FOUR STORM-EVENT BEDS AND THE TROPICAL CYCLONES THAT PRODUCED THEM: A NUMERICAL HINDCAST[1]

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ABSTRACT: A three-dimensional, numerical prediction system for storm sedimentation has been constructed to compute a cyclonic wind field, coastal circulation, storm waves generated over the continental shelf, the combined effects of steady currents and waves on the benthic boundary layer, both suspended and bed load transport of sediment, and conservation of the sea floor. It has been used to hindcast the oceanographic and sedimentological responses of the western Gulf of Mexico to four historical tropical cyclones in order to investigate the effects of coastal configuration and storm variability on event bed genesis.

The simulations reveal several common responses to these storms: 1) onshore flow to the right of the storm track generally transports fine sediment landward; 2) off-shore flow to the left transports coarser sediment seaward; and 3) for an observer facing the coast, right to left along-shelf flow transports finer sediment in deep water and coarser sediment in shallow water. The main source of sandy sediment on the inner shelf is the shoreface which is eroded by currents driven by wind stress, geostrophy, and offshore flows associated with collapse of the coastal setup. Coastal geometry is the dominant factor in determining sedimentation patterns. Along the coast in front of each storm, the volume of sediment transported obliquely onshore or offshore is a function of shelf gradient and coastal configuration. Steeper gradients constrain flow to a more longshore pattern. Concave coastlines promote greater shoreface erosion because of increased coastal setup.

None of the simulations reveals the vertical current structure predicted by the geostrophic model for continental shelf circulation, because the calculated depth of the wind-mixed layer exceeded local water depth everywhere over the shelf. Thus, in these experiments, most of the continental shelf fell within the friction-dominated zone in which the upper and lower boundary layers overlap, resulting in vertically uniform along-shelf flow.

INTRODUCTION

Both modern and ancient continental shelf strata frequently consist of hummocky cross-stratified sand or sandstone layers intercalated with mud or shale. The sandy beds are called tempestites, or event beds, because their erosive bases, and sedimentary and biogenic structures indicate that they were emplaced by flows at the event scale (Seilacher 1982) on the order of a few hours or days duration. On storm-dominated coasts, it is natural to assume that storms are the causal agent.

The specific storm processes that generate event beds are still open to question (see Walker 1984 for a summary). Some geologists (Hayes 1967; Bouma et al. 1982; Harms et al. 1982; Brenchley et al. 1986; Leckie and Krystinik 1989), using sediment patterns from rocks and modern shelves, have suggested that liquefaction, density flows, and the super-imposed effects of storm waves and currents are responsible, thereby requiring predominantly offshore sand transport. For example, Hayes (1967) observed cross-shelf thicknesses and textures for the Hurricane Carla bed from the shoreface to a depth of 35 m off Padre Island, Texas, along 50 km of coast, and argued that storm surge-ebb turbidity currents carried the sand offshore. Other geologists (e.g., Swift et al. 1987) have suggested that evolving wind-driven geostrophic currents are responsible, thereby requiring essentially isobathic or oblique offshore sand transport. Morton (1981) studied the Carla bed at Matagorda Bay on the central Texas coast using vibracores taken across the inner shelf to a water depth of 20 m. By correlating beds over distances of about 3 km, he argued that wind-driven shelf currents were the principal transporting agents. The distribution of the Carla bed was further evaluated by Snedden et al. (1988) using box cores collected offshore of Corpus Christi to a water depth of 140 m. They also correlated the base of the inferred Carla bed within this region over distances of up to 32 km offshore and argued for geostrophic flows.

Our present understanding of storm sedimentation is contained within the models of Dott and Bourgeois (1982), Walker (1984), Brenchley (1985), Duke (1985), and Duke et al. (1991). They used textures in modern storm sediments, geostrophic flow concepts, results of flume experiments, and inferred storm-generated structures within ancient sandstones to construct a cross-shelf facies sequence dependent upon water depth, sediment availability, and storm parameters such as return frequency and strength (Curray 1960; Hayes 1967; Kumar and Sanders 1976; Morton and Winker 1979; Morton 1981; Figueiredo et al. 1982; Nelson 1982; Swift et al. 1981; Swift et al. 1986a; Nummedal and Snedden 1987; Snedden et al. 1988; Morton 1988; Gagan et al. 1990; Snedden and Nummedal 1990; Southard et al. 1990). While representing an important conceptual advance, these models are primarily qualitative and have not been rigorously tested against oceanographic data collected for that purpose, nor compared to results of numerical experiments.

It is our thesis that the origin of event beds could be better understood if their geometry and textures, as observed in the field, could be compared to values calculated from a deterministic, physics-based model of sedimentary processes in coastal oceans during tropical cyclones. By introducing the evolving flow field during a storm, as well as the volume of sediment eroded and deposited, it should be possible to relate an event bed to a particular

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shelf setting and storm type, thereby testing the present conceptual models.

Here we use a Storm Sedimentation System (S^3) to study event-bed genesis during tropical cyclones. This system consists of: 1) a cyclonic wind-field prediction model; 2) a three-dimensional ocean circulation model; 3) a wind-sea prediction scheme; 4) a combined current-wave benthic boundary-layer model; 5) bed and suspended load transport algorithms; and 6) a bed-conservation scheme to keep track of sedimentation with time. The system predicts the temporally evolving event-bed geometry and texture at evenly spaced nodes within a basin in response to a specified storm. Our ultimate objective is to determine the relationships between storm bed characteristics, especially thickness and grain size, and storm characteristics such as track, forward speed, and magnitude. In addition, we want to know the influence of coastal configuration on event-bed geometry.

These relationships are investigated using hindcasts of four tropical storms that have made landfall within the western Gulf of Mexico coastline in historic time. The dependence of storm-bed deposition on storm track is studied for four track-coastline configurations: 1) direct approach to a straight coastline with a low continental-shelf sea-floor gradient; 2) direct approach to a straight coast with a relatively steep sea-floor gradient; 3) direct approach to a concave coast; and 4) oblique approach to a shallow shelf. A comparison is also made between strong and weak storms passing obliquely over a wide, shallow continental shelf.

THE STORM SEDIMENTATION SYSTEM

The Storm Sedimentation System used in this study is a combination of several FORTRAN programs which solve the finite difference equations for physical processes operating on the continental shelf during a tropical storm. The system is more fully described in Keen and Slingerland (1993).

Atmospheric circulation is limited to the purely cyclonic motion about a low-pressure center, and synoptic-scale meteorology is neglected. The wind field is calculated by the empirical model of Harris (1958). A tropical cyclone is simulated by specifying the position of the storm eye, as well as other parameters, within the model grid at successive time steps. The eye thus moves across the grid and the wind field is calculated at intervals of 1 hour.

Ocean circulation is calculated at 60-second intervals using a modified version of the 3-D turbulent coastal ocean model of Leendertse et al. (1973). This model solves the primitive equations for fluid motion in Cartesian coordinates on a rotating earth, using an f-plane approximation (Leendertse and Liu 1975, 1977). Vertical mass and momentum exchange are parameterized using a vertical eddy viscosity which is calculated in terms of subgridscale turbulent energy. Turbulent energy in turn is calculated from a conservation equation. The surface mixed layer is represented by effectively decoupling the upper ocean from the deep at an Ekman friction depth calculated from $D_E = \pi\sqrt{2A_Z/f}$ where A_Z is the vertical eddy viscosity and f is the inertial frequency (Pond and Pickard 1983). The horizontal currents in the lowest model level predicted by this model are written to files at 1-hour intervals for use as input to a combined current-wave benthic boundary-layer model for bed shear stresses.

The wind sea is computed at 60-second intervals using a simplified version of the finite-depth wave model of Graber and Madsen (1988) which excludes swell. This model solves the wave energy transport equation in terms of the JONSWAP (Joint North Sea Wave Project) parameters, calculating the significant wave height, mean frequency, and mean wind-sea direction at every grid point. These variables are printed to files at 1-hour intervals coinciding with the circulation model output. The maximum wave orbital amplitude and velocity are then calculated from linear wave theory and placed in files for use in the boundary-layer calculations.

Shear stresses at the sea floor depend on the combined boundary layer in which the oscillatory wave currents and steady currents interact. It is considered important to include these nonlinear effects for the calculation of sediment entrainment, and this is done using the benthic boundary-layer model of Glenn and Grant (1987), which is applicable to wave-dominated conditions.

Sediment transport and mass conservation for the sea floor are computed every hour from the combined shear stresses following van Niekerk et al. (1992) and Vogel et al. (1992). Bed load is found from a modified Bagnold formulation, and suspended sediment concentration is predicted using the Rouse equation. The total suspended load transport rate for a given size class is then determined by integrating the mass transport rate-per-unit-volume over the width of the grid and the height of the boundary layer. Bed conservation equations account for mass exchange between the bed and the flow.

The system is not without problems. The simple cyclonic wind-field algorithm used herein is not adequate far from the storm eye and cannot capture atmospheric processes preceding the actual arrival of the storm at the shelf, nor does it accurately hindcast the complex winds associated with breakup of the cyclone. To keep this initial effort simple, there is no coupling of processes with known feedback. For example, the effects of wave-current interaction and suspended sediment stratification on bottom friction (as calculated by the benthic boundary-layer model) are not explicitly fed back into the ocean-circulation and wind-sea models. Furthermore, the suspended sediment concentration profiles are calculated independently by the boundary-layer and sediment-transport models, with the transport rates found by the boundary-layer model only used to calculate the shear stresses. Several factors affecting entrainment of fine-grained sediment, such as bed armoring, cohesion, and grain hiding, are neglected. These effects are included in the complete sediment-transport model as discussed by van Niekerk et al. (1992) but have been deleted in the present study for simplicity.

In these experiments, the water column is unstratified,

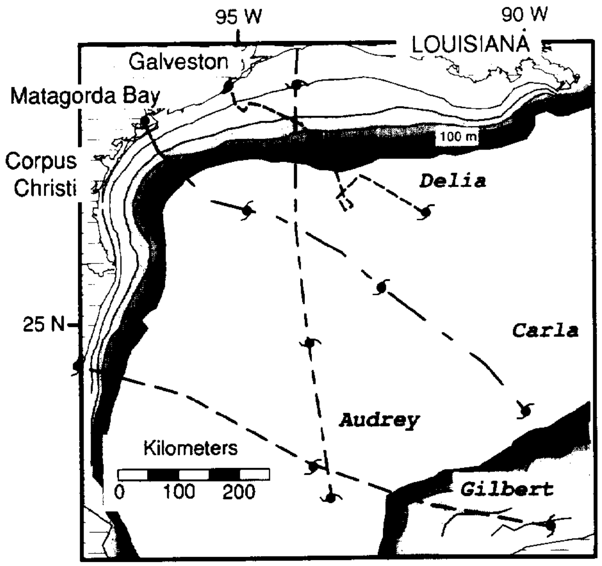


FIG. 1.—The paths of Tropical Storm Delia (1973), and Hurricanes Audrey (1957), Carla (1961), and Gilbert (1988). The tropical cyclone symbols show the location of the eye every 24 hours, except for Delia, where the last symbol coincides with hour 28. Also shown is the bathymetry used in the model. The contour interval is 20 m above the 100 m isobath, and 100 m below. Deep water is represented by a flat bottom 400 m deep.

whereas during the late summer, Texas shelf bottom waters can be about 3 σ_t units denser than the surface mixed layer. This assumption is not as unrealistic as it may seem, however. A summary of hydrographic data before and after Hurricanes Hilda (1965) and Inez (1966) in the western Gulf of Mexico shows significant homogenization of the upper ocean and deepening of the mixed layer (Ichiye 1972). Deepening of the mixed layer is further documented by Price (1981), with final depths ranging from 50 m to over 100 m (Brooks 1983). Therefore, the homogeneous water column used in this study is probably reasonable, at least within the region of highest winds.

The swell component of the wind-wave field is neglected in these experiments, and this is certainly a problem for the interval preceding the arrival of the storm at the shelf. However, numerical experiments comparing the wind-sea model results to those of Graber and Madsen (1988), as well as other oceanic conditions, showed the error introduced by neglecting swell to be minor for sea states approaching wind seas (Keen 1992). A more significant problem is associated with the incorporation of excessive bottom friction in the original model (S.M. Glenn, personal communication), which resulted in a 30% under-prediction of wind waves in shallow water.

The circulation model was run on an IBM 3090/J supercomputer at the Cornell Theory Center, where a simulation of 40 hours on the present grid required approximately 45 minutes of CPU time. The wind-sea model was run on an HP workstation (Model 319) and took about 300 minutes. The benthic boundary-layer and sediment transport program was run on an HP workstation (Model 370) and required around 600 min of computation time.

EXPERIMENTAL DESIGN

We evaluated the dependence of storm-event beds on continental shelf sea-floor gradients using simulations of two hurricanes which approached straight coasts perpendicularly. Hurricane Audrey crossed the western Gulf on a northerly path from 25 to 27 June 1957 (Harris 1963), making landfall along the western Louisiana coast where the sea-floor gradient is 5.8×10^{-4}. Gilbert crossed the southwestern Gulf from 15 to 16 September 1988 (Clark 1988), making landfall in Mexico where the shelf gradient is 2×10^{-3} (Fig. 1). We investigated the effects of a curved coastline using a simulation of Hurricane Carla, which followed a northwesterly path from 8 to 11 September 1961 (Harris 1963) and struck the concave Texas coast at Matagorda Bay (Fig. 1). The average peak winds hindcast by the wind model for Audrey, Gilbert, and Carla are 38, 43, and 45 m/s, respectively. For Carla and Audrey, these modeled peak winds did not occur until landfall (Fig. 2). To evaluate the role of an oblique storm path, we compared model results for Audrey and Carla. Carla approached the wide, shallow Louisiana shelf obliquely (45 degrees), whereas Audrey's path was directly onshore. Finally, sedimentation patterns for strong and weak storms were compared using model results for Hurricane Carla and Tropical Storm Delia. The latter crossed the northwestern Gulf from 3 to 4 September 1973 (Forristall et al. 1977) and made landfall at Galveston, Texas (Fig. 1). Peak sustained model winds for Delia were 29 m/s (Fig. 2D).

All simulations were run on a 43×56 model grid with a horizontal grid size of 20 km. The water column within the circulation model was represented by nine levels, each with uniform thickness throughout the grid. The upper four levels were each 10 m thick, the fifth through seventh levels were each 20 m thick, the next-to-bottom level was 100 m thick, and the lowermost level was 300 m thick. The seaward boundary condition allows no flow, because direct storm effects were expected to dominate the coastal ocean response.

The initial sediment distribution on the shelf for each simulation consisted of a mud line at the 40 m isobath which divided inner shelf sands from outer shelf muds. This idealized distribution was chosen for ease of interpreting model results. The inner shelf sand was well sorted and fine, with a mean μ, of 2.5 ϕ and standard deviation σ, of 0.5 ϕ. The outer shelf sediment was very-fine silt mud ($\mu = 7.5\ \phi$ and $\sigma = 1\ \phi$). The entire range of sediment used for the simulations was represented by 10 size classes, from 1 to 10 ϕ.

The western Gulf of Mexico is ringed by barrier islands with sandy shorefaces which together supply sediment to the storm current system (Morton 1988). Processes operating on these shorefaces are not included in our system, because the shoreface lies landward of the 10 m isobath, the minimum water depth represented by the system grid. In order to represent this sediment source in the simu-

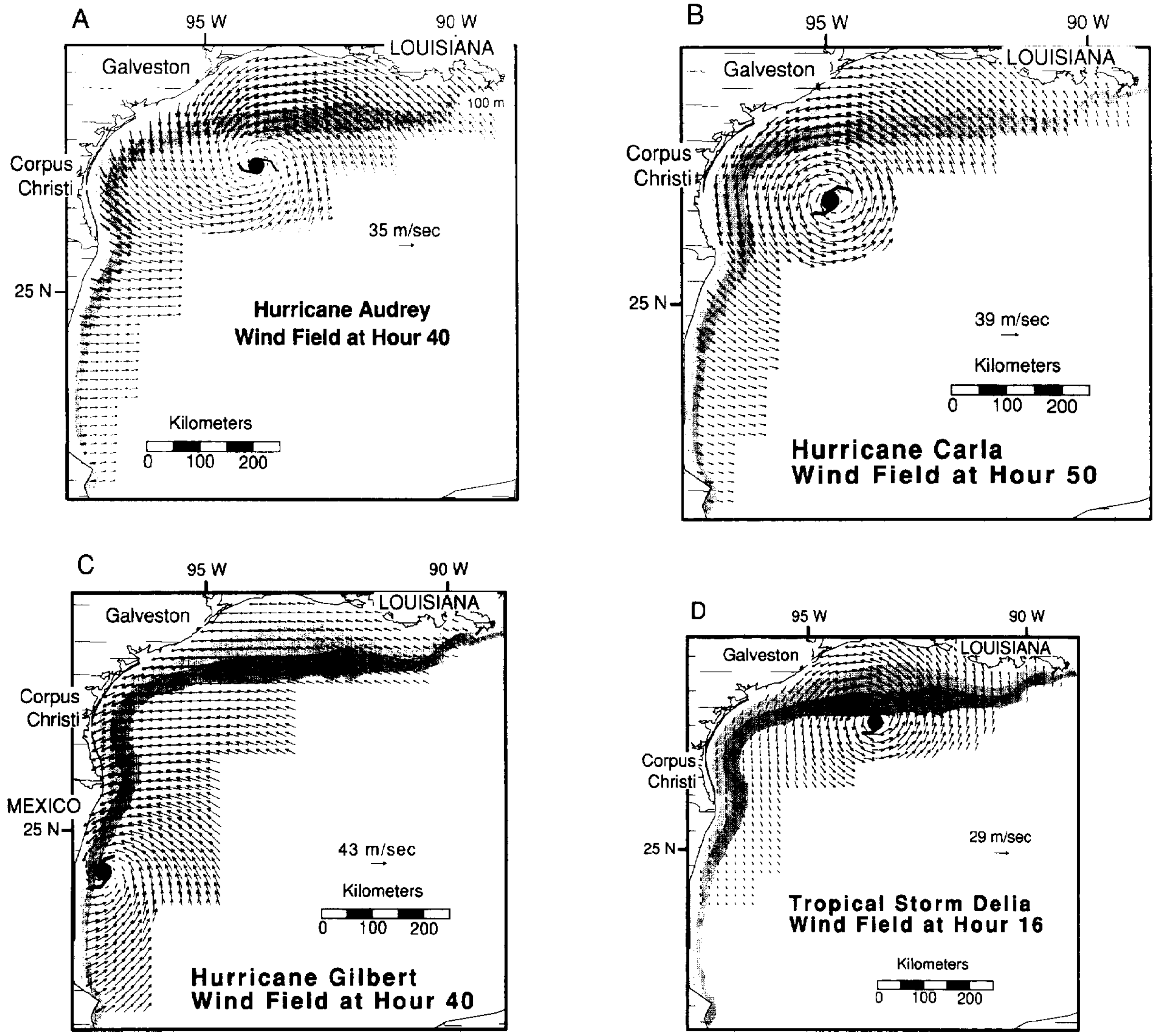


FIG. 2.—Examples of computed cyclonic wind fields for the hindcast storms. **A)** Hurricane Audrey at simulation hour 40, 2300 26 June 1957. **B)** Hurricane Carla at hour 50, 2100 10 September 1961. **C)** Hurricane Gilbert at hour 40, 1600 16 September 1988. **D)** Tropical Storm Delia at hour 16, 0900 4 September 1973. The vector scale length is the maximum vector present on the plot. Bathymetry is represented by shading.

lations, each size class of sand was added to grid points adjacent to land at a rate equal to sand removal there, with the landward boundary treated as an infinite sediment source. Thus, net erosion is prohibited at these model grid points, and they serve as either depositional sites or conduits for offshore transport.

RESULTS

Simulation of Circulation, Wave, and Bed Shear-Velocity Fields

Typical patterns for modeled coastal setup, horizontal circulation, storm waves, and bed shear-velocities will be presented as snapshots at simulation hours when they are best developed. For coastal setup and circulation these patterns are established sometime before landfall, whereas for the storm wave and bed shear-velocity fields, maxima (which govern sediment entrainment) occur just before landfall. Because the horizontal circulation field does not vary significantly in the vertical, the following presentation refers to the horizontal currents calculated for the uppermost level, at a depth of 5 m, even though the horizontal circulation field calculated for the lowest model level is used to compute the combined shear stresses at the sea floor and transport suspended sediment.

Hurricane Audrey.—Model-predicted coastal setup during Hurricane Audrey reached 70 cm near Galveston at simulation hour 30 (Fig. 3A), while surface currents along the coast attained a predicted maximum of 104 cm/s (Fig. 3B). After hour 30, the predicted storm surge collapsed and, as the pressure gradient decreased offshore,

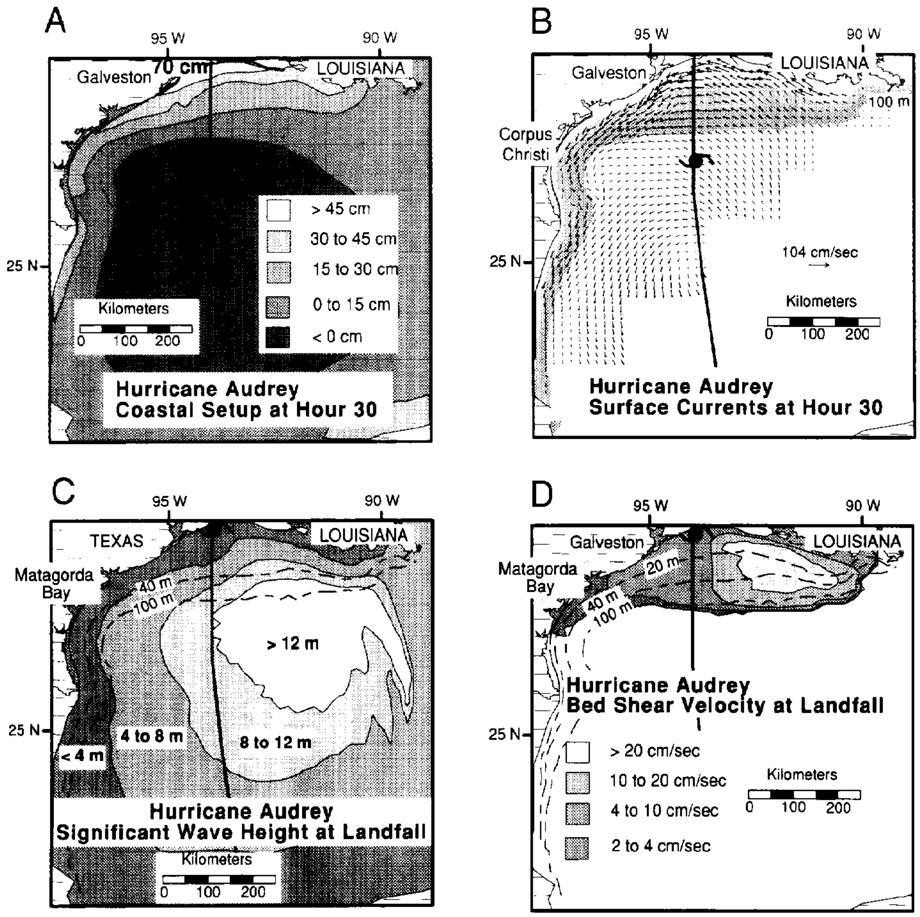


FIG. 3.—Snapshots of the computed oceanographic response to Hurricane Audrey. **A)** Coastal setup at simulation hour 30. The peak setup of 70 cm occurs at Galveston. **B)** Surface currents (at 5 m depth) at hour 30. The vector scale length is the maximum vector present on the plot. **C)** Significant wave height at landfall (hour 50). **D)** Bed shear velocity u_* at hour 50. The location of the eye is indicated by the tropical storm symbol.

the modeled currents diminished and rotated to high angles from the coast to the right of the storm track. Simultaneously, predicted storm waves east of the track grew with approach of the eye and exceeded 4 m over much of the Louisiana shelf by landfall (Fig. 3C).

The hourly average, combined bed shear velocities u_* (equal to $\sqrt{\tau/\rho}$ where τ is the bed shear stress and ρ is the water density) are strongly dependent on wave orbital amplitude and peak velocity at the bed, both of which are functions of significant wave height, mean frequency, and water depth. Strong currents and moderate waves, such as predicted for simulation hour 30, resulted in only intermediate values of u_*. Peak magnitudes and steep gradients occurred when high storm waves were predicted for shallow water (Fig. 3C). Thus, bed shear velocities peaked at landfall (Fig. 3D) with magnitudes of 26 cm/s predicted between the 20 and 40 m isobaths off the central Louisiana coast. Steep gradients were hindcast for the eastern Louisiana shelf, whereas the lower gradients in the west resulted from the reduced winds predicted near the storm eye.

Hurricane Carla.—The predicted storm surge for Carla peaked at 60 cm near the Texas-Louisiana border at simulation hour 30 (Fig. 4A). This is much earlier than the observed tide and significantly lower (Harris 1963); also, the southern peak near landfall is absent in the model results. These discrepancies are due to the simplified storm wind pattern, especially as the storm approached landfall. Also, it must be remembered that this calculation of coastal setup is for a node 10 km from land and thus may not match coastal tide gauge data. Modeled currents extended from Galveston to Mexico with maximum surface speeds of 98 cm/s (Fig. 4B). Surface currents over the outer shelf were about 60 cm/s and parallel to shore, but a significant offshore component was predicted for the inner shelf.

Hindcast storm waves over the shelf exceeded 2 m from eastern Louisiana to southern Texas for more than 24 hours and, as the eye approached landfall, waves surpassed 4 m over the inner shelf (Fig. 4C). Shear velocities greater than 4 cm/s were predicted for most of the Louisiana shelf by hour 24 because of Carla's oblique approach. However, the largest magnitudes occurred just before landfall (Fig. 4D), when storm waves were greater than 8 m over the outer shelf. At this time, u_* was ap-

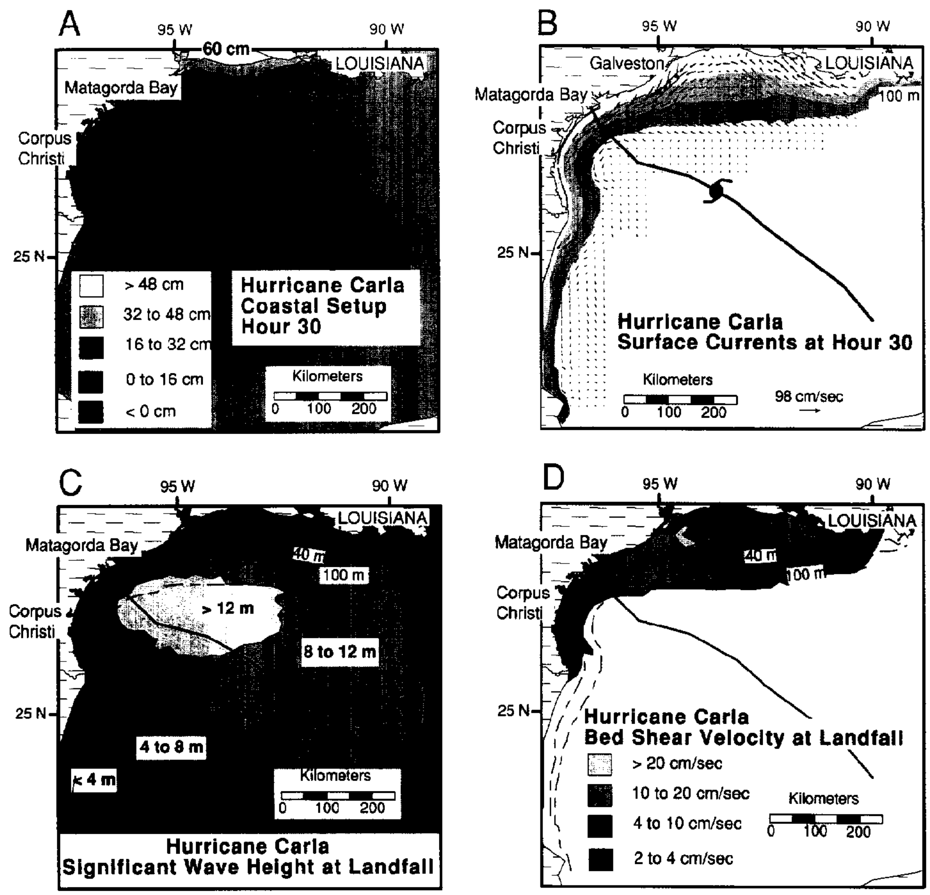


FIG. 4.—Snapshots of the computed oceanographic response to Hurricane Carla. **A)** Coastal setup at simulation hour 30. The peak setup is 60 cm. **B)** Surface currents (at 5 m depth) at hour 30. The vector scale length is the maximum vector present on the plot. **C)** Significant wave height at landfall (hour 70). **D)** Bed shear velocity u_* at hour 70. The location of the eye is indicated by the tropical storm symbol.

proximately 3 cm/s along the southern Texas coast and in excess of 4 cm/s along the outer shelf of central Texas.

Hurricane Gilbert.—During Gilbert, predicted coastal setup reached a maximum of 100 cm at Galveston by hour 30 (Fig. 5A) and decreased steadily to 60 cm just before landfall. Along the Louisiana coast the modeled storm surge behaved as a forced Kelvin wave because of the constant along-shelf winds. Modeled surface currents extended from eastern Louisiana to the southern edge of the model grid by hour 30 with a maximum of 150 cm/s (Fig. 5B). As the eye approached the coast, the current system evolved into northern and southern cells. The greater setup calculated within the northern cell caused currents within it to be primarily pressure-driven, as against wind forcing for the southern cell. The down-flow ends of both cells developed offshore flow.

As Gilbert made landfall, storm waves approached 8 m in height over the inner shelf and surpassed 12 m over the outer shelf along the central Texas coast (Fig. 5C). Thus u_* exceeded 10 cm/s over an 800 km length of coastline with a peak of 22 cm/s at the Mexican border (Fig. 5D).

Tropical Storm Delia.—Delia's hindcast storm surge evolved as a forced Kelvin wave along the Louisiana coast, peaking at Galveston at hour 20 with an amplitude of 170 cm (Fig. 6A). The pressure gradient helped drive oblique offshore surface currents at Galveston of more than 200 cm/s (Fig. 6B). Surface currents decreased to 50 cm/s at the shelf edge with onshore flow over the central Louisiana shelf. Coincident with these strong flows, storm waves were above 4 m over the Louisiana shelf (Fig. 6C); however, the largest waves were not predicted in the same area as the strongest currents, being located to the east.

Predicted peak magnitudes of u_* during Delia exceeded 10 cm/s from eastern Louisiana to Galveston at hour 20 (Fig. 6D) and coincided with maxima in hindcast storm surge and coastal currents. The computed values result from the distribution of large storm waves and fast currents; the reduction in bed shear stresses caused by lower hindcast storm waves near the coast was offset by large pressure-gradient-driven currents.

Modeled Event Beds

Hurricane Audrey.—More than 1 cm of erosion was hindcast over an area of 3×10^4 km^2 to the right of

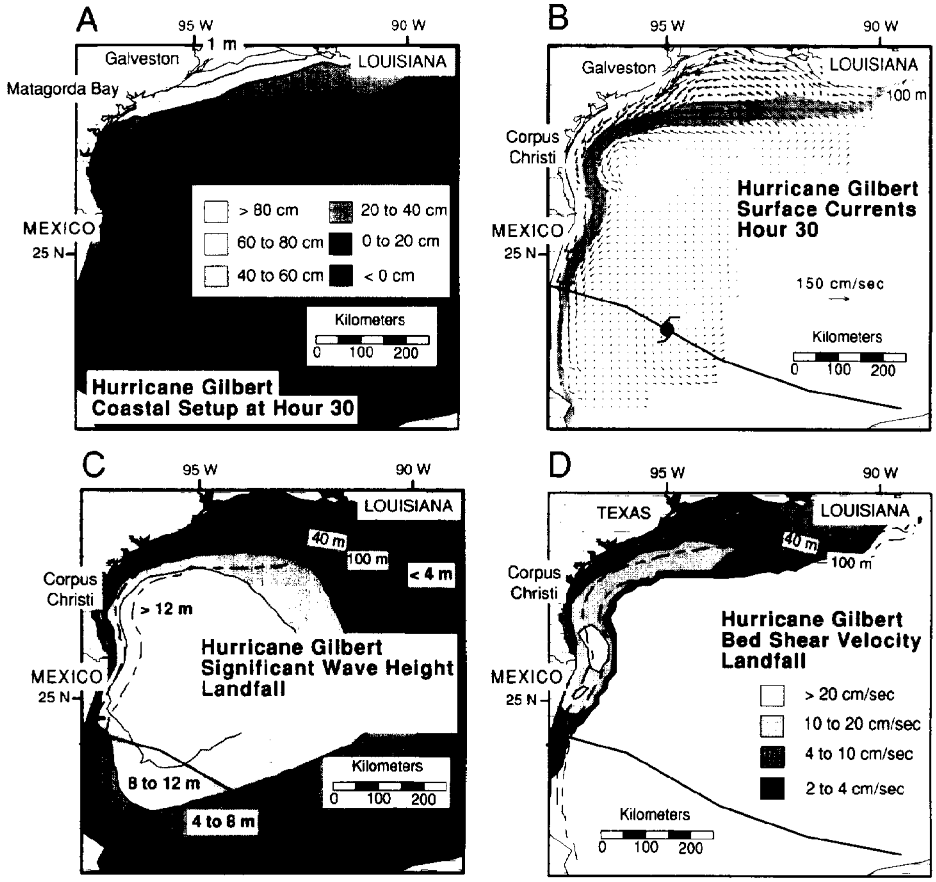


FIG. 5.—Snapshots of the computed oceanographic response to Hurricane Gilbert. **A)** Coastal setup at simulation hour 30. The peak setup is 1 m. **B)** Surface currents (at 5 m depth) at hour 30. The vector scale length is the maximum vector present on the plot. **C)** Significant wave height at landfall (hour 46). **D)** Bed shear velocity u_* at hour 46. The location of the eye is indicated by the tropical storm symbol.

Audrey's path over the shelf (Fig. 7A), with maximum scour predicted along isobaths where u_* gradients were greatest (Fig. 3D). (This along-shelf pattern was partly caused by the discretization of bathymetry.) Erosion was greatest over the outer shelf, because the bed shear-velocity gradients were larger there, and because the critical shear velocity u_{*c} for the silty sediment is less than 2 cm/s.

The predicted Audrey bed covers most of the Louisiana continental shelf with a maximum thickness of more than 35 cm in water less than 20 m deep (Fig. 7B). Except for the thick sediments along eastern Louisiana, and the thin blanket to the west, it was deposited on a scour surface produced during the storm (compare Fig. 7A, B). The longest transport path suggested by Figure 7 was about 100 km along the 40 m isobath. Relationships between predicted erosion and deposition suggest oblique onshore transport for the eastern Louisiana shelf with path lengths less than 50 km. This resulted from the modeled currents in the east (Fig. 3B) which transported silt landward from the mud line (Fig. 7C), and sand obliquely shoreward over the inner shelf (Fig. 7D). The only inferred transport path not indicated by the surface currents in Figure 3B is the offshore flow required to predict the eastern nearshore depocenter. This sandy sediment was deposited just before landfall, when the collapsing coastal setup to the east generated weak offshore currents which removed sediment from the shoreface.

Hurricane Carla.—More than 10 cm of erosion was predicted for over 5.5×10^4 km^2 of the Texas-Louisiana continental shelf during Hurricane Carla (Fig. 8A), with scour exceeding 100 cm southeast of Galveston and off eastern Louisiana. These regions coincided with the largest model gradients in u_* (Fig. 4D). Offshore of southern Texas, however, erosion fell along the 2 cm/s isopleth within a region where modeled storm currents flowed offshore against the bed-shear gradient. Because of the high storm waves hindcast for this area, this may have been a case of resuspension.

The maximum predicted bed thickness (Fig. 8B) is more than 50 cm, and at least 10 cm of sediment was deposited on an erosional surface covering most of the northwest shelf. Three depocenters where the bed is thicker than 50 cm reflect processes operating on different parts of the shelf at different times during Carla's passage. The elongate bed on the inner shelf of eastern Louisiana was de-

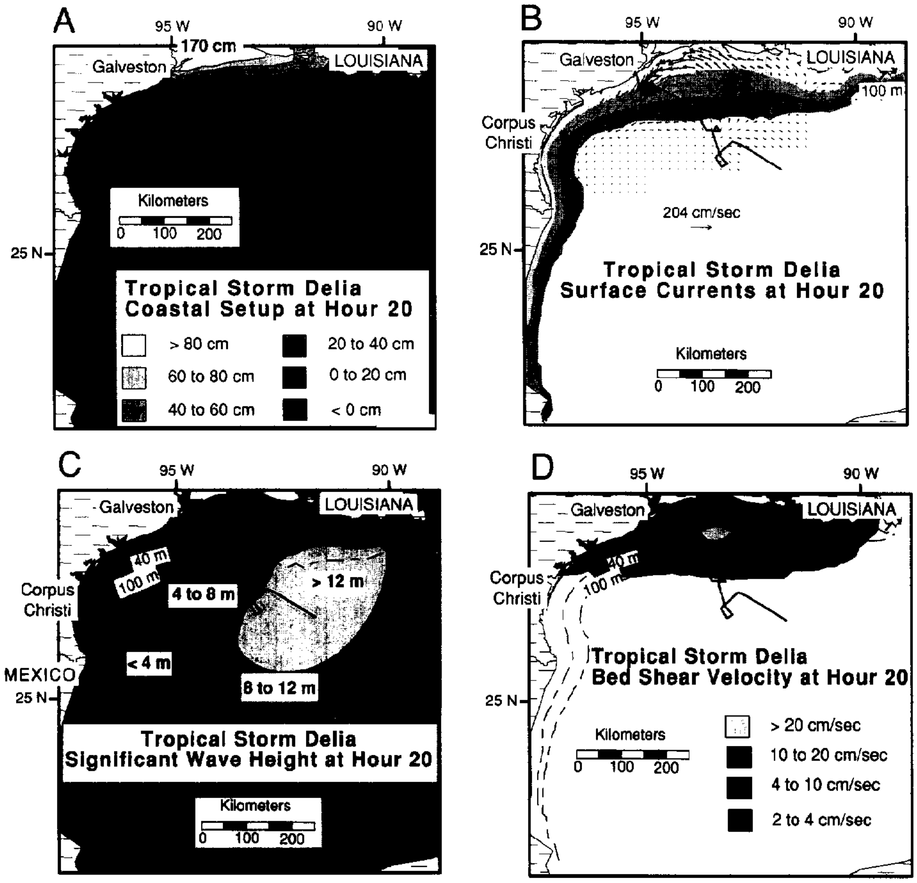


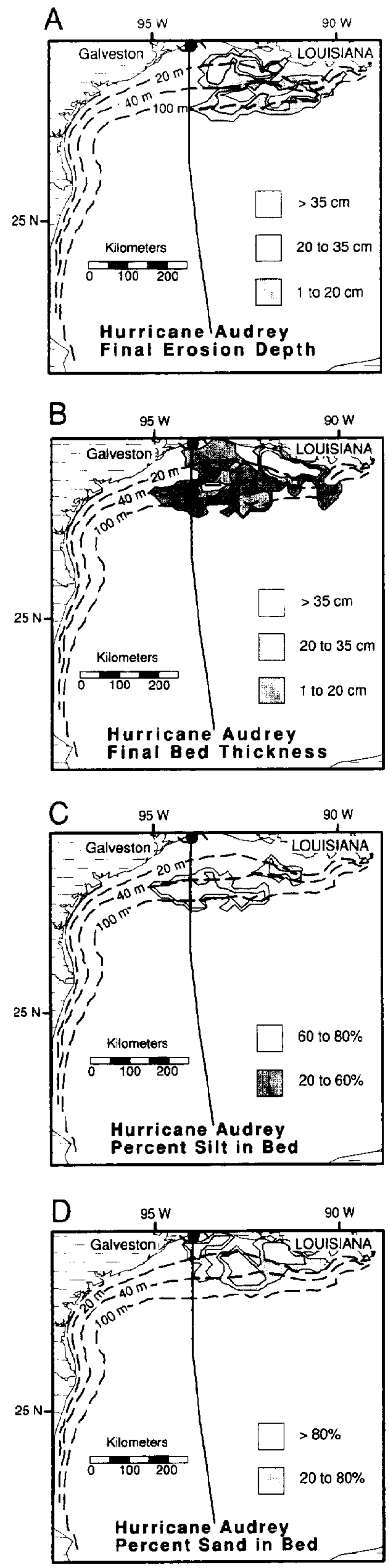
FIG. 6.—Snapshots of the computed oceanographic response to Tropical Storm Delia. A) Coastal setup at simulation hour 20. The peak setup is 170 cm. **B)** Surface currents (at 5 m depth) at hour 20. The vector scale length is the maximum vector present on the plot. **C)** Significant wave height at landfall (hour 28). **D)** Bed shear velocity u_* at hour 28. The location of the eye is indicated by the tropical storm symbol.

posited from oblique onshore flow before simulation hour 20, as suggested by the decreasing silt content of the predicted bed along a northwestward bearing from the 40 m isobath (Fig. 8C). This trend is complemented by increasing sand (Fig. 8D). A westward extension of this depocenter along the 40 m isobath is composed of greater than 50% sand which was deposited during the first 30 hours of simulation (see Fig. 4B). A second depocenter predicted on the northeast Texas shelf varies from more than 50% sand at the shoreface to none at the outer shelf. The third hindcast depocenter located at Matagorda Bay contains shoreface sand, and silt which was transported as far as 150 km along-shelf. The predicted silt content is greater than 50% for water deeper than 20 m, whereas sand is restricted to the shallowest depths and increases towards Galveston. The modeled 1 to 10 cm thick bed at the southern end of the Texas coast contains only silt and clay which were transported obliquely onshore.

The real Carla bed was observed to the south of the storm track by Hayes (1967), Morton (1981), and Snedden et al. (1988) (Fig. 9A). The post-Carla graded bed observed by Hayes (Fig. 9B) attains a maximum thickness of more than 9 cm just south of the bed predicted in the present study (Fig. 8B). At the southern extent of his field area, Hayes observed a graded bed up to 9 cm in thickness at the 120 ft. isobath. The silty bed predicted at this location extends landward to the 20 m isobath and is composed exclusively of outer-shelf sediment (compare Fig. 8C, D). Morton (1981) collected vibracores to a depth of 20 m at Matagorda Bay (Fig. 9A) and inferred that the uppermost persistent bed was the Carla bed (Fig. 9C). This bed thinned from 20–25 cm near the 10 m isobath to 1–2 cm at the 20 m contour. The hindcast bed within this area (Fig. 8B) is slightly further offshore and is composed of less than 25% sand (Fig. 8D).

Snedden et al. (1988) investigated the area between the previous studies (Fig. 9A) and used all available data to contour the actual Carla sand bed (Fig. 9D). This bed was not predicted within this area except near the storm track (Fig. 8D); however, the finer sediment found further offshore by Snedden et al. was hindcast better (Fig. 8C). As suggested by the poorly predicted storm surge for this region, the lack of significant offshore transport of sand is due to much lower currents than probably existed as landfall approached.

Hurricane Gilbert.—Between 5 and 20 cm of erosion were hindcast along central Louisiana (Fig. 10A), with scour increasing to greater than 100 cm at the Mexican



border. Erosion was restricted to the outer shelf, however, because of bottom-friction damping of storm waves in shallow water. The predicted deposition of 5 to 20 cm of mixed sediment on the inner shelf from Matagorda Bay to Corpus Christi (Fig. 10B) comprised silt (Fig. 10C) and shoreface sand (Fig. 10D), with only silty mud found on the outer shelf from Matagorda Bay to Corpus Christi (Fig. 10C). More than 50 cm of almost pure sand was hindcast for the shelf edge north of the Mexican border (Fig. 10D), having been transported offshore along a 50 km path. Predicted sediments on the Mexican shelf consist almost entirely of silty mud (Fig. 10C) which had been transported locally at low angles towards the coast (Fig. 5B).

Tropical Storm Delia.—Predicted erosion landward of the 40 m isobath during Delia was limited to 20 to 35 cm at isolated locations with a maximum of more than 35 cm on the outer shelf (Fig. 11A), coinciding with steep modeled u_* gradients (Fig. 6D). Less than half of the model bed was deposited on this scour surface (compare Fig. 11A, B). The predicted bed thickness ranges from 1 to 10 cm over much of the Louisiana shelf seaward of the 20 m isobath and is composed of outer shelf mud (Fig. 11C) which was transported as much as 50 km at a high angle to the coast. More than 30 cm of sand was deposited at Galveston (Fig. 11D) after being eroded from the shoreface by persistent, oblique offshore currents (Fig. 6B). A curvilinear bed, between 10 and 30 cm thick, was predicted from eastern Louisiana to the storm track southeast of Galveston. This bed comprises as much as 80% sand near the coast, with silt increasing offshore to more than 50% by volume at the mud line. The sand within it originated at the shoreface and inner shelf, whereas the silt was transported as far as 75 km parallel to isobaths by the coastal current system.

DISCUSSION

The Structure of Storm Currents

The prevailing model of event bed deposition, herein called the geostropic model, assumes that water depths over the continental shelf are sufficient to allow separate upper and lower Ekman friction layers to develop. Thus, most of the shelf is assumed to lie within the geostrophic zone rather than the friction-dominated zone (Swift and Niedoroda 1985). Because of leftward veering within the lower friction layer, the geostrophic model predicts oblique offshore flow at the bottom (e.g., Swift et al. 1981; Cacchione and Drake 1982; Swift et al. 1986b; Cacchione et al. 1987) which could transport sediment from the shoreface and inner shelf, at depths of 10 to 20 m, to the middle and outer shelf (Morton 1988; Snedden et al. 1988).

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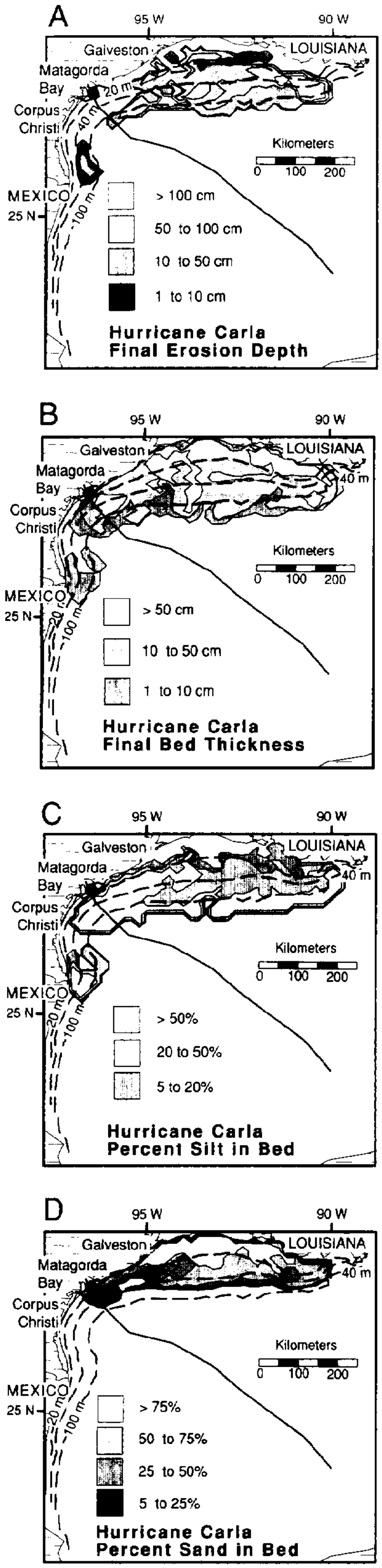
FIG. 7.—Predicted event bed properties for Hurricane Audrey. **A)** Final erosion depth (total depth of scour into the original sea floor). **B)** Final event bed thickness. **C)** Volumetric percent silt within the bed. **D)** Volumetric percent sand within the bed. The location of the eye is indicated by the tropical storm symbol.



Although several studies have collected current meter data during hurricanes at lower latitudes (Murray 1970; Forristall et al. 1977; Smith 1978, 1982), the data are ambiguous as a test of the geostrophic model of event bed deposition. Other data collected from the continental shelf at various water depths during extratropical storms at higher latitudes may not be applicable to tropical cyclones because of different magnitudes and patterns for wind stresses, and the increased Coriolis force at higher latitudes.

The numerical results of this study are more consistent with an alternative model for storm currents on the continental shelf wherein slab-like flows are driven by the wind stress and pressure gradient (Forristall 1974; Morton 1981; Gordon 1982). Slab flows arise because the upper and lower Ekman layers overlap and prevent the development of a rotated current structure within these friction layers. In the present study, calculated Ekman depths were greater than 50 m within the area directly beneath the cyclones. Thus, most of the shelf fell within the friction-dominated or transition zones. This explains why our hindcast sediment transport is predominantly along-shelf. Note, however, that the coarser sediment was predicted to move offshore. This occurred because of bottom friction which created leftward veering in lower model levels for most shallow grid points.

Sedimentation Patterns

The response to a hurricane passing directly over a wide, shallow shelf is partly controlled by the sea-floor gradient, as suggested by the Hurricane Audrey hindcast. Small cross-shelf depth changes reduced the effects of potential-vorticity conservation (see Swift and Niedoroda 1985), and model currents could more easily develop a cross-shelf component. Significant erosion occurred where wave heights were greatest (compare Figs. 3C and 7A); however, because of the poorly constrained flow and greater bottom friction, the hindcast sediment transport paths were often at angles to the coast and located to the right side of the storm (Fig. 12A). Predicted sedimentation along the coast consisted of sand. The modeled flow field was along-shelf from right to left at intermediate water depths, and primarily fine material was transported towards the storm track. In deeper water, mud was transported along oblique onshore paths.

Hurricane Carla approached the wide, shallow Louisiana shelf obliquely, but model-computed u_* magnitudes were no higher than those for Audrey (compare Figs. 3D and 4D). Along the Louisiana shelf, the sedimentation pattern is very similar to that of Audrey (Figs. 7 and 8). However, the extensive and long-lasting shelf flows

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FIG. 8.—Predicted event bed properties for Hurricane Carla. **A)** Final erosion depth (total depth of scour into the original sea floor). **B)** Final event bed thickness. **C)** Volumetric percent silt within the bed. **D)** Volumetric percent sand within the bed. The location of the eye is indicated by the tropical storm symbol.

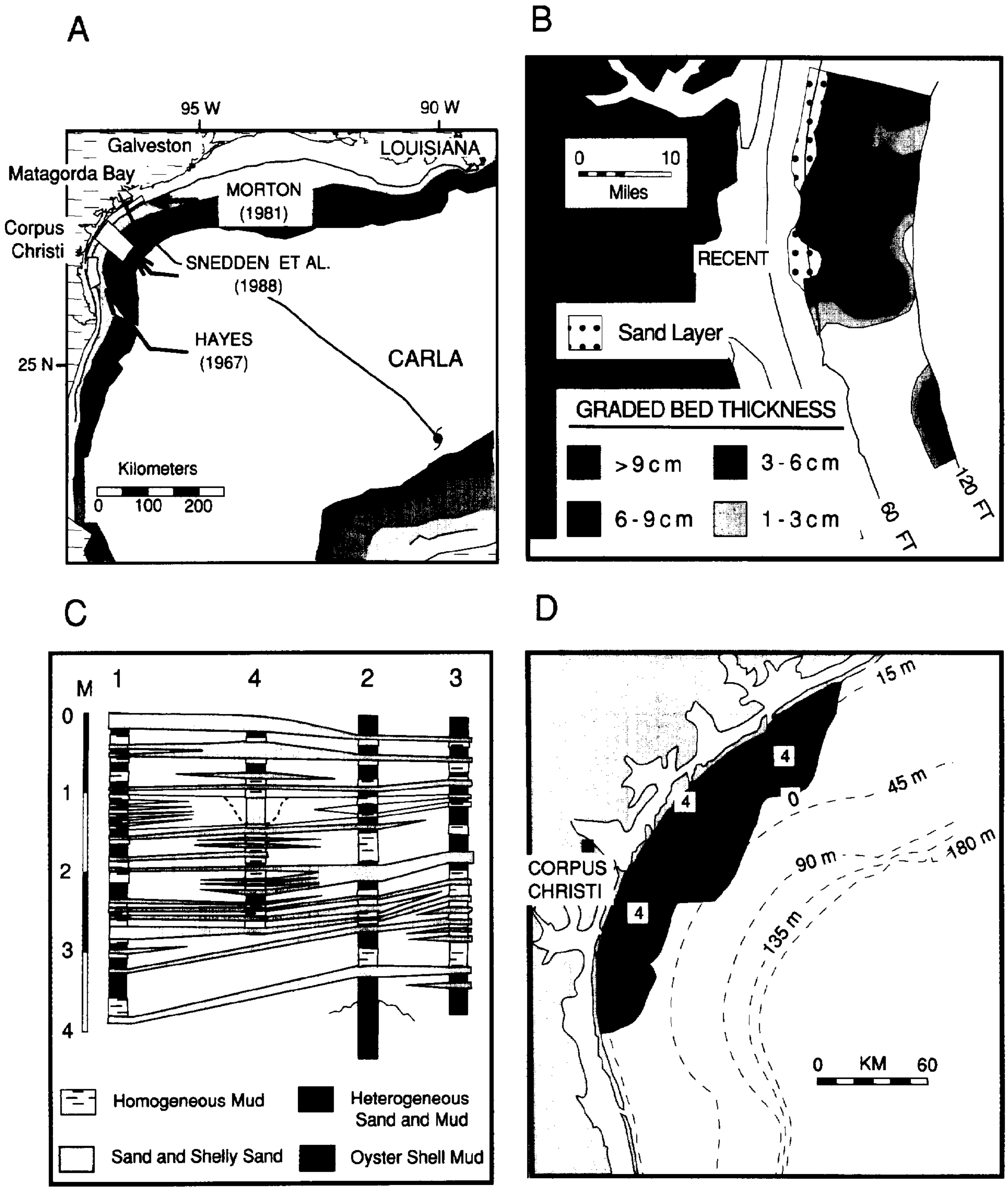

FIG. 9.—Summary of observed properties of the Carla bed. **A)** Location of previous field study areas on the central Texas shelf. The present model study area is bounded by the map edges. **B)** Contour map of sediments deposited over the inner shelf at Laguna Madre, Texas. The map shows the graded bed and the sand layer (see legend for details). The contour interval is in centimeters. Note that bathymetry is in feet and the horizontal scale in miles (from Hayes 1967). **C)** Lithologic units preserved in vibracores from the inner shelf. Core 1 was from the southern end of the study area, and 4, 2, and 3 were spaced evenly between the 10 and 20 m isobaths (from Morton 1981). **D)** Contour map of the Carla sand bed. Contour interval is 2 cm. The dashed line indicates areas where post-storm reworking has removed the bed (from Snedden et al. 1988).

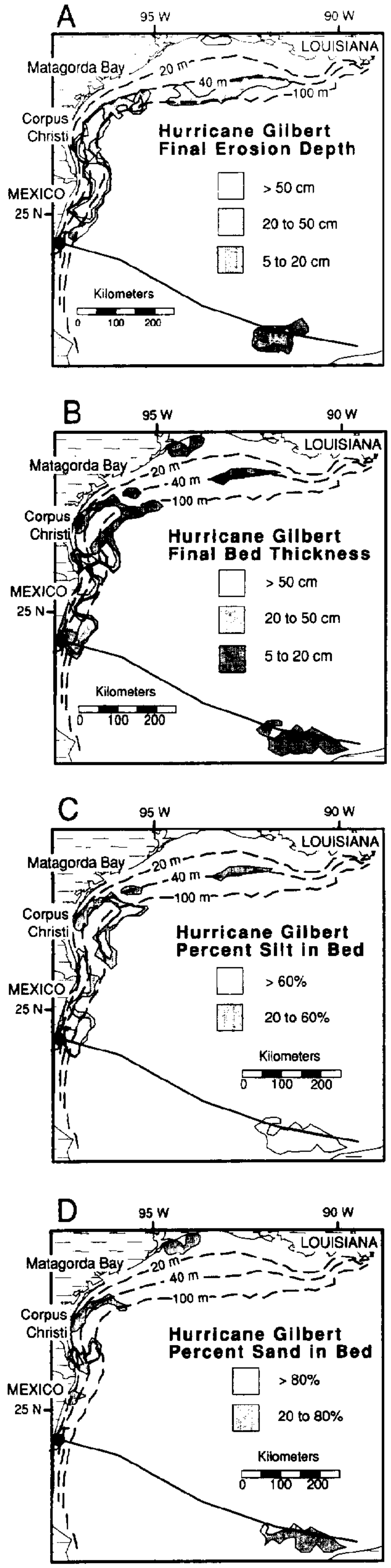

FIG. 10.—Predicted event bed properties for Hurricane Gilbert. A) Final erosion depth (total depth of scour into the original sea floor). B) Final event bed thickness. C) Volumetric percent silt within the bed. D) Volumetric percent sand within the bed. The location of the eye is indicated by the tropical storm symbol.

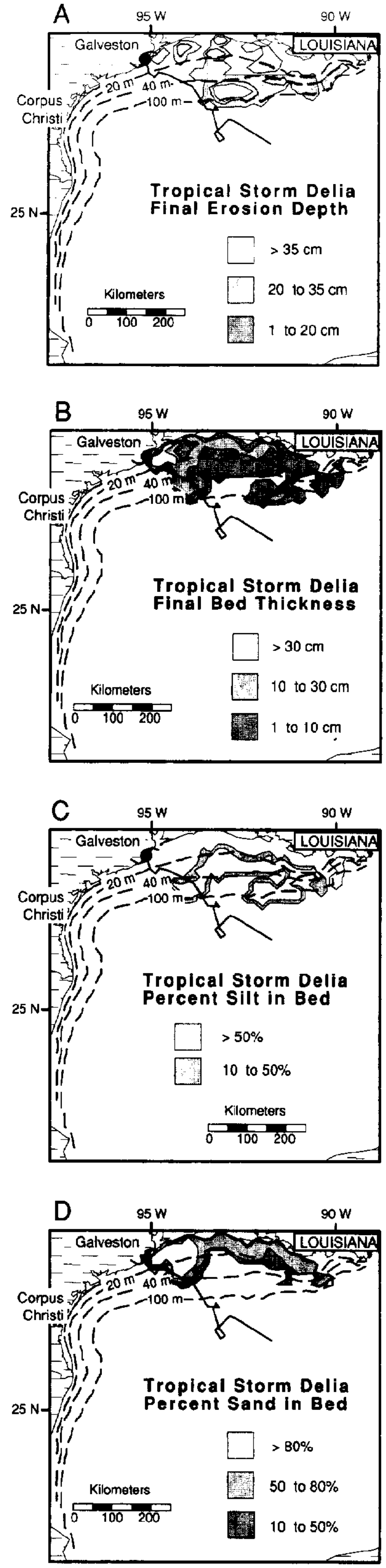

FIG. 11.—Predicted event bed properties for Tropical Storm Delia. A) Final erosion depth (total depth of scour into the original sea floor). B) Final event bed thickness. C) Volumetric percent silt within the bed. D) Volumetric percent sand within the bed. The location of the eye is indicated by the tropical storm symbol.

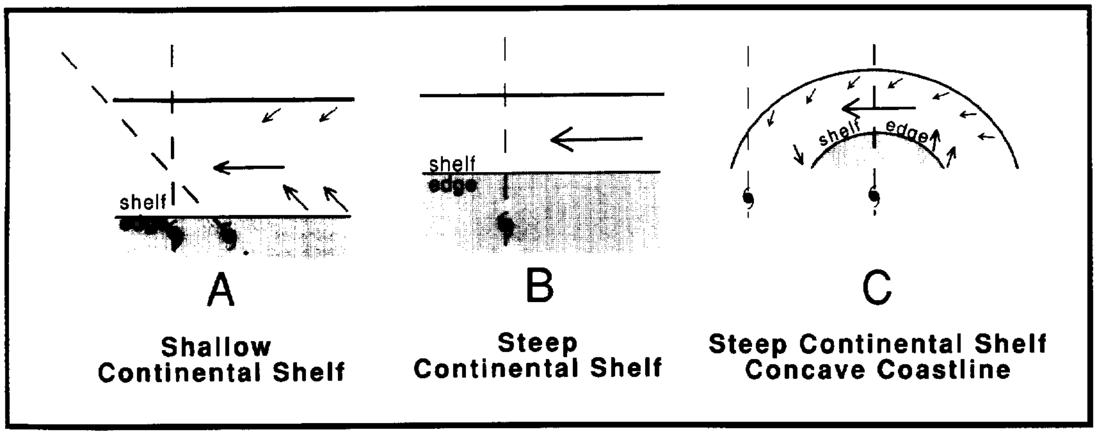

FIG. 12.—Schematic suspended sediment transport paths. **A)** Transport paths for a shallow continental shelf with orthogonal and oblique storm paths (dashed lines). **B)** A steep continental shelf produces simple, along-shelf transport to the right of the storm path. **C)** Transport paths for a concave coastline experiencing a storm that tracks either through the middle or to the left of the basin. The length of the arrows is an indication of the relative volume of sediment transported along each path.

resulted in regionally extensive sedimentation. The transport pattern can be summarized as above (Fig. 12A), with the path represented by the oblique dashed line in the figure.

Hurricane Gilbert struck the straight coastline of northern Mexico where the continental shelf sea-floor gradient is 10^{-3}. Because of the steep sea floor, cross-shelf current components were reduced and extensive along-shelf transport paths were predicted, bounded by weak onshore and offshore flow to the right and left of the storm path, respectively. High storm waves over the outer shelf produced higher computed peak shear velocities and greater maximum scour than for the Louisiana shelf (compare Figs. 7A and 10A). Fine-grained sediment eroded from the outer shelf was transported along-shelf with localized oblique onshore and offshore transport (Fig. 12B).

Hurricane Carla approached the concave Louisiana–Texas coast perpendicularly, and the hindcast sedimentation pattern was the most complex among these numerical experiments. A complete transport cell was predicted, containing onshore, offshore, and alongshore transport components (Fig. 12C). Fine-grained sediments were carried landward to the far right of the storm path with a general westward decrease (Fig. 8D). Coastal setup along the Texas coast was responsible for the removal of shoreface sand to water depths less than 20 m (Fig. 8D). This modeled process may represent the prototype mechanism responsible for the observed Carla bed. The distribution of silt in the predicted Carla bed (Fig. 8C) indicates preferential transport of finer sediment along the shelf. Finally, sand was transported offshore to the far left of the storm path. The transport paths predicted for Carla (Fig. 12C) are also seen in the numerical results for Gilbert off Texas.

The coastal current system predicted for a weaker storm such as Delia was similar in plan to that of larger storms, reflecting as it did the cyclonic wind field. However, because of its path and the match between the hindcast wind field (Fig. 2D) and coastal configuration, coastal setup for Delia was disproportionately greater (Fig. 6A). This was reflected in the higher magnitudes of coastal currents (Fig. 6B) which were sufficient to remove sand from the shoreface to the inner shelf at Galveston (compare Fig. 10A and D).

The preceding discussion has highlighted the preeminence of coastal geometry in governing sedimentation paths during tropical cyclones. This influence can be seen at an even finer scale in the following example. A small promontory south of Galveston connects two lengths of coastline with different sea-floor gradients, western Louisiana and south Texas. This convexity caused the modeled storm surge to attain maximum heights at Galveston for all of these storms (Figs. 3A, 4A, 5A, and 6A). The resulting pressure gradient drove persistent offshore currents (Figs. 3B, 5B, 6B, and 6B). These currents were strong enough that, despite the lower waves over the inner shelf, significant transport of sand occurred, and all simulations of storms with a westward component of motion produced a sandy bed at Galveston (Figs. 8, 10, and 11). The change in sea-floor gradient produced convergence of inner and outer shelf currents, with concurrent mixing of inner and outer shelf sediments predicted seaward of the 20 m isobath for Carla (Fig. 8C, D) and Delia (Fig. 11C, D). Inner shelf sand was transported offshore by pressure-driven currents, whereas finer outer shelf sediments were transported along-shelf to the west by wind-driven currents.

CONCLUSIONS

The coastal circulation pattern predicted by these hindcasts is different from that predicted by the mid-latitude geostrophic model. In these experiments the upper and lower friction layers overlap, thereby minimizing coastal downwelling. Flow at all depths is along shore over much of the continental shelf because of the increased depth of the wind-mixed layer for tropical-storm strength winds and the decrease in the Coriolis force at low latitude.

These hindcasts reveal several features common to the ideal storm transport system. Storm-driven coastal current systems (cells) incorporate onshore flow to the right of the storm path (the up-coast end of a cell with the observer facing the coast), offshore flow at the down-coast end of a cell, and along-shelf flow from right to left within a cell. The development of a cell depends on storm strength, coastal curvature (concavities and convexities), and sea-floor gradient. Outer shelf mud is transported landward at the up-coast end of a cell. Along the central part of a cell, sediment transport paths are predominantly isobathic at intermediate water depths, slightly offshore adjacent to the coast, and slightly onshore at the shelf edge, depending on the local sea-floor gradient. Shoreface and inner-shelf sand are transported seaward at the down-coast end.

Coastal configuration and storm strength determine the extent to which this ideal coastal cell will develop. Straight, steep shelves show primarily longshore transport. Straight, shallow shelves also experience onshore transport in deep water and offshore transport over the inner shelf. Concave coastlines contain all the components of an ideal cell. Complete cells also result from oblique approach of a storm. The primary effect of storm strength appears to be a reduction in the size of the transport cell for weaker storms.

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REFERENCES

BOUMA, A.H., BERRYHILL, H.L., KNEBEL, H.J., AND BRENNER, R.I., 1982, Continental shelf, *in* Scholle, P.A. and Darwin, S., eds., Sandstone Depositional Environments: American Association of Petroleum Geologists, 410 p.

BRENCHLEY, P.J., 1985, Storm influenced sandstone beds: Marine Geology, v. 9, p. 369–396.

BRENCHLEY, P.J., ROMANO, M., AND GUTTIERREZ MARCO, J.C., 1986, Proximal and distal hummocky cross-stratified facies on a wide Ordovician shelf in Iberia, *in* Knight, R.J. and McLean, J.R., eds., Shelf Sands and Sandstones: Canadian Society of Petroleum Geologists, Memoir No. 11, p. 241–256.

BROOKS, D.A., 1983, The wake of Hurricane Allen in the western Gulf of Mexico: Journal of Physical Oceanography, v. 13, p. 117–129.

CACCHIONE, D.A. AND DRAKE, D.E., 1982, Measurements of storm-generated bottom stress on the continental shelf: Journal of Geophysical Research, v. 87, p. 1952–1960.

CACCHIONE, D.A., GRANT, W.D., DRAKE, D.E., AND GLENN, S.M., 1987, Storm-dominated bottom boundary layer dynamics on the northern California continental shelf: measurements and predictions: Journal of Geophysical Research, v. 92, p. 1817–1827.

CLARK, G.B., 1988, Preliminary report, Hurricane Gilbert 08–19 September 1988: National Hurricane Center, National Oceanic and Atmospheric Administration, 8 p.

CURRAY, J.R., 1960, Sediments and history of Holocene transgression, continental shelf, northwest Gulf of Mexico, *in* Shepard, F.P. and van Andel, T.H., eds., Recent Sediments, Northwest Gulf of Mexico: American Association of Petroleum Geologists, p. 221–266.

DOTT, R.H. AND BOURGEOIS, J., 1982, Hummocky stratification: significance of its variable bedding sequences: Geological Society of America Bulletin, v. 93, p. 663–680.

DUKE, W.L., 1985, Hummocky cross-stratification, tropical hurricanes, and intense winter storms: Sedimentology, v. 32, p. 167–194.

DUKE, W.L., ARNOTT, R.W.C., AND CHEEL, R.J., 1991, Shelf sandstones and hummocky cross-stratification: new insights on a stormy debate: Geology, v. 19, p. 625–628.

FIGUEIREDO, A.G., JR., SANDERS, J.E., AND SWIFT, D.J.P., 1982, Storm-graded layers on inner continental shelves; Examples from southern Brazil and the Atlantic coast of the central United States: Sedimentary Geology, v. 31, p. 171–190.

FORRISTALL, G.Z., 1974, Three-dimensional structure of storm-generated currents: Journal of Geophysical Research, v. 79, p. 2721–2729.

FORRISTALL, G.Z., HAMILTON, R.C., AND CARDONE, V.J., 1977, Continental shelf currents in Tropical Storm Delia: observations and theory: Journal of Physical Oceanography, v. 7, p. 532–546.

GAGAN, M.K., CHIVAS, A.R., AND HERCZAG, A.L., 1990, Shelf-wide erosion, deposition, and suspended sediment transport during Cyclone Winifred, central Great Barrier Reef, Australia: Journal of Sedimentary Petrology, v. 60, p. 456–470.

GLENN, S.M. AND GRANT, W.D., 1987, A suspended sediment stratification correction for combined wave and current flows: Journal of Geophysical Research, v. 92, p. 8244–8264.

GORDON, R.L., 1982, Coastal ocean current response to storm winds: Journal of Geophysical Research, v. 87, p. 1939–1951.

GRABER, H.C., AND MADSEN, O.S., 1988, A finite-depth wind-wave model. Part I. Model description Journal of Physical Oceanography, v. 18, p. 1465–1483.

HARMS, J.C., SOUTHARD, J.B., AND WALKER, R.G., 1982, Structures and sequences in layered rocks: SEPM, Short Course No. 9, 175 p.

HARRIS, D.L., 1958, Meteorological aspects of storm surge generation: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 84, Paper No. 1859, 25 p.

HARRIS, D.L., 1963, Characteristics of the hurricane storm surge: U.S. Department of Commerce, Weather Bureau, Technical Paper No. 48, 136 p.

HAYES, M.O., 1967, Hurricanes as geological agents: case studies of Hurricanes Carla, 1961, and Cindy, 1963: Texas Bureau of Economic Geology, Report of Investigations No. 61, 54 p.

ICHIYE, T., 1972, Circulation changes caused by hurricanes, *in* Capurro, L.R.A. and Reid, J.L., eds., Contributions on the Physical Oceanography of the Gulf of Mexico: Houston, Gulf Publishing, p. 229–257.

KEEN, T.R., 1992, A three-dimensional numerical investigation of storm event bed genesis on the Texas-Louisiana continental shelf [unpublished Ph.D. dissertation]: The Pennsylvania State University, 361 p.

KEEN, T.R. AND SLINGERLAND, R.L., 1993, A numerical study of sediment transport and event bed genesis during Tropical Storm Delia: Journal of Geophysical Research, in press.

KUMAR, N. AND SANDERS, J.E., 1976, Characteristics of shoreface storm deposits: modern and ancient examples: Journal of Sedimentary Petrology, v. 46, p. 145–162.

LECKIE, D.A. AND KRYSTINIK, L.F., 1989, Is there evidence for geostrophic currents preserved in the sedimentary record of inner to middle-shelf deposits?: Journal of Sedimentary Petrology, v. 59, p. 862–870.

LEENDERTSE, J.J. AND LIU, S.K., 1975, A three-dimensional model for estuaries and coastal seas. Volume II. Aspects of computation: Rand Report No. R-1764-OWRT.

LEENDERTSE, J.J. AND LIU, S.K., 1977, A three-dimensional model for estuaries and coastal seas. Volume IV. Turbulent energy computation: Rand Report. No. R-2187-OWRT.

LEENDERTSE, J.J., ALEXANDER, R.C., AND LIU, S.K., 1973, A three-dimensional model for estuaries and coastal seas. Volume I. Principles of computation: Rand Report No. R-1417-OWRR.

MORTON, R.A., 1981, Formation of storm deposits by wind-forced currents in the Gulf of Mexico and the North Sea, *in* Nio, S.D., Shuttenhelm, R.T.E., and vanWeering, Tj.C.E., eds., Holocene Marine Sedimentation in the North Sea Basin: International Association of Sedimentologists, Special Publication No. 5, p. 385–396.

MORTON, R.A., 1988, Nearshore responses to great storms: Geological Society of America, Special Paper No. 229, p. 7–22.

MORTON, R.A. AND WINKER, C.D., 1979, Distribution and significance of coarse biogenic and clastic deposits on the Texas inner shelf: Gulf Coast Association of Geological Societies Transactions, v. 29, p. 136–146.

MURRAY, S.P., 1970, Bottom currents near the coast during Hurricane Camille: Journal of Geophysical Research, v. 75, p. 4579–4582.

NELSON, C.H., 1982, Modern shallow-water graded sand layers from storm surges, Bering shelf: a mimic of Bouma sequences and turbidite systems: Journal of Sedimentary Petrology, v. 52, p. 537–545.

NUMMEDAL, D. AND SNEDDEN, J.W., 1987, Sediment exchange between the shoreface and continental shelf—evidence from the modern Texas coast and the rock record: Coastal Sediments '87, p. 2110–2125.

POND, S. AND PICKARD, G.L., 1983, Introductory Dynamical Oceanography: New York, Pergammon Press, 329 p.

PRICE, J.F., 1981, Upper ocean response to a hurricane: Journal of Physical Oceanography, v. 11, p. 153–175.

SEILACHER, A., 1982, General remarks about event deposits, *in* Einsele, G. and Seilacher, A., eds., Cyclic and Event Stratification: New York, Springer-Verlag, p. 161–174.

SMITH, N.P., 1978, Longshore currents on the fringe of Hurricane Anita: Journal of Geophysical Research, v. 83, p. 6047–6051.

SMITH, N.P., 1982, Response of Florida Atlantic waters to Hurricane David: Journal of Geophysical Research, v. 87, p. 2007–2016.

SNEDDEN, J.W. AND NUMMEDAL, D., 1990, Coherence of surf zone and shelf current flow on the Texas (U.S.A.) coastal margin: implications for interpretation of paleo-current measurements in ancient coastal sequences: Sedimentary Geology, v. 67, p. 221–236.

SNEDDEN, J.W., NUMMEDAL, D., AND AMOS, A.F., 1988, Storm- and fair-weather combined flow on the central Texas continental shelf: Journal of Sedimentary Petrology, v. 58, p. 580–595.

SOUTHARD, J.B., LAMBIE, J.M., FEDERICO, D.C., PILE, H.T., AND WEIDMAN, C.R., 1990, Experiments on bed configurations in fine sands under bidirectional purely oscillatory flow, and the origin of hummocky cross-stratification: Journal of Sedimentary Petrology, v. 90, p. 1–17.

SWIFT, D.J.P. AND NIEDORODA, A., 1985, Fluid and sediment dynamics on continental shelves, *in* Tillman, R.W., Swift, D.J.P., and Walker, R.G., eds., Shelf Sands and Sandstone Reservoirs: SEPM Short Course No. 13, p. 47–132.

SWIFT, D.J.P., YOUNG, R.A., CLARKE, T.L., VINCENT, C.E., NIEDORODA, A., AND LESHT, B., 1981, Sediment transport in the Middle Atlantic Bight of North America: synopsis of recent observations, *in* Nio, S.D., Shuttenhelm, R.T.E., and vanWeering, Tj.C.E., eds., Holocene Marine Sedimentation in the North Sea Basin: International Association of Sedimentologists, Special Publication No. 5, p. 361–383.

SWIFT, D.J.P., HAN, G., AND VINCENT, C.E., 1986a, Fluid processes and sea-floor response on a modern storm-dominated shelf: Middle Atlantic shelf of North America. Part I. The storm current regime, *in* Knight, RJ. and McLean, J.R., eds., Shelf Sands and Sandstone Reservoirs: Canadian Society of Petroleum Geologists, Memoir No. 11, p. 99–119.

SWIFT, D.J.P., THORNE, J.A., AND OERTEL, G.F., 1986b, Fluid processes and sea-floor response on a modern storm-dominated shelf: Middle Atlantic shelf of North America. Part II. Response of the shelf floor, *in* Knight, RJ. and McLean, J.R., eds., Shelf Sands and Sandstone Reservoirs: Canadian Society of Petroleum Geologists, Memoir No. 11, p. 191–211.

SWIFT, D.J.P., HUDELSON, P.M., BRENNER, R.L., AND THOMPSON, P., 1987, Shelf construction in a foreland basin: storm beds, shelf sand bodies, and shelf-slope sequences in the Upper Cretaceous Mesaverde Group, Book Cliffs, Utah: Sedimentology, v. 34, p. 423–457.

VAN NIEKERK, A., VOGEL, K.R., SLINGERLAND, R.L., AND BRIDGE, J.S., 1992, Routing of heterogeneous size-density sediments over a movable stream bed: Model development: Journal of Hydraulic Engineering, v. 118, no. 2, p. 246–262.

VOGEL, K.R., VAN NIEKERK, A., SLINGERLAND, R.L., AND BRIDGE, J.S., 1992, Routing of heterogeneous size-density sediments over a movable stream bed: model verification: Journal of Hydraulic Engineering, v. 118, no. 2, p. 263–279.

WALKER, R.G., 1984, Shelf and shallow marine sands, *in* Walker, R.G., ed., Facies Models: Geological Association of Canada Reprint Series 1, Kitchener, Ontario, Canada, Ainsworth Press Limited, p. 141–170.