1978-3

Physical Characteristics of Suspended Sediments, South Texas Continental Shelf

A.2

MMS U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

PHYSICAL CHARACTERISTICS OF SUSPENDED SEDIMENTS,

SOUTH TEXAS CONTINENTAL SHELF

by

Gerald L. Shideler
U.S. Geological Survey
P. O. Box 6732
Corpus Christi, Texas 78411

Contract No. AA551-MU8-11
1978

Report to the Bureau of Land Management

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

This report presents the results of a three-year study of suspended sediments within the South Texas OCS region. The investigations were a part of the environmental studies of the South Texas Outer Continental shelf sponsored by the Bureau of Land Management. The physical properties of the suspended particulate system studied were the turbidity of the water and the texture of the suspended particulates. The objective of the study was to determine the spatial and temporal variability in the distribution of suspended sediments in an effort to gain insight into the regional sediment transport system.

Efforts the first two years were concerned with the field monitoring of suspended sediments during six cruises conducted over an eighteen month period; the results are included in Berryhill and others, 1976b and Berryhill and others, 1977. The effort for the third year augments the field results from the previous two years with supplemental hydrographic data, and with supplemental turbidity patterns derived from an analysis of Landsat imagery. This report integrates and summarizes the final results of the overall three-year program.

METHODS

Field Techniques

Regional variations in the amounts of suspended sediment were determined on the basis of water-column measurements (turbidity, sediment texture, hydrography) at 26 monitoring stations during the first two years of the program. A total of six cruises was conducted on the following dates:

November 15-21, 1975; March 2-6, 1976; May 21-25, 1976; October 29-November 3, 1976; March 17-21, 1977; May 24-27, 1977; The cruise dates were dictated largely by ship availability and did not provide complete seasonal coverage. However, they did provide comparative coverage from two consecutive years of the spring and fall, the two seasons characterized by the most variable and complex circulation patterns on the South Texas shelf. Supplemental seasonal coverage of summer and winter turbidity patterns was obtained from an analysis of Landsat imagery during the third-year study.

The 26 STOCS monitoring stations were located to provide optimum geographic coverage of the region, and to provide concentrated coverage of three coastal inlets (Matagorda Bay inlet, Aransas Pass, Rio Grande-Brazos Santiago channel) that serve as major sources of sediment (Fig. 1). The inlet stations were located along 3.2 km radii from the center of the respective inlets, and were occupied during ebb tides at the approximate time of maximum current flow. Measurements during each cruise were obtained over a maximum period of 6 days, thus providing quasi-synoptic regional coverage. Radar navigation was used for inlet station positioning; deeper stations were located and repositioned by LORAN-A.

For each of the six cruises, regional wind and surface-drift conditions were determined. Daily wind speed and azimuth data compiled by the National Weather Service at Corpus Christi were considered to be representative of the OCS region, although wind velocity can vary from offshore to onshore. The wind data were added vectorially over a 15 day interval that was centered on the cruise period, in order to determine the resultant wind directions during each cruise. Quasi-synoptic surface drift patterns were determined by releasing ballasted surface drifter bottles at each station

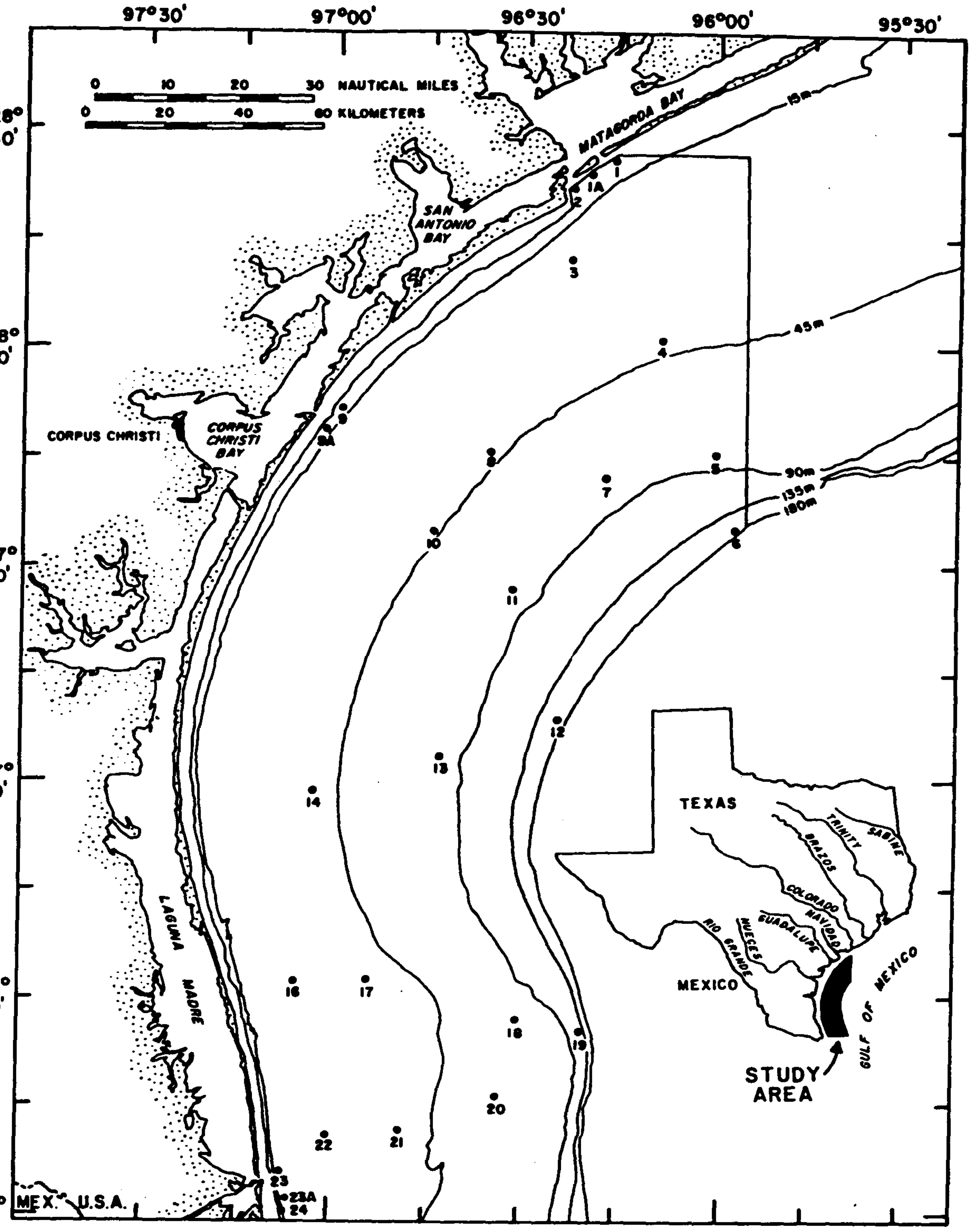

Figure 1. STOCS study area and locations of 26 monitoring stations.

during the cruise. Only drifters recovered within 30 days of the release date were used to determine net drifter trajectories. Drifters recovered within 15 days from the date of release also were used to calculate net minimum drift velocities, based on straight-line trajectory distances and the corresponding elapsed time intervals.

Vertical transmissivity/temperature profiles were recorded at each station. Processing of the profiles consisted of manually digitizing the field analog recordings at selected depth intervals, tabulating the corresponding transmittance and temperature values, and reducing the profiles to a common scale. The recorded transmittance values (percent T per 25 cm optical path) were converted to values corresponding to a 1 m optical path, a more commonly used mode of comparison. Light transmittance values are a complex function of several variables that can influence the optical absorption properties of sea water. These variables include the amount of dissolved organic matter and the compositional characteristics of the suspended particulate system (particle mineralogy, shape, and size distribution). However, perhaps the most influential variable is the amount of total suspended matter with the water column; consequently, the transmissivity measurements were used to approximate the relative degrees of water turbidity. Time-sequence profiles from the 6 cruises were prepared for each of the 26 monitoring stations to document the transmissivity and temperature variability within the water column.

At each station, water samples also were obtained at three levels: top, mid-depth, and approximately 2 m above the bottom. They were collected in 30-liter NISKIN bottles and were transferred to particle-free amber polypropylene storage bottles for laboratory analyses. To inhibit organic growth, a 5 percent concentration of formalin was added to the storage bottles. The patterns of sediment dispersal indicated by the study are based on the hydrographic, textural, and turbidity gradients observed at the 26 monitoring stations.

Laboratory Techniques

The suspended sediment from the water samples collected during the 6 cruises was analyzed for both texture and total particle concentrations using the following procedures:

Textural analyses

1. The field samples were brought to room temperature and thoroughly agitated; a representative split was taken.
2. The work sample was then filtered through a 125 µm sieve to remove particles capable of blocking the COULTER COUNTER 200 µm tube aperture.
3. Grain-size distributions were determined at a 0.5 Ø interval electronically, employing a 16-channel model TA COULTER COUNTER. Duplicate analyses were conducted with 200 µm and 30 µm tube apertures, providing an effective analytical range from 0.63 to 81 µm. All COULTER analyses were conducted using the following standard procedures:
   a. The sample concentrations were maintained at a level sufficiently low to produce less than 5 percent coincidence error. If dilution was required, a particle-free sea water diluent, passed through a 0.2 µm filter, was used.
   b. The 200 µm tube analysis was conducted first to determine the coarser half of the size distribution; the sample was agitated during analysis at a standard speed.
   c. The residual sample from the 200 µm tube analysis was passed through a clean 20 µm sieve and was analyzed with the 30 µm tube to determine the finer half of the size distribution. No agitation was used during the 30 µm tube analysis.

d. The results from both 200 µm and 30 µm tube analyses were combined to obtain the total size distribution, using standard two-tube overlap techniques.

4. The textural data were processed by computer to derive statistical grain-size parameters over a 3.5-11.0 ∅ analytical range. Derived parameters include the silt/clay ratios and the four moment measures (mean diameter, standard deviation, skewness, and kurtosis).

5. The regional variability of selected size parameters (silt/clay ratio, mean diameter, standard deviation) was then mapped for both surface and bottom water sediments.

Particle concentration analyses

Suspended sediment particle concentrations within the size range of 0.63 to 81 µm also were determined for each water sample. The particle concentrations (counts/cc), as determined by COULTER COUNTER, were used as a second index of relative water turbidity, supplementing the transmissivity measurements. Particle counts were made using the following procedures:

1. The water sample was brought to room temperature and thoroughly agitated.

2. Counts were made first with the 200 µm tube, running the sample full strength after passing it through a 125 µm sieve. A standard 150 ml sample volume was agitated at a standard speed. Duplicate counts were made; if they agreed within ±10 percent, the average value was used. If the deviation was greater than ±10 percent, additional counts were run until the value spread was within the ±10 percent

limits. The 200 μm tube analysis counted particles within the size range of 12.7 to 81 μm.

3. The residual sample from the 200 μm tube analysis was passed through a 20 μm sieve and then used for the 20 μm tube analysis to obtain the particle count within the size range of 0.63 to 12.7 μm. The sample was diluted to produce less than 3 percent coincidence error. The particle count was determined and adjusted by the dilution factor. Duplicate counts were made using a ±10 percent value spread, as described in the 200 μm analysis.
4. Particle counts from both the 200 μm and 30 μm tube analyses were arithmetically combined to provide total particle counts/cc. The regional variability of total particle counts was then mapped for both surface and bottom water sediments.

Supportive data

In addition to the textural analyses and particle counts, surface water samples also were analyzed in the laboratory for salinity (°/∘∘) as additional supportive hydrographic data. Salinities were determined with an induction salinometer, using the average values from two replicate measurements.

Trends in river discharge that might have influenced OCS circulation were noted (fig. 2). The discharge volumes (m^3/sec) were taken from the U.S. Geological Survey's Water Resources Data Reports (1975-1977).

As a way of summarizing and comparing average turbidity, hydrographic, and textural characteristics observed among the six cruises, descriptive

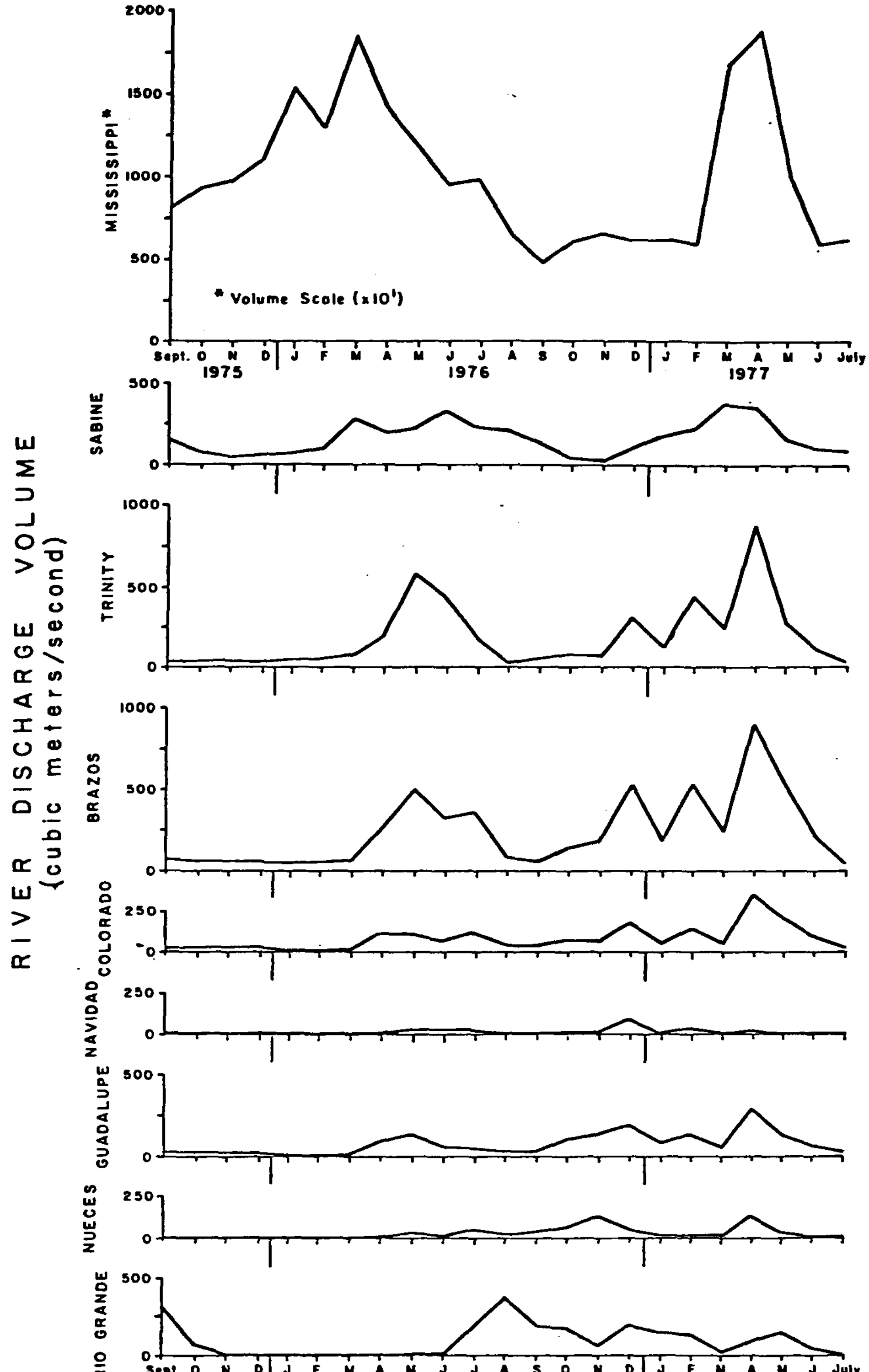

Figure 2. Monthly discharge volume of major rivers in proximity to STOCS during the monitoring period.

statistics were derived by computer program (SAS program, 1976). Derived statistics included the ranges, means, and standard deviations of the parameter values measured at all 26 monitoring stations. General characteristics associated with the six cruises are summarized in tables 1-3.

Landsat Imagery Analysis

Supplemental turbidity patterns to augment the field observations were obtained from an analysis of Landsat imagery available from the U.S. Geological Survey's EROS Data Center, Sioux Falls, South Dakota. A total of ten Landsat overpass dates were selected to provide coverage of: 1) turbidity patterns during summer and winter months, the two seasons not covered during the six cruises; and 2) additional fall and spring turbidity patterns that were as close as possible to the dates of the cruises. The selection of specific overpass dates was based on imagery quality, acceptable cloud covering, and the availablity of sufficient images to form a complete mosaic of the STOCS region. Selected overpass dates are the following: November 12-13, 1975; February 1-2, 1976; February 27-29, 1976; May 28-29, 1976; August 8-9, 1976; October 10-11, 1976; February 13-14, 1977; April 7-9, 1977; May 31-June 2, 1977; and July 12-14, 1977.

The Landsat imagery consisted of multispectral scanner (MSS) black and white film negatives at a 1:1,000,000 scale. The spectral band used was the red Band 5 (0.6-0.7 micrometers) which was judged to provide the optimum resolution of OCS turbidity patterns, especially within the critical inner-shelf sector. The imagery was qualitatively analyzed for turbidity patterns and flow directions; a composite mosaic map was then prepared for each overpass date (figs. 13-23). The turbid water zones outlined on

Table 1 - Summary of Surface Turbidity Characteristics at 26 Monitoring Stations

	Cruise Period	Water Transmissivity Range (% T/m)	Water Transmissivity Mean ($\bar{X}$)	Particle Concentration (Counts/cc x 10^4) Range Minimum	Particle Concentration Range Maximum	Mean ($\bar{X}$)
First Year	Fall (Nov. 15-21, 1975)	0-99	48	12 (Station 5)	244 (station 9)	66
First Year	Early Spring (March 2-6, 1976)	0-90	47	4 (station 12)	203 (station 2)	43
First Year	Late Spring (May 21-25, 1976)	7-90	61	11 (station 5)	192 (station 1A)	49
Second Year	Fall (Oct. 29-Nov. 3, 1976)	0-96	23	12 (station 7)	433 (station 1A)	85
Second Year	Early Spring (March 17-21, 1977)	0-89	49	13 (station 22)	177 (station 2)	45
Second Year	Late Spring (May 24-27, 1977)	0-75	47	19 (station 6)	374 (station 1A)	86

Table 2 - Summary of General Surface Hydrographic Characteristics Associated with the Monitoring Cruises

Cruise Period	Daily Wind Speed Range (km/hr)	Regional Drift Direction	Total Drifters Released	Total Drifter Recovery (%)	0-15 day Recoveries (%)	16-30 day Recoveries (%)	Minimum Drift Rate Range (km/day)	Mean Minimum Drift Rate (km/day)	Temperature Range (C°)	Salinity Range (°/oo)
November 15-21, 1975	16-25	SSW	148	11	7	4	1-47	24	20.0-24.7	27.2-35.4
March 2-6, 1976	16-40	SW	192	28	23	5	1-41	12	14.2-20.5	32.3-35.8
May 21-25, 1976	6-20	WSW/NNW	217	37	27	10	3-25	14	21.0-24.0	27.3-35.5
October 29 -November 3, 1976	2-19	SSW	336	4	3	1	9-23	16	16.7-24.5	28.6-36.7
March 17-21, 1977	7-26	SSW	312	22	20	2	2-40	15	15.7-19.5	28.6-36.1
May 24-27, 1977	13-18	N/NE	336	29	16	13	2-54	16	25.0-28.0	22.7-33.9

Table 3. Statistical Summary of Suspended Sediment Textural Properties at 26 Monitoring Stations.

Year	Cruise Period	Water Depth	Silt/Clay Ratios		Mean Diameters (Ø)		Standard Deviation (Ø)	
			Mean ($\bar{X}$)	Standard Deviation (σ)	Grand Mean ($\bar{X}$)	Standard Deviation (σ)	Mean ($\bar{X}$)	Standard Deviation (σ)
First Year	Fall (Nov. 15-21, 1975)	Surface	1.26	0.46	7.66	0.35	1.72	0.39
		Bottom	1.75	0.59	7.55	0.32	1.39	0.27
		Total Column*	1.48	0.57	7.58	0.35	1.61	0.38
	Early Spring (March 2-6, 1976)	Surface	1.13	0.43	7.68	0.36	1.75	0.37
		Bottom	1.22	0.56	7.79	0.33	1.44	0.31
		Total Column*	1.18	0.46	7.71	0.33	1.64	0.38
	Late Spring (May 21-25, 1976)	Surface	1.82	1.46	7.41	0.38	1.83	0.32
		Bottom	2.32	1.51	7.41	0.33	1.33	0.27
		Total Column*	2.09	1.46	7.35	0.37	1.64	0.37
Second Year	Fall (Oct. 29-Nov. 3, 1976)	Surface	0.90	0.36	7.98	0.33	1.47	0.30
		Bottom	1.05	0.35	7.94	0.23	1.26	0.17
		Total Column*	0.98	0.40	7.94	0.33	1.39	0.29
	Early Spring (March 17-21, 1977)	Surface	1.39	0.89	7.52	0.55	1.83	0.24
		Bottom	1.72	1.03	7.57	0.52	1.41	0.24
		Total Column*	1.60	1.16	7.52	0.55	1.66	0.30
	Late Spring (May 24-27, 1977)	Surface	1.25	1.15	7.63	0.50	1.94	0.34
		Bottom	1.19	0.40	7.74	0.29	1.60	0.34
		Total Column*	1.23	0.79	7.66	0.43	1.79	0.35

* Based on surface, bottom, and mid-depth measurements.

each mosaic map were the visually discernible areas of lighter-toned waters on the imagery that indicated a relatively high degree of turbidity. Wind and tidal conditions associated with each overpass period also were plotted on each map, in an effort to relate the imagery patterns to possible forcing agents. The wind and tidal data were respectively obtained from the U.S. Weather Service facility and the U.S. Army Corps of Engineers tide gauges within the Corpus Christi area, which was considered as being representative of the OCS region. The imagery data was then integrated with the field observations, in an effort to formulate inferences about the regional sediment-transport system.

SURFACE DISPERSAL PATTERNS

The emphasis of the suspended sediment study has focused on the mechanics of surface transport for several reasons: 1. The acquired data base is more extensive for the surface; 2. Surface conditions are more readily associated with meteorological forcing effects; and 3. Subsurface transport seems largely involved with a bottom nepheloid layer whose development and movement are not adequately understood. Inferences regarding surface dispersal patterns are based largely on the turbidity and associated hydrographic variability observed through field measurements over the eighteen-month monitoring period.

The general composition of the suspended particulate system in the South Texas OCS is predominantly inorganic terrigenous detritus, as indicated by a microscopic analysis of the first year samples (fall, 1975 to spring, 1976). Minor organic admixtures of phytoplankton, primarily diatoms, also were present. Based on all 26 monitoring stations, the mean percentages of organic constituents for the first-year cruise samples are: November 1975 (9%); March 1976 (11%); and May 1976 (11%).

Synopsis of First-Year Field Results

Regional surface turbidity variations observed during the first-year field program (fall, 1975 - spring, 1976) are illustrated by a time-sequence of water transmissivity (fig. 3) and supplementary particle concentration (fig. 4) patterns. Ambient surface hydrographic conditions associated with the turbidity patterns are illustrated by complementary time-sequence patterns of drifters (fig. 5), temperature (fig. 6), and salinity (fig. 7).

During the fall (November 15-21, 1975), regional turbidity patterns indicated both offshore transport and southward alongshore transport of sediments derived from coastal sources (figs. 3A, 4A). The transmissivity values and particle concentration values exhibit a well-defined inverse relationship. As expected, areas of lowest transmissivity are also characterized by the highest particle concentrations. Hydrographic conditions during the period included strong regional surface drift to the SSW (fig. 5A). This drift pattern was associated with the passage of a cold front over the shelf (Nov. 20), a stormy period accompanied by northeasterly winds and high seas. Poor drifter recovery (11%) could have been attributed either to landfall on remote Mexican beaches to the south, or to a strong offshore component. Additional indications of water-mass movements were provided by associated surface temperature (fig. 6A) and salinity (fig. 7A) gradients which appear to have reflected a counterclockwise gyre-like circulation pattern. The pattern suggests the offshore and southward movement of relatively cool water of low salinity over the inner shelf, and the simultaneous shoreward incursion of warmer and higher salinity outer-shelf waters in the northeastern sector. The circulation pattern is compatible with drifter data, and shows excellent correlation with the sediment dispersal pattern indicated by turbidity gradients (compare figs. 6A, 7A with figs. 3A, 4A).

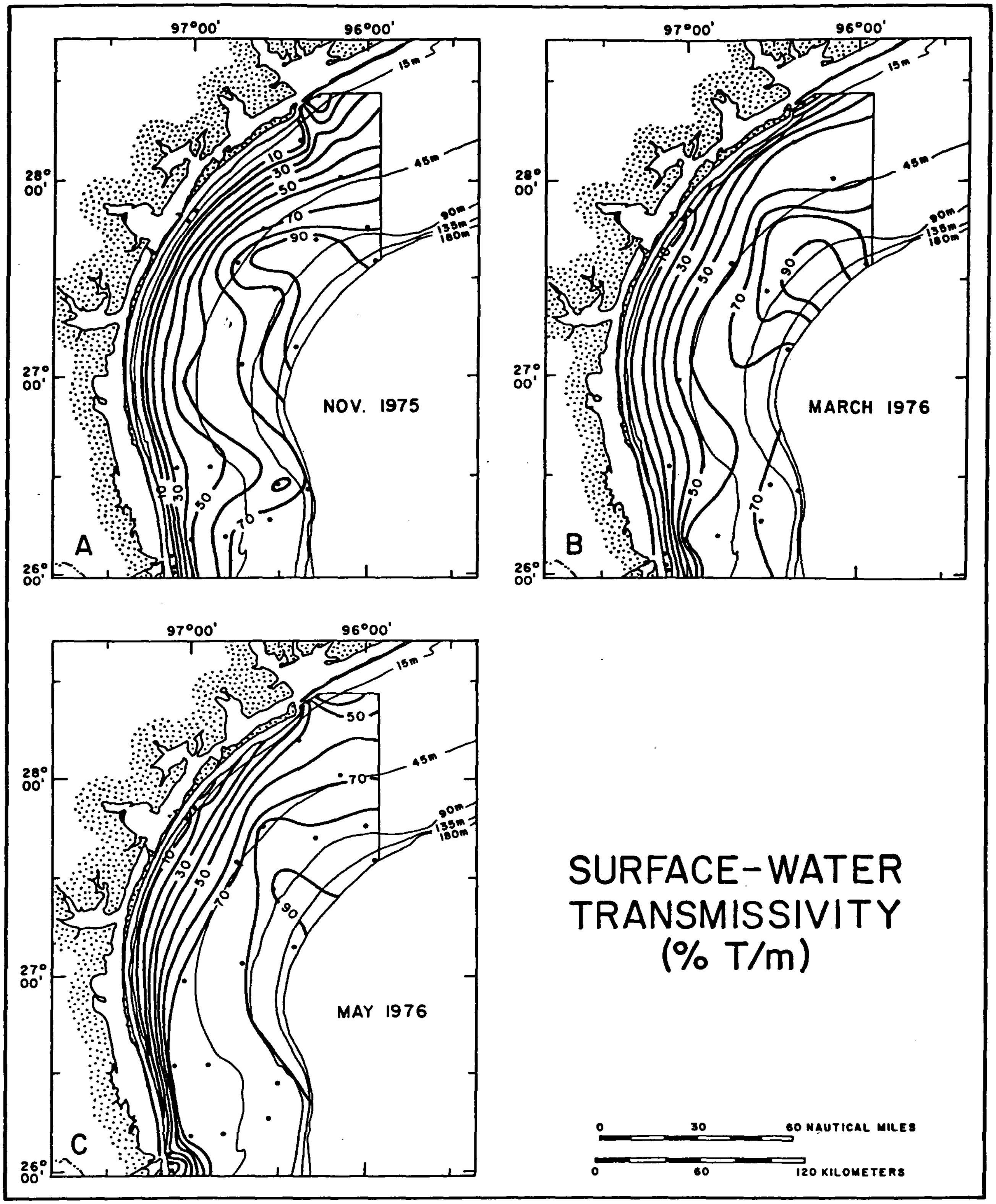

Figure 3. Time-sequence of surface-water transmissivity patterns during the first-year field study.

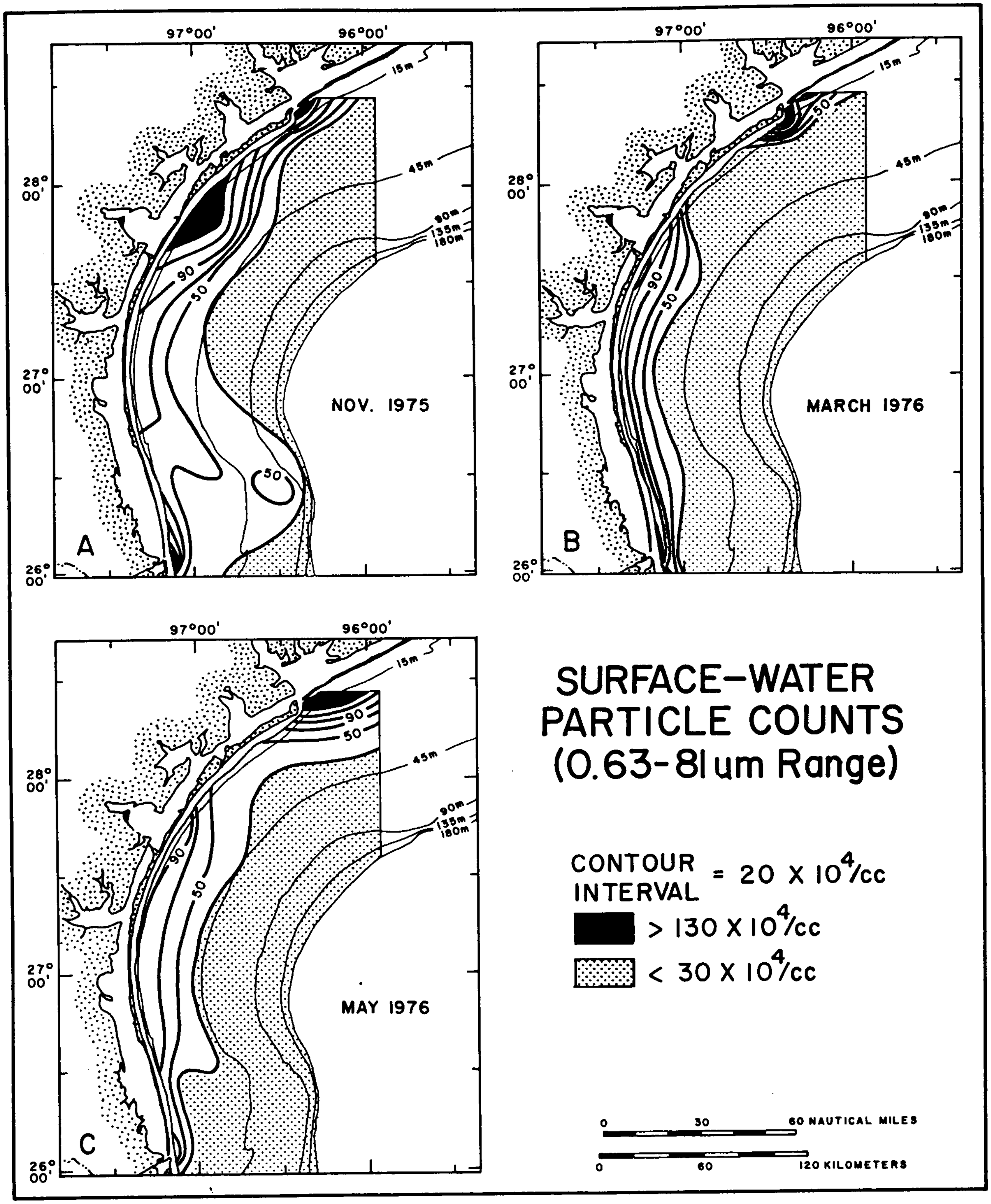

Figure 4. Time-sequence of surface-water particle concentration patterns during the first-year field study.

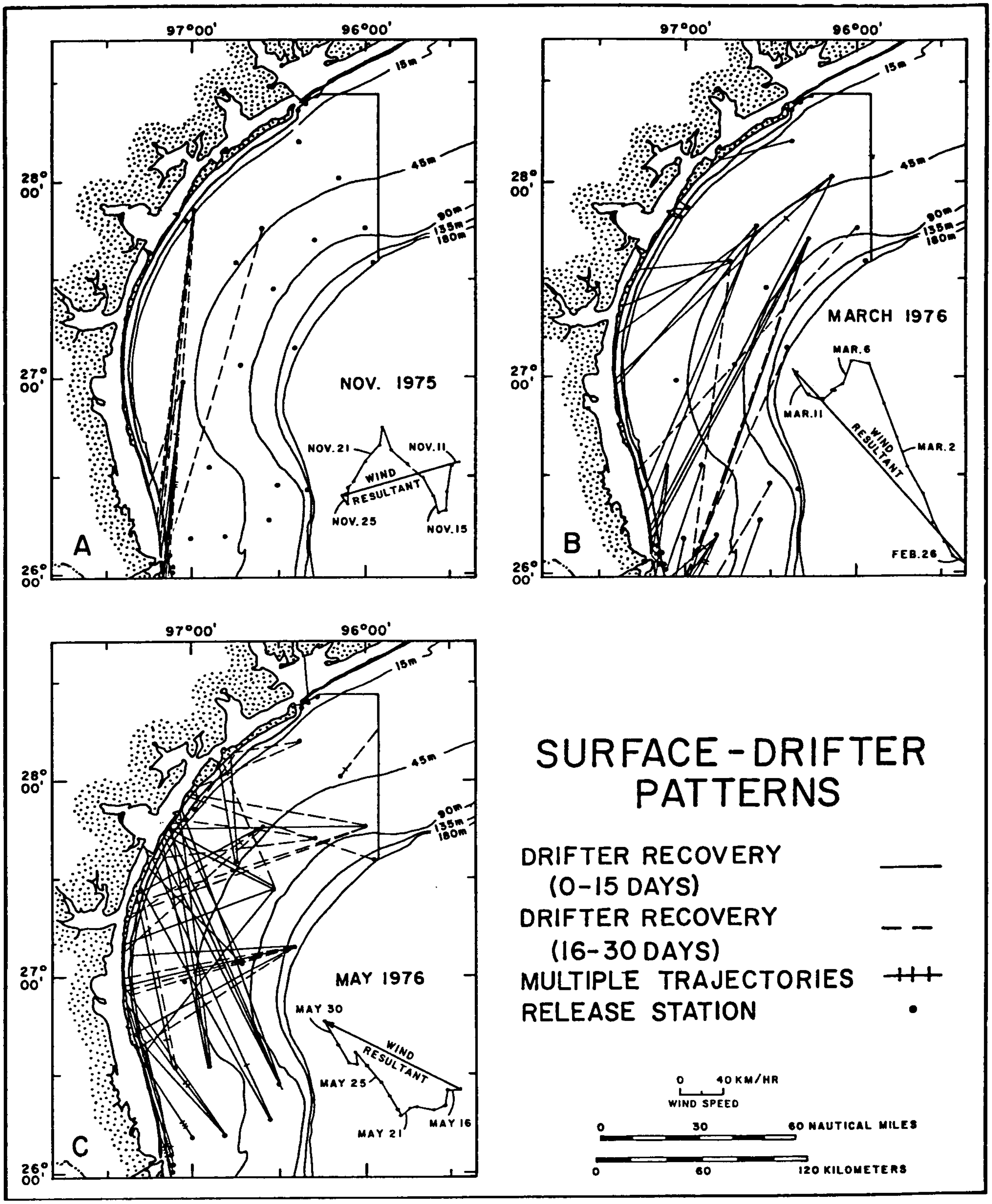

Figure 5. Time-sequence of surface drifter patterns during the first-year field study.

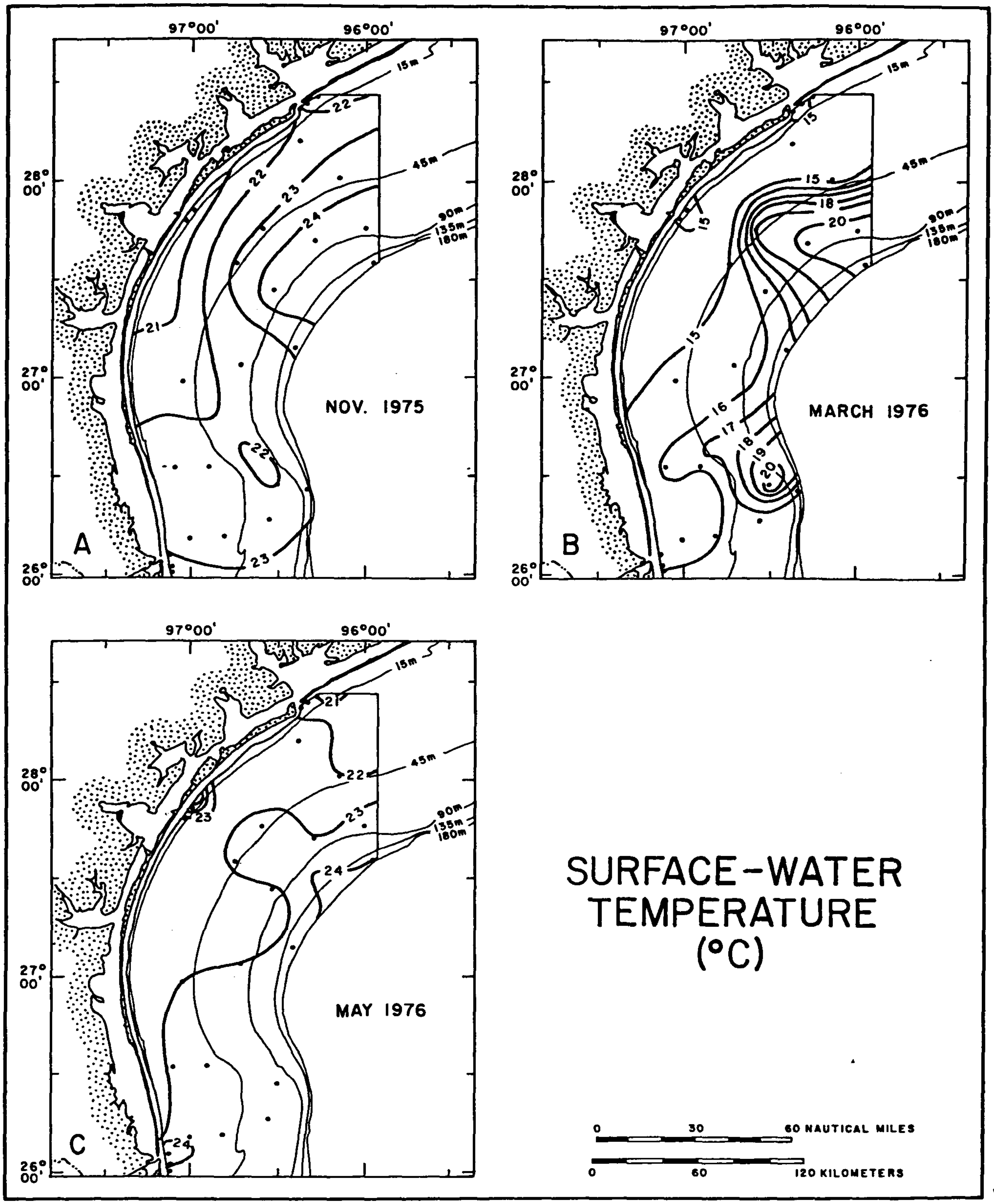

Figure 6. Time-sequence of surface-temperature patterns during the first-year field study.

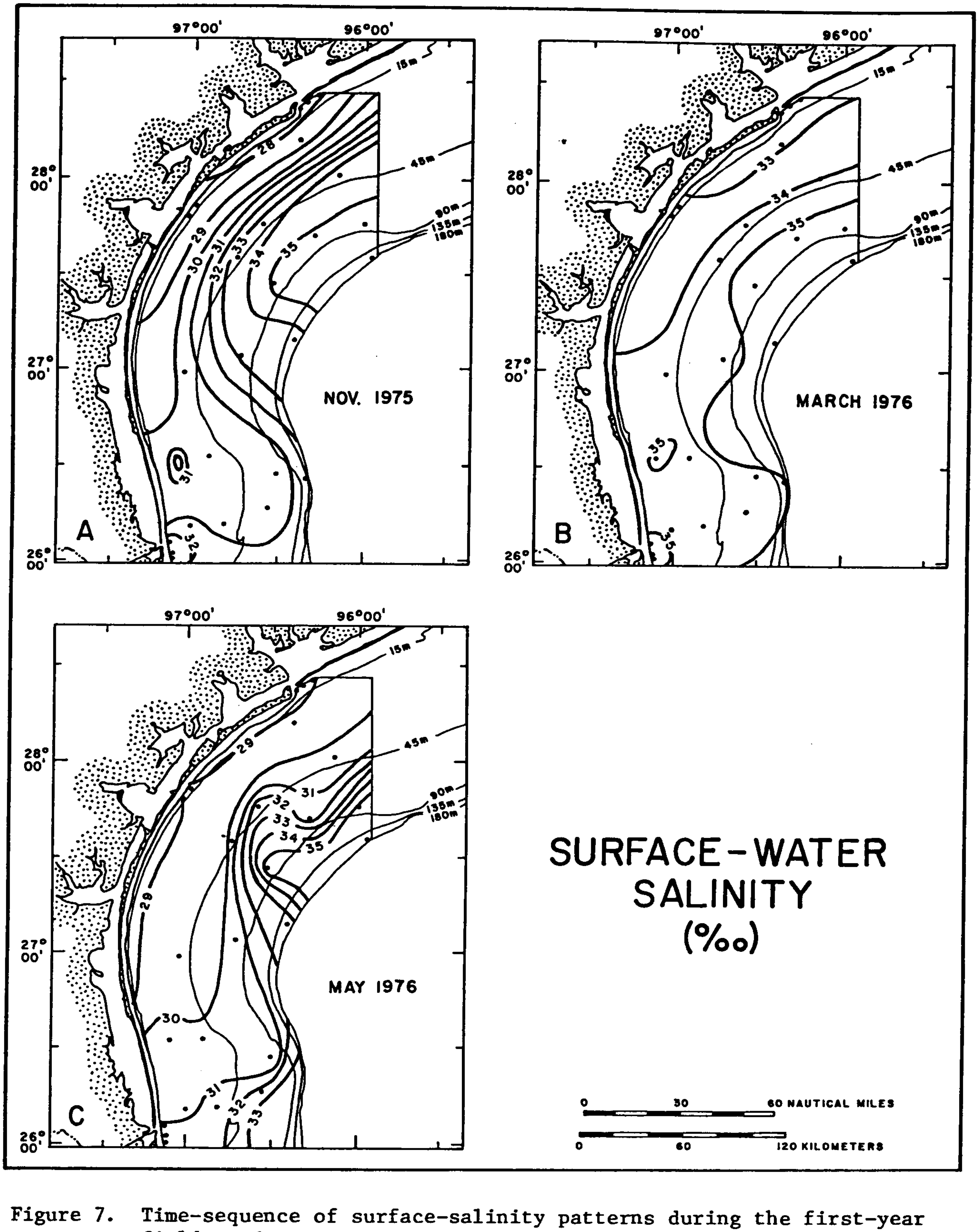

Figure 7. Time-sequence of surface-salinity patterns during the first-year field study.

During the early spring (March 2-6, 1976), regional turbidity patterns largely indicated the offshore transport of sediment from coastal sources, and provided no strong indication of an alongshore transport component (figs. 3B, 4B). Hydrographic conditions included regional surface drift toward the SW (fig. 5B). The associated surface temperature (fig. 6B) and salinity (fig. 7B) gradients further suggest the shelfward incursion of a relatively warm and more saline deeper Gulf water mass along the outer shelf. The gradients also suggest some southward alongshore movement of relatively cool and less saline inner-shelf waters, which would be in agreement with the regional drifter pattern.

During the late spring (May 21-25, 1976), the regional turbidity patterns indicated the offshore transport of coastal derived sediment and no well defined alongshore transport component (Figs. 3C, 4C). Hydrographic conditions included variable surface-drift directions, which formed a distinct bimodal distribution pattern indicating regional convergence (fig. 5C). Although such a convergent pattern could result simply from the change in coastline orientation relative to constant onshore easterly winds, the pattern is interpreted as reflecting a shifting wind-drift current regime. The northern station drifters were released during the first half of the cruise period, and largely appear to reflect wind-drift currents generated by the easterly and northeasterly winds of the pre-cruise and early cruise periods. In contrast, the southern station drifters were released during the latter half of the cruise, and appear to reflect currents generated by the predominantly southeasterly winds that occurred during the May 22-30 period. Shifting wind patterns are relatively common in the Gulf during the spring season. The associated surface temperature (fig. 6C) and salinity (fig. 7C) gradients further suggest the shelfward incursion of a relatively warm and more saline deeper Gulf water mass, with the shoreward extent of incursion increasing southward. Regional shoreward incursion would be in agreement with the strong onshore component illustrated by the surface-drifter pattern. It would also be compatible with the regional turbidity patterns (figs. 3C, 4C).

Synopsis of Second-Year Field Results

The regional turbidity variations observed during the second-year field monitoring program (fall, 1976; spring, 1977) are illustrated by water transmissivity (fig. 8) and supplementary particle concentration (fig. 9) patterns. Associated surface hydrographic conditions are illustrated by patterns of drifters (fig. 10), temperature (fig. 11), and salinity (fig. 12).

During the fall (Oct. 29-Nov. 3, 1976), the regional turbidity patterns suggested both the offshore and net southward transport of sediment from coastal sources (figs. 8A, 9A). Hydrographic conditions during the monitored period included regional surface drift toward the SSW (fig. 10A). The drift pattern reflected a southward alongshore transport component on the inner shelf apparently generated by winds with strong northerly components, thus supporting the dispersal pattern indicated by turbidity gradients. The absence of drifter recoveries from most outer-shelf stations could suggest their possible transport to remote Mexican beaches further to the south, with little chance of recovery. Alternatively, they may have been transported either northward or into the deeper Gulf by an outer-shelf countercurrent; this possibility is suggested

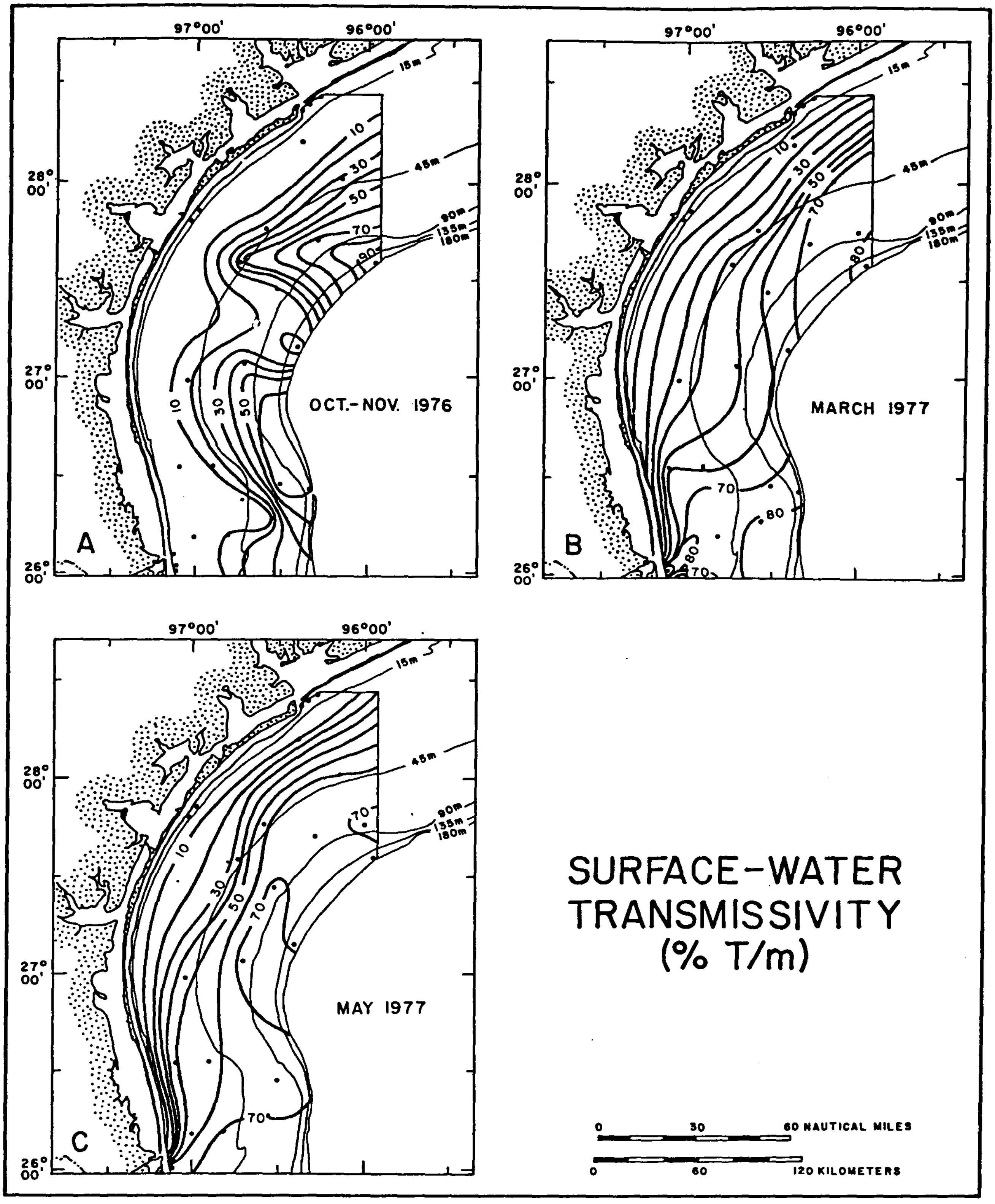

Figure 8. Time-sequence of surface-water transmissivity patterns during the second-year field study.

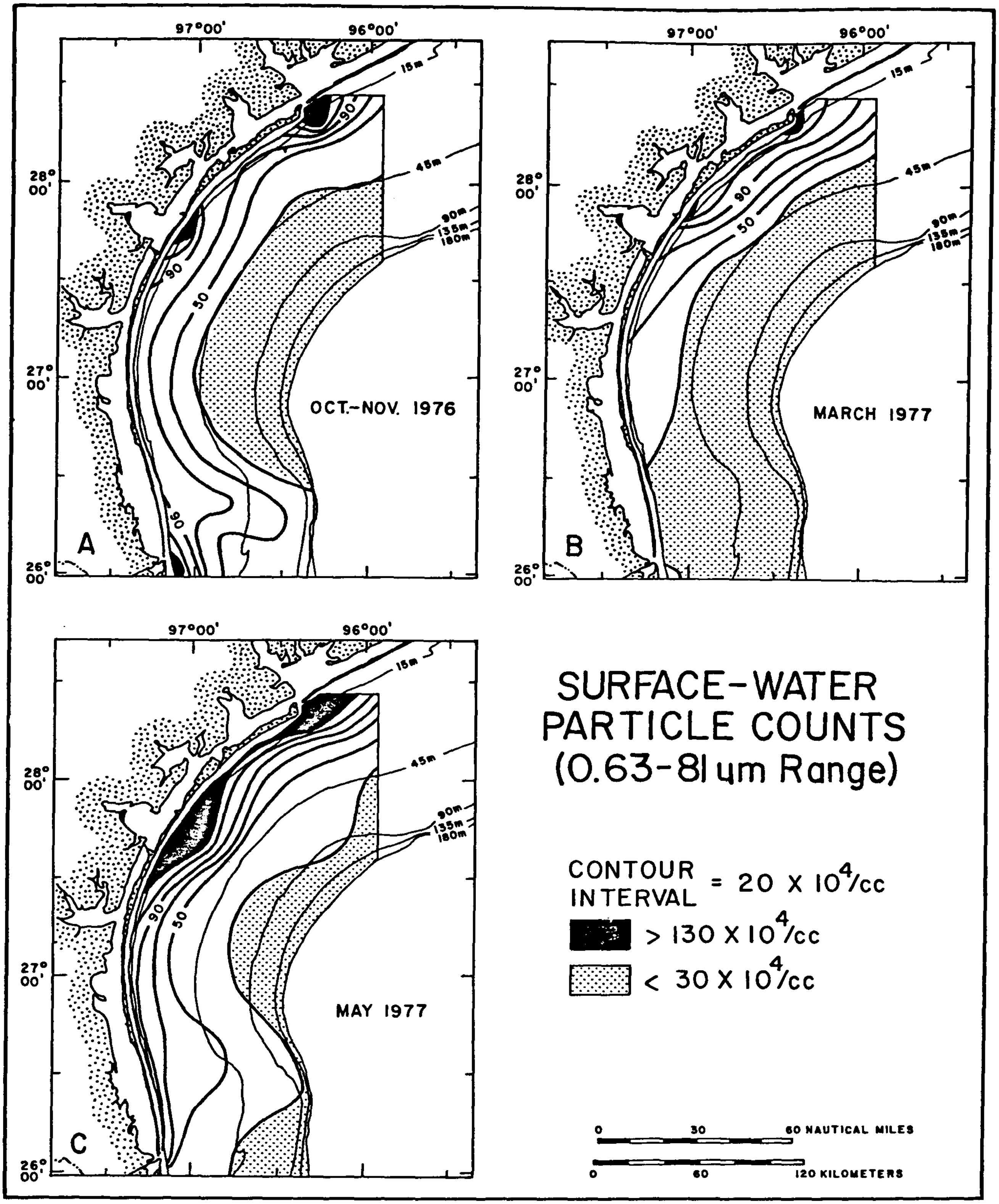

Figure 9. Time-sequence of surface-water particle concentration patterns during the second-year field study.

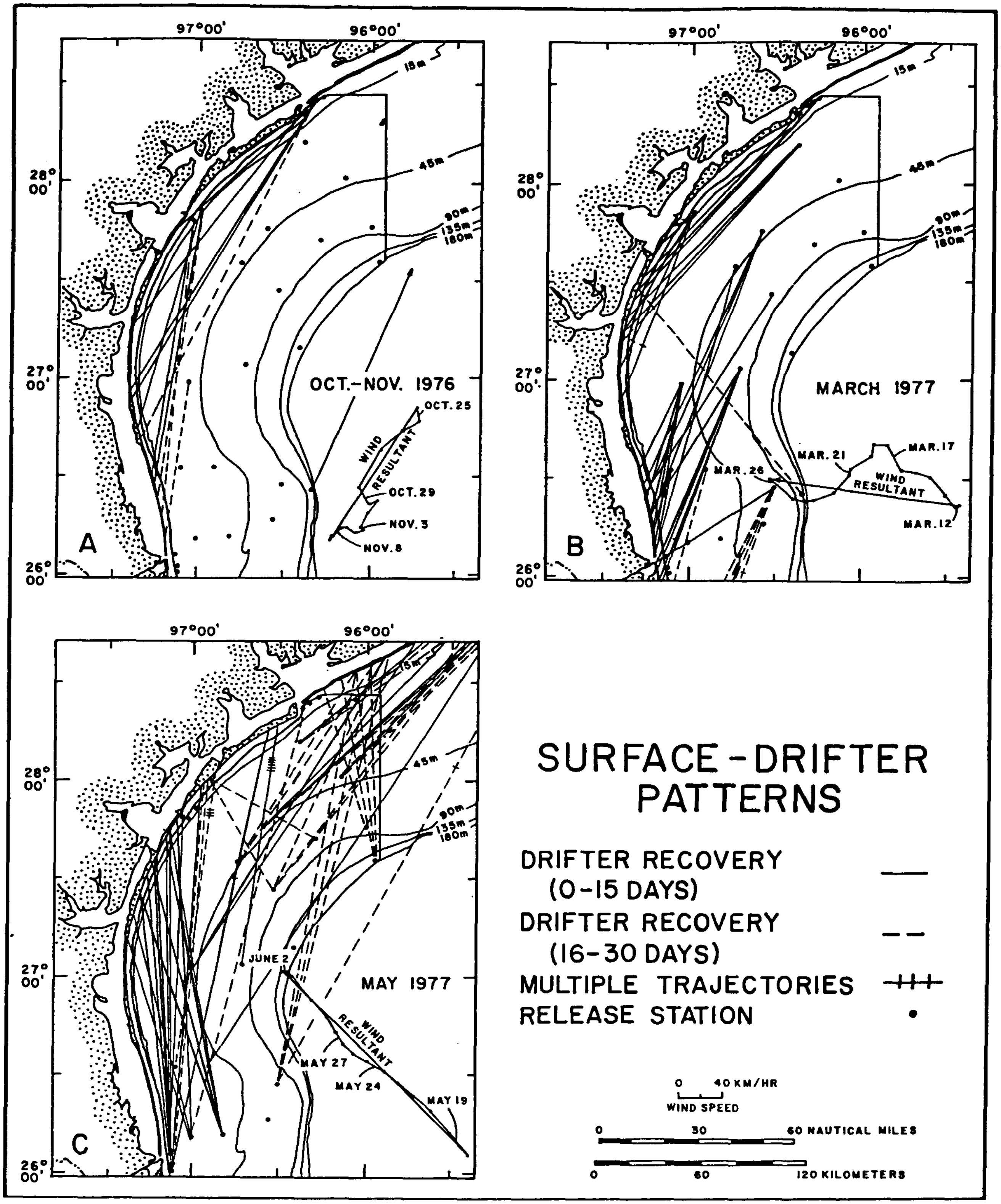

Figure 10. Time-sequence of surface-drifter patterns during the second-year field study.

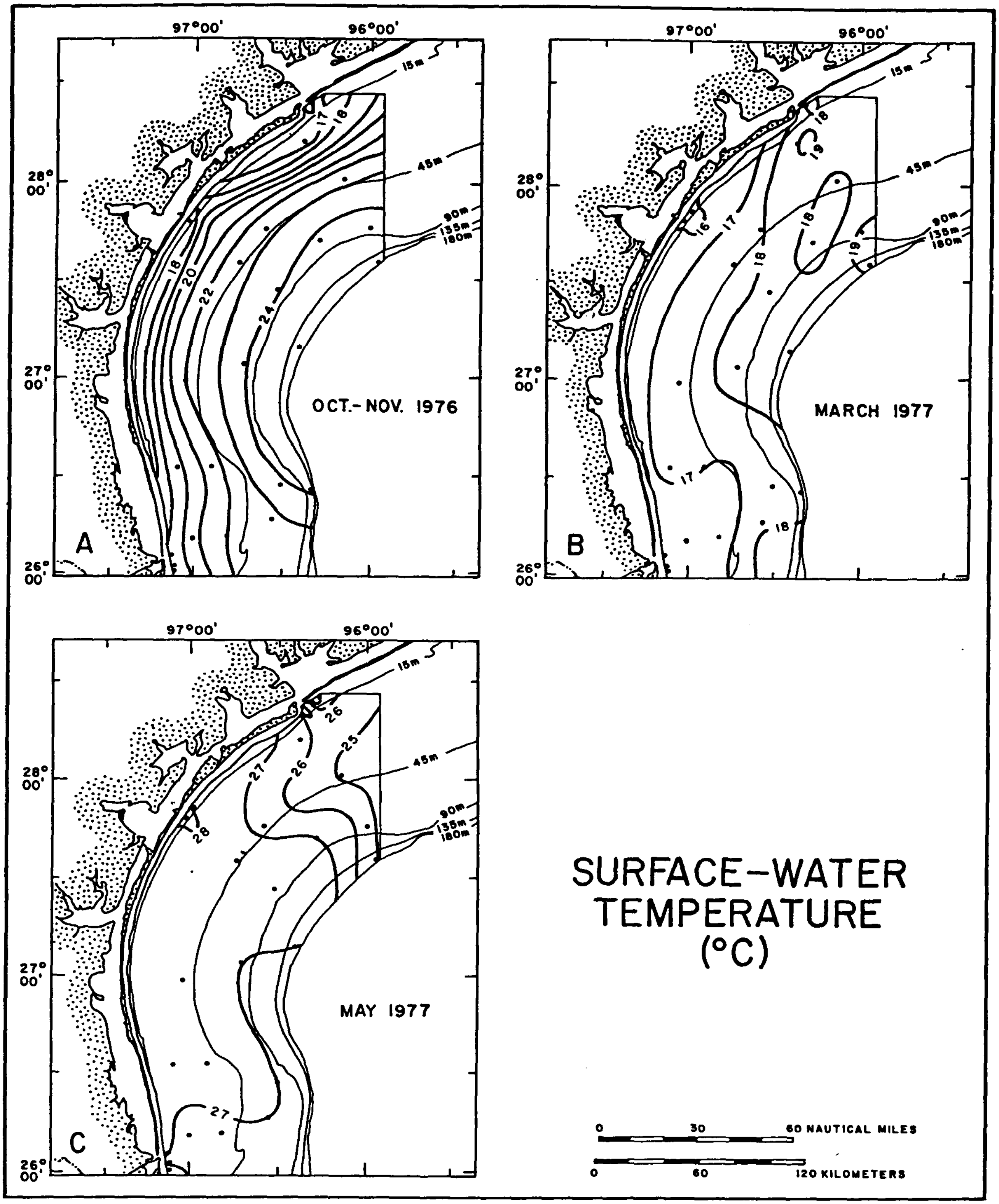

Figure 11. Time-sequence of surface-temperature patterns during the second year field study.

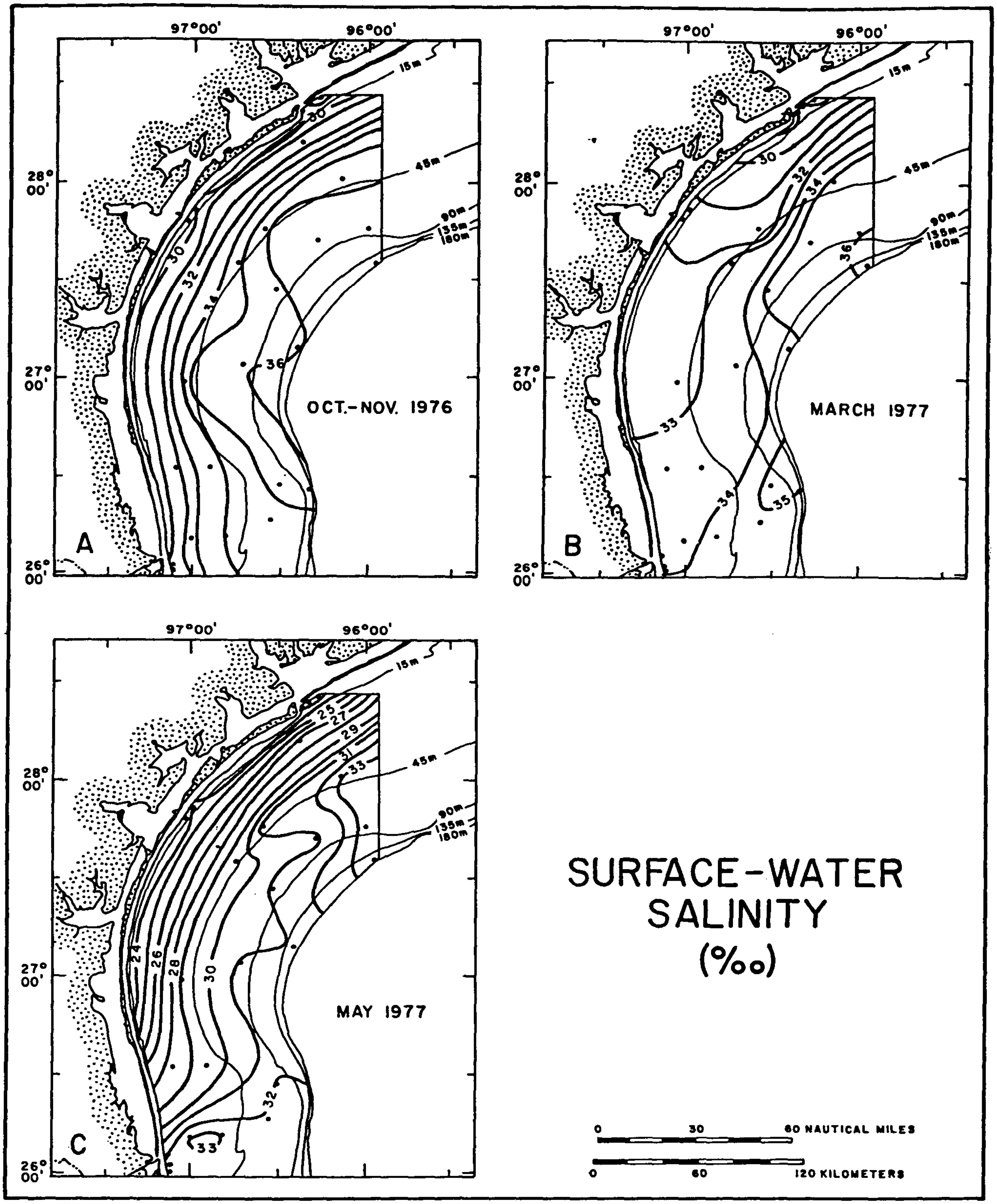

Figure 12. Time-sequence of surface-salinity patterns during the second-year field study.

by the single station-19 trajectory, which exhibited the highest velocity (23 km/day) within the drifter pattern. The associated surface temperature (fig. 11A) and salinity (fig. 12A) gradients both progressively increased seaward, and were largely concordant with coastline orientation. A notable exception was the discordant relationship of the salinity gradients along the outer shelf, a relationship similar to the transmissivity pattern (fig. 8A) which suggests the shoreward incursion of nonturbid, higher salinity deeper Gulf waters, However, the temperature and salinity gradients did not provide any evidence of the southward alongshore transport component indicated by the turbidity and drifter patterns.

During the early spring (March 17-21, 1977), regional turbidity patterns indicated both offshore and southward alongshore transport components (figs. 8B, 9B). Regional surface drift was toward the SSW (fig. 10B). The southward alongshore drift component largely may reflect northeasterly winds during the late cruise/early post-cruise period. A significant onshore-drift component also is indicated by the several drifter recoveries from outer-shelf stations. Associated surface temperature (fig. 11B) and salinity (fig. 12B) gradients suggested a plume of relatively cool, lower salinity inner-shelf waters moving southward; this would be in agreement with both the drifter pattern and with the southward sediment-dispersal pattern indicated by regional turbidity gradients (figs. 8B, 9B). Although offshore sediment transport also appears to have occurred to some degree, it may have been minimized by a relatively strong onshore drift component.

During the later spring (May 24-27, 1977), regional turbidity patterns indicated the offshore transport of coast-derived sediment; the direction of any possible alongshore transport component was not well defined (figs.

8C, 9C). Regional surface drift was toward the north in the southern half of the area, changing toward the northeast in the northern half of the area, in conformity with a change in coastline orientation (fig. 10C). The drift pattern was probably a response to the persistent southeasterly onshore winds during the cruise and contiguous periods. The pattern illustrated not only strong northward alongshore drift, but also suggests a substantial onshore drift component, as reflected by the numerous drifter recoveries from outer-shelf stations. Regional surface temperature (fig. 11C) and salinity (fig. 12C) gradients suggested the irregular shelfward incursion of relatively cool and more saline nonturbid deeper Gulf waters, in agreement with the regional turbidity gradients (fig. 8C, 9C). However, neither parameter provided any definitive evidence of the northward alongshore-transport component indicated by the drift pattern.

Discussion of Field Results

The time sequence of regional shelf turbidity and hydrographic patterns over the eighteen-month observational period illustrated both substantial variability in time and space, as well as some consistent trends. The surface patterns appeared to reflect a regional sediment-dispersal system regulated by a shelf-water exchange process characterized by the seaward movement of inner-shelf waters and the opposing shoreward incursion of outer-shelf waters.

Spatial Variability

Inner-shelf waters were relatively turbid, with a high shoreward-increasing concentration gradient; the turbidity structure was concordant with coastline orientation and bathymetry. This persistent regional gradient along the inner shelf probably reflects both the diffusive and advective offshore transport of sediment from a coastal line source, as well as a progressive shoreward increase in wave surge intensity that maintains sediment in suspension. Superimposed on this regional gradient were local gradients established at the major coastal inlets that served as prominent point sources and dispersal centers of sediment introduced into the shelf environment via ebb tide discharge. The presence of both active and detached ebb tide sediment plumes and bands of turbid water from coastal inlets have been well documented on the South Texas shelf in Landsat imagery, both by previous workers (e.g. Hunter; 1973; 1976) and in the present report (Landsat Imagery Analysis section). The relative sediment flux and gradients associated with individual inlets varied temporally. The seaward tidal flushing of adjacent turbid lagoonal-estuarine waters appeared to be especially effective during periods of strong northerly storm winds, such as associated with the passing of cold fronts over the Texas shelf (e.g. November 1975 cruise). In addition to offshore transport, suspended sediments in inner-shelf waters also exhibited an alongshore transport component that appeared to be largely the result of wind-driven currents. The variability of inner-shelf turbidity patterns was probably attributed jointly to spatial and temporal variations in a combination of factors such as relative sediment flux from individual inlets, and ambient wind and wave conditions.

In contrast to the inner shelf, the outer-shelf waters were relatively nonturbid, with low shoreward-increasing gradients; the turbidity gradient was largely discordant with coastline orientation and bathymetry. These characteristics appear to reflect the shelfward incursion of adjacent deeper

Gulf waters, the extent of which varied both spatially and temporally; in essence, the variability of outer-shelf turbidity patterns appeared to be regulated largely by deeper Gulf circulation mechanisms. The shelfward incursion of open-ocean waters is supported, not only by hydrographic evidence, but also by microzooplankton studies (Casey, 1976, 1977). Casey noted that certain radiolarian and foraminiferan groups indicated the presence of deeper Gulf water masses on the South Texas shelf, which he interpreted as having possibly been brought in as anticyclonic gyres or rings detached from the Gulf Loop Current. The shoreward advection of deeper Gulf waters would certainly introduce some biogenic constituents into the shelf-water's total particulate system. However, as noted by McCave (1972), perhaps the most significant influence of shoreward advection would be to restrain the Gulfward escape of terrigenous shelf sediment; this would tend to accentuate or reinforce the regional turbidity gradients along the inner shelf that result from the opposing offshore transport of coast-derived sediment.

In summation, regional surface-sediment dispersal appears to be controlled by a shelf-water exchange process. Regional variations in shelf turbidity may reflect the degree of interchange between nonturbid shoreward-moving deeper Gulf waters, and the gulfward movement of turbid inner-shelf waters. Ambient wind conditions seem to be highly influential in regulating water movement along the inner shelf; whereas, shoreward incursion of open-ocean waters along the outer shelf is probably more influenced by deeper Gulf circulation mechanisms.

Temporal Variability

Observed temporal variations in regional turbidity and hydrographic patterns occurred at both the seasonal and annual time scales.

Seasonal variations.--During the first-year program (fall, 1975-spring, 1976), turbidity in terms of mean particle concentrations was highest in the fall and lowest in early spring (table 1). The turbidity distribution patterns also were quite variable. The fall pattern appeared to reflect the maximum seaward dispersion of turbid inner-shelf waters. Because runoff from adjacent rivers was relatively low during November (fig. 2), this widespread dispersion of turbid water was apparently in response to efficient tidal flushing of the lagoonal-estuarine system during associated storm conditions. In contrast, the spring patterns appeared to reflect maximum shoreward incursion of nonturbid outer-shelf waters. This incursion apparently confined turbid waters to the shallower inner shelf. Maximum shoreward incursion or upwelling of deep Gulf waters into the OCS during the spring season also has been suggested by microzooplankton studies (Casey, 1976, 1977).

During the second-year program (fall, 1976-spring, 1977), mean particle concentrations indicate nearly equal turbidity during the fall and late spring, both of which were substantially more turbid than during the early spring (table 1). The turbidity distribution patterns also were highly variable, suggesting a maximum seaward dispersion of turbid inner-shelf waters during the fall. Conversely, a maximum shoreward incursion of nonturbid outer-shelf waters was suggested during the early spring.

Annual variations.--A comparison of the first and second-year surface turbidity and hydrographic patterns illustrate differences between respective seasons, thus indicating some variability at the annual time scale. During the fall season, turbidity was substantially higher in the second year on the basis of both mean transmissivity and particle concentration values (table 1). The fall turbidity distribution patterns also suggest a greater seaward dispersion of turbid inner-shelf waters during the second year. Because storm tidal flushing during the first year should have resulted in more effective seaward dispersal of turbid coastal waters, the greater turbidity observed during the second year might be attributed to a greater discharge from adjacent fluvial systems (fig. 2).

During the early spring season, mean turbidity was essentially the same during both years. However, differences in the turbidity distribution pattern did suggest more extensive seaward dispersion of turbid inner-shelf waters during the second year. This might be attributed to generally higher discharge from adjacent rivers during the second year (fig. 2); this is supported by the patterns of lower salinity and higher temperatures along the inner shelf during the second year.

In the late spring, mean turbidity was substantially higher during the second year. In addition, the turbidity distribution patterns also indicated more extensive seaward dispersion of turbid inner-shelf waters during the second year. This might jointly reflect the generally higher spring discharge of adjacent rivers during the second year, and a lower degree of restraint from the shelfward incursion of deep Gulf waters. Less incursion during the second year was suggested by lower salinities along the outer shelf.

In general, the OCS region was substantially more turbid during the second-year (fall, 1976-spring, 1977) monitoring season. This is interpreted as at least partially resulting from a higher regional discharge volume from Texas fluvial systems during the second year period from September 1976 to July 1977 (fig. 2). Of notable interest is the relatively high volume discharge of the Mississippi River located approximately 250 nautical miles east of the Sabine River. The influx of spring runoff from the voluminous Mississippi into the OCS region previously has been suggested by the presence of low-salinity water masses trending southward along the inner shelf (e.g. Smith, 1976). Consequently, a greater spring runoff from the Mississippi during the second year also may have had some influence on spring turbidity. However, the Mississippi does not appear to have been influential during the fall season. The greater second-year turbidity probably also partially reflects variations in deep Gulf circulation which resulted in a lower degree of shelfward incursion by nonturbid open-ocean waters.

Landsat Imagery Analysis

In an effort to supplement our knowledge of regional surface turbidity based on field measurements, selective Landsat imagery also was qualitatively analyzed for turbidity patterns. The region of imagery coverage, as well as the types of observed features, are illustrated by figure 13.

First Year Imagery

November 12-13, 1975 Overpass.--This overpass sequence (fig. 14) is the closest available coverage to the first-year fall monitoring cruise (November 15-21, 1975). The imagery shows relatively turbid water masses

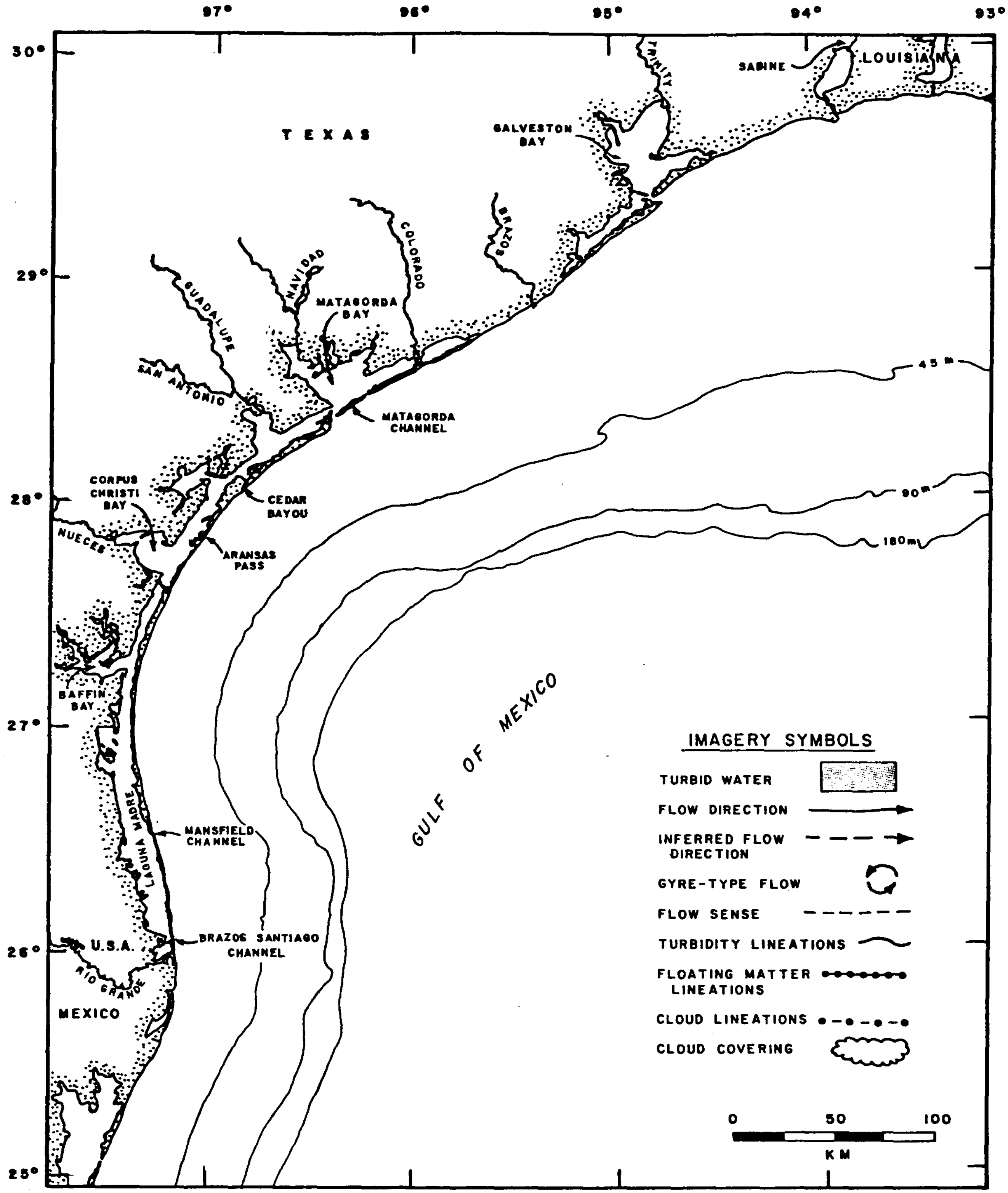

Figure 13. Region of Landsat imagery coverage and legend of observed features.

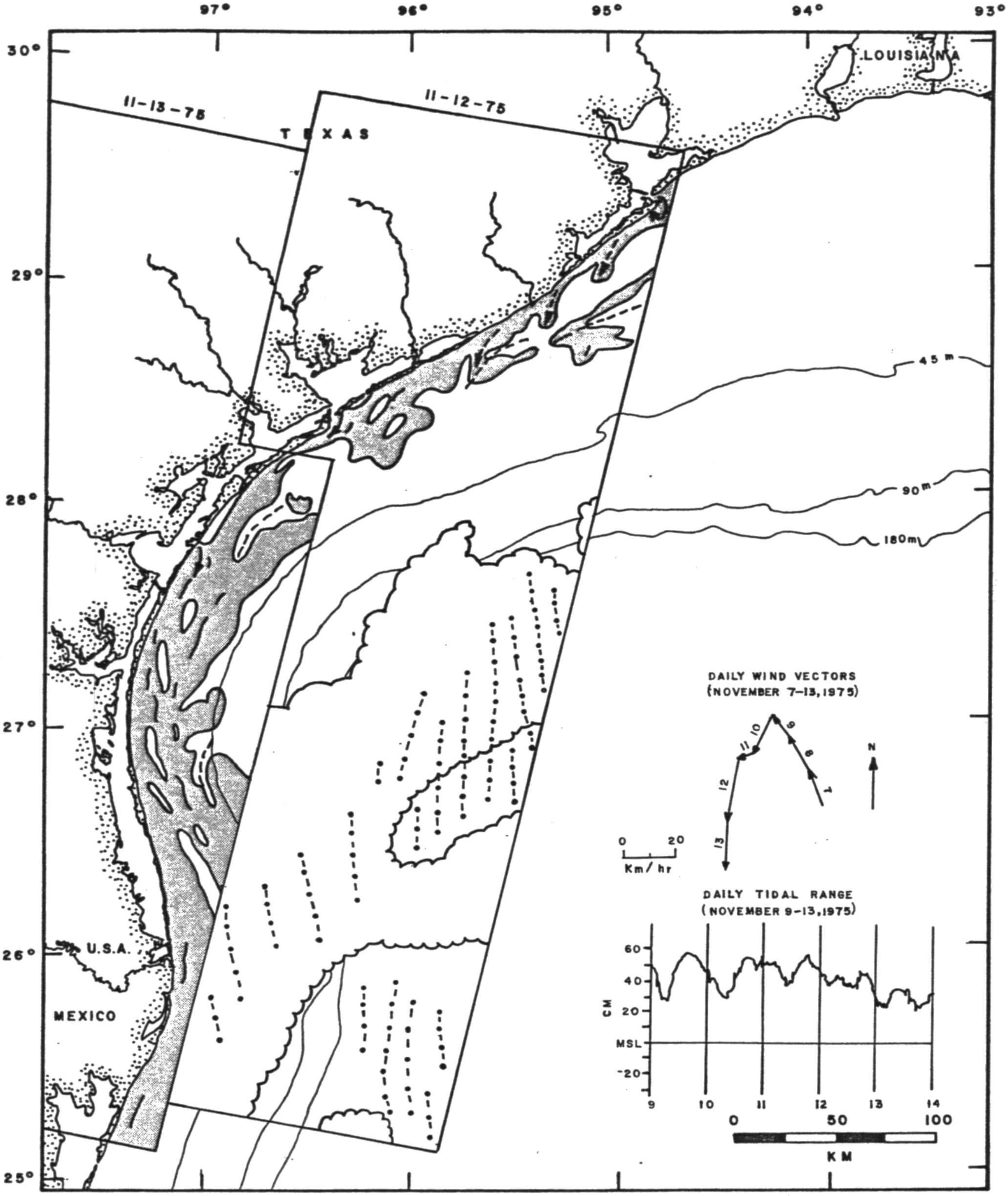

Figure 14. Landsat imagery patterns and associated wind/tidal conditions during November 12-13, 1975 overpass.

throughout much of the inner shelf (<45 m). The turbid zone extends seaward from the coastline and increases in width southward. Several features are indicative of sediment dispersal direction. A regional southward alongshore transport component throughout the inner shelf is suggested by turbidity lineations, by the trends of shear structures developed between turbid and nonturbid water masses, and by ebb tide sediment plumes associated with Matagorda ship channel and Aransas Pass. Regional southward transport is further supported by a series of oblique south-trending tongues of turbid coastal water northeast of the Colorado River, and by clockwise gyre-type flow at Galveston Bay inlet which appears to reflect the interaction of ebb tidal currents with south-flowing littoral currents.

Meteorological conditions during the overpass period consisted of substantial offshore cloud covering with some north-south lineations. The daily wind vector during November 12 was from the north/northeast at 25 km/hr. Winds during the previous two-day period were of lower speed but also had northerly components. Semi-diurnal neap tides during the overpass period had a maximum range of about 20 cm.

The regional southward transport of sediment along the inner shelf appears to have resulted from currents driven by the northerly winds, and was essentially the same as the transport pattern indicated by the water column data collected during the subsequent November 15-21, 1975 monitoring cruise (figs. 3,4). The dispersal pattern is believed to represent the sea state conditions that are associated with winds having strong northerly components, such as are relatively frequent during the late fall and winter seasons.

February 1-2, 1976 Overpass.--This overpass sequence provides supplement winter coverage during the first-year monitoring program (fig. 15). The imagery illustrates a relatively narrow zone of turbid nearshore waters that diminishes in width toward the central sector. Sediment plumes were associated with most principal rivers and inlets, and they generally indicate regional alongshore sediment transport northeastward on the inner shelf. The only exception is the plume associated with the Brazos Santiago channel which suggests more radial seaward dispersion without any apparent alongshore component.

The area was cloudless during the overpass period. Winds were from the west/northwest on February 1 (15 km/hr), from the south (12 km/hr) on February 2, and variable during the previous four-day period. Tides were mixed diurnal to semi-diurnal and had a maximum range of about 35-40 cm. The northeastward movement of the sediment along the inner shelf within the northern half of the region could reflect the strong westerly component of the February 1 wind vector.

February 27-29, 1976 Overpass.--This overpass sequence provides the closest available coverage to the early spring (March 2-6, 1976) cruise of the first-year monitoring program (fig. 16). Turbid waters were confined to the nearshore zone of the inner shelf and the band of turbid water decreased in width toward the central sector. The largest ebb-sediment plume was from Galveston Bay inlet which indicated a radial seaward dispersal pattern with no dominant alongshore component. Radial dispersal also was indicated by a plume from Matagorda ship channel, but in contrast the plumes from inlets within the southern half of the region (Aransas Pass, Mansfield Channel, Brazos Santiago Channel) indicated northward drift.

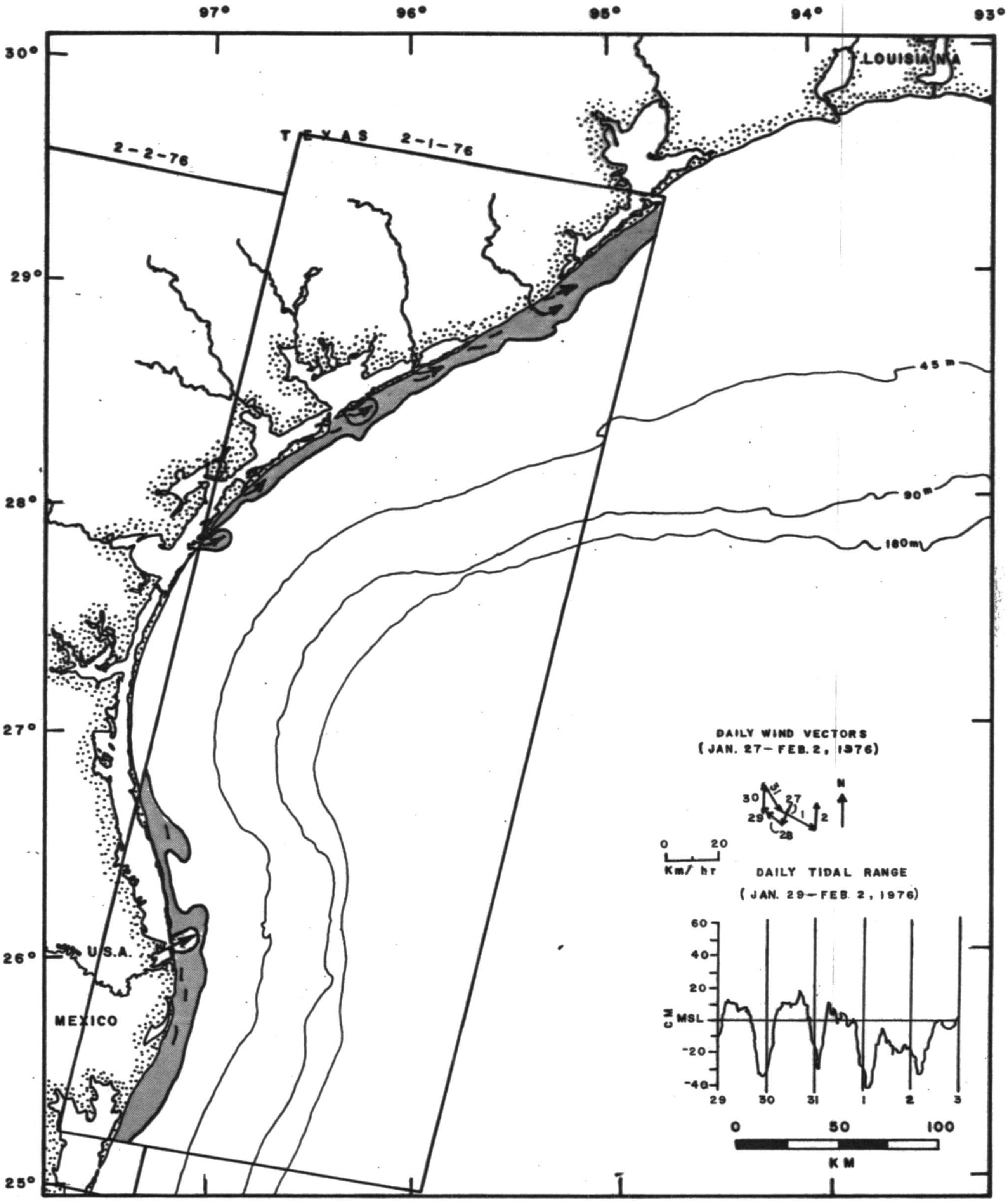

Figure 15. Landsat imagery patterns and associated wind/tidal conditions during February 1-2, 1976 overpass.

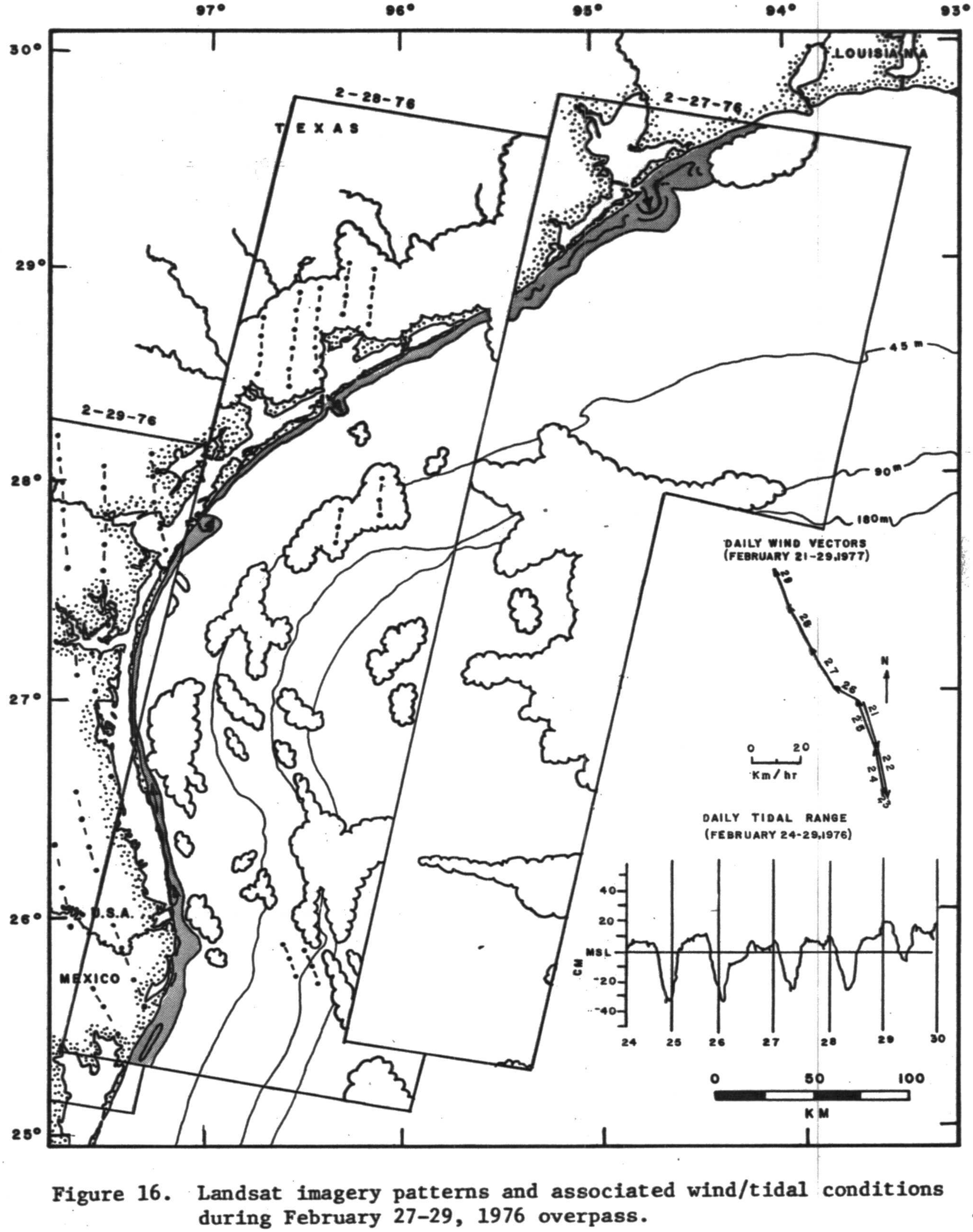

Figure 16. Landsat imagery patterns and associated wind/tidal conditions during February 27-29, 1976 overpass.

Meteorologically, the overpass period was characterized by substantial cloud covering, which included north-south trends of onshore cumulous clouds; winds ranged from 16 to 22 km/hr, and were consistently from the south/southeast. Tides during the period were largely diurnal and had a maximum range of about 35 cm. The contrast in sediment dispersal directions between the northern and southern sectors of the region may have been the result of the northward change in coastline orientation relative to the consistent south/southeasterly wind direction. The sediment dispersal pattern during the subsequent March 2-6, 1976 monitoring cruise was essentially seaward, with no apparent alongshore transport component.

May 28-29, 1976 Overpass.--This overpass sequence (fig. 17) is the closest available coverage to the first-year late spring monitoring cruise (May 21-25, 1976). Turbid water masses were restricted to the nearshore area with the turbid zone generally decreasing in width southward. Sediment plumes from the Brazos River, Matagorda ship channel, and Mansfield channel all indicated regional north/northeastward alongshore drift.

Meteorological conditions during the period consisted of substantial cloud covering with a few NW-SE lineations. Winds on May 28 were east/southeasterly (9 km/hr), shifting to southeasterly (20 km/hr) on May 29. Except for northerly winds on the day preceeding the overpass (May 27), the previous four-day period had consistent southeasterly winds. During the overpass, diurnal spring tides had a maximum range of about 55 cm. The regional north/northeastward dispersal of inner-shelf sediment would be consistent with forcing effects resulting from the prevailing southeasterly winds. It is noteworthy that during the preceeding cruise period (May 21-25), a major shift from northeasterly to southeasterly winds had occurred,

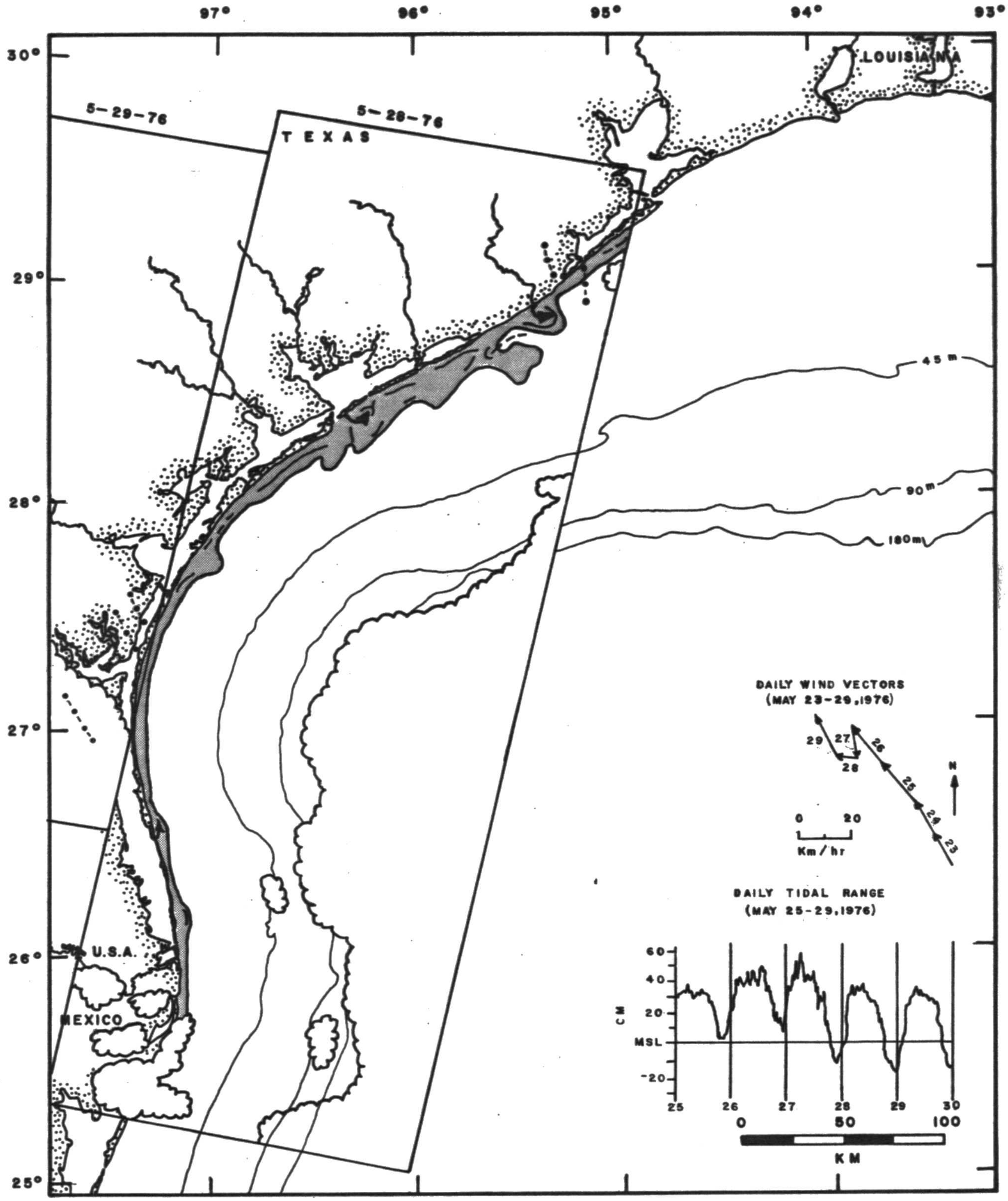

Figure 17. Landsat imagery patterns and associated wind/tidal conditions during May 28-29, 1976 overpass.

resulting in a surface drifter convergence pattern, and no apparent net alongshore transport component (figs. 3-5). Consequently, it appears that inner shelf circulation had completely adjusted to the southeasterly wind shift by the time of the overpass. Such shifting wind patterns are common in the South Texas OCS during the spring and fall seasons.

August 8-9, 1976 Overpass.--This overpass sequence provides supplemental summer coverage during the first-year monitoring program (fig. 18). Turbid waters were localized along the nearshore sector. The width of the turbid zone decreased from the northern and southern sectors toward the central sector; no significant coastal turbidity was observed within the central sector (Corpus Christi Bay to Baffin Bay). Regional sediment dispersal to the north/northeast was indicated by all sediment plumes. Plumes were associated with the Brazos and Colorado rivers, the Matagorda ship channel, the Mansfield channel, the Brazos Santiago channel, and the Rio Grande but none with Aransas Pass.

Weather conditions during the overpass period consisted of substantial offshore cloud covering and a few north-south oriented rows of cumulous clouds within the southern onshore sector. Winds were relatively weak and consistently from the south during August 8 (9 km/hr) and August 9 (7 km), and were southeasterly during the three-day period prior to the overpass. Tides during the overpass were diurnal, and were near the end of the spring-tide phase with a maximum range of about 45-50 cm.

The regional alongshore sediment transport to the north/northeast appeared to be caused by the weak southerly winds, and the pattern probably is typical of general summer circulation within the region.

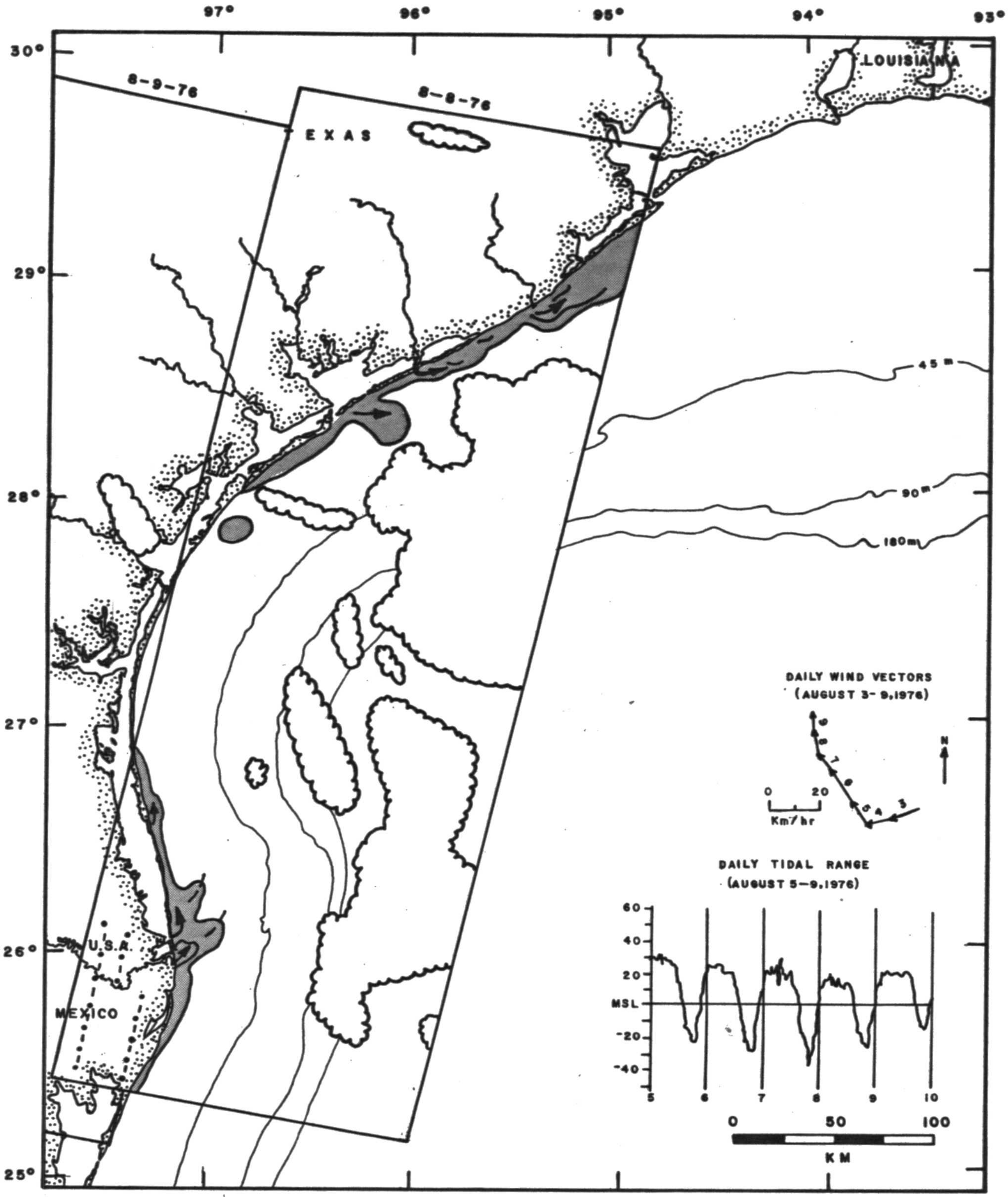

Figure 18. Landsat imagery patterns and associated wind/tidal conditions during August 8-9, 1976 overpass.

Second-Year Imagery

October 10-11, 1976 Overpass.--This overpass sequence (fig. 19) provides the closest coverage to the second-year fall monitoring cruise (Oct. 29-Nov. 3, 1976). Inner shelf turbidity was relatively low, and was confined to the nearshore. The turbid zone decreased in width toward the central sector. Sediment plumes were associated with all principal outlets. All plumes indicated sediment dispersal to the north/northeast except the Rio Grande plume. During the overpass period, cloud covering was minor. Winds were from the SSW and relatively weak (3 km/hr) on October 10, changing to slightly stronger (7 km/hr) southerly winds on October 11. Tides were diurnal and had a maximum range of about 35 cm.

The regional alongshore transport to the north/northeast appeared to have been caused by the forcing effects of the southerly winds. Although relatively strong northerly winds prevailed during the previous October 5-8 period, no residual forcing effects from these winds were indicated by the imagery. The observed northward dispersal pattern was in contrast to the regional southward dispersal pattern observed during the subsequent Oct. 29-Nov. 3 monitoring cruise when winds had northerly components (figs. 8-10).

February 13-14, 1977 Overpass.--This imagery provides supplemental winter coverage for the second-year monitoring program (fig. 20). Turbidity was relatively high during the overpass and the turbid water extended seaward across much of the inner shelf; the turbid zone was widest within the northern sector. Ebb-tide sediment plumes were well developed during the period and all were oriented toward the south/southwest.

Weather conditions consisted of substantial offshore cloud covering. Winds were from the NNW during February 13 (6 km/hr), shifting to the SSE

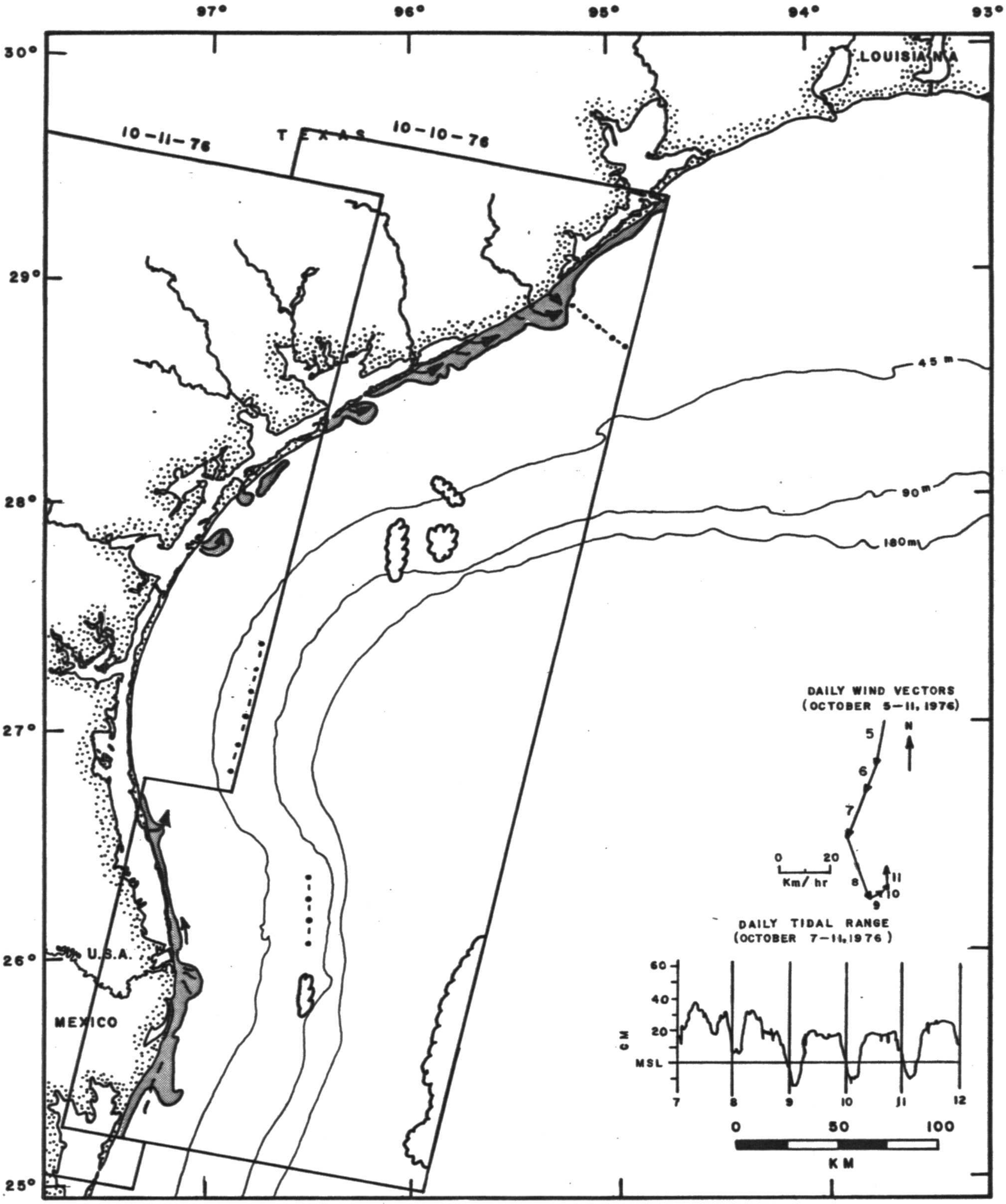

Figure 19. Landsat imagery patterns and associated wind/tidal conditions during October 10-11, 1976 overpass.

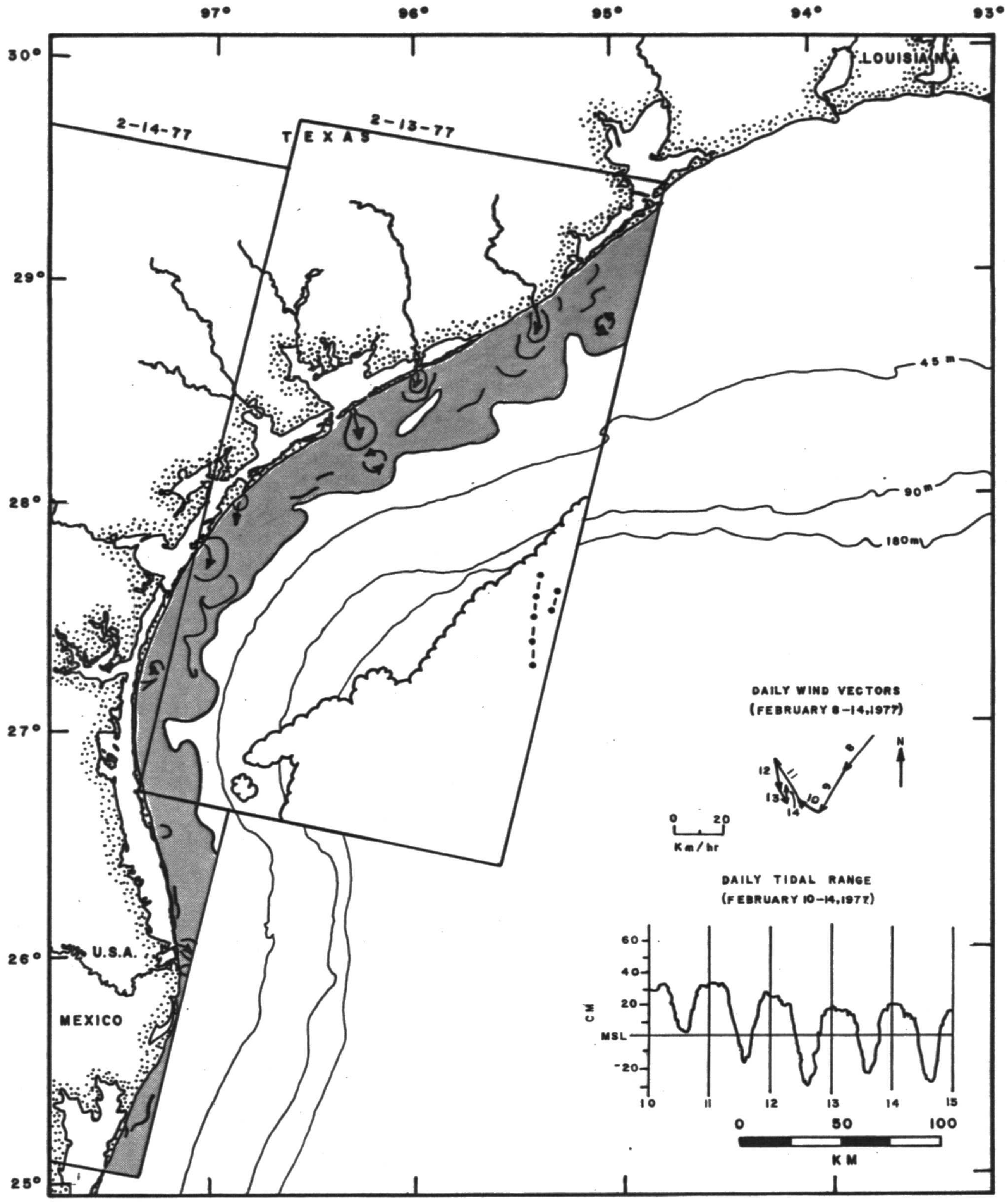

Figure 20. Landsat imagery patterns and associated wind/tidal conditions during February 13-14, 1977 overpass.

on February 14 (6 km/hr). During the overpass, diurnal spring tides exhibited a maximum range of about 50 cm.

The regional alongshore transport to the south/southwest appeared to have been caused by the NNW winds, and is a dispersal pattern that is probably typical of the winter season. Time-lapse coverage of the plumes associated with Aransas Pass and Cedar Bayou during both overpass dates illustrates a reduction in southward orientation on February 14, thus suggesting some compensating forcing effects from the wind shift to the SSE that occurred on February 14. The relatively high turbidity during the overpass period might be partially attributed to efficient tidal flushing of the lagoonal-estuarine system by spring tides associated with an off-shore wind.

April 7-9, 1977 Overpass.--This imagery sequence (fig. 21) provides the closest available coverage to the early spring cruise (March 17-21, 1977) of the second-year monitoring program. The inner shelf turbidity was highly variable throughout the region. The extent of the turbid water zone was minimal within the central sector, and extremely wide within the northernmost sector. Northeast of Galveston Bay, the turbid zone was of maximum width, extending from the shoreline to 33 km offshore.

All coastal sediment plumes indicated regional alongshore transport to the north/northeast. The Brazos River exhibited an unusually strong sediment plume; time lapse imagery indicated that the Brazos plume persisted at least two days (April 7-8) with decreasing intensity on the second day. Moderate plumes were associated with Matagorda ship channel and Aransas Pass, and small plumes were developed at the Mansfield and Brazos Santiago channels.

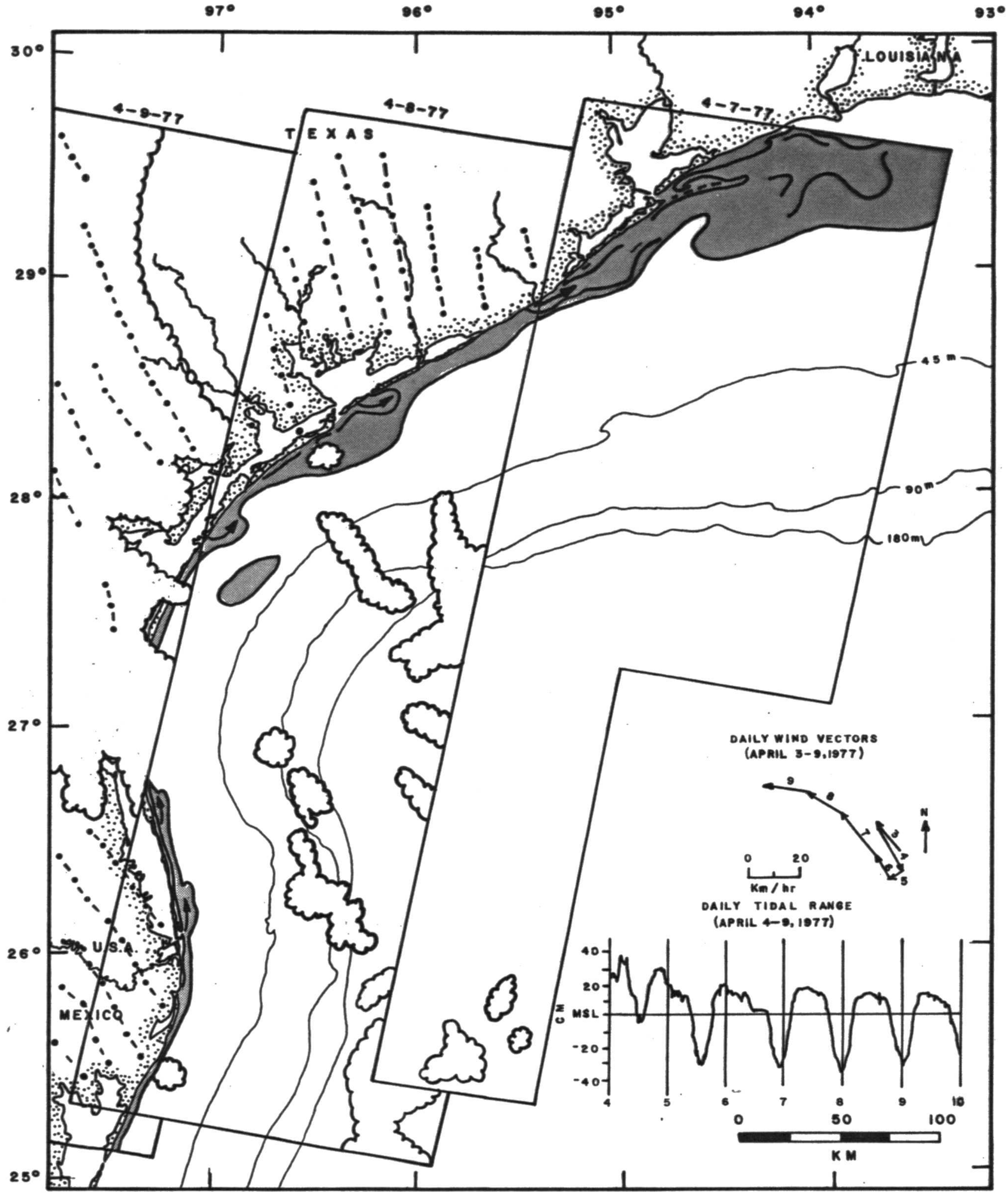

Figure 21. Landsat imagery patterns and associated wind/tidal conditions during April 7-9, 1977 overpass.

Meteorological conditions consisted of substantial offshore and onshore cloud covering, with prominent northwest/southeast oriented rows of onshore cumulous clouds. Winds were southeasterly during April 7 (21 km/hr), shifting to easterly/southeasterly on April 8 (16 km/hr) and April 9 (18 km/hr). During the overpass, diurnal spring tides exhibited a maximum range of 50-55 cm.

Regional sediment dispersal to the north/northeast appears to have resulted from the forcing effects of southeasterly winds. The regional influence of southeasterly winds during the overpass period is supported by the widespread occurrence of rows of cumulous clouds oriented NW/SE. Strong plume development during this period could have been enhanced by the spring tides. The extremely wide turbid zone east of Galveston Bay may result from a combination of possible factors: 1) the turbid zone is concordant with bathymetry, occurring where the shelf widens and shoals substantially. This suggests that it could be partially attributed to resuspension of bottom sediment by wave surge along this shallow sector; 2) it could partially reflect easterly transported effluent from Galveston Bay and the Sabine River; and 3) it might also partially reflect the prior westward transport of turbid runoff waters from the Mississippi River and other Louisiana rivers to the east. This possibility is suggested because the overpass occurred during the spring high discharge stage of the Mississippi River (fig. 2). The spring influx of Mississippi River effluent into the South Texas OCS previously has been suggested by Smith (1976); he noted the presence of south-trending, low salinity coastal water masses, which occasionally extended as far as 60 km offshore.

The regional sediment dispersal pattern was in contrast to the southward regional transport observed during the early spring monitoring cruise some three weeks earlier (March 17-21). The contrast is attributed to northerly winds during the cruise period.

May 31-June 2, 1977 Overpass.--This imagery sequence (fig. 22) provides the closest available coverage to the late spring cruise (May 24-27, 1977) of the second-year program. The band of coastal turbid water was of minimal width within the southernmost sector, and increased in width northward; during the earlier overpass (April 7-9), the turbid zone was widest (37 km) northeast of Galveston Bay.

Coastal sediment plumes associated with the Rio Grande and Brazos Santiago channel indicated northward alongshore transport. A substantial alongshore component within the southern half of the region also is suggested by the north/south trends of narrow bands of floating matter; these appear to be spring plankton bands aligned along the direction of flow. A possible weak plume from the Colorado River suggests northeasterly transport; whereas, a plume at Galveston Bay inlet suggests mainly eastward transport.

Weather conditions during the overpass period consisted of substantial cloud covering. Winds from May 27 to June 1 were consistently from the southeast, shifting to weak easterlies on June 2. During the overpass, diurnal spring tides reached a maximum range of 60-65 cm.

The regional sediment dispersal pattern is in agreement with consistent southeasterly winds which appeared to have been the dominant forcing agent. The relatively high degree of inner shelf turbidity might be partially attributed to the efficient flushing of adjacent estuaries by spring tides. Similar to the early spring overpass (April 7-9), the wide turbid zone east

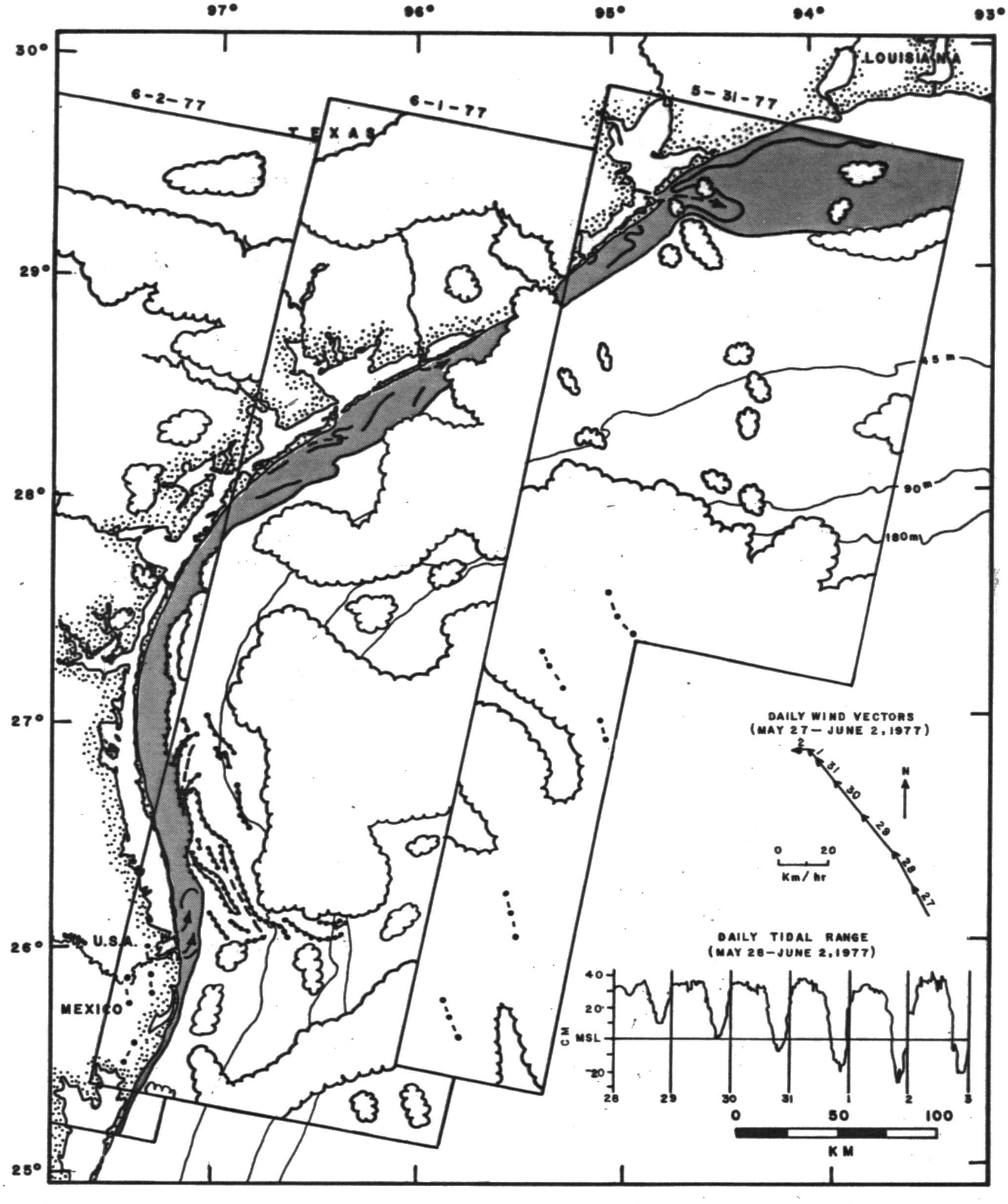

Figure 22. Landsat imagery patterns and associated wind/tidal conditions during May 31-June 2, 1977 overpass.

of Galveston Bay was present. The regional dispersal pattern during the overpass is in contrast to the pattern observed during the previous late spring (May 24-27) cruise when no alongshore component was apparent.

July 12-14, 1977 Overpass.--This imagery provides supplemental summer coverage during the second-year monitoring program (fig. 23). The width of the coastal turbid-water zone was minimal within the central sector south of Baffin Bay, and widest (58 km) within the northern sector east of Galveston Bay. Sediment plumes trending north/northeast were associated with the following: The Brazos River and an adjacent stream northeast of it, Matagorda ship channel, Aransas Pass, Brazos Santiago channel, and the Rio Grande.

Meteorological conditions during the period consisted of substantial cloud covering both offshore and onshore, with the regional development of NW/SE trending cumulous rows. Winds were persistently from the southeast during the July 8-13 period, shifting to easterly on July 14. During the overpass, diurnal spring tides reached a maximum range of 45-50 cm. Regional sediment transport to the north/northeast is in agreement with forcing effects resulting from the consistent southeasterly winds. The regional influence of these winds is supported by the widespread development of the NW/SE trending cumulous rows. The wide turbid zone east of Galveston Bay that was present during the previous spring overpasses persisted until mid July, a time when discharge from the Mississippi, Sabine, and Trinity rivers was relatively low (fig. 2). This suggests that bottom-sediment resuspension by wave surge within this shallow shelf sector, rather than continental runoff, may be the dominant cause of the wide turbid zone east of Galveston Bay.

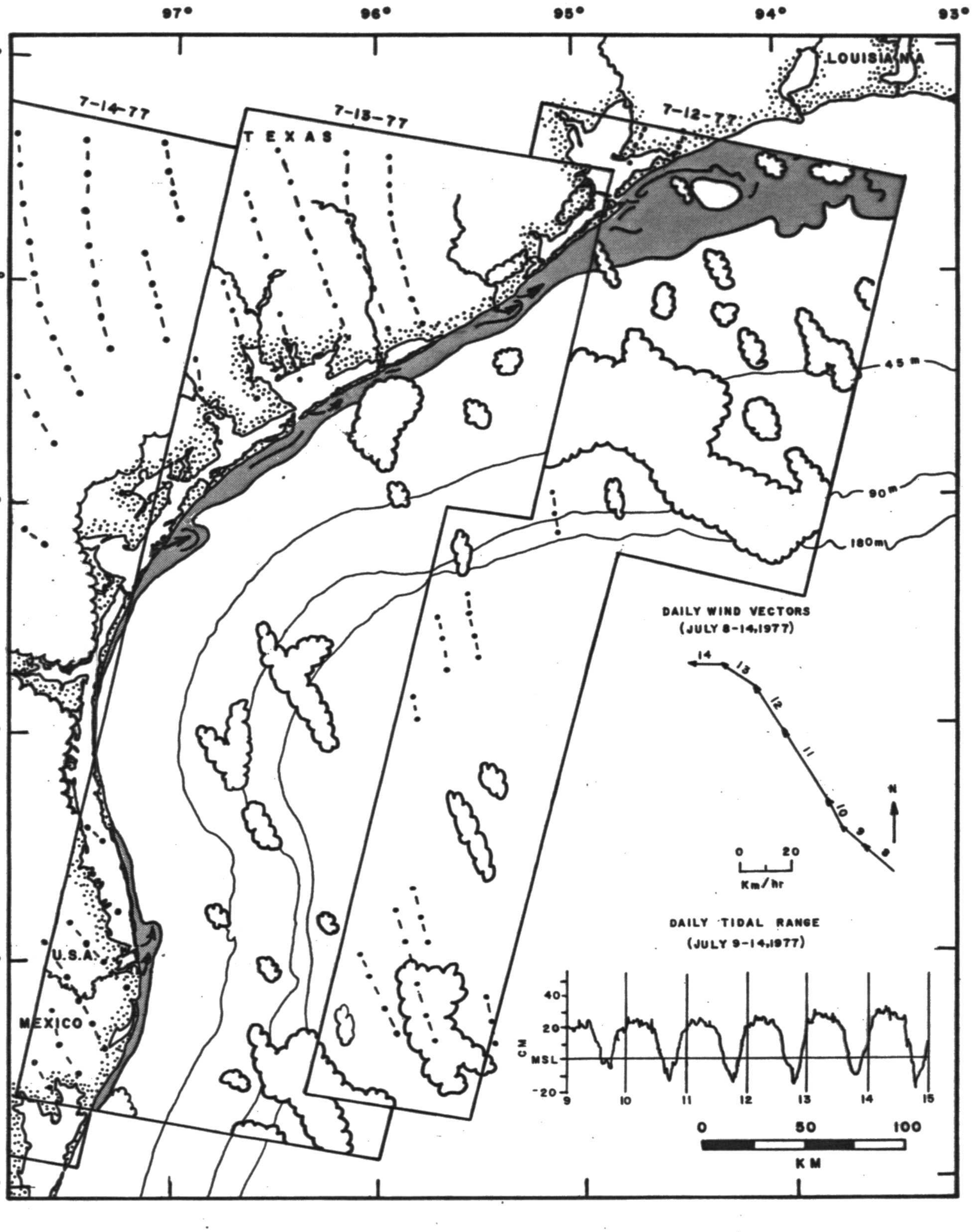

Figure 23. Landsat imagery patterns and associated wind/tidal conditions during July 12-14, 1977 overpass.

Synopsis

Regional turbidity patterns observed on the Landsat imagery corroborated inferences based on surface-water measurements, and indicated that regional surface-sediment dispersal directions along the inner shelf are primarily controlled by coastline curvature and ambient wind conditions. Alongshore sediment transport results from both littoral currents and wind-driven inner-shelf currents. Winds with strong northerly components, such as commonly occur during winter months, resulted in alongshore transport to the south/southwest; in contrast, winds with strong southerly components, such as prevail during summer months, resulted in transport to the north/northeast. The influence of seasonal wind direction on circulation patterns of the Texas shelf also has been well documented by previous drifter studies (e.g. Watson and Behrens, 1970; Hunter and others, 1974; Hill and others, 1975). The results of the present study are in agreement with the findings of these previous studies.

The zone of turbid nearshore waters was of maximum width east of Galveston Bay where the shelf widens substantially. In contrast, the width of the nearshore turbid zone was frequently minimal within the central sector between Corpus Christi Bay and Baffin Bay, a sector of maximum coastal curvature.

SUBSURFACE TURBIDITY

As one phase of the STOCS suspended sediment study, the variability of the turbidity structure and associated thermostructure within the water column also was investigated to provide further insight into the regional sediment-dispersal system. This was accomplished by establishing a time-sequence of transmissivity/temperature gradients at each observation station over the eighteen-month field monitoring period. These time-sequence gradients are presented in detail by Berryhill and others (1976b, 1977).

Quantitatively, much of the suspended sediment in the STOCS region appears to be transported in the subsurface, primarily within a benthic nepheloid layer. On the basis of total mass (mg/l), average bottom water sediment concentrations were generally over 2.5 times greater than surface concentrations during the monitored period (Berryhill and others, 1976b, 1977). The nepheloid layer was observed repeatedly during the field period. However, the origin and characteristics of the nepheloid layer are very poorly understood, and require further detailed study. In addition, the variability of the water-column turbidity structure, as well as its relationship to thermostructure, are complex and inadequately understood. An understanding of these aspects would require a long-term monitoring study of turbidity and hydrographic properties within the water column, a study that was beyond the time framework of the STOCS program. Although additional data are required to provide definitive answers regarding subsurface turbidity, some general conclusions can be formulated on the basis of the data bank acquired over the eighteen-month field period.

Inlet Areas

The three major inlets adjacent to the OCS (Matagorda Bay Inlet, Aransas Pass, Rio Grande-Brazos Santiago Channel) are of importance because they represent the major sources and dispersal centers for sediment entering the OCS region. The inlet areas were monitored at the following stations: 1, 1A, 2, 9, 9A, 23, 23A, 24. In general, the transmissivity/temperature gradients at inlet stations were highly variable in time and space. Temporally, no systematic trends were apparent near the inlets, other than a tendency for the water column to be most thoroughly mixed and homogeneous during the fall season.

The turbidity structure and thermostructure of the water column at inlet stations appear to be controlled largely by short-term diurnal variations in ambient hydrographic conditions which control the degree of interaction between inlet tidal waters and coastal currents. Important hydrographic variables include: tidal current strength, longshore currents which control the dispersal direction of ebb-tide sediment plumes, and wave-surge intensity which controls the degree of benthic sediment resuspension and water homogenization. Water-column structures near inlets ranged from frequently well-mixed isothermal/isoturbid conditions, to well-stratified conditions. A common stratified structure consisted of three water layers: 1) a turbid upper layer reflecting the seaward dispersal of an ebb-tidal sediment plume. The plume maintains its identity as a relatively low-density surface flow consisting of low salinity coastal runoff; 2) a turbid bottom layer probably reflecting the resuspension of benthic sediments by wave surge; and 3) an intermediate-depth layer of relatively low turbidity.

Turbidity discontinuities were frequently associated with thermal discontinuities. However, this did not appear to be a systematic casual relationship. Instead, it probably reflects the ability to differentiate discrete coastal water masses on the basis of a combination of turbidity and temperature criteria.

Inner-Shelf Sector

Excluding the immediate inlet areas previously discussed, the inner shelf is here defined as the sector less than 45 meters deep. This sector includes the following stations: 3, 4, 8, 10, 14, 16, 17, 21, and 22. The turbidity and thermostructures of water columns at stations within this sector also illustrated a high degree of spatial and temporal variability. This is largely attributed to their shallowness and associated hydrographic variability. In general, no systematic seasonal trends in water column structure were apparent along the inner shelf. The only exception was at station 4, where there was the progressive seasonal development of a benthic nepheloid layer from fall to late spring; this occurred during both years, and was associated with a systematic change in thermostructure.

Turbidity structures within the water column at individual stations ranged from isoturbid conditions to well-stratified two and three-layer structures. The intermittent development of a benthic nepheloid layer generally occurred among inner-shelf stations. This was not associated with any systematic change in thermostructure, but the layer was best developed in the presence of thermoclines and negative temperature gradients. In contrast, nepheloid layer development was minimal or nonexistent in isothermal waters.

Outer-Shelf Sector

The outer shelf includes all parts of the study area deeper than 45 meters and contains the following stations: 5, 6, 7, 11, 12, 13, 18, 19, and 20. The turbidity structures and thermostructures of the water column at individual stations within the outer-shelf sector had substantial spatial and temporal variability; however, the turbidity structure appeared to be somewhat less variable than within the inner-shelf sector. In general, no systematic temporal trends were apparent; the only exceptions were at stations 7 and 9, where some annual similarities in turbidity and thermo-structure were indicated.

The water columns at individual stations were occasionally isoturbid. However, the most prevalent turbidity structure consisted of stratified two-layer or three-layer water column with a well-defined benthic nepheloid layer. The thickness of the nepheloid layer at individual stations was seasonally variable; occasionally, the nepheloid layer was seasonally absent. In addition to temporal variations in nepheloid layer thickness, spatial variations also were present. The greatest thickness generally occurred along the southern shelf edge (station 19). No systematic correlation was observed between turbidity structure and water thermostructure. However, some stations did illustrate a close relationship between the two parameters (e.g. stations 7, 19), the significance of which is presently conjectural.

SUSPENDED SEDIMENT TEXTURE

A second approach for gaining insight into regional sediment-dispersal patterns was to establish a time-sequence of lateral textural gradients in both surface and bottom suspended sediments for each of the six cruises during the eighteen-month monitoring period; this time-sequence is presented in Berryhill and others (1976b, 1977). The textural parameters investigated were: silt/clay ratios, which provide a general overview of suspended sediment composition; mean grain size (first moment), which provides a more sensitive indicator of sediment composition; and standard deviation (second moment), which provides an indication of sediment sorting or uniformity. A statistical summary of the sediment textural properties observed throughout the water during the six cruises is presented in table 3. All size terminology is in accordance with the Udden-Wentworth grade scale and is expressed in terms of Krumbein's (1934) phi (Ø) transformation.

Synopsis of First-Year Results

During the first-year program (fall 1975-spring 1976), the suspended sediment size composition in terms of both silt/clay ratios and mean diameters showed a high degree of temporal and spatial variability. No consistent regional grain-size trends were noted in either surface or bottom waters. In addition, bottom-water trends were substantially different than surface-water trends. The size of suspended sediment was predominantly very fine silt within the 3.9-7.8 μm (7.0Ø-8.0Ø) range. In general, bottom-water sediments tended to be somewhat coarser than surface-water sediments. Temporally, the average grain size of sediments throughout the entire water column was coarsest during the late spring and finest in the early spring, in terms of both silt/clay ratios and mean diameters (table 3).

Sediment sorting characteristics, in terms of standard deviation also showed some spatial and temporal variability, but were more consistent than grain-size characteristics. Using Folk's (1965) sorting classification, standard deviation values showed that the sediments ranged from poorly sorted to very poorly sorted. Consistent regional trends were noted showing a general seaward reduction in sorting or uniformity (increasing standard deviation) in both surface and bottom waters; the best sorted sediments generally occurred at the major tidal inlets. In general, bottom sediments were better sorted than surface sediments (table 3). Temporally, the sediments throughout the water column were slightly better sorted in the fall than during the spring; however, the sorting differences between seasons was relatively minor (table 3).

Synopsis of Second-Year Results

During the second-year program (fall, 1976-spring, 1977), the size composition of suspended sediment also was spatially and temporally variable, as indicated by both silt/clay ratios and mean diameters. The most prevalent regional size trend in both surface and bottom waters was a general seaward increase in coarseness, probably indicating a progressive seaward increase in the proportion of relatively large biogenic particulates. In general, the size of suspended sediment was predominantly very fine silt (3.9-7.8 µm). Temporally, the average grain size of sediment throughout the water column was coarsest in early spring and finest in the fall, in terms of both silt/clay ratios and mean diameters (table 3).

The sorting characteristics of suspended sediments in terms of standard deviations also illustrated spatial and temporal variability. The sediments ranged from poorly sorted to very poorly sorted. The most prevalent regional trend was a general reduction in sorting (increasing standard deviation) seaward. In general, sediments in bottom waters were more uniform than surface-water sediments (table 3). Temporally, the sediments throughout the water column were best sorted in the fall, and least sorted in the late spring. Seasonal variability was substantially higher than during the first-year program (table 3).

Discussion of Results

The textural gradients observed during the eighteen-month monitoring period were extremely variable in time and space, thus illustrating a highly complex and transient suspended particulate system within the STOCS region. The regional trends do not appear to be strong indicators of sediment-dispersal patterns resulting from hydraulic processes, but appear to largely reflect compositional variations of the multicomponent particulate system. The particulate system, which is composed of size-variable phytoplankton, zooplankton, and inorganic subpopulations is a highly transient suspensate; consequently, any variations in the relative proportions of component subpopulations will be manifested as variations in sediment texture.

Although regional textural patterns of suspended sediments were highly variable within the OCS, the following general relationships were noted:

1) Very-fine silt is the predominant size of suspended sediment within the STOCS region.

2) The most common regional trends consisted of a seaward increase in sediment coarseness, and a seaward reduction in uniformity or sorting. These trends are interpreted as reflecting a progressive seaward increase in the proportion of relatively large biogenic components (mainly diatoms) incorporated within the particulate system.

3) The regional textural patterns of surface-water sediments were generally different than bottom-water sediment patterns, probably reflecting differences in composition. Bottom sediments were consistently better sorted than surface sediments, suggesting a lower concentration of size-variable organic constituents.

4) Seasonal comparisons during the first year (table 3) indicated that the average sediment throughout the entire water column was coarsest in late spring (May), and finest in early spring (March); it was best sorted in the fall (Nov.). During the second year, the average sediment was coarsest in early spring and finest in the fall; it was best sorted in the fall, and most poorly sorted in late spring. The only consistent seasonal variation for both years is that average sorting was best during the fall, possibly reflecting a relatively low proportion of size-divergent organic particulates.

5) Annual comparisons of the average sediments throughout the water column (table 3) indicate that first-year sediments were coarser in the fall and late spring, but finer in the early spring. In total, the average sediment was coarser during the first-year program, whereas sorting was not significantly different between the two years.

The foregoing relationships illustrate the general textural characteristics which may largely reflect the system's component organic and inorganic subpopulations. In turn, these subpopulations are highly variable in time and space, being controlled both by hydrographic conditions and by organic productivity.

SUMMARY

The integrated results of the STOCS suspended sediment study over the FY 76-78 period indicate a complex regional sediment-disperal system characterized by substantial temporal and spatial variability. The time-sequence of surface turbidity and hydrographic patterns appear to reflect surface dispersal system largely regulated by a shelf-water exchange process that is in dynamic equilibrium. The exchange process consists of the interaction of relatively turbid, inner-shelf waters moving both alongshore and gulfward, and the opposing shoreward incursion of nonturbid open-Gulf waters onto the outer shelf. Water movement along the inner shelf appears to be largely wind-driven; whereas, outer-shelf water movement results from forcing effects associated with deep-Gulf circulation mechanisms. The degree of interchange between these opposing water mass movements appears to determine the regional turbidity patterns. Temporal variability of sediment-dispersal patterns occurs at both the seasonal and annual time scales. This apparently reflects variations in a combination of factors that affect the shelf-water exchange process; these factors probably include ambient wind conditions, the runoff volume from adjacent fluvial systems, and the degree of shoreward incursion by open-Gulf waters.

A major objective in establishing the eighteen-month sequence of turbidity and hydrographic patterns was to provide an initial test of a working conceptual model for the regional sediment-dispersal system based exclusively on previously observed sea-floor sediment distribution patterns (Shideler, 1978). This model was based on data acquired during the FY 75 OCS baseline study (Berryhill and others, 1976a), and it postulated both net offshore transport and net southward alongshore transport components on a wind-dominated shelf. Offshore transport was attributed both to diffusion and to the advective ebb-tide discharge of turbid lagoonal-estuarine waters from coastal inlets. Net southward transport was attributed mainly to advection by seasonally alongshore wind-driven currents, reflecting a winter-dominated hydraulic regime characterized by frequent storms and associated strong northerly winds. In the present study, the observed surface turbidity and hydrographic patterns are compatible with this proposed working model.

Although no winter cruises were conducted, the observed November turbidity patterns from the two consecutive years indicate that they are the resultant of both offshore and southward alongshore transport components, a dispersal pattern that appears to closely approximate "winter-type" conditions characterized by winds having strong northerly components. Additional evidence supporting this wind-dominated shelf model is provided by the supplemental analysis of Landsat imagery. Overpasses obtained during all four seasons within the fall, 1975-summer, 1977 period indicated that inner-shelf turbidity patterns are highly dependent upon wind direction and coastal curvature. The alongshore dispersal of coastal sediment plumes was generally southward when winds had strong northerly components (frequent winter conditions); whereas plume dispersal was generally northward when winds had strong southerly components (normal summer conditions). The compatibility of observed surface turbidity and hydrographic patterns with the proposed model based on seafloor sediment patterns is indeed encouraging, but not conclusive. As noted by Meade (1972), one of the problems encountered in relating suspended-sediment patterns to bottom-sediment patterns is that they reflect processes within highly disparate time scales; the former patterns reflect essentially instantaneous processes, whereas the latter patterns reflect the integral results of long-term processes. Consequently, relationships between the two types of evidence must be evaluated cautiously. Final verification of the proposed model would, of necessity, require future long-term monitoring to establish reliable annual trends. The present study, using a relatively short eighteen-month time base, has been sufficient only to establish the presence of seasonal and annual variability. The verification of a winter-dominated hydraulic regime would require seasonal monitoring over a period of several years.

Subsurface patterns during the study have demonstrated the highly variable nature of the water column's turbidity structure and thermostructure, both spatially and temporally. The study has also demonstrated the widespread occurrence of a benthic nepheloid layer, the development of which is also highly variable in time and space. The nepheloid layer exhibited a general increase in thickness seaward, as well as a complex relationship to thermostructure. Since most suspended sediment transport within the STOCS region probably occurs within the poorly understood benthic nepheloid layer, this aspect warrants further investigation. Future detailed studies designed to determine the nepheloid layer's characteristics, origin, and response to changing hydrographic conditions would be necessary to more fully understand one of the most currently perplexing facets of modern shelf sedimentation. The present study was a beginning.

REFERENCES CITED

Berryhill, H. L., Jr., Shideler, G. L., Holmes, C. W., Hill, G. W., Barnes, S. S., and Martin, R. G., Jr., 1976a, Environmental Studies, South Texas Outer Continental Shelf, 1975: Geology: U.S. Department Commerce, NTIS Publ. no. PB 251-341, 350 p.

Berryhill, H. L., Jr., and others, 1976b, Environmental Studies, South Texas Outer Continental Shelf, 1976: Geology: Report to the Bureau of Land Management (Contract AA550-MU6-24), U.S. Geological Survey, 626 p.

Berryhill, H. L., Jr., and others, 1977, Environmental Studies, South Texas Outer Continental Shelf, 1977: Geology: Report to Bureau of Land Management (Contract AA550-MU7-27), U.S. Geological Survey, 306 p.

Casey, R. E., 1976, Microzooplankton and microzoobenthos project: In Parker, P. L. (ed.), Environmental Assessment of the South Texas Outer Continental Shelf - Chemical and Biological Survey Component: Report to Bureau of Land Management (Contract 08550-CT5-17), Univ. of Texas, Texas A&M Univ., and Rice Univ., p. 82-153.

_______, 1977, Shelled microzooplankton, general microplankton and shelled microzoobenthon of the South Texas Outer Continental Shelf (1976): in Grover, R. D. (ed.), Environmental Assessment of the South Texas Outer Continental Shelf - Chemical and Biological Survey Component: Report to Bureau of Land Management, Univ. of Texas, Texas A&M Univ., and Rice Univ., 146 p.

Folk, R. L., 1965, Petrology of Sedimentary Rocks: Hemphills, Austin, Texas, 159 p.

Hill, G. W., Garrison, L. E., and Hunter, R. E., 1975, Maps showing drift patterns along the north-central Texas coast, 1973-1974: U.S. Geol. Survey Misc. Field Studies Map MF-714.

Hunter, R. E., 1973, Distribution and movement of suspended sediment in the Gulf of Mexico off the Texas coast: In Freden, S. C., E. P. Mercanti, and M. A. Becker (eds.), Symposium on Significant Results Obtained from the Earth Resources Technology Satellite-1: Vol. 1, Sec. B: NASA, SP-327, p. 1341-1348.

_______, 1976, Movement of turbid-water masses along the Texas coast: In Williams, R. S., and W. D. Carter (eds.), ERTS-1, A New Window on our Planet: U.S. Geological Survey Professional Paper 929, p. 334-336.

Hunter, R. E., Hill, G. W., and Garrison, L. E., 1974, Maps showing drift patterns along the South Texas coast, 1970-1973: U.S. Geol. Survey Misc. Field Studies Map MR-623, 2 sheets.

Krumbein, W. C., 1934, Size frequency distributions of sediments: Journal Sedimentary Petrology, v. 4, no. 2, p. 65-77.

McCave, I. N., 1972, Transport and escape of fine-grained sediment from shelf areas: In Swift, D. J. P., D. B. Duane, O. H. Pilkey (eds.), Shelf Sediment Transport: Process and Pattern, Dowden, Hutchinson, and Ross, Stroudsburg, Pa., p. 225-248.

Mead, R. H., 1972, Sources and sinks of suspended matter on continental shelves: In Swift, D. J. P., D. B. Duane, O. H. Pilkey (eds.), Shelf Sediment Transport: Process and Pattern, Dowden, Hutchinson, and Ross, Stroudsburg, Pa., p. 249-262.

Shideler, G. L., 1978, A sediment dispersal model for the South Texas continental shelf, northwest Gulf of Mexico: Marine Geology, v. 26, p. 289-313.

Smith, N. P., 1976, Hydrography project: In Parker, P. L. (ed.), Environmental Assessment of the South Texas Outer Continental Shelf - Chemical and Biological Survey Component: Report to Bureau of Land Management (Contract No. 08550-CT5-17), Univ. of Texas, Texas A&M Univ., and Rice Univ., p. 12-45.

Watson, R. L., and Behrens, E. W., 1970, Nearshore surface currents, southeastern Texas Gulf Coast: Univ. Texas, Contr. Marine Sci., v. 15, p. 133-143.

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.