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Sea-Level Rise on the South Carolina Coast: Two Case Studies for 2100

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ABSTRACT

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Over the next century a "greenhouse"-induced sea-level rise (SLR) of 0.25 m to 2.00 m may occur. This SLR, when combined with local vertical movements along coasts, has the potential to cause significant changes in the South Carolina coastline. These changes may occur through the inundation of low-lying coastal areas, increases in erosion rates from increased wave heights and possible increases in tropical cyclone intensities and frequencies.

To explore the potential effects of climate change on the South Carolina coast, four SLR scenarios were applied to two USGS 7.5′ quadrangles (Wampee and Hilton Head, South Carolina). The impacts of SLR were measured in terms of the amount of land that would be lost to the sea permanently (from SLR and local vertical movement) and episodically (from tropical cyclone-induced storm surges) if the current coastline was abandoned and the retreat option taken.

Based on results from the case studies, the following conclusions were drawn: (1) studies on the regional effects of SLR must consider local vertical movement in order to be valid, (2) as sea level rises the relief of coastal areas will decrease, increasing the percentage of land above mean sea level subject to episodic inundation, and (3) as local sea surface temperatures rise, the maximum tropical cyclone-induced surge obtainable along the South Carolina coast will increase, and the probability of a storm occurring may also increase.

ADDITIONAL INDEX WORDS: *Climate change, local vertical movement, sea-level rise, storm surge, tropical cyclones, wave prediction.*

INTRODUCTION

Increases in the global mean air temperature (GMAT) over the last 100 years are associated with a concurrent increase in the concentration of atmospheric "greenhouse" gases (JONES, 1988; HANSEN and LEBEDEFF, 1988; PEARMAN, 1988). These greenhouse gases are transparent to short-wave radiation, but absorb the long-wave energy (*i.e.,* heat) radiating from the Earth into space; this could cause the Earth's GMAT to rise from 1.0 to 5.0 °C in the next century (MITCHELL *et al.,* 1990). A rise in the GMAT of this magnitude is capable of causing large-scale, global climatic change as oceanic and atmospheric circulation patterns are altered and sea levels rise (GABLE and AUBREY, 1990).

The issue of how much oceans will rise is still open to debate, with predicted values ranging from 0.25 to 2.0 m for the year 2100 (SMITH and TIRPAK, 1989; HOUGHTON *et al.,* 1990). Whatever the rise, social, economic, and environmental losses will occur due to the inundation of wetlands and lowlands. A report prepared by the U.S. Environmental Protection Agency for Congress in 1989 (SMITH and TIRPAK, 1989) demonstrated that sea-level rise has the potential to cause drastic changes in the nature and size of wetlands and in the stability of coastal barrier islands (KRAFT *et al.,* 1987; SALLENGER *et al.,* 1987). For example, 25 to 80% of the U.S. coastal wetlands would be at risk from inundation by a 1 m sea-level rise (*i.e.,* 13,000 to 26,000 km^2 of wetlands could be inundated); these losses would be exacerbated as people attempted to protect their property from sea-level rise by building erosion-control structures.

Aside from the destruction of important natural ecosystems through inundation, sea-level rise may increase rates of erosion in coastal lowlands, remove beaches, and most importantly, increase the risk of flooding in coastal areas (TITUS, 1989). Flooding would increase along the coast for sev-

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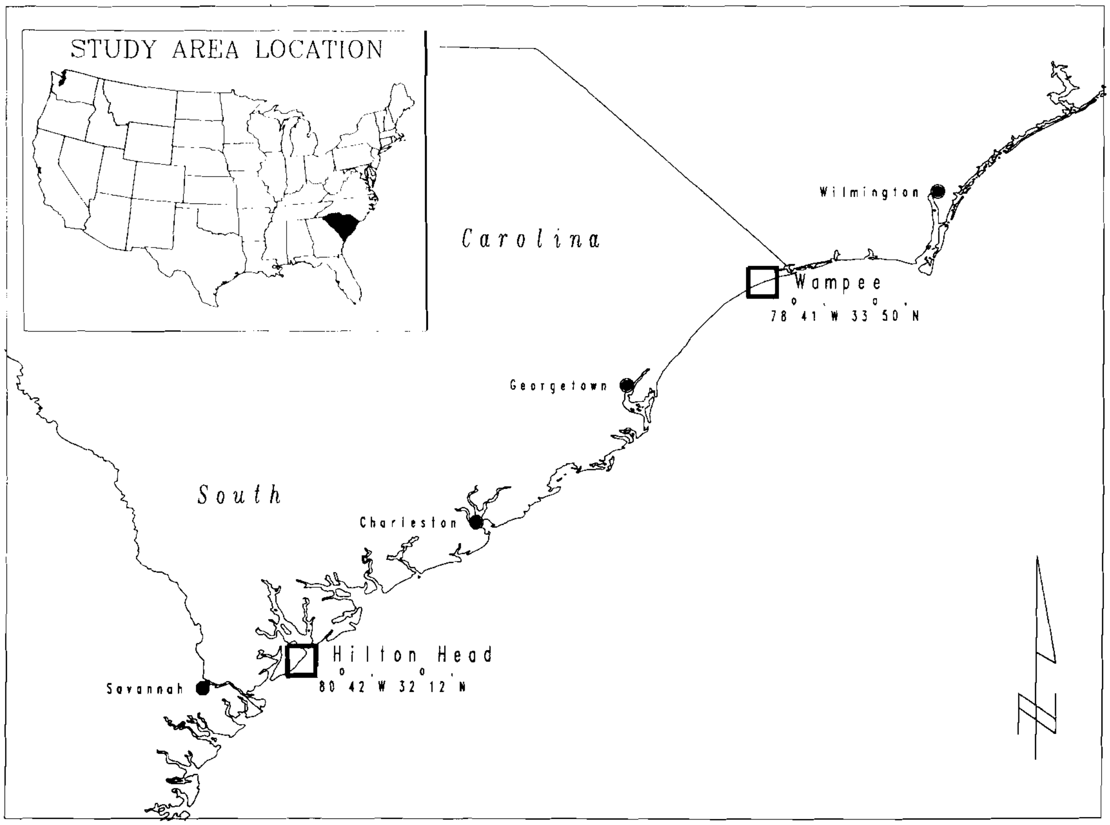

Figure 1. Location of the two study areas on the South Carolina Coast.

eral reasons: (1) a higher sea level would provide a higher base for storm surge buildup, thus enabling a storm that occurs once in 15 years to flood many areas that today are flooded only by storms with recurrence intervals of 100 years or more (LOVE, 1987; LEATHERMAN, 1984); (2) the destruction or overwash of barrier islands by increases in sea level would destroy ocean front properties and leave inland properties vulnerable to storm waves (KRAFT *et al.*, 1987); and (3) higher water levels would reduce coastal drainage gradients. Reductions in these gradients would increase flooding attributable to rainstorms, could promote saltwater intrusion into coastal aquifers, and may force water tables to rise—in some cases emerging at the surface (SMITH and TIRPAK, 1989).

This study quantifies the inland extent of permanent and episodic inundation that may be expected by the year 2100 based on four different sea level rise (SLR) scenarios and three tropical cyclone storm surges if the retreat option to SLR is taken. These scenarios and tropical cyclone storm surges were applied to two 7.5′ USGS quadrangles (Wampee [near North Myrtle Beach] and Hilton Head, South Carolina) and the amount of land that would be permanently and episodically inundated was determined with the aid of a geographic information system (GIS) (Figure 1).

Digital elevation models were used within the GIS to produce figures and tables showing (1) the effects of tropical cyclones on the current coastline, (2) the "new" coastline and the amount of land permanently flooded from SLR and local vertical movement for each scenario, and (3) the amount of land subject to episodic inundation from a minimal tropical storm, minimal hurricane, and the peak surge-producing hurricane under each scenario.

SITE SELECTION

The two study areas selected were initially identified using a coastal vulnerability index developed from tidal, geologic, geomorphic, erosional, and subsidence variables contained within a Global Coastal Hazards Data Base (GORNITZ *et al.*, in press). The index was calculated for the segments that make up the U.S. East Coast (where each segment is approximately 4.5 km long) and the "high-risk" segments identified and mapped for South Carolina, where areas characterized as high-risk have mean coastal reliefs of 0 to 10 m, substrates made of unconsolidated sediments, and erosion rates of over 1.1 m/year (GORNITZ and KANCIRUK, 1989).

From the many areas identified as being at high-risk, two were selected that are representative of the most common coastal landforms in South Carolina (*i.e.*, accretion-type islands and exposed coasts). By selecting these, and possible future study areas, using a set of well-defined criteria, in this case the coastal vulnerability index, it should be possible in the future to draw regional generalizations on the geologic and geomorphic characteristics of areas in danger from SLR—greatly simplifying the risk assessment process (GORNITZ *et al.*, in press).

The two areas selected for study are located within the North Atlantic Geomorphic province. Up-warping within the province has created two major arches and three major basins or embayments on the Atlantic seaboard (MURRAY, 1961). The study areas are located on two of these major formations: the Cape Fear Arch and the Savannah Basin. The Cape Fear Arch is a broad arch or area of relative positive vertical movement. This arch extends for approximately 300 km (190 miles) from Cape Lookout, North Carolina, to Georgetown, South Carolina, and has a shoreline with prominent capes and shoals with cuspate bays (WALKER and COLEMAN, 1987). Wampee, South Carolina, is located within one of these bays and is on an exposed coast (*i.e.*, the area is unprotected by offshore barrier islands). The lack of barrier islands to protect this study area allows storms to directly attack and erode the coast and has resulted in the formation of relatively steep slopes at the study area's seaward edge (*i.e.*, 4%).

The Savannah Basin, in contrast, is an area of relative subsidence that extends from Charleston, South Carolina, southward to Jacksonville, Florida. This basin has a history of sediment accumulation, a process that continues to the present day (MURRAY, 1961). The large amount of sediment available from fluvial sources in the Savannah Basin has allowed for the formation of islands at, and down-current from, river mouths (WALKER and COLEMAN, 1987). The Hilton Head study area is located on a sand island that developed at the mouth of Port Royal Sound. This island developed in a manner similar to that of a barrier island except that barrier islands are relatively long and straight, while river mouth accretion-type islands have multiple ridges, tend to be fan-shaped, and have a handle pointing away or down-current from the river's mouth (WALKER and COLEMAN, 1987). The depositional origin of Hilton Head Island has resulted in its low relief and gentle beach slopes (*i.e.*, 1%).

SEA-LEVEL RISE SCENARIOS

After the two study areas were identified, estimates of future sea surface temperatures and GMAT were obtained for the year 2100 from RIND (1987) and MITCHELL *et al.* (1990). These estimates predict that by 2100 the GMAT will increase by 1.0 to 5.0 °C and that this will occur concurrently with a sea surface temperature rise and a rise in the world's sea levels of 0.25 m to 2.0 meters (RIND, 1987; HOUGHTON *et al.*, 1990).

This association among sea surface temperature, GMAT, and SLR has been hypothesized before (EMANUEL, 1987). However, the ocean acts as a thermal buffer, so that the warming experienced within a region lags the GMAT warming by 25 to 50 years (RAHMSTORF, 1991). The Goddard Institute for Space Studies (GISS) 4° × 5° global circulation model allows for this variation in sea surface temperature warming (by latitude) by taking into account different magnitudes of high-latitude amplification (RIND, 1987). The ocean warming predicted to occur using the GISS model at 30°N to 35°N, the general latitude of our study areas, is in the range 0.8 to 4.1 °C and corresponds to the estimated GMAT increase of 1.0 to 5.0 °C.

The four SLR scenarios used in this study, shown in Table 1, are based on GMAT rises of 1.0, 2.0, 3.5, and 5.0 °C for the year 2100 (MITCHELL *et al.*, 1990). The sea surface temperature rises equated with these four GMAT scenarios were estimated from RIND (1987) who used the GISS global circulation model to estimate the impact that increases in GMAT would have on sea surface temperature gradients. After determining the GMAT and sea surface temperature rises for each scenario, the SLR for each scenario was determined based on extrapolations from current trends (HOFFMAN *et al.*, 1983; HOUGHTON *et al.*, 1990).

The "very low" scenario is based on the as-

Table 1. *Characteristics of sea-level rise scenarios 1, 2, 3, and 4 for the year 2100.*

Scenario	Sea-Level Rise	Global Mean Air Temperature Rise	Sea Surface Temperatures Rise for 30° to 35°N
0. Current	+0.00 m	+0.0 °C	+0.0 °C
1. Very Low	+0.25 m	+1.0 °C	+0.8 °C
*2. Low	+0.50 m	+2.0 °C	+1.6 °C
3. Moderate	+1.25 m	+3.5 °C	+2.9 °C
4. High	+2.00 m	+5.0 °C	+4.1 °C

*Indicates best estimate for sea-level rise

sumption that the current rate of SLR (*i.e.*, 1.0 mm/yr) will quadruple over the next 110 years (GORNITZ and LEBEDEFF, 1987). Based on current expectations, that a tenfold or greater increase in SLR rates will occur by 2100, this scenario may be seen as a lower bound for predicted SLR. The SLR for the "low" scenario is close to the best estimate of 0.66 m for 2100 made by the Intergovernmental Panel on Climate Change (IPCC) for their Business-as-Usual Scenario (HOUGHTON *et al.*, 1990). As such, the "low" scenario should be seen as the most likely of the four SLR scenarios used here, while the "high" scenario contains the maximum SLR increase currently expected (TITUS, 1989).

TROPICAL CYCLONES

Tropical cyclones play an important role in determining the extent to which coastal areas are at risk from episodic inundation and coastal erosion (CRUTCHER and QUAYLE, 1974). Because of this each SLR scenario will consider the effects of the surge produced by the minimal tropical storm, minimal hurricane, and the maximum surge-producing hurricane (Table 2).

The tropical cyclones defined in Table 2 form from clusters of convective clouds that, in the case of the North Atlantic, tend to originate from the Sahelian zone just south of the great Sahara Desert in Africa and to a lesser extent in the Caribbean and Gulf of Mexico (AVILA and CLARK, 1989; GRAY, 1990). Only a small proportion of the clusters that occur throughout the tropics ever develop into tropical cyclones because specific meteorological requirements must be fulfilled (*e.g.*, sea surface temperatures of at least 26 °C, weak vertical windshears over pre-storm clusters, and mean vertical upward winds). Detailed explanations of these requirements may be found in GRAY (1968, 1990), FRANK (1987), HOLLAND *et al.* (1987), and MCBRIDE and ZEHR (1981).

The size of the area over which these formation requirements are met, as well as their duration, provides an indication of the frequency of occurrence and the maximum obtainable intensity of tropical cyclones (GRAY, 1968). Several studies, notably MILLER (1958), FISHER (1958), WENDLAND (1977), NYOUMURA and YAMASHITA (1984), and EMANUEL (1987), have demonstrated this and have found that, in general, after a tropical cyclone has initially formed the sea surface temperature field over which the storm passes provides the best means of evaluating the maximum possible pressure drop near the eye of a storm and the storm's maximum possible intensity. The size of the sea surface temperature field with temperatures >26 °C may also be used to predict the annual frequency of tropical storm and hurricane occurrence in the North Atlantic.

MILLER (1958) developed an empirical relationship between tropical cyclone intensity and sea surface temperature that estimates the maximum possible decrease in surface air pressure (*i.e.*, the MCP) resulting from the saturated ascent of air from the sea surface in the cyclone eye wall, and the descent of dry air in the storm's eye. This relationship has been supported by recent

Table 2. *Definitions and criteria of the tropical cyclones for which storm surges* were calculated.*

Stage of Development	Criteria 1-Minute Sustained Wind Speed	 Minimum Central Air Pressure
Minimum tropical storm	17.5 m/sec	998.25 hPa
Minimum hurricane	33.0 m/sec	947.90 hPa
Maximum surge-producing hurricane	>33.0 m/sec	975.0 to 933.0 hPa[1]

*Storm arrives at the area under study on the critical path and optimum rate of movement that will produce the largest possible storm surge

[1] Minimum central air pressure and wind speed varies based on sea surface temperature

observations. For example, Super Typhoon Tip, the strongest tropical cyclone on record, had a minimum central air pressure (MCP) of 870 hPa versus a predicted pressure of 860 hPa based on the sea surface temperature field of the region (DUNNAVAN and DIERCKS, 1980). The equation developed by MILLER (1958) will be used in this study to predict the MCP of the maximum surge-producing hurricane for each SLR scenario based on the current and predicted sea surface temperature offshore from each study area.

The MCP plays an important role in determining the size of the surge, as surge heights are primarily increased in two ways: (1) as the MCP decreases the resultant force of the atmosphere against the ocean decreases, resulting in an upward expansion of the sea of 1 cm for each 1 hPa drop in air pressure; (2) as the maximum sustained wind speed increases, the wind-stress on the ocean's surface increases, resulting in an increase in wave size (YOUNG, 1988). Unfortunately, for forecasting purposes these parameters are not available, and for hindcasting, the coastal gauges that monitor these variables tend to fail during the extreme events of interest. For those reasons methods have been developed by the U.S. Army Corps of Engineers and the National Oceanic and Atmospheric Administration (NOAA) to predict storm surges based on wind conditions (Department of the Army, 1984; Department of Commerce, 1979).

These methods were used in combination with MILLER'S (1958) empirical relationship to determine the maximum storm surge on the open coast for the three tropical cyclones in each SLR scenario. The forecasting methods are based on the following parameters: the forward speed of the hurricane, the maximum 1-minute sustained wind speed, the radius of maximum wind, the coriolis parameter, and the MCP of the storm (D.O.A., 1984).

Several of these parameters can be estimated based on the MCP of a storm. For example, the maximum 1-minute wind speed and the radius of maximum winds can be determined based on the MCP, the average forward velocity at the point of MCP, and the coriolis parameter (which varies by the latitude of the storm). Thus, to estimate the maximum surge associated with a given storm, only four parameters must be known: the coriolis parameter, the MCP, the maximum sustained 1-minute wind speed, and the forward velocity of the storm at the point of MCP.

Estimating the Maximum Sustained Wind Speed

To derive the storm surge for each tropical cyclone, the wind speed must be known. Several relationships between MCP and maximum sustained 1-minute wind speeds have been empirically derived (ATKINSON and HOLLIDAY, 1977; LOVE, 1987). The relationship used in this study is adopted from an equation developed by the Australian Bureau of Meteorology to predict maximum wind gusts based on a cyclone's MCP (LOVE, 1987). This relationship has been calibrated for the Atlantic basin using published data showing maximum sustained surface wind and equivalent minimum sea-level pressures (PLANTE and GUARD, 1989). The derived equation is of the form:

$$U_r = 2.585 \cdot (1013 - \mathrm{MCP})^{0.7} \qquad (1)$$

where U_r is the maximum 1-minute wind speed, and MCP is the minimum central air pressure of the tropical cyclone.

Estimating Forward Velocity of Movement

When determining the maximum obtainable storm surge for each tropical cyclone, the mean forward velocity of the storm at its maximum intensity will be assumed to be a function of the pressure gradient. This function was developed based on the average forward velocity of all North Atlantic tropical storms and hurricanes at the point when lowest MCP was reached for the period 1970 to 1979. Of the 81 tropical storms and hurricanes that occurred during this period, 75 had sufficient data or records of acceptable length to be used in this analysis. The data for the storms were obtained from NOAA, which operates an extensive tropical cyclone monitoring and tracking network (D.O.C., 1986). These forward velocities were then plotted and the least squares/best fit line derived ($N = 75$, $\alpha < 0.10$, $r^2 = 0.1$):

$$V_f = 0.03 \cdot (1{,}013 - \mathrm{MCP}) + 3.26 \qquad (2)$$

where 1,013 hPa is normal sea level air pressure; MCP is less than or equal to the minimal central pressure of the minimal tropical storm (MCP = 998.25 hPa); 3.26 is the y-intercept that, when evaluated at MCP = 998.25 hPa, gives the optimum forward velocity of a minimal tropical storm; and 0.03, a constant derived to obtain the best-fit line.

Storm Surge and Wave Setup

The measured storm surge of a tropical cyclone is the sum of: (1) upward expansion, brought about by a reduction in surface air pressure; (2) the wave setup, the superelevation of the mean water level caused by waves breaking offshore; (3) the shallow water significant wave height; (4) the tidal deviation from mean sea level; and (5) the wave run-up, the movement of water landward after a wave breaks onshore. For simplicity the contribution of wave run-up to the storm surge is ignored, the astronomical tide will be set to 0.00 m (*i.e.*, mean sea level) and effects of bottom topography are simplified through the use of depth correction factors. The error introduced by this simplification is considerably less than that associated with the climatic parameters that were used in developing the SLR scenarios themselves and should not affect the conclusions drawn from these case studies.

With these simplifications, and the assumptions that the maximum sustained 1-minute wind speed (Eq. 1) and the forward velocity at the time of maximum winds (Eq. 2) are a function of the MCP, the maximum tropical cyclone-induced storm surge becomes relatively easy to solve using the storm surge function in Equation 3.

$$\begin{aligned} \mathrm{SS} = {} & \mathrm{Ex[MCP]} + \mathrm{Ws}[\mathrm{H_m}, \mathrm{V_f}, \mathrm{T_s}, \mathrm{d_b}, \mathrm{g}] \\ & + \mathrm{Hs}[\mathrm{U_r}, \mathrm{Ws}, \mathrm{g}] + \mathrm{At} \end{aligned} \tag{3}$$

where SS is the maximum storm surge on the open coast; Ex is the upward expansion of the ocean from a reduction in air pressure; Ws is the wave setup determined from H_m, the deep water significant wave height, V_f, the storm's forward velocity, T_s, the significant wave period, d_b, the water depth at the breaker point, and g, the acceleration due to gravity; Hs is the significant shallow-water wave height determined from U_r, the maximum sustained 1-minute wind speed, g, and Ws (defined above); and At is the tidal deviation from mean sea level (a detailed explanation of the equations associated with this function are given in D.O.C. [1979] and D.O.A. [1984]).

Modeling the Effects of Tropical Cyclones

In Table 3 the results of the storm surge calculations (Eq. 3) for each study area are shown. The results are the maximum storm surge for each storm in the current climatic state and for each SLR scenario. The storm surges calculated in Table 3 will be combined with the local vertical movement for each study area (*e.g.*, from subsidence or isostatic rebound in each area) and the SLR for each scenario to determine the maximum landward extent of flooding.

Table 3. *Maximum storm surge (SS), expansion (Ex), wave setup (Ws), shallow water significant wave (Hs), and astronomical tide (At) for the minimal tropical storm, minimum hurricane, and maximum potential storm surge at Hilton Head and Wampee, South Carolina (surge at mean sea level).*

Study Area	*SS m =*	*Ex +*	*Ws +*	*Hs +*	*At*
Wampee, South Carolina, present sea level conditions					
Min. T.S.	1.98	0.15	0.39	1.44	0.00
Min. Hurr.	3.24	0.38	0.76	2.10	0.00
Max. Surge	3.54	0.43	0.85	2.25	0.00
SLR scenario					
1. Max. Surge	4.15	0.57	1.05	2.53	0.00
2. Max. Surge	4.53	0.74	1.17	2.62	0.00
3. Max. Surge	4.55	0.80	1.18	2.58	0.00
4. Max. Surge	4.55	0.80	1.18	2.58	0.00
Hilton Head, South Carolina, present sea level conditons					
Min. T.S.	2.02	0.15	0.40	1.48	0.00
Min. Hurr.	3.41	0.38	0.81	2.22	0.00
Max. Surge	3.87	0.46	0.95	2.46	0.00
SLR scenario					
1. Max. Surge	4.52	0.57	1.16	2.76	0.00
2. Max. Surge	4.85	0.77	1.27	2.81	0.00
3. Max. Surge	4.86	0.80	1.27	2.78	0.00
4. Max. Surge	4.86	0.80	1.27	2.78	0.00

Note: "At" at high tide is +0.75 m
T.S.—Tropical Storm
Hurr.—Hurricane

The surge calculated for the minimum tropical storm and hurricane for each scenario is constant by definition (Table 2); however, the surge produced by the maximum surge-producing hurricane is dependent on the MCP of the hurricane (which is dependent on the sea surface temperature field offshore from each study area) and the maximum forward velocity (V_f) of the cyclone.

In the two study areas the mean sea surface temperature used for determining the MCP of the maximum surge-producing hurricane varies for each scenario. In the "moderate" and "high" scenarios the predicted sea surface temperature warming of 2.9 °C and 4.1 °C, when added to the maximum mean monthly sea surface temperatures for Wampee and Hilton Head, South Carolina (*i.e.*, 27.6 °C and 27.8 °C, respectively), are greater than is necessary to produce the maximum obtainable storm surge, which may occur when sea surface temperatures $\geq$ 29.6 °C and MCP = 933 hPa (D.O.C., 1985). Thus, the peak surge-producing hurricanes are constant for the "moderate" and "high" sea-level rise scenarios.

Table 4. *Episodic and permanent land inundation based on current conditions and sea-level rise scenarios 1, 2, 3, and 4 for Wampee, South Carolina (values in hectares).*

Scenario	Permanent Inundation	Episodic Inundation	Total Area (at MSL)	% of Original Area Inundated
Current				
MSL	0.0	—	7,521.3	0
Min. T.S.	0.0	289.0	7,232.3	4
Min. Hurr.	0.0	524.2	6,997.1	7
Max. Surge	0.0	595.4	6,925.9	8
1. Very Low				
SLR[a] + LVM[b]	42.4	—	7,478.5	1
Min. T.S.	42.4	349.3	7,172.0	5
Min. Hurr.	42.4	607.3	6,914.0	8
Max. Surge	42.4	838.1	6,683.2	11
2. Low				
SLR + LVM	75.1	—	7,446.2	1
Min. T.S.	75.1	320.3	7,125.8	5
Min. Hurr.	75.1	600.2	6,846.0	9
Max. Surge	75.1	934.4	6,511.8	13
3. Moderate				
SLR + LVM	176.1	—	7,345.2	2
Min. T.S.	176.1	364.1	6,981.1	7
Min. Hurr.	176.1	685.0	6,660.2	12
Max. Surge	176.1	1,215.0	6,130.2	19
4. High				
SLR + LVM	308.1	—	7,213.2	4
Min. T.S.	308.1	425.4	6,787.8	10
Min. Hurr.	308.1	766.8	6,446.3	14
Max. Surge	308.1	1,603.8	5,609.4	25

[a] SLR—sea-level rise
[b] LVM—local vertical movement

Table 5. *Episodic and permanent land inundation based on current conditions and sea-level rise scenarios 1, 2, 3, and 4 for Hilton Head, South Carolina (values in hectares).*

Scenario	Permanent Inundation	Episodic Inundation	Total Area (at MSL)	% of Original Area Inundated
Current				
MSL	0.0	—	5,092.1	0
Min. T.S.	0.0	913.3	4,178.8	18
Min. Hurr.	0.0	2,405.4	2,686.7	47
Max. Hurr.	0.0	2,925.2	2,166.9	58
1. Very low				
SLR[a] + LVM[b]	151.1	—	4,941.0	3
Min. T.S.	151.1	1,319.6	3,772.5	26
Min. Hurr.	151.1	2,936.9	2,155.2	58
Max. Hurr.	151.1	4,081.8	1,010.2	80
2. Low				
SLR + LVM	238.2	—	4,853.9	5
Min. T.S.	238.2	1,343.5	3,510.4	31
Min. Hurr.	238.2	2,961.6	1,892.3	63
Max. Hurr.	238.2	4,365.3	488.6	90
3. Moderate				
SLR + LVM	560.1	—	4,531.9	11
Min. T.S.	560.1	1,935.7	2,596.2	49
Min. Hurr.	560.1	3,405.4	1,126.6	78
Max. Hurr.	560.1	4,455.7	76.3	99
4. High				
SLR + LVM	1,076.7	—	4,015.4	21
Min. T.S.	1,076.7	2,237.8	1,777.7	65
Min. Hurr.	1,076.7	3,570.9	444.6	91
Max. Hurr.	1,076.7	4,010.0	5.5	100

[a] SLR—sea-level rise
[b] LVM—local vertical movement

Case Study 1: Wampee, South Carolina

A sampling of transects at 1 km intervals along the coastline of the study area obtained an average beach slope of 4% (used in determining the wave setup), and an examination of tidal gauge records of stations (*e.g.*, Wilmington, North Carolina) that are located on the Cape Fear Arch were used to estimate the relative sea-level rise of the study area (*i.e.*, +1.8 mm/year from 1936 to 1983) (Pugh *et al.*, 1987). When the effects of eustatic SLR, 1.0 mm/year (Gornitz and Lebedeff, 1987), for the past century were subtracted from this value, a local vertical movement of −0.8 mm/year, or −0.09 m by the year 2100 (*i.e.*, 110 years from present), was obtained.

After calculating the average beach slope (4%), local vertical movement (−0.09 m), and the mean September sea surface temperature of the study area [*i.e.*, 27.66 °C—obtained from the Department of Commerce, *Comprehensive Ocean-Atmospheric Data Set* (COADS) (1985)], the amount of land that is vulnerable to both permanent flooding (from SLR and local vertical movement) and to episodic flooding (from storm surges) was calculated and is shown in Table 4. For comparison, the effects of the minimal tropical storm, minimal hurricane, and maximum surge-producing hurricane on the study area in the current climatic state are also shown. Figures 2, 3, and 4 depict the current, "low", and "high" SLR scenarios. These figures show the "new" coastline for each SLR and storm scenario for the year 2100.

The effects of SLR on the Wampee study area are limited due to the stabilized dunes that overlook the ocean along this portion of the South Carolina coast. The relatively steep slope of this coastline will limit the loss of land to the sea. However, as the stabilized dunes begin to be di-

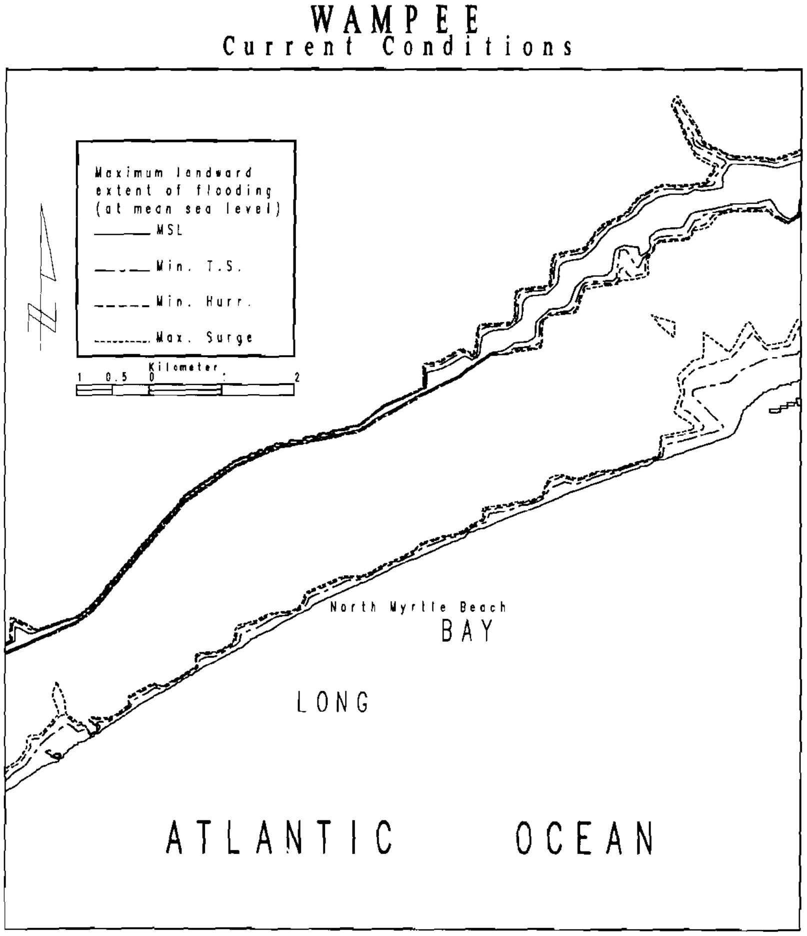

Figure 2. Wampee, South Carolina, coastlines produced under current climatic conditions for each tropical cyclone.

rectly attacked by ocean waves, which will occur as the sea rises, the dunes will tend to erode landward (Bruun, 1962). Although the actual loss of land in this study area will be minimal (*e.g.*, under the "very low", "low", "moderate", and "high" SLR scenarios, 3.3, 5.9, 13.7, and 24.1 ha of land were lost per 1 km of coastline), the attractiveness of living near the sea has resulted in the establishment of several large communities, such as North Myrtle Beach, on the stabilized dunes. Thus, these towns are in danger of being undermined by erosion, causing significant monetary losses, from even the "low" SLR scenario.

Case Study 2: Hilton Head, South Carolina

A sampling of transects along the coastline of the study area obtained an average beach slope of 1% (used in determining the wave setup), and an examination of tidal gauge station records at Savannah, Georgia, obtained a relative sea level change of +3.0 mm/year from 1935–1986 (Pugh *et al.*, 1987). When the effects of eustatic SLR (*i.e.*, +1.0 mm/year) for the past century were subtracted from this value, a local vertical movement of −2.0 mm/year, or −0.22 m by the year 2100, was obtained (Gornitz and Lebedeff, 1987).

After calculating the average beach slope (1%), local vertical movement (−0.22 m), and mean September sea surface temperature (27.81 °C) for the study area, the amount of land that is vulnerable to both permanent flooding (from SLR and local vertical movement) and to episodic flooding (from storm surges) was determined and is shown in Table 5. For comparison purposes the

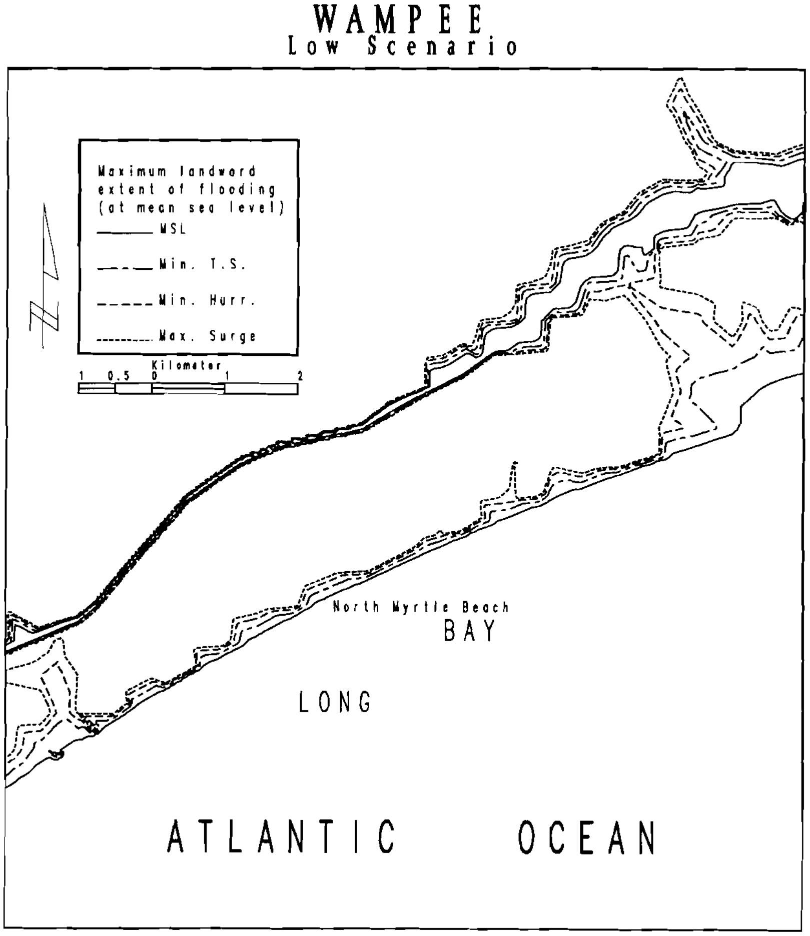

Figure 3. Wampee, South Carolina, coastlines produced with sea-level rise scenario 2, and three tropical cyclones.

effects of the minimal tropical storm, minimal hurricane, and maximum surge-producing hurricane in the current climatic state have also been calculated. Figures 5, 6, and 7 graphically depict the "new" coastline for the study area under the current, "low", and "high" scenarios for the year 2100.

For each scenario the amount of land that would be lost per kilometer of coastline has been calculated. For the "very low", "low", "moderate", and "high" scenarios a loss of 9.2, 14.4, 34.0, and 65.2 ha/km of coastline were obtained, respectively. These losses are approximately 2.4 times greater than those experienced in the Wampee, South Carolina, study area for each scenario and indicate how vulnerable acccretion-type islands, and Hilton Head Island in particular, are to the threat of SLR.

For example, based on the digital elevation model used in this study, Hilton Head, South Carolina, will lose 3 to 21% of its total area to SLR by the year 2100. This coastal erosion will be exacerbated by the fact that the low dunes that overlook the beaches along this portion of the South Carolina coast will be unable to retreat inland as sea level rises because the area behind the first dune has been extensively developed. Thus, the relatively shallow slope of the coast will result in significant loss of land to the sea as beaches erode and larger waves break onshore (Bruun, 1988).

TROPICAL CYCLONE FREQUENCIES

The violent intensity of the tropical cyclones modeled here makes it desirable to derive tropical

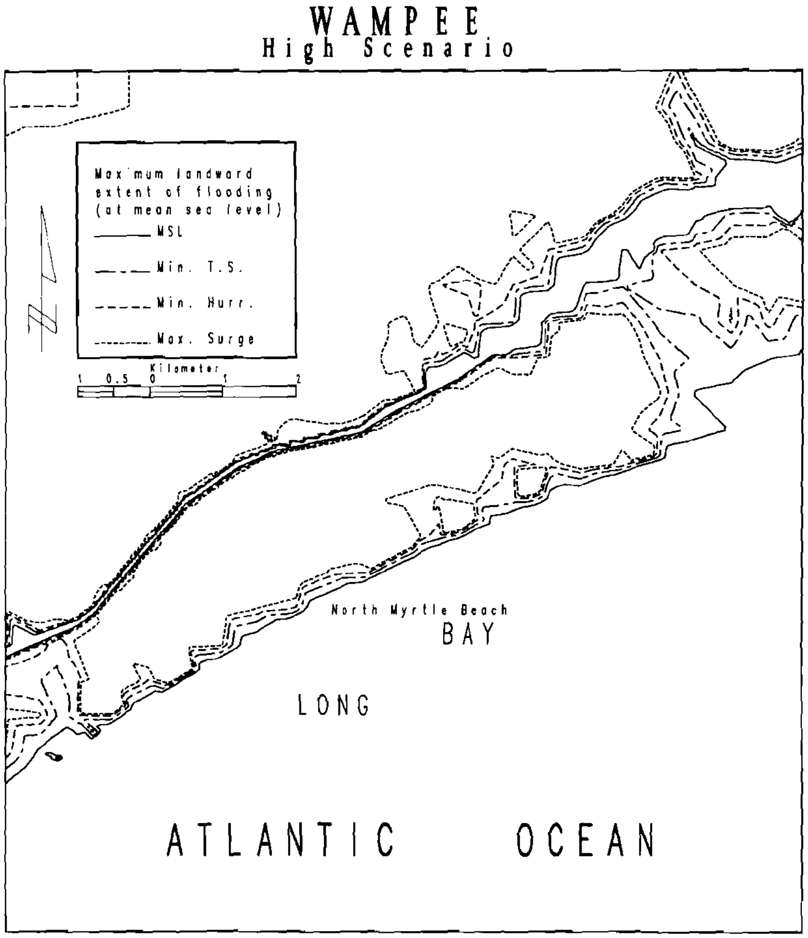

Figure 4. Wampee, South Carolina, coastlines produced with sea-level rise scenario 4, and three tropical cyclones.

storm and hurricane occurrence probabilities for each scenario. The relatively low number of tropical cyclones that occur in any given year makes this a difficult task, as a hurricane or tropical storm may cross a particular section of coastline infrequently. In addition, the fact that a section of coastline has not experienced a severe hurricane in recorded history does not preclude its happening in the future. These factors make it necessary to have a relatively long period of record to estimate probabilities.

Current Frequencies

The tropical storm and hurricane probabilities used in this study were obtained from a data set with 90 years of record that contains tropical storm and hurricane probabilities for each 1° × 1° longitude/latitude cell along the North American East Coast. The data values are expressed as the annual probability that a tropical storm (or hurricane) will pass through a given cell per year (BIRDWELL and DANIELS, 1991).

These probabilities may be seen as the probability that a tropical storm or hurricane of at least minimal intensity (as defined in this study for the minimal tropical storm and minimal hurricane) will occur in a given cell per year for the current climatic state. The current probability of a tropical cyclone occurring per year in the grid cell in which the Wampee, South Carolina, study area is located is 18.7% for tropical storms and 11.0% for hurricanes. The percentages for the Hilton Head study area are 18.7 and 7.0%, respectively.

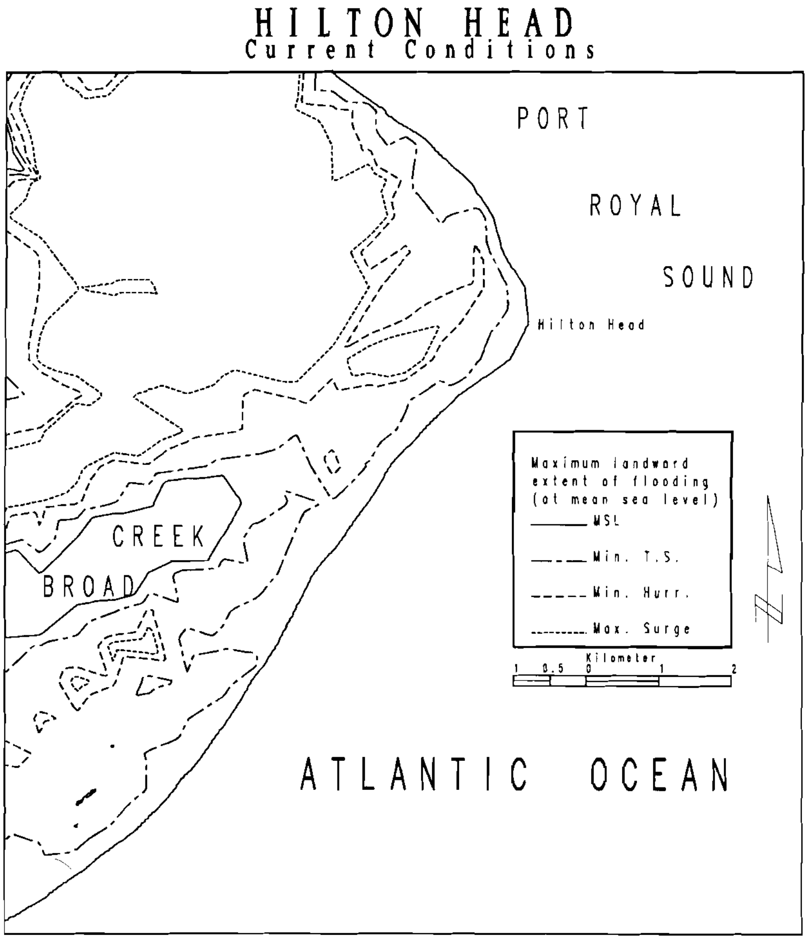

Figure 5. Hilton Head, South Carolina, coastlines produced under current climatic conditions for each tropical cyclone.

Future Tropical Cyclone Frequencies for each SLR Scenario and Study Area

Sea surface temperature plays an important role in determining tropical storm/hurricane probabilities, as the location of sea surface temperature fields (with temperatures over 26 °C) tend to correlate with both the seasonal variations in tropical storm activity and the trajectories of storms in the North Atlantic (FISHER, 1958; WENDLAND, 1977; GRAY, 1990). This relationship indicates that the total number of tropical cyclones occurring in the North Atlantic should increase as sea surface temperature does. However, even if the *frequency or total number* of tropical cyclones does not increase (HOLLAND *et al.*, 1987), the relationship would still allow the average period that a tropical cyclone is classified as a tropical storm/hurricane to increase (GRAY, 1990). This increase in period would result in the lengthening of storm tracks. Thus, the same number of storms would affect a greater area and increase the probability that a tropical storm/hurricane would occur in each grid cell along the U.S. East Coast.

In an attempt to estimate the tropical storm and hurricane probabilities for the U.S. East Coast, for each SLR scenario, the relationship between sea surface temperature and tropical cyclones was considered. A 2° × 2° grid of mean monthly sea surface temperatures for September (*i.e.*, the month with the warmest sea surface temperatures), derived from the COADS data set (D.O.C., 1985), was correlated with the 1° × 1° grid of tropical storm and hurricane probabilities for the

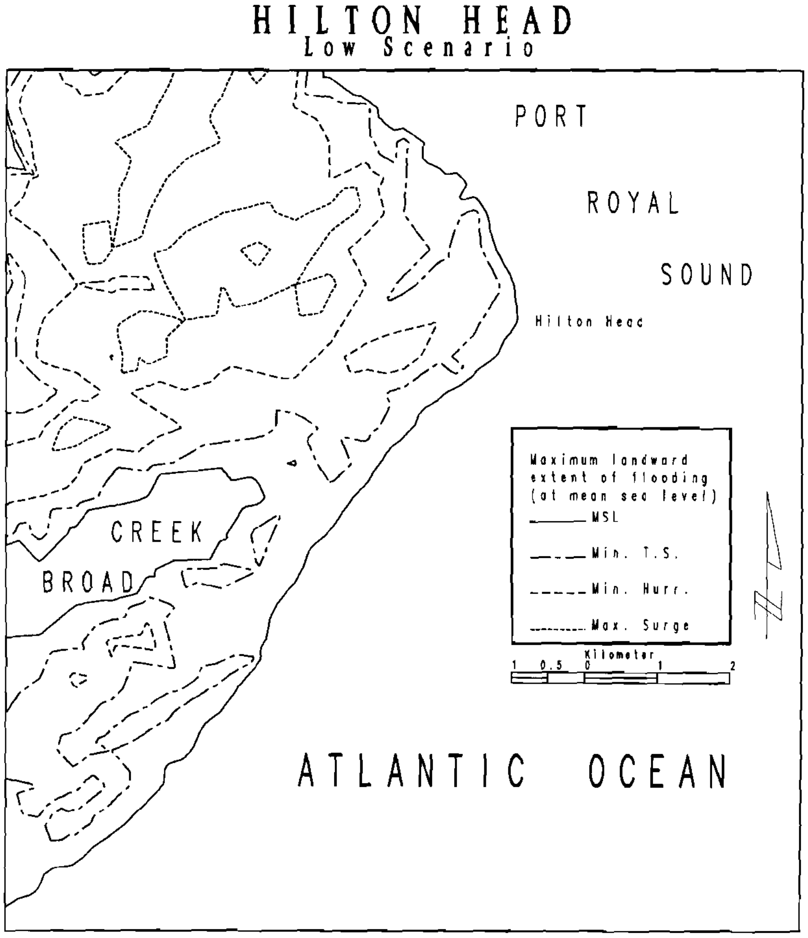

Figure 6. Hilton Head, South Carolina, coastlines produced with sea-level rise scenario 2, and three tropical cyclones.

U.S. East Coast (Birdwell and Daniels, 1991). The correlation between tropical cyclone probabilities and sea surface temperature had an r^2 of 0.72 for tropical storms and 0.42 for hurricanes ($N = 21, \alpha \leq 0.01$).

The two equations derived from the correlations (between sea surface temperature and tropical storms, and sea surface temperature and hurricanes) were then adjusted so that the actual storm probabilities for each study area would fall on the line produced by each equation. These adjusted equations were then employed to estimate the tropical storm and hurricane probabilities for each study area based on the predicted variations in sea surface temperature for each SLR scenario and each area (*i.e.*, sea surface temperature increases by 0.8, 1.6, 2.9, and 4.1 °C for each of the four SLR scenarios). Table 6 contains the results of this analysis.

The tropical storm and hurricane probabilities for the cell containing Wampee, South Carolina, increased over current values (*i.e.*, Probability Increase = 1 − Estimated ÷ Current) by 5.3% to 27.2% and by 4.7% to 23.6%, respectively. For Hilton Head, South Carolina, the probabilities increased over current values by 5.3% to 27.2% for tropical storms and by 6.7% to 33.8% for hurricanes.

CONCLUSIONS

In this study four "greenhouse" scenarios have been derived based on varying assumptions on the extent of global warming and SLR that will occur by the year 2100. These four scenarios were

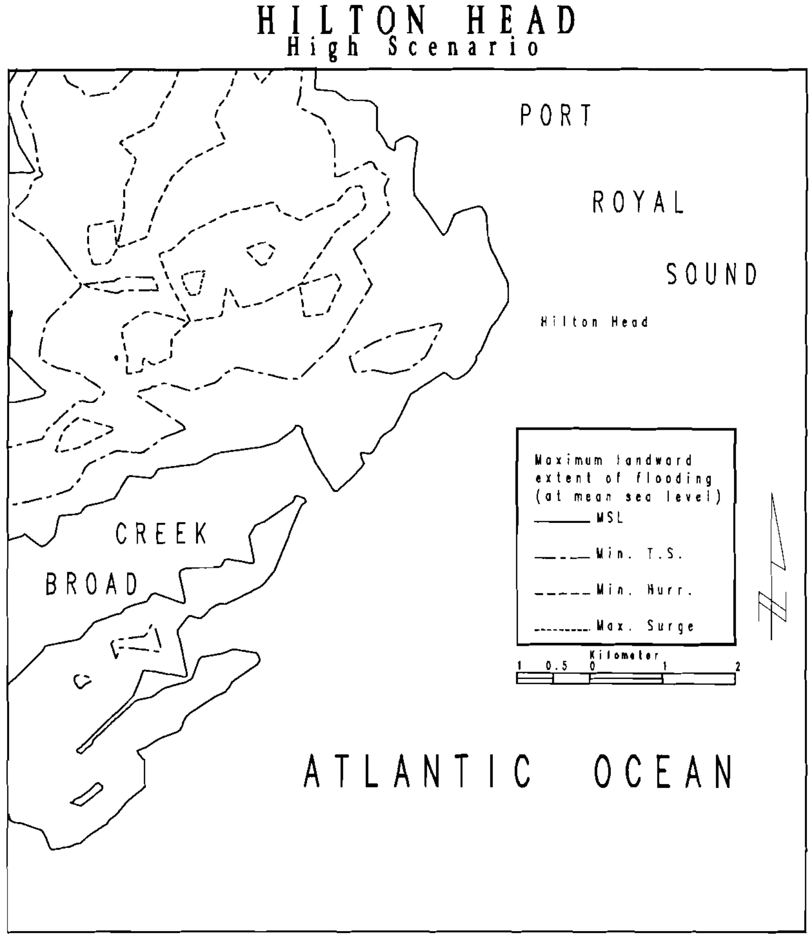

Figure 7. Hilton Head, South Carolina, coastlines produced with sea-level rise scenario 4, and three tropical cyclones.

then applied to two study areas located in different regions of South Carolina. Of these scenarios the second or "low" scenario (*i.e.*, SLR of 0.5 m) is currently seen as the most likely (HOUGHTON, *et al.*, 1990).

The Wampee, South Carolina, study area is subsiding at a rate of 0.8 mm/year. When this local vertical movement rate was combined with each of the SLR scenarios, it was found that the effects of SLR on this study area were limited. However, the probability of episodic inundation may rise as sea surface temperatures increase (*i.e.*, resulting in a decrease in the recurrence interval for tropical storms and hurricanes).

The second study area, Hilton Head, South Carolina, is subsiding at a rate of 2.0 mm/year, which, when combined with the SLR for each scenario, indicates that even the "very low" scenario will result in a relative SLR of 0.47 m by 2100. This rise is enough to result in the landward retreat of the coastline. Besides reducing the size of the study area, the higher mean sea level will also allow larger waves (generated during storms) to break onshore; thus increasing the percentage of the island that is subject to episodic flooding from storm surges. For example, the surge produced currently by the minimal tropical storm (*i.e.*, sustained winds of 17.5 m/sec) is capable of inundating 18% of the island, while with the most conservative scenario, over 23% of the island will be subject to episodic inundation from a storm of the same magnitude in the year 2100.

Based on the two case studies, the following conclusions were drawn: (1) studies on the re-

Table 6. *Current and estimated tropical storm (hurricane) probabilities and recurrence intervals (R.I.) for the minimum tropical storm (huricane) at Wampee and Hilton Head, South Carolina.*

Scenario	Tropical Storm Probability and R.I.		Hurricane Probability and R.I.	
Wampee, South Carolina				
0. Current	18.7%	5.3 yr*	11.0%	9.0 yr*
1. Very Low	19.7%	5.0 yr	11.5%	8.7 yr
2. Low	20.7%	4.8 yr	12.0%	8.3 yr
3. Moderate	22.3%	4.5 yr	12.8%	7.8 yr
4. High	23.8%	4.2 yr	13.6%	7.3 yr
Hilton Head, South Carolina				
0. Current	18.7%	5.3 yr*	7.7%	13.0 yr*
1. Very Low	19.7%	5.0 yr	8.2%	12.2 yr
2. Low	20.7%	4.8 yr	8.7%	11.5 yr
3. Moderate	22.3%	4.5 yr	9.5%	10.5 yr
4. High	23.8%	4.2 yr	10.3%	9.7 yr

*Values are from Birdwell and Daniels, 1991

gional effects of SLR must consider local vertical movement in order to be valid, (2) as mean sea level rises, the local relief of coastal areas will decrease, increasing the percentage of land above mean sea level subject to episodic inundation from tropical cyclones, and (3) as local sea surface temperatures rise, the maximum tropical cyclone-induced surge obtainable on the South Carolina coast will increase, and the probability of such a storm occurring may also increase.

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