Reprinted from JOURNAL OF PHYSICAL OCEANOGRAPHY, Vol. 10, No. 5, May 1980
American Meteorological Society
Printed in U. S. A.

On the Hydrography of Shelf Waters off the Central Texas Gulf Coast[1]

NED P. SMITH

Harbor Branch Foundation, Fort Pierce, FL 33450

7 September 1979 and 21 January 1980

ABSTRACT

Temperature and salinity data from 1976 and 1977 are used to describe low-frequency hydrographic variations in Gulf of Mexico shelf waters off the central Texas coast. Data from 23 approximately monthly cruises define the annual cycle and suggest annually recurring seasonal events. Minimum salinities occur in late spring, when values decrease to as low as 18‰ over the inner shelf. Inner shelf salinities during the rest of the year average 31–32‰. Surface salinities over the outer shelf may decrease to 32–33‰ in late spring, but deviate little from 36‰ at other times. Both the mean salinity and the standard deviation suggest that freshwater runoff effects are restricted largely to inner and mid-shelf waters, within 30 km of the coast. Highest annual surface temperatures are 28–29°C across the shelf in late summer. Lowest temperatures in February range from 12–13°C over the inner shelf to 20–21°C over the outer shelf; minima appear to be highly dependent on the severity of the winter season in a given year. Bottom temperatures are dominated by the annual cycle over the inner shelf. Near-bottom temperatures over the outer shelf vary over shorter time intervals and cannot be resolved by monthly sampling.

1. Introduction

Investigations of continental shelf hydrography are complicated by the relatively great temporal and spatial variability that characterizes shelf waters. The shallower water depths result in a relatively rapid response to local air-sea heat energy exchange processes. Wave mixing and convective overturning can quickly homogenize the water column from top to bottom, except perhaps in near-bottom layers over the outer shelf. Spatial variability across the shelf depends on the cross-shelf transport of river runoff from adjacent estuaries and the existence of coastal upwelling, among other things. Longshore gradients in hydrographic variables may occur in response to the proximity of estuaries and, to a lesser extent, to longshore gradients in weather conditions in the overlying atmosphere. The temporal and spatial variability characteristic of shelf waters in a particular area, in turn, are related directly to the necessary and sufficient sampling frequency and station density for hydrographic surveys.

Information on the hydrography of Texas shelf waters has been accumulating for the past 35 years. Gunter (1945) included hydrographic data in a study emphasizing fish populations in the western Gulf of Mexico. Jones *et al.* (1965) conducted a one-year study of the hydrography of shelf waters off the central Texas coast. Available data have been summarized as monthly average surface temperatures (Rivas, 1968; Devine, 1976), as the multi-annual mean variation in temperature through the upper 225 m (Etter and Cochrane, 1975), and as surface and bottom temperatures recorded at inner and mid shelf locations off the central Texas coast over a three-year period (Armstrong, 1976).

A well-defined annual cycle dominates the time plots of both temperature and salinity over most of the shelf. Throughout the upper 70 m, temperatures exhibit the customary annual maximum in late August or early September, and a minimum in the late winter months. Highest surface temperatures

[1] Contribution No. 176, Harbor Branch Foundation, Inc.

0022-3670/80/050806-08$06.00

across the shelf are 28–29°C; lowest temperatures range from 12–13°C over the inner shelf to 21–22°C over the shelf break, approximately 80 km offshore. The variation in the annual temperature range across the shelf in the surface layer appears to be closely related to the local water depth. Surface salinities across the entire shelf decrease briefly in late spring and early summer, as a plume of low-salinity water moves southwestward along the Texas shelf. At other times of year, surface salinities vary little from 36.4‰ over the outer shelf, or from the range of 32–36‰ over the inner shelf. Significant stratification in salinity appears to be largely restricted to inner and mid-shelf waters.

Here the emphasis is on both spatial and temporal variability in temperature and salinity along a transect extending to the shelf break from a point along the central Texas coast. Approximately monthly sampling during 1976 and 1977 provided data to document seasonal events occurring within the annual cycle, and the two-year study period provides information on the recurrence of specific events. The purpose of this note is to focus on processes occurring over time scales on the order of several weeks to several months. The combination of relatively closely spaced stations across the shelf and relatively frequent sampling provides an improved picture of both temporal and spatial variability in Texas shelf waters.

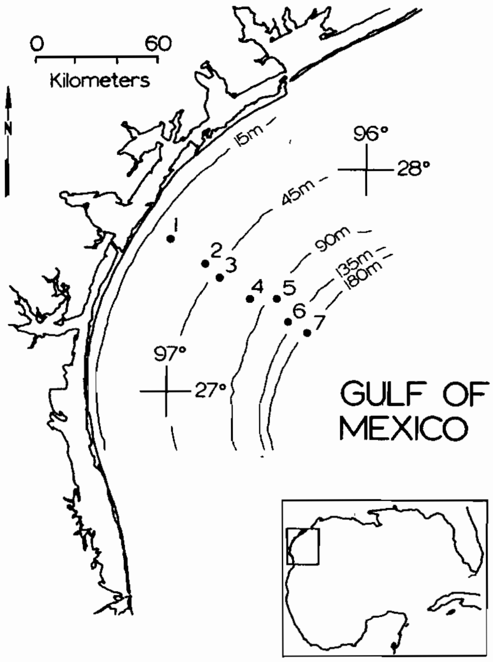

FIG. 1. Location of sampling stations off the central Texas coast. Insert shows study area in the northwestern Gulf of Mexico.

2. The observations

Hydrographic data were obtained at seven stations along a transect extending southeastward to the shelf break from a point approximately midway along the Texas Gulf coast at latitude 27°45′N (Fig. 1). Temperature and salinity (*T-S*) profiles from surface to near-bottom levels were provided in analog form by a Plessey Model 9060 Salinity/Temperature/Depth Measuring System, or by a Martek Model TDC Metering System in shallow water, or when salinities were below 30‰. Hydrographic data were digitized at 3 m intervals.

All hydrographic profiles were calibrated at top and bottom levels with reversing thermometer temperatures and with salinities determined with a laboratory salinometer. Calibrated temperature and salinity values were accurate to ~0.01°C and 0.05‰, respectively.

A total of 11 cruises in 1976 and 12 in 1977 provided most of the data base for this investigation. Additional surface and bottom *T-S* data collected from the same stations at intermediate dates were provided by Dr. J. S. Holland of the University of Texas. These supplementary hydrographic data were obtained on cruises aboard the R/V *Longhorn* with the equipment described above. Cruises were scheduled approximately monthly, and the time interval between successive cruises was well suited for tracing the seasonal progression in temperature and salinity. The more transient events associated with meteorological forcing that may have preceded a cruise could not be resolved by the data.

3. Results

Data presented in this paper are selected to emphasize temporal variations at surface and near-bottom levels over the inner and outer shelf, and in the surface layer across the shelf. A good overview of temporal variability at a point is given by plotting temperature and salinity data on a standard *T-S* diagram. One sees immediately the annual range in temperature and salinity at that location. In addition, the characteristic shape of the figure that results can be interpreted in terms of the physical processes affecting the local hydrography over the course of the year.

Fig. 2 is a composite of the *T-S* data collected from Station 1, in 22 m of water, in 1976. Surface hydrographic data (left) from the inner shelf trace out a pattern that resembles somewhat a quarter-moon shape. Both the period of heating and that of cooling indicate a concave pattern, with highest and lowest temperatures associated with relatively high-salinity water in late summer and late winter. Lowest salinities of near 28‰ occur with the spring runoff in March and April; a second relative minimum is suggested for the early fall months.

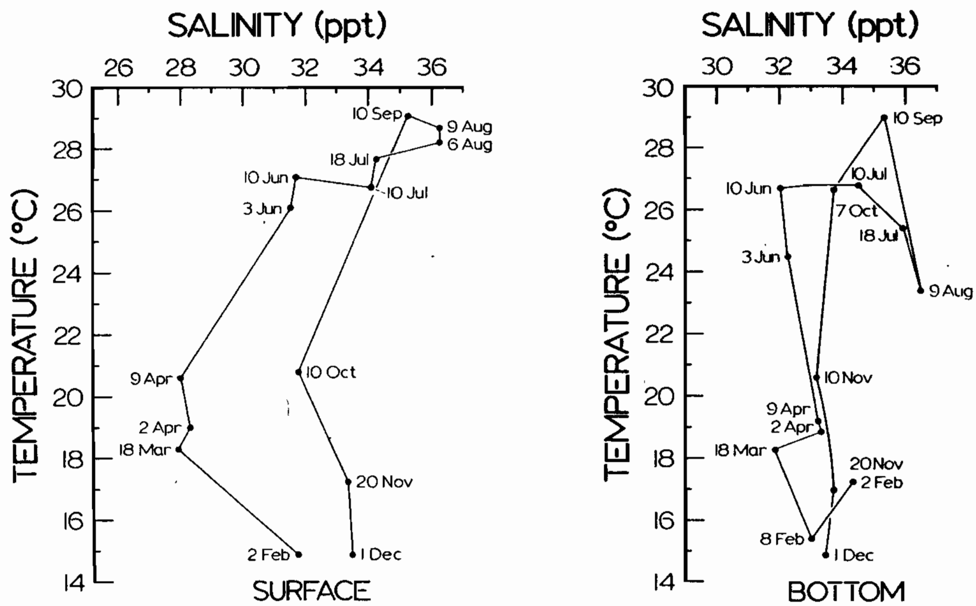

FIG. 2. Surface (left) and bottom (right) hydrographic data from Station 1, 1976. See Fig. 1 for station location.

It is of interest to note that there is a well-defined counterclockwise loop in the pattern during the late summer months. The last 1°C of warming occurs simultaneously with a small decrease in salinity. Temperatures then decrease with the onset of fall cooling. The pattern as a whole indicates an annual temperature range of ~14°C and a salinity range of just over 6‰. This may be an underestimate, however, since it is doubtful that extrema coincided with the approximately monthly sampling.

Bottom hydrographic data collected from Station 1 in 1976 are shown in the right half of Fig. 2. The pattern is basically similar, with two exceptions. Lowest salinities of ~32‰ are 4‰ higher than surface values. This indicates that water associated with the spring runoff is not mixed through the water column at the time of the data collection. The counterclockwise loop formed by the bottom *T-S* data collected during the late summer months is greatly elongated as a result of low temperatures recorded in mid-July and early August. This is followed by a warming of nearly 6°C to the annual maximum of 29°C reached in mid-September. Fall cooling recorded at the bottom is nearly identical to that recorded at the surface at this location.

Fig. 3 is the composite of surface and bottom data obtained from the same location during 1977. Although the details of the *T-S* data undoubtedly are influenced strongly by the particular sampling dates, the data do permit a general comparison of seasonal events occurring during these two years. Several points are noteworthy. First, in 1977 the effects of the spring runoff are much less apparent in March and April. Lowest salinities are recorded on 9 May and values increase quickly over the following six weeks to the annual maximum. Second, the counterclockwise loop is again clearly evident in late summer. The last of the seasonal warming coincides with a slight freshening just before the onset of fall cooling. Third, fall cooling decreases surface temperatures only 7°C by early December. It is probable that this is a direct result of the severity of the early winter. The National Weather Service office in Corpus Christi, recorded a monthly average November temperature that was 5.7°C cooler in 1976 than in 1977. This is in good agreement with early December water temperatures that were 6.7°C colder in 1976 than in 1977.

Bottom hydrographic data are shown in the right half of Fig. 3. The pattern is dominated by the annual temperature cycle; salinities range between 32 and 36.4‰. The counterclockwise loop formed by the late summer data is exaggerated as a result of slight cooling recorded between 19 May and 6 July. Bottom temperatures over the inner shelf are nearly 4°C cooler in early 1977 than in early 1976. Again, this can be attributed partially to the severity of the winter. The National Weather Service recorded a mean January temperature 3.4°C colder in 1977 than in 1976.

Temperature and salinity data from the outer shelf station during 1976 (Station 6 in Fig. 1) are shown in Fig. 4. Several features are useful for comparing the waters over the inner and outer shelf, as well as for contrasting in a crude way the hydrographic climate of the near-surface and near-bottom layers.

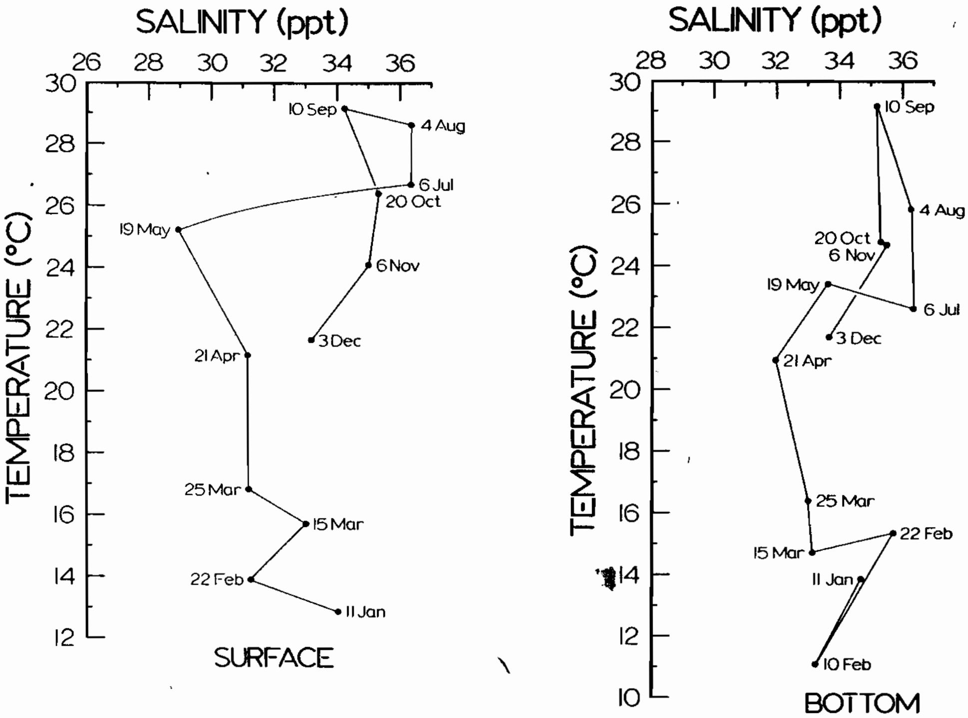

FIG. 3. Surface (left) and bottom (right) hydrographic data from Station 1, 1977. See Fig. 1 for station location.

In the surface layer, the annual temperature range is substantially less over the outer shelf. The 1976 data show temperatures decreasing only to 20°C in the winter months. The higher annual minimum over the outer shelf suggests strong cross-shelf temperature gradients during the winter months. On the other hand, surface temperatures of ~29°C in late summer across the entire shelf indicate nearly isothermal conditions in the surface layer at that time of year.

Some lowering of surface salinities is indicated in the spring and early summer months even at this distance from the coast, approximately 85 km offshore. The start of a counterclockwise loop is suggested by a 1‰ decrease in surface salinity recorded between 17 July and 10 August. Salinities then increase over the following two weeks, however, and remain at 36‰ until fall cooling begins in late September.

Hydrographic data from a depth of 117 m (17 m

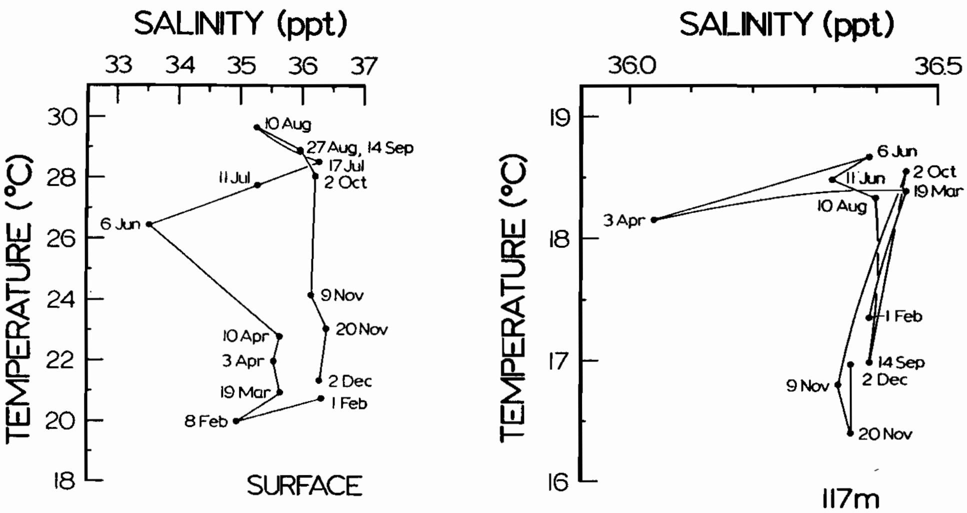

FIG. 4. Surface (left) and 117 m level (right) hydrographic data from Station 6, 1976. See Fig. 1 for station location.

above the bottom) at Station 6 are presented in the right half of Fig. 4. Data are presented on an expanded scale to reveal the relatively minor *T-S* variations recorded during 1976. The 117 m level is the greatest depth reached by all 23 profiles during the two-year study. Except for the value of 36.04‰ recorded on 3 April, all salinities are between 36.35 and 36.45‰ at this level. After the spring minimum, there is little indication of an annual progression in the salinity data.

The temperature range is less than 2.3°C in the 1976 data. Lowest temperatures are recorded in early winter; highest temperatures are recorded during the summer months, but there is at least a brief period of warming in early October.

Fig. 5 shows the hydrographic data obtained at Station 6 during 1977. The pattern formed by the surface *T-S* pairs suggests substantially lower late spring salinities, though this may be due as much to the exact sampling date as to the extent of the spring runoff. The counterclockwise loop is well defined by the data collected between early July and early September. Fall cooling lowers the surface temperature only 5°C between 9 September and 2 December. Surface waters are therefore 3°C warmer in early December of 1977 than they had been in 1976 at this location. *T-S* data from the 117 m level, shown on the right side of Fig. 5, gives some indication of an annual progression in temperature, with a 1°C warming in late July separating lower temperatures recorded during the first seven months of 1977 from higher temperatures recorded during the last five months of the year. Little continuity is apparent in the salinity data, and there is no indication of an annual repetition in the *T-S* pattern at this location.

Surface temperature and salinity data from the seven stations across the shelf and for all 23 cruises have been combined in Fig. 6 to describe low-frequency variations in cross-shelf gradients. The isohalines in the upper part of the figure show surface salinity gradients confined primarily to inner and mid-shelf waters through most of the year. An exception, in both 1976 and 1977, is found in late spring and early summer, when lowered salinities associated with increased runoff extend across the entire shelf at this location. Through the fall and winter months, the surface layer is relatively isohaline beyond a point ~40 km from the coast.

The temperature data shown in the lower half of Fig. 6 indicate substantial cross-shelf gradients during the winter months only. Cross-shelf gradients during the late winter months can be as high as 5–6°C, with most of this occurring within 50 km of the coast. Between early spring and late fall, cross-shelf temperature gradients are minimal, with greatest differences generally less than 1°C. Both spring warming and fall cooling stand out clearly and may be characterized by rapid temperature changes occurring simultaneously and nearly uniformly across the entire shelf. Nowlin and Parker (1974) have documented cooling in shelf waters of as much as 5°C in 15 days in response to frontal passages.

Two elementary statistics, the mean and the standard deviation, computed from the surface temperature and salinity data, provide information that is useful in describing the hydrographic climate along this part of the Texas coast (Fig. 7). The mean salinity increases rather uniformly from about 31.5‰ at Station 1 to 35‰ at Station 3. Salinities then increase only slightly beyond a point ~40 km from the coast. The standard deviation in salinity indicates substantially greater variability in surface salinity over the inner shelf, within ~30 km of the coast. Spatial variations in both the mean and the standard

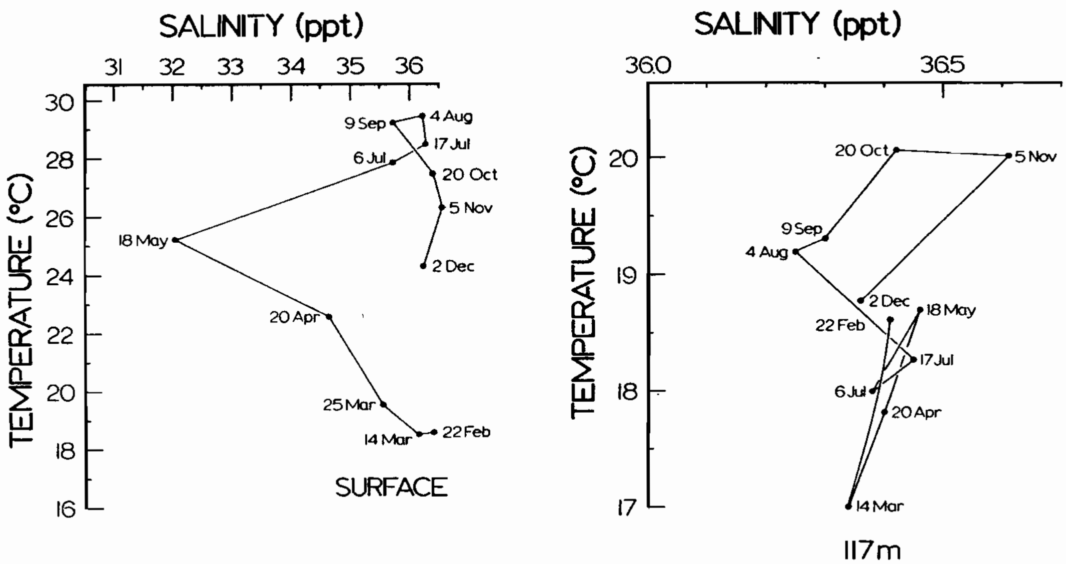

FIG. 5. Surface (left) and 117 m level (right) hydrographic data from Station 6, 1977. See Fig. 1 for station location.

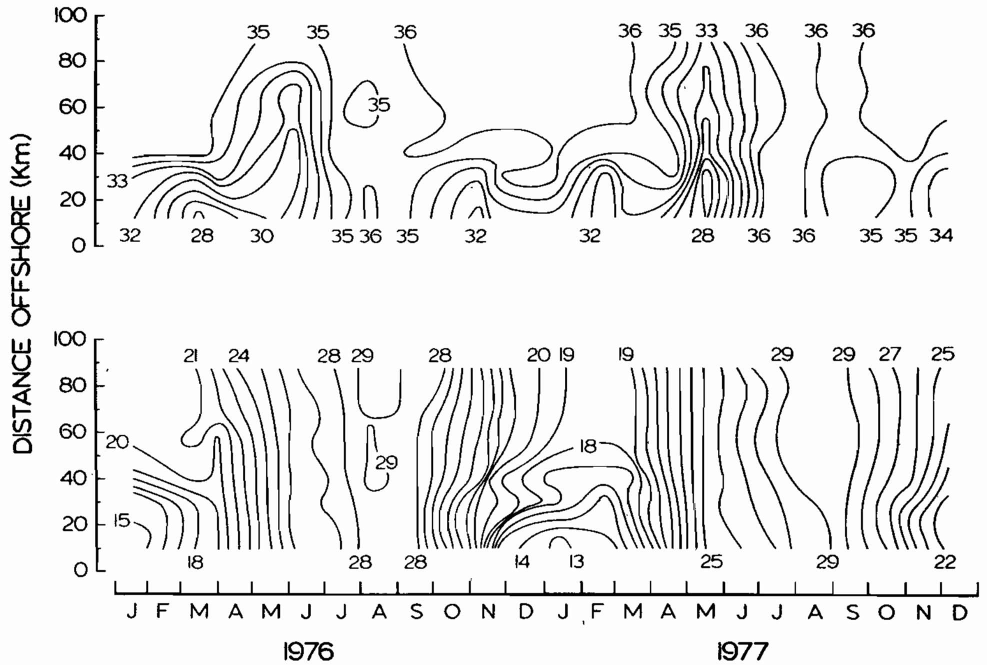

FIG. 6. Composite of surface salinity (top) and surface temperature (bottom) for Stations 1–7, 1976–77.

deviation support the idea that freshwater runoff effects in the surface layer are confined largely to the inner half of the shelf along this part of the coast.

In sharp contrast to the spatial discontinuity in the salinity data over the middle shelf, the cross-shelf variation in both the mean surface temperature and in the standard deviation of the temperature are relatively uniform. The mean increases gradually from 22°C at the innermost station to just over 25°C at Station 6, then decreases slightly at the outer station. The lower mean temperature over the inner shelf is a result of significantly lower temperatures in late winter, coupled with a nearly isothermal surface layer during the summer months. In general, there appears to be an approximately inverse relationship between water depth and the low-frequency variability in surface temperature along the transect.

4. Discussion

The two years of hydrographic data presented here show clearly the seasonal variations in temperature and salinity across the shelf and suggest something of the year-to-year repetition of various events. The late spring decrease in salinity dominates the annual salinity cycle. This along with the slight freshening noted in late summer seem to be the only two events involving salinity worthy of note. The spring minimum appears to be a result of the outflow from the Mississippi River moving westward along the northern rim of the Gulf of Mexico (Smith, 1977) though the Atchafalaya River may make a significant contribution (Devine, 1976). While one would expect a lowering of salinity in response to the spring runoff, the counterclockwise loop in the *T-S* diagrams is a somewhat surprising

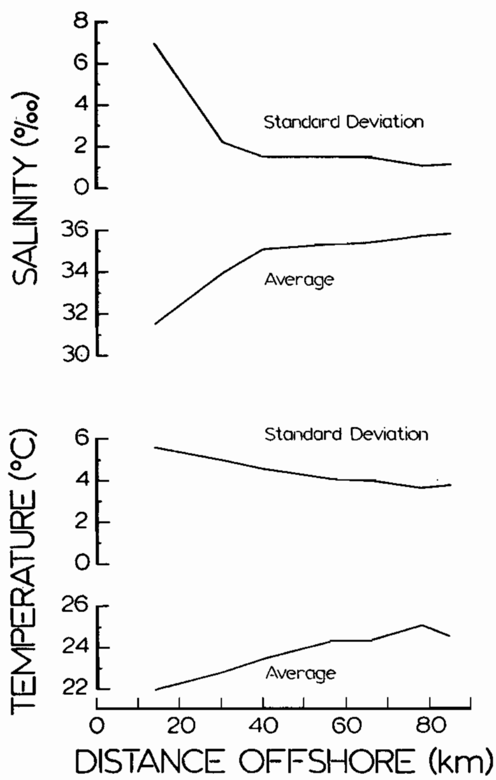

FIG. 7. Means and standard deviations of salinity (top) and temperature (bottom) for Stations 1–7, calculated from surface measurements, 1976–77.

result. A late summer increase in precipitation is not indicated in weather data recorded by the National Weather Station at the International Airport in Corpus Christi in 1976 or 1977. These measurements are made ~50 km inland, however, and thus may poorly approximate conditions over the shelf. The similarity in 1976 and 1977 of both the late spring salinity decrease (Fig. 6) and the slight freshening in late summer suggest that both these events may be repeated from one year to the next.

The temperature data suggest a dominant annual cycle at all depths over the inner shelf, and through approximately the upper 80 m over the outer shelf. The amplitude of the annual temperature curve decreases both with increasing depth and with distance from the coast. In the near-bottom layers over the outer shelf, the annual cycle appears to be a minor component of the temporal variability in the data. Instead, temperature variations appear to occur over much shorter time scales and they are most likely associated with vertical motions in the top of the permanent thermocline. This, in turn, could be in response to internal waves or perhaps meteorological forcing. Thus, significant variations in temperature may be occurring over time scales on the order of several hours to several days. These characteristics of the local thermal activity at this location cannot be quantified with the available data.

The bottom temperatures from the inner station are consistent with the idea of transient upwelling during the summer months. Hydrographic cross sections show isotherms sloping up the shelf during July and August (Smith, 1977), when surface winds are generally out of the south-southeasterly quadrant. In view of the 033–213° orientation of the coastline (Fig. 1), there may be at least occasional periods of offshore-directed Ekman transport. At Station 1, the decrease in bottom temperature of over 3.5°C between 10 July and 9 August 1976 (Fig. 2) suggests an advection of cooler water from further offshore.

The plots of temporal variability in cross-shelf gradients of surface temperature and salinity (Fig. 6) show clearly the relatively rapid transition occurring during the late spring and early summer months. At these times, the orientation of the isopleths is very nearly perpendicular to the time axis. Nevertheless, it appears that monthly sampling is adequate to reveal the gross features of the annual progression in salinity and temperature. Certainly, during the mid-winter and mid-summer months, and especially over the mid and outer shelf, requirements for the necessary and sufficient sampling frequency and station density are substantially reduced for the surface layer at least.

This study may be compared with the results of previous work to define the annual cycle better and to investigate the year-to-year similarity of various features superimposed onto the annual cycle. Combined with the work of Jones *et al.* (1965), it appears that highest late summer surface temperatures lie between 29 and 30°C at any point across the shelf. Minimum temperatures, on the other hand, appear to be a function of both water depth and the severity of the winter during a given year. Jones *et al.* recorded lowest surface temperatures of approximately 12°C at a point 11 km from the coast. This compares with temperatures of just under 15°C recorded in early February of 1976 and values of ~13°C in mid-January of 1977. As noted above, air temperatures recorded by the National Weather Service in Corpus Christi were substantially lower in 1977 than in 1976. Multiannual mean monthly surface temperatures for this part of the Gulf of Mexico (Rivas, 1968) suggest mid-winter temperatures of ~20°C; however, it is not clear how many observations reflect conditions over the inner shelf.

Salinity data presented by Jones *et al.*, show a minimum in late spring, but the lowest values recorded probably are influenced as much by the particular sampling dates as by the precipitation patterns during the preceding winter. Lowest values are just over 30‰, while minimum values recorded in this study at approximately the same location are slightly under 28‰ in March of 1976 and just below 29‰ in late May 1977.

The sampling frequency necessary to define even the annual *T-S* variations may be influenced significantly by shelf circulation. Longshore currents over the inner shelf during the spring months, for example, are toward the southwest and may advect a plume of low-salinity water rapidly past a particular sampling point. Unpublished current data obtained over the inner shelf during the spring of 1977 suggest that the daily longshore transport at mid-depth was as much as 40 km during a 36-day period in March and April. The average longshore current during this time was 14 cm s^{-1} (12 km day^{-1}). The horizontal scales of the salinity plume, as well as the spatial gradients themselves, are unknown along the northern rim of the Gulf of Mexico, but with at least occasional bursts of stronger current speeds, extrema in the longshore distribution of salinity could easily be missed by monthly sampling.

The data obtained in this two-year study complement the existing body of literature of Texas shelf water hydrography, and provide further information on the recurrence of seasonal events within the annual cycle. Perhaps more important, however, is the improved picture of cross-shelf and, to a lesser extent, vertical variations that exist in the local hydrographic patterns. At near-bottom levels over the outer shelf, the otherwise dominant annual cycle all but disappears, requiring a correspondingly higher sampling frequency. The salinity data show a well-defined discontinuity in mid-shelf waters, separating the more stable conditions over the outer shelf from the more pronounced variations over the inner shelf. The data reported here exemplify the temporal and spatial variability characteristic of shelf waters in general, and they are useful for quantifying this variability for the Texas shelf in particular.

Acknowledgments. The assistance of Mr. James C. Evans and Mr. William A. MacNaughton in the data collection aboard the University of Texas R/V *Longhorn*, and later in the computer reduction of the hydrographic data is gratefully acknowledged. Dr. J. S. Holland provided additional temperature and salinity data obtained as part of the benthos study in Texas shelf waters. Financial support for this study was provided through the Bureau of Land Management through Contracts AA550-CT6-17 and AA550-CT7-11.

REFERENCES

Armstrong, R., 1976: Historical physical oceanography; seasonal cycle of temperature, salinity and circulation. Environmental assessment of the South Texas outer continental shelf, 1975. NOAA Final Report (Draft), Vol. III, Oceanography, 27 pp.

Devine, M., 1976: Physical oceanography program, historical analysis. Environmental assessment of the South Texas outer continental shelf, 1975. NOAA Final Report (Draft), Vol. III, Oceanography, 205 pp.

Etter, P., and J. Cochrane, 1975: Water temperature on the Texas-Louisiana shelf. Texas A&M University, TAMU-SG-75-604, 24 pp.

Gunter, G., 1945: Studies on marine fishes of Texas. *Publ. Inst. Mar. Sci., University of Texas*, **1**, No. 1, 9–190.

Jones, R. S., B. J. Copeland and H. D. Hoese, 1965: A study of the hydrography of inshore waters in the western Gulf of Mexico off Port Aransas, Texas. *Publ. Inst. Mar. Sci., University of Texas*, **10**, 22–32.

Nowlin, W. D., and C. A. Parker, 1974: Effects of a cold-air outbreak on shelf waters of the Gulf of Mexico. *J. Phys. Oceanogr.*, **4**, 467–486.

Rivas, L., 1968: Fisherman's atlas of monthly sea surface temperatures for the Gulf of Mexico. *U.S. Fish Wild. Serv. Bur. Comm. Fish., Circ.* 300, 33 pp.

Smith, N. P., 1977: Hydrography Project. Environmental studies, South Texas outer continental shelf, biology and chemistry, R. D. Groover, Ed., pp. 3-1 to 3-82. University of Texas Final Report to the Bureau of Land Management, Contract AA550-CT6-17.