Morphological Impacts of Extreme Storms on Sandy Beaches and Barriers

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ABSTRACT


Historical extreme storms that struck the Gulf Coast and Atlantic Coast regions of the United States caused several different styles of morphological response and resulted in a wide range of washover penetration distances. The post-storm erosional responses included dune scarp, channel incisions, and washouts, whereas depositional responses included perched fans, washover terraces, and sheetwash lineations. Maximum inland extent of washover penetration ranged from approximately 100 to 1000 m and estimated sediment volumes associated with these deposits ranged from about 10 to 225 m³/m of beach. Unusual styles of morphological response (sheetwash lineations and incised channels) and maximum washover penetration distances are closely correlated, and they also correspond to storm intensity as defined by the Saffir-Simpson wind-speed scale.

The regional morphological responses and washover penetration distances are controlled primarily by the interactions among heights and durations of storm surge relative to adjacent land elevations, differences in water levels between the ocean and adjacent lagoon, constructive and destructive interference of storm waves, and alongshore variations in nearshore bathymetry. For barrier segments that are entirely submerged during the storm, impacts can be enhanced by the combined influences of shallow water depths and organized flow within the wind field. The greatest washover penetrations and sediment accumulations are products of shallow water, confined flow, and high wind stress.

Transport and deposition of washover sediments across barrier islands and into the adjacent lagoon are common processes along the Gulf of Mexico but not along the western Atlantic Ocean. This fundamental difference in storm impact underscores how microtidal and mesotidal barriers respond respectively to extreme storms, and provides insight into how different types of barrier islands will likely respond to future extreme storms and to a relative rise in sea level.

ADDITIONAL INDEX WORDS: Washover, sediment transport, hurricane, extra-tropical storm, wind stress.

INTRODUCTION

The large, rapid changes in coastal landscapes caused by extreme storms have long captured the attention of geological observers. For example, the flooding, beach erosion, and resulting property damage from the 1938 hurricane in New England were so profound that several reports were published describing the same event (BROWN, 1939; HOWARD, 1939; NICHOLS and MARSTEN, 1939; WILBY et al., 1939). In the past few decades there have been many investigations of the impacts of individual mid-latitude storms in the U.S. (e.g. HAYES, 1967; WRIGHT et al., 1970; DOLAN and GODFREY, 1973; LEATHERMAN et al., 1977; NUMMEDAL et al., 1980; KAHN and ROBERTS, 1982; MORTON and PAINe, 1985; STONE and WANG, 1999 among others), and entire volumes have been dedicated to the diverse geological and biological effects of recent extreme storms (FINKL and PILKEY, 1991; STONE and FINKL, 1995).

Washover deposits are one of the most commonly observed depositional responses to extreme storm events. Consequently, hundreds of papers have been published on such topics as washover processes, textural grading and stratification of washover deposits, beach erosion and overwash potential, and the role of overwash in the aggradation and lateral migration of barrier islands (see previous lists of references). The wealth of post-storm data provides an opportunity to synthesize the regional impacts of extreme coastal storms, and to develop a basis for further understanding the physical conditions that produced the morphological changes.

OBJECTIVES AND METHODS

The primary purposes of this study were to document morphological impacts of extreme storms in the Gulf of Mexico and western Atlantic Ocean and to evaluate ground and flow conditions that influence washover penetration distances, styles of washover deposition, and the associated sediment volumes stored in these nearly ubiquitous coastal features. To meet these objectives, post-storm aerial photographs were used to classify the types of morphological impacts and to measure washover penetration for the shores (Figure 1) impacted by Hurricanes Carla (1961), Camille (1969), Frederic (1979), Alicia (1983), and Hugo (1989), and the Ash Wednesday storm (an extreme Atlantic northeaster in 1962). Washover penetration on aerial photographs was measured inland from the beach scarp or berm crest for the extreme storms
identified in Table 1, except for the measurements in coastal Louisiana, which were calculated from data reported by Ritchie and Penland (1990). The Louisiana data were included to compare washover penetration for low-intensity hurricanes with washover penetration for more intense storms. The thicknesses of washover sediments deposited by Hurricanes Carla, Alicia, and Gilbert were measured in the field to estimate the volumes of sediment deposited onshore (Table 2) and rapidly removed from the littoral system.

**MORPHOLOGICAL RESPONSES TO EXTREME STORMS**

The erosional and depositional responses observed on post-storm photographs and in the field included dune scarps, channel incision, and washout, and construction of perched fans, washover terraces, and sheetwash lineations (Figure 2). Terms for the erosional features (scarps and channels Figures 2A and 2B) are well established, but those for washout and the depositional features may require brief definitions. Morton (2002) presented photographs illustrating each of the different morphological responses.

Washout involves channel erosion across the beach and foredunes (Figure 2C) as a result of floodwaters flowing from the lagoon to the ocean. The term washout is used because the process is opposite to that of overwash (Morton and Paine, 1985). This relatively rare phenomenon occurs where the lagoon is higher than the ocean and also higher than the foredunes (El Ashty and Wanless, 1968; Pierce, 1970; Wright et al., 1977).

Table 1. *Minimum, maximum, and mean washover penetration distances for the areas most affected by selected storms. Hurricane intensity at landfall from the National Hurricane Center; intensity of the 1962 storm from Dolan and Davis (1992).*

<table>
<thead>
<tr>
<th>Storm and Year</th>
<th>Intensity Category</th>
<th>Location</th>
<th>Number of Measurements</th>
<th>Range (m)</th>
<th>Mean (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962 northeaster</td>
<td>5</td>
<td>U.S. mid Atlantic coast</td>
<td>200</td>
<td>123–750</td>
<td>287</td>
</tr>
<tr>
<td>Hur. Camille (1969)</td>
<td>5</td>
<td>Gulf Islands, MS</td>
<td>30</td>
<td>82–752</td>
<td>220</td>
</tr>
<tr>
<td>1985 hurricanes</td>
<td>1</td>
<td>Caminada, LA</td>
<td>84</td>
<td>15–226</td>
<td>114</td>
</tr>
<tr>
<td>Hur. Hugo (1989)</td>
<td>4</td>
<td>Central and eastern SC</td>
<td>134</td>
<td>15–204</td>
<td>83</td>
</tr>
</tbody>
</table>
Perched fans (Figure 2D) are small lobate to elongate washover features that are oriented perpendicular to the shore. The fans can be either isolated or regularly spaced alongshore. Isolated fans are constructed when wave runup superimposed on the storm surge exceeds the lowest dune elevations, but elsewhere the surge is blocked by higher dune elevations. Most studies of washover deposits on the Atlantic Coast of the U.S. are of small isolated perched fans (Schwartz, 1975; Deery and Howard, 1977; Leatherman et al., 1977; Kochel and Dolan, 1986; Leatherman and Zaremba, 1987). Morphological criteria that favor construction of regularly spaced fans include a narrow barrier island, low dunes, and minor alongshore differences between dune gaps and dune crests. At some locations, perched fans are so closely spaced that they merge to form a washover terrace (Morton, 2002).

Washover terraces (Figure 2E) are elongate deposits oriented parallel to the shore (Schwartz, 1975; Morton and Paine, 1985). Terraces form where land elevations are relatively uniform alongshore and lower than the maximum storm surge. They may form a uniformly wide band, or their landward margins may be highly irregular, depending on the interactions between breaking waves and currents during washover deposition.

Sheetwash involves laterally unconfined flow where sediment transport is continuous across the barrier island. Sheetwash may result in either deposition of sand eroded from the adjacent beach/dune system or redistribution of sand eroded locally. Common bedforms resulting from sheetwash are narrow elongate zones of erosion and deposition that form alignments parallel to the direction of flow (Figure 2F).

### WASHOVER PENETRATION AND VARIABLE ALONGSHORE PATTERNS

#### Washover Penetration Distances

Washover penetration distances associated with the extreme storms span at least two orders of magnitude and approach one kilometer (Table 1, Figures 3–5). Sallenger et al. (in press) also reported that sand bodies of the Isle Dernieres in Louisiana migrated about 1 km during Hurricane Andrew. The maximum washover penetration for hurricanes occurs in the right-front quadrant at landfall in a zone about 20 to 50 km from the eye (Figures 3 and 4). This alongshore position coincides with the inner eyewall where the highest storm surges and onshore wind velocities typically occur (Simpson and Riehl, 1981). Beyond this first approximation, washover penetration depends on factors other than storm surge elevations. For example, washover penetration away from the eye of Hurricane Camille was generally greater where storm surge elevations were lower (Figure 4), and washover penetration for the March 1962 storm was highly variable despite relatively uniform storm surge elevations (Figure 5). Hurricane Hugo generated a maximum open-coast surge of 5 m near Bulls Bay, South Carolina (Schuck-Kolben, 1990), but high foredunes and forested beach ridges prevented the surge from transporting sand across the nearby barrier islands. However at Myrtle Beach, about 120 km
northeast of the maximum surge, washover sediments were deposited more than 100 m from the shore (Figure 6).

The frequency distributions and averages of washover measurements (Figure 7A and Table 1) show that even extreme storms, such as Hurricanes Carla, Camille, Hugo, and Frederic and the 1962 Ash Wednesday storm, cause different levels of impact. The greatest average washover penetration (425 m) was associated with Hurricane Frederic because it overtopped the entire western two-thirds of Dauphin Island. Average washover penetration for the 1962 storm (287 m) was only slightly greater than average penetration for Camille (220 m) but the number of sites where penetration exceeded 300 m was substantially greater for the 1962 storm than for any of the other storms (Figure 7A). By comparison, washover penetration was relatively low for Hurricane Hugo, which caused less than 100 m of washover penetration at most sites (Figure 7A). Hurricane Carla caused greater than 600 m of washover penetration at more sites than any other storm, however, most of Carla’s washover penetration was less than 300 m (Figure 7A).

Combining the washover penetration data for all seven storms provides a basis for estimating the potential washover impact for an extreme storm that falls within the intensity range of those studied (categories 3–5). The combined data show a progressive decrease in probability as penetration distances increase (Figure 7B). The function that best fits the data roughly describes an exponential decline curve. Washover penetration of at least 100 m has a probability of 67%, whereas there is a 50% chance of at least 160 m of washover penetration. Penetration distances of at least 200 m have a probability of about 42% and washover penetration greater than 400 m has a probability of less than 10% (Figure 7B). These results for both Gulf Coast and Atlantic Coast settings are consistent with the general observations of Leatherman (1983), who concluded that Atlantic Coast barriers less than 200 m wide should be overwashed frequently.

Different storms can generate similar patterns of washover penetration along the same coastal segment even though the actual penetration distances may differ from storm to storm. This was demonstrated by Ritchie and Penland (1990) who compared the impacts of three hurricanes in 1985 that caused extensive washover of the Caminada deltaic headland in Louisiana (Figure 8). The washover penetrations for storms before 1978 and combined effects of Hurricanes Danny, Elena, and Juan in 1985 were greatest along the beach separating Bay Champagne from the Gulf of Mexico and least where the
Figure 3. Maximum washover penetration and storm surge elevations in areas of Texas most impacted by Hurricane Carla (1961). General location shown in Figure 1.

Figure 4. Maximum washover penetration and storm surge elevation in the areas of Mississippi and Alabama most impacted by Hurricane Camille (1969). General location shown in Figure 1.
Figure 5. Maximum washover penetration and storm surge elevations in areas along the Atlantic Coast most impacted by the March 1962 northeaster. General location shown in Figure 1.

Figure 6. Maximum washover penetration and storm surge elevations in the areas of greatest impact from Hurricane Hugo (1989) along the coast of South Carolina. General location shown in Figure 1.
nals across the barriers (Figure 2B). Hurricanes Camille and Frederic also caused repeated morphological changes on west Dauphin Island, even though the peak surge during Frederic (3.6 m) was higher than during Camille (2.8 m). Camille constructed regularly spaced perched fans between sheetwash lineations to the east and washover terraces to the west (Figure 4). Hurricane Frederic (Figure 9) caused essentially the same styles of washover response as Camille. The sheetwash lineations produced by Frederic were laterally more extensive than those produced by Camille, but their positions and construction between washover terraces were the same for both storms.

The most common responses for the March 1962 northeaster and Hurricane Hugo along the Atlantic Coast were either washover terrace construction or dune erosion. For both storms, washover penetration was greatest across the ends of low-lying spits near inlets or across narrow barrier segments that were subjected to sheetwash (Figures 4 and 5). HOSIER and CLEARY (1977) presented maps showing where Hurricane Hazel (1954) and the March 1962 storm repeatedly constructed washover terraces and perched fans at the same locations on Masonboro Island, NC.

**INFLUENCES OF TOPOGRAPHY, WATER DEPTH, AND WIND STRESS**

**Topography, Bathymetry, and Flow Depth**

Topography plays an important role in controlling washover penetration and washover patterns. Low, relatively uniform backbeach elevations promote unconfined flow and construction of washover terraces or sheetwash deposits (Figures 2E and 2F), whereas highly irregular backbeach elevations promote confined flow and construction of individual perched fans or excavation of subtidal washover channel and fan complexes (Figures 2D and 2B). Less certain are the influences of nearshore bathymetry, overwash flow depth, and proximity to open water on these same parameters.

Overwash flow depth determines the water column available for current generation and inland sediment transport. Overland flow depths were approximated for Hurricane Carla by subtracting the highest dune elevations (contoured on USGS 1:24,000 topographic maps) from the maximum open-coast storm surge elevations (field surveys by the Corps of Engineers). Comparing washover penetration with estimated flow depths for Carla (Figure 10A) shows a reasonably close correlation between the two parameters where washover terraces were deposited, but the trend reversed where flow depths decreased dramatically and the morphological response was incised channels. Although there is considerable scatter in the paired data (Figure 10B), the trends suggest that washover penetration was directly proportional to flow depth up to about 350 m and 2.5 m respectively, but greater inland penetration of washover deposition depended on an inverse relationship associated with shallower flow depths. This relationship suggests that a third factor was responsible for the enhanced sediment penetration distances in the zone of channel incision. Field observations indicate that the subtidal depths of erosion in the channels were at least 1 m. A better correlation between washover penetration and flow
Figure 8. Sequential comparison of washover penetration along a rapidly retreating shore of the Mississippi delta in southcentral Louisiana. Modified from Ritchie and Penland (1990). Storms of variable intensity and track produce similar patterns of washover penetration.

Figure 9. Graph showing the influence of bathymetry on washover penetration distances and morphologies of washover sediments deposited on Dauphin Island, Alabama by Hurricane Frederic.
Elevations are generally 2 to 3 m and the maximum open-coast surge during Hurricane Camille was about 2.8 m, consequently flow depths during the storm were extremely shallow across most of the barrier. The washover styles on Dauphin Island produced by Hurricane Camille (Figure 4) gradually changed westward from closely-spaced lineations, to perched fans, to a washover terrace with irregular landward margin, to a washover terrace with a uniform landward margin. These morphological changes coincided with the alongshore trends of nearshore shoaling and differences in overwash flow depths. High dunes and the ebb-tidal delta protect the eastern end of Dauphin Island from storm waves and prevent overwash (NUMMEDAL et al., 1980). To the west where island orientation changes and dunes are substantially lower, bathymetric gradients are steeper, and deeper water is close to the shore (see distance to offshore bar in Figure 9). The deeper water waves produce greater washover penetration in the zone of shoreline reorientation. Because barrier elevations decrease to the west, overwash flow depths generally increase in the same direction (Figure 9), which also contributed to the westward change from perched fans to a washover terrace.

The styles and alongshore patterns of storm impacts on Dauphin Island were essentially the same for Camille and Frederic, but the inland sediment transport distances were much greater for Frederic (compare Figures 4 and 9), reflecting the greater flow depths. Both storms produced sheetwash lineations where the barrier is narrow, dunes are uniformly low, and the shoreface is moderately steep. Minor differences in flow depths may have also contributed to the contrasting styles of washover response. Dauphin Island has a history of being breached repeatedly (HARDIN et al., 1976) and the sheetwash lineations formed where breaching previously occurred. A wave refraction analysis by NUMMEDAL et al. (1980) showed that the zone of prior breaching was also the zone of bathymetric wave focussing and highest wave energy. The washover terraces, on the other hand, formed where the island core was slightly higher and flow depths were slightly shallower. The alongshore changes in washover morphologies also reflect the flow structure in the washover currents. The sheetwash lineations were formed by highly organized streamlines of shore-normal currents that probably were generated by wind stress, whereas the terrace deposits were formed by shore-parallel fronts of breaking waves that produced essentially uniform shore-normal flow.

The influence of overland flow and distance to open water (large-scale surface roughness) on washover penetration can be illustrated for Hurricane Carla (Figure 3), the 1985 hurricanes (Figure 8), and the March 1962 northeaster (Figure 12). In all of these examples washover penetration generally increases where the ocean is close to inland water (narrow barrier), and penetration decreases where the land is wider and surface friction is greater. DOLAN and HAYDEN (1981) reported that washover penetration from the March 1962 storm correlated well with average decadal rates of shoreline movement. Although shoreline movement can be an indicator of washover potential, the significance of the correlation has to do with the fact that shoreline movement commonly correlates directly with dune construction. Dune construction is
Figure 11. Comparison of A. alongshore variations in flow depth and washover penetration for Hurricane Carla (1961), and B. plot of flow depth and washover penetration data pairs. Flow depth represents the difference between surge height and estimated land elevation adjusted for scour by incised channels.

minimized or prevented along beach segments that are eroding rapidly, whereas dune construction is facilitated where the beach is stable or accreting slowly. The distances of washover deposition presented by DOLAN and HAYDEN (1981) correlate equally well with the width of adjacent backbarrier marsh and proximity to open water (Figure 12).

The plots of washover penetration (Figures 3–6) exhibit two primary scales of variability. The large first-order scaling appears to be related to overland flow distances and proximity to open water as described in the preceding paragraphs. The smaller secondary scaling is related to morphology of the washover deposits, which is partly determined by constructive and destructive wave-to-wave interference that enhance and suppress washover fan construction. Where shoals and storm waves combine to produce peak breaker heights the beach segments commonly experience the greatest beach erosion and overwash (NUMMEDAL et al., 1980). CARTER and ORFORD (1981) suggested that zones of washover on a coarse-grained barrier in Ireland correlated closely with areas of wave convergence and attendant increased breaker heights. ORFORD and CARTER (1982) also speculated that edge waves produced the closely-spaced washover channels. Although other studies have attempted to link the spacing of wave-runup maxima with edge waves, there are no field data for storm conditions that support the edge wave hypothesis for washover channel construction.

Wind Stress and Sediment-Bypass Distances

Wind stress can augment overwash processes by accelerating currents and generating water velocities that otherwise would not be obtained by wave runup alone. The greatest enhancement of flow velocity occurs when the wind direction and the angle of wave approach are both directed onshore. These optimum conditions frequently occur in the Gulf of Mexico during the landfall of hurricanes that track at high angles to the shore (MORTON, 1979). On the other hand the maximums winds of extreme northeasters commonly blow parallel to the shore and reduce the coupling between wind and the water flowing over land.

Where breaking waves and runup are the predominant current-generating processes, the washover sediments are deposited immediately landward of the berm, erosional scarp, or foredunes. However, in those cases where high wind stress is the driving force, there commonly is a zone landward of the backbeach across which sediments are transported, but deposition is either absent or minor (MORTON, 1979). This bypass zone separates the washover deposits from the topographically high areas adjacent to the backbeach. Onshore
Figure 13. Variations in sediment bypass along the 120 km of Texas shore most impacted by Hurricane Carla. Compare with Figures 4 and 11A.

sediment transport and minor local reworking characterize the zones of sediment bypass, which coincide with areas of maximum storm surge and highest wind speeds.

Wind-driven currents during Hurricane Carla (category 4) transported sediment 400 to 550 m inland from the beach (Figure 13) before surface roughness decelerated the flow and initiated deposition. The striking effects of wind stress also were observed on Dauphin Island after Hurricanes Camille (category 5) and Frederic (strong category 3). Frederic constructed sheetwash lineations, flame-shaped fans with narrow levee-like margins, a narrow bypass zone, and a few incised channels. The surface lineations observed after Hurricanes Carla, Camille, and Frederic are comparable to the flow-aligned patterns of ridges and intervening troughs produced experimentally as a result of unstable pulsating flow (KARCZ and KERSEY, 1980). Although the shore-normal alignment and close spacing of sheetwash lineations argue for high velocity flow generated by wind stress, there are no surface wind data available to directly support that interpretation. Furthermore, the coarse temporal and spatial scaling of storm wind observations, and time averaging methods of analysis (POWELL, 1982), prevent close correlation between the observed morphological patterns and the interpreted surface wind structure.

Morphological changes caused by extreme coastal storms typically have spatial scales of 10s to 100s of meters and they are nearly instantaneous events (minutes to hours) because the non-cohesive sediments respond rapidly to the high water velocities. This fine-scale resolution cannot be compared directly with the widely spaced sites used to reconstruct the horizontal low-level hurricane wind fields, but there is evidence from the wind field analyses and wind damage surveys at the sedimentological scales of interest. Some hurricanes are characterized by alongshore velocity gradients that produce an inner eyewall and an outer secondary maximum in wind velocity farther from the eye (SIMPSON and RIEHL, 1981). Some of the alongshore variations in washover morphologies could be related to the reported alongshore variability in wind speed and direction at hurricane landfall. The most detailed near-surface wind field reconstructions come from the orientations and distributions of blown down trees and structural debris. After Hurricane Andrew, Fujita (1992) and Wakimoto and Black (1993) reported organized patterns of damage with length scales of a few hundred meters caused by microscale vorticity. Further evidence of the fine-scale high velocity coupling between wind and water is provided by photographs of the sea surface during Hurricane Eloise, which show linear foam streaks that are aligned with the surface wind (Powell, 1982).

**WASHOVER SEDIMENT VOLUMES**

Thicknesses and widths of washover deposits are rarely reported because the deposits are typically large and the field measurements can be highly variable. Consequently, there is a general lack of information regarding volumes of sediment transported inland of the beach and deposited during extreme storms. The few published data for washover volumes (Table 2) are mostly single, generalized values without any indication of alongshore or crossshore variability. Therefore, it is unknown how representative these data are in terms of washover sediment volumes.

Table 2 suggests that normalized washover volumes of a few 10s of m$^3$/m of beach are common, whereas sediment volumes of more than 100 m$^3$/m of beach are rare. The largest normalized sediment volumes are associated with confined flow where landward sediment transport is laterally restricted by higher elevations either as a result of channel incision or breaching of the dune complex. Furthermore, the largest sediment volumes are related to the broad areas covered by washover deposition, rather than great thicknesses of the deposits.

Few attempts have been made to estimate the total volume of sediment removed from the active beach and dune system by an extreme storm and stored as washover deposits. Morten and Paine (1985) used field measurements at 62 sites to characterize washover volume along the 30-km segment of Galveston Island most affected by Hurricane Alicia. They reported that thicknesses of Alicia terrace deposits ranged from 2 to 69 cm and averaged about 23 cm. The total volume of Alicia washover sediments deposited on west Galveston Island was approximately 184,000 m$^3$, or only about 12% of the total volume of sediment eroded from the adjacent beaches and dunes.

Both erosional and depositional impacts of Hurricane Carla are well preserved along the southeastern Texas coast where they still can be observed more than 40 years after the storm. Measurements on post-storm aerial photographs indicate that washover deposits covered about 18.4 million m$^2$ along the 200-km stretch most impacted by Carla. Field measurements at six representative sites show that thicknesses of Carla proximal washover deposits ranged from 60 to 126 cm, whereas distal deposits associated with the flame-shaped fans were relatively uniform in thickness (26–31 cm). Using the minimum (26 cm) and average (56 cm) washover thick-
nesses to estimate total washover sediment volume, between 4.8 and 10.3 million m³ of sand and shell were stripped from the beaches and dunes by Hurricane Carla in a few hours. Considering the moderate wave energy of the Texas coast, instantaneous losses from the sediment budget of that magnitude are equivalent to many years of net longshore sediment transport.

There should be a high correlation between the type of storm impact and the percent volume of sediment eroded from the beaches and dunes that is transported onshore and stored in washover deposits. Where the morphological response is erosion of a dune scarp, 100% of the eroded sediment is transported alongshore or offshore and no sediment (0%) is transported onshore (Figure 2A). Washover terrace deposits constructed where Hurricane Alicia partly inundated Galveston Island represented only about 12% of the total volume of sediment eroded from the adjacent beaches and dunes (Morton and Paine, 1985). But where Santa Rosa Island, Florida was completely inundated during Hurricane Opal, 95–99% of the sand eroded from the beach and dunes was conserved in the washover terrace and sheetwash deposits (Stone et al., 1996). These data indicate that the volume of eroded sediment that moves beyond the berm crest or dunes as washover sediment progressively increases from the perched fans (small percent) to the washover terraces, and to the sheetwash deposits that can account for most of the sediment in a mass balance between beach/dune erosion and washover deposition.

DISCUSSION AND CONCLUSIONS

The regional morphological impacts of seven extreme storms were analyzed to compare impact responses and patterns of washover penetration for beaches and barriers of the Atlantic and Gulf Coasts of the United States. These analyses indicate correlations among storm intensity, morphological storm impacts, and inland sediment transport distances associated with overwash. There is no overwash and inland sediment transport when the storm response is strictly beach and dune erosion, but sand transport tends to progressively increase with greater morphological impacts associated with overwash and complete inundation of the landscape. The analyses also indicate that the inland penetrations of washover terraces are typically less than those of perched fans, and perched fan penetrations are typically less than those of sheetwash or incised channels.

Inland sediment transport distances of storm washover can be greatly augmented by shallow water, confined flow, and high wind stress. Normal washover penetration and ground elevation are inversely correlated, but when coupled with wind stress, they can be directly correlated. Under those conditions, slightly higher ground elevations contribute to channel incision, increased flow depths, higher wind-driven flow velocities, and greater inland sediment transport distances.

There are reasonably good qualitative correlations among washover penetration distances, washover styles, and the Saffir-Simpson storm intensity scale, which is defined on the basis of wind speed (Simpson and Riehl, 1981). Average and maximum washover penetration distances (Table 1) indicate that only the most intense storms are capable of transporting sand more than 300 m inland (Figure 7B) for long segments of coast. Hurricanes Camille (category 5), Carla (category 4), and Frederic (strong category 3), and the 1962 northeaster (category 5) all deposited sand more than 300 m from the beach but washover penetration for Hurricane Alicia (weak category 3) and the 1985 Louisiana hurricanes (category 1) was generally less than 125 m from the beach (Figures 7B and 8). Not all extreme storms, however, cause washover penetration > 300 m. High elevations and dense vegetation can limit or prevent washover penetration for even the strongest storms. This happened along the South Carolina coast during Hurricane Hugo (Figures 6 and 7B). In fact the average and maximum washover penetration for the 1985 Louisiana hurricanes (category 1) and Hurricane Hugo (category 4) are very similar (Table 1 and Figure 7B) despite the great differences in storm intensity.

The storms that caused washover penetrations > 300 m (Carla, Camille, Frederic, and the 1962 northeaster), were also the only storms that constructed extensive areas of either sheetwash lineations or incised channels (Figures 3, 4, 5, and 9). Washover penetration distances > 300 m were generally associated with the sheetwash features and incised channels (Figures 3, 4, 5, and 9). Many storms can cause beach and dune erosion, and minor overwash, but only extreme extratropical storms and hurricanes with intensities of category 3 and higher are generally capable of producing geologically preserved regional morphological responses that are associated with complete inundation of the coast. The data also suggest that only category 3 and higher hurricanes have sufficiently well organized wind fields and wind speeds capable of constructing closely-spaced lineations and incising closely-spaced channels across barrier islands (Figures 3, 4, 5, and 9).

Determining accurate thicknesses and volumes of storm deposits for regional sediment budgets are inexact because the deposits exhibit substantial three-dimensional variability that depends on pre-storm topography and overwash flow depths. Thicknesses of washover sediments deposited by a single storm typically range from 1 m to 1.5 m (Table 2). Field observations after Hurricanes Carla, Beulah, Eloise, and Alicia indicate that the thickest storm deposits are associated with washover terraces or fans emerging from incised channels. Normalization of washover sediment volumes on the basis of a unit beach length demonstrates that the largest washover volumes are associated with extensive inland penetrations rather than great thicknesses, and they are deposited by confined flow (Table 2).

The similar patterns of washover penetration regardless of specific storm characteristics (Figure 8 and Morton and Paine, 1985) suggest that some coastal sectors are preconditioned to overwash processes and relative magnitudes of washover penetration. The spatial persistence of washover styles (Dauphin Island Figures 4 and 9) is further evidence of the preconditioning of some coastal segments not just to overwash processes, but to specific morphological responses because of their geological setting. The linkages between onshore storm responses and the offshore geologic framework are poorly understood but there is some evidence that sub-
merged features can influence the onshore impact of storm processes. GAYES (1991) illustrated how coastal processes interacted with coastal development during Hurricane Hugo to construct shallow closely-spaced channels and lineations on the shoreface of South Carolina. Although these were examples of onshore structures influencing offshore processes, the reverse would also be true. Submerged shore-normal channels, scour depressions, hardgrounds, rock ledges and other types of antecedent topography could alter storm wave heights and cause focussing of wave energy. Locally increased wave heights in concert with local variations in backbeach topography are probably responsible for the observed repeated patterns of washover penetration and repeated styles of washover response.

The 1962 northeaster had the greatest potential of any historical storm to cause extensive barrier migration along the Atlantic Coast. This is because the prolonged storm surge eroded the beach, destroyed the dunes, and promoted overwash of long segments of the shore (U.S. ARMY CORPS OF ENGINEERS, 1963). Within the 510 km of storm-impacted coast between New Jersey and North Carolina, no entire barrier island experienced migration as a result of the 1962 storm (MORTON et al., in press). Despite optimum topographic and oceanographic conditions for overwash, only a few barrier segments experienced sheetwash (26 km) or incision of closely-spaced channels (19 km) that conveyed sediment entirely across the barrier (MORTON et al., in press). The most common morphological response to the 1962 storm was deposition of a washover terrace (400 km), which aggraded the barrier islands but did not cause them to become transgressive landforms. The lack of barrier island migration from such an extreme storm is consistent with the observations of LEATHERMAN (1983) who, on the basis of historical morphological studies of Hatteras Island, North Carolina and Fire Island, New York, concluded that most Atlantic coast barriers were either relatively stable narrowing landforms or migrating landforms that move episodically and infrequently as a result of inlet construction.

In the Gulf of Mexico, entire barrier islands have migrated frequently as a result of repeated overwash by hurricanes. Well-documented examples of migrating barriers or barrier segments are South Padre Island and Matagorda Peninsula (Figure 3) in Texas (MORTON, 1994), Isles Dernieres, Timbalier Islands, Breton Islands, and the Chandeleur Islands in Louisiana (PENLAND and BOYD, 1985; KAHN and ROBERTS, 1986), west Dauphin Island (Figure 9) in Alabama (NUMMEDAL et al., 1980), and Santa Rosa Island, FL (STONE et al., 1996). The number of migrating barriers in the Gulf of Mexico is high because many of them are associated with either abandonment and foundering of lobes of the Mississippi delta (PENLAND and BOYD, 1985), or late Quaternary reductions in sediment supply of major coastal plain rivers (MORTON, 1994). Apart from the issues of vertical stability and sediment supply, there appear to be other factors that influence the susceptibility to complete overwash and barrier migration. The microtidal range and relatively low wave energy of the Gulf of Mexico construct backbeach elevations that are generally low (< 1.5 m) compared to the surge elevations of major hurricanes (Carla 3.7 m, Camille 4.9 m, Fig.

ures 3 and 4). In contrast, the mesotidal range and moderate wave energy of the Atlantic Ocean construct backbeach elevations (> 2 m) that are closer to the surge elevations of extreme storms such as the 1962 northeaster (2.4 m, Figure 5) and Hurricane Hugo (5 m, Figure 6). The fundamental differences in storm processes between these two regions underscore how microtidal barriers of the Gulf Coast and mesotidal barriers of the Atlantic Coast respond respectively to extreme storms. These different responses on a historical time scale provide insight into how the different types of barriers will likely respond to future extreme storms and to a relative rise in sea level.

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LITERATURE CITED


