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Longshore Currents on the Fringe of Hurricane Anita

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Subsurface current data from a 2-week period in August and September 1977 are compared with coastal wind stress and water level data to describe longshore motion in reponse to the passage of Hurricane Anita across the northern Gulf of Mexico. Current meters 2 and 10 m above the bottom 21.5 km off the central Texas Gulf coast indicate strongest speeds of approximately 70 and 80 cm/s, respectively, coinciding closely with the time of maximum wind stress. A qualitative comparison of the variations in sea surface slope and wind stress with the recorded longshore current suggests that both wind stress and the longshore pressure gradient combined to produce the strong flow recorded during the storm but that the pressure gradient was primarily responsible for decelerating the current after the storm made landfall.

INTRODUCTION

The most dramatic forcing of shelf waters is undoubtedly that associated with the relatively infrequent movement of tropical storms and hurricanes along or across continental margins. The extreme magnitude of the wind stress, the often rapid change in direction of the wind stress vector near the storm center, and the circulation associated with the movement of the storm surge all combine to produce a profound, if short-lived, effect on shelf circulation.

Understandably, most of the information on hurricane effects in shelf waters is restricted to coastal and intracoastal water level variations associated with the storm surge. Direct current measurements are relatively rare, though a few papers have appeared within the past several years. *Chew et al.* [1962] reported results of a drift bottle study coincidentally started 3 weeks before Hurricane Carla crossed Gulf of Mexico shelf waters and made landfall along the central Texas coast. Drift bottle returns were concentrated near the point of landfall, some 400 km west of the drop site.

Direct current measurements from a point 160 km east of the path of Hurricane Camille have been reported by *Murray* [1970]. Variations in the near-bottom current 360 m offshore were interpreted as a response both to the seaward flux of longshore momentum, as forerunners began breaking in the surf zone, and to direct wind stress, as the storm center approached the coast.

Recently, *Forristall et al.* [1977] have presented direct observations of currents from three levels, as tropical storm Delia passed over an instrumented drilling platform and crossed the Texas Gulf coast near Galveston. Currents in excess of 200 cm/s were recorded, and little vertical variation in either current speed or direction was noted under storm conditions. A numerical model of the observed subsurface current incorporated both direct wind stress and sea surface slope effects. Results closely approximated the acceleration phase as the storm approached the coast. In view of the relatively infrequent occurrence of such storms and the high probability of loss or damage to at least a part of an adequate array of instruments, it may be some time before a completely suitable data base becomes available to set up and verify the numerical models capable of predicting the response of shelf waters to hurricane forcing.

This descriptive note compares nearshore motion along the central Texas Gulf coast with both surface wind stress and longshore water level slopes from a 2-week period during which Hurricane Anita moved west-southwest from its origin, approximately 250 km south of the Mississippi Delta, to landfall, about 250 km south of Brownsville, Texas. Wind speeds never exceeded 48 km/hr (26 kn) along the central Texas coast at Port Aransas, and the nontidal water level rose to only 1 m above mean sea level at Freeport and Port Mansfield, Texas. Nevertheless, the recorded current measurements show a distinct response to the forcing associated with the movement of the storm center across the northern Gulf of Mexico. A comparison of the current, wind stress, and water level time series makes it possible to postulate some of the mechanisms forcing shelf circulation under these conditions.

OBSERVATIONS

Hourly time-averaged current speeds and directions were provided by Environmental Devices Corporation type 105 recording current meters. Two current meters were positioned 2 and 10 m above the bottom in approximately 17 m of water. The study site was 21.5 km off the coast near Port O'Connor, Texas, at latitude 28°23'45"N, 96°01'57"W (Figure 1). The accuracy of the current meter speed and direction measurements is approximately 2.7 cm/s and 7.2°, respectively, according to the manufacturer.

Coastal winds were monitored from an anemometer 33 m above the ground and approximately 35 m above sea level, 0.5 km from the coast at Port Aransas, Texas (Figure 1). Analog traces of the north-south and east-west components of the wind were digitized at hourly intervals and were converted to the longshore and cross-shelf components of the wind stress, using the method suggested by *Wu* [1969]. Wind speeds were read to the nearest mile per hour, and it is felt that the precision of the computed wind stress varies from approximately ±0.04 to ±0.17 dyn/cm^2 within the range of wind speed recorded during the 2-week study period (August 24 through September 6, 1977).

Water level data were obtained with Stevens type A water level recorders at Port Mansfield and Freeport, Texas (Figure 1). Values were read hourly to the nearest 0.3 cm (0.01 ft). Owing to the effect of swell on the analog trace during the storm, the precision of the water level data is felt to be approximately ±3 cm. Water level recorders at Port Aransas and Port O'Connor, Texas, were not operating during this time period.

RESULTS

Hurricane Anita formed quickly and attained hurricane strength at approximately 26.5°N, 90.6°W after about 18

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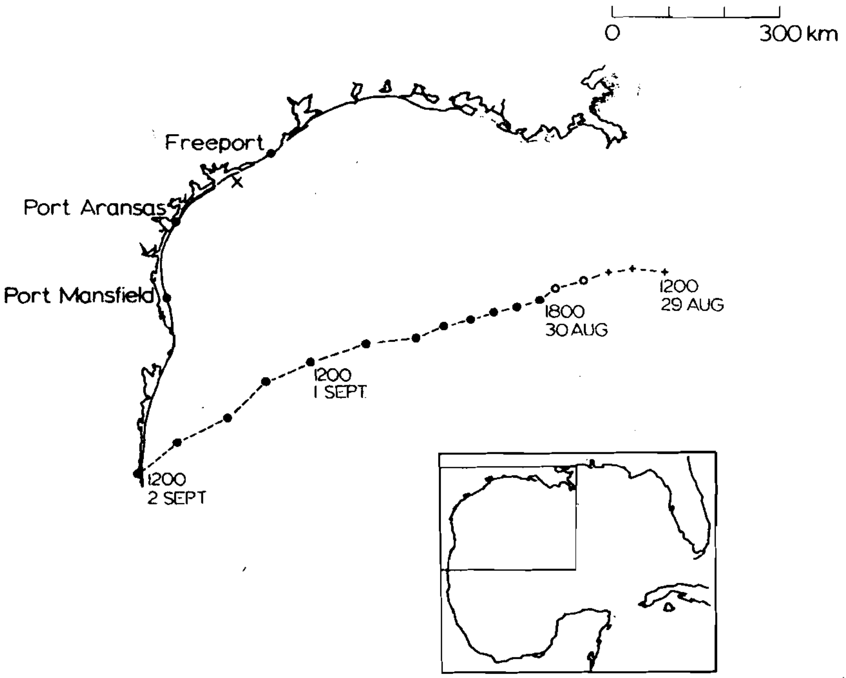

Fig. 1. Study area along the Texas coast in the northwestern Gulf of Mexico (inset). The trajectory of Hurricane Anita is shown, plus signs indicating tropical depression, open circles indicating tropical storm, and solid circles indicating hurricane strength. The cross denotes the study site.

hours as a tropical depression and 12 hours as a tropical storm [*U.S. Department of Commerce*, 1977]. The eye moved fairly consistently to the west-southwest over the next three days (see Figure 1), as highest sustained winds increased to an estimated 280 km/hr. The storm center came to within 350 km of the study site on September 1 before continuing to the west-southwest and eventually crossing the coast approximately 250 km south of Brownsville, Texas.

Figure 2 shows longshore component current speeds recorded hourly, 2 and 10 m above the bottom, during a time interval beginning 5½ days before Anita became a tropical depression and continuing 4½ days after the hurricane made landfall. At the upper level, longshore motion is initially toward 062°, but there are approximately diurnal period tidal or inertial variations (inertial period 25.3 hours) through midday on August 26. Following a reversal in longshore motion late

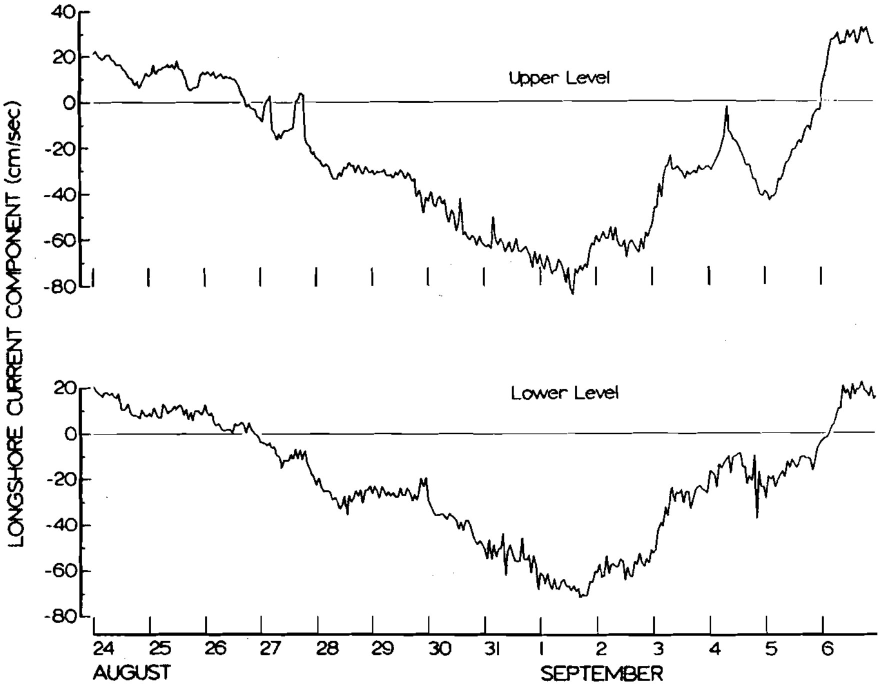

Fig. 2. Composite of longshore current components, in centimeters per second, measured 2 m (lower level) and 10 m (upper level) above the bottom in 17 m of water 21.5 km off the central Texas Gulf coast, August 24 to September 6, 1977. See Figure 1 for the study site. Positive values indicate motion toward 062°.

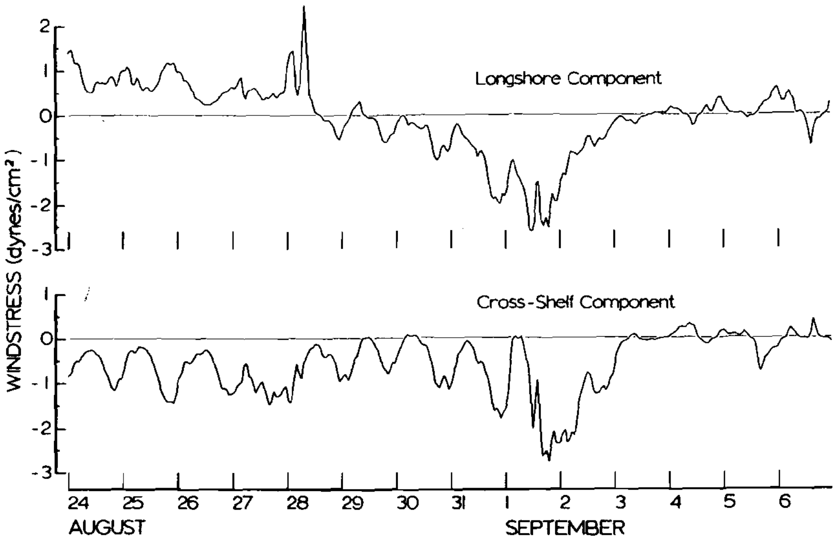

Fig. 3. Composite of longshore and cross-shelf wind stress components, in dynes per square centimeter, calculated from winds measured at Port Aransas, Texas, August 24 through September 6, 1977. Positive values for longshore and cross-shelf components are toward 033° and onshore, respectively.

on August 26, motion is toward the west-southwest. Current speeds increase gradually and more or less regularly to highest values of just over 80 cm/s, recorded at 1400 CST on September 1.

The deceleration of the longshore motion between September 1 and 6 presents an interesting, pulsing pattern. It is likely that these are simply tidal or inertial oscillations superimposed onto a deceleration of about −20 cm/s/d. The west-southwesterly motion ceases very abruptly on September 5, and the longshore current quickly returns to an east-northeasterly direction at speeds of approximately 30 cm/s.

Longshore motion recorded at the lower level provides a rather similar pattern in the bottom part of Figure 2. As would be expected, the range of current speeds is somewhat less. East-northeasterly flow diminishes from approximately 10 cm/s on August 24–25 and reverses early on August 27. Highest speeds of just over 70 cm/s to the west-southwest were recorded briefly at this level late on September 1. Deceleration begins immediately thereafter and continues at a rate of approximately −17 cm/s/d. The longshore component reverses early on September 6, as it had at the upper level, and speeds appear to level off at about 20 cm/s toward the east-northeast by the end of the day.

Subsurface transport was computed between August 27 and September 5 by multiplying component current speeds by the time intervals they represent. Over the 10-day period, during which longshore motion was consistently to the west-southwest, 345 km of water moved past the study site at the upper level, while 294 km of water moved past the lower current meter. The observed slight vertical shear in the lower part of the water column is consistent with results reported by *Forristall et al.* [1977] for currents associated with tropical storm Delia.

Although this paper deals with the longshore component of the nearshore current, it is of interest to note that during the time interval of the above longshore transport, 88 km of water moved past the upper current meter in an onshore direction, while just under 20 km of water moved past the lower instrument in an offshore direction.

Wind stress forcing of Texas shelf waters can be estimated from anemometer measurements made at Port Aransas, Texas, approximately 120 km from the current meters, during the 14 days between August 24 and September 6. Both longshore and cross-shelf wind stress components are shown in Figure 3. Owing to the concave configuration of the Texas coastline, the longshore direction at Port Aransas (033°–213°) differs by approximately 30° from the longshore direction at the study site (062°–242°). It is felt that Port Aransas winds closely approximate those over the study site; however, the unknown spatial variations in the surface wind field plus the

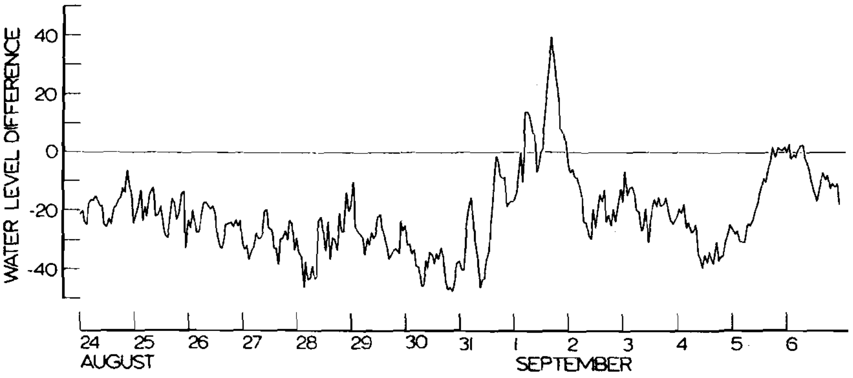

Fig. 4. Water level differences, in centimeters, between Freeport and Port Mansfield, Texas, August 24 to September 6, 1977. Negative values indicate Freeport water levels higher.

short record length discouraged a quantitative comparison between the wind stress and current meter time series.

The longshore component of the wind remained positive (toward 033° at Port Aransas) though somewhat variable through August 28. The approximately diurnal variations continue; however, the general pattern indicates a reversal and an increase in negative values (toward 213°) to a maximum of approximately -2.5 dyn/cm^2, occurring on September 1. At that time the storm center was located at approximately 25.5°N, 94.7°W, or 350 km from the study site, the nearest point of the hurricane trajectory. Although the storm continued to intensify over the next 24 hours, the increasing distance between the eye and the study site resulted in a gradual decrease in the computed wind stress. Longshore wind stress components return to near zero values on September 3 and remain low through the end of the study period. Wind stress forcing therefore appears to be small between September 3 and 6.

The lower part of Figure 3 shows the cross-shelf component of the computed wind stress over the same time interval. The general pattern is similar, though cross-shelf components rarely become positive (offshore). Diurnal variations in the cross-shelf component are well defined through late August, prior to the fringe effects of the storm. Maximum negative values of approximately -2.7 dyn/cm^2 are reached briefly on September 1 but quickly decrease to near zero over the next 1½ days.

Water level records from Freeport and Port Mansfield, Texas, separated by a distance of approximately 340 km, were used to compute the longshore slope in sea level and thus investigate the possibility of longshore motion in response to barotropic forcing. It is important to note, however, that water levels at both locations were read in relation to the local mean sea level rather than to a common datum plane. Thus water level differences do not necessarily indicate a longshore pressure gradient. Furthermore, along the fringe of a well-developed tropical storm, spatial variations in sea level may well reflect a dynamic balance with wind stress forcing or the surface atmospheric pressure field.

Water level differences of -20 cm (Freeport higher) early in the 2-week period (Figure 4) begin to increase slowly and irregularly on August 26, about the time the longshore component of the current reverses. Greatest differences of just under -50 cm are reached early on August 31, or approximately 1½ days before strongest winds and currents were recorded at Port Aransas and the study site, respectively. A rapid rise in water levels at Port Mansfield, resulting in positive differences, occurs between August 31 and September 1, as the storm surge moves southwestward along the coast. A maximum value of approximately $+40$ cm is recorded briefly late on September 1, at the time of strongest southwesterly current speeds and as the longshore motion to the southwest began decelerating. The longshore sea surface slope quickly decreases and reverses, Freeport water levels again becoming higher early on September 2. The slope remains negative through the end of the record, except for an approximately 14-hour period of near-zero differences during September 5–6.

DISCUSSION

To put the results of the study in perspective, it is of interest to compare the current speeds and directions recorded along the fringe of the storm with those obtained in previous studies in the same general area and at the same time of year. Several studies have been conducted over the inner shelf off Port Aransas (Figure 1) over the past 4 years. Specifically, measurements were made during the summer months of 1973 [*Smith,* 1975] and 1974 [*Smith,* 1978] at a sampling site in 18 m of water approximately 11 km off Port Aransas, Texas. Current data reveal an alternating longshore flow with low-frequency reversals in the current direction occurring in response to slight variations in the longshore component of predominantly onshore winds. A histogram of current speeds constructed from the 1973 data shows the highest percentage of current speed observations within the 6- to 9-cm/s interval. Current speeds in excess of 21 cm/s were rare, and no speeds faster than 45 cm/s were recorded during this approximately 38-day period. The scalar average current speed 4 m above the bottom was 10.5 cm/s. The study carried out at the same location in the summer of 1974 indicated a generally similar pattern. Alternating longshore motion was characteristically between 3 and 15 cm/s.

Perhaps more appropriate for a direct comparison with currents recorded during Hurricane Anita are the measurements made at this same location before and after the passage of the storm. The study site was occupied between June 21 and September 11, 1977. During this time, current directions were primarily longshore and bimodally distributed, with maxima between 40° and 70° and between 210° and 260°. Most frequently recorded current speeds fell within the range of 3–21 cm/s at the upper level and 3–15 cm/s at the lower level. With this as background, the approximately 10 days of longshore motion to the southwest during the passage of the hurricane was not unusual for the summer months; however, the current speeds of approximately 80 cm/s at the upper level and 70 cm/s at the lower level are of the order of 2–3 times those characteristic of the summer months along the central Texas coast.

A qualitative integration of the wind stress, water level, and current data makes possible some inferences regarding the dominant current-driving forces along the fringe of the hurricane. There is a marked similarity in the time plots of the longshore component of the current at both levels and the plot of both the longshore and the cross-shelf wind stress components (Figures 2 and 3). The intensification of the southwesterly current at both levels clearly corresponds to the increase in both longshore and onshore wind stress components on August 29. The strongest longshore currents correspond very closely in time with the strongest wind stress forcing. Nevertheless, several features of the current data suggest that the longshore motion recorded during this time was not primarily wind driven. The current speeds recorded simultaneously 2 and 10 m above the bottom rarely differed by more than 15 cm/s. One would expect greater differences in a wind-driven current with speeds decreasing approximately exponentially with increasing depth.

Also, the bottom stress estimated from the current data is substantially greater than the wind stress estimated for the study site from the measurements made at Port Aransas. By vector addition, maximum wind stress over inner shelf waters is estimated to be just over 3.5 dyn/cm^2. The bottom stress at the study site can be estimated from the expression $\tau_0 = \rho u^{*2}$, where u^* is the friction velocity and ρ is the density. The friction velocity can be determined graphically as the slope of the line connecting the observed current speeds, plotted against the natural log of the height above the bottom. The temporal variability of u^* determined in this way (not shown) is similar to that found by *Forristall et al.* [1977] for measurements made during tropical storm Delia. The friction velocity increases from values of less than 2 cm/s before Anita forms to values that are quite variable but generally between 8 and 10 cm/s after the storm had attained hurricane strength. *Weatherly* [1972] has demonstrated that calculations of friction velocities made using current speeds measured above the logarithmic layer may overestimate the true value. Here, data from 2 and 10 m above the bottom are most likely above the logarithmic layer. But even assuming a friction velocity of the order of 5 cm/s, the resulting bottom stress would be just over 25 dyn/cm^2, which is nearly an order of magnitude larger than the overlying wind stress. It is thus highly probable that forcing in another form made a greater contribution to the observed longshore motion.

A close inspection of the longshore slope in the sea surface suggests that the associated pressure gradient may have played a significant role in driving the longshore current. The indicated longshore gradient between Freeport and Port Mansfield was approximately -25 cm/340 km at the time the longshore motion reversed late on August 26. Assuming a 25-cm offset in the datum planes of the two water level recorders, the corrected slope in the sea surface increased to a peak value of approximately 65 cm/340 km, or 1.9×10^{-6}. This corresponds to a longshore acceleration of 1.9×10^{-3} cm/s^2. By comparison, the maximum wind stress of 3.5 dyn/cm^2, distributed through a 17-m water column, would produce an acceleration which is also of the order of 2×10^{-3} cm/s^2. However, except for the maximum slope reached on September 1, values were generally within the range of $1.5\text{–}7.5 \times 10^{-7}$, and thus accelerations were nearly an order of magnitude less. Computed wind stress values were also significantly less both before and after peak values on September 1 and 2. One may tentatively conclude that neither wind stress nor the longshore pressure gradient played a dominant role in driving the observed longshore motion but that both forms of forcing made a significant contribution. The available data base is not adequate to describe the forcing consistent with the large bottom stress calculations.

It is of interest to note that longshore motion to the southwest began at the study site approximately 1½ days before the longshore component of the wind stress reversed at Port Aransas and approximately 2½ days before the tropical depression formed. Mesoscale variations in the surface wind field between the anemometer and the study site may explain the poor correspondence between these two events, or it may be that local wind stress forcing became temporarily less important than other current-driving forces. In any case, the reversal noted on August 27 may be nothing more than an example of the alternating nearshore motion that characterizes summertime circulation in the northwestern Gulf of Mexico. That it was soon reinforced by unusually strong winds on the fringe of a hurricane may be only a coincidence.

The deceleration of the longshore component of the current begins late on September 1 but becomes more rapid the following day, about the time the storm crosses the coast. Wind stress forcing decreases rapidly during this time (Figure 3) and remains relatively insignificant through the end of the study period. With the study site 120 km further from the storm center than the anemometer, it is likely that the decrease in wind stress occurred there about ½ day before it was recorded at Port Aransas. Thus it is unlikely that wind stress was responsible for slowing and eventually reversing the strong longshore flow recorded during the storm. A comparison of Figures 2 and 4, however, indicates that the deceleration of the southwesterly current begins about the time the sea surface slope changes sign and Port Mansfield water levels become temporarily higher. One might therefore argue that the deceleration is brought on by longshore currents flowing against the gradient.

The variability in both surface wind stress and longshore sea surface slope shows that under hurricane fringe conditions, meteorological forcing exists in various forms to drive shelf waters. The details of the air-sea coupling are less obvious; shelf dynamics are complicated even under quasi-steady conditions. The main point to be made here is that the forcing associated with a well-developed hurricane, in whatever form, extends well out into the fringe areas of the storm and that the effects of a hurricane on ocean waters can be more spatially widespread than might generally be believed.

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