policy committee, a scientific committee (SC), and a regional technical working group (RTWG) for each region (except the Atlantic, which, because it has 14 coastal states, has three RTWGs). The Advisory Board reviews political, scientific, and technical aspects of OCS development and attempts to balance state, local, federal, public, and private interests. The SC was established specifically to provide guidance and to review the ESP. The RTWGs make recommendations pertaining to the entire leasing and development process (including the ESP) (U.S. DOI, 1987c) (see Fig. 3).

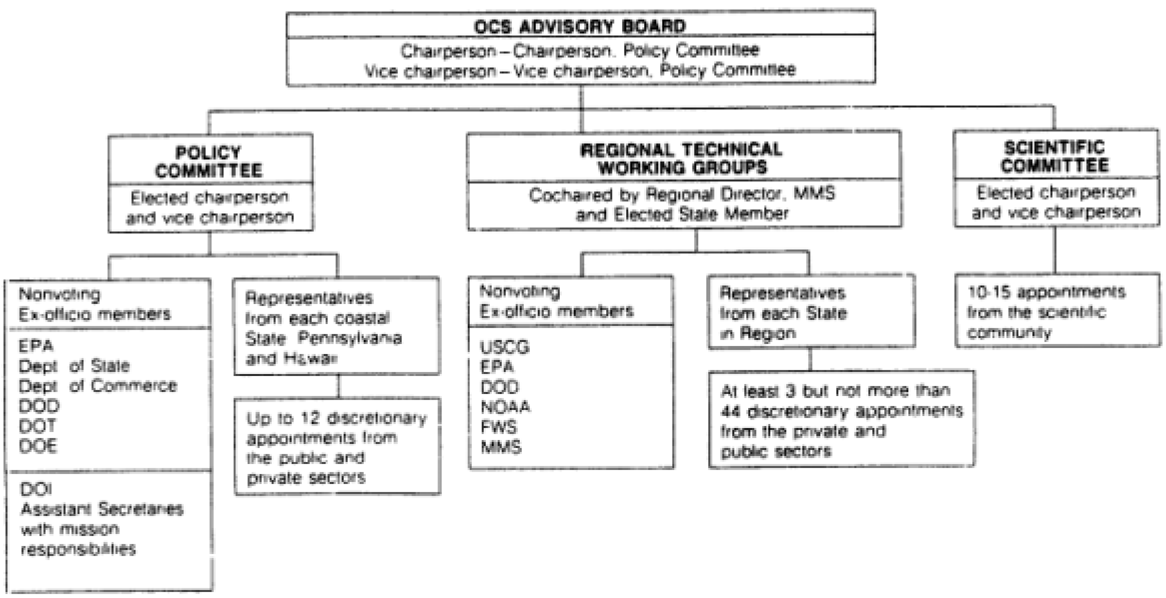

Figure 3
Outer Continental Shelf Advisory Board organizational chart.
Source: U.S. DOI, 1987c.

The stated goals of the ESP are to

1. Provide information on the status of the environment that can be used to predict the impacts of OCS oil and gas development;
2. Provide information on the ways and extent to which OCS development can potentially affect the human, marine, biological, and coastal environments;
3. Ensure that information already available or being collected under the program is in a form that can be used in the decision-making process associated with a specific leasing action or with longer-term OCS minerals management responsibilities; and
4. Provide a basis for future environmental monitoring of OCS operations, including assessments of short-term and long-term impacts attributable to the OCS oil and gas program (Aurand, 1988).

Planned changes in the ESP designed to support the current lease schedule include a change of emphasis from prelease studies to studies of postlease environmental effects, more emphasis on generic studies, and development of a strategy for postlease monitoring (Aurand 1988; U.S. DOI, 1988b).

THE PRESENT STUDY

In 1986, in response to a request from MMS to review the ESP and recommend future directions, the Board on Environmental Studies and Toxicology of the NRC formed the Committee to Review the Outer Continental Shelf Environmental Studies Program. That committee, consisting of experts in ecology, energy production, geochemistry, marine geophysics, oil-field technology, geology, law, physical and biological oceanography, policy, and resource management, is charged to provide an unbiased, independent evaluation of the adequacy and applicability of the studies used to inform leasing decisions and the prediction and management of environmental impacts of OCS oil and gas activities, provide specific recommendations for future ESP studies, identify issues about which there is sufficient information, and provide a state-of-the-art review of the available information relevant to the program. Three panels were established to examine specific subject areas—physical oceanography, ecology, and socioeconomics.

The current report by the Physical Oceanography Panel is the first of three panel reports. It evaluates the physical oceanographic aspects of the ESP and includes recommendations for future directions the program should follow.

The main objectives of the evaluation were

- to provide an unbiased, independent evaluation of the adequacy and applicability of ESP physical oceanography studies;
- to provide specific recommendations for future ESP physical oceanography studies; and
- to provide a state-of-the-art overview of available information on each major issue reviewed, based on MMS studies and other relevant data bases and literature.

The panel recognizes that the ESP is not intended to be a broad, general science program, but is designed instead to answer questions about the environmental and socioeconomic effects of oil and gas exploration and production. Nonetheless, the answers to those questions must be based on sound science.

This chapter describes the ESP and the nature of OCS activities. Chapter 2 identifies physical oceanographic processes and analytical methods that are relevant to understanding the impacts of OCS activities and provides a state-of-the-art review of current knowledge of these topics. Chapter 3 provides descriptions of the four OCS regions and evaluations of the studies done to date, and Chapter 4 provides recommendations for future ESP physical oceanography studies. Appendix A is a glossary of physical oceanographic terms used in this report, Appendix B is a summary of a workshop on numerical modeling initiated by the panel, and Appendix C is a list of physical oceanographic projects funded by the ESP.

PLANNING AND PROCUREMENT OF ENVIRONMENTAL STUDIES

Development of a Studies Plan

In 1978, a framework was established for setting study priorities, based on their importance for decision making, timeliness, generic applicability of results, availability of information, and applicability to issues of regional or program concern. To develop a list of study topics, MMS identifies issues, primarily through the regional offices and with the help of advisory groups (e.g., the RTWGs or the SC) and interested parties (e.g., environmental groups and industry associations). The ESP staff then translates the issues into questions that reflect information needed for decision making.

MMS regional offices, with help from the RTWGs and the SC, evaluate the resulting list of study topics for scientific and technical feasibility, availability of information, scientific merit, and the time during which or by which the information is needed. The list of study topics is also reviewed by other federal agencies and scientists in the academic community, in state and local governments, and in industry. After the review is finished, each regional office submits a draft regional studies plan to the BES in Washington, D.C. The plan includes a statement of regional needs for information, the regional perspective on the priorities of these needs, a list of proposed study topics, and a brief description of the rationale for each proposed study. The BES coordinates the development of a "national studies list" from the proposed study topics and ranks them for funding priority based on criteria that include consideration of how the proposed study fulfills legislative mandates and other legal requirements and of whether the study will be completed in time for use in specific leasing decisions. Once approved, the final national studies list serves as the basis for requesting the yearly research appropriation from Congress. Contracts for the studies are then funded by MMS from its appropriated budget according to rank, until funds are exhausted. Since 1982, MMS has been providing support for the review, publication, and dissemination of ESP results, including publication in refereed journals (pers. comm., U.S. DOI, MMS, 1989).

Contractors include private industry, universities, research institutes, or nonprofit organizations. The procurement process normally is competitive and is based on requests for proposals (RFPs) and associated statements of work prepared by MMS.

In Alaska, marine environmental studies have been administered in part by the National Oceanic and Atmospheric Administration (NOAA) as part of the OCS Environmental Assessment Program (OCSEAP), under an interagency agreement with MMS that is renewed every 5 years. After the national studies list is approved, NOAA prepares a technical development plan for studies in the Alaska region (U.S. Department of Commerce, 1988). In June of 1988, the General Accounting Office (GAO) issued a report that concluded that, because of reductions in funding, the duplication of administrative functions between NOAA and MMS had become inefficient and that consolidation of the programs could save up to $1.3 million a year. GAO recommended that MMS develop alternatives to make the program more efficient and, in the selection of alternatives, consider other issues such as staffing, public perception of objectivity, and continuity of scientific expertise in addition to potential dollar savings (U.S. GAO, 1988). MMS and NOAA have been working to reduce management duplication by attempting to use NOAA staff for scientific investigation rather than as technical managers of contracted studies. In response to the GAO recommendation, MMS is negotiating an agreement by which NOAA will cease to issue contracts by the beginning of FY 1991 and will propose only in-house studies beyond that date. MMS would support an agreed-upon 3-year work plan (U.S. DOI, 1988a; pers. comm., K. Turgeon, MMS, May 9, 1990).

Implementation of Studies According to Lease-Sale Schedules

The planning process for individual studies has been governed primarily by a lease-sale schedule, which is established in a 5-year planning document. The most recent 5-year program plan covers mid-1987 through mid-December 1992. Studies must be initiated well in advance of a lease sale or any other decision they are intended to support if they are to be useful. A prelease, 15-month study would normally be included in a regional studies plan approximately 34 months before the beginning of the lease-sale process, which begins with the identification of areas having hydrocarbon potential. Table 7 provides an example of how a prelease study is tied to the planning and implementation steps in the ESP and in the OCS leasing process (pers. comm., U.S. DOI, MMS, 1988). The actual timing varies with the individual studies and lease sales.

TABLE 7 Planning and Implementation Steps in the OCS Environmental Studies Program and Lease-Sale Process

Month	Step
-34	Draft regional study plan (described above)
-30	Final regional study plan (described above)
-27	national study plant (described above)
-20	Procurement plan
-17	Draft statement of work
-12	Final statement of work
-7	Request for proposal
-3	Contract
0	Area of hydrocarbon potential identified
1	Call for information: MMS publishes notice of intent to prepare EIS in the Federal Register. Industry invited to indicate areas of interest. Interested parties may comment on topics and areas of concern. No decision yet made about proceeding with sale.
5-9	Identification of area to be analyzed in EIS, identification of alternatives for EIS, estimation of resources, and preparation of oil spill report for proposed action and for alternatives. Draft report of study results due.
12	Draft EIS and final report of study results—describes planning area, analyzes potential environmental effects of oil and gas leasing, and discusses mitigating measures proposed to resolve conflicts. Followed by public comment period.
13	Public Hearing—opportunity for oral comments on draft EIS
14	Close of comment period on draft EIS
18	Final EIS—assesses comments from the state and the public. Secretarial issue document (SID) prepared that analyzes all issues involved in the proposed sale and possible coastal zone consistency conflicts. The SID. accompanied by the EIS, is sent to the assistant secretary for review and decision on whether to issue a proposed notice of sale.
19	Proposed notice of sale—details terms and conditions of proposed sale, blocks proposed for leasing, stipulations and other mitigating measures to be required, and proposed bidding systems
21	Governors' comments due—used by MMS to develop recommendations to the secretary. SID and final EIS sent to the secretary. The secretary is required to accept the recommendations of a governor if he determines that they provide a reasonable balance between the national interest and the interests of the state(s).
22	Final notice of sale—published at least 30 days before sale. Specifies date, time, location, blocks to be offered, and terms and conditions of sale.
23	Sale—sealed bids opened and read by regional director
24	Bid review—high bids evaluated to assure receipt of fair-market value. Sale results also reviewed by Justice Department to ensure that awarding leases does not violate antitrust laws.
25	Leases issued—bids accepted or rejected within 90 days of receipt. Leases issued for accepted bids 1 to 2 months after sale.

NOTES: In this example, 5 years elapse from the completion of a draft regional studies plan to the lease sale.
The postlease process includes (1) exploration plan evaluation and drilling permit approval, (2) development and production plan evaluation and approval, (3) pipeline permit issuance, (4) lease termination or expiration.
Source: Pers. comm., U.S. DOI, MMS, 1988.

WHY MMS NEEDS PHYSICAL OCEANOGRAPHIC INFORMATION

Physical oceanography provides important inputs for calculating estimates of the transport and fate of oil and related materials in the ocean. These calculations in turn provide the basis for estimating potential impacts of oil on resources; the latter is the primary environmental concern in the management of the ESP. Projection of potential oil-spill impacts is based on results generated by the Oil Spill Risk Analysis (OSRA) model, developed by USGS in 1975. OSRA predictions provide the basis for imposing stipulations or deleting certain tracts from leasing where there is high probability that an oil spill would affect particularly sensitive areas and valuable resources. Because potential risks are principally evaluated through OSRA modeling, the ESP has used physical oceanographic information primarily to support the OSRA model and to prepare associated EISs. Because results of ESP studies are used by MMS's Branch of Environmental Modeling (BEM) and by producers of EISs (the four regional offices of the Branch of Environmental Evaluation (BEE) among others), some discussion, conclusions, and recommendations pertain to those entities as well as to the ESP. The interrelationships between BES (the coordinator of the ESP), BEM, and BEE are shown in Figure 4.

The OSRA model estimates the probability of oil spills in a specific lease area, calculates oil-spill trajectories from selected launch points, and estimates the probability that an environmental resource or coastline segment will be contacted by releases from the selected launch points. It provides the quantitative basis for calculating the probability of occurrence of an oil spill combined with the probability that a given spill will come into contact with resources. Physical oceanographic support of OSRA modeling has been provided directly through numerical modeling studies of the circulation of each of the major OCS regions—the outputs of the circulation models are "data" for OSRA models—and indirectly in the form of extensive data bases obtained through large-scale field observation programs. The OSRA model is further described below.

Physical oceanographic information is also used to support biological and ecological studies and to predict the transport of drilling muds and cuttings and discharges of coproduced waters containing petroleum compounds and other byproducts of oil exploration and production. Variability of physical oceanographic characteristics, for example, may be a cause of variation in biological communities and may be useful in interpreting long-term monitoring and cumulative impact studies. Winds, waves, currents, and circulation in general determine the extent of pollutant transport, dispersion of waste products, transport of drilling muds and cuttings, discharges of coproduced waters containing petroleum compounds, and flushing of waste material from an area.

ACQUISITION AND USE OF PHYSICAL OCEANOGRAPHIC INFORMATION

Physical oceanography studies acquired by MMS tend to be of two separate types: (1) large-scale, multiyear, observational field programs with associated data analysis and interpretation and (2) numerical modeling studies of the circulation of major shelf areas (e.g., the Gulf of Mexico, California Shelf, Atlantic coast, Bering and Chukchi seas, and so on). Rarely are the two study types mixed. The only case found of such integration was in the Santa Barbara Channel circulation study (Gunn et al., 1987), in which the numerical modeling and observational programs were joined into a comprehensive study that included comparing model results with data from field studies.

For the observational studies, the primary product is a final report documenting the study results. In addition, at least in recent years, the contractors have been encouraged and in some cases required to publish the results of their investigations in the refereed literature. Data generated during the field studies are also sent to NOAA's National Oceanographic Data Center (NODC) for archiving.

The deliverables of the modeling studies generally include a final report, a user's manual for the model, and some form of model predictions. For modeling studies on the east, west, and gulf coasts, the principal data deliverables have been predictions of the mean climatological flows over various time scales at spatial resolutions of typically 15 to 30 km. These have been the

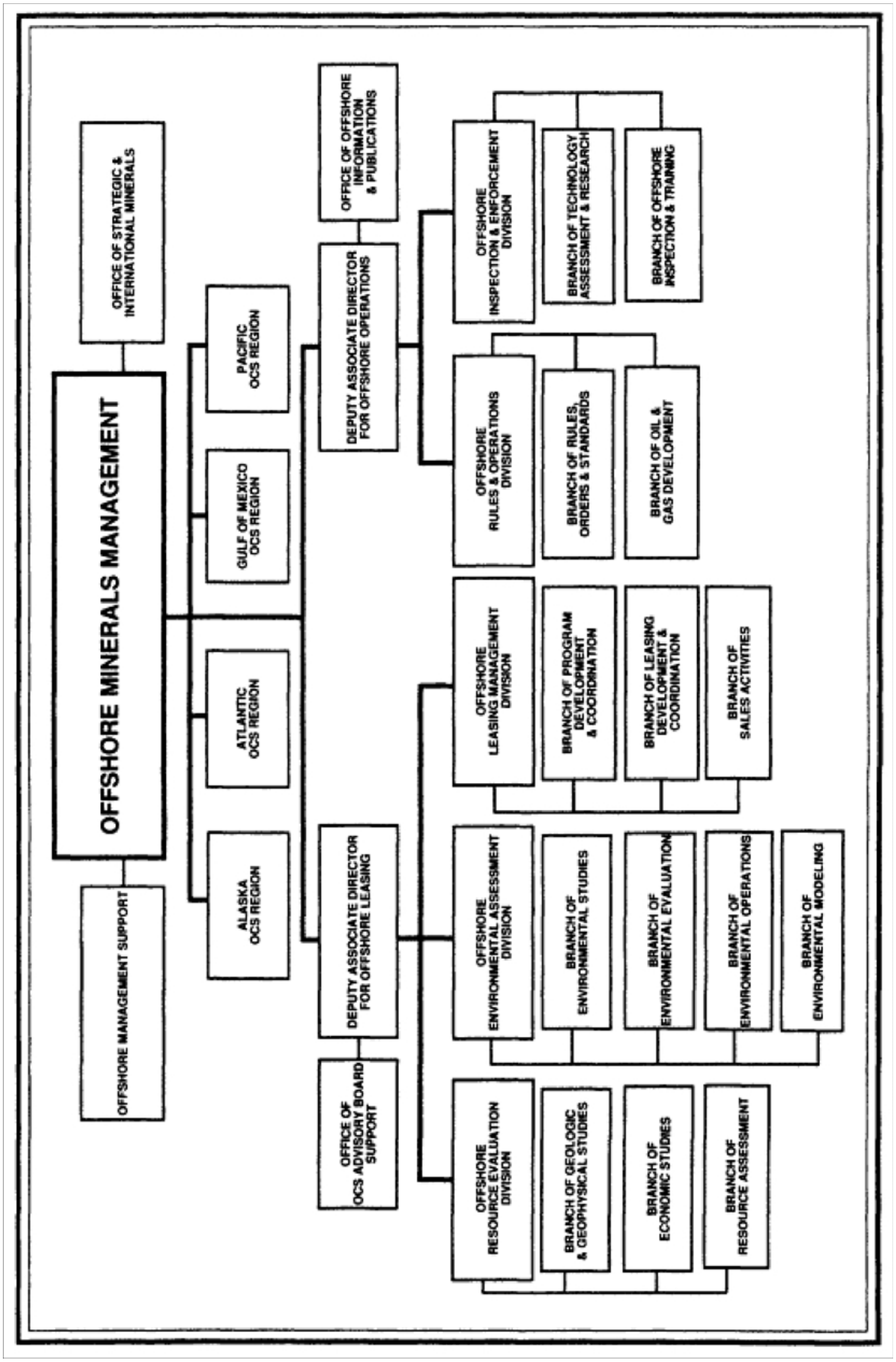

Figure 4
Offshore minerals management organizational chart.
Source: U.S. DOI, 1988c.

principal oceanographic inputs for oil-spill trajectory calculations. Recently, MMS has specified time-dependent velocity fields. Mean climatological flows have been primarily used in forecasting oil-spill trajectories. The principal forcing mechanisms are density and the seasonal mean wind stress. These data sets are then used as input to the OSRA model (Smith et al., 1982) to define the mean flow fields. Incorporation of higher-frequency variations (tides, Ekman transport, slope currents, eddy/ring dynamics) in the flow are either ignored as being unimportant or are parameterized in the OSRA model.

The OSRA model uses a Monte Carlo technique to calculate spill trajectories for selected launch points in a proposed lease area by season or month. The model then predicts (1) the probability of oil-spill occurrence using historical data, (2) the "hits" or number of times a spill encounters an environmental resource target (wildlife, fishing area, rookery, spawning area, nesting area, and so on) or shoreline segments, and (3) the probabilities of conditional impact probabilities on the resource within a preselected time.

In Alaskan waters, however, the method of predicting oil-spill trajectories for selected launch points and seasons depends on the contractor. The most recent contractor has assembled the hydrodynamic field from a series of superimposed model simulations. The spatially and temporally varying wind field is obtained from a meteorological model. The environmental data sets are typically 10 years in duration. Trajectory calculations are made by assuming random start times within the time period of the environmental data sets. The OSRA model is then used to complete predictions of the probability of oil-spill occurrence, hits on environmental resources and shoreline segments, and conditional impact probabilities, just as for lease areas of the contiguous United States. The contractors for Alaskan studies hence perform simulations for circulation and oil-spill trajectories.

In Alaskan waters, simulations for tide, wind, and density-induced forcing are performed. Early contract efforts focused on tides as the principal forcing mechanism. Later studies have taken a more comprehensive view of the circulation. Simulations of oil-spill trajectories have generally followed the same methodology as in the OSRA model; however, the exact formulation has depended on how the contractor chose to describe the circulation field. An additional complication in Alaskan waters is the role of ice and its influence on oil-spill trajectories (ice occurs only occasionally in coastal waters of New England and nowhere else in coastal waters of the contiguous United States). Contractors have used numerical simulations of ice motion, satellite or in situ observations, or climatology or some combination of these to define the ice dynamics. Oil-spill-trajectory algorithms are modified to account for the effects of oil-ice interaction.

Another important difference between trajectory calculations for the contiguous United States and Alaskan waters has been in the selection and use of meteorological information. For the east, west, and gulf coasts, the wind fields used to drive the circulation model have not generally been consistent with those used in the OSRA model. Spatially and seasonally varying climatological mean wind and density data are generally used to drive the circulation models whose output provides input for the OSRA model. On the other hand, the OSRA model for the east, west, and gulf coasts until 1989 used a transition-probability matrix approach, normally based on an analysis of winds observed at selected stations over long periods, to describe the wind field. Spatial variability has been addressed by selecting discrete zones over which data from a given station and its associated transition-probability matrix are assumed to apply. This may not have produced an accurate representation of the wind field. Since 1989, MMS has used LFM and FNOC (see glossary) gridded wind products instead of the transition matrix (pers. comm., MMS, 1990).

In reviewing the models of oil-spill trajectories and environmental-resource impacts used by or developed for MMS, it is evident that, despite differences between the approaches in Alaskan waters and the contiguous United States, the general strategy is to rely extensively on the use of model-derived results to estimate the circulation for a given area. The use of circulation data sets based solely on field observations or derived from a melding or assimilation of field observations and model results appears to be minimal at present. On the other hand, the meteorological forcing used in circulation and trajectory modeling for most areas has been based on a synthesis of wind or pressure field observations to obtain a climatological description, a transition-probability matrix, or a weather-pattern typing.

Circulation and trajectory model results are ultimately integrated into the EISs used for lease sales through the prediction of hits on resources and the associated conditional probability that a resource will be hit for a given oil-field exploration and development scenario. However, the actual influence of the results of the large-scale physical oceanographic field programs on preparation of impact assessments in EISs is less clear. The information derived from the observational programs is integrated with the model results to describe the circulation that is ultimately summarized in the EISs, but observations are not adequately used to validate the models on which the impact assessments in the EISs are based. The field information also appears to be used by other investigators (biologists, chemists, and geologists, for example) to assist them in interpreting and analyzing their data. Other obvious uses of the observational data and associated interpretations would be (l) to evaluate and improve circulation model predictions and (2) to provide data from which an independent circulation field can be described for input to the OSRA model. However, cases in which detailed model-data comparisons were done are extremely few. As noted above, the use of observational data to define circulation fields or to supplement model results is limited.

WHAT INFORMATION IS NEEDED

Information Needed for Leasing Decisions

To make predictions of trajectories for water parcels and materials, a representation of the current field that is in quantitative agreement with existing observations is needed. Preliminary calculations using robust assumptions and the simplest of models, statistical representations, and representations of the circulation based on observations can provide a useful distillation of the observational data for preliminary assessments and for checking and refining models. The panel believes that a rapid and cost-effective method of improving the representation of the circulation would be based on field observations.

The observational information and the representations of circulation should include contributions from motions in the following frequency bands, which are known to be important, or adequate parameterization of the effects of these motions:

- the seasonal mean circulation, including known contributions from the local density field, nonlinear tidal current interactions, and the regional circulation;
- low-frequency currents induced by winds and major current excursions; and
- tidal currents, including internal tides.

The information should include data on the vertical structure in the currents and appropriate vertical mixing rates. The currents associated with other processes, such as fronts and various eddy motions, may need to be included or parameterized, depending on the results of sensitivity studies.

A quantitative intercomparison of predicted and observed currents is imperative. Error estimates must be computed for trajectory predictions. The intercomparison must involve the latest data bases of Lagrangian (drifter) and Eulerian (moored measurements) currents and must involve comparisons for particular (frequency-band) flow components.

Studies should be conducted on the sensitivity of circulation model results to initial- and boundary-current features, processes, and parameterizations. These studies should be used to identify important factors and to quantify uncertainties in predictions. Particular attention should be given to the sensitivity of Lagrangian trajectories to the model representation of the current field.

The development of the above information is a nontrivial task. Communication with the scientific community must be maintained, including ongoing peer review. Results of this research effort, and other information used in the OSRA model, should be clearly referenced in EISs. Full trajectories and impact probabilities must be presented, independent of and in addition to spill probabilities.

Information Needed for Development and Production Decisions

Chronic discharges that might have adverse ecological impacts are more likely to occur during the development and production of oil and gas than at earlier stages. Thus, appropriate knowledge pertaining to the inputs, fate, and effects of expected chronic discharges must be integrated before development and production occur. The physical oceanographic component of the required information should consist of robust estimates of fields of exposure—including expected duration—to chemical contaminants for valuable living resources in and near a lease area.

In addition, physical oceanographic knowledge must be sufficient to estimate oil-spill trajectories for projected specific sites of production and transport (e.g., platforms, pipelines, and barge and tanker routes) for a lease area. The uncertainties associated with these estimates must be provided.

Criteria for Judging Adequacy of Scientific Information

The panel's operational definition of "adequacy" for scientific information has two aspects: completeness and scientific quality. Of course, "complete" scientific information in the ultimate sense is neither feasible nor necessary for making decisions. Rather, the panel's criteria for completeness are based on whether the coverage of physical oceanographic topics is appropriate for the ESP's mandate. The standards of scientific quality entail repeatability, reliability, and validity of measurements and analyses, including appropriateness of methods and subject. The measure of scientific quality used by the panel is whether the study methods described represent the current state of good practice in each scientific field (i.e., whether the studies would be likely to pass peer review). This does not imply that the criterion is actual publication in a peer-reviewed scientific journal, but rather that the quality of the data and scientific interpretations used to make OCS decisions should meet this basic scientific standard.

2

State-of-the-Art Overview: Physical Oceanographic Processes, Features, and Methods of Potential Importance to the Esp

INTRODUCTION

This chapter provides a state-of-the-art overview of available information on the major issues reviewed by the Physical Oceanography Panel and considered to be of potential importance in meeting the MMS requirement to predict the risk to the environment from OCS oil activity. It includes for each, as feasible, an assessment of the present state of knowledge and of the information of particular importance to the ESP and MMS and an indication of the major research needs considered most likely to enhance the current knowledge. The material is arranged by subject matter and it is in no way intended to represent priorities; priorities will differ according to the physical setting. The panel has focused on the movement of oil by the water, considering, where appropriate, the effects of ice and of sediment. Its findings have been grouped for discussion into the following major sections: Transport, Stirring, and Mixing Processes Numerical Models; Sea Ice; and Sediment Transport.

The Problem of Assessing Impacts of Oil Exploration: A Physical Oceanographic Perspective

Before discussing the state of knowledge of the physical oceanography of a region and the adequacy of this information for impact assessments of oil and gas exploration or production, it is appropriate to consider the specific physical information that is needed. The problem of predicting the movement and concentration of material released into the ocean can be formally stated as follows: Given a source of some material (e.g., oil, gas, or routine discharge) as a function of space and time, what is the probability that the material's concentration at a particular spatial point and time will be greater than some specified value? In addition, it is also necessary to know how probable it is that the flux of the material into the sediments at a particular point and time will exceed some given value, and likewise to know the same for the flux into the atmosphere.

The primary physical oceanographic processes that must be considered in predicting the movement of material released into water are:

1. Advection or transport: These terms refer to flows that move patches of material around but do not significantly distort or dilute them.
2. Stirring: This is the process whereby flows with strong shear and strain fields on the scale of the patch size generate "streakiness," with tendrils of material from the patch drawn out into unpolluted water and streaks of water intruding into the patch. By itself, stirring does not alter concentrations, although it affects the probability of finding material at a particular point.
3. Mixing: This process is responsible for the decrease in concentration of material. At the most fundamental level, mixing is accomplished by molecular diffusion intermingling water with other molecules. However, molecular mixing is usually coupled with stirring to produce

turbulent mixing wherein stirring produces concentration gradients on scales small enough where molecular mixing can efficiently erase those gradients. As discussed below, estimates of turbulent mixing rates are scale-dependent (Eckart, 1948).

Collectively, these three processes are referred to as "exchange." Both horizontal and vertical exchange must be considered since, for flow fields with a complex spatial structure, exchange in a particular plane can be dependent on velocities in the orthogonal direction.

In addition, the density of the material and biological and chemical processes can play roles in the probability problem stated above. If different from that of the ambient sea water, the material's buoyancy can result in transport and mixing at rates that differ from those of water parcels (e.g., sinking, accumulation in surface convergence zones, and differential wind drifts). Biological and chemical processes can produce effective sources and sinks of particular materials and introduce additional exchange mechanisms (e.g., adsorption to sinking particles).

Transport Processes in the Water Column

The fate of biological, chemical, and sedimentary constituents in the coastal zone results from a convolution between transport processes and the mechanical and chemical properties of the various constituents. Coastal circulation and the attendant variability in physical parameters characterizing the coastal ocean result from complex interactions between processes with a broad range of time scales, from interannual periods to surface-gravity-wave periods of a few seconds. As a consequence of these diverse motions, describing the circulation is both challenging and expensive.

Oil and pollutants are carried from one place to another by currents. But surface spills are also moved relative to the water by the wind. Waves breakup and mechanically modify surface spills and drive the modified material below the surface. The material drifts with subsurface currents—sometimes to reappear later at the surface under calmer conditions. Products from surface spills and effluents from drilling operations or from subsurface leaks (from pipelines or blowouts) may ultimately end up in bottom sediments, possibly accumulating to unacceptably high concentrations in localized regions. They may even be transported from place to place within the sediments over long periods. All of these processes are of potential importance in estimating the fate of spilled or leaked material. The first and second processes, advection by currents and wave effects, are of major importance in the immediate translation and dispersal of a spill.

Sediment Transport Processes

The physical processes responsible for the deposition, mixing, resuspension, and transport of bottom sediments are most closely tied to the long-term effects of petroleum exploration, development, and production. A portion of the chemicals of environmental concern emanating from drilling activities, discharge of coproduced waters, and oil spills eventually passes to the bottom by adsorption to fine, suspended particulates or by incorporation into detrital materials, which settle out in regions or during periods of deposition (see, e.g., NRC, 1985; U.S. DOI, 1988d). The subsequent fate of the particulates and the associated chemicals is then largely determined by patterns of physical mixing, resuspension, and transport. Vertical mixing and resuspension of surface sediments tend to disperse initially high concentrations of contaminants and to increase chemical interactions between particulate and dissolved phases (see, e.g., Bothner et al., 1987). Horizontal transport often leads to further dispersal and lower contaminant concentrations (NRC, 1983), but it may also lead to the physical concentration of contaminated particulate material in depositional environments. Toxics in the bottom sediments, pore waters, and material suspended just above the bottom may then enter the benthic food web, depending on the bioavailability of the material to the local benthic community (Boesch et al., 1987; Howarth, 1987; Neff, 1987)

Sedimentary accumulation and subsequent release of toxics may prolong the impact of a spill or discharge long past the initial occurrence. Thus, physical processes responsible for the deposition, mixing, resuspension, and transport of bottom sediments are closely tied to the long-term effects of petroleum exploration, development, and production. Boesch et al. (1987) have defined long-term effects to include effects that persist for a long time as a result of some brief activity and effects that result from low-level, chronic exposure over a long period. Examples of the former include oiling of sediments or sedimentary accumulation of undegraded hydrocarbons in the aftermath of an oil spill and the impact of drilling muds and cuttings from exploratory drilling. Examples of the latter include chronic releases of oil during production and repeated discharges of drilling muds and cuttings during development. In all cases, impacts are likely to be worst in shallow-water, depositional environments (Boesch et al., 1987; Howarth, 1987). The effects of chronic discharges on the deeper depositional environments of the OCS are still largely unknown, however (NRC, 1983; Boesch et al., 1987; Neff, 1987), because of the difficulty of separating long-term effects from natural environmental variability.

Space and Time Scales

Oceanic flows have energy at many different space and time scales. Physical oceanographers often discuss motions in different frequency bands separately, as this panel does below. Although this is convenient for organizing information and understanding the mechanisms involved, care must be taken in superimposing different frequency bands to obtain the total flow field.

The Fourier decomposition of a current-meter record can be recombined to give the flow versus time; however, band-pass-filtered records of currents and pressure (for example) will not satisfy the Navier-Stokes equations when there are significant nonlinearities in the flow. The problem becomes even more severe when looking at the movement of particles in the flow—the Lagrangian description of the motion—because the evolution equation for particle position involves a nonlinear function (the flow velocity) of the position. Simple Eulerian flow fields varying in time and space with a single frequency and wave number give particle motions with a complex spectrum, containing both harmonies and a zero-frequency component. The latter corresponds to a net drift rate for a particle—a Lagrangian mean flow—which is different from the average velocity measured at a point (the Eulerian mean). The difference is called the Stokes velocity (see, e.g., Longuet-Higgins, 1969). Flows only slightly more complex can lead to chaotic particle trajectories and efficient turbulent mixing (see, e.g., Zimmerman, 1986). When the Eulerian flows have a broad frequency spectrum, the Lagrangian motions become even more complex and can have a spectrum quite different from the Eulerian one. The probability of a particle entering a particular volume of space can depend upon the flows in all parts of the Eulerian spectrum; of particular concern are those bands in frequency and wave-number space that are not resolved by a given model.

The dependence of stirring and mixing on the complex relationship between the Lagrangian and Eulerian spectra implies that turbulent mixing is scale-dependent: the inferred rate of mixing depends strongly on the range of scales that are resolved. In addition, turbulent diffusion processes do not always transport material at a rate proportional to the larger-scale gradient, nor is the flux vector necessarily parallel to the mean gradient. Although it is almost universal practice to model subgrid-scale exchange processes as a kind of diffusion, that practice may be inappropriate, especially in a region with strong and variable topography and density fronts.

Forcing Mechanisms

Predictive capability is usually premised on the identification and understanding of the mechanisms that couple response to forcing. The preceding section has illustrated that the coastal ocean is subjected to forcing over a broad range of periods, ranging from interannual variations in the coupled ocean-atmosphere system (for example, the El Niño-Southern Oscillation (ENSO) process) to the atmospheric forcing responsible for the generation of surface-gravity waves. Some forcing mechanisms are better understood than others: the forcing imposed by the barotropic tide on the continental margins is probably the best-understood forcing mechanism, and the influence of adjacent deep ocean currents and eddies may be the least-understood forcing mechanism. Each mechanism or process responsible for forcing the coastal ocean is modulated as a function of space and time. Predicting coastal circulation and its statistics thus entails a knowledge of at least the amplitude and variation of the processes that drive the coastal ocean. For example, currents are often observed to converge in the vicinity of Cape Mendocino, California; there, the convergence results in an offshore transport of coastal waters. This process is of obvious importance in determining the path of water masses initially on the shelf. Whether this convergence results from of f shelf oceanic processes or simply reflects spatial variations in the wind that forces the coastal ocean is not known.

Oil Spill and Circulation Models

The above points regarding mixing and transport have important implications for the models used in oil-spill-risk analysis. Generally, the models resolve only a limited set of scales, often just the seasonal mean circulation. In the absence of most of the temporally and spatially varying parts of the spectrum, the predicted Lagrangian motion may miss many aspects contributing to drift, especially on the shorter time scales.

The OSRA model used by MMS deals only with inert surface-layer material, although MMS has sponsored some work involving simultaneous calculation of the fates of the oil—a prediction of some of the chemical and physical changes in the hydrocarbons. This report focuses primarily on the prediction of exchange of passive materials; it is likely, however, that other processes are also important.

The OSRA model deals with a point patch (a material particle only) and does not resolve mixing processes or, given the lack of small-scale detail, much of the stirring process either. Different realizations of the random aspects of the movement of oil spills come only from wind drift variability, not from the oceanic currents. Vertical redistribution of the material by turbulent mixing is not included, although this may result in dilution, reduced evaporation, different transport (due to vertical shear in the horizontal currents), and enhanced horizontal mixing (e.g., vertical shear dispersion). These points indicate that, in assessing the adequacy of a practical model for a task such as oil-spill-risk analysis, it is necessary to evaluate the potential transport, stirring, and mixing caused by many different processes.

It is important to recognize that all models are inherently limited in their predictive capability. Lorenz (1969) demonstrated that a model calculating from initial conditions derived from data would diverge from the actual system within a finite time. Two factors were responsible: errors in measurement of the flow (and other physical quantities) and uncertainties in the values at points where no measurements were taken. While the predictive capability of a model dependsion the dynamics, the physical processes incorporated in his model have similarities to those acting in the atmosphere and in the ocean. Although using new data to readjust the model ("data assimilation") can greatly improve the predictions, it cannot eliminate the errors (as is obvious from weather forecasting experience). Errors in model dynamics and in the forcing parameters applied will also limit the model's predictive capabilities. Diminished predictability also occurs when an attempt is made to extend information into a region where inadequate or no data exist.

The ability to predict the trajectory of an actual spill is certainly important for spill containment and management; thus, the extent of our ability to make such predictions is certainly relevant to leasing decisions. But there is also another related question: how well can we predict the statistical variability of dispersal? Failure of a model to predict individual trajectories does not necessarily mean that the statistics produced are wrong; for example, radioactive decay cannot be predicted at all, yet models that describe the statistical probability of such events work extremely well. How well fluid dynamical models will reproduce the statistics of trajectories in the ocean is not known. Frisch and Orszag (1990) caution, ". . . it is well known that detailed properties of turbulent flows at far-off times cannot be predicted. However, even the statistical properties of these flows may be 'uncomputable.' . . . [This] would imply, in the context of meteorology for example, that while the weather clearly is not predictable at long times, neither, in fact, is the climate." (Note that "far-off" is measured in the time scales of the dominant motions as described above and may be only on the order of days.) Again, the capability to predict statistical probabilities of spill trajectories will depend on the nature of the dynamics of a system, the degree to which the model resolves different scales, and the reliability of the input that describes the forcings and boundary conditions. It is simply not known how well even an optimal model can do. It is important to stress that data are needed both as independent estimators of trajectory statistics and as input and verification for modeling.

Scope of the Overview

The content of this chapter is restricted in two ways. First, attention is focused on physical oceanographic processes that are of direct importance to the motion and fate of oil in oceanic waters. Primary emphasis is given to processes that control the advection of oil in surface and near-surface waters. Second, only processes that are active over the OCS are considered, because these are the waters that are under federal control. Processes that are specific to nearshore (i.e., state-controlled) waters, such as in bays and estuaries, are not included. Although nearshore processes are not represented in the OSRA model, oil is assumed to hit the shoreline if it reaches particular sections of a grid (imposed on an area map) that encompasses the shoreline. These sections cover areas extending well into OCS waters (see Fig. 5). These restrictions reflect the primary bias of ESP physical oceanography. They do not imply that nearshore and benthic processes are unimportant in a full consideration of the ecological impacts of oil spills but simply place such processes beyond the purview Of this review.

As a consequence of surface concentration of oil and relatively rapid weathering, the principal physical oceanographic problems that must be addressed are understanding and predicting the motion of oil in surface waters over periods of up to about 30 days. During this 30-day period, response to wind forcing is very important to the net motion and variability of spill trajectories. Small-scale spatial and temporal processes in the near-surface environment (e.g., fronts, convergence zones, Langmuir cells, shingles, and interleaving) can affect the course of spill movement and alter spill dynamics substantially. The variability of underlying currents within this time frame is also important. Flows with temporal scales substantially greater than a month contribute to individual mean trajectory paths but do not contribute substantially to the variability of an individual trajectory over the time frame of interest. Tidal motion is important only insofar as it contributes to mean motion (through tidal rectification), affects smaller-scale dynamics (e.g., through the generation of internal waves), and is a contributing factor to horizontal dispersion (through stirring).

For subsurface transport of spilled oil, the time frame of interest is extended to 30 to 90 days following the spill's release. This extension is made to account for the dilution of subsurface oil associated with relatively large spill events to low concentrations (<1 ppb). The first 30 days after the oil is released remains of greatest interest, however, because this is the period when oil is most toxic and has the largest impact on the environment.

TRANSPORT, STIRRING, AND MIXING PROCESSES

Wind Stress—Drag Coefficient and Space and Time Resolution

Determination of surface-wind stress depends on (1) determination of the wind speed and direction at the appropriate space and time scales and (2) knowledge of the factors necessary to transform the wind speed into wind stress. This latter is usually accomplished by determining a drag coefficient, which depends on several oceanographic and meteorological parameters. For example, Walsh et al. (1986) showed that stress and near-surface drift determinations are sensitive not only to the geostrophic wind at the top of the Ekman layer, but also to the air and surface

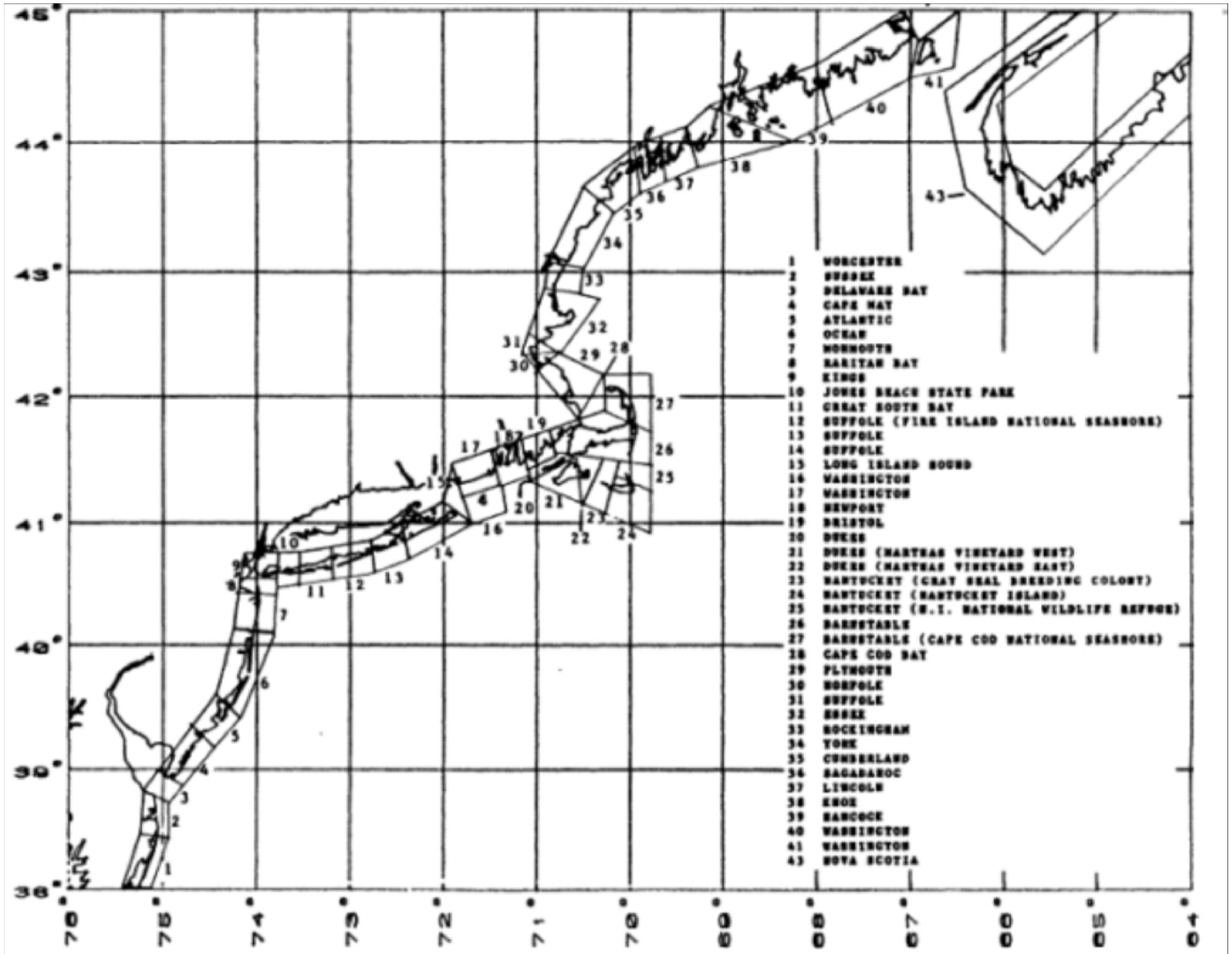

Figure 5
Example of coastal land segments considered as targets for contact with spilled oil. The study area is divided into 43land segments of approximately equal length for North Atlantic Outer Continental Shelf Lease Sale 96.
Source: U.S. DOI, 1988d.

ocean temperatures, the mean horizontal temperature in the planetary boundary layer, and the surface roughness. Their work is a good example showing the significant sensitivity of numerical model results to the data used as input.

The difficulties of converting wind speed and direction to wind stress by determining a drag coefficient usually can be overcome. However, specification of the wind field based on observations from coastal stations, ships, sea-level atmospheric pressure, low-level cloud motions, satellite microwave scatterometry, and instrumented buoys usually is inadequate and is the limiting factor to determining the surface stress distribution. The nature of the difficulty in relating the wind at an offshore location to that observed at a coastal station is described by Weisberg and Pietrafesa (1983):

> The surface wind field over the South Atlantic Bight. . . varies on seasonal, synoptic, and diurnal time scales... over the entire region while the sea breeze induced diurnal oscillations are coherent only over the coastal area . . . both the synoptic and sea breeze oscillations were found to be seasonally modulated. .. *The coherence* between stations was also found to be seasonally modulated, with winter time synoptic scale fluctuations being coherent over the entire [South Atlantic Bight]. . . while only marginal coherence occurs in the summer. A distinct seasonality therefore exists in both the ability to predict offshore winds from coastal station data and in the matrix of linear operators. . . used for that prediction. Since the structures of the synoptic disturbances change as they progress offshore, the matrix of linear operators depends upon the vector wind at the coast and not just a single component of that vector . . . During the fall season, the time series are significantly coherent for time scales longer than 1.5 days; the phases are very nearly zero; and the predicted series are underestimated by as much as 30-40 percent in amplitude with somewhat better results for u (east/west velocity) than for v (north/south velocity). During the winter season, the time series are most coherent at time scales longer than 2 days, the phases are very nearly zero, and the amplitudes are either underestimated or overestimated by as much as 30 percent. (Copyright 1983 by the American Geophysical Union.)

Another example of wind field complexity is presented by the detailed observations of the Coastal Ocean Dynamics Experiment (CODE) (Beardsley et al., 1987), which showed significant temporal and spatial structure to the wind field off northern California during the upwelling season. Their measurements showed

> . . .after the atmospheric spring transition the airflow in the marine layer is dominated by the North Pacific high, and the surface wind field over the shelf is characterized by periods of strong (7-15 m/s), upwelling-favorable alongshelf winds lasting for up to 30 days, interrupted by shorter periods of much weaker winds directed either equatorward or poleward. These periods of weak or reversed winds typically last several days and are called wind relaxations, even though they are primarily associated with coastally trapped perturbations of the marine layer along the central and northern California coast and not with a large-scale weakening of the North Pacific high. The atmospheric boundary-layer measurements made in CODE suggest a simple conceptual model which can explain much of the physiology or structure of the marine layer and associated surface wind field during periods of persistent upwelling-favorable winds. During these periods, which represent the quasi steady state regime during the upwelling season, the inversion base of the marine layer drops eastward towards the coast until it intersects the coastal mountain range at a height of several hundred meters, and the associated thermal wind produces an alongshelf wind jet which has a maximum speed just below the inversion base. Turbulent mixing tends to homogenize any stratification in the marine layer beneath the jet and couple the jet to the ocean surface, producing strong upwelling-favorable winds over the shelf. Day/night heating/cooling over the narrow coastal strip beneath the marine layer generates a weak cross-coast secondary circulation which causes the core of the alongshelf jet to drop in elevation and shift onshore. This diurnal change in the marine layer structure explains both the daytime acceleration of the surface winds observed over and near the coast and its offshore decay and the associated offshore increase in the subdiurnal alongshelf wind. Thus, the quasi-steady component of the wind stress has a significant curl (up to 1 m/s/kin in wind speed observed) over the inner shelf during periods of active upwelling. This mean summer atmospheric boundary-layer regime is occasionally interrupted by synoptic and/or mesoscale events or anomalous conditions. Analysis of the CODE observations suggests free types of events, two primarily synoptic-scale conditions which lead to stronger-than-normal upwelling-favorable winds over the shelf and three primarily mesoscale events which lead to wind relaxation. About half of the wind relaxation events observed in 1981 and 1982 are believed to be associated with either coastal-trapped gravity currents or internal Kelvin waves that

propagate northward in the marine boundary layer along the central and northern California coastal mountain range. (Copyright 1987 by the American Geophysical Union.)

Surface Wind Drift and Ekman Dynamics

Price et al. (1987) reported on an important verification of the classical Ekman theory of wind-driven transport in the ocean surface layer, based on a careful analysis of upper ocean data from the Long-Term Upper Ocean Study (LOTUS) (Briscoe and Weller, 1984):

> By assuming that the momentum balance of a steady wind-driven current was between the turbulent stress caused by the wind and the Coriolis force caused by the earth's rotation, Ekman derived the archetypal solution for the vertical structure of a wind-driven current. . . There are two noteworthy results from [the solution]. The first is that the current profile from Ekman's theory has a spiral structure, called an Ekman spiral, in which current amplitude decays by one e-folding [a factor of l/e] over a depth D as the current vector rotates to the right [in the northern hemisphere] through 1 radian. Typical values, from observations, are D = 30 m and the eddy coefficient, A = .05 m^2/s. However, the range of inferred A covers more than an order of magnitude so that neither A nor D can be regarded as well known. The detailed specific structure of the spiral depends on A being constant in depth and time, which now seems unlikely to hold in the upper ocean . . . [Recent] theories yield somewhat different spiral structures, but there is no consensus on, for example, the sense of the depth dependence of A. The structure of the mean wind-driven current thus remains an open theoretical question.
>
> A second and fundamental result from the theory is that the vertically integrated current, or volume transport per unit width, is given by the Ekman transport relation. .. But just as D is not known beforehand with confidence, neither is [the depth where the wind-driven current vanishes]. However, the magnitude and direction of the transport follow directly from the presumed momentum balance between wind stress and the Coriolis force and are independent of A or any other aspect of vertical mixing . . . There have been repeated, but inconclusive, attempts to verify the Ekman transport relation directly by using in situ measurements of wind and currents. Although wind-driven transport more or less to the right of the wind [in the northern hemisphere], its magnitude has seldom been found to be consistent with Ekman transport computed from estimated wind stress to closer than a factor of about 2. This has not been interpreted to mean that the [Ekman transport is not given by the equation] in principle; there are significant technical difficulties in making accurate in situ current and wind measurements, some of which have only recently been appreciated and overcome. There are also analysis and interpretation problems in trying to separate the wind-driven current from the measured current. .. By separating the wind-driven current from the measured current and by constructing a coherent average over a long record, [they] find that the Ekman transport relation is consistent to within experimental error. The mean current has a spiral structure qualitatively similar to an Ekman spiral. In this case, however, the scale depth depends on the stratification, and in general the dynamics of the spiral appear to be much richer [more complex] than implied by the original Ekman theory . . .
>
> The principal results of [their] analysis are that (i) the Ekman transport relation was found to give an estimate of wind-driven transport consistent with the transport estimated from in situ current measurements, and (ii) the mean current was found to have a spiral-like structure that is strongly surface trapped on account of the solar heating and the resulting stable stratification. A simple numerical model that takes into account the important effect of stratification was successful in simulating the diurnal variability of current and the mean current spiral. (Copyright 1987 by the AAAS.)

Present-day systems like the LOTUS surface buoy and the VACM instruments make it **possible to obtain the kind of data required to build and test models of the Ekman drift with all the natural complexity taken into account**.

Definition Of The Mixed Layer

Müller and Garwood (1988) defined the mixed layer as follows:

> The "mixed layer" is [the] part of the upper ocean where temperature and salinity are quasi-homogeneous with depth, according to some appropriate criterion. This layer has to be

distinguished from the "turbulent boundary layer," which is the part of the upper ocean that contains turbulence generated by air-sea interaction processes. Traditionally, it has been presumed that the mixed layer is the vertical extent of an earlier turbulent boundary layer and that therefore the depth of the turbulent boundary layer at any given time and geographical position is less than or equal to the mixed layer depth. This maxim has recently proven to be incorrect (H. Peters, University of Washington, Seattle). . . it is now very clear that the turbulence, which is at least initiated by the exchanges of energy, buoyancy, or momentum across the air-sea interface and is hence properly considered a part of the ocean surface turbulent boundary layer, may penetrate the pycnocline well below what would be deemed the mixed layer by any of the algorithms for determining mixed layer depth.

The more traditional measures of mixed layer depth, based solely on temperature profiles, often do not apply in special regions. One such region is the western equatorial Pacific (R. Lukas, University of Hawaii, Honolulu). There are cases in which the temperature profile by itself (neglecting salinity) is clearly hydrostatically unstable. The high-resolution salinity observations reveal that salinity controls both density structure and the often shallow mixed layer depth in this region. Hence the monsoonal rains may play a significant role by stratifying the upper ocean with fresher water that overlays a remotely subducted (or previously created) warmer and saltier mixed layer. (Copyright 1988 by the American Geophysical Union.)

Mixed Layer Turbulence

According to Mailer and Garwood (1988):

Because observations of the vertical fluxes of momentum, mass, and heat are still lacking in the upper ocean, observations of the dissipation of turbulent kinetic energy are still the single best evidence of the intensity of turbulent mixing in the mixed layer. Such observations, if they are of sufficient vertical and temporal resolution, provide information on the depth of mixing. They also yield a measure of entrainment if the net sources of turbulence are known or can be estimated. The net dissipation for the whole mixed layer cannot yet be computed with great precision because it is still not possible to observe dissipation accurately in the top several meters of the ocean, the region that probably has the largest rate of shear production of turbulence. Nevertheless, the order of magnitude of the net dissipation may be computed.

Similarity theory, which applies to the atmospheric surface layer, can be used to extrapolate dissipation values from several meters depth to the surface through the unobserved near-surface zone. When this technique is applied to a deep mixed layer that is strongly free convective, it is found that the wind shear production plus the estimated buoyant production of turbulence is inadequate to explain observed rates of mixed layer deepening (M. Gregg, University of Washington, Seattle) . . .Although there are other possible explanations for this discrepancy, occasional observations of "bursts" of very high dissipation rates suggest an additional (previously unexpected) source of turbulent kinetic energy.

The phenomenon may be related to the sudden injection of energy from breaking surface waves. If this is the case, the similarity relationship between dissipation and the friction velocity (which is used successfully in the atmospheric surface layer) may be inadequate for the oceanic turbulent boundary layer. Although breaking waves are technically a conversion of mean wave energy to turbulent kinetic energy (a shear production mechanism), the phenomenon may act more like the buoyant transport of turbulence in a free convection regime in that it is not dissipated locally but is transported vertically to the base of the mixed layer and there converted to potential energy by the action of entrainment.

There are a number of critical questions. Clearly, profiles need to be extended to the surface. The upward profiler may provide a solution (T. Dillon, Oregon State University, Corvallis). We don't yet have adequate horizontal sampling. Inadequate consideration of horizontal variability in the case of the atmospheric surface layer also caused an apparent breakdown of the expected similarity scaling between dissipation and the surface friction velocity, and the similarity theory was ultimately verified only with adequate sampling (C. Fairall, Pennsylvania State University, University Park). Acoustically detected bubbles may provide a tracer to determine the vertical extent of turbulent transport that is caused by breaking of surface waves (see Thorpe, 1985; also W. Large, National Center for Atmospheric Research, Boulder) . . . Near the. . . surface, bubbles injected downward from the surface following the breaking of surface gravity waves are the main scatterers. The intensity of the backscattered signal hence provides a measurement of the extent of the bubble penetration. Such observations of the bubble envelope, correlated with profiles of dissipation, may shed light on the role of breaking surface waves in mixing and entrainment.

> When the "dissipation method" is extended to the ocean, Reynolds stress profiles can be estimated by assuming a balance of dissipation and local shear production. If this method is applied to measurements at the equator, however, it is found that there is a discrepancy between the observed rates of dissipation (and inferred Reynolds stresses) and the assumed sources of momentum (T. Dillon, Oregon State University, Corvallis). More investigation is needed to determine if in fact there are significant discrepancies in the momentum budget or if the dissipation technique may not be applied to the possibly unique equatorial mixed layer because (for example) the radiation of internal gravity waves becomes a significant part of the turbulent kinetic energy budget. (Copyright 1988 by the American Geophysical Union.)

Surface Waves and Stokes Drift

Mailer and Garwood (1988) summarized:

> Surface waves are an integral part of mixed layer dynamics. It is generally believed that most of the atmospheric momentum and mechanical flux is first absorbed by the surface wave field. However, it cannot be retained there, and it is quickly dissipated into the underlying ocean by whitecaps and other wave-breaking processes. Considerable effort has been spent to construct models of the evolution of the surface wave field under the influence of wind forcing, nonlinear interaction, and dissipation. One of the most advanced models is that developed by the WAM (Wave Modeling) group (G. Komen, Royal Netherlands Meteorological Institute, De Bilt). The best estimates from this model of momentum and mechanical energy fluxes from the wave field to the ocean are large. For a wind speed of 20 m/s, an energy flux of a few watts per square meter is calculated, which greatly exceeds typical turbulent fluxes estimated below the surface wave zone. Also, the momentum and energy fluxes from the atmosphere to the surface waves and from the waves to the ocean are of the same magnitude, and only a small fraction is used for wave growth. Under certain fetch conditions, the momentum flux into the ocean turns out to be even larger than the downward momentum flux at 10 m height above the ocean. Something seems to be wrong. The discrepancy may be resolved by changing the model parameters or the spectral parameterization at high frequencies, but it might also indicate that the atmosphere surface layer is not a "constant flux layer" because of deceleration effects over growing waves. (Copyright 1988 by the American Geophysical Union.)

In addition to their role in near-surface mixing, surface waves may contribute to a Lagrangian mean surface drift velocity, known as Stokes drift. Stokes drift results from nonlinearity of the surface wave field and increases with wave height; essentially, particles or passive tracers travel farther forward with the crest of the wave than they travel backward with the trough. Kenyon (1969) has estimated the Stokes-drift velocity as a function of wind velocity by using the directional wind wave spectra for fully developed seas of Pierson and Moskowitz (1964). He found the ratio of surface Stokes drift velocity to wind speed measured at 19.5 m above sea surface to range from 1.6 to 3.6%, which is large enough to make a significant contribution to the overall surface wind drift.

Response To Severe Storms

Allen et al. (1987) stated that

> strong storms cause large flows and increased transports and mixing in coastal areas. For example, although the typical mean flow in the Middle Atlantic Bight is 0.05 m/s, episodic storm currents associated with subinertial motions exceed 0.4 m/s and last for several days. The strength and pattern of the storm-induced flow is not well known and is probably a function of coastal geometry, the size and shape of the storm systems, and the rate at which the storms move and intensify. The effect of the large currents, mixing, and the transport associated with the storms on the shelf budgets and on the transport of material are important unsolved coastal problems. Coupled meteorology and physical oceanography programs [are needed] to understand the detailed cyclogenesis and subsequent meteorological forcing. (Copyright 1987 by the American Geophysical Union.)

A recent example of a coupled meteorological and oceanographic experiment was project GALE (Genesis of Atlantic Lows Experiment), which studied these processes over the southeastern U.S, continental shelf in early 1986. Blanton et al. (1987), reporting on the oceanographic studies carried out during GALE, wrote:

> The GALE study area was located in an area where major cyclones develop during winter (Colucci, 1976). The occurrence of these extratropical cyclones is manifested by wind forcing over the continental shelf in the 2-10 day synoptic period. Cold an' outbreaks that follow the passing of cyclones advect cold, dry continental air across the relatively warm shelf and Gulf Stream waters. Cold air outbreaks produce offshore winds that can last several days and strongly influence the observed mean winter wind stress, directed toward the southeast (Weber and Blanton, 1980). Synoptic wind events have spatial scales similar to the alongshelf scale between Cape Canaveral and Cape Hatteras. This results in coherent wind forcing over the total shelf domain. Wind speeds are typically more than two times greater over the shelf than over the adjacent coast (Lee and Atkinson, 1983; Blanton et al., 1985). (Copyright 1987 by the American Geophysical Union.)

Organized Motions

Müller and Garwood (1988) wrote:

> The development of organized cellular motion in the mixed layer can be seen by surface scattering Doppler sonars (J. Smith, Scripps Institution of Oceanography, La Jolla , Calif.). The Doppler shift of the sonar return signal provides a measurement of the velocity field. These organized motions or secondary flows have a vertical scale comparable to the depth of the mixed layer and are frequently identified as Langmuir cells. Langmuir cells are a classical phenomenon (Langmuir, 1938), yet there is still dispute about how they are generated. One widely accepted cause is related to an interaction between surface gravity waves and Reynolds stresses. Other possible causes or contributing factors include the surface buoyancy flux, planetary rotation and rotation stress, and dynamic instabilities that are not directly caused but are modulated by the surface wave field. There may be more than one mechanism leading to phenomena subjectively identified as "Langmuir cells."
>
> The quantification of the energetics of these Langmuir cells is of particular importance for understanding mixed layer dynamics. Is their total kinetic energy content to be considered a part of the turbulent kinetic energy budget? Although these circulations are apparently not ubiquitous, are they an organization of the "normal" integral scale motions of the turbulence generated by shear production? Is their energy available for mixing in the thermocline? Are these motions dissipative, that is, quickly dissipated/altered when the source of energy is removed? Are energy and momentum from these cells transferred to internal waves in the entrainment zone, and do these waves contribute to mixing well down into the pycnocline? Does the present-day parameterization of the turbulent kinetic energy budget adequately include the effects of these organized motions? (Copyright 1988 by the American Geophysical Union.)

Diurnal Cycle and Shallowing Mixed Layers

Müller and Garwood (1988) summarized:

> Recent field experiments and theoretical investigations have concentrated on entrainment or deepening aspects of the ocean surface mixed layer. Now there is a growing concern with the shallowing of the mixed layer, in particularly with the diurnal shallowing.
>
> Data taken during the Tropic Heat study show that there is a significant diurnal cycle of mixing on the equator that had not been observed previously (Peters). Dissipation changes by two oders of magnitude . . . The high values of dissipation penetrate well into the thermocline and may be associated with the breaking of downward propagating internal waves that are generated by nighttime convective motions in the mixed layer. Convective cloud lines are a possible cause for the diurnal cycling of mixing at the equator (C. Gautier, Scripps Institution of Oceanography, La Jolla, Calif.). This mechanism has a strong diurnal variability with pronounced nighttime cooling bursts concurrent with wind stress bursts.
>
> The equatorial mixed layer is worth special attention because it may prove to be a "laboratory" for certain mixed layer processes. Since the vertical component of planetary rotation vanishes, rotational aspects might be less complex at the equator than at mid-latitudes. The large vertical shear of the equatorial undercurrent is a unique source of turbulent kinetic energy that can be

released by the diurnal penetration of Reynolds stresses. Although undersampling of the strong diurnal cycle causes aliasing, there is evidence that dissipation is significantly higher on the equator.

The diurnal mixed layer at higher latitudes may also show a flux of momentum and energy into the underlying deeper pycnocline. Although the diurnal mixed layer "retreats" to a length scale proportional to the Obukhov scale (L) when the turbulent kinetic energy budget is considered alone, without entrainment, both momentum and buoyancy will penetrate deeper than L due to a shear instability at the base of the mixed layer (R. Garwood, Naval Postgraduate School, Monterey, Calif.). Because this mechanism is set up by the inertial wind-driven current, the depth to which it penetrates is proportional to u^*/f and is independent of the surface buoyancy flux and the Obukhov length. Although these suggested scaling arguments are not applicable on the equator, they are consistent with the much deeper entrainment zone into which turbulence is able to penetrate in the near-equatorial mixed layer, as reported.

Data from the LOTUS (Long-Term Upper Ocean Study) experiment in the Sargasso Sea show the diurnal surface heating to be as large as 3°C (J. Price, Woods Hole Oceanographic Institution, Woods Hole, Mass.). The diurnal temperature change is proportional to the net downward surface heat flux to the 3/2 power, and it is inversely proportional to the wind stress magnitude . . . These diurnal temperature changes may be of considerable importance for air-sea interaction and also possibly for the radiation budget of the planet, due to the greatly increased back radiation from the sea surface. They are not well represented in the sea surface temperature fields derived from ship injection and bucket temperature observations. (Copyright 1988 by the American Geophysical Union.)

Monitoring

Muller and Garwood (1988) wrote:

Monitoring surface fluxes and the upper ocean is particularly challenging because of the numerous processes at work there and the rapid response scales. In situ observations, satellites, and atmospheric global general circulation models will all play a role in producing global fields on a regular basis (W. Large). When the net radiation flux at the sea surface is computed from satellites, the downward long-wave radiation in cloudy conditions is still the most complex to derive (C. Gautier).

The diurnal cycling of sea surface temperature (changes of up to 3°c) can be monitored from satellites and is an example of a process that, once understood from the intense local studies, could be observed on a much broader scale by using data from a monitoring network (W. Large and C. Gautier). Another example is the monitoring of episodic cooling events in autumn that are indicative of intense vertical mixing in the seasonal thermocline (W. Large). Day-to-night changes in the intensity of mixed layer turbulence can be inferred from thermal measurements obtained from drifting thermistor chains and shortwave radiation fluxes obtained from satellites (W. Large). Such measurements indicate that the strong diurnal cycle observed during Tropic Heat extends throughout the year and is also evident at other than equatorial locations. (Copyright 1988 by the American Geophysical Union.)

Coastal-Trapped Waves

Brink (1987) declared:

The term "coastal-trapped waves" refers to a class of wave motions at subinertial frequencies which always propagate such that their phase travels with shallow water to the right (left) in the northern (southern) hemisphere. These vorticity-conserving motions are of some interest in their own right, in that free (not influenced by local wind driving) coastal-trapped waves have been observed occasionally in nature, both in connection with diurnal tides, e.g. Daifuku and Beardsley (1983), and at subtidal frequencies, e.g. Ou et al. (1981), Enfield and Allen (1983). Generally speaking, only fairly long waves (wavelength much greater than the cross-shelf topographic scale) have been observed, although Gordon and Huthnance (1987) have presented evidence for the existence of "short" coastal-trapped waves east of Scotland. Despite the observations of truly free coastal-trapped waves, the main value of the wave theory is in its ability to explain the character of wind-forced pressure and alongshore velocity fluctuations over the continental shelf and slope. The following discussion will thus focus mainly on this more general aspect of the theory.

Some of the most successful results of coastal-trapped wave theory arise when the "long wave" assumption (Gill and Schumann, 1974) is made. This requires that alongshore length scales are much greater than cross-shelf scales, and that wave periods are much longer than the inertial period. These assumptions then result in the alongshore component of flow being in geostrophic balance, as indeed it is often observed to be. It is often further assumed that model inputs such as shelf-slope topography, stratification, the Coriolis parameter, and the bottom resistance coefficient vary slowly (if at all) in the alongshore direction. Mathematically, the long wave assumption leads to a reduction of the wind-forcing problem to one of finding a set of free wave pressure eigenfunctions and eigenvalues (inverse phase speeds), and then solving an infinite set of coupled, wind-driven first order wave equations, e.g. Clarke and Van Gorder (1986). Currents and pressures are then found by summing the products of the amplitude functions (from the wave equations) with their respective modal structures. The eigenfunctions are mathematically orthogonal, a property which leads to a powerful ability to address seemingly difficult problems involving bottom friction or topographic irregularities. [With the "long wave" assumption the resulting waves propagate nondispersively.] . . .

In principle (Clarke and Van Gorder, 1986), O(10) long-wave modes need to be found for an accurate representation of alongshore currents over the shelf, but in practice (e.g. Chapman, 1987), fewer modes (about 2-3) may be sufficient. Finding the modal structures and free-wave parameters has been expedited by the availability of "community" algorithms for their calculation under fairly arbitrary conditions (Brink and Chapman, 1985). Solutions to the first order wave equations using observed wind time series and calculated model properties have led to some rather skillful hindcasts of alongshore currents and pressure over the shelf, e.g. Halliwell and Allen (1984), Battisti and Hickey (1984), Mitchum and Clarke (1986), and Chapman (1987). Chapman (1987) further made an extensive study of the quality of the model's predictions versus the choice of input parameters. He found that the model is most sensitive to the quality of the wind data employed. One property common to the Mitchurn and Clarke (1986), Chapman (1987) and Brink et al. (1987a) studies, however, is that the magnitude of current fluctuations is generally underpredicted. This underestimation of fluctuations is not understood at present, but is one of the few blemishes on the long-wave theory.

Although the fundamentals of coastal-trapped wave theory were laid down in the 1970's, the growing appreciation of the applicability of the theory has led to an emphasis on improved realism, especially with regard to the coupled effects of stratification and shelf-slope topography on wave behavior. For example, Chapman (1983) has demonstrated the effects of variations in stratification on free-wave dispersion curves. He demonstrates that if the maximum value of

$$A = (\text{bottom slope}) \times (\text{Brunt-Väisälä frequency})/(\text{Coriolis parameter})$$

evaluated along the bottom exceeds one, then the free waves can exist at any subinertial frequency, in contrast to results in the barotropic limit. Generally speaking the gross effects of stratification can be estimated by A and by the stratification parameter

$$S = (\text{Brunt-Väisälä frequency}) \times (\text{deep-sea depth})/(\text{Coriolis parameter})/(\text{width of shelf})$$

As S increases, the free-wave frequency must always increase (Clarke, 1977; Huthnance, 1978), and the modal structure becomes progressively more depth dependent. Small values of S^2 often allow the barotropic assumption to be made. Clarke and Brink (1985) have also shown that when S, evaluated with values representative of the shelf alone, is small, then the simplifying assumption of barotropic waves (i.e., neglecting stratification) and of no pressure fluctuations at the shelf break can be employed. This simplification, however, leads to the omission of those wave modes which have their primary structure over the continental slope, hence presumably to some degradation of the quality of the model prediction . . .

[A] recent advance in coastal-trapped wave theory has come from the development of stochastic approaches to forced wave modeling. These approaches can represent simply a statistical study of numerical model results (e.g. Carton and Philander, 1984), or they can rely on the more idealized wave-equation physics. For example, Allen and Denbo (1984) have demonstrated that, when a single first order wave equation (with friction) is driven by a realistic space-time spectrum of wind stress, currents and sea level fluctuations at a given point are always best correlated with wind fluctuations earlier in time and farther to the south. Under most realistic conditions, their model predicts smaller, although still substantial correlations with winds over a range of space (including local) and time lags. The structure of their predicted correlation diagrams is simply a result of the tendency for forced coastal-trapped waves to spread information only in the direction of free-wave propagation. Allen and Denbo's (1984) model results agree well with the observations of Halliwell and Allen (1984), which motivated their study, and qualitatively with those of Denbo and Allen (1987) and of Winant et al. (1987). The success of the Allen and Denbo (1984) and the related Brink et al.

(1987a) theories lies in their ability to rationalize the importance of local versus nonlocal forcing. In practice, local forcing (away from the surface boundary layer) can be difficult to distinguish observationally because wind patterns are correlated over large spatial scales. Thus, high correlation of local winds with local currents need not mean that the currents are driven locally: rather, they could be driven by winds at a remote location (which are coherent with local winds), and then the information can propagate as free waves into the measurement region. The issue of local wind driving is thus subtle, and it depends strongly on how the strength of wind fluctuations varies with alongshore distance.

The theory of coastal-trapped waves has repeatedly demonstrated its ability to provide accurate hindcasts of fluctuations in sea level and alongshore currents, at least within the period range of about 3-20 days. Seldom mentioned, however, is the general inability of the theory to provide useful information about the onshore currents or density fluctuations (but see Chapman, 1987). It seems that the time is right to shift attention to those variables and parameter ranges which are not well described by present models. (Copyright 1987 by the American Geophysical Union.)

Mean-Flow Generation

Brink (1987) stated:

Over the last several years, interest has grown considerably in processes which govern time-averaged flow over the continental shelf and dope. Early attempts to explain mean flow patterns centered on wind-driven, frictionally dominated models which ignore alongshore variations. Csanady (1974) provides an example of such an approach. Allowing for alongshore variability made the problem much richer and demonstrated the tendency for mean flow patterns to "stretch out" in the direction of free coastal-trapped wave propagation (Pecdlosky, 1974; Csanady, 1978; Winant, 1979). This type of model would suggest that mean alongshore flow should be in the same direction as the local winds, or of the winds "backward" (with respect to the direction of free coastal-trapped wave propagation) from the measurement location. This presumption does not hold up terribly well in light of observations, however. In the Mid-Atlantic Bight (Beardsley and Boicourt, 1981), off Oregon (Kundu and Allen, 1976), off Northern California (Winant et al., 1987; Strub et al., 1987a), off Peru (Brink et al., 1980), and in the Leeuwin current off Australia (Thompson, 1984), mean currents, at least near the bottom, run counter to the direction that wind stresses might suggest. Winant et al. (1987) demonstrate that in the absence of wind driving, currents are directed strongly in the poleward direction throughout the water column. In all cases mentioned, the anomalous mean flow is directed in the sense of free coastal-trapped wave propagation. This may, of course, simply be a coincidence. The number of cases of currents which run contrary to winds has led oceanographers to explore several new driving mechanisms, as well as to look at new variations on wind driving.

In steady stratified three-dimensional models of wind-driven coastal currents, an undercurrent (opposite to the wind) often develops (e.g., McCreary et al., 1986). McCreary and Chao (1985) have made an important advance in this type of theory by including shelf-slope topography. Their model, which is remarkably simple conceptually, can be thought of as an extension of Csanady's (1978) to include stratification. As with all three dimensional models, their current system spreads poleward (for the U.S. west coast) from the driving region. Although their model still admits an undercurrent, its strength is extremely sensitive to details of the topography and frictional parameterization.

Csanady and Shaw (1983), Wang (1982), and Chapman et al. (1986) all used steady barotropic models to demonstrate that alongshore pressure gradients imposed by oceanic lows do not penetrate onto the continental shelf proper. An exception can exist in bounded basins, however, where interrupted depth contours allow the formation of a 'western" boundary current (Kinder et al., 1986). Chapman et al. (1986) also used their simple model to show that the observed mean flow in the Mid-Atlantic Bight could be driven simply by the inflow from the shelf off Nova Scotia. This result, of course, leaves open the question of what drives the flow along the Scotian shelf.

Thermohaline effects have often been invoked as possible mechanisms for driving shelf currents, most often in the context of river runoff, e.g., Csanady (1984). More recently, attention has focussed upon the effects of basin-scale density variations and their effects on coastal currents. McCreary et al. (1987) investigated the effects of a basin-wide north to south imposed surface density gradient in a flat-bottom ocean. The gradient, through the thermal wind equation, drives an eastward flow pattern which must be closed by a poleward eastern boundary current, which they compare to the Leeuwin Current. Huthnance (1984) and Csanady (1985) concentrate instead on the more local "JEBAR" (Joint Effect of Baroclinicity and Relief) effect defined by an alongshore density radient imposed over a continental shelf and slope. Simply stated, the density gradient implies (through the thermal wind equation) a flow across the topography. Due to the shoaling of the water column,

> onshore convergence results and an alongshore flow must then arise in order to remove the water which can not cross the isobaths. Huthnance (1984) presents arguments that the density gradients observed along the west coast of the United States are strong enough to drive a measurable poleward current along the continental slope that can be identified with the California Undercurrent.
>
> All of the theories mentioned above treat mean currents as a response to a steady forcing agency. A conceptually separate class of models has also developed, which treats mean currents as a result of nonlinear rectification of current fluctuations. One such example is the tidal rectification model of Loder (1980), which drives a mean flow as a result of tidal currents crossing steep changes in topography in the presence of bottom friction. Butman et al. (1983) attempted to test this theory by seeking fortnightly modulations in mean currents, using long time series from the south side of Georges Bank. Their results are inconclusive, partly because, at their mooring location, no strong tidal rectification was to be expected. The more detailed barotropic numerical model of Greenberg (1983) nevertheless tends to vindicate Loder's results with regard to the mean jet along the north flank of Georges Bank.
>
> Another rectification model is that of Denbo and Allen (1983). They investigate the across-shelf momentum fluxes associated with wind and offshore driving in a barotropic, frictional, time dependent model. Their results indicate only a weak, generally equatorward mean current in response to fluctuating wind driving for a case resembling Oregon. Offshore forcing also drives weak mean currents, but in the poleward sense. Overall, their results do not appear to account for observed currents.
>
> A novel candidate for mean current generation has been presented by Haidvogel and Brink (1986). Martell and Allen (1979) and Brink (1986) motivated their study with models of steady, inviscid barotropic currents over topographical irregularities on the continental shelf with a rigid lid. A topographic drag is only experienced when the flow is in the opposite sense to shelf wave propagation. Flow in the sense of wave propagation experiences no topographic drag of this sort. Thus, a flow with no time-mean might be expected to experience a non- zero mean drag, or, alternatively a zero-mean forcing might lead to a net mean flow. Haidvogel and Brink (1986) conducted numerical experiments with a barotropic primitive equation model driven by a fluctuating (zero mean) wind stress. The topographic drag asymmetry then results in a net flow of about 0.01-0.07 m/s in the direction of shelf wave propagation (poleward off the west coast of Noah America). Their idealized model geometry and wind forcing, and their neglect of stratification make the model very difficult to compare with observations, but the results are, so far, encouraging.
>
> At present, there are many potential mechanisms for driving mean flow patterns over the continental shelf and slope. Indeed, the above collection is not even complete. At this time, there is little point in intercomparing the models, because their results are generally quite dependent upon the details of parameter choices, geometry and forcing. It is likely that many existing models have applications at specific locations in the world's oceans, but generally, it is not clear which mechanism dominates at each location. Likewise, it is improbable that any one model will explain all observations. The real challenge now is to formulate models that are sufficiently realistic to be compared with observations, allowing their proper evaluation to begin. (Copyright 1987 by the American Geophysical Union.)

More recently, since Brink's (1987) review article, Holloway (1987) has shown that random eddies also will generate a mean flow in the direction of shelf wave propagation.

Interactions Of Western Boundary Currents With Shelves

Allen et al. (1987) wrote:

> Western boundary currents, such as the Gulf Stream, interact with shelf and slope waters through a variety of means, some of which are relatively well understood, for example, through Gulf Stream filaments in the South Atlantic Bight. Less well understood are other interactions, such as the interactions of warm core rings (spawned by the Gulf Stream) with shelf waters in the Mid-Atlantic Bight. The most recently discovered interaction takes place northeast of Cape Hatteras and involves the relation between shifts of the Gulf Stream axis and changes in the transport of slope currents 100-300 km to the north. The dynamics associated with this coupling are unknown and should be examined as a part of a more general study of the physical oceanography of the mid-and upper dope. (Copyright 1987 by the American Geophysical Union.)

Brink (1987) summarized:

In the South Atlantic Bight, the shelf break problem can be treated as a question of the deflection of the shelf break or Gulf Stream front. Although some attention has been given to wind-driven effects (e.g. Oey, 1986), most of the effort has been centered on meanders and their accompanying warm surface filaments. Although these features are most often observed in the Atlantic, seemingly analogous features have also been found where the Loop Current contacts the west Florida shelf break (Paluszkiewicz et al., 1983; Vukovich, 1986). The meander structures typically consist of an upwelled dome of cold water at the shelf break about which the warm, shallow filament wraps backward relative to the Gulf Stream flow. Flow within the filament appears to parallel surface isotherms, forming a backward-tilting meander of the Gulf Stream. Cross-shelf and alongshore scales of the meander are typically about 10-25 km and 130 km, respectively (e.g., Lee and Atkinson, 1983). The cold domes appear often to be deep-rooted: Levine and Bergin (1983) find that they are detectable down to at least 700 m, and represent vertical displacements of up to 200 m. Individual meanders have lifetimes of about 1-3 weeks (Lee and Atkinson, 1983) and propagate poleward (in the same direction as the Gulf Stream) at rates in the range of 0.28-0.98 m/s, with typical values of the order of 0.4-0.7 m/s (Brooks and Bane, 1983; Lee and Atkinson, 1983; McClain et al., 1984). The meanders are uncorrelated with the meteorological forcing (Brooks and Bane, 1983), but instead seem to be the result of a hydrodynamic instability of the Gulf Stream front (Luther and Bane, 1985). Some verification of the stability hypotheses can be found in the remote sensing results of Olson et al. (1983), who found that the envelope enclosing the meanders broadens from about Cape Canaveral, Florida to Charleston, South Carolina. Off North Carolina, the envelope narrows, suggesting that the meanders begin to lose energy. Indeed, evidence is mounting that the meanders transport both northward momentum (Brooks and Bane, 1983; Lee and Atkinson, 1983) and energy (Hood and Bane, 1983) into the Gulf Stream.

Alternative approaches to assessing Gulf Stream effects on shelf flow have involved the study of bulk statistics, as opposed to the study of individual coherent features such as meanders. For example, Lee et al. (1984) used momentum balances and correlation studies to show that current-meter records from the mid- to outer shelf (40 m isobath and deeper) show some Gulf Stream influence, but that the inner shelf does not. Liet al. (1985) were able to monitor the Gulf Stream position using inverted echo sounders, and then did a multivariate analysis of currents with Gulf Stream deflection and wind stress components. They found that at the outer shelf, currents at 17 m depth were dominated by Gulf Stream influences, while at 72 m at the same location wind effects played some role in driving the currents. At midshelf (45 m isobath, about 20 km away), wind driving dominated. Thus, the Gulf Stream influence on currents appears to be stronger near the surface, and confined to the outer reaches at the shelf. Atkinson et al. (1983) found evidence from the climatological hydrography that active exchange of water properties occurs across the shelf break: about 20% of the volume of the shelf water is replaced by the Gulf Stream water per month. . . .

As in the South Atlantic Bight, oceanic effects do not seem to influence currents far onto the shelf. Beardsley et al. (1985) found that anomalous currents associated with warm core rings could be distinguished right at the shelf break, but not at a position 20 km onshore from there. The rest of the shelf was not disturbed by this mechanism.

The Northeast Channel is one of the few (if not only) places where exchange between shelf and slope waters takes place freely (Ramp et al., 1985). This channel is a relatively deep (about 250 m) north-south passageway east of Georges Bank which connects the Gulf of Maine to the continental slope. Water from offshore flows into the Channel on its eastern side while less saline water flows out on the western side. Fluctuations in the flow are closely related to wind and sea level fluctuations around the Gulf of Maine and the response is like that expected for coastal upwelling. Ramp et al. (1985) estimate an eleven month residence time for water in the Gulf of Maine. Some of the details of the distribution of slope water within the Gulf are described by Brooks (1985). (Copyright 1987 by the American Geophysical Union.)

Mesoscale Features: Jets, Eddies, Squirts, And Filaments

Brink (1987) wrote:

The variously-called jets, squirts or filaments in the California Current system have become a particularly active topic of research. Their cold temperatures, high nutrients, and high chlorophyll contents suggest that they are sinks for freshly upwelled water (Traganza et al., 1980; Abbott and Zion, 1985). New observational approaches, such as drifters and Doppler profiling current measurements (Davis, 1985a; Kosro and Huyer, 1986) have provided an exciting new view of these energetic features. Breaker and Mooers (1986) present evidence that they typically first appear around May, and that they become larger as the upwelling season progresses. Whether similar current (but

> not thermal) features exist in the wintertime is not known, because in the absence of cold, upwelled water as a "label", they would be invisible. Experience to date suggests that a typical mature filament has an offshore velocity of. . .0.5 m/s. . .within an area about 20-50 km wide and about 100-200 m deep. Kelly (1985) presents evidence, based on satellite imagery, that the filaments are "rooted" at a fixed location near capes, although they can meander considerably at a greater distance from the coast.
>
> Very often the filaments have a pronounced thermal front along their equatorial edge, but a more gradual temperature gradient along their poleward edge (Flament et al., 1985; Rienecker et al., 1985; Kosro and Huyer, 1986; Barth and Brink, 1987). This front is sometimes density-compensated by salinity changes (Flament et al., 1985; Rienecker et al., 1985), and it may also be accompanied by an extremely sharp along-front velocity shear of. . .[10'4/s] (Kosro and Huyer, 1986). Flament et al. (1985) also present an example of interleaving near the front which was apparently caused by near-surface waters being forced underneath lighter waters from the north. The waters within filaments appear to be injected by the offshore deflection (by some unknown mechanism) of the equatorward coastal current found over the shelf north of the feature's origin (Kosro and Huyer, 1986; Barth and Brink, 1987).
>
> Some evidence exists that an onshore (eastward) jet can parallel the filament on its southern side (Flament et al., 1985; Kosro and Huyer, 1986; Barth and Brink, 1987), although this feature is observed intermittently enough as to have an uncertain repeatability. More serious issues are raised by the observations (e.g. Rienecker et al., 1985) that, once offshore, the filaments tend to thread between deeper-rooted (at least 500 m) eddies in the California current system. This raised the question of whether the filaments are simply drawn offshore by the eddies. If, however, this deep-ocean explanation alone were valid, then it would be difficult to account for the possibility of fixed coastal origin of the features. (Copyright 1987 by the American Geophysical Union.)

The Office of Naval Research Coastal Transition Zone (CTZ) program to study squirts and jets conducted a pilot experiment in 1987 and had planned a major experiment for the summer of 1988, roughly coinciding with the MMS northern California study. The CTZ study is focused from the shelf break to 300 km offshore. The results from the 1987 Acoustic Doppler Current Profiler and Conductivity Temperature Depth surveys showed that the high velocities are found along density fronts (often the edge of the cold features) and not generally at the temperature minima of the cold features (R.L. Smith, personal communication, 1987). The results are consistent with a strong meandering alongshore geostrophic jet, with cold upwelled water filling the coastward region as the alongshore jet meanders.

Fronts And Convergences

Fronts and convergences are common features in the waters over continental shelves and slopes. They may be caused by a number of factors, as the following examples illustrate. Allen et al. (1987) wrote:

> Fronts frequently occur during coastal upwelling. Although their existence and their main features are relatively well known, little is known about their evolution or the exchange of water across them. These issues are particularly important because of the high biological productivity associated with upwelling and the role that fronts play in setting the geographic bounds of different ecosystems. There is a clear need for a systematic study of cross-frontal exchanges (both advective and turbulent) and of the growth, decay, and meandering of such fronts. (Copyright 1987 by the American Geophysical Union.)

According to Brink (1987):

> The Mid-Atlantic Bight differs from its southern neighbor in one major way: no persistent oceanic current impinges on its outer edge. Instead, a well-defined front separates the shelf and slope water masses throughout the year, especially in the lowest half of the water column. During the summer, no density front exists in the upper water column because the lower temperatures of the shelf waters are sufficient to counteract salinity differences. The front is far from a quiescent feature: its position can vary dramatically from day to day and it frequently exchanges parcels of water along isopycnals during the summer (Houghton and Marra, 1983). Some of this exchange appears related to small, O(10 km), energetic eddies existing just offshore of the front (Houghton et al., 1986). More dramatic removal of shelf water takes place when occasional warm core rings entrain substantial

> volumes of shelf water which can be traced by satellite images (Evans et al., 1985), moored instruments (Churchill et al., 1986), drifters (Bisagni, 1983), or through radioactive tracers (Orr et al., 1985). Despite the availability of these exchange mechanisms, very little offshore water is found to penetrate onto the shelf (Chapman et al., 1986).
>
> The dynamics of the shelf break front have been somewhat puzzling because it is often not a density front, hence it may not play an active role in the momentum balances. Further, its tendency to "anchor" at the shelf break suggests that somehow this is a special location. A simple theory by Chapman (1987) appears to explain the front's existence. . . in a way that addresses the above constraints. Simply stated, shelf water is treated as a passive tracer advected by the barotropic flow field. At the shelf break, a front is maintained by the balance of geometrically induced vertical spreading with offshore advection and lateral mixing. Deflections of the front, once it is formed, appear to be due to wind effects (Ou, 1984a, b), the passage of eddies, and of hydrodynamic instabilities (Ramp et al., 1983). (Copyright 1987 by the American Geophysical Union.)

A series of fronts is maintained on the Bering Shelf by the varying balance between buoyancy input and turbulent mixing caused by the tidal currents as the depth of the water changes (Coachman, 1986) (see Chapter 3). Surface-floating material, such as oil, will collect in fronts and follow their movements.

Cross-Shelf Transport

Allen et al. (1987) stated:

> Although the large-scale alongshelf flow in many regions has been described to lowest order, the structure and strength of the cross-shelf flow is poorly known. Cross-shelf flows are difficult to measure because they are weak and have short spatial scales. At the outer edge of the shelf, episodes of very strong offshore flow occur, but they are hard to measure because of their short alongshore scales and their episodic nature. Nonetheless, the cross-shelf flow is critical to exchange of water, heat, salt and nutrients [and oil]. In addition, the cross-shelf flow transport of particles and various dissolved chemicals is of direct practical importance. The cross-shelf component is also important dynamically, often providing a clearer diagnostic of the flow [dynamics] than does the alongshelf component. (Copyright 1987 by the American Geophysical Union.)

Buoyancy-Driven Flows

According to Allen et al. (1987):

> The continental margin represents the region where saline oceanic waters contact and mix with the freshet waters associated with runoff from land. Since there is usually a density contrast between the two types of water, associated structures in the currents are expected. These effects are most dramatic in high-latitude regions with large runoff, such as Norway or southern Alaska, where salinity contrasts cause large density contrasts and large currents. Despite their importance, buoyancy driven currents are not well understood. (Copyright 1987 by the American Geophysical Union.)

Studying buoyancy-driven flows and their variability involves several aspects of oceanography including hydrology, meteorology, glaciology (in some regions), and forcing.

Tides

Tides are ubiquitous features of the marine environment caused by the gravitational attractions of the sun-moon-earth system. They are generated primarily in the deep ocean basins and then propagate over the continental shelves and into coastal waters as long gravitational waves damped by bottom friction. Tidal propagation may range between being almost normal to the shelf, as for the semidiurnal tide on the U.S. Atlantic coast, to being primarily an alongshore Kelvin wave, as for the semidiurnal tide on the Pacific coast. For the diurnal tide, a continental-shelf wave is often present as well. Daifuku (1981) shows that in the Mid-Atlantic

Bight, the Kelvin wave accounts for most of the diurnal surface tide, whereas roughly 80% of the diurnal current variance is due to a continental-shelf wave.

Tidal currents typically run from 0.01 to 0.1 m/s, with values reaching up as high as 1 m/s in the vicinity of certain banks, shoals, and passes. While the alongshore tidal variance is an important signal in many, but by no means all, conditions, its cross-shore variance usually dominates the variance due to other processes. Tidal currents are sufficiently energetic to vertically mix the water column inshore of the 50-m isobath in the Bering Sea shelf (Schumacher et al., 1979) and on Georges Bank, in the Great South Channel, and on Nantucket Shoals (Garrett et al., 1978). In other cases, the effective mixing is restricted to a well-mixed bottom layer.

With rather simple wave models, it is possible to match the observed sea-surface elevation and bottom-pressure records on the shelf and slope. The model and observed currents, however, can be drastically different, with the observations varying significantly over a shorter distance scale than would be expected from the modeled wave lengths. It is believed that small-scale bathymetry and an irregular coastal boundary may be largely responsible for this effect (see, e.g., Rosenfeld and Beardsley, 1987). Furthermore, when continental-shelf waves are present in the diurnal signal, their currents are effectively independent of the tidal sea-level changes. The conclusion to be reached is that verification of a model against sea-level and bottom-pressure records does not verify the model for currents. Furthermore, in order to account for their shorter scale of horizontal variation, currents must be verified on a denser network than is required for sea level.

Due to nonlinearities in the governing equations, tidal motions can generate mean flow. This flow may be an important component of the overall surface drift, as it apparently is on Georges Bank (Loder, 1980; Hopkins and Garfield, 1981; Butman et al., 1983; Greenberg, 1983, for example).

Internal Waves

The generation of internal waves by the interaction of surface tides with topography has been well documented observationally and theoretically. These internal waves take one of two forms depending on the linearity of the generation process.

In the linear regime, the internal waves have tidal periods (usually semidiurnal), are generated at the continental shelf, and propagate shoreward, starting as a tidal beam but changing to a lower-mode wave as the higher modes lose their energy through dissipation. Simple models (Rattray, 1960; Baines, 1973; Prinsenberg and Rattray, 1975) illustrate the basic physics involved, while observational data presented by Reid (1956), Lee (1961), Torgrimson and Hickey (1979), DeWitt et al. (1986), and numerous others demonstrate that the waves can be significantly modified by the natural background variability. The high shears associated with these internal tides near their generation region can potentially increase the rate of mixing occurring at the shelf break.

The nonlinear regime is typified by trains of internal waves occurring at regular intervals of tidal period. They are essentially generated by the interaction of a tidally varying flow with topography to generate transient internal waves, modified by the tidal current advection, at particular phases of the tidal current (Hibiya, 1986). As the tidal current changes, internal waves propagate shoreward and evolve into a train of solitary waves as shown by the model of Lee and Beardsley (1974). There are numerous observations of these waves propagating shoreward over continental shelves, earlier by Ewing (1950), through the observation of surface slicks, and then later by Halpern (1971), by thermistor measurements. More recently, satellite observations have demonstrated the presence of similar internal wave trains propagating shoreward over many shelves, as summarized by Apel et al. (1975) and Sawyer (1983).

The surface convergences occur at intervals of a wavelength and are associated with the onshore propagating wave packets. They can collect and transport shoreward floating material such as oil, as reported by Shanks (1987). Shanks also suggested that oil caught in these convergence zones could kill or injure larvae that are often concentrated there. Furthermore, he stated the possibility that the downwelling currents at the convergence zones could pull less buoyant fractions of an oil spill underwater, making them less accessible for cleanup.

Lagrangian Motions

Lagrangian motions, as determined by the use of drifters, have been characterized in terms of their diffusive properties (see, e.g., Davis, 1985b) and their means, which may not always correspond to the Eulerian mean (see, e.g., Chelton et al., 1987). Davis found that drifter displacement statistics in CODE indicated that the probability density of particle displacements was reasonably well modeled by eddy diffusion with an anisotropic and inhomogeneous eddy diffusivity. At an offshore distance of the order of 10 km, he found the cross-shelf component of the diffusivity $K_{xx} \sim 10^2$ m^2/s, and the alongshelf component $K_{yy} \sim 3 \times 10^3$ m^2/s; K_{xx} increased offshore, while K_{yy} decreased. Although he found that eddy diffusion may adequately characterize the mean scalar transport, there seemed to be no simple relation between lateral eddy fluxes of momentum and mean shear. Use of the above Lagrangian determinations of K_{xx} and K. as estimates of the Eulerian horizontal eddy viscosity leads to variable errors of at least an order of magnitude.

Particle-pair statistics describe stirring processes such as the dispersal of a scalar contaminant cloud. Davis (1985b) found that these processes cannot be modeled as diffusion in CODE, even if appeal is made to a scale-dependent diffusivity. Examination of particle-separation probability densities suggests that the relative velocity between widely separated particles is approximately normally distributed. The relative velocity between closely spaced particles, however, is intermittent, perhaps because closely spaced particles can be trapped within the same small-scale convergence.

Chelton et al. (1987) found that off central California the drifters gave results consistent with current-meter measurements and surface dynamic topography in July 1984. In contrast, the drifter trajectories for the two winter surveys were difficult to rationalize in terms of the flow patterns inferred from other data. For example, most of the February 1984 drifters moved in a generally southward or southwesterly direction. Yet the geostrophic flow was consistently poleward in the drifter survey region. Similarly, the January 1985 geostrophic flow was quite strongly poleward in the drifter region, but the drifter trajectories are more indicative of variable flow. Windage of the drifters was not believed to be a problem. Chelton et al. (1987) considered a more likely explanation for the discrepancies between drifter and hydrographic data to be poor representation by the hydrographic data of near-surface currents. However, the difference between Lagrangian and Eulerian mean flows could be real.

NUMERICAL MODELS

Circulation Modeling

Circulation modeling was one of the topics considered at a recent workshop on U.S. plans for research on the physical oceanography of the continental margins, held in Boulder, Colorado, from March 30-April 1, 1987. The workshop report (Allen et al., 1987) summarized the topic as follows:

> Oceanographic models range from qualitative conceptual models through analytical and laboratory models to extremely complex numerical models. Each type [has] a role to play. Although emphasis should be placed on numerical models, analytical models will always be important because they provide quantitative expression of individual physical processes. They are thus useful for the interpretation of both field observations and results from more complex numerical models.
>
> The various types of numerical models each have important applications. A simple idealized model is sometimes the best way to study a single process. The comprehensive model, which in principle could contain all macroscopic ocean processes, provides interpretations of observations and extensions of experimental results. Extension is especially important because no field program can hope to study all parts of the coastal ocean. [Numerical models also allow extension in time as well as in space; this is essential to get sufficient statistics.] A well-verified and well-understood numerical model could, with proper inputs, be used for quantitative prediction in regions where observations are limited. Further, the results of numerical models are needed so that observational programs cart be planned to distinguish clearly between competing hypotheses and also to provide a context for other models, for example, for biological oceanography or sediment transport.

> As an element of a. . . program [i.e., ESP research], a modeling effort should take as its objectives both the improvement of our modeling capability and the use of that capability for the study of specific processes or regions. Some issues concerning the improvement of modeling capability can be clearly identified:
>
> (1) Most existing models need improvement in their parameterization of processes that are smaller than the grid scales, both vertical and horizontal. Mixing and energy dissipation are especially significant on continental margins because of the shallowness of the coastal ocean and [the large gradients in properties]. Refined understanding of dissipation in surface and bottom layers, as well as of interior mixing processes, should be reflected in improved formulations of these processes in numerical models. A related issue is understanding the extent to which processes with different time scales (e.g., surface waves, tides, and wind-driven motions) can be separated in a nonlinear ocean.
> (2) The construction of appropriate lateral open boundary conditions has proved troublesome in practice; improvement is needed. Correct representation of the offshore boundary conditions for coastal models is not well established and may be complicated by phenomena such as upwelling filaments and warm ring impingement. Further, the fact that the shelf has the characteristic of a waveguide complicates the imposition of [boundary conditions across the shelf at the upstream and downstream ends of the domain of interest].
> (3) Driving forces at the surface and at the coast need to be better incorporated. Wind stress, freshwater runoff, stresses due to wave breaking, surface heat exchange, and surface evaporation and precipitation all need to be included. [Better understanding of the accuracy of forcing function description needed to obtain desired model output accuracy is also needed.]
> (4) Data-assimilative models need to be devised to serve as both diagnostic and predictive tools. The derivation of the full benefit from a set of observations depends on the use of such models. (Copyright 1987 by the American Geophysical Union.)

Testing Of Numerical Models

There is a need for synthesizing the results of field programs and modeling efforts to achieve the maximum utility from both (a particularly important goal for MMS's OSRA modeling efforts). Validation is needed to elucidate how well models reproduce the necessary processes and phenomena. Allen et al. (1987) continued:

> Only by combining the results of individual field and modeling efforts can an increase in understanding (and thus utility) be achieved. As numerical models become more comprehensive, they must be subjected to continuous testing. Field results will be interpreted through the dynamical concepts embodied in the models. Because of the importance of models to the program, they must be carefully evaluated first by comparing them quantitatively and objectively with observations and second by interpreting their results in terms of simpler, process-oriented analytical or laboratory models. There is little use for models that are not well tested and well understood in terms of their dynamical behavior.
> Synthesis of field experiments also needs to take place on two levels: first, a quantitative description of all of the interesting phenomena that can be resolved and second, an understanding in dynamical terms. The critical questions are: what processes dominate at what places and times, and for what reasons? Oceanographic models can, and should, be used to help achieve this synthesis. Models can be used to interpolate and fill in gaps in sparsely sampled data sets, and models can be used to further a dynamical understanding. (Copyright 1987 by the American Geophysical Union.)

With regard to the objective evaluation of numerical model performance, Willmott et al. (1985) further commented:

> With the development and use of simulation models becoming a major focus in the geophysical community, the need to evaluate a model's performance comprehensively and objectively or to compare competing models has become an important but underinvestigated aspect of modeling research. Not only is the model evaluation literature sparse, but the discussion is often specific to a small class of problems (e.g., air pollution or solar radiation models) and frequently the recommendations are contradictory. (Copyright 1985 by the American Geophysical Union.)

Willmott et al. (1985) presented several techniques for quantitatively comparing model predictions with the results of observations:

> . . . [A] small set of complementary difference measures can represent an objective and meaningful description of a model's ability to reproduce reliable observations precisely or accurately, regardless of whether the events of interest are scalars, directions, or vectors. The core of this set of difference measures is made up of the root-mean-square error, the systematic root-mean-square error, the unsystematic root-mean-square error, and the index of agreement, although the mean absolute error and a modified index of agreement supply related but useful information. [Bootstrapping also] provides a general and reliable way to evaluate the difference indices or, for that matter, any statistic of interest. When these difference measures are used in conjunction with the appropriate univariate statistics and data-display graphics, the operational evaluation of the performance of one or more models can be comprehensively accomplished. (Copyright 1985 by the American Geophysical Union.)

They concluded with the statement that their methods

> . . . .may be extended to several other interesting problems, such as the comparison of model-predicted and observed flow fields. Model-predicted and observed wind velocity maps, for instance, could be quantitatively compared. If the model-predicted and observed variables are time series, on the other hand, time-dependent errors within the model could be detected by the calculation and interpretation of the difference measures at lags other than zero. To gain even further insight into the nature and sources of the error variable or field, it may also be useful to partition the difference variable into its spectral (cf. Weisberg and Pietrafesa, 1983) or eigenvector (cf. Preisendorfer and Barnett, 1983) components. Several other extensions also could be conceived, but even when the [suggested] evaluation is conducted in its most basic form, the ability of one or more models to reproduce nature accurately can be dependably assessed. (Copyright 1985 by the American Geophysical Union.)

Modeling The Spreading And Dispersion Of Oil

A comprehensive review of the state of the art in oil-spill-fate modeling was recently completed by Spaulding (1988). Earlier model reviews included Huang (1983), Huang and

Monastero (1982), Davidson and Lawrence (1982), and Stolzenbach et al. (1977). General reviews of the fate of hydrocarbons in the marine environment have been presented by Jordan and Payne (1980), Mackay (1985), NRC (1985), Payne and McNabb (1985), and Payne and Phillips (1985). The purpose of this section is to highlight the current state of the practice in the modeling of spreading and dispersion of oil. These two processes have been selected for review because they are closely tied to near-surface physical oceanographic processes (see Fig. 6). An NRC report on oil-spill dispersants also reviews oil-spill-fate modeling and the chemistry and physics of dispersed oil as well as the use of dispersants (NRC, 1989b).

Spreading

Spreading is one of the most important processes in oil-spill dynamics, because it determines the areal extent of spilled oil and affects the various weathering processes influenced by surface area, including evaporation, dissolution, dispersion, and photo-oxidation. Spreading has historically been considered to be controlled by the driving forces of gravity and surfacetension and the retarding forces of inertia and viscosity. Various researchers have investigated this process based on this conceptual model, and several methods are available for use in its modeling. Fay's (1971) three-regime spreading theory is the most widely used approach (Huang, 1983). Most other methods are variations of Fay's spreading theory, incorporating diffusion and dispersion, random Fickian diffusion, and the thick-thin slick approach (Mackay et al., 1980a).

These modifications are an attempt to account for observations that show that 80-90% of the total area of a slick consists of thin sheen and about 10% thick slick. Most of the oil, however, is observed to be in the thick slick (Huang, 1983). They also attempt to address the fact that turbulence at the sea surface can dominate spill spreading in the final spreading regime rather than the surface tension-viscous force balance employed by Fay (1971). None of these

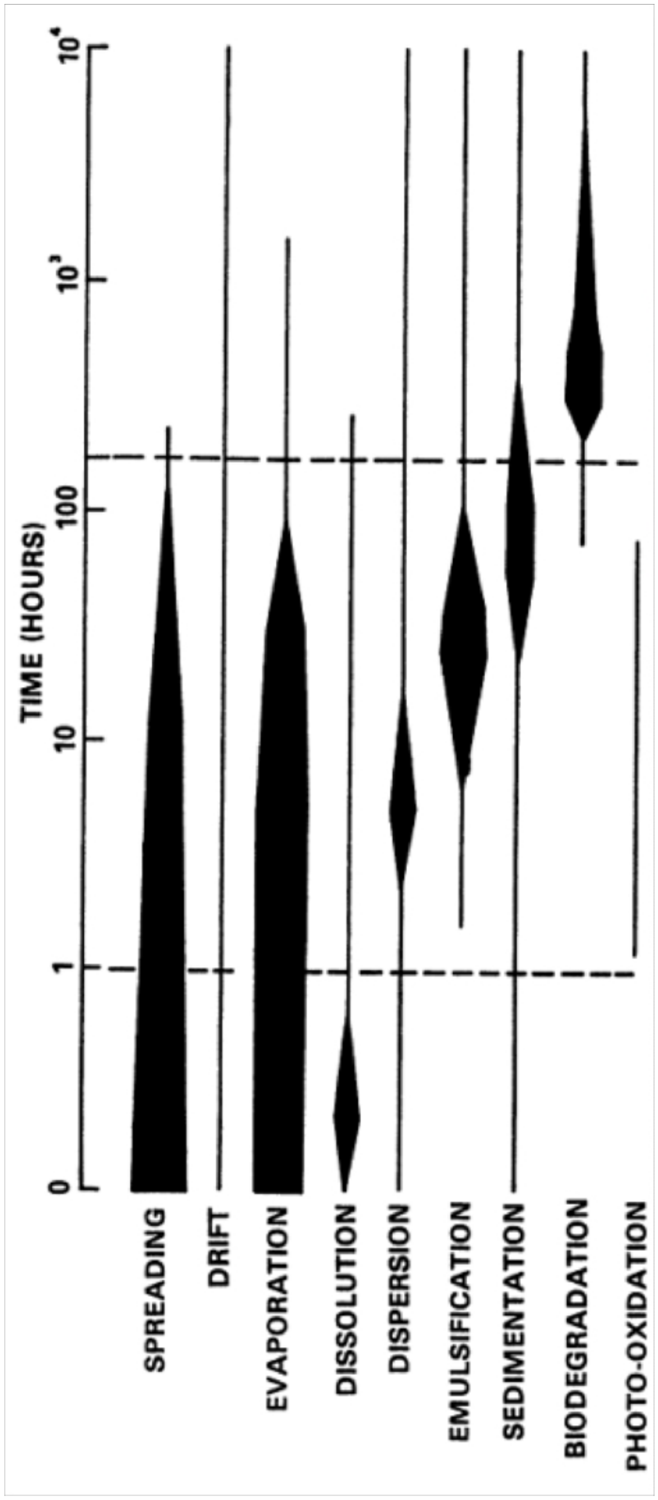

Figure 6
Fate of spilled oil.
Source: Koons, 1987. Reproduced by permission of the American Institute of Chemical Engineers.

techniques, however, addresses the inherent "patchiness" of actual spills or the thickening of spills near the leading edge.

One of the important recent developments in spill spreading is the work by Johansen (1982, 1983, 1985, 1987), Johansen and Audunson (1982), Elliott (1986), and Elliott et al. (1986). In their approach, oil is modeled as a distribution of droplets that are driven into the sea by breaking-wave events. Once in the water column, the droplets are advected and dispersed by the near-surface currents, where vertical shears are important. Most of the droplets, each with its own buoyancy, eventually resurface. Oil spreading is hence controlled by the droplet-size distribution and the shear-diffusion process. This model correctly predicts the occurrence of thicker oil toward the leading edge of a slick and the alignment and elongation of slicks in the direction of the wind. This technique will undoubtedly replace procedures based on Fay's theory. The percent of spill "patchiness," however, remains a problem that will require improved insight into near-surface transport processes before substantial progress can be made.

Dispersion

Dispersion is generally assumed to result from wind-generated breaking waves dispersing oil in the water column (Raj, 1977; Lin et al., 1978; Milgram et al., 1978). The simplest approach uses tabulations of dispersion as a function of sea state and time after the spill. Audunson (1979) suggested an empirical formulation based on the square of the wind speed, reflecting the amount of energy available for driving oil droplets into the water column. Reed (1980) and Spaulding et al. (1982) used a variation of Audunson's approach, including an exponential decay function, to account for weathering and mousse formation. According to this formulation, 99% of dissolution and dispersion is complete within the first few days after release of oil onto the sea surface. Mackay and Leinonen (1977) and Mackay et al. (1980b) formulated a two-stage dispersion process. The equations describing this process treat dispersion from thin and thick slicks separately, and agree qualitatively with observed behavior, but they have yet to be verified. Spaulding et al. (1982) proposed an approach that calculates the mass flux rate of oil into the water column by breaking-wave-induced turbulence, but the technique is not sufficiently developed for use in spill models. Aravamudan et al. (1982) developed a simplified but highly theoretical model of dispersion based on turbulence generated at the sea surface due to breaking waves. The approach has not been widely adopted because of its complexity and lack of validation.

Recently, Delvigne (1983; 1984a, b) completed a series of measurements of the dispersion of oil in the water column (below the breaking-wave zone) and developed a theoretical model (Delvigne et al., 1987) that was verified by laboratory data of the vertical dispersion coefficients for oil and oily, suspended particulate matter. However, the study did not address the dispersion caused by breaking waves.

Chemical dispersants applied on the surface of oil slicks can decrease the oil-water interfacial tension (NRC, 1989,b). This results in an increase in the oil surface area and the breakup of the slick into tiny droplets. These droplets may then disperse in the upper water column under the influence of natural turbulence and wave action. In some cases, depending on sea state and the type of dispersant used, additional mixing energy must be applied from a boat, as with a pressurized water spray. The concentration of oil droplets in the water column is highest near the surface and declines with depth. The depth and degree of dispersion will vary from case to case, depending primarily on sea state. Field tests conducted in moderate seas have detected dispersed oil at low concentrations (1-20 ppm) down to depths of 6-9 m shortly after dispersion. Oil on the sea surface will drift in response to wind and currents. Dispersion of oil into the water column isolates it from the effects of wind, and the dispersed oil plume will drift with the near-surface currents. Depending on specific conditions and the slick-drift forecasts, it may be tactically advantageous to disperse the oil to reduce wind effects.

SEA ICE

Ice Modeling

Several well-developed ice models are available for application to the Alaskan OCS waters (Rothrock, 1970; Kowalik and Untersteiner, 1978; Hibler, 1979; Pritchard, 1980; Kowalik, 1981, 1984; Thorndike and Colony, 1982; and Overland et al., 1984). Many are even integrated with hydrodynamic models for Alaskan waters. However a sense of how well these models actually perform in representing the range of ice conditions for the OCS areas is missing. Hence, a fully coupled ice/hydrodynamics model should be applied to selected areas and times for which data are available, and a detailed model-data comparison should be done. Chapter 4 includes more detailed suggestions for improving the modeling of ice movements.

Ice-Oil Interaction

Summaries of the fate and behavior of oil in the arctic environment are included in Walker (1975), Mackay (1984), Payne and McNabb (1985), Bobra and Fingas (1986), and Reed et al. (1986a, b). Ice conditions are highly influential in determining the movement and final disposition of spilled oil. In open water (10% ice cover or less), the primary processes affecting the oil are spreading, advection, and evaporation under calm conditions. In rough water, dispersion and emulsification also become important (Buist et al., 1983). Even at temperatures of 0°C, evaporation occurs, with estimates of up to 30% evaporation in 48 hours (Buist et al., 1983) and up to 40% evaporation over a 2-week period (Logan et al., 1975). Such weathering results in greater density of the remaining oil, which in turn causes increased thickness of the oil by increasing the viscosity. The low temperatures encountered in the Arctic further increase the viscosity and also increase the oil's equilibrium film thickness. Rosenegger (1975) reported a minimum equilibrium thickness of 0.0025 m for the spread of crude oil on the water surface. When oil temperatures drop below -9.5°C, oil gels and spreading due to surface forces cease to occur (Rosenegger, 1975). As oil spreads on the water surface, some of it is deposited on, in, and under ice with which it comes in contact. This oiled ice can be transported for a considerable distance before melting occurs and the oil is released. Under freezing conditions, ice forms beneath the oil slick. The oil remains as a film on the ice if conditions are calm, but surface-oiled pancake ice develops under rough conditions. The oil will most probably be covered by snow and will stabilize until the spring melt. Deterioration of the ice sheet in the spring releases most of the oil in first-year ice back into the water; the rest travels with the broken ice sheet (Logan et al., 1975).

In ice-infested waters (10-80% ice cover), the spreading and movement of oil are highly dependent on ice dynamics. The same processes described for open water are in effect. However, ice dominates advection and spreading by increasing surface drag and thereby reducing the velocity of wind-blown slicks. Furthermore, a medium-to-heavy concentration of ice tends to herd the oil, and the the oil's motion is constrained to follow the motion of ice, which moves more in response to surface currents than does the oil. The oil remaining on the water surface is restricted to leads and to areas between floes, where damming increases the oil thickness beyond that experienced in open water. Estimates of probable oil thickness range from 0.01 m (Walker, 1975) to several hundredths of a meter (Logan et al., 1975). The progressive opening and closing of leads and the continuous motion of the pack ice could transport the oil for long distances, leaving a path of oiled ice. Freezing sea water would incorporate the surface oil, and the entombed oil could then be transported up to hundreds of kilometers from the site of its release in an essentially unweathered state (Logan et al., 1975). These factors make it difficult to predict the extent of areal contamination. Oil incorporated into ice as the result of leads having frozen may eventually be deposited in newly formed ridges, because leads are areas of structural weakness and are, therefore, particularly susceptible to pressure ridging.

Oil spilled on the surface of solid ice (e.g., oil from a tanker spill) remains on the surface, with spreading due only to gravity. The surface roughness of the ice determines the extent of areal coverage, and an average oil thickness of 0.03 m is expected (Buist et al., 1983). The thickness of the slick and the low temperatures cause weathering to proceed very slowly. Eventual snow cover of the oil essentially halts weathering until spring and summer.

Oil spilled beneath solid ice (e.g., a well blowout) coalesces to form a slick between the ice and water. The underside contours of the ice determine the amount of oil that can be stored in the absence of currents. Irregularities on the bottom of sea ice occur on several characteristic scales. Under smooth ice, crude oil forms films of 0.005 to 0.01 m (Walker, 1975), and differential currents of 0.03 to 0.07 m/s are required to move the slick (Stringer and Weller, 1980). Bottom irregularities are important in containing oil under ice and limit the extent of its spread. Oil will collect in lenses a few meters across and up to a few centimeters thick (Walker, 1975) rather than in a continuous layer. Oil will remain in these undulations unless disturbed by an appreciable current along the ice bottom. Oil deposited under ice with a 0.01-m amplitude roughness requires a current of 0.25 m/s to initiate movement (Stringer and Weller, 1980). The presence of gas escaping with oil from an underwater release may increase the spread of oil under solid sheet ice, since buoyant gas bubbles will displace the oil from concavities (Logan et al., 1975).

From autumn through early spring, oil beneath the ice will become entombed in the growing sea ice within approximately a week, and thereafter will not weather appreciably. During this period, the buoyancy force of oil causes no significant penetration of oil into the ice from below. Large brine drainage channels in first-year ice offer the most likely means for the limited penetration that may occur. In the spring, as ice temperatures approach freezing and melting proceeds, the drainage channels open in first-year ice. The brine drainage structure of first-year ice probably provides the major pathway for the rapid upward migration of oil in the spring. From 70-80% of the entombed oil rises to the surface of the ice over a period of approximately I week (Walker, 1975). As the surface snow and ice melts, the oil covers the surface of melt pools, decreasing albedo and speeding melting. The oil may reach temperatures of 5 to 10°C (Walker, 1975), and rapid evaporation of the lighter fractions will occur. Once the ice has melted completely, the oil will reside on the sea surface, possibly being incorporated in a weathered state into the first-year ice of the next winter. Alternatively, such weathered residual oil may sink to the seafloor and become incorporated into the sediments.

In multiyear ice, similar processes are active, but the time scale is much longer. Oil most probably becomes entombed at greater depths, where the temperature increase in the spring is slower than in thinner ice. The surface layer of multiyear ice is essentially fresh and does not contain brine channels to facilitate oil movement. The upward migration of oil is therefore much slower, but oil should reach the surface within a maximum of 4 years (Walker, 1975). Once on the surface, its behavior is much like that described for oil on first-year ice, except that the ice will not necessarily melt sufficiently for the oil to return to the water surface.

Several researchers have attempted to quantify and predict some aspect of oil-ice interactions. Free et al. (1981) developed a set of empirical equations to describe the spreading of oil in a broken ice field. The properties of the spilled oil, the size and concentration of the ice field, and the velocity of currents and wind are required as input. The equations match data obtained from ice flume tests, but certain limitations were noted. Due to the method of data acquisition, the results are valid only for one-dimensional situations, and the empirical constants are possibly biased by scale and one-dimensionality effects. Furthermore, the equations are not general enough for application to all situations.

Rosenegger (1975) presented results of laboratory investigations of the flow of crude oil beneath sea ice. Functional expressions were developed that describe interfacial tensions between oil and brine at the brine and ice interface, and the force required to initiate motion of an oil bubble below an ice sheet. Equilibrium thicknesses of the two types of crude oil were determined. A separate study by Nelson and Allen (1981) examined the migration of oil through first-year sea ice and the effect of entrained oil on ice growth rates. Surface insulation of the ice sheet was found to induce upward oil migration by raising the ice sheet temperature and enlarging brine channels. Equations are presented that predict brine volume changes with temperature. The thermal conductivity of sea ice can be as much as 20 times greater than that of oil. Entrained oil can therefore be expected to greatly alter ice growth rates under the oil layer.

Evaporation of the lighter fractions Of oil under arctic conditions has been studied by several researchers. Laboratory studies reported by Tebeau et al. (1982) showed a well-defined quantitative relationship between the physical properties of oil and evaporative exposure levels, particularly when emulsification had not occurred. This study also noted a functional relationship between the rapid decrease in aqueous solubility of oil and increasing evaporative exposure. Weathering was also seen to decrease the oil-water interfacial tension, but no well-defined relationship could be found. Stiver et al. (1983) presented an analytical expression to describe the extent of evaporation as a function of evaporative exposure and a dimensionless air-oil partition coefficient.

The spreading and the evaporative and dispersive losses of oil in broken ice fields are poorly known at best. The consensus is that medium to heavy oils exhibit a herding effect and that the evaporative and dispersive losses decrease due to sheltering from the wind by the ice field (Cox and Schultz, 1981a,b; Free et al., 1981; Reimer, 1981; Ross and Dickens, 1987a). The behavior of oil under freezing and thawing conditions is just beginning to be studied with a view toward modeling (Wilson and Mackay, 1986). Recent work by Ross and Dickens (1987b) should also markedly improve the ability to model oil in leads.

Numerical Models Including Oil-Ice Interactions

Extension of spill models to handle oil-ice interactions has been extremely limited. Applied Science Associates, Inc. (1984) formulated a model based on the existing state of knowledge for arctic waters. The model addresses oil-ice interactions, including drifting, spreading, evaporation, emulsification, and dispersion for spills under ice and in ice-infested waters, but excludes freezing and thawing situations. Data on ice, temperature, wind, and current conditions are derived from available atlases (Brower et al., 1977; LaBelle et al., 1983) or model predictions. Wotherspoon and Swiss (1985) present an oil-ice interaction model but do not describe the theoretical or empirical formulations employed or the results from any simulations.

When oil is located under ice, researchers have a reasonable set of algorithms to describe its motion (advection), based on the work of Sayed and Abdelmour (1982), Uzuner et al. (1979), and Cox and Schultz (1981a,b), and to describe trapping in under-ice roughness elements (Kovacs, 1977, 1979). If oil is incorporated in a broken ice field, we know from Coon and Pritchard (1979), Reimer (1981), Allen (1983), and Thomas (1983) that the oil drifts with the ice. Belore and Buist (1988) have recently developed a detailed model for oil spills in snow that fills an important gap in our knowledge.

SEDIMENT TRANSPORT

Bottom Boundary Layer and Transport of Suspended Materials

Brink (1987) wrote:

> The surface and bottom boundary layers represent the areas where shelf waters absorb the wind and bottom stresses, respectively. These stresses are particularly important over the shelf, since they influence a relatively shallow ([about] 100 m) depth, water column. Further, since the turbulent layers themselves are typically 5-20 m thick, they often represent a substantial part of the shelf's volume. Thus, understanding the shelf in general requires a knowledge of boundary-layer processes within this environment.
>
> The study of the bottom boundary layer over the shelf has recently been strongly influenced by nonlinear models coupling [long] surface gravity waves (e.g., swell) with lower-frequency motions within the bottom boundary layer. Physically, a thin ([about] 0.05 m) near-bottom sublayer associated with both the waves and currents is generated, and it is an area of extremely active turbulence. The effect of this nonlinear coupling can ultimately be parameterized as an enhanced bottom roughness. Thus, the existence of [long] surface gravity waves will act to increase the bottom stress on lower-frequency flow patterns. Farther from the bottom, rotational effects become important and "Ekman spirals" such as those observed by Dickey and Van Leer (1984) are to be expected. The original simple models of wave-current coupling (Smith, 1977; Grant and Madsen, 1979) have since been extended to include the effects of stable ambient stratification, the earth's rotation, and self-stratification due to sediment suspension (Glenn and Grant, 1987). Accompanying these theoretical advances was the demonstration that the wave-current theories actually compare quite favorably with field observations (Grant et al., 1984). Further, accounting for wave-induced enhancement of bottom stress

> considerably improves the comparison between shelf-wide model results and observations (Brink et al., 1987a). A comprehensive review of bottom boundary-layer processes over the shelf can be found in Grant and Madsen (1986). While recent advances in boundary-layer modeling have been substantial, a good deal remains to be done in terms of field verification, subsequent refinement, and incorporation into larger scale circulation models. Bottom boundary-layer models need more testing in the field, because truly realistic environments simply cannot be created in the laboratory. Present boundary-layer models are [only one dimensional, while circulation models] need to average bottom stresses over larger areas (several kin) which may have very inhomogeneous microtopographies. Finally, more work needs to be done on the nearshore area where the surface and bottom boundary layers overlap. To date, only simple models (e.g., Mitchurn and Clarke, 1986) have been advanced. (Copyright 1987 by the American Geophysical Union.)

Knowledge of the general circulation and bottom-boundary flow conditions provides a basis for estimating the transport of suspended materials. However, with few exceptions, there appears to be a dearth of specific data on suspended matter concentrations in the water column collected in conjunction with ESP studies conducted in continental margin areas.

Bottom-boundary layer and sediment transport studies carried out as part of the ESP have been performed mainly by USGS scientists via a memorandum of understanding with MMS. These studies have been carried out in Alaska (see, e.g., Cacchione et al., 1982), on the Pacific coast (see, e.g., Drake et al., 1985; Cacchione et al., 1984), and on the Atlantic Coast (see, e.g., Butman and Noble, 1978; Butman et al., 1980). Similar work in the economically active and potentially active areas of the Gulf Coast has not been carried out.

Sediment Transport and The Effect of Oil

One significant fate of inputs of oil drilling fluids, or tailings, is deposition to sediments or incorporation into surface sediments (NRC, 1983, 1985). Incorporation of compounds from spilled oil or from oil compounds chronically discharged from coproduced waters into surface sediments may have effects on benthic organisms for months to years depending on the amount and type of oil and the type of benthic ecosystem (NRC, 1985; Boesch and Rabalais, 1987). Transport of the oil-contaminated sediment or the drilling mud and tailings is an important consideration in terms of the spreading of potentially harmful contaminants to a wider area or another area, and also in terms of spreading and dilution with cleaner sediment.

The transport of drilling muds and cuttings is most likely limited to the immediate vicinity of drilling activity for the coarse fraction, which makes up about 90% of the effluent (see, e.g., NRC, 1983). The fine, suspended fraction is carried further downstream by ambient currents and is rapidly dispersed; this dispersion is in agreement with both theoretical predictions and direct observations (NRC, 1983). In relatively quiescent environments, such as much of the deeper continental shelf and upper continental slope, the fine suspensate may settle out in detectable concentrations within several kilometers of transport during storms (EG&G, 1982; Neff, 1987). In more active environments, the fine fraction is often dispersed to less than detectable concentrations within a very short distance (NRC, 1983). Uncertainties still exist for low-energy, depositional environments that are exposed to repeated discharges over long periods of time, and for extremely sensitive environments (NRC, 1983).

Boundary-layer processes have significant influence on circulation in the continental margin areas and cannot be neglected in studies and models of circulation important to oil-spill fate considerations.

3

Regional Oceanography and Evaluation of The Regional Studies Programs and Washington Office Generic Studies Programs

INTRODUCTION

Primary responsibility for planning, organizing, and synthesizing data from site-specific ESP studies has rested with the four regional offices of the ESP. These offices cover the four main regions of the U.S. OCS (see Fig. 2): the Alaskan coast, the Pacific coast, the Gulf of Mexico, and the Atlantic coast, and are coordinated by BES in Washington, D.C. The ESP's internal division of responsibility alone justifies separate consideration of each regional program in this review. There are also, however, good geological and oceanographic reasons for considering the four U.S. margins independently.

Geologically, the separation of the various U.S. margins is founded on primary differences in the crustal structure of the earth. The basic processes of plate tectonics create several characteristic continental margin forms, which can be simplified into (1) broad shelf-slope-rise with large continental drainages, formed by passive spreading, and (2) narrow shelf-steep slope-marginal trough with steep local drainages, formed by active convergence. The Gulf Coast and Atlantic coast are variants of the passive form, whereas the Pacific coast is a convergent active form with two or three variations. The Bering Sea and Arctic Ocean margins are of the broad type, but glacial effects also have played a major role in modifying the inner portions of the continental shelf. Since the morphologies of the coastline and seafloor have a major influence on circulation in the coastal ocean, these geological differences lead directly to oceanographic differences. In addition, the U.S. margins differ significantly in their mass budgets of terrigenous sediment input and removal.

Oceanographic and climatological differences further distinguish the waters of the U.S. continental margins. For example, the first-order circulation of the surface ocean differs on the western and eastern sides of oceans, and ice clearly is more important in Alaskan waters than it is on the other U.S. margins. The net result of these geological, oceanographic, and climatological differences was stated succinctly by Allen et al. (1983): "In general, observations from geographically distinct continental shelves have shown that the nature of the flow may vary considerably from region to region. Although some characteristics, such as the response of currents to wind forcing, are common to many continental shelves, the relative importance of various physical processes in influencing the shelf flow field frequently is different."

This chapter briefly reviews the important physical oceanographic characteristics of each of the four major U.S. continental margins—the Alaska, Pacific, Gulf of Mexico, and Atlantic regions—and evaluates the adequacy and applicability of the ESP physical oceanographic studies carried out under the auspices of each regional office. In Alaska, much of the research was carried out by NOAA's Outer Continental Shelf Environmental Assessment Program under an interagency agreement with MMS. The WO is also evaluated.

The panel's criteria for evaluating a study's adequacy are described at the end of Chapter 1.

THE ALASKA REGION

The continental shelf off the coast of Alaska can be divided into three distinct subregions defined by the topography and bathymetry of the Alaskan coast. Approached from the southern coast clockwise around the Alaska Peninsula, these subregions are the Gulf of Alaska (Fig. 7), the Bering Sea (Fig. 8), and the Chukchi and Beaufort Sea in the Arctic (Fig. 9), which are further subdivided into planning areas (see Fig. 3). The meteorology and circulation of each of the subregions are discussed below, followed by a discussion of sea ice in Alaskan waters.

Meteorology and Circulation

Gulf of Alaska

The shelf in the Gulf of Alaska is in general broad, up to 200 km, and contains several deep troughs. Cook Inlet extends inland from the northern apex of the gulf. The northeastern shelf has two major islands (Kayak and Middleton), and to the west, Kodiak Island is midshelf. To the west of Kodiak Island, the Aleutian Islands form a leaky boundary between the North Pacific and the Bering Sea. The Shelf is quite deep, with depths in excess of 200 m within several kilometers of the mountainous coastline. Approximately 20% of the coastal region east of Cook Inlet is covered with glaciers. The only major river to empty onto the shelf is the Copper River, although the total freshwater input to the shelf is appreciable (Allen et al., 1983), equivalent to the flow of the Mississippi River.

Meteorology

The weather over the Gulf of Alaska has large seasonal variations in temperature, wind, pressure, and precipitation, all of which affect the ocean. Winter winds over the gulf result from strong cyclonic systems that tend to be trapped in the gulf. This leads to alongshore winds, onshore Ekman transport, and coastal downwelling. A weak high-pressure system replaces the Aleutian low in summer, which results in relaxation of the coastal winds and cessation of coastal downwelling (Royer, 1975). Adiabatic ascent of moist marine air over the coastal mountains due to trapped storms results in high precipitation rates and runoff in the coastal drainage areas. As much as 8 m/yr falls in the coastal mountains. Although its significance has generally been disregarded, this runoff is equivalent to the flow of the Mississippi River, with a peak in fall and a weak secondary peak in spring.

Circulation

Off the shelf on the east side of the Gulf of Alaska is the Alaska Current, which is wide (greater than 100 km) and flows at about 0.3 m/s. This current becomes the Alaska Stream as it turns toward the west-southwest off Kodiak Island. Here it narrows to less than 60 km, with speeds of 1 m/s (Royer, 1981). High-frequency variability is not typical of this system, although eddies have been observed, and the consequent flux of momentum into coastal waters has not yet been established.

The shelf circulation system, which is generally separated from the Alaska Stream and the Alaska Current by a midshelf "doldrum," is strongly influenced by freshwater input from the coast (Allen et al., 1983). Along the Kenai Peninsula, this flow is distinct narrow coastal current flowing westward with typical speeds of 0.2 m/s. However, currents can reach speeds as high as 1.5 m/s in the fall due to maximum freshwater discharge in September to October, resulting in surface salinities as low as 25 parts per thousand at the coast. This maximum current precedes the maximum winter winds by several months. An important role of the alongshore winds, which cause coastal downwelling, is to trap the fresh water along the coast even after being transported hundreds of kilometers from the source. These features are clearly seen in

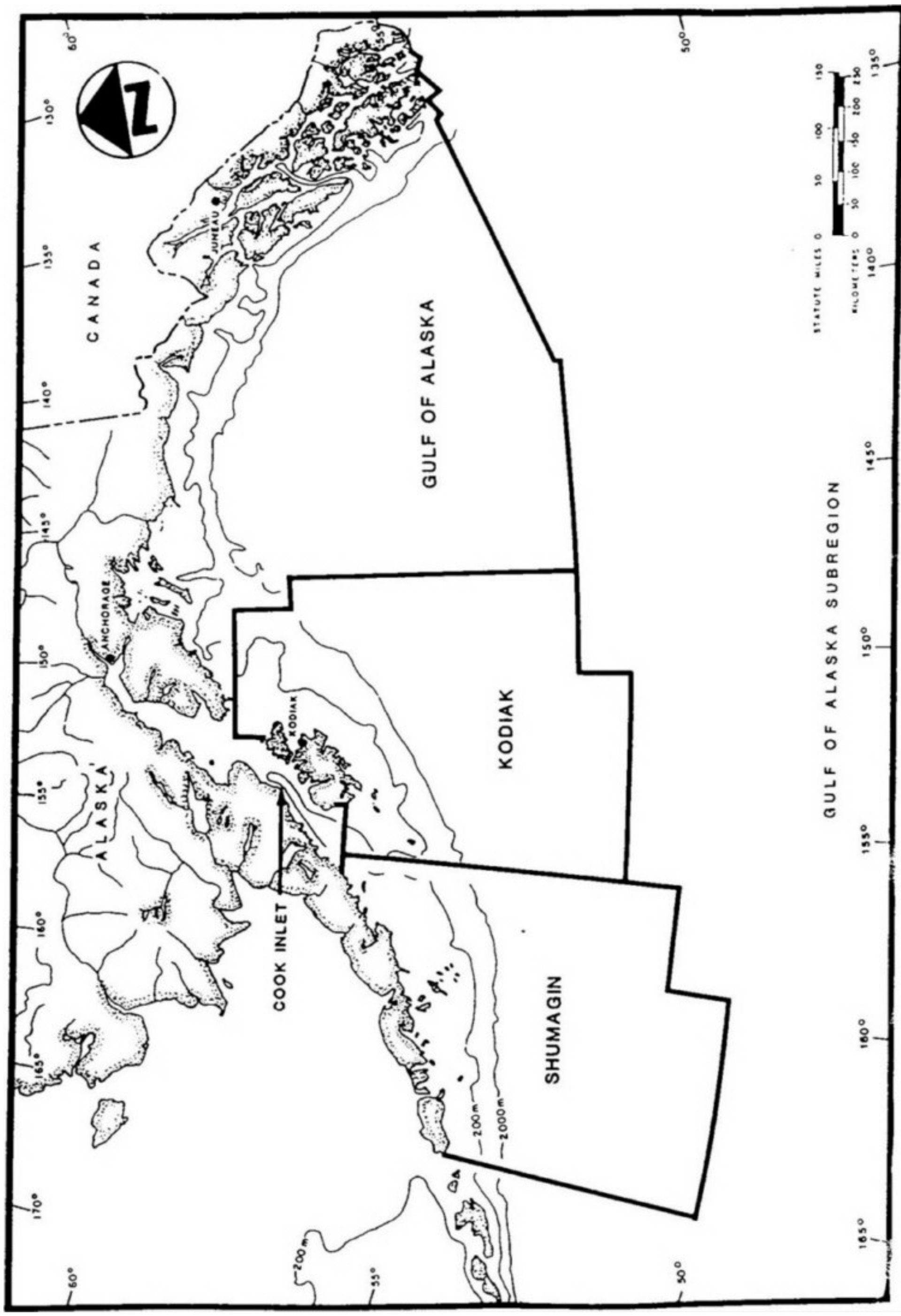

FIGURE 7 Gulf of Alaska subregion. Source: MMS.

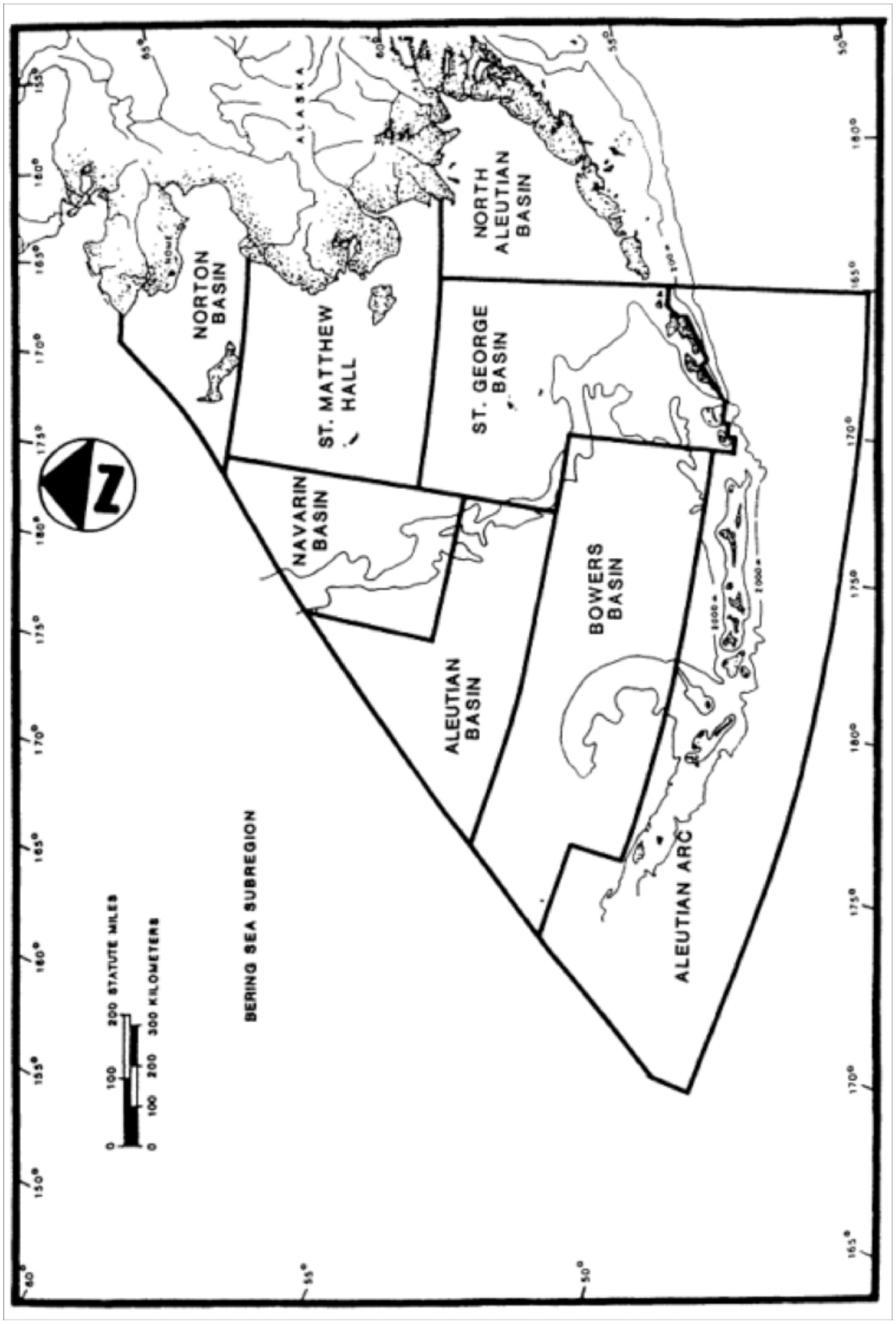

Figure 8
Bering Sea subregion.
Source: MMS.

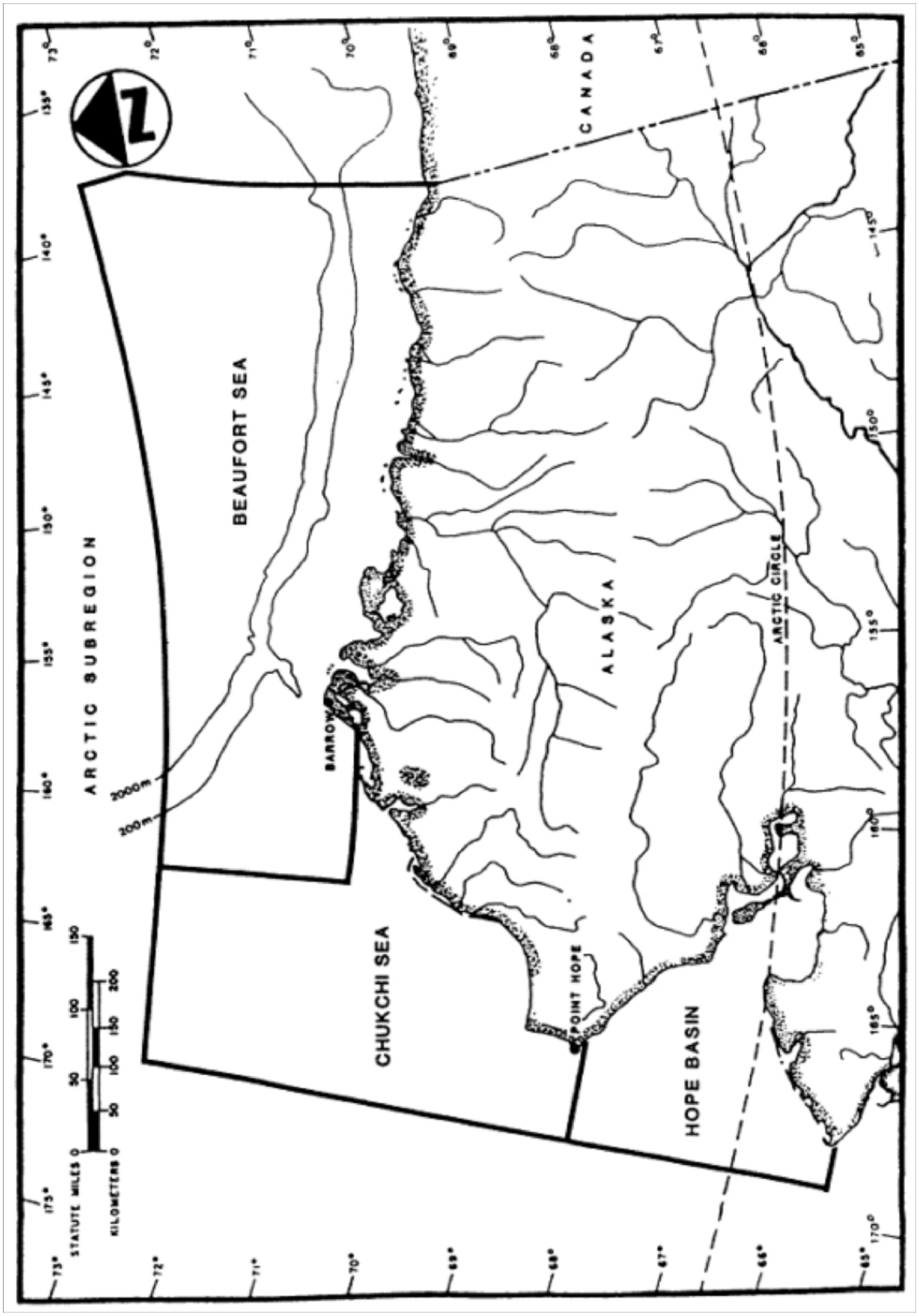

Figure 9
Arctic subregion.
Source: MMS.

seasonal sea-level cycles at various tide stations as the circulation responds to the seasonal wind stress.

The absence of the strong cyclonic wind field in summer permits relaxation of onshore Ekman transport and cessation of coastal downwelling. This allows the onshore intrusion of denser water over the continental shelf bottom. Renewal of bottom water in the fjords along the coast takes place by late summer (Muench and Heggie, 1978). This type of deep-water renewal is indicated by seabed drifter studies near Kodiak Island, where some drifters released near the shelf break have been found within local bays (Allen et al., 1983).

Measurements of currents in the northeastern Gulf of Alaska indicate that the flow tends to follow the shelf topography in the nearshore (Allen et al., 1983). With increasing distance offshore, the eddy kinetic energy increases as the Alaska Current is approached at the shelf break. However, in the western gulf, as the Alaska Stream is approached seaward, the mean energy of the current increases so that the relative eddy kinetic energy decreases. This suggests that eddies play a more important role in the northeastern gulf shelf-break region than in the northwestern part. The eddies embedded in the Alaska Stream and the Alaska Current appear to be transient. However, there is at least one permanent eddy in the downstream flow to the west of Kayak Island (Gait, 1976). This island plays an important role in deflecting part of the relatively fresh coastal current that recirculates behind Kayak Island and forms the permanent Kayak Island Eddy.

Satellite-tracked drifters released east of Kayak Island in 1976 meandered over the outer and midshelf regions before they slowly headed inshore and were caught up in the coastal current (Allen et al., 1983). They were then kicked back out onto the shelf by Kayak Island and made circuits in the Kayak Island Eddy. After the drifters exited the eddy, they entered Prince William Sound through Hinchinbrook Entrance (where tankers bring the Alaska Pipeline oil out for shipment elsewhere) and became stranded inside Prince William Sound. The flow continues out of Prince William Sound and around through Montague Strait to the west.

The circulation in Cook Inlet is strongly tidal, with a great deal of local variability due to coastal and topographic complexity. Cook Inlet is the only part of the Gulf of Alaska that is substantially affected by sea ice, although elsewhere floating ice near glaciers can be a navigational hazard, as the recent *Exxon Valdez* accident illustrates.

Interannual Variability

ENSO signals can be seen in the Gulf of Alaska in sea temperatures off Seward, especially deeper in the water column (Xiong and Royer, 1984). Strong interannual variability also occurs in the position and intensity of the Aleutian low, both as a result of interaction with ENSO and with the Pacific-North American weather pattern (Niebauer, 1988). Although the effects of these changes in the Aleutian low can clearly be seen in the Bering Sea, especially in ice cover, they are not as obvious in the Gulf of Alaska.

Bering Sea

The Bering Sea continental shelf is one of the widest in the world outside of the Arctic Ocean. It is 1200 km long and 500 km wide but is fairly shallow, with a shelf break at 170 m. Several large canyons indent the continental slope. Bristol Bay is located to the southeast, and Norton Sound is to the northeast. The Kuskokwim and Yukon rivers empty onto the eastern shelf. The Bering Sea shelf connects with the Arctic Ocean through the Bering Strait with about 1 sverdrup (Sv) flow toward the north (Allen et al., 1983). However, there are reversals in the flow that can last at least I week and are often associated with weather patterns. Unimak Pass is the only large pass from the Pacific onto the shelf, with transport of only about 0.15 Sv into the Bering Sea. Much of the remaining water required to balance the outflow through the Bering Strait comes through the deep water Aleutian passes west of the shelf and flows across the northern shelf south of Cape Navarin.

Meteorology

The Bering Sea shelf is characterized by strong variability, including interannual variability, due to its high latitude and to the great variability in weather. Insolation ranges from nearly continuous darkness in winter to nearly continuous light in summer. The wind torque varies by an order of magnitude from summer to winter. The shelf region is ice covered in winter, but the entire Bering Sea is ice free in summer.

Circulation

Tidal currents dominate the southeastern shelf region, varying from 60% of the horizontal kinetic energy in the outer shelf to 90% in the coastal domains (Kinder and Schumacher, 1981). About 80% of the tidal energy is semidiurnal. Farther north, the tides are less energetic. The M_2 constituents vary from 0.35 m/s along the Alaska Peninsula to about 0.03 m/s or less in Norton Sound. Mean flow over the shelf is described qualitatively by the dynamic topography, with some low-frequency pulses driven by weather systems.

From more than 20 record-years of direct current measurements on the southeast Bering Sea shelf, three mean and low-frequency current regimes have been identified. These regimes are nearly coincident with the previously described hydrographic domains. In the coastal domain, coastal water from the Gulf of Alaska flows through Unimak Pass and then northeastward along the Alaska Peninsula. The flow is counterclockwise in Bristol Bay and follows the 50-m isobath northward. Currents are strongest near the inner front and parallel the front at 0.01 to 0.06 m/s, with the highest speeds in winter. Although about 96% of fluctuating kinetic energy is dominated by tides, there are wind-driven events. However, the combination of baroclinic geostrophic currents with residual flow produced by the interaction of the tides with the bottom topography seems to account for the observed mean flow.

In the middle-shelf regime or domain that lies between the inner and middle fronts, there is little mean flow (~0.01 m/s) except near the fronts. There are wind-driven pulses corresponding to meteorological forcing at periods of 2 to 10 days that are similar in magnitude to those in the coastal domain. Due to the width of the shelf, no coasts are within a Rossby radius of deformation, so there is no coastal upwelling or downwelling, or any associated currents, in this regime. This lack of mean flow, along with the strong seasonal pycnocline, allows the retention of the cold bottom layer throughout the summer.

In the outer-shelf regime or domain, there is significant mean flow. The flow along the isobaths toward the northwest is 0.01 to 0.1 m/s and across the isobaths onshore toward the northeast is 0.01 to 0.05 m/s. Because the cross-shelf flow does not usually extend into the middle-shelf regime, the middle front is often a region of surface convergence, and advection is as important as diffusion in cross-shelf fluxes. This outer-shelf current regime has more kinetic energy at periods greater than 10 days than do the two inshore regimes, due probably to propagation of energy from the Bering Slope Current and associated eddies, although no eddies have been found up on the shelf.

The Bering Slope Current flows northwestward seaward of the shelf-break front at alongslope speeds of 0.05 to 0.15 m/s. This current parallels the shelf break, flowing from Unimak Pass to near Cape Navarin at a speed of 0. I m/s with a transport of about 5 Sv. The slope current is characterized by mesoscale eddies that appear to be formed and/or trapped by bottom topography, especially in the undersea canyons that are present in the slope. Eddies have been found not to propagate up onto the shelf.

Currents on the northern shelf are dominated by the northward flow into the Arctic, with temporary reversals caused by storms, particularly in winter (Kinder and Schumacher, 1981). The mean flow seems generally to parallel the isobaths, with currents moving at speeds of 0.1 to 0.25 m/s in the Bering Strait and east and west of St. Lawrence Island. In Norton Sound the flow is generally weak, although instantaneous wind-driven currents flowing at up to 1 m/s have been measured.

Interannual Variability

In the Bering Sea, in addition to the strong annual variability, extraordinary multiyear or interannual variability in ice cover, air and sea temperatures, and winds over the eastern Bering Sea shelf have been observed (see, e.g., Niebauer, 1988). For example, sea-surface temperature (SST) was 2 to 3°C below normal and winter ice-cover about 20% above normal in 1976. By 1979., SST was 2°C above normal and ice cover about 35% below normal. This resulted in an interannual ice-cover retreat of about 400 kin, or about 40% of the ice extent in the Bering Sea. These observations have led to a conceptual model in which variability in the winter atmospheric circulation, primarily the Aleutian low, appears to be the primary driving force behind the interannual variability in the eastern Bering Sea oceanic environment. This model implies that the interannual signal is not driven by the Bering Sea ocean circulation because of the sluggish mean flow on the shelf and because of the restricted flow through the Aleutian passes. In addition, the flow through the Bering Strait is mainly northward out of the Bering Sea. The variability in the Bering Sea occurs primarily in winter because of the interannual variability in the mean winter atmospheric circulation and because the Aleutian low essentially disappears in summer. Recently, this interannual variability has been linked to ENSO variability (Niebauer, 1988).

Hydrography

The immense width of the shelf tends to spread the various sources of energy (e.g., tides, wind, and fresh water) over a large area. Over the southeastern shelf the mean flow is low, of the order of 0.1 to 0.2 m/s toward the northwest. Most of the horizontal kinetic energy is tidal. Seaward of the shelf break, the Bering Slope Current flows at speeds of approximately 0.1 m/s, with frequent mesoscale eddies. The hydrographic structure on the shelf, which seems little influenced by the slow mean flow, tends to be formed by the boundary inputs from insolation, cooling, melting ice, freezing, and river runoff, as well as lateral exchange with bordering oceanic water masses.

Three distinct shelf hydrographic domains and an oceanic domain can be defined, delineated by water depths and separated by fronts that generally parallel the isobaths (see, e.g., Coachman, 1986):

1. The coastal domain, inshore of the 50-m isobath, is vertically homogeneous due to bottom tidal shear and surface wind shear overcoming the buoyancy input and mixing the water column from top to bottom. The coastal domain is separated from the middle domain or middle shelf by a narrow (10-km) front, called the inner front, where the tidally mixed bottom layer is separated from the wind-mixed surface layer as depth increases.
2. The middle domain or middle shelf, between the 50- and 100-m isobaths, tends to be strongly stratified and has a two-layered structure in summer due to the vertical separation of the tidal and wind mixing and due to seasonal buoyancy input (insolation and/or ice melt). In winter this region tends to be homogeneous due to strong winter storms and lack of buoyancy input. There is no significant advection, so heat content is determined by air-sea interaction. The salt flux required to maintain the relatively constant mean salinity is due to cross-shelf, tidally-driven diffusion. The middle shelf is separated from the adjacent outer domain or shelf by a weak front, called the middle front, located over the 100-m isobath.
3. The outer domain, located between the 100-m isobath and the shelf break, has surface (wind-mixed) and bottom (tidally mixed) layers above and below a stratified interior. Oceanic water tends to intrude landward along the bottom, whereas middle-shelf water extends seaward in the surface layers so that in the water column of the outer domain, vertical fluxes are enhanced. This interior region of enhanced vertical flux has pronounced fine structure due to the interleaving of sheets of warmer, but more saline, oceanic water intruding shoreward and cooler, less-saline water moving seaward. The interleaving occurs at vertical scales of 1 to 25 m.

The shelf-break front, which is manifested mainly in enhanced salinity gradients, separates the outer shelf from the Bering Slope Current water. This water is a mixture of Alaska Stream and Bering Sea water. The Alaska Stream water has its source in the Aleutian passes.

On the northern Bering shelf (approximately north of 62°N), including Norton Sound, there are three identifiable water masses (Coachman et al., 1975). The Gulf of Anadyr water is the most saline and 'lies west of St. Lawrence Island and on the west side of the Bering Strait. Alaskan coastal water lies along the Alaskan coast to the east. In between lies Bering Sea shelf water of intermediate salinity.

The Arctic Chukchi Sea and Bering Strait

The Bering Strait-northern Bering Sea-Chukchi Sea system water-mass characteristics and currents are dominated by the general northward flow (Coachman et al., 1975). The Bering Strait is only 85 km wide and is 30 to 50 m deep. Winds tend to be channeled north or south through the strait. The mean northward flow is due to the sea surface tilting downward toward the north and averages about I Sv. Reversals of about 1-week duration have been observed and are significantly correlated with atmospheric pressure gradients over this region.

Three water masses are squeezed through the strait from the Bering Sea. Definition of the water masses is based mainly on salinity. Water from the Gulf of Anadyr (actually 20% from the Gulf of Anadyr and 80% from the Bering Sea), which is the most saline (32.8 to 33.2 parts per thousand (ppt)), occurs on the west side. Bering shelf water, which comes around both sides of St. Lawrence Island and occupies the center of the strait, has salinities of 32.4 to 32.8 ppt. Alaskan coastal water occupies the eastern strait and has a salinity of 32 ppt. Temperatures are strongly seasonal but are typically cooler to the west (more oceanic water) and warmer to the east (more coastal water and freshwater runoff from the Yukon River).

There are strong current shears across the Bering Strait. The strongest currents are in the upper layers of the east side and can have speeds of more than **2 m/s**. Currents at lower-level speeds are half as strong. The flow on the western side is of the order of 0.5 to 0.6 m/s with little vertical shear.

The Chukchi Sea area widens quickly north of the Bering Strait, with Kotzebue Sound immediately to the east of the strait. The shelf is shallow (20 to 60 m), with Herald Shoal (20 to 30 m) about 200 km due north of the strait. Many of the capes and headlands in the region on the U.S. side are high mountains that tend to cause "corner effect" accelerations in winds along the coast (Kozo, 1984).

The three water masses that flow northward through the Bering Strait cross the Chukchi Sea enroute to the Arctic (Coachman et al., 1975). North of the strait, the Gulf of Anadyr water and Bering Sea water tend to combine and flow northward at 0.15 to 0.2 m/s, splitting around Herald Shoal so that some water goes straight into the Arctic Ocean through Hope Canyon and some turns eastward along the outer shelf of the Beaufort Sea. The Alaskan coastal water also flows along the Alaskan coast, gaining fresher, cooler water from Kotzebue Sound and flowing at speeds of 0.25 to 0.30 m/s along Point Hope, Cape Lisburne, and Icy Cape toward Barrow and the Beaufort Sea beyond. Water also "drains" from the Chukchi Sea through the Barrow Canyon into a layer 50 to 200 m deep in the Arctic Ocean.

The Arctic: Beaufort Sea

Meteorology

Winds are a major factor in the timing of ice freezing and ice breakup as well as storm and ice surges along the Arctic coast. They also create nearshore currents. However, along this coast there are subscale (subsynoptic surface-pressure grid) phenomena that are important to the shelf oceanography. Monsoon-type winds occur during the summer, caused by a semipermanent arctic front due to the thermal contrast along the coast (Kozo, 1984). Heating of the land causes a pressure deficit, leading to easterly coastal winds that are in quasi-geostrophic balance with the pressure gradient (Kozo, 1984).

The sea breeze is related to the monsoon. Along the Beaufort coast, sea breezes are characterized by large diurnal sea-land temperature contrasts, clockwise rotation of surface winds, and surface winds opposing offshore gradient winds (Kozo, 1984). At least 25% of the time, surface wind direction is dominated by sea breeze. The effects of these winds are the maintaining of coastal (up to 20 km from shore) currents toward the west that cause lagoon flushing, and a general masking of synoptic wind conditions in this first 20 kin. In addition, sea breezes along the Beaufort coast are not followed by land breezes, because the land stays warmer than the water, in part because the sun does not set in summer.

Circulation

The offshore portion of the Beaufort Sea is characterized by a mean westward flow of ice and water at the outer edge of the anticyclonic Beaufort gyre (Aagaard, 1984). Over the slope and shelf seaward of the 50-m isobath, the flow is eastward. This is called the Beaufort Undercurrent (Aagaard, 1984). The Beaufort Undercurrent is characterized by a temperature maximum associated with eastward flow originating in the Bering Sea. This flow seems to be trapped along the outer continental shelf and slope and centered at a depth of 40 to 50 m. Bering Sea water can be traced at least as far as Barter Island. Closer to the coast, local winds appear to dominate the ocean flow and drive it toward the west. This coastal flow appears to be primarily a summer phenomenon.

Different circulation regimes occur on the inner and outer shelf, and the 50-m isobath seems to be a boundary. The inner circulation is strongly wind-driven but is also highly seasonal and less energetic in winter. Outside the 50-m isobath, the circulation is consistent (about 0.1 m/s) throughout the year, topographically steered toward the east and not, apparently, locally driven. Near the inshore side of the Beaufort Undercurrent, frequent cross-shelf transport events are possible, with time scales of about 3 days.

Although currents and tides along the Arctic coast are relatively small, storm surges due to strong winds can cause considerable flooding (up to 1 km onshore).

Orography

The Brooks Range, some 250 km inland but parallel to the coast and with a mean height of 1.5 kin, has an effect on the winds over much of the Beaufort coast. Near Barter Island, orographic modification of the winds can cause wind speeds 50% greater than that of the geostrophic wind due to the "corner effect" (Kozo, 1984). This effect can be felt as much as 350 km away.

Mountain-barrier baroclinicity occurs when stable air moves toward and up a mountain without heating from below. This causes the isobaric and isothermal surfaces to tilt away from the mountain range, resulting in winds parallel to the axis of the mountain range. This is mainly a winter phenomenon and is a major reason for wintertime west-southwest winds between Barter Island and Prudhoe Bay. This results in a nearly 180° difference in wind direction when compared to the easterly winds at Barrow. Mountain-barrier baroclinicity depends on high surface albedo and so disappears in summer. This effect has a horizontal extent of 120 km and occurs about 25% of the time in the coastal zone from east of Barter Island to Prudhoe Bay.

In winter, temperature inversions are common in the Arctic. This results in strong surface stability, leading to diminished vertical turbulent exchange and hence to reduced wind stress on the surface.

Sea Ice in Alaskan Waters

Ice along the Alaskan coasts shows large seasonal and interannual variability (Niebauer, 1988). The seasonal cycle of ice cover in Alaskan waters is the largest of any of the arctic regions, averaging about 1,700 km in the north-south direction. Interannual variability in the Bering Sea is as high as 400 kin.

In general, the greatest northerly retreat of the ice occurs in September to October, when there is no ice in the Bering Sea and the ice has pulled away from the Arctic coast. At this time the ice can be as much as 250 km off Barrow. Under conditions of northerly winds, extensive pileup and run-up of ice onto the Arctic coast can occur (Weeks and Weller, 1984).

The maximum extent of ice in the Bering Sea generally occurs in April. Most of this ice is open pack ice that is driven by current and wind. Fast ice occurs in the Bering Sea in protected bays. In the Beaufort Sea, fast ice is more extensive due to the barrier islands and grounded pileups of sea ice.

Winter ice characteristics in the Bering Sea can be described by a "conveyor belt" analogy. Ice growth is primarily along south-facing coasts, where polynyas are created as the predominantly northerly winds advect the ice southward away from these ice-generation sites. The ice is pushed southward until it hits its thermodynamic limit and melts. The sea ice limit thus advances southward as melt water cools the upper layer, but probably moves no farther than the deep water at the shelf break.

Ice-drift rates are variable, with the Bering Sea rates being on the order of 20 to 50 km/d. In the Bering Strait speeds as high as 50 km/d have been observed. Although the direction of this flow is generally southward, strong northerly events have been observed, with ice passing northward through the Bering Strait before turning around and flowing back southward. In the Chukchi Sea, drift rates are lower (on the order of 0.4 to 4.8 kin/d) for mean annual drift, but rates as high as 7.4 km/d have been observed (Weeks and Weller, 1984).

In the Beaufort and Chukchi seas, offshore ice circulation generally follows the east to west anticyclonic ocean circulation, which is essentially parallel to the coast. Near the coast, fast ice does not move much, perhaps less than I km/yr (Weeks and Weller, 1984).

The thickness of undeformed sea ice increases toward the north, ranging from about 0.5 to 1 m in the open Bering Sea, to I m in Bristol Bay, to 2 m off the Arctic coast (Weeks and Weller, 1984). The Bering Sea ice is almost entirely first-year ice, whereas north of the Bering Strait, the ice is 25-75% second-year or older ice. The older ice is thicker, perhaps with a mean thickness of 4 m. However, deformed ice in pressure ridges has been observed with maximum keels of 50 m and sails of 13 m. These keels can cause appreciable gouging of the shelf when they become grounded. The ice over the arctic shelf is highly deformed, with up to 10 ridges per km due to shearing. Farther offshore, 2-3 ridges per km is more typical. There are fewer ridges in Bering Sea ice due to the free-floating nature of this ice.

Although relatively rare, ice islands composed of freshwater glacial ice are also found in the Arctic. They are tabular icebergs with typical thicknesses of tens of meters and lateral dimensions of up to 10 km (Weeks and Weller, 1984).

Interannual variability of ice cover can be quite large (Niebauer, 1988). In 1976 in the Bering Sea, ice cover was about 15-20% above normal. By 1979, the ice cover was about 15-20% below normal. The edge of the sea ice had retreated about 400 km over this period. Some of this variability has been related to E1 Niño events as well as to atmospheric variability in the North Pacific.

Evaluation of Mms-Funded Research in the Alaska Region

Synopsis

Gulf of Alaska

From the mid-1970s into the 1980s, data from nearly 130 current-meter moorings were collected on the Gulf of Alaska continental shelf supported by hundreds of current, temperature, and depth (CTD) profiles as well as water-pressure-gauge observations, drift cards, and a few Lagrangian drifter buoys. The impetus for this work was to provide a description of circulation in the Gulf of Alaska and a reference for circulation modeling as well as to connect nearshore and deeper-water circulations. Meteorological studies included placing temporary weather stations (approximately 7) supported by ship-borne airsonde observations as well as regular weather service observations. The impetus here was to provide a description of nearshore winds as an aid to prediction of oil-spill transport and to better define steering of winds by orographic effects as input to circulation and trajectory modeling.

Modeling efforts included analytic diagnostic modeling as well as three-dimensional, time-dependent, layered circulation models to predict circulation and provide oil-spill trajectories.

Bering Sea

In the Bering Sea (including, at times, the Chukchi Sea to the north through the Bering Strait), data from approximately 90 current-meter moorings and 2,000 stations measuring CTD along with various drift buoys, bottles, meteorological stations, and ice-drift buoy/stations were collected from the mid-1970s into the 1980s. Sea ice morphology, concentration, openings, and seasonal ice edges were also documented through the use of LANDSAT imagery. The declared impetus for these observations was to provide a description of circulation (including tidal), mixing processes, frontal structure, and ice movement in the Bering (and Chukchi) Sea as input to circulation and oil-spill-trajectory modeling. Additional information was sought to assist in prediction of oil movement at the marginal ice edge as well as spilled oil motion in sea ice.

The primary modeling efforts were three-dimensional, time-dependent, layered circulation models to predict circulation as well as to provide oil-spill trajectories. Work was also done on comparing modeled tidal currents to observed tidal currents as well as storm-surge prediction.

Arctic

In the Arctic Ocean (Chukchi and Beaufort seas as well as, at times, the Bering Sea), data from about 85 current-meter moorings and about 850 CTD stations along with tens of various drift buoys, meteorological stations, tide gauges, and ice drift buoy/stations were collected from the mid-1970s into the 1980s. Work was done using meteorological and satellite imagery of sea ice to look at seasonal and interannual variation in sea ice and fast ice. The drive for this work was to provide a description of the water masses and circulation of the region and to assist modeling the movement of ice and of oil in ice. Some of this work was aimed at understanding the circulation and flushing of arctic lagoons along the north coast of Alaska.

The primary modeling efforts were three-dimensional, time-dependent, layered circulation models to predict circulation as well as to provide oil-spill trajectories. Work was also done on comparing modeled tidal currents to observed tidal currents as well as storm surge prediction.

Sea Ice

Sea ice studies were conducted in the Bering, Beaufort, and Chukchi seas as well as on the edge of the arctic ice pack itself and in the coastal and fast ice zones. These studies included current-meter moorings, a few hundred CTD casts, satellite imagery, and ice drifting buoys. In addition, existing and archived meteorology as well as satellite and ice-drift data were used, and laboratory studies were conducted. Much of the research was done both to understand and to try to predict ice movement and circulation as well as to try to understand how oil interacts with and moves with ice. In situ measurements of the mechanical properties of sea ice were also made.

Evaluation of Observational Studies

The overall quality of physical oceanographic work, including studies of the atmosphere and ice, done so far in the Alaska region under OCSEAP seems sound based on the relatively large amount of the work that has been reviewed and published in the open literature for a region that is so large, varied, and variable. Some of the Alaska OCSEAP work has been bolstered by other programs (e.g., Processes and Resources of the Bering Sea Shelf (PROBES), Inner Shelf Transport and Recycling (ISHTAR), and Gulf of Alaska Recirculation Study (GARS)). In addition, the physical oceanographic knowledge and information that was gained under these programs in the Gulf of Alaska seem to have been borne out during the tracking along the Alaskan coast of the oil spilled from the *Exxon Valdez* (Jayko and Spaulding, 1989).

The panel notes that the circulation of Prince William Sound has not been well studied. Although MMS's responsibility is for the OCS, it is reasonable to expect, and the panel recommends that MMS know about critical nearshore areas, such as Prince William Sound. Such areas could be affected by OCS activities, and the OSRA requires this information to predict hits reasonably. Increased attention should be focused in the offshore areas of the Beaufort and Chukchi seas, because the background data are sparse. Exploration is taking place there, and it will be difficult to determine the path and fate of the oil spilled, especially in winter, when that whole region is ice-covered.

Little research has been done on interannual variability in the oceanic, atmospheric, and ice environment of Alaska. There is significant interannual variability in Alaskan waters, for example in the Gulf of Alaska (Xiong and Royer, 1984) and in the Bering Sea (Niebauer, 1988). For example, the maximum seasonal advance of sea ice in the Bering Sea decreased about 400 km between 1976 and 1979. This is about 40% of the average seasonal ice extent. Sea-surface temperature, wind direction, and air temperatures showed' similar variations and seem to be related to North Pacific atmospheric variability as well as ENSO variability.

The Bering Sea slope circulation also has not been addressed very much under OCSEAP. In addition, eddies in this current system have not been observed moving up onto the shelf, but it is not clear if this is always true, or if this current system and associated eddies impact lease sites. Eddies are ubiquitous in most oceanic regions, and it is unknown if the Bering Sea region is that different.

Near Barter Island, orographic effects cause wind speeds 50% greater than the synoptic or geostrophic winds, and these winds can be felt as much as 350 km away (Kozo, 1984). This type of phenomenon needs to be considered in field and modeling studies of the circulation off the north coast of Alaska as well as in the Gulf of Alaska.

Evaluation of Modeling Studies

OCSEAP modeling of Alaskan waters concerned the ocean circulation as affected by winds, tides, density gradients, ice, and large-scale boundary conditions, such as sea-surface slope. The modeling also concerned oil-spill trajectories.

The 1977-1985 modeling program (Liu and Leendertse, 1987) considered tides, wind input, density-induced flows, wind-induced flows, and sea ice. Tides were emphasized. In some cases, the model did not cover enough of the regions so that some important physical oceanographic features were not modeled (e.g., the Bering Slope Current). Comparison with actual data was not quantitative in most cases, with the exception of tides. The model and results were not published in the refereed literature.

Since 1985, the models of the Alaskan region have been using more realistic driving forces such as Fleet Numerical Oceanographic Center (FNOC) winds, which represent actual varying conditions (Spaulding et al., 1987) better than the technique used by Liu and Leendertse (1987), a series of transitions between certain states of the weather. Data-assimilation techniques have also been used recently (e.g., the Navy/NOAA Joint Ice Center ice observations). It also appears that much more quantitative comparison with field data has been done as well as more statistically valid oil-trajectory studies (compare, e.g., Liu and Leendertse (1987) and Spaulding et al. (1988a,b).

However, there are still not enough data sets available to fully verify the current models, especially in the Chukchi and Beaufort seas. This is especially true as regards surface circulation. In addition, few data sets are available for the Bering Slope region as well as the area of the Alaska Stream in the Gulf of Alaska.

No matter how good the models are, unpredictable variability always will exist. This is especially true with respect to winds, which are probably the primary drivers of oil in water. Thus, the models should be treated as guides, and the EISs should take into account the unpredictability of the real world.

There is a great deal of interannual variability in Alaskan waters that probably has not been taken into account in the simulations. For example, there have not been "anti-E1 Niños" (now called "La Niña" or "El Viejo") since the mid-1970s (Niebauer and Day, 1989) until one in the winter of 1988-1989. In the Bering Sea, El Niño causes "warm" conditions while La Niña causes "cold" conditions, often with expanded ice cover. The drivers of these conditions in the Bering Sea are the Aleutian low in concert with the southern oscillation. Another source of interannual variability is the Pacific-North American pattern of weather over the North Pacific. The present method of modeling the circulation takes the interannual variability into account but only to the extent that the FNOC winds represent the atmospheric circulation. This data set is apparently limited to the past 10-12 years, and thus covers only one La Niña, but does cover the three El Niños that have occurred since the mid-1970s.

The stated impetus for many of the observational studies in the Alaska Region was to provide observational data for input to modeling, and this did occur (see, e.g., Gait, 1976; Spaulding et al., 1987). However, many of the observations were not input to the model. The modeling in the Alaska Region is different from that in the other regions in that the modeling and oil-spill trajectories were done by the same contractor in Alaska (as opposed to having the trajectories calculated by MMS based on circulation modeling results from a contractor, as in the other OCS regions).

THE PACIFIC REGION

The Pacific Region (see Figs. 10 and 11) is characterized by a narrow continental shelf. Freshwater input to the shelf generally increases from south to north. Currents are variable, with the seasonal variability increasing to the north.

Meteorology and Circulation

Mean and Seasonal Winds

Mean and seasonal winds are dominated by the seasonal migration of the North Pacific High and the passage of Aleutian lows during winter. North of about 40°N, the wind direction varies seasonally from a northerly or northwesterly direction in the summer to southerly in the winter. In the northern regions, the winter regime is stronger and lasts for a greater portion of the year than does the summer one, whereas the reverse is true in the south. Further south, the seasonal cycle is still strong, but the monthly mean wind does not reverse direction.

Hickey (1979) has given an estimate of the amplitude of wind-stress fluctuations as a function of month and latitude, based on Bakun's upwelling indices (Bakun, 1975). South of and at 36°N (Point Conception), the variance is greatest in the spring (generally in April), except at 24°N; north of 36°N the variance is greatest during the stormy winter months (in December north of Cape Mendocino and in January at 39°N). The largest amplitude of the seasonal fluctuation of the variance and the largest variance are observed at 48°N.

The largest variance during spring and summer occurs near 39°N (Cape Mendocino), where maximum southward stress is observed. The variance during those months generally decreases both north and south of this latitude, with a more rapid rate of decrease to the south. Hence, the variance off Baja California for a given month is always less than that off Oregon and Washington, except during August. During spring and early summer, the variance between these

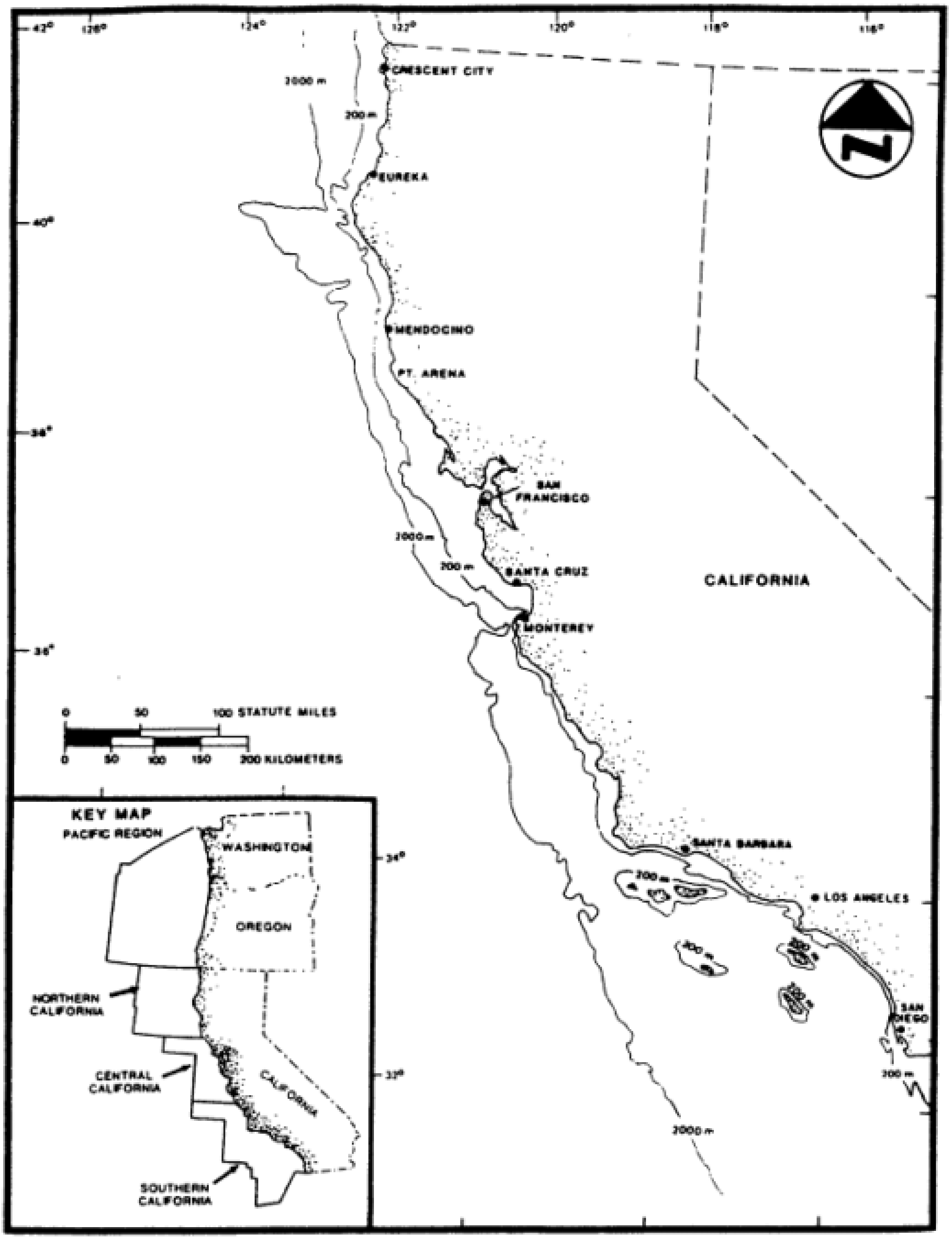

Figure 10
Southern, central, and northern California planning areas of the Pacific region.
Source: MMS.

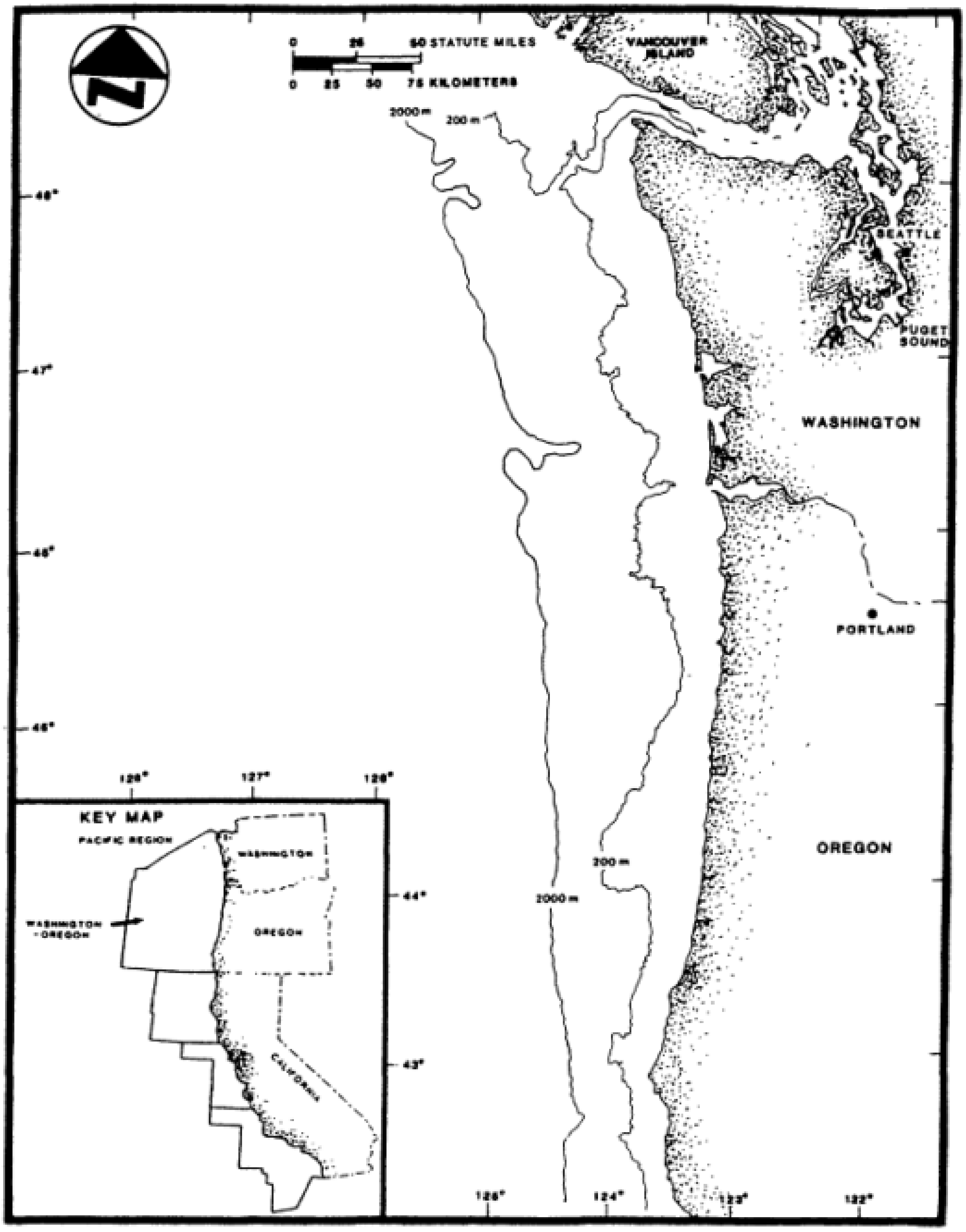

Figure 11
Washington-Oregon planning area of the Pacific region.
Source: MMS.

two areas can differ by as much as a factor of 2. Although maximum southward wind stress occurs during July and August off Oregon and Washington, maximum variance during the period of mean monthly southward stress occurs during May at those latitudes.

Hickey (1979), in discussing the variability of the wind stress off the U.S. West Coast, wrote:

> Although southward wind stress begins to increase in February at most latitudes, the rate of increase is not uniform alongshore. South of 28·N (Punta Eugenia), the maximum increase occurs from March to April and maximum southward stress is observed in April, whereas at 47·N, the maximum increase occurs from May to June and the maximum southward stress expands both offshore and alongshore as the maximum stress advances northward, so that during June and July, when the northerly wind system is most strongly developed, southward stress exceeds 1 dyne/cm^2 in a region 500 km offshore by 1000 km alongshore. Maximum southward wind stress is generally observed 200-300 km offshore, rather than adjacent to the coast.
>
> The magnitude of the southward wind stress begins to weaken in May south of 27·N and in August at most other locations, and the region of strongest stress moves southward to a location south of Point Conception (36·N) by December or January. Weakest southward wind stress is observed in August south of 25·N and in the winter months at all other locations along the coast. As the summer wind system weakens, the northerly winds are replaced by the southwesterly winter wind system, from northern Washington in September to Cape Mendocino by November. During December and January when the southwesterly wind system is most strongly developed, the alongshore maximum in northward wind stress is most often observed at about one degree of longitude off the coast. As distance offshore increases, the wind stress is more eastward and less northward, but the magnitude is relatively constant. During March and April, when the southwesterly system is weakening, the wind stress is almost entirely eastward off Washington and Oregon, except right at the coast.
>
> Substantial year-to-year variations in mean monthly wind stress can occur, so that in any given year, mean monthly stress can even oppose the long-term stress direction, particularly in regions where the long-term value of wind stress indicates light winds. Bakun (1975) has tabulated daily values of "upwelling indices" which are equal to the alongshore component of the wind stress near the coast divided by the Coriolis parameter. The indices are computed from six-hourly synoptic maps of surface atmospheric pressure. Whereas Nelson's (1977) long-term data show that mean monthly wind stress south of 40·N along the coast is always southward, Bakun's data for seven years (1967-1973) show that mean monthly wind stress was northward at 36·N during January of 1968, 1969, 1970 and 1973, December of 1968 and February of 1973; and at 33·N during January of 1968 and 1972, and December of 1967.
>
> Superimposed on seasonal fluctuations in winds are higher frequency events that have time scales of a few days (Bakun, 1975). Although such events generally result in an amplitude variation of the mean seasonal northward or southward wind stress, reversals in direction sometimes occur, so that, for example, off Oregon, northward stress events often occur during winter. The number of reversals in direction at these higher frequencies is a function of the alongshore location relative to the position of the seasonal high and low in atmospheric pressure; that is, although southward stress events can occur during winter at any latitude, the frequency of such events increases towards the south, so that south of 36·N they represent the norm rather than an anomaly. Northward wind stress events during summer are relatively rare south of 45·N, although they become more common in late summer south of Baja California (21·N). (Reprinted with permission from Progr. Oceanogr. Volume 8, B.M. Hickey, The California Current system: Hypotheses and Facts, copyright 1979, Pergamon Press.)

The statistical properties of the coastal winds were demonstrated further by Halliwell and Allen's (1987) study of the coastal wind field along the west coast of North America for two summers, 1981 and 1982, and the intervening winter using measured winds and geostrophic winds calculated from the FNOC atmospheric pressure analyses. Halliwell and Allen found that:

> Summer wind fluctuations are driven primarily by the interaction between two relatively stationary pressure systems, the North Pacific subtropical high and the southwest U.S. thermal low, and by their interactions with propagating atmospheric systems to the north. In particular, propagating cyclones and associated fronts are often followed by a northeastward intensification of the high, producing strong upwelling events along the California coast. This summer event sequence occurred more frequently and was displaced farther to the south on average during summer 1981. Winter wind fluctuations are primarily driven by the propagating cyclones and anticyclones, and they tend to have larger variance and space scales than in summer. A preference for poleward (equatorward) propagation exists in summer (winter), and the largest time scales were observed in

> summer 1982. Coastal atmospheric boundary-layer processes substantially modify winds within 100.200 km of the coast. Consequently, measured wind fluctuations are strongly polarized in the alongshore direction and have means and rms amplitudes that can vary considerably between nearby stations along the coast. Calculated wind fluctuations are less polarized in the alongshore direction and have alongshore correlation scales about 60% larger than those for measured winds. They represent fluctuations with alongshore wavelengths of ≥900 km rather well but represent poorly those with smaller wavelengths and those due to coastal atmospheric boundary-layer effects. (Copyright 1987 by the American Geophysical Union.)

Strub et al. (1987b) concluded that

> the seasonal cycles of measured wind stress confirm that the magnitude of the seasonal cycle is maximum around 40·N and that annual mean winds change from northward at latitudes north of 40·N to southward at latitudes south of 40·N. At some latitudes south of 38·N a semiannual signal is seen in the seasonal cycles of measured wind stress but not in those of the calculated wind stress. Because of the limited length of the directly measured wind data, the presence of a semiannual signal in alongshore wind stress in the south must be taken as a tentative finding. (Copyright 1987 by the American Geophysical Union.)

Circulation

Much information exists on the seasonal currents and property distributions driven by the wind and runoff cycles over the shelf along the West Coast (Hickey, 1979; Huyer, 1983; Strub et al., 1987a,b; Hickey, 1988), with the exception of the nearshore (depths less than 60 m) areas of the Pacific Northwest.

The Columbia and Fraser rivers introduce appreciable amounts of fresh water into the ocean, affecting the stratification on the shelf. The rivers of northern California and San Francisco Bay have a small but noticeable effect.

At midshelf along the Pacific Northwest, the mean seasonal current is primarily alongshore: northward at all depths in the winter, southward at all depths in the spring, and southward at the surface but weak or northward near the bottom in summer. Fall is a time of gradual transition as the surface flow reverses to go north and the isopycnals become horizontal. Similar behavior occurs at the shelf break, but with the currents enhanced. Further south the spring-summer southward flow diminishes in magnitude and duration, with the surface flow at 35°N exhibiting southward flow for only two spring months. The alongshore flow is well correlated with local coastal sea level in accordance with geostrophy. The seasonal variations in alongshore components of wind and currents also are well correlated, although the wind and current may be opposed because of an annual mean current unrelated to local wind.

Writing on the alongshore coastal currents north of Point Conception, Strub et al. (1987b) concluded that the best present picture of alongshore coastal currents describes roughly three regimes between 35°N and 48°N and that:

> (1) From 45·N to 48·N, north of the maximum seasonal wind stress signal, the seasonal cycles of currents (midsheff at 45·N and shelf break at 48·N) reach their greatest magnitudes. These currents are southward with baroclinic shear in spring and summer and northward and more barotropic in the fall and winter. The observations of Freeland et al. (1984) suggest that currents over midsheff at 48·N are weakly northward in summer. The seasonal cycles account for a large proportion (30% to over 50%) of the variance in these currents. The annual mean current in the middle of the water column is southward, opposing the annual mean wind. Superimposed on these regular seasonal cycles are short-period (periods less than 1 month) fluctuations that are weaker in summer and stronger in fall and winter.
>
> (2) In a mid-latitude regime, from 39·N to 43·N, where the seasonal cycle of wind stress is greatest, the seasonal cycles of currents are qualitatively similar to those found to the north but are dominated by the shorter-period fluctuations. In this regime the seasonal cycles account for only 10% to 20% of the variances. At 43·N the shorter-period fluctuations decrease in magnitude in the summer, as they do farther north, but at 39N they are strong during most of the year. This suggests a geographic transition zone between 43·N and 45·N, from a shelf dominated by... shorter-period fluctuations south of 43·N to one dominated by smoother seasonal cycles at 45·N. The dynamics of this

transition remain to be explained. In the middle-latitude regime in summer, strong barotropic fluctuations are superimposed on the mean baroclinically sheared southward flow; in winter, strong baroclinic fluctuations are superimposed on the mean barotropic northward flow. The annual mean currents over midshelf are weakly northward, whereas over the shelf break at 43·N they are weakly southward at 35 m and are northward deeper in the water column.

(3) In the south around 35·N the annual mean currents are northward, in opposition to the annual mean wind. The period of sheared, southward currents over the shelf is limited to 1-3 months in spring. During the rest of the year a fluctuating but northward (monthly mean) current exists. The seasonal cycles account for only 10% to 20% of the variances in the alongshore currents, as they do from 39·N to 43·N. The seasonal mean northward current appears (from hydrography) to extend over the slope and may have a semiannual nature, with peaks in early summer and early winter, similar to those found by Chelton (1984) in the undercurrent farther offshore at the same latitude. These peaks are roughly coincident with periods of relaxation seen in the measured winds.

> Temperature and sea level seasonal cycles have their greatest magnitudes in the middle latitudes (39·N to 45·N) Both drop suddenly in spring, especially at 39·N, and increase suddenly in fall, especially at 43N. These transitions decrease in the far north (48·N) and south (35·N), as do the seasonal cycles themselves. Temperatures have less short-period variability, and their seasonal cycles account for 30% to 80% of their variances, while sea level cycles account for 30% to 50% of their variances.
>
> The seasonal cycles of alongshore currents lead those of adjusted sea-level (ASL) slightly, and both lead those of the wind and temperature by 1-2 months, confirming results of Hickey (1979) and Chelton (1984), who lacked simultaneous directly measured currents. An approximate 2-month lag between the summer regime in the south and in the north is seen in all variables. This lag has been documented previously in sea level (Enfield and Allen, 1980), calculated wind stress (Bakun, 1973, 1975), and climatological wind stress data from ship reports (Nelson, 1977). (Copyright 1987 by the American Geophysical Union.)

El Niño-Southern Oscillations and Interannual Variations

Knowledge about interannual variations has been obtained from observations of sea level and coastal temperatures. Most of the variation, occurring south of Oregon, can be attributed to the ENSO events in the tropical Pacific (Enfield and Allen, 1980; Chelton and Davis, 1982). These increases in sea level propagate up the coast from the equator with speeds less than the low-mode coastal-trapped wave celerity. Off Oregon, the 1982 El Niño increase in sea level and temperature followed that at the equator by about I month (Huyer and Smith, 1985). The interconnections between the coastal, oceanic, and atmospheric responses are not well known at present.

Upwelling and Associated Events

Brink (1987) has written a concise review of wind-driven coastal upwelling and associated features on the U.S. West Coast. He stated:

> The process of wind-driven coastal upwelling is particularly important off the west coast of the United States. This is so because the winds are predominantly equatorward (upwelling-favorable) throughout the summer over most of the Pacific coast. Since upwelling introduces nutrients to the euphotic zone, the process is of interest as well to biological oceanographers and fisheries scientists. Over the last decade, interest has focused increasingly on the three-dimensional aspects of upwelling, with added attention to alongshore and temporal variability in the more traditionally studied cross-shelf and vertical structure.
>
> The upwelling season off the Northwestern United States generally commences with a single, dramatic shift to seasonally permanent upwelling-favorable winds. The event, called the spring transition, is part of a global scale shift in circulation patterns (see, e.g., Lentz, 1987) and is most pronounced north of about 37·N (Strub et al., 1987a). The oceanic response to the wind shift consists of the onset of upwelling, formation of an upwelling front, a drop in coastal sea level and a decrease in stratification over the shelf (Lentz, 1987; Strub et al., 1987a). South of about 37·N, the spring transition is less abrupt (Strub et al., 1987a) and appears to be accompanied by comparably slow changes in subsurface hydrography (Brink et al., 1984). On a shelf-wide scale, the heat balance near

> 38N is essentially two-dimensional, with near-surface offshore advection of warm water and onshore advection of deeper, colder water Lentz, 1987). Strub et al. (1987a) present a large-scale composite of the transition event which suggests that coastal-trapped wave physics tend to affect strongly the detailed oceanic response. For example, the maximum change in coastal sea level occurs north of where the winds are strongest. The detailed character and timing of the spring transition vary from year to year (Strub et al., 1987a), with the most extreme oceanic responses tending to occur after El Niño events (Breaker and Mooers, 1986).
> After the spring transition, an upwelling front usually exists over the outer shelf near 38·N (Huyer, 1984). At 36·N, on the other hand, Breaker and Mooers (1986) report a tendency for the frontal location to continue moving offshore during the entire spring and summer. At both locations, the average frontal locations tend to parallel the local isobaths and/or coastline (Kelly, 1985; Breaker and Mooers, 1986). Drifter measurements near upwelling fronts often suggest convergence (Davis, 1985a; Barth and Brink, 1987), but really solid evidence is generally lacking. The fronts also appear to be sharpest during weak winds (Davis, 1985a). During the occasional cessations of upwelling-favorable winds near 38N, the front tends to remain stationary (i.e., not retreat toward the coast), and the nearsurface warming nearshore is dominated by alongshore advection (Send et al., 1987). This advection appears particularly effective because of the propensity of shelf currents in the region to flow poleward unless strongly opposed by equatorward winds (Winant et al., 1987). (Copyright 1987 by the American Geophysical Union.)

The variously called jets, squirts, and filaments of the California Current system are quite important for shelf-ocean exchange and are currently under intensive investigation (see Fig. 12). Capes or major discontinuities in shelf depth tend to be locations that initiate these features, but their dynamics and the importance of topographic interactions are as yet poorly understood. They currently appear to be associated with the coastal upwelling process. These features are discussed in greater detail in Chapter 2, in text also quoted from Brink (1987). Brink (1987) concludes his remarked on these phenomena with the statement:

> Much more work has yet to be done on the dynamics of filaments off the U.S. West Coast. Indeed, a major field study on this subject (the Coastal Transition Zone program funded by the Office of Naval Research, Coastal Sciences and Oceanic Biology Sections) was carried out during 1987 and 1988. Perhaps the most pressing problems to be addressed include the dynamical origins of the features, the extent to which they exist in other areas of the world (and in other seasons), and how they dissipate and mix their properties into ambient oceanic waters. (Copyright 1987 by the American Geophysical Union.)

Internal Waves

Internal tide beams have been observed off the shelf of Washington with current amplitudes comparable to or slightly larger than typical low-frequency onshore velocities. The shear in these currents could possibly enhance vertical mixing, particularly near the shelf break where they are generated.

High-frequency internal waves are commonly found propagating shoreward over the southern California shelf during spring and summer. These waves can transport shoreward surface-floating material that is caught in the resulting surface convergences.

Bottom Boundary Layer

A review of boundary-layer processes is available in Grant and Madsen (1986). The nonlinear bottom-stress law yields a mean or low-frequency bottom-stress variation that depends on the existing surface gravity waves as well as the motion of interest. Numerical modeling will need to take this variation into account.

Topographic Effects-Canyons and Capes

Submarine canyons affect the flow above them depending on their scale and the stratification of the overlying water. The bottom flow over the shelf tends to be diverted along

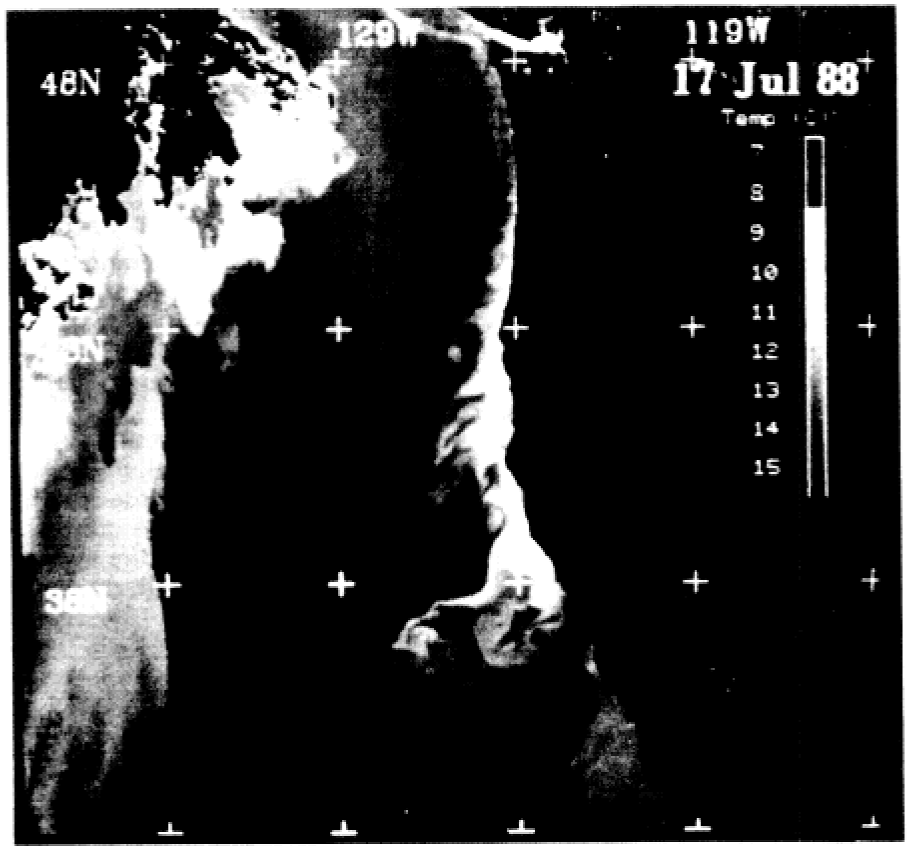

Figure 12
Jets, squirts, and eddies off the California coast.
Source: Mark Abbott and Ted Strub. Used by permission.

the isobaths to conserve vorticity. The penetration of this effect into the interior occurs with a vertical scale H ` fLN, where f is the Coriolis parameter, L is the horizontal scale of the canyon, and N is the Brunt-Väisälä frequency. Recirculation may occur at locations where the canyon depth is greater than any depth occurring in the adjacent shelf.

Capes or major discontinuities in shelf depth tend to be locations that initiate features such as eddies, meanders, and squirts that enhance cross-shelf advection. Recent results indicate that high velocities are found along the maximum-density gradient edges of the squirts, much like the behavior of a large-amplitude, small-wavelength meander. However, topographic effects and the dynamics of squirts and jets have not been well described to date.

Modeling

Several numerical models are available whose results are quite dependent on input and boundary assumptions. Quantitative comparisons of observed currents with predictions for the complete West Coast are nonexistent. Predictions over short reaches have been made based on appropriate boundary conditions being specified on the relevant geostrophic contours. However, it is not clear whether the model can be considered to be predictive or to be acting merely as a reasonable data-assimilation and interpolation scheme.

Use of coastal-trapped-wave theory provides qualitative agreement for alongshore components of velocity for frequencies that are not influenced by turbulent exchanges of momentum, heat, and salt or by surface heating and cooling. However, the magnitudes of the velocities are consistently predicted to be lower than those observed. The cross-shelf component of velocity is difficult to predict, possibly because of its dependence on the shorter alongshore scales, but possibly for other reasons as well. A recent paper by Pares-Sierra and O'Brien (1989) shows promise in using numerical models to predict current velocities in the upper ocean near the coast. It is possible that a new procedure proposed by Clarke and Lopez (1987), which treats higher modes as locally generated and includes remote forcing for only the lowest-order modes, will improve model results.

Evaluation of Mms-Funded Research in the Pacific Region

History of Mms-Funded Research in the Pacific Region

Modern process-oriented shelf circulation studies, carried out in the late 1960s and in the 1970s primarily by investigators from Oregon State University and the University of Washington with funding from the National Science Foundation and the Department of Energy, led to a major improvement in the understanding of the dynamics of wind-driven currents and their associated effects over the continental shelf of Oregon and Washington. More recently, oceanographic studies supported by MMS, ONR, and NSF have focused on the shelf and adjacent waters of California. These studies have included some of the most intensive field programs carried out to date for the purpose of providing detailed information on the dynamics of this region.

MMS began its research on the West Coast with a circulation model for the entire domain. Subsequently, MMS has been methodically working its way up the West Coast with oceanographic measurement programs. Two studies have been completed, one is in progress, and at least three contracts are being negotiated at the present time. These studies are listed in Appendix C.

The California Shelf Circulation Model is based on a well-known general circulation model (Blumberg and Mellor, 1983). The model is the same three-dimensional, time-dependent model that has been used in the Gulf of Mexico, the mid-Atlantic and south Atlantic bights, and the Santa Barbara Channel. The model incorporates turbulent mixing via turbulent closure techniques; it includes wind and density forcing and tides. It can be run in diagnostic and prognostic modes. Climatological density fields were obtained and were used to initialize the general circulation model. A vorticity-conserving model (the characteristic tracing model, or CTM) is used to prescribe open-ocean boundary conditions, in an area from 20°N to 50°N and from 110°W to 135°W. The model was used to simulate currents for a year-long period in 1981, during which the CODE experiment took place. The California Shelf Circulation Model was successfully completed in 1985. A final report was submitted, but no refereed papers have been prepared.

The Santa Barbara Channel project involved a combined modeling and observational effort. The same general circulation model was used; however, boundary conditions were specified by current meters (~16 moorings) instead of CTM. Observations also included CTD, drifter, and satellite studies. A pilot field program preceded the main program. This project has been completed, and one refereed journal article has appeared from the pilot program. No refereed articles based on the main program or on the model-observation comparisons have appeared to date.

The Central California Circulation Study was a purely observational program off central California involving 11 moorings, seasonal CTD surveys, and drifter studies conducted over 18 months. Problems occurred with mooring design, current-meter design, fishing, and vandalism. MMS did not accept the draft final report and requested changes, saying that the analysis of the data was preliminary and inadequate (Sigurd Larson, MMS Pacific Regional Office, pers. comm., March 16, 1989). The contractor asked for more money to complete the original and additional, more specific tasks, and effectively stopped work on the project for 9 months pending the outcome of negotiations. The original objectives seem to have been stated in rather broad, general terms. According to one of the subcontractors, the project seemed to be funded inadequately to achieve the original objectives. Furthermore, the company that was responsible for the instrumentation problems is no longer in business (A.W. Bratkovich, personal communication, March 21, 1989). Two papers have been published based on the study (Chelton et al., 1987; 1988). More journal articles are forthcoming, including one based on the observation of the actual behavior of oil that happened to be spilled while the array of instruments was in place, and an overview that was requested by MMS (A.W. Bratkovich, personal communication, March 21, 1989).

The Northern California Circulation Study is an observational study similar in scope to that done off central California. The pilot program occurred in 1987. A data report was published in September, 1988 (Magnell et al., 1988).

The Oregon-Washington Coastal Circulation Project involves assessing what data are available in this area and whether additional experiments are necessary. The contract for this project had not been awarded as of March 1990. The report of the statistical characterization project, which involves analyses of all available data on West Coast circulation patterns, is due to be released in July 1990.

A contract for modeling the circulation of the southern California bight is still under negotiation. The same general circulation model used in other California modeling studies will be applied to the whole California bight and the results compared with available data for the Santa Barbara Channel and for the Santa Monica-San Pedro basin and shelf area.

Evaluation of Observational Studies

To date, the contributions by the West Coast programs to state-of-the-art knowledge, as measured by the number of refereed publications, have not been impressive; only one refereed journal article has appeared as a result of the Santa Barbara Channel program, and the lead author on that paper (Brink and Muench, 1986) was not funded by MMS but by NSF through the Organization of Persistent Upwelling Structures (OPUS) program. Moreover, that paper addressed only the approximately 3-month pilot program rather than the year-long study. Even though MMS has increased the available data base by an order of magnitude, the potential return from these experiments has not yet been realized.

Evaluation Of Modeling Studies

The modeling work, if published, could make a contribution by illustrating the inadequacies of a state-of-the-art numerical model, that is, identified deficiencies can provide important clues as to the physics and processes that might still need to be incorporated into the model. To date, the modelers have not performed careful statistical comparisons between the model and the observations. They usually stop short of coherence and phase calculations, percentage of variance explained, and so on, even in their unpublished "gray literature" reports to MMS.

The quality of the modeling work has remained constant, because the same model and group have been used in each study. This model generally is perceived as one of the few state-of-the-art numerical circulation models currently available. Nevertheless, the California modeling studies have had serious inadequacies that are reported in the reviewers' comments on the final reports (Allen et al., 1985; Brink et al., 1957b). For example, the flow predicted by the California Current model is more equatorward than is the flow actually observed; also, the mass field used for the model is inappropriate because it was not the actual mass field that would have been in equilibrium with surface fluxes of heat and momentum in 1981. Predicted current amplitudes are smaller by at least a factor of two than those observed in the Santa Barbara Channel, probably because of the way the contractor filtered the boundary conditions.

Given the above reported inadequacies, the Physical Oceanography Panel believes that MMS puts too much faith in the results of modeling studies. This reduces, both directly and indirectly, the quality of its efforts to predict the fate and trajectory of oil spills. In most cases, at the present time, it would be preferable to use observed rather than modeled statistics. However, the emphasis on modeling has detracted from the ability to obtain high-quality observations. In the Santa Barbara Channel program, for example, the model requirements and resource limitations meant that all but three current-meter moorings were placed along a boundary (at the channel ends or between the islands). Thus, a good observational description of the interior How was not obtained, and worse, model-observation comparison could be performed only at one interior site.

THE GULF OF MEXICO REGION

The Gulf of Mexico is a semi-enclosed sea that is bounded to the north by the southern United States; to the south by Mexico, the Yucatan Peninsula, and Cuba; to the west by Mexico; and to the east by Florida. The Gulf of Mexico opens to the Caribbean Sea through the Yucatan Strait, between the Yucatan Peninsula and Cuba, and to the Atlantic Ocean through the Straits of Florida, between Cuba and Florida. Sill depths at the two straits are approximately 1,400 m and 800 m, respectively. Water from the Caribbean enters the Gulf of Mexico through the Yucatan Strait and exits to the Atlantic Ocean through the Straits of Florida. The maximum depths in the Gulf of Mexico are around 4,000 m and occur in the central portion of the basin. The continental shelf of the Gulf of Mexico is broadest along the west coast of Florida and along the northern portion of the Yucatan Peninsula (Campeche Bank). The narrowest portion of the shelf is found along the east coast of Mexico and south of the Mississippi River delta. For MMS planning purposes the Gulf of Mexico is divided into the three subregions: the eastern Gulf of Mexico subregion (Fig. 13) and the western and central Gulf of Mexico subregions (Fig. 14).

Several rivers empty into the Gulf of Mexico, the largest of which is the Mississippi River. Along the fringes of the Gulf of Mexico are numerous marshes and estuaries. Also, portions of the gulf coast consist of barrier islands, bays, and lagoons, all of which are influenced by circulation processes that occur on the adjacent continental shelf.

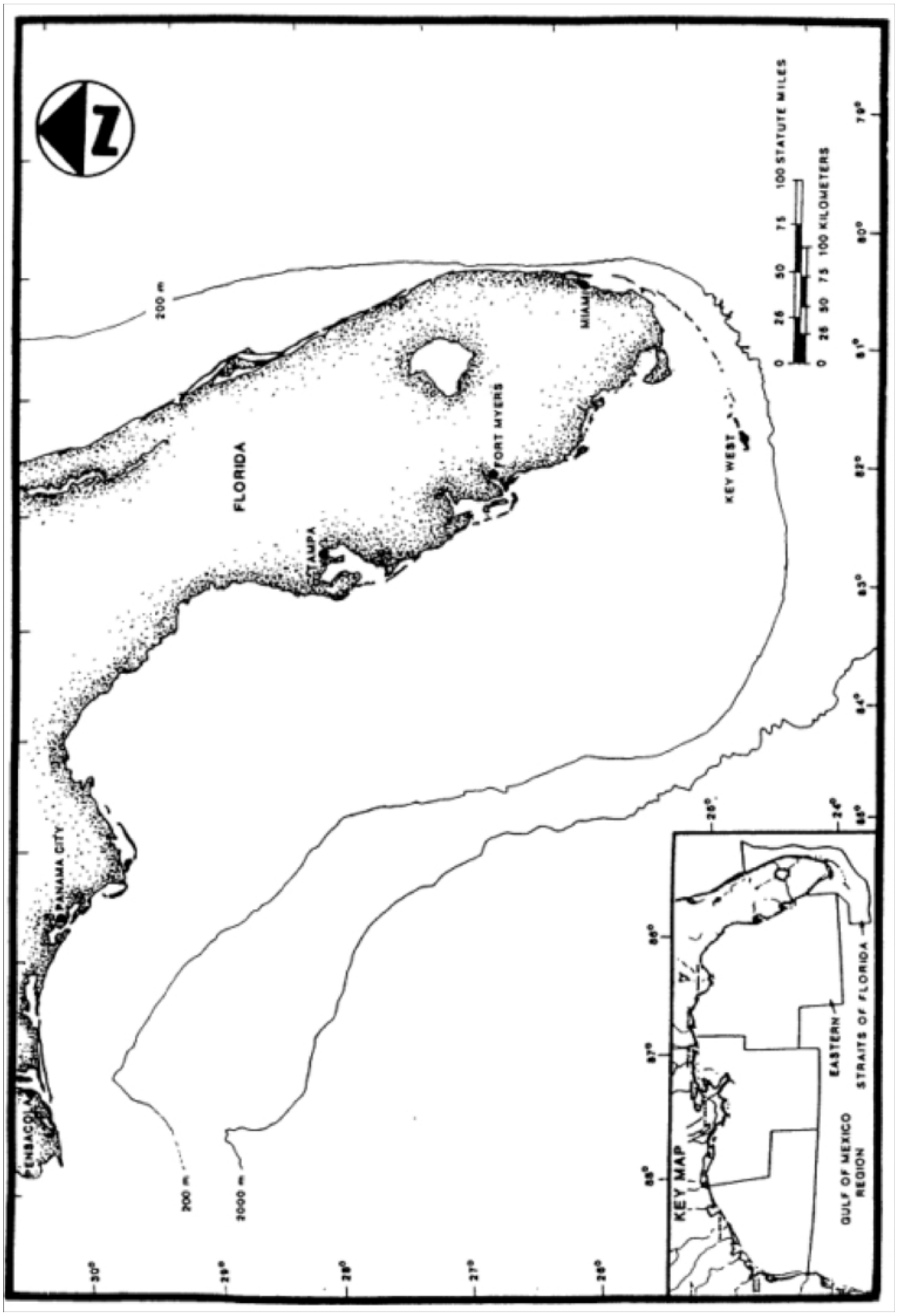

Figure 13
Eastern Gulf of Mexico and Straits of Florida planning areas in the Gulf of Mexico region.
Source: MMS

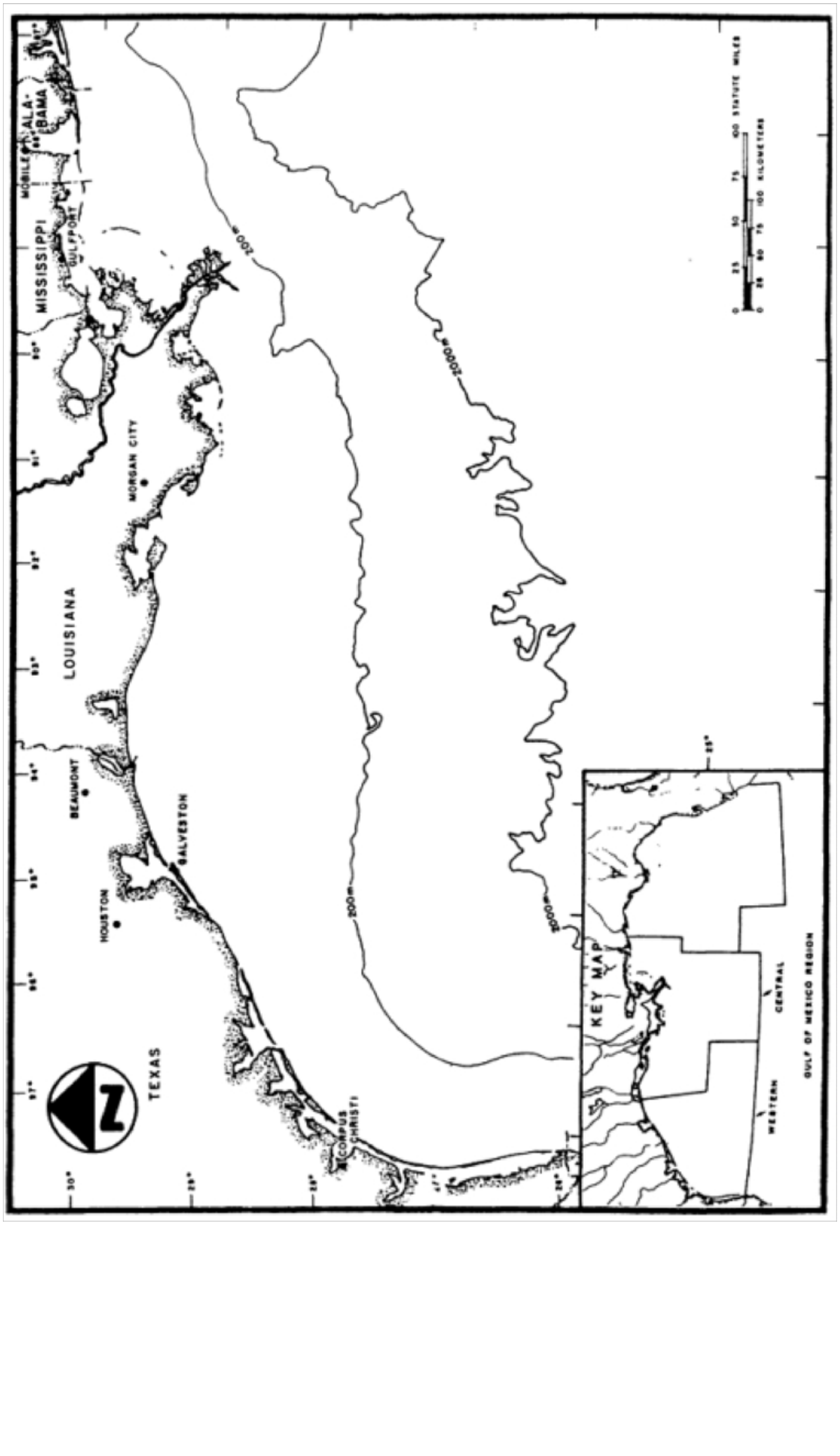

Figure 14
Central and western planning areas in the Gulf of Mexico region.
Source: MMS.

Meteorology and Circulation

Meteorology

Surface winds over the Gulf of Mexico exhibit seasonal changes in magnitude and direction. Winter winds are predominantly from the east-northeast, spring winds from the southeast, summer winds from the south-southeast, and fall winds from the east-northeast. Winter winds are typically the strongest. The seasonal change in the winds over the gulf is in response to seasonal migrations of the Azores-Bermuda high-pressure cell that dominates the atmospheric circulation over the Caribbean and Gulf of Mexico. Low-pressure weather systems that move out into the gulf from the continental United States have a large effect on the winter wind patterns. These systems usually occur every 3-10 days.

The atmospheric systems that have the most dramatic effect on the wind patterns over the Gulf of Mexico are the intense tropical cyclones (hurricanes) that occur in this region between May and October. The effects of these storms on land as well as on nearshore and coastal regions of the gulf have been well documented. The most recent ElS for lease sales in the Gulf of Mexico (U.S. DOI, 1987d) lists several instances in which hurricanes have caused the destruction of OCS platforms and breakage of pipelines.

These storms can also have an effect on the large-scale circulation of the gulf. Brooks (1983) described the current oscillations that were caused by Hurricane Allen as it moved across the western Gulf of Mexico. Also, upwelling is known to occur in the wake of hurricanes. This can result in large heat exchanges and in the introduction of nutrients into the euphotic zone, which can stimulate biological production.

Circulation

General Circulation Features

The large-scale water-mass distribution in the Gulf of Mexico reflects the limited exchange the gulf basin has with the adjacent oceans. In general, the gulf waters consist of three distinct water masses: subtropical underwater, antarctic intermediate water, and North Atlantic deep water. The subtropical underwater enters the gulf from the Caribbean at depths of 200 to 500 m and is found throughout the eastern portion of the gulf. This water is readily recognized by its high salinity, >37.00 ppt. Antarctic intermediate water also enters the gulf through the Yucatan Strait and is found throughout the gulf between depths of 500 to 1,200 m (in the eastern gulf) and 600 to 800 m (in the western gulf). This water mass is recognized by a distinct minimum, <34.00 ppt, in salinity. North Atlantic deep water is found below 1,200 to 1,400 m throughout the Gulf of Mexico. McLellan and Nowlin (1963) suggested that waters deeper than 1,500 m in the Gulf of Mexico have long residence times (300-500 years) and are not frequently exchanged with outside waters. Hydrographic observations indicate that additional water masses—gulf water, for example—are formed locally in the Gulf of Mexico during periods of intense winter cooling.

Numerous studies (see, e.g., Nowlin and McLellan, 1967; Molinari et al., 1978; Hofmann and Worley, 1986) have shown that the general large-scale circulation in the upper 1,400 m of the Gulf of Mexico is anticyclonic (clockwise). The transport in the northern limb of the anticyclonic gyre is a combination of flow from the Texas shelf and from the southern portion of the gyre. The contribution from the Texas shelf can at times be as high as one-third of the total transport of the easterly flow in this limb of the gyre (Molinari et al., 1978). The westerly flow in the southern part of the anticyclonic gyre is composed predominantly of water recirculating in the southern gulf, although at times water separating from the Loop Current can contribute to this transport (Molinari et al., 1978; Hofmann and Worley, 1986). Average geostrophic velocities and volume transports associated with the large-scale anticyclonic circulation of the Gulf of Mexico are 10 cm/s and 5 x $10^6 m^3/s$ (Hofmann and Worley, 1986). Additionally, large-scale cyclonic (counterclockwise) circulation gyres are found in the Bay of Campeche and over the northern portion of the west Florida shelf (Nowlin and McLellan, 1967; Molinari et al., 1978; Hofmann and Worley, 1986).

Major Circulation Features

Superimposed upon the large-scale circulation of the gulf are two major circulation features, the Loop Current and Loop Current rings. Both of these have considerable influence on the circulation characteristics of the Gulf of Mexico. *Loop Current*. The Loop Current is a swift, narrow current that enters the Gulf of Mexico through the Yucatan Strait. This current can be traced as a coherent feature that extends into the northern portion of the eastern gulf, where it turns to the east and then flows southward along the west Florida shelf. At the southern extent of the Florida shelf, the Loop Current again turns east and exits the Gulf of Mexico through the Straits of Florida. The Loop Current is part of a larger circulation system that feeds into the Gulf Stream along the eastern boundary of the United States.

The Loop Current can be readily distinguished in vertical-density distributions down to depths of 1,000 to 1,200 m in the region where it enters the Gulf of Mexico (Morrison and Nowlin, 1977). Surface geostrophic velocities into the gulf associated with the Loop Current have been estimated to be 100 to 150 cm/s and the corresponding volume transport has been estimated to be 25 to 35 x 10^6 m^3/s. Surface velocities diminish somewhat as the Loop Current extends into the gulf and widens. Outflow surface velocities of the Loop Current are on the order of 50 to 100 cm/s and the corresponding volume transport is the same, approximately 25 to 35 x 10^6 m^3/s. It should be noted that the sill depth of the Straits of Florida is shallower than that of the Yucatan Strait. Hence, part of the inward-directed flow of the Loop Current through the Yucatan Strait does not flow out through the Straits of Florida, but rather is deflected back into the gulf. It has been suggested that there is a recirculation of Loop Current water in the region north of Cuba.

The extent of penetration of the Loop Current into the Gulf of Mexico has been studied extensively. At times the Loop Current has been observed to extend northward into the gulf as far as the Louisiana and west Florida continental shelves (Huh et al., 1981). A seasonal cycle in the depth of penetration of the Loop Current northward into the gulf is well documented (see, e.g., Leipper, 1970; Maul, 1977; Behringer et al., 1977). Increased penetration of the Loop Current has been observed in winter and spring, with the maximum northward extension occurring in early summer. However, Vukovich (1988a) has found ring separation that is not periodic. It has been suggested (Maul, 1977) that inflow at the Yucatan Strait must exceed outflow through the Straits of Florida in the upper 500 m in order for the Loop Current to grow in northward extension. The implication is that the seasonal cycle in the penetration of the Loop Current is a response to variations in the large-scale circulation associated with the Gulf Stream system.

Along the northern and eastern boundaries of the Loop Current, where it comes into contact with the west Florida shelf, cold-core eddies have been observed to form on the Loop Current front (Paluszkiewicz et al., 1983; Vukovich and Maul, 1985). These features result in intense but short-lived upwelling events along the west Florida shelf break.

Loop Current Rings. The warm-core (anticyclonic) rings that separate from the Loop Current are a major feature of the large-scale circulation of the Gulf of Mexico. Observations (see, e.g., Behringer et al., 1977) show that these rings typically separate from the Loop Current at the time of the maximum northward penetration of this current into the Gulf of Mexico. On an average, one to three anticyclonic rings per year may separate from the Loop Current.

Loop Current rings are approximately 300 to 400 km in diameter and have a depth signature that extends to approximately 1,000 m (Brooks, 1984). After detaching from the Loop Current, these rings move westward across the Gulf of Mexico, and observations have shown that the rings exist as identifiable features for periods of several months (Elliott, 1982). Geostrophic surface velocities within the rings have been estimated to be on the order of 25 to 100 cm/s, and volume transports associated with the rings are on the order of 5 to 10 x 10^6 m^3/s (Merrell and Morrison, 1981; Merrell and Vazquez, 1983; Hofmann and Worley, 1986). Consequently, these rings represent a major mechanism by which properties such as temperature and salinity are transported from the eastern to the western gulf. Once in the western Gulf of Mexico, the rings encounter the Texas or Mexican continental shelf. The fate of the rings at this time is not fully understood. These rings represent a mechanism by which the shelf waters in the western gulf are exchanged with the gulf waters originating in the eastern gulf.

Shelf Circulation

On the Texas-Louisiana continental shelf, west of 92.5°W, the predominant feature of the circulation is a cyclonic (counterclockwise) gyre, elongated in the alongshelf direction (Cochrane and Kelly, 1986). The inshore portion of this gyre is directed westward (downcoast). An eastward-flowing countercurrent at the shelf break constitutes the offshore portion of the shelf gyre. Flow in the western extent of the gyre is directed offshore, while that in the eastern gyre—near Louisiana—is directed onshore. The alongshore wind stress is the primary mechanism driving the circulation of this cyclonic gyre. Because the gyre is primarily wind driven, it exhibits seasonal variability in strength and occurrence that reflects the seasonal variability in the wind patterns over the Texas-Louisiana shelf. In July, when the downcoast (to the west) wind stress is diminished, the cyclonic gyre on the Texas-Louisiana shelf disappears and is replaced by an anticyclonic gyre centered off Louisiana. In August and September, the prevailing wind direction changes abruptly so that the predominant winds are again downcoast (westward), and the cyclonic gyre is re-established. Thus, shelf currents on the Texas-Louisiana shelf reverse with a seasonal frequency.

The circulation on the continental shelf east of the Mississippi River delta is directed toward the west during the winter. As with the Texas-Louisiana shelf, this flow diminishes and reverses direction in the summer months. Currents over the west Florida shelf are predominantly to the south. Several studies (see, e.g., Molinari et al., 1978) suggest that a cyclonic gyre exists in the northeastern corner of the Gulf of Mexico over the west Florida shelf.

Evaluation of MMS-Funded Research in the Gulf of Mexico Region Observational Studies

Observational Studies

MMS supported a 5-year (1982-1987) observational program—the Gulf of Mexico Physical Oceanography Field Study—designed to study physical oceanographic processes in the Gulf of Mexico. The focus during the first 2 years and the fourth year of the observational program was the eastern Gulf of Mexico. In particular, processes associated with Loop Current dynamics, eddy shedding from the Loop Current, and interactions of the Loop Current with the west Florida continental slope/shelf region were of interest. During the third year the observational program emphasized processes in the western Gulf of Mexico, primarily Loop Current eddy interactions with the shelf/slope region in the western gulf. The final year of the observational program shifted emphasis to the north-central gulf, offshore of Louisiana. Below are brief reviews of the observational programs in the various regions of the Gulf of Mexico. The contracts for the reports that describe the results of the studies in the various regions are listed in Appendix C.

Eastern Gulf Of Mexico

The components of the MMS-sponsored physical oceanography observational program in the eastern Gulf of Mexico consisted of moored current and temperature measurements; a coordinated ship-airplane hydrographic survey of the Loop Current, with emphasis on the west Florida shelf region; satellite thermal imagery and advanced, very high-resolution radiometer (AVHRR) data; satellite-tracked Lagrangian surface drifters deployed in Loop Current eddies;

and a ship-of-opportunity program that provided temperature measurements (from expendable bathythermographs (XBTs)) along a north-south transect in the eastern Gulf of Mexico. The moored current and temperature measurements on the west Florida shelf were made with a current-meter mooring array that consisted of a single mooring located in approximately 180 m of water near 27°N and a line of five moorings south of 26°N that extended from the mid-portion of the west Florida shelf offshore into water that was deeper than 3,000 m. The three shelf moorings were located at water depths of 30, 75, and 180 m, and each mooring consisted of three current meters. The two off-shelf moorings were at water depths of 1,700 and 3,400 m and consisted of five and six current meters, respectively. The configuration of this mooring array was such that it provided information primarily on across-shelf motions that occur at large-scales. Mooring deployments were for 2 years, which provides current and temperature time-series of sufficient length to consider water motions that result from atmospheric (short-term and seasonal) and Loop Current forcing. An additional current-meter mooring was maintained near the Mississippi River delta in South Pass Block. This mooring was in 80 m of water and consisted of instruments at depths of 13, 25, 40, and 70 m.

Two intense hydrographic surveys of the Loop Current and Loop Current interactions with the west Florida shelf were sponsored by MMS. On each cruise, the hydrographic transects were designed to intersect the Loop Current front on the west Florida shelf side of the Loop Current. The water properties measured on these cruises consisted of temperature, salinity, dissolved oxygen, and nutrients as well as several properties of biological interest. The station spacing and cruise track design from the two hydrographic cruises were adequate to map the Loop Current front and the frontal eddies (also referred to as boundary eddies and cyclonic cold domes) associated with the Loop Current front. In particular, the hydrographic surveys focused on the interaction of the Loop Current frontal eddies with the adjacent continental-shelf waters. The hydrographic surveys were complemented by larger-scale temperature distributions obtained from airplane surveys of the Loop Current and eastern Gulf of Mexico waters.

The MMS Loop Current studies program contained a considerable remote-sensing component, which is appropriate given the scale of the features of interest. Sea-surface temperatures obtained from the infrared sensors on the NOAA and geostationary operational environmental satellites (GOES)'were used to study fluctuations in the seasonal cycle of the depth of penetration of the Loop Current into the Gulf of Mexico, to study the separation of warm-core (anticyclonic) rings from the Loop Current, and to study the frontal eddies that form on the boundary of the Loop Current (Vukovich, 1988b). Also, Lagrangian surface drifters were placed into the warm-core (anticyclonic) rings that separated from the Loop Current. These drifters provided information on the trajectories and translation velocities of the warm-core rings as they moved westward across the Gulf of Mexico. The drifter data were also used to calculate dynamic quantities such as local vorticity and horizontal deformation rates that can be used to investigate changes in the dynamics of the warm-core ring throughout its lifetime, contributing greatly to our understanding of drifter data (see, e.g., Lewis et al., 1989).

Western Gulf of Mexico

The moored current and temperature measurements in the western Gulf of Mexico were made with an L-shaped mooring array that was deployed in the region approximately between 24°N and 26°N. The array consisted of five current-meter moorings, all of which were deployed in water depths greater than 2,000 m. Three of the moorings were placed alongslope and three moorings (one mooring is the apex of the array) extended offshore into the gulf. This array design is appropriate to capture the motions of large-scale features, such as warm-core Loop Current eddies, as they move toward and along the slope in the western Gulf of Mexico. The moorings remained in place for approximately one year, which is sufficient to provide current and temperature time-series from which mesoscale motions can be extracted.

Extensive hydrographic surveys were made in the region around the current-meter moorings. These observations were complemented by an air-dropped expendable bathythermograph (AXBT) survey of a warm-core ring in the western gulf. This type of survey provides synoptic large-scale coverage of oceanographic features that is not possible from ship observations. With assistance from the Mexican Navy, it was possible to obtain frequent surveys of a warm-core ring observed in the western Gulf of Mexico.

The study of warm-core rings in the western Gulf of Mexico made extensive use of surface Lagrangian drifters. Surface drifters were placed in rings after separation from the Loop Current, and the drifters remained with the rings as they moved westward across the Gulf of Mexico. The drifter data were used in conjunction with sea-surface temperature measurements obtained from satellite observations, and with vertical temperature distributions obtained from AXBT surveys of the warm-core rings. This combination of data allowed study of the dynamics governing the circulation in the warm-core rings.

North-Central Gulf of Mexico

The general objective of the MMS-sponsored study of the north-central Gulf of Mexico is to develop a data base that can be used to describe the circulation patterns and processes of this region. The measurements and observations being made in this region follow those made in the eastern and western gulf. These consist of moored current and temperature measurements, hydrographic surveys, satellite thermal imagery, satellite-tracked drifting buoys, and a ship-of-opportunity program.

The proposed current-meter mooring array for this region consists of seven moorings deployed along a transect that extends from the mid-continental shelf offshore to water depths of 3,000 m. The shelf moorings are between the 15- and 150-m isobaths, while the deeper moorings are on the 1,000, 1,500 and 3,000-m isobaths. This type of array design provides information on across-shelf motions. It is intended to provide insight on shelf circulation processes and the effects of the larger-scale gulf circulation processes.

Evaluation of Observational Studies

The MMS-funded, 5-year physical oceanography observational program was adequate to study the large-scale circulation of the Gulf of Mexico. The field programs were structured to provide data on the major oceanographic features in the gulf: the Loop Current and the rings and eddies associated with the Loop Current. With few exceptions, the physical oceanography program in the Gulf of Mexico focused on circulation processes that occur in waters deeper than 1,000 m. Essentially no studies were performed on the Texas-Louisiana continental shelf, or in waters shallower than 500 m, in any part of the gulf. The exception to this is the study of Loop Current frontal eddies on the west Florida shelf.

The field program designed to investigate Loop Current processes and interactions of the Loop Current with the west Florida shelf was thorough, given the budgetary and time constraints imposed on the overall program. It can always be argued that more observations and data are needed; however, the data obtained were adequate to describe the basic circulation features, i.e., the frontal eddies. The panel has reached similar conclusions about the observational programs in the western and the north-central Gulf of Mexico. The western gulf program in particular has resulted in a considerable data base on warm-core rings and progress in the development of techniques to analyze and understand Lagrangian measurements. Overall, the MMS studies of the gulf circulation made good use of a combination of data sources, in particular sea-surface temperature distributions obtained from satellites.

It should be noted that a significant portion of the results from the Gulf of Mexico physical oceanography program has been published in the refereed scientific literature (see, e.g., Kirwan et al., 1984a,b; Lewis and Kirwan, 1985, 1987; Kirwan et al., 1988). Also, many of the results of this program have been presented at national scientific meetings such as the annual meeting of the American Geophysical Union. It can be concluded that the MMS study of the circulation of the Gulf of Mexico yielded scientifically credible information.

Although the MMS physical oceanography program in the Gulf of Mexico did yield substantial information on large-scale and mesoscale circulation features in the gulf, it did not provide any substantial information on shelf-circulation processes. Given that most oil-drilling activities occur over the continental shelf in water shallower than 150 m, the lack of focus on shelf circulation is disturbing. Little attention has been paid to the Texas-Louisiana shelf, where oil exploration and drilling activities are the most intense. However, projects are being started in this area.

The Texas-Louisiana shelf region is occasionally influenced by warm-core rings of Loop Current origin, but these rings are not the major oceanographic process governing the circulation on the shelf, and the frequency of occurrence of rings in the western gulf is not high. Thus, although MMS has been supporting a physical oceanographic observational program that was adequate to describe some aspects of the general circulation of the Gulf of Mexico, the focus of this program was on circulation features that are of minor importance to the needs of programs designed to perform oil-spill risk-analysis assessments. In summary, the MMS physical oceanography program was designed to look at space and time scales that are too large to be of use for oil-spill risk-assessment analysis.

Modeling Studies

The MMS-supported modeling studies of circulation in the Gulf of Mexico consisted of the development of models to predict the seasonal water circulation over the southwest Florida shelf, the geostrophic circulation on the Texas-Louisiana shelf, and the basin-wide circulation of the Gulf of Mexico. Brief descriptions of these models are given below. Details of the models can be found in the reports based on the contracts listed in Appendix C.

Southwest Florida Shelf Model

The model developed for the southwest Florida shelf (Cooper, 1982) was a linear hydrodynamic model that included vertical and lateral friction effects and a free surface. The model allowed for forcing due to surface-wind stress, atmospheric-pressure gradients, and bottom stress. The vertical structure of the flow was represented by a series of functions that allowed for vertical variation in the velocity fields. The model used a time-invariant density field that was specified from seasonally averaged hydrographic observations made on the west Florida shelf. Model boundaries were specified as land boundaries (inshore) and as either closed or open along the north, south, and offshore boundaries. Model output consisted of distributions of the horizontal velocity components (u and v) on a grid with a 30-km resolution. Steady-state and time-varying velocity distributions were computed with the model. The maximum depth allowed in the model was 200 m.

The effect of the Loop Current was included in the model by specifying a velocity distribution along the outer (offshore) boundary of the model. This flow was specified as a constant velocity along the boundary or as a velocity that linearly increased or decreased along the outer boundary of the model. This approach assumes that the Loop Current is essentially baroclinic and does not allow for any baroclinic structure or adjustments of the flow.

The use of a time-invariant density field places a severe restriction on the usefulness and reliability of the simulated circulation distributions. The assumption made in this approach is that the wind field does not interact with the density structure of the shelf waters. This is contrary to understanding of coastal circulation processes. In general, the calculation of seasonal circulation patterns is questionable.

Texas-Louisiana Shelf Model

The circulation distributions used to perform oil-spill risk-assessment analyses for the Texas-Louisiana continental shelf region were derived from geostrophic velocity calculations. The geostrophic velocity fields were obtained using seasonally averaged density fields for the shelf waters. Consequently, the circulation fields, at best, can only be representative of seasonal circulation patterns. Such circulation patterns are not appropriate for determining the trajectories that may be followed by an oil spill. Oil-spill trajectories are determined by the prevailing circulation, which may not be represented in a seasonally averaged circulation pattern. For example, wind forcing can produce currents that flow in a direction opposite to that suggested by a long time-averaged circulation.

The use of geostrophic calculations for determining circulation patterns in continental-shelf waters is questionable, particularly in shallow waters. Furthermore, the accuracy of the density fields that go into the geostrophic calculation will determine the reliability of the derived circulation. Also, the shelf circulation models might not account for such climatological variations as timing in the maximum river runoff and changes in wind patterns, which can vary from year to year. In summary, the Texas-Louisiana Shelf Model is not adequate to meet the stated objectives of oil-spill risk-assessment modeling studies.

Basin-wide Circulation Model

The circulation model used by MMS for the basin-wide Gulf of Mexico modeling studies is a modification of an existing model developed by Hurlburt and Thompson (Wallcraft, 1986). The Hurlburt and Thompson (1980) model is a two-layer, nonlinear, hydrodynamic, free-surface, primitive equation model on a beta plane, with a realistic coastline geometry and full-scale bottom topography confined to the lower layer. This model provides velocity distributions on a grid with a resolution of 0.2 degrees. The model is forced by inflow through the Yucatan Strait and compensated by outflow through the Straits of Florida. Wind forcing was not treated in the Hulburt and Thompson model but was included in some experiments with the modified model.

MMS supported a modeling effort that had the overall objectives of modifying the Hurlburt and Thompson model so that it had a finer spatial resolution (0.1 degrees) and included an additional layer (3 versus 2 layers), so that the circulation results could be coupled with a mixed-layer model, specifically the Navy's operational mixed-layer forecast model. It should be pointed out that these are all modifications to an existing model; initial model development was not necessary.

A major problem with a layer model is that the model becomes unstable when the layer surfaces intersect the bottom topography, or the surface. Much of the effort in modifying the Hurlburt and Thompson model has been directed at correcting this problem. This is a particular problem for the objectives of the MMS modeling program, because it means that the model is not valid for shallow depths. Indeed, the basin-wide circulation model produced for MMS does not provide usable velocity distributions in regions of the gulf with depths of less than about 500 m.

Evaluation of Modeling Studies

The circulation models developed for the southwest Florida shelf, the Texas-Louisiana shelf, and the Gulf of Mexico (the basin-wide model) are inappropriate for the objectives of the MMS modeling program. In particular, the first two models are not designed to provide more than a best guess at the circulation pattern.

The basin-wide circulation model is interesting from a scientific standpoint, but is of little practical use in meeting the goals of the MMS modeling program. Given the inability of this model to produce realistic flows in the shelf/slope regions, it is not clear what MMS has gained by funding the modifications to the Hurlburt and Thompson model. Furthermore, this modified model is complex, and understanding the simulated circulations produced with the model would require considerable effort. It is not clear that MMS would (or perhaps should) fund such an analysis. It is doubtful that the basin-wide model would be of much use in oil-spill risk-assessment analysis. It should be noted that few of the results obtained with the modified Hurlburt and Thompson model have been published in the refereed scientific literature. One interpretation of this is that the modified model does not represent any significant advance over what was learned from the Hurlburt and Thompson studies. However, the MMS Gulf of Mexico modeling effort has attempted to incorporate flux-corrected transport techniques that will remedy some of the problems encountered in layer models when interfaces intersect the surface or bottom topography. If this effort is successful, it will represent an advance over the Gulf of Mexico model done by Hurlburt and Thompson.

In summary, the MMS modeling program has not been successful. It appears that inappropriate decisions as to what models would be used were made in the early stages of the program. Instead of those decisions being reevaluated at the mid-point of the study, for example, the models were continued, even when it should have been obvious that they were inappropriate. The results of the Gulf of Mexico circulation modeling program have not yet been used by BEM in oil-spill-risk assessments because the work is not complete, and the results have not been verified (personal communication, T. Paluszkiewicz, April 18, 1989).

On the positive side, the data obtained from the physical oceanography observational program are adequate to form the basis of circulation modeling studies in some specific regions and for some specific oceanographic features. However, there seems to have been insufficient interaction between the observational and modeling programs. This is not a new problem and should be avoided in future MMS studies.

THE ATLANTIC REGION

The Atlantic region can be divided into two parts. The region south of Cape Hatteras is known as the South Atlantic Bight, and that north of Cape Hatteras is known as the Mid-Atlantic Bight. In the South Atlantic Bight, the mid- and outer-shelf region is dominated by the Gulf Stream flow, with eddies at the shelf edge providing very strong variability in the currents. The shelf is about 100 km wide. The shelf widens over the Mid-Atlantic Bight, with the Gulf Stream further offshore. There are strong southwestward currents in the slope water and the shelf with, again, strong variability associated with winds, tides, and offshore meandering of the Gulf Stream, mesoscale eddies, and Gulf Stream rings. For MMS planning purposes the Atlantic region is divided into the north Atlantic, mid-Atlantic, and south Atlantic subregions (Figs. 15, 16, and 17).

Meteorology and Circulation

Meteorology

The meteorological conditions differ in the northern and southern parts of the Atlantic region. Seasonal winds in the South Atlantic Bight stem from circulations around either the Azores-Bermuda high-pressure center (tropical, maritime air) or a high-pressure region in the Ohio Valley (colder and drier air). In the spring, the Azores-Bermuda high dominates, and the flow is to the west over south Florida, turning to the north and northeast over the Blake Plateau. Monthly averaged velocities are 1 to 2 m/s. In summer, the northward flow strengthens. In autumn, there is a transition to southwestward flow as the Ohio Valley pressure center becomes dominant. Warm northward flowing air persists only over the Blake Plateau and offshore. The winter regime is dominated by southeastward winds of about I to 2 m/s. However, to a large degree, this mean is the average of numerous weather systems passing through the area.

In the Mid-Atlantic Bight, the seasonally averaged winds show strong southeastward flows in the winter, due to the Icelandic low and the weak North American high, but become less organized in spring. Northward to northeastward winds develop in summer (Azores-Bermuda high), shifting to southwestward winds in fall (Canadian high). In the Georges Bank region further north, this pattern persists: the mean winds are eastward to southeastward during the fall to spring months, averaging 3 to 6 m/s, and are weaker and northeastward in the summer.

Interannual variability in the monthly mean wind speeds is substantial, partly because the transitions from one regime to the other occur at differing times. Representations of the wind field need to appropriately account for the long-term distribution of speeds and directions in the monthly averages.

For simulations of currents and oil-spill motion, the synoptic variability in the wind field is as important as the mean, especially in the more northerly regions. Major wind systems in the

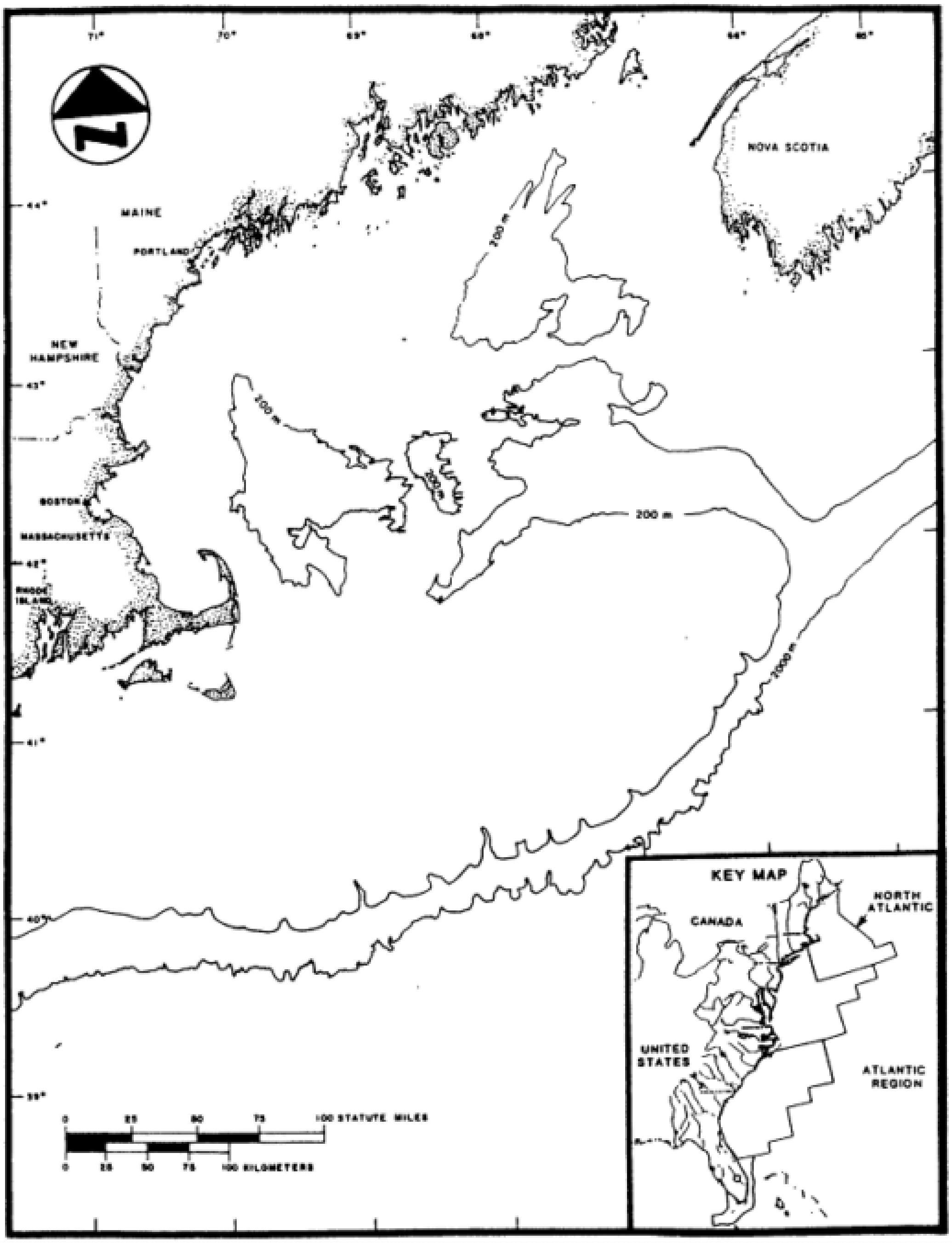

Figure 15
North Atlantic planning area of the Atlantic region.
Source: MMS.

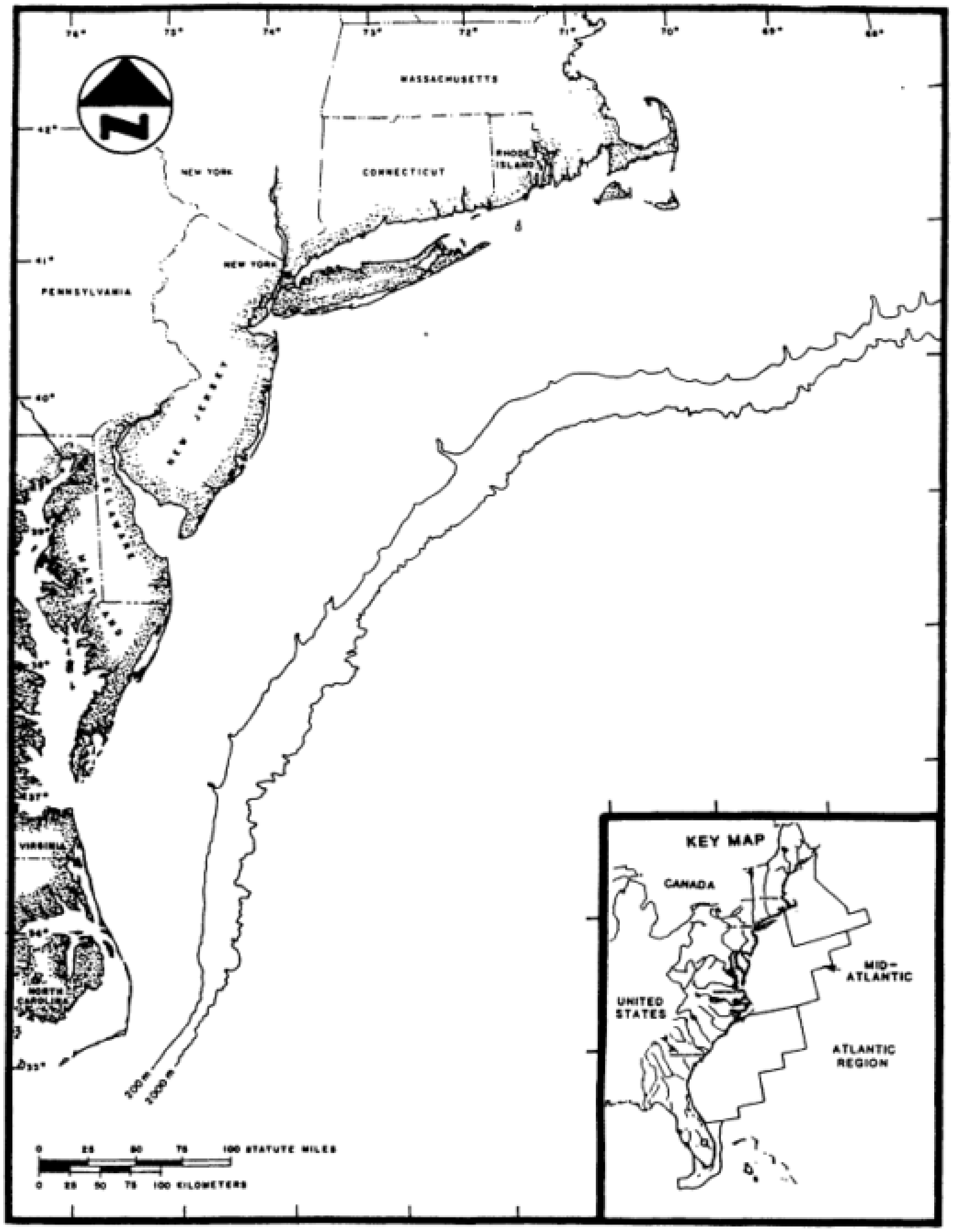

Figure 16
Mid-Atlantic planning area of the Atlantic region.
Source: MMS.

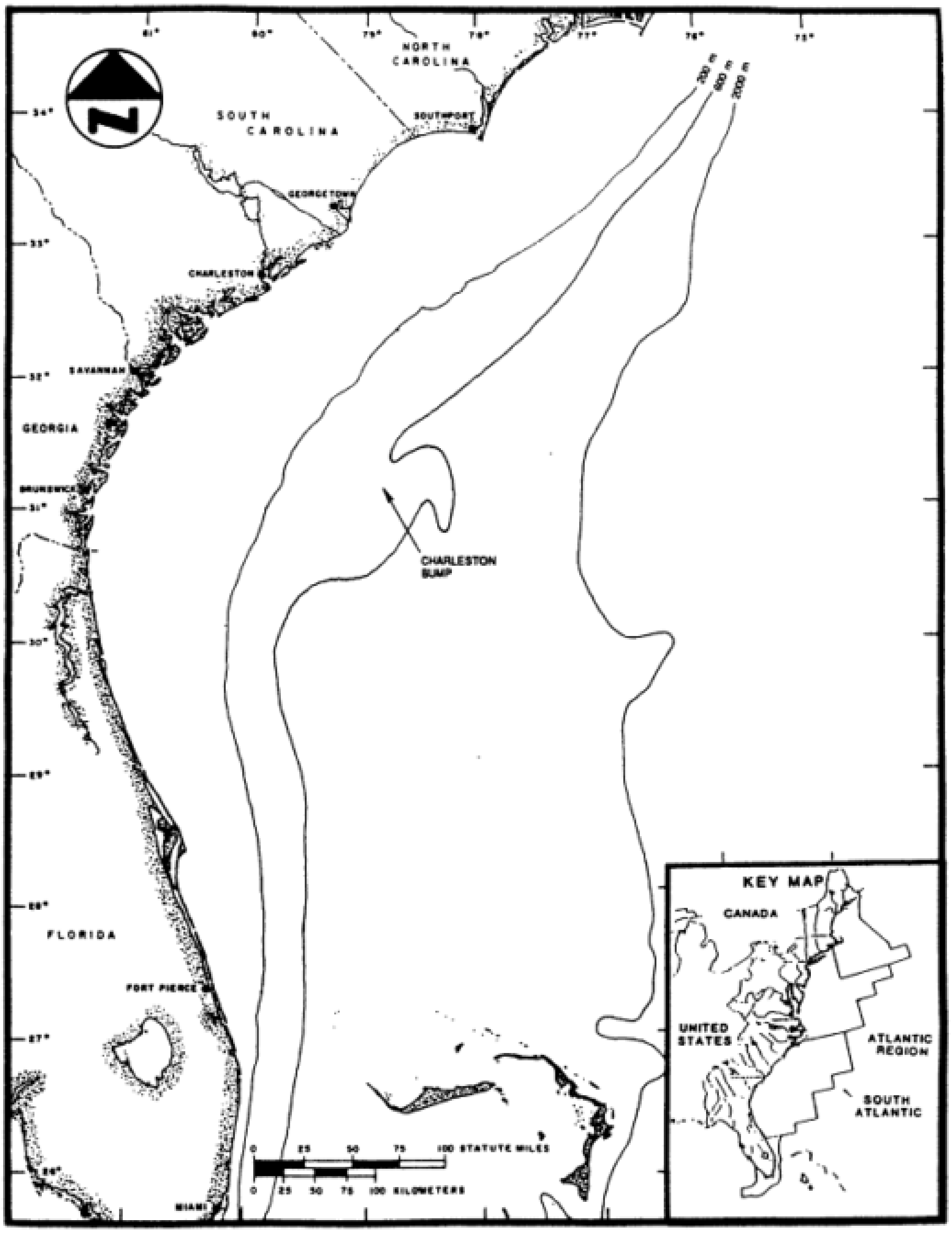

Figure 17
South Atlantic planning area of the Atlantic region.
Source: MMS.

South Atlantic Bight have 2- to 14-day periodicities, with shorter diurnal periods also appearing near the coast. These sea-breeze cycles can also be seen nearshore, peaking during the summertime. The major frontal events move offshore nearly parallel to the coast, setting up large-scale, alongcoast current patterns. In addition, the varying wind strengths are important in establishing the amount of vertical mixing and the depth and strength of the seasonal pycnocline.

The variability in winds in the winter is caused by the fairly regular passage of cyclonic disturbances along a storm track lying in the Mid-Atlantic Bight. In addition, some cyclogenesis occurs off Cape Hatteras, and some storms do come up from the Gulf of Mexico. Fewer cyclones occur in summer, with the storm tracks lying further north. Anticyclonic events are less frequent, but again the storms follow storm tracks lying in the Mid-Atlantic Bight north of Cape Hatteras. In an average year, 5 (Florida) to 20 (New England) cyclone events occur. The synoptic scale variance shows a strong anticyclonic component to the rotary spectrum over the Blake Plateau, especially in winter.

Nor'easters, large (1,000-2,500 km), severe low-pressure systems moving from the west or southwest with winds at speeds up to 35 m/s from the northeast, are frequent in the wintertime. Over 10% of the observations in December through March at Georges Shoal show wind speeds higher than 17 m/s; most of these high-wind periods are associated with these nor'easter events. They also contribute significantly to the observed higher average wind speeds. Because the winds generally have a long fetch, the associated waves are on the order of 3 m in height, occasionally reaching 12 m on Georges Bank. Precipitation, consisting of rain or snow, is also heavy.

Tropical cyclones and hurricanes may strike many of the offshore sites along the Atlantic coast. Wind speeds of 50 m/s may occur, along with heavy rain.

For the purpose of simulating oil motion, winds in nearshore regions have two effects. They can directly produce surface currents by creating a turbulent Ekman layer with surface drifts to the right of the winds. Secondly, the winds in the presence of a lateral boundary may also cause setup of the ocean surface. Currents, driven by the resulting pressure gradients and retarded by bottom friction, can have a magnitude comparable to or larger than the directly driven flows. These flows depend in a complicated way on the direction, strength, and history of the wind stress, as well as on the topography.

Wind measurements are most readily available from shore stations. However, the atmospheric boundary layer changes character significantly over water as moisture and heat are exchanged with the sea surface, so that the wind field measured on land is quite different from that taken from stations 20 to 50 km offshore. Schwing and Blanton (1984) found that the ocean stations had more energy by a factor of 4 in the synoptic time scales; the directions were also significantly different. The shore-normal component, in particular, was not well predicted by even an appropriately magnified form of the winds measured on land. Thus, the estimated wind stress based on data from shore stations may easily be too low by a factor of 2 to 5 and may be off by 40 degrees in direction.

Circulation

The South Atlantic Bight

The oceanography of the South Atlantic Bight region is very well summarized in Atkinson et al. (1983). This region is characterized by a relatively narrow shelf (50 to 120 kin) with a water depth of about 50 m, bounded by the coast on one side and the Gulf Stream on the other. South of the topographic feature known as the Charleston Bump (at 32°N), the Gulf Stream flows in about 400 to 600 m of water, with currents of I m/s. The stream is deflected eastward by the bump and then returns to the shelf edge near Wilmington (at 33.5°N) and continues slightly farther offshore to Cape Hatteras. In the midshelf region (water depths of 15 to 400 m), the currents are, on the average, in the same direction as the Gulf Stream, although reverse flows can often be found around the low-pressure center formed by the offshore meander. In the shallowest part of the shelf, there is often a baroclinic southward current associated with the layer of fresh river runoff water. The rivers in the South Atlantic Bight provide from 3 to 7.7 km^3 of fresh water per month, distributed fairly evenly along the shelf. This can significantly alter the flow and stratification near the shore.

Currents are highly variable; tides, wind-driven motions, and mesoscale eddies all cause significant fluctuations on the shelf. The tides (predominantly M_2) have a range of I to 3 m along the coast, with tidal excursions of 4 to 20 km in the inner shelf region. Currents may reach 0.4 m/s nearshore. In the midshelf areas, the tides account for 80 to 90% of the cross-shelf variability and 20 to 40% of the alongshelf current fluctuations. Over the outer shelf, tides become less significant, accounting for less than 30% of the variability.

Wind-driven currents lead to strong motions at 5- to 10-day periods as well as mean northward drift. These are significantly correlated with the coastal sea-surface pressure and the alongshelf component of the winds, but are not very coherent spatially. Fluctuations of 0.1 to 0.3 m/s are common. Modeling work by Lee et al. (1984) suggested that displacements of 70 km over 8 days were *characteristic* of the midshelf region; of this, about half was caused by wind-driven currents. It should be noted that the winds in this region show strong variability from synoptic systems moving through the area. The winds over the ocean are consistently stronger by a factor of 2 than those measured even at nearby onshore stations. Furthermore, the directions may be off by as much as 40 degrees during periods of changing winds. The alongshore winds are usually well represented (except for strength) by the coastal stations, but the onshore or offshore winds may be quite different. Sea breeze contributes significantly to currents nearshore.

Mesoscale variability is primarily produced by the frontal waves and eddies of the Gulf Stream at the outer edge of the shelf. These disturbances, with wavelengths of 100 to 300 km, displace the shelf break front by 10 to 100 km across the shelf. Cyclonic circulations develop in the trough, corresponding to reverse flow nearshore. About once a week, the disturbances grow and fold backwards to form a cold pool and a pattern of northeast-southwest-northeast currents. Upwelling at a rate of about 10^{-4} m/s occurs in the cold pool; this may significantly influence the biological and chemical distributions. Transient upwelling also occurs over topographic features. The current fluctuations are about 0.8 m/s and are coherent for about 100 km along the Gulf Stream. The average propagation rate for these waves or eddies is 0.5 m/s, dominated by the advection by the strong currents of the Gulf Stream.

The waters on the shelf of the South Atlantic Bight are vertically well mixed during the winter, with a strong horizontal temperature gradient occurring across the shelf into the Gulf Stream. During the summer, the shelf area is stratified, and the surface thermal gradient is quite small. Some estimates of horizontal mixing and flushing times exist for this region. Bumpus (1973) has estimated a residence time of about 3 months based on the transport and volume of the shelf waters.

The Mid-Atlantic Bight And Georges Bank

North of Cape Hatteras, the physical oceanography changes significantly: the shelf is wider (150 km), and the Gulf Stream moves further offshore (200 to 300 km from the shelf break). Georges Bank lies off Cape Cod, separating the Gulf of Maine from the slope water, with most of the water exchange occurring through the Great South Channel and Northeast Channel. There are fairly strong temperature-salinity contrasts across the shelf, with the shelf-slope front along the 100-m isobath in winter separating the two water masses. The front leans outward by about 30 km as it extends to the surface. The density contrast is relatively weak, so that, although the currents along the front are fairly strong, there is not a large baroclinic component. In the summer, a strong seasonal thermocline develops, and a cold pool of water cuts off along the 100-m isobath; there is still a moderate salinity gradient.

Mean currents in the Mid-Atlantic Bight are generally along-isobath, with flow along the bottom into estuaries and strong currents in canyons. There is a complicated circulation around Georges Bank, with flow into the Gulf of Maine near Nova Scotia, cyclonic circulation around the gulf, and a strong jet (0.3 m/s) around the northeast side of Georges Bank, which turns to the southwest along the 70-m isobath. Some of this flow appears to recirculate around the bank through the Great South Channel, while some proceeds to the west and south into the Mid-Atlantic Bight. In addition, some of the Gulf of Maine circulation passes through the Great

South Channel and joins the general alongshelf drift. Further offshore, in the slope water, the mean circulation also has a southwestward flow at about 0.7 m/s at the surface.

Tidal currents are strong in the northern region; tidal range varies from 0.5 to 4 m, and current speeds can reach I m/s in the Northeast Channel, with tidal excursions on the order of 20 km. In shallow areas, these currents are sufficient to vertically mix the water even during the summer and to cause substantial sediment transport. Rectification of tidal fluctuations is thought to be an important driving mechanism for mean flows.

Low-frequency motions on the shelf of the Mid-Atlantic Bight are dominated by the wind, which drives energetic alongshelf fluctuations of 2 to 3 times the mean flow velocity, with periods on the order of 5 days. The onshore-offshore flows are at least twice as weak. Alongshelf currents are fairly coherent all along the shelf, but the cross-shelf flows are incoherent over distances of 50 km and across the shelf.

Another source of variability on the shelf is forcing from the slope water mesoscale eddy field, the Gulf Stream rings passing down the coast, and the large meanders of the Gulf Stream (and the waves associated with these). Warm-core rings bring strong currents to the edge of the shelf and can force slope water or Gulf Stream water into shallower regions and entrain material off the shelf. Several of these pass by Georges Bank each year. They significantly reduce the residence time for water on the bank and increase the mixing of waters on the bank.

Summaries of drogue experiments and model estimates indicate that water is resident on Georges Bank for 40 to 80 days, with the nearly closed circulation being responsible for the long period. Further south in the Mid-Atlantic Bight, the flushing time is shorter, about 30 days. Mixing is strong on the shelf, both because of the tides, which disperse material over a scale of the tidal excursion in one period, and because of energetic fluctuations driven by winds and by eddy and meander events.

Evaluation of MMS-funded Research in the Atlantic Region

History of MMS-funded Research in the Atlantic Region

MMS has funded a number of large physical oceanographic studies in the Atlantic region. Among these are the Blake Plateau Current Measurement study (October 1982 to September 1986), the Florida Atlantic Coast Transport Study, or FACTS (January 1984 to February 1986), the South Atlantic Bight numerical modeling study, and the Mid-Atlantic Slope and Rise study, or MASAR, two of which are discussed below. Appendix C contains a full list of MMS-funded studies in the Atlantic region.

Evaluation of Observational Studies

These studies have generally consisted of gathering current, hydrographic, and surface imagery data. In most cases, the studies were carefully done and provided good data on the mean and variable circulations in the various areas. The mooring programs have been quite ambitious: the FACTS program began with 41 current meters deployed on 10 moorings, one line of 7 spanning the Gulf Stream and 3 more located along the continental slope upstream. The Blake Plateau study maintained three lines of moorings across the stream at Onslow Bay, Long Bay, and the Charleston Bump for over 2 years. However, the programs all suffered from instrument failures and losses, partly because of the difficulty of mooring work in strong, highly sheared currents and probably also in part from fishing activity.

The FACTS program also involved drifting-buoy and drift-card releases. Buoys launched about 50 km offshore of Melbourne Beach stayed within the stream, whereas those launched nearer inshore or in the Straits of Florida tended to move into the coastal waters. Drift-card returns indicated more significant onshore motion, perhaps associated with increased wind influence. No attempts were made to relate either directly to oil motion.

Hydrographic data provided tracers of water masses, including river runoff, and indicated the occurrence of strong wind mixing, upwelling, and injection of water onto the shelf from Gulf Stream frontal eddies. Surface satellite imagery was also used to observe and describe eddy features, both to provide a context and to obtain estimates of the frequency of strong onshore events.

MMS has included a fairly high proportion of investigators from universities and research institutions in the FACTS program. The analyses of the individual data sets by the subcontractors have been competent. However, there has been no quantitative synthesis of the various types of data to produce a dynamically consistent description of the flow. It does not appear that much of the information from this study (or any synthesis work) has been published in the reviewed literature. This problem can be seen in a number of other MMS-sponsored programs, although the work on Georges Bank has been published and some synthesis has been presented.

In the Atlantic region, MMS has generally made good efforts to coordinate its field programs with other ongoing projects. This has enabled the various scientists involved to gain a broader perspective on their observations and has contributed to the other programs as well.

Evaluation of Modeling Studies

Modeling work in the Atlantic region has progressed in two stages. The contractor (Dynalysis of Princeton) has worked with equations for horizontal momentum, heat, salt, turbulent energy, and turbulent length scale (as part of a second-order closure scheme). Dynalysis first produced a characteristic tracing model CTM, which neglects advection in the momentum and turbulent energy/length scale equations. The equations are solved by integrating along contours of the Coriolis parameter divided by the depth (also known as f/h contours). This diagnostic calculation produces a steady flow pattern under fixed boundary conditions. In the second stage, the CTM is used to produce boundary information for a full primitive equation general circulation model (GCM). The contractor uses diagnostic and prognostic forms of the temperature and salinity equations. These models do not appear to produce significant eddying, despite the fairly fine grid resolution. The contractor is working on incorporating more variability into its model by varying the boundary conditions. It is not clear why instabilities do not appear to be significant, in contrast to the calculations of Orlanski and Cox (1973) for a similar region.

The models use data for initialization, forcing, and boundary conditions. There appears to be little relationship between the modeling work and the data collection. The reports do not reference each other, and the modeling does not appear as a subcontract in the same project as the observational work. (MASAR is an exception to this, although the modeling work in that study does not seem to be of the directly applied numerical simulation kind.) The data used in the models come from the historical record; verification of the models has been rather minimal.

Environmental Impact Statements

It is disappointing to note that the OSRAs produced in 1984 and 1985 continued to use the CTM model, despite the fact that the GCM reports were available in 1981 (Blumberg and Melior, 1981). MMS judged the GCM calculations to be too short and to cover too limited an area and, therefore, chose not to incorporate this information into their risk analysis (pets. comm., MMS, 1990). In addition, large amounts of field data on the magnitude and importance of the variability were available, but were not used in the risk analysis.

The ElS for the sales in the Georges Bank region (U.S. DOI, 1983a) exhibits similar problems and is discussed in more depth here as an example of poor use of the available data base. The document has a 15-page summary of the physical oceanography of the region. This draws on both published and unpublished reports and is a good summary of the currents, hydrographic structure, and wave conditions. Then, 143 pages later, risk analysis is finally discussed, and there is a 2-page discussion of the analysis, which is based entirely on modeling as discussed further below. There is no reference at all in the risk analysis section to the preceding summary of oceanographic knowledge.

Furthermore, the modeling work, reported in Appendix D (2 pages) of the EIS document, uses the CTM south of 41.5°N and west of 69.5°W. These boundaries correspond to Rhode Island and Cape Cod to the north and to Nantucket Shoals on the eastern edge. Thus, the numerical model does not cover the Great South Channel or Georges Bank at all. Instead, currents based on a "geostrophic assumption," calculated by F.A. Godshall in a NOAA unofficial report and cited in Appendix D of the EIS, were used for the rest of the study area (U.S. DOI, 1983b). None of the simulated trajectories are shown, so it is impossible to judge the performance of this calculation. Again, no comparisons with the actual observations are offered.

Thus, we have a fairly elaborate and expensive field study and (perhaps unique to this region) synthesis work in the EIS, giving a rather full picture of the circulation and mixing, all of which was ignored when oil motion was estimated.

THE WASHINGTON OFFICE

The efforts of the WO, in contrast with the regional offices' goal of data collection, analysis, and synthesis, are focused on supporting regional studies, addressing issues that are common to several or more of the regions (generic studies), and summarizing or documenting previous studies. From 1973 to 1988, physical oceanography studies funded by the WO accounted for 4% of all MMS funding for physical oceanography.

The number of physical oceanography studies funded under the WO is extremely limited (see Appendix C). According to the summary list of studies (FY 1973 to FY 1986, 3rd quarter) appended to the Washington Office Regional Studies Plan for FY 1988, only seven studies have been funded for that period, and only two since the previous NRC review (NRC, 1978). The major effort is an interagency agreement with NOAA for bathymetric mapping services Another study, proposed in the Regional Studies Plan for FY 1989, which requires study of near-surface physical oceanographic processes, is assessing the use of satellite-tracked surface buoys in simulating the movement of spilled oil in the marine environment.

According to the material available, the physical oceanographic studies completed under the WO of the ESP address areas of real concern and have been completed with quality products in a timely manner. An important question is why the WO budget is so small compared with those of its regional counterparts. Several important generic research efforts that have been carried out by the regional offices clearly seem appropriate for the WO. These include, among others, efforts to characterize the transport and fate of oil in the marine environment, to develop models of atmospheric and drill-cuttings dispersion and of coastline-oil interaction, to investigate oil-sediment interaction, to characterize coastal wave dynamics, and to develop methodologies for specifying wind and atmospheric forcing for circulation and trajectory models. It appears that such studies could have been better directed and more efficiently executed, with results that would have been more widely useful, if they had been managed by the WO. It is likely that these investigations were not organized under the WO generic studies program because of the historical strength of the regional offices in establishing the total ESP for MMS. The mandate to complete these overview or generic efforts clearly belongs with the WO. The management structure and funding allocations should clearly reflect that fact.

4

Conclusion and Recommendations

INTRODUCTION

The Physical Oceanography Panel of the Committee to Review the Outer Continental Shelf Environmental Studies Program was formed to evaluate physical oceanographic aspects of' the OCS oil and gas leasing program. In completing its review, the panel considered four basic subject areas:

1. The acquisition and use of physical oceanographic information by the ESP and use of the information by BEM and in EISs;
2. A review of' the state of knowledge of general physical oceanographic processes that are most important for understanding and modeling the motion and fate of oil spills in the ocean;
3. A review of the state of knowledge of the physical oceanography of each of the ESP regions, based on all available sources; and
4. An evaluation of' the adequacy and applicability of' each of' the ESP regional physical oceanography programs and the Washington office generic studies program, as measured by (a) the success of the field programs and modeling efforts in meeting ESP needs, (b) contributions to the general state of physical oceanographic knowledge, and (c) interactions with other agencies and the scientific community in the region.

This chapter presents a brief summary of the current role of physical oceanography in the ESP, followed by the conclusions of the panel's review and its recommendations for future ESP physical oceanography studies.

THE ROLE OF PHYSICAL OCEANOGRAPHY IN THE ESP

Physical oceanography and meteorology provide the basis for calculating estimates of the transport and fate of oil spills in the ocean. These calculations in turn provide the basis for estimating potential impacts of oil spills on resources. Projection of potential oil-spill impacts is based on results generated by the OSRA model that was developed by the USGS in 1975 to model oil-spill trajectories. Because potential risks are principally evaluated through OSRA modeling, the primary use of physical oceanographic information within the ESP has been in support of the OSRA model and in preparation of associated EIS documents. Physical oceanographic information has also been used to support biological and ecological studies, and to predict the transport of drilling muds and cuttings and other byprducts of oil exploration and production. The Physical Oceanography Panel has concentrated its review on the needs and uses of physical oceanographic (and associated meteorological) information as input to the OSRA model.

Most oil-spill models, including the OSRA model, require physical oceanographic and meteorological data for environmental input. Definitions of the wind, current, temperature, and ice fields (if present) in space and time constitute the typical environmental input parameters.

These data can be derived from other meteorological or oceanographic circulation models or from field observations, but in either case, accurate spill predictions require high-quality environmental data that are carefully integrated into the spill model. The environmental data are subsequently used in the algorithms that calculate probable spill trajectories and fates; the version of the OSRA model currently used to support OCS leasing decisions does not include any calculation of oil-spill fate, but an experimental version (under development) does incorporate fate calculations.

In present usage, physical oceanographic input to the OSRA model is provided through the predictions of regional circulation models for all of the regions. These predictions have been provided in the form of mean climatological flows over various time scales at spatial resolutions of typically 15 to 30 km, with the principal forcings being the mean density field and the seasonal mean wind stress. Recently, MMS has begun to specify time-dependent velocity fields. In the Atlantic, Pacific, and Gulf of Mexico regions, until 1989, meteorological input has been provided in the form of transition-probability matrices of wind speed and direction, calculated from observed winds over long periods of time at selected coastal and offshore buoy stations. In 1989, MMS began to use the output from meteorological models for wind fields instead of transition-probability matrices (pers. comm., MMS, 1990). The OSRA model then uses a Monte Carlo technique to calculate spill trajectories for selected launch points in a proposed lease area by season or month. In the Alaska region, meteorological input has recently been provided through the use of the Fleet Numerical Oceanographic Center weather model, which estimates spatially and temporally varying winds in Alaskan waters, assimilating observed wind and pressure fields when these are available. In Alaskan waters, the method of predicting spill trajectories depends on the contractor. In all cases, the OSRA model then calculates the hits, or number of' times a spill encounters an environmental resource target or shoreline segments, using historical data and the conditional impact probabilities on the resource within a preselected time.

CONCLUSIONS

Acquisition and Use of Physical Oceanographic Information

MMS-funded studies have contributed to the dramatic increase in knowledge of the oceans that has occurred during the past decade. These contributions have included the development of circulation models and the observational study of circulation patterns. MMS funded physical oceanography studies have fit in well with those of other agencies. This improved information has resulted in many excellent summaries of the relevant physical oceanography occurring in the "Description of the Affected Environment" section of the EISs.

The panel has noted several discrepancies between the physical oceanographic information that is potentially available as input to the OSRA model, either through MMS-funded studies or through cooperation with other agencies, and the information that is actually used. The most important of these are summarized below:

1. In reviewing the oil spill trajectory and environmental resource impact modeling performed by or for MMS, it was evident that the general strategy is to rely extensively on the use of model-derived results to estimate the circulation for a given area. The use of circulation data sets based solely on field observations or derived from a melding or assimilation of field observations and model results appears minimal at present. This same discrepancy was noted in reviewing the regional programs; in general, it was found that the physical oceanographic field studies carried out for MMS have been extensive, with the exception of those conducted in the Gulf of Mexico, but that the data collected have been underused.

   Circulation- and trajectory-model results are ultimately integrated into EISs for lease sales through OSRA predictions. How the results of the large-scale physical oceanographic field programs influence the EIS preparation process is not clear. The information derived from the observational programs appears to be used along with the model results to describe the circulation that is ultimately summarized in the EIS. The information also appears to be used by other investigators (biologists, chemists, and geologists, for example) to assist them in interpreting and analyzing their data. However, although observational data sets and associated interpretation could be used to improve, calibrate, or validate circulation model predictions or to provide an independent source of data to describe the circulation for input to the OSRA model, they have seldom been used for these purposes.

2. A related problem is that the best available circulation-model results in the OSRA calculations have not always been used, notably in several calculations done in the Atlantic region (including the OSRA calculation for the Georges Bank EIS).
3. Studies funded in physical oceanography have tended to be of two types: (a) large-scale, multiyear observational field programs with associated data analysis and interpretation, and (b) numerical modeling studies of the circulation of major shelf and adjacent deep-water areas. Rarely are the two study types combined. This separation has made the integration of modeling and field program results difficult and has hampered the most efficient use of either type of study.
4. The wind fields used in calculating spill trajectories for the Atlantic, Pacific, and Gulf of Mexico regions have been inconsistent with the wind fields used to drive the circulation models. The use, until recently, of transition-probability matrices based on observations at a limited number of stations could have led to inaccuracies in the resultant trajectory calculations, especially when spatial variability is addressed by selecting discrete zones over which a given station and its associated transition-probability matrix are assumed to apply. Recent detailed analyses of winds observed onshore and offshore found large spatial and temporal variability in the structure of the wind field and the coherence between onshore and offshore stations. This variability is greatest near the coast, where land-sea interaction is an important factor.

Physical Oceanographic Models and Processes of Importance to the Esp

MMS's present and probable future reliance on numerical circulation models for physical oceanographic input to the OSRA model makes it imperative that the strengths, weaknesses, and limitations of the modeling approach be fully understood. This is true whether the circulation models are used in a predictive mode or for spatial and temporal extrapolation of observed data. In addition to considerations of the accuracy of the models used, attention must be paid to the time and space scales of motion that are required for accurate trajectory simulation. Also, an accurate representation of the physical processes that contribute to weathering is needed for the development of oil-spill-fate models. In considering these problems, the panel reached several conclusions about the present state of numerical circulation modeling and the physical processes that must be represented for accurate modeling of the transport and fate of oil spills in the ocean:

1. MMS puts too much faith in the available circulation models. Although the models used by MMS contractors often represent the state of the art, the state of the art does not justify MMS's implicit trust. Verification, intermodel comparison, and sensitivity studies are needed. Areas for possible improvement that are common to most numerical models have been identified in this review, including the parameterization of subgrid-scale processes, in vertical and horizontal dimensions; construction and use of appropriate lateral open-boundary conditions; better incorporation of driving forces at the surface (e.g., wind, heating, and cooling) and at the coast (e.g., riverine inputs); and incorporation of data directly into the model, to derive full benefit from a set of observations. In all cases, it is important to test fully a model against observations and to understand its behavior. Techniques to accomplish these often difficult tasks quantitatively are becoming available but are too seldom used.

   Numerical general circulation models alone will not simulate the circulation with enough realism for trajectory prediction or estimation of trajectory statistics in the next few years. Model studies need to be supplemented with more field observations. Trajectory predictions or estimations of trajectory statistics realistic for use in risk analysis or in accident management cannot be obtained without new fieldwork, including drifter studies. Although these observations ultimately might help the development of circulation models-and it is hoped that they will be in quantitative agreement with existing data-MMS's immediate priority should be to take more field observations and to incorporate them into trajectory predictions.

2. Although physical oceanography does not usually include considerations of the behavior of oil and other contaminants per se, oil-spill-fate modeling is quite important for accurate prediction of oil-spill behavior. The panel's review has concentrated on spreading and dispersion of oil, since they are the most closely tied to near-surface physical oceanographic processes. Spreading is one of the most important processes in oil-spill dynamics, because it determines the areal extent of spilled oil and affects the various weathering processes influenced by surface area. Dispersion is generally assumed to result from wind-generated breaking waves dispersing oil in the water column. Both processes are as yet poorly understood, but both depend critically on the interactions of the wind, the surface wave field, the response of near-surface waters, and the use of chemical dispersants. Thus, the incorporation of oil-spill-fate models into the OSRA framework will require accurate representation of physical processes occurring at and near the surface.
3. As a consequence of surface concentration of oil in oil spills and relatively rapid weathering, the principal physical oceanographic problems are understanding and predicting the motion and fate of oil in surface waters over periods of up to 30 days. During this period, several physical oceanographic factors are important to the net motion and variability of spill trajectories. Primary among these is the response of surface waters to wind forcing, including spatial and temporal variability of both the wind field and the surface response. Variability of underlying currents in this time frame also is important, but to an unknown degree relative to direct wind forcing. Mesoscale oceanic features are principal examples of this variability, affecting the motion of water over the OCS and slope and the exchange of water and material across the shelf break, although they do not appear to influence currents over the inner and midshelf. Important examples of mesoscale motions can be found on all U.S. margins: Gulf Stream meanders and filaments in the South Atlantic Bight; warm core rings in the North Atlantic Bight; the jets, squirts, and filaments of the California Current system; eddies of the Loop Current in the Gulf of Mexico; and (probable) eddies of the Bering Slope Current in the Bering Sea. The current practice of specifying only seasonal mean currents for input to the OSRA model does not properly account for the variability that may be associated with these mesoscale motions.
4. Mean flows do not contribute much to the variability of oil-spill trajectories but can be responsible for substantial advection of oil. Mean flows are often observed to run counter to the direction of the mean wind stress, often in the direction of coastal-trapped-wave propagation. There are several possible driving mechanisms, including undercurrents of the wind-driven circulation, density-driven flows due to input from rivers of fresh water at the coast, response to alongshore pressure gradients in the adjacent deep ocean (probably not very important), and nonlinear rectification of current fluctuations, among others. It is likely that different mechanisms are dominant in different locations, but it is not yet possible to determine causality for any given location. Prediction of seasonal mean currents based on the seasonal mean wind stress and the density field alone may not yield correct results.
5. At higher frequencies, surface and internal tides and higher-frequency internal waves generated by the interaction of tides and topography are a ubiquitous feature of continental shelf flows. Alongshore tidal currents may not be a dominant component of the alongshore variance, but can be highly amplified by local topography. Cross-shelf tidal currents are often the dominant component of the cross-shelf variability. Rectification of tidal currents is the dominant component of the mean flow in some locations. Tides and the internal motions generated by tides may be an important mechanism for mixing, especially over the inner shelf and at the shelf break. In addition, surface convergences associated with internal waves concentrate buoyant material quite effectively. The importance of these smaller-scale processes for the motion of oil spills needs to be investigated, especially nearshore.
6. Strong storms produce major perturbations in transport and mixing in continental shelf waters, but storm-induced flow and mixing are poorly understood. According to Allen et al. (1987), "The effect of the large currents, mixing, and the transport associated with the storms on the shelf budgets and on the transport of material are important unsolved coastal problems. Coupled meteorology and physical oceanography programs [are] needed to understand the detailed cyclogenesis and subsequent meteorological forcing." The effects of storms are particularly important for near surface-mixing and transport, including the motion and fate of oil spills.

7. The details of the structure and dynamics of the surface mixed-layer are very important to understanding and predicting the behavior of oil in near-surface waters, as well as the transfers of mass, momentum, and heat across the ocean surface and down into the ocean interior, and the structure of the surface and near-surface velocity fields. Research on the dynamics of the oceanic surface layer has resulted in significant advances over the past decade, but there are still important questions that have not been answered or even adequately addressed. Current parameterizations for the moisture, momentum, and heat fluxes across the air-sea interface are workable, but there is little consensus on the actual physical processes that control the fluxes. Candidate processes are surface wave breaking, Langmuir cells, and shear-generated turbulence, among others. It is also well known that upper-ocean processes are intrinsically three-dimensional, and that the three-dimensionality can have important consequences for all of the important transfer processes in the surface layer, especially in the vicinity of fronts associated with upwelling and other larger scale processes. Thus, two-dimensional models are of limited use. The models used for oil-spill transport and fate calculations need improved parameterizations for subgrid-scale variability in surface layer processes in both the vertical and horizontal dimensions.
8. Cross-shelf flows, although particularly difficult to measure, are of direct importance to cross-shelf exchange processes and often provide a clearer diagnostic signal for model and data comparison than do alongshelf flows.
9. Direct measurements of Lagrangian motion with drifters, although few, have indicated that the Lagrangian mean transport may not match transports derived from Eulerian measurements. This is certainly the case in the presence of strong horizontal gradients in velocity, but the problem also may depend on season and location in some unknown way. Since oil spills are inherently Lagrangian, whereas the circulation fields used as input to the OSRA model are Eulerian, the problem is of direct relevance for spill trajectory calculations.
10. The presence and dynamics of ice are clearly an important feature for modeling oil trajectories in most Alaskan waters and some nearshore New England waters during especially cold winters; ice conditions are highly influential in determining the movement and final disposition of spilled oil. The panel concluded that the problems of modeling sea ice and ice-oil interaction were truly at the process level and not simply at a descriptive level for the Alaska region. Several well-developed ice models are currently available for application to the Alaskan OCS waters, but there is little sense of. how well these models actually perform in representing the range of ice conditions for the OCS areas; verification against data and sensitivity studies are needed. Interactions between oil spills and sea ice are extremely complex, depending on the percentage of ice cover, ice motion, temperature, wind, duration of ice cover, and the history and location of ice-oil contact. Several researchers have attempted to quantify and predict some aspect of oil-ice interactions, but most research has been carried out under laboratory conditions only and thus is limited in either dimension or scale; more research is needed. Extension of spill models to handle oil-ice interactions has been extremely limited.

    A fully coupled ice/hydrodynamics model should be applied to selected areas and times for which data are available, and a detailed model-data comparison should be done. In addition, an extensive series of sensitivity studies should be performed to determine those parameters critical in controlling the solution (stress-strain relationship, elastic, plastic, viro-elastic, type of yield surface, air-ice drag coefficient, ice-water drag coefficient, boundary conditions, initial conditions). Such studies will document the present ability to predict ice motion and probably, and most importantly, indicate where present understanding is weak and needs improvement.

    Some of the conditions that should be reproduced in ice models include the location of the pack-ice edge and the various percentages of ice coverage of areas versus time (including interannual, seasonal, and short-time-scale, wind-forced variability); occurrence, dynamics, and causes of breakout events through the Bering Strait; the movement of the pack ice; the ice thickness distribution; the freezing and thawing processes at the ice edge and in leads; and the response of ice in free drift motion to wind and current forcing.
11. Studies of bottom boundary-layer and sediment-transport processes on the continental shelf are germane to the overall goals of the ESP in two ways. First, the drag exerted by the bottom on the flow, and the structure of the flow within the bottom boundary layer, are important for understanding the overall structure and dynamics of flow on the continental shelf;

this is increasingly true as the depth decreases. Recent advances in boundary-layer modeling have indicated that the nonlinear nature of the turbulent bottom boundary layer necessitates inclusion of motions at higher frequencies and consideration of stratification effects for accurate calculation of bottom stresses. Second, sediment-transport studies support concerns about both the long-term effects of oil incorporated into bottom sediments and the motion of drilling muds and cuttings.

In the view of the panel, however, bottom boundary-layer and sediment-transport studies are outside the immediate domain of this review. The focus of this review and of ESP physical oceanography in general is the motion and fate of oil in surface and near-surface waters. Accurate modeling of bottom stress and boundary-layer velocity remains an important consideration, particularly because of their effects under extreme conditions, but at a secondary level relative to understanding the processes that directly influence surface flow and mixing. The transport of drilling muds and cuttings is most likely limited to the immediate vicinity of drilling activity for the coarse fraction, which makes up about 90% of the effluent (see, e.g., NRC, 1983). Long-term ecological effects of oil incorporated into the sediments may be important and may depend on sediment-transport processes, but the panel felt that these considerations are properly the domain of the Ecology Panel.

Regional Oceanography

The continental margins covered by the four regional offices of MMS's ESP are distinguished by far more than MMS's internal division of responsibility. The four regions have fundamental differences in their geology, topography, and bathymetry and in the processes that control the circulation of shelf waters and affect the motion of oil in surface waters of the regions. These differences are apparent even between subregions within each region. In general, the physical oceanography of all of the major continental margins is reasonably well understood, especially from a basin-wide, descriptive point of view. There are exceptions for specific areas (e.g., the shelf of the Gulf of Mexico), and the details of specific processes that are active in the various regions are still under investigation.

In addition to the mesoscale oceanic motions identified above, there are some general circulation processes in each of the regions that require particular attention. Briefly, these are as follows:

1. In the Alaska region, the presence of sea ice, which varies from season to season and from subregion to subregion, is an important factor. Large interannual variability associated with ENSO events has also been observed. Sea ice and interannual variability combine in the Bering Sea to create a large interannual and seasonal variability in ice cover, temperature, and winds. Two topics worthy of investigation are interannual variability in all the Alaskan waters (Gulf of Alaska, Bering Sea, and Beaufort Sea-Chukchi Sea-Arctic Ocean) and the circulation along the Bering Sea continental slope.

   The subsynoptic-scale weather associated with orographic effects is important, particularly in the Gulf of Alaska and along the Beaufort Sea coast, but no general algorithms and approaches exist to define the winds in these areas. The FNOC model does not adequately address this problem in that it does not include realistic topography. In addition, these winds tend to be at subsynoptic or subgrid-scales. Further modeling of the effects of orographic winds would be useful.

   Freshwater runoff is a major forcing mechanism for circulation in the Gulf of Alaska.
2. In the Pacific region, the process of wind-driven coastal upwelling is particularly important, because the winds are predominantly southward throughout the summer over most of the coast. Interannual variability associated with ENSO events in the tropical Pacific has been identified, but interconnections between coastal, oceanic, and atmospheric responses are not well understood as yet.
3. In the Gulf of Mexico region, 21 major estuaries are found on the U.S. coast. A number of rivers dominated by the Mississippi River provide sufficient freshwater input so that the basin may be classified as a positive estuary. An additional, very important factor for

oil-spill-risk analysis is the regular presence in the gulf of major tropical storms and hurricanes that can cause great damage and may result in rapid, extreme, wind-forced surface transport.

4. In the Atlantic region, storms are common in the winter, with cyclogenesis occurring south of Cape Hatteras and intense nor'easters occurring over the Mid-Atlantic Bight. Tropical cyclones and hurricanes may strike many of the offshore sites along the Atlantic coast. A distinct feature of the Atlantic shelf regions is a seasonal shelf break front, which separates well-mixed water over the shelf in the winter from the slope waters in the Mid-Atlantic Bight and from Gulf Stream waters in the South Atlantic Bight. The front is weakened in summer by uniform thermal stratification in the surface layers. The contributions of shelf-break frontal dynamics to cross-shelf exchange and to the concentration and transport of surface buoyant material are poorly understood.

Evaluation of Regional Programs

In evaluating the physical oceanographic components of the ESP of the four regional offices and the WO, the panel noted several general tendencies. Those not mentioned above are summarized below:

1. In general, MMS-funded physical oceanography studies have fit in well with studies funded by other agencies (e.g., USGS, NOAA, and NSF) and have contributed to the increase in our knowledge of the coastal oceans that has occurred over the past decade.
2. Although there are variations from region to region, too little of the work carried out for MMS has been published in the open, refereed literature. This is particularly true of the modeling and model-data intercomparison studies. Publication in the open literature would both improve quality control of MMS-funded efforts through the peer-review process and substantially increase the body of knowledge available to the oceanographic community, at little extra cost. MMS's recent efforts in this direction are commendable.

   Specific conclusions for the regional evaluations are as follows:
3. In the Alaska region, more of the observational study results appear to have been published in the open literature compared to other regions; some of the modeling work has been published, but not enough. The general state of knowledge appears to be good, given the enormous size of the region. More site-specific observational studies will probably be required once oil production starts. The recent Alaska region modeling efforts have incorporated improved techniques, especially with regard to use of temporally and spatially varying wind fields that are consistent between the hydrodynamic model and the spill trajectory model; this is due partially to the practice of the contractor performing spill trajectory calculations.
4. There have been a number of large studies in the Pacific region, both observational and modeling, but to date the contributions by the West Coast programs to state-of-the-art knowledge, as measured by the number of refereed publications, have not been impressive. Only one refereed journal article on an observational study has appeared, and the lead author on that paper was funded by NSF, not MMS (Brink and Muench, 1986). The potential return from these experiments has not yet been realized, possibly because contractors have not employed sufficient outside (university) personnel and have not spent sufficient resources on detailed analyses. The modeling work, if published, could make a contribution by illustrating the inadequacies of a state-of-the-art numerical model; that is, deficiencies can provide important clues as to the physics that might be missing and other model shortcomings. The circulation model used in all West Coast modeling studies is a state-of-the-art model, but the modeling studies have had serious inadequacies.
5. In contrast to the other regions, there have not been many extensive basic research programs in the Gulf of Mexico, in spite of the fact that the gulf has had by far the greatest amount of acreage leased and the greatest amount of oil produced. In particular, no major shelf circulation studies have been conducted, although there have been several small-scale investigations. There have been few useful results of MMS-funded modeling efforts, except for

recent efforts using the Hurlburt and Thompson two-layer model. These modeling efforts have led to an improved understanding of the major circulation features in the gulf, and of the boundary conditions required for modeling the shelf circulation, a task that remains to be done. In addition, the long history of offshore drilling and large numbers of active leases in the Gulf of Mexico make long-term impact studies crucial. It is clear that the MMS Gulf of Mexico regional office cannot afford to fund such extensive studies without significant additional support.

6. MMS has funded many large physical oceanographic studies in the Atlantic region, both observational studies and modeling. In most cases, the observational studies have provided fairly high-quality data on the mean and variable circulations in the various areas. The analyses of the individual data sets by the subcontractors are competent; however, there is no quantitative synthesis of the various types of data to produce a dynamically consistent description of the flow, and it does not appear that much of this information (or any synthesis work) has been published in the reviewed literature. There appears to be little relationship between the modeling work and the data collection. The reports do not reference each other and the modeling does not appear as a subcontract in the same project as the observational work (with the exception of the Mid-Atlantic Slope and Rise Study). The data used in the models comes from the historical record; verification of the models has been minimal.
7. The efforts of the WO, in contrast to the regional offices' goals of data collection, analysis, and synthesis, are focused on supporting regional studies, addressing generic process and modeling issues, and summarizing or documenting previous studies programs. The number of physical oceanographic studies funded under the WO is extremely limited, but according to the material available, those studies completed under the WO have addressed areas of real concern and have been completed with quality products in a timely manner. An important question is why the WO budget is so small compared to its regional counterparts. There are several important generic research efforts that would clearly seem appropriate for the WO under the generic studies category that have in the past been carried out by the regional offices. It appears that these studies could have been better directed and more efficiently executed, with results that would have been more widely useful, if they had been conducted under the aegis of the WO. The mandate to complete these overview or generic efforts belongs with the WO, and the management structure and funding allocations should clearly reflect that.

RECOMMENDATIONS

There are three general recommendations of the panel for future ESP physical oceanography and oil-spill studies, each of which has several associated specific recommendations:

1. **The Minerals Management Service should support continuing research on relevant physical oceanographic and meteorological processes and features that are poorly understood, poorly parameterized in existing models, or poorly represented by existing modeling methodology. Improvements should continue to be incorporated into the OSRA model.**

a. MMS should support continuing investigations of surface-layer physics, aimed at improving basic understanding and modeling. The detailed physics of the surface layer is poorly understood, and many potentially important physical processes are not included in oil-spill-trajectory models as a result. These include surface and subsurface fronts and convergence zones, Stokes drift, Langmuir cells, shingles, interleaving, and breaking wave dynamics. It is not known how these factors might affect oil movement, but it is time that the "3.5% rule" or one of its variants be replaced by a more accurate description of near-surface drift. (MMS accounts for wind-induced drift by assuming it to be 3.5% of surface wind velocity with a variable drift angle to the right). Advances in this area will also help to better approximate near-surface physical processes that control the dispersion of oil into the water column.

The dispersion models currently available give order-of-magnitude estimates for oil incorporation into the water column but are not sufficient to provide accurate, quantitative predictions. New fundamental insights into the near-surface processes are required to provide improved estimates of these fluxes.

b. Understanding and modeling oil-spill-fate processes are very important to the leasing and environmental assessment studies program. MMS should continue to support research in these areas. Although considerable MMS funds have been invested in such studies to date, the return in terms of improved algorithms to estimate oil-spill fate has been minimal. Fate processes that deserve particular attention are drifting, spreading, dispersion (naturally or chemically enhanced), and dissolution. Studies on actual large spills, such as the *Exxon Valdez* spill in Prince William Sound, would be useful in this regard. The interaction of oil and ice, particularly in freezing, thawing, and partial ice-cover conditions, also needs further research.

c. Additional studies of sea ice, both modeling and observation, are needed. Better representations of ice thickness and constitutive relationships need to be explored to determine whether these give better estimates of ice motion. Detailed model-data comparisons need to be done, and sensitivity studies are required to determine the parameters that are critical in controlling model solutions.

d. Calculations of oil-spill trajectories at the sea surface and those for the underlying currents should be consistent. The MMS practice, until recently, of using wind patterns that are not related to the winds driving the water motions may have led to substantial errors in estimating the oil motion. The same considerations apply to calculations of ice motion in Alaskan waters. In addition, MMS should be sure that sufficient trajectory simulations are performed to develop stable, robust statistics for impacts on environmental resources. This requires that sufficient trajectories be calculated such that the distribution of impacts is independent of the number of trajectories simulated.

e. The meteorological input to oil-spill-trajectory simulations needs to be improved to account correctly for the spatial and temporal structure of the wind field. The use of transition-probability matrices, either based on wind time series or weather patterns, as used until recently for many OCS areas, does not yield accurate temporal correlation and has little or no spatial structure. A meteorological model (e.g., limited-area fine-mesh), with appropriate interpolation to smaller scales, is one way to address the need for an accurate and consistent definition of the wind field. Such a model would help to accurately reproduce mean, storm, and extreme events that characterize the meteorology of an area. In Alaskan waters, orographic effects require particular attention. MMS's recent moves to adopt such procedures are commended.

f. More consideration needs to be given to extreme events (e.g., hurricanes) that may lead to both higher spill probability and more rapid water and oil motion. The present MMS procedure is least accurate at low probability levels associated with extreme events. However, even extremely small impact probabilities may be critical if important resources are affected. MMS might consider studying several extreme-event scenarios as special case studies for each lease area.

g. Future trajectory simulations should incorporate a methodology to address the inherent variability in both the wind field and the current field at subgrid space and time scales. For each realization, the resulting random contribution to the trajectory and effective dispersal of the oil needs to be included or evaluated.

h. MMS's study of the use of drifters to represent oil spills should be extended to actual field trials in varied areas of the OCS, and similar regions worldwide as the opportunities occur. The drifters must reasonably represent oil movements. Experiments should be fairly extensive, in order to acquire sufficiently large data sets to test models. Multiple deployments of ARGOS-tracked drifters from selected high-risk launch points should be compared with model-predicted trajectories. This comparison will provide an excellent test of the ability of the model to predict trajectories and, of equal or greater importance, help to identify model weaknesses.

2. **MMS should reduce its present overreliance on model results until the models can be more fully tested and verified; such testing will require sensitivity analyses and model intercomparisons. MMS should use its extensive observational data base more fully. Verification will require close cooperation between field scientists and modelers in all future MMS programs.**

a. It is recommended that MMS use a more balanced integration of model and field-data products for future trajectory calculations. MMS has adopted a de facto procedure of using hydrodynamic model simulation results to describe the current fields for input to oil-spill-trajectory calculations. Unfortunately, this strategy has ignored the extensive data collected in physical oceanographic field programs and the subsequent analysis and interpretation of that information. The possibility that numerical models may never provide a simulation of the circulation adequate for determining trajectory statistics needs to be considered.

b. For scientific credibility, it is imperative that detailed sensitivity studies be carried out for all modeling work. Hydrodynamic model parameters that should be studied include boundary conditions, initial conditions, eddy viscosity and turbulence representations, grid size, bottom friction coefficients, and forcing functions. For oil-spill-trajectory models, the relative roles of wind and current forcing should be assessed, at a minimum. Without some understanding of the factors and processes that limit the oil-spill-motion calculation, it is difficult to either assess or improve the modeling. These sensitivity studies will also allow insight into model strengths and weaknesses.

c. Systematic model intercomparison and verification must also be carried out for scientific credibility. MMS should have an intercomparison study performed between the various hydrodynamic models used for predicting current fields, to allow model strengths and weaknesses to be documented and to enable rational scientific evaluation of the various approaches. Verification against data—including data from actual spills—must be much more thorough. Systematic model evaluation and verification against all available data, for both currents and oil-spill trajectories, should be routine. More attention needs to be paid to cross-shelf currents in this process, because cross-shelf currents are more sensitive to model assumptions than are alongshelf flows.

d. Future MMS-sponsored physical oceanographic field programs should require close cooperation between field scientists and modelers. More input from field scientists is also needed in model design, application, and verification. Physical oceanographers engaged in field work and modeling should work closely together to design observational and numerical experiments so that necessary and sufficient initial, boundary, and updating data, as well as critical data sets for calibration and verification, are all obtained. Consideration should be given to the latest techniques for obtaining the required amount of observational data. For example, use of aircraft and spacecraft data from NASA and NOAA could prove of value.

e. Given the present level of understanding for most shelf regions of interest to the OCS leasing program, a carefully integrated program using field observations and numerical hydrodynamic modeling is suggested to provide a description of the circulation necessary as input to the OSRA model. The exact details of a modeling strategy to be used are critically dependent on the principal forcing and circulation features of the shelf area of interest. A practical general strategy to achieve representative circulation data would include the following: (1) Predict the circulation associated with known forcing (tides, winds, and density) using separate simulations for each forcing. The dimensionality of the model should be selected to provide the most accurate and efficient computation for each forcing parameter. As an example, two-dimensional, vertically averaged simulations might be adequate to model tides. Three-dimensional simulations are probably required for the density and wind-driven flows. The duration and temporal resolution of the predictions will depend on the particular forcing parameters of interest. (2) Assess the potential interactions between the various forced flows by model-sensitivity analyses. This might lead to modifications of the simulation procedures for the individually forced flows noted above. (3) Compare the model predictions with observations of the current (Eulerian and Lagrangian), sea-surface elevation, and hydrographic structure. (4) Use data-assimilation procedures and modifications of the hydrodynamic model parameters and open-boundary conditions to optimize agreement with observations. (5) Assemble circulation data sets that accurately define the flow field and its associated spatial and temporal variability for input to the OSRA model. The circulation data set should cover a long enough time (about 8-10 years) to represent the important time scales of variability in the circulation so as to assure accurate oil-spill-trajectory predictions. The recommended modeling strategy allows a practical, cost-effective methodical approach to describing the circulation as input to the OSRA model. The model can also be used as a research tool to investigate the sensitivity of predicted currents and spill trajectories to interactions between the variously forced flows, poorly known model parameters (e.g., vertical eddy viscosity), and open-boundary conditions. This approach should also serve to advance knowledge of the circulation dynamics and assist in planning observational programs.

f. The Minerals Management Service should strengthen its ability to respond scientifically to accidental oil spills, such as the *Exxon Valdez* spill. MMS should maintain the capability to initiate studies of oil spills rapidly and should have workable plans to coordinate such studies with those of other federal agencies, in particular the Fish and Wildlife Service, NOAA, and EPA; state agencies; and industry. Oil spills are rare scientific opportunities for MMS to assess its current understanding of oil-spill transport and fate. These opportunities should allow MMS to validate models of oil-spill fate, and oil-shoreline interaction. In physical sciences, such studies should include (but not be limited to) the deployment of drifters as MMS did in the Prince William Sound spill, chemical studies of oil and sea water, and verification of models.

g. The recent oil spill in Prince William Sound illustrates the importance of analyzing worst-case scenarios. For individual lease sales, MMS has historically used a probabilistic representation to assess the potential impact associated with development and production scenarios. Although this appears to be a reasonable approach, MMS should supplement this approach by studying (in a non-probabilistic manner) several worst-case scenarios as well, as was done for the siting of the Alyeska terminal in Valdez (U.S. DOI, 1972). These scenarios should include spill location, volume, rate of release, oil type, and environmental conditions and should address a variety of likely cleanup responses.

h. Although technically MMS's jurisdiction covers the OCS, MMS should consider oil spills occurring shoreward of the OCS. The panel notes that oil spilled inshore of the OCS could well be OCS oil.

3. **Program priorities and operating procedures in the ESP should be modified as necessary to ensure that improved scientific input is obtained at all stages of ESP operation in all regions, that available data from cooperating agencies are used, that development of a better-integrated national program continues, and that study results are published in the open literature.**

a. Appropriate balance between national and regional priorities is needed. Physical oceanographic and hydrodynamic modeling studies have been performed for all the major offshore lease areas, with particular focus on basin-wide studies (South Atlantic, Gulf of Mexico, Southern California shelf, Bering and Chukchi seas, and the Beaufort Sea). Some shelf areas, however, have not been adequately studied, the most striking example being the Gulf of Mexico. Long-term studies are also crucial.

b. Improved scientific input needs to be obtained and used more fully in the formulation of 5-year plans, in the preparation of RFPs, and in program assessment, including the synthesis of field data and models and production of final probabilities for oil-spill distribution. Possibilities for improved scientific input include:

- Having university research scientists and faculty and government agency researchers (e.g., EPA, NOAA, ONR, NASA, U.S. Army Corps of Engineers, Coast Guard) work with the ESP staff in a visiting scientist capacity. Similar programs have been successfully used by ONR and NSF.
- Individually or jointly sponsoring a specialty conference or special sessions at an existing conference (OCEANS, Offshore Technology Conference, Oil Spill Conference, American Society for Testing and Materials) on modeling of oil-spill fate and impact assessment.
- Continuing to expand the use of peer review for RFP preparation, proposal evaluation, and critique of contract work products. Peer review, properly used, is an excellent way to maintain the quality and scientific integrity of a contracted scientific research program.

c. MMS's cooperation with other agencies is commended. These collaborations can provide much valuable information at low cost. Efforts to synthesize data from experiments of other agencies into a form usable by MMS should be encouraged.

d. The establishment of the ESP was accomplished historically by assembling, and to a limited extent integrating, the study programs of the regional offices. Recently the WO has taken a more active role in shaping the program by developing a 5-year plan and fully integrating the regional study efforts. This is a positive step in managing the overall program. Efforts should continue to develop a better-integrated national program while maintaining the regional office structure.

e. MMS should continue to strengthen its program and have the results of its studies presented at scientific meetings and published in the open, refereed literature. This includes funding for manuscript preparation, publication charges, and travel to attend meetings. Interagency agreements that MMS has with NOAA, USGS, and others should also include this requirement when specifying contract deliverables.

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Appendices

Appendix A

Glossary Of Physical Oceanography Terms

Aliasing.	The result, in the determination of the spectrum of a data set, that signals with periods shorter than twice the sampling interval have their energy appear at longer periods (lower frequencies) in the spectrum.
ARGOS.	A commercial satellite service that operates by receiving information from drifters and subsequently relaying the information to ground-based stations.
AXBT.	Air-dropped expendable bathythermograph.
Baroclinic.	Baroclinic flow is the portion of the flow due to the additional horizontal pressure gradients resulting from density variations (as Opposed to the portion caused by the slope of the free surface).
Barotropic.	Refers to flow fields that are not affected by the density stratification.
BEE.	MMS's Branch of Environmental Evaluation.
BEM.	MMS's Branch of Environmental Modeling.
BES.	MMS's Branch of Environmental Studies.
Beta plane.	An approximation in which the variation of the Coriolis parameter is taken to be linear with latitude.
BLM.	Bureau of Land Management.
Brunt-Väisälä frequency or buoyancy frequency.	The largest temlporal frequency that internal waves can have. Typical oceanic values are 10^{-3} $s^{-1<}$
Buoyancy-driven flow.	Currents occurring due to thermodynamic ocean forcing. An example is the flow field due to freshwater input from rivers or precipitation.
Circulation model.	A physical oceanographic mathematical model that calculates estimates of the currents and mass distribution as a function of time and space.
Coastal-trapped waves.	Waves that propagate along the shore and not out to sea. These can be either surface waves or internal waves.
CODE.	Coastal Ocean Dynamics Experiment.
Convergence zones.	Areas where currents come together.
Coriolis parameter.	The strength of the apparent force that, as a result of the earth's rotation, tends to divert objects to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.
CTD.	Current, temperature, and depth. A CTD station will continuously monitor these three quantities.
CTM.	Characteristic tracing model.
Curl.	A measure of rotation in the wind-stress field.
Cyclogenesis.	The processes that create atmospheric or oceanic counterclockwise (clockwise) rotation eddies in the Northern (Southern) Hemisphere.
Deep-water wave.	A wave whose length is small compared to water depth and whose speed is determined by wave length.
Diagnostic model.	Steady-state (stationary) ocean circulation model determined from real data.

Dispersion.	The spreading of waves as opposed to the steepening of waves (wave dynamics usage); transport of oil from the sea surface into the water column primarily due to breaking wave activity and associated near surface turbulence (oil-spill-modeling usage).
Doppler shift.	The change in frequency due to relative motion; e.g., the whistle of an approaching train has a higher frequency than the whistle of a departing train.
Eddies.	In this report, organized horizontal structures that rotate either clockwise or counterclockwise. Gulf Stream rings are examples of eddies.
Eddy coefficient.	The horizontal or vertical mixing coefficient with units of velocity * length. e-folding. A factor of l/e, represents the time/space scale for a change of I/e if exponential decay/growth is assumed.
Ekman layer.	The upper few tens of meters of the ocean, which are susceptible to wind-induced transport.
Ekman pumping velocity.	The vertical velocity in the ocean that is proportional to the curl of the wind stress.
Ekman spiral.	The flow direction of the Ekman transport. It rotates clockwise with increasing depth.
Ekman transport.	The horizontal transport of mass by currents in the upper few tens of meters of the ocean by the local wind. It is a function of latitude due to the effect of the Coriolis acceleration (the effect of rotation of the earth) and the wind stress.
El Niño.	The appearance of anomalously warm water off South America in the eastern tropical Pacific.
ENSO.	El Niño-Southern Oscillation. ESP. Environmental Studies Program.
Eulerian.	See *Lagrangian*.
FACTS.	Florida Atlantic Coast Transport Study.
Filaments.	Typically, narrow mesoscale ocean circulation features in the upper ocean that have temperature and/or density characteristics of nearby prominent features. For example, patches of water originating from the Gulf Stream are found inshore off the Carolinas.
FNOC.	Fleet Numerical Oceanographic Center.
Friction velocity.	The square root of the wind or ocean horizontal shear stress divided by the local density, which has the unit of velocity; an important velocity scale for shear generated turbulence. GALE. Genesis of Atlantic Lows Experiment. GARS. Gulf of Alaska Recirculation Study.
GCM.	General circulation model.
GOES.	Geostationary operational environmental satellite.
Geostrophic currents.	Horizontal currents in which the Coriolis acceleration is balanced by the horizontal pressure gradient.
Gulf Stream rings.	The Gulf Stream sheds 10-20 strong eddies each year. These are called rings because they have a ring of strong currents (1-3 m/s) at a radius of 50-150 km. The eddies shed to the north of the Gulf Stream have warmer centers and the currents are clockwise (warm-core rings). The rings to the south have relatively cold centers and the currents are counter-clockwise. These rings usually propagate slowly westward and thus the warm-core rings eventually strike the continental shelf/slope region north of the Gulf Stream.
Hamiltonian.	An integral rather than differential statement of the dynamics of a system.
Internal waves.	The up-and-down movement of horizontal density surfaces. These structures propagate horizontally and vertically in the ocean.
Internal Kelvin waves.	(See *coastal-trapped waves*). These propagate with the coast to the right in the Northern Hemisphere, with the maximum amplitude at the coast. They are named after Lord Kelvin, who discovered the phenomenon mathematically in the late 19th century.
Inversion.	An increase of temperature with increasing altitude in the atmosphere, or with increasing depth in the ocean.
Inviscid.	Without friction as a mechanism in the motion of a fluid.
ISHTAR.	Inner Shelf Transport and Recycling.

Isopycnal.	Line of equal density.
Lagrangian.	Refers to motion following a specific small parcel of fluid, oil, or buoy. The opposite is *Eulerian*, which refers to motion at a fixed point.
Langmuir cells.	Long (1-20 km), organized mesoscale structures in the mixed layer that occur in light winds and transport material in the upper ocean.
LFM.	Limited-area fine-mesh meteorological model.
Loop Current.	The clockwise bend in the surface ocean current that flows northward past the Yucatan Peninsula toward Florida and then turns to the southwest toward the Straits of Florida, where the current is called the Florida Current.
M_2 constituent.	The principal lunar component of semidiurnal tides.
MASAR.	Mid-Atlantic Slope and Rise study.
Mesoscale.	In this report, circulation features on horizontal length scales of 5-100 km.
Microstructure.	Small (1-20 cm) vertical variations in the oceanic temperature, salinity, or density structure.
Mixed layer.	The upper few tens of meters of the upper ocean, which have an almost uniform temperature. The depth at which the ocean temperature decreases by 0.2°C is a common definition of depth of the mixed layer.
MMS.	Minerals Management Service of the U.S. Department of the Interior.
Modes.	In this report, vertical structures. *Higher mode* means smaller vertical structures
Monte Carlo technique.	A statistical sampling technique used to create estimates of random processes.
NOAA.	National Oceanic and Atmospheric Administration.
NODC.	NOAA's National Oceanographic Data Center.
Obukhov scale.	A vertical atmospheric or oceanic length-scale that is proportional to the vertical transport of heat and momentum.
OCSEAP.	OCS Environmental Assessment Program (Alaska, operated by NOAA and MMS).
OCSLA.	Outer Continental Shelf Lands Act of 1953.
OCSLAA.	Outer Continental Shelf Lands Act amendments of 1978.
OPUS.	Organization of Persistent Upwelling Structures program.
Orography.	Branch of geography dealing with mountains.
OSRA(M).	Oil Spill Risk Analysis (Model).
Polynya.	An open area of water surrounded by ice. Usually applied to areas of km size or larger.
Positive estuary.	Estuary having a higher freshwater input than evaporation.
Ppt.	Parts per thousand.
PROBES.	Processes and Resources of the Bering Sea Shelf.
Prognostic model.	Time-dependent ocean circulation model; a model that can produce forecasts.
Pycnocline.	The vertical section in the vertical density profile where the density changes most rapidly with depth.
Rectification.	Generation of time mean flows in an otherwise harmonic flow (i.e., tides) due to nonlinearities in the flow (convective accelerations, frictional dissipation, or violations of shallow water wave assumptions).
Reynolds stress.	The horizontal shearing stress due to turbulence.
Rings.	See *Gulf Stream rings*.
RMS.	Root Mean Square.
Rossby radius of deformation.	A horizontal length-scale equal to the gravity-wave speed divided by the Coriolis factor.
RTWG.	Regional technical working group.
SC.	Scientific committee.
Scatterometry.	A remote sensing technique to determine wind speed and direction using active microwave energy refracted from short (5-20 cm) surface waves.
Shallow water wave.	Wave length is much greater than water depth and wave height is small compared to the wave length. Wave speed determined by water depth.
Shallowing mixed layer.	A mixed layer whose depth decreases with time.

Shelf break.	The position in the ocean where the rate of deepening of the total depth abruptly changes. The inshore region is the continental shelf. The offshore region is the continental slope. The break usually occurs in depths of 100-200 m.
Similarity theory.	A mathematical technique that asserts the structural shape of a function and not its absolute shape.
Slope currents.	The currents at the edge of the continental shelf on the continental slope. The slope current is usually in water between 200-400 m deep.
Southern Oscillation.	A large atmospheric east-west circulation over the tropical Pacific and Indian Oceans that oscillates in intensity every 4-5 years.
Squirts.	Narrow (0-5 km wide) circulation features in the ocean surface layer that are highly time-dependent and transport mass and constituents onshore and offshore.
Stokes drift.	The Lagrangian net motion associated with finite amplitude waves. It transports mass in the direction of surface wave propagation.
Storm surge.	Rise in sea level, particularly noticeable at the coast, due to wind-induced setup and barometric pressure effects. Normally associated with the passage of atmospheric low-pressure systems (storms).
Subduction.	In this report, the sinking of dense, high-latitude surface water under the lighter surface water at lower latitudes.
Subinertial motion.	Time-dependent motions with periods less than the period of the earth's rotation. In middle latitudes this period is about 12 hours but it is a function of latitude and decreases toward the poles.
Sverdrup.	Transport of 1 x 10^6 m^3/s of water.
Synoptic scale.	A meteorological term indicating the scale of eddies resolved on weather maps, which is on the order of 1,000 km.
Subsynoptic-scale.	A meteorological term indicating the scale of eddies smaller than those resolved on weather maps.
Terrigenous.	Designating or of sea-bottom sediment derived from the erosion of land.
Thermal wind.	The change of wind or current with depth due to horizontal density variations; not a flow, but a rate of change of the flow in amplitude and direction.
Thermocline.	The vertical section in the vertical temperature profile where the temperature changes most rapidly with depth.
Transition probability matrix.	A matrix giving the probabilities that a variable will change from each possible state to every other possible state. For wind speed and direction, such a matrix would give the probability that a wind of a given speed and direction would change to any other speed and direction in a particular time.
Undercurrent.	A subsurface current that flows in an opposite direction to the surface current.
Upwelling.	The vertical movement of ocean water toward the surface.
VACM.	Vector-averaging current meter.
Waveguide.	Bathymetric or dynamic feature that controls wave propagation. The continental shelf guides waves to propagate in the alongshelf direction.
Wind stress.	The tangential force per unit area due to the horizontal movement of the wind over the sea.
WO.	MMS's Washington Office.

Appendix B

Workshop On Modeling In Physical Oceanography

The Physical Oceanography Panel convened a workshop in Seattle on August 5-6, 1987 to assess the current state of modeling for MMS, to compare these efforts to other state-of-the-art physical oceanographic models, and to recommend future modeling developments for MMS. The attendees, listed below, were MMS-funded modelers and outside experts (in addition to the panel members).

The panel is very grateful to these experts for their time and thoughtful discussions. The panel found the discussions and the workshop recommendations useful in the preparation of its report and in the development of its own recommendations.

Physical Oceanography Panel Workshop On Oil-Spill Modeling August 5-6, 1987

Participants

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Workshop Recommendations

Oil-spill motion:

The MMS procedure for analysis of oil-spill risks used in the lower 48 states has four parts:

- Estimation of spill probability, based on historical records.
- Monte Carlo simulation of trajectories (~500 spills per season, 30-day trajectories). This step uses water motions predicted form a numerical model and a separate simulation of winds, based on 3-hour transition probabilities and velocities usually from shore stations. The contribution from the wind is calculated at 3.5% of the wind with a variable drift angle to the right of the wind. This is added to the model's surface currents.
- The probability of hitting various "environmentally sensitive" areas is calculated from these trajectories.
- The conditional impact probability for a particular resource is then the spill probability times the hit probability.

In Alaska, the procedure has been different: more detailed consideration of the surface layer was made and trajectory calculations were carried out in conjunction with the circulation modeling.

The workshop focused primarily upon the numerical model predictions of water motion; however, the participants did also make more general recommendations about oil motion calculations.

1) The calculations of oil-spill movement should be made consistent with the modeling of water motion. The current MMS practice of using wind patterns that are not related to the winds driving the water motions may lead to substantial errors in estimating the oil motion. We recommend that the calculations of oil movement be made as a part of the model run. Models may have difficulty calculating Lagrangian trajectories; we suggest that it may be possible to calculate the probability distribution for oil as an alternative to trajectory modeling. It also seems reasonable to include weathering/fate calculations at the same time.
2) The meteorological effort needs to be more thorough. Representing wind changes by transition-probability matrices does not yield accurate temporal correlations. In addition, the spatial structure is not at all represented. Simulated winds, perhaps from an LFM (limited fine mesh model) with appropriate interpolation to even smaller scales, should be used whenever possible. The 3.5% rule needs more analysis or should be replaced by more accurate surface-layer models.
3) Extreme events and statistics must be considered. In any environmental problem, even extremely small impact probabilities may be important if an important resource is affected. The MMS procedure is probably least accurate at low levels of probability, right where the concern may be greatest. More consideration needs to be given to the extreme event—e.g., hurricanes—that may lead both to higher spill probability and more rapid water and oil motion.

   Models:

   Realistic, applied modeling of ocean dynamics is a rapidly evolving field. In the view of the workshop participants, there are a number of state-of-the-art models for calculating water flows that have been made available to MMS by their contractors. However, participants recommended:
4) The ice modeling has not been state-of-the-art; more modern models include calculations of thickness distribution and use of an elastic-plastic or viscous-plastic constitutive relationship with the strength calculated from an energy balance statement. Some participants felt that such models may be more sophisticated than required for estimating oil-spill motion.

5) Other physics must be assessed. A number of potentially important physical processes are not included in these models—surface fronts and convergences, Stokes' drift, Langmuir cells, and other near-surface processes. It is not known how these factors might affect oil movement. In each region, MMS needs to take a careful scientific look at both modeling and data-gathering efforts to ensure that the work is matched to the kinematics and scales of the transport processes and to assess the necessity for including other processes.

6) Sensitivity analyses should be carried out for all modeling work. There is essentially no information on the sensitivity of the model results or, even more seriously, of the final trajectories to the initial conditions, fluid and ice boundary conditions, forcing functions, etc. Without some understanding of the factors and processes that limit the oil-spill-motion calculation, it is difficult to either assess or improve the modeling.

7) Model intercomparison and verification cannot be neglected. In addition to better validation against data (discussed below), the group suggested more model-to-model comparisons, independent critiques, and more efforts on quality control.

Relationship to field work:

The workshop participants agreed that the relationship between MMS-funded field work and modeling activity is insufficient and does not reflect state-of-the-art practice.

8) Verification against data must be much more thorough. A new program should be initiated to perform systematic model evaluation and verification against data not only for currents but also the trajectories/probability distributions themselves.

9) Better cooperation between observers and modelers is essential in planning work in new regions. Physical oceanographers engaged in field work and modeling should work together closely to design observational and numerical experiments so that necessary and sufficient initial, boundary, and updating data, as well as critical data sets for calibration and verification, are all obtained.

10) Data-assimilation techniques should be explored. In future MMS studies, efficient regional simulations may best be carried out by employing the methodology of data assimilation, which melds fields calculated from models and from data.

Appendix C

Physical Oceanography Study Contracts Awarded By The Minerals Management Service 1973-1989

Compiled by the committee from information provided by MMS.

Region	Contract No.	Title	Year	Amount($)
Alaska	16699	Shoreline Segment Characteristics Handbook for SMEAR Model Application	1988	4,000
Alaska	29177	Establishment of Tidal Datum and Profile of Dinkum Sands	1980	104,720
Alaska	29180	Establishment of Tidal Datum and	1980	967,217
Alaska	30130	Coastal and Surf Zone Smear Model	1984	487,417
Alaska	30146	Integration of Suspended Particulate Matter (SPM) Distribution and Transport Studies	1984	385,878
Alaska	30413	Circulation and Oil Spill Trajectory Model	1988	633,000
Alaska	30420	Develop SMEAR Model Application Handbook	1988	11,728
Alaska	30481	SMEAR Model Application Handbook	1988	94,176
Alaska	RU-048	Development and Operation of Current High Frequency Radar Mapping Units	1979	1,723,264
Alaska	RU-081	Beaufort Shelf Surface Currents	1977	81,593
Alaska	RU-091	Current, CTD and Pressure Measurements in Possible Dispersal Regions of the Beaufort and Chukchi Seas	1982	1,723,264
Alaska	RU-111	Effects of Seasonality and Variability of Stream Flow on Nearshore Coastal Areas	1975	81,144
Alaska	RU-138	Gulf of Alaska Study of Mesocale Oceanographic Processes	1980	3,158,927
Alaska	RU-140	Numerical Studies of the Alaskan Outer Continental Shelf	1979	991,376
Alaska	RU-141	Bristol Bay Oceanographic Processes	1979	1,572,973
Alaska	RU-151	Salinity, Temperature, and Depth Measurements of the Beaufort Sea Shelf	1977	302,016

Region	Contract No.	Title	Year	Amount($)
Alaska	RU-153	Frontal Dynamics and Water Mass Trajectory Using Methane as a Tracer	1982	1,310,027
Alaska	RU-217	Lagrangian Surface Current Measurements in Alaska	1977	392,573
Alaska	RU-235	Hydrodynamic Numerical Modeling for Coastal Waters in the Gulf of Alaska	1975	61,303
Alaska	RU-289	Circulation and Water Masses in the Gulf of Alaska	1980	1,591,842
Alaska	RU-307	Historical and Statistical Oceanographic Data Analysis and Ship-of-Opportunity Program	1975	147,798
Alaska	RU-335	Transport of Pollutants in the Vicinity of Prudhoe Bay	1975	76,399
Alaska	RU-347	Marine Climatology of Gulf of Alaska, Bering and Beaufort Seas	1977	338,899
Alaska	RU-351	Transport - Physical Oceanography	1977	1,859,037
Alaska	RU-357	Physical Oceanography of the Gulf of Alaska	1975	70,579
Alaska	RU-367	Nearshore Meteorology	1980	1,223,752
Alaska	RU-399	Surface Oil Film Surveillance by Radiometric Sensing	1975	44,423
Alaska	RU-435	Modeling of Tides and Circulation in the Bering Sea	1982	3,493,400
Alaska	RU-436	Oil Spill Trajectory Analysis, Lower Cook Inlet, Alaska	1980	327,730
Alaska	RU-499	Modeling Algorithms for the Weathering of Oil in the Marine Environment	1977	127,103
Alaska	RU- 519	Nearshore Meteorologic Regimes in the Arctic	1982	1,225,564
Alaska	RU-526	Characterization of the Nearshore Hydrodynamics of Arctic Barrier Island-Lagoon Systems	1981	1,782,232
Alaska	RU-531	Numerical Modeling and Current Measurements of Oceanographic Processes in the Beaufort Sea Barrier Island-Lagoon System	1982	826,781
Alaska	RU-536	Development and Operations of Remote Sensing Data-Acquisition Platform for OCS Studies	1977	111,936
Alaska	RU-541	Norton Sound and Chukchi Sea Oceanographic Processes	1980	2,910,081
Alaska	RU-549	Bristol Bay, Oceanographic Processes(RU-549-550)	1982	1,459,719
Alaska	RU-567	The Transport and Behavior of Oil Spilled in and under Sea Ice	1982	1,131,218
Alaska	RU-578	Numerical Modeling and Oil Spill Trajectory Analysis in the Beaufort Sea	1979	24,057
Alaska	RU-583	Under-Ice Currents in Norton Sound	1980	205,338
Alaska	RU-594	Suspended Particulate Matter Distribution and Transport in the North Aleutian Shelf Area	1982	330,446

Region	Contract NO.	Title	Year	Amount($)
Alaska	RU-596	Regional Meteorology of the Southeast Bering Sea	1982	438,029
Alaska	RU-597	Multivariate Experimental Analysis of Petroleum Weathering Under Marine Conditions	1982	1,762,081
Alaska	RU-600	Coastal Oceanography of the Northeastern Gulf of Alaska	1980	434,353
Alaska	RU-616	Bering Sea Marginal Ice Zone: Temperature and Salinity Analysis	1981	35,182
Alaska	RU-621	Boundary Conditions and Verification for the Model of Circulation and Oil Spill Trajectories on the Eastern Bering Sea Shelf	1982	337,705
Alaska	RU-627	Numerical Modeling of Storm Surges in the Beaufort, Chukchi and Northern Bering Seas	1982	225,481
Alaska	RU-642	Oceanographic Data from the Bering, Chukchi, and Beaufort Seas	1983	373,840
Alaska	RU-646	Nearshore and Coastal Circulation in the Northeastern Chukchi Sea	1983	572,800
Alaska	RU-657	Western Gulf of Alaska Oceanographic Processes	1984	248,404
Alaska	RU-666	Western Gulf of Alaska Oceanographic Processes	1984	263,187
Alaska	RU-670	Study of the Yukon Delta Processes: Physical Oceanography	1985	629,769
Alaska	RU-674	Arctic Ocean Buoy Program	1985	678,888
Alaska	RU-676	Circulation Model and Oil Spill Risk Analysis	1985	1,271,629
Alaska	RU-678	Beaufort Shelf Mesoscale Circulation Study (feasibility study)	1985	80,364
Alaska	RU-683	Interpolation, Analysis, and Archival of Data on Sea Ice Trajectories	1986	34,600
Alaska	RU-686	Beaufort Sea Mesoscale Circulation Study	1986	3,462,970
Alaska	RU-700	Dynamic Processes	1987	50,292
Alaska	RU-705	Coastal Fisheries Oceanography of the Southeastern Bering Sea: Physical Oceanography of Port Moller	1988	154,660
Alaska	RU-706	Performance and Compatibility Analysis of Oil Weathering and Transport - Related Models in the Environmental Assessment Process	1988	312,808
Alaska	RU-MMS	Beaufort Sea Monitoring Study - NOAA/OCSEAP	1986	94,152
Atlantic	29007	Meteorological Monitoring Buoy Network for the Atlantic OCS	1978	413,367
Atlantic	29012	South Atlantic OCS Physical Oceanography Data Collection	1979	60,400
Atlantic	29133	South Atlantic OCS Physical Oceanography Field Study, Year 1	1977	1,318,729
Atlantic	29138	South Atlantic OCS Physical Oceanography, Year 2	1978	1,181,864

Region	Contract No.	Title	Year	Amount($)
Atlantic	29159	New England Physical Oceanography - First Year	1976	3,812,767
Atlantic	29161	Second Year North Atlantic Physical Oceanography	1978	2,122,850
Atlantic	29162	New England Physical Oceanography - Second Year	1978	696,990
Atlantic	29170	South Atlantic OCS Circulation Model Application, Phase II	1979	407,922
Atlantic	29173	South Atlantic Physical Oceanography Study, Year 3	1980	1,079,505
Atlantic	29176	Blake Plateau Bottom and Mid-Water Current Study, Year 1	1980	359,319
Atlantic	29186	South Atlantic Physical Oceanography Study, Year 4	1981	537,921
Atlantic	29187	Blake Plateau Bottom and Mid-Water Current Study, Year 2	1981	383,851
Atlantic	29188	Interpretation of Physical Conditions and Their Application to Pollutant Transfer and Biological Resource Modeling	1981	824,414
Atlantic	29201	Synthesis of South Atlantic Physical Oceanography Program Information (Year 5)	1982	423,755
Atlantic	29202	Physical Oceanography - Blake Plateau Current Study	1982	3,191,971
Atlantic	29203	Physical Oceanographic Modeling in the Atlantic	1982	339,089
Atlantic	30066	Physical Processes on U.S. Mid-Atlantic Continental Slope and Rise Study	1983	2,764,638
Atlantic	30082	Florida Atlantic Coast Transport Study	1984	2,004,758
Atlantic	30152	Analysis of Physical Oceanography Data Offshore North Carolina	1984	19,250
Atlantic	30180	North Atlantic Slope and Canyon Study	1984	873,048
Atlantic	30260	Review of Oil Spill Model in Support of North Carolina Memorandum of Understanding	1985	22,253
Atlantic	30318	Ocean Circulation for the U.S. Atlantic Coast and Florida Straits (North Carolina Memorandum of Understanding)	1986	692,305
Atlantic	30340	Assessment of Satellite - Tracked Surface Buoys in Simulating the Movement of Spilled Oil in the Marine Environment	1986	86,925
Atlantic	30349	Gulf Stream Frontal Dynamics Study Offshore North Carolina	1987	719,312
Atlantic	30350	Summary of U.S. Atlantic and Southeastern GOM Physical Oceanography Processes Relevant to Offshore Oil and Gas Activities	1987	528,601

Region	Contract No.	Title	Year	Amount($)
Atlantic	CT1-26	Third Informal Workshop: Oceanography of the Gulf of Maine and Adjacent Sea	1981	5,058
Atlantic	CT6-50	New England Outer Continental Shelf Physical Oceanography - First Year	1976	1,416,804
Atlantic	CT7-16	South Atlantic OCS Physical Oceanography Literature Synthesis FY 1977	1977	177,648
Atlantic	CT8-05	Operation of R/V SUB SIG II	1978	16,000
Atlantic	CT8-34	South Atlantic OCS Physical Oceanographic Modeling Evaluation	1978	186,586
Atlantic	IA6-03	Meteorological Buoy Monitoring Network	1976	152,600
Atlantic	IA6-12	Mid- Atlantic Physical Oceanographic and Meteorological Study	1976	128,000
Atlantic	IAS-14	Georges Bank Climatological and Oceanographic Atlas	1978	394,847
Atlantic	IA8-39	South Atlantic OCS Satellite Oceanography	1978	150,000
Gulf of Mexico	10137	Hydrographic Survey of N.W. Gulf of Mexico	1989	9,328
Gulf of Mexico	10310	Chapman Conference on the Physics of the Gulf of Mexico	1989	15,000
Gulf of Mexico	29021	Southwest Florida Shelf Circulation Modeling Study	1980	233,455
Gulf of Mexico	29031	Gulf of Mexico Physical Oceanography Study Ship-of-Opportunity Program, I	1982	5,000
Gulf of Mexico	29034	BLM/NDBO Cooperative Drifting Buoy Program, I	1982	117,945
Gulf of Mexico	29039	Southwest Florida Circulation Model Review	1982	1,200
Gulf of Mexico	29040	Physical Oceanography Data Transfer	1982	500
Gulf of Mexico	29094	Gulf of Mexico OCS Satellite Oceanography, I	1980	223,000
Gulf of Mexico	29158	Gulf of Mexico OCS Physical Oceanography Field Study, Year I, II, and III	1982	5,499,579
Gulf of Mexico	30012	Generic Mud Plume Modeling Study	1983	10,800
Gulf of Mexico	30034	MMS/NMFS Cooperative Ship-of-Opportunity Program	1983	16,200
Gulf of Mexico	30045	Gulf of Mexico Drifting Buoys Program, II	1983	67,000
Gulf of Mexico	30073	Gulf of Mexico Circulation Modeling Study	1983	452,756
Gulf of Mexico	30191	Gulf of Mexico Meteorological Data Base Compilation and Analysis	1984	210,501
Gulf of Mexico	30199	Gulf of Mexico Drifting Buoys, Year 3	1984	54,672
Gulf of Mexico	30200	MMS/NMFS Ship-of-Opportunity Program	1984	20,900
Gulf of Mexico	30234	MMS/NMFS Cooperative Ship-of-Opportunity Program - Year IV	1985	24,100

Region	Contract No.	Title	Year	Amount($)
Gulf of Mexico	30289	Gulf of Mexico Physical Oceanography Study	1986	2,029,387
Gulf of Mexico	30313	Gulf of Mexico Physical Oceanography Ship-of-Opportunity (Year 5)	1986	77,000
Gulf of Mexico	30314	Gulf of Mexico Physical Oceanography Drifting Buoy (Year 5)	1986	45,000
Gulf of Mexico	30363	Numerical Modeling Studies of the GOM and Caribbean Sea Using the Bryan-Cox Model	1987	47,565
Gulf of Mexico	IA5-26	Model Studies of the Circulation Patterns in the Gulf of Mexico Physical Oceanography	1975	187,763
Pacific	14906	Central California Coastal Circulation Study	1987	5,318
Pacific	17667	Page Charges for Poleward Flow Off Central California during the Spring and Summer of 1981 and 1984	1988	2,500
Pacific	29026	Central California Nearshore Current Study	1982	74,000
Pacific	29097	Establishment and Operation of a Northern California Meteorological Buoy Network	1980	304,100
Pacific	29109	Establishment and Operation of a West Coast Buoy Network	1981	631,000
Pacific	29113	California Shelf Physical Oceanography Circulation Model	1981	629,874
Pacific	29117	Establishment and Operation of a West Coast OCS Meteorological Buoy Monitoring Network	1982	648,700
Pacific	29123	Santa Barbara Channel Circulation Model and Field Study	1982	2,491,468
Pacific	30008	Establishment and Operation of a West Coast OCS Meteorological Buoy Monitoring Network	1983	700,000
Pacific	30020	Central California Coastal Circulation Study	1983	3,080,932
Pacific	30143	Operation of a West Coast OCS Meteorological Buoy Monitoring Network - Year 4, Southern California	1984	684,600
Pacific	30248	West Coast OCS Meteorological Buoy Monitoring Network	1985	670,000
Pacific	30303	Operation of a West Coast OCS Meteorological Buoy Monitoring Network	1986	681,907
Pacific	30312	Northern California Coastal Circulation Study	1986	5,084,767
Pacific	30322	Coastal Wave Statistical Data Base	1986	231,848
Pacific	30352	Operation of a West Coast OCS Meteorological Buoy Monitoring Network	1987	715,907
Pacific	30384	Initial Statistical Characterization of the Variability of Coastal Winds and Currents	1988	254,713

Region	Contract No.	Title	Year	Amount($)
Pacific	30389	Coastal Circulation Along Oregon and Washington	1987	133,469
Pacific	30397	Modeling Circulation of the Southern California Bight	1987	520,075
Pacific	30425	Operation of a West Coast Data Buoy Network	1988	700,000
Pacific	30473	Operation of a West Coast OCS Meteorological Buoy Monitoring Network	1989	717,000
Pacific	CT0-62	California Meteorological Buoy Data Analysis	1980	38,773
Pacific	IA9-02	Climatology and Oceanographic Analysis of the California Pacific Outer Continental Shelf Region	1979	393,700
Wash., D.C.	14751	Drifting Buoys Field Test	1987	35,260
Wash., D.C.	29084	Bathymetric Mapping	1978	1,142,905
Wash., D.C.	30013	Bathymetric Mapping Service	1983	2,758,080
Wash., D.C.	30088	NSF Support for University - National Oceanographic Laboratory System	1983	63,510
Wash., D.C.	30463	LFM Wind Skill Assessment and Enhancement	1988	121,387
Wash., D.C.	CT6-32	Evaluation of Proposals for Physical Oceanography Program in the New England OCS	1976	584
Wash., D.C.	CT6-39	Evaluation of Proposals for Physical Oceanography Program in the New England OCS	1976	757
Wash., D.C.	CT7-26	Operation of R/V SUB SIG II	1977	40,000
Wash., D.C.	IA7-37	Support for University - National Oceanographic Laboratory System	1977	18,501
Wash., D.C.	NONE	Testing of Visco-Elastic Additive	1987	20,000
Wash., D.C.	NONE	Transfer of Hydrographic Cable from Scripps Institute to the Republic of Mexico	1988	1,800