DISSECTING AND CLASSIFYING THE IMPACTS OF HISTORIC HURRICANES ON ESTUARINE SYSTEMS

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ABSTRACT

Since the Great Hurricane of 1667 hit Chesapeake Bay, many have tried to describe the impacts caused by these destructive storms. Other than Hurricane/Tropical Storm Agnes in 1972, however, only sporadic efforts have assessed the many changes that can occur during and after these tropical visitors pass. One problem is that hurricanes vary widely in their impact, both temporally and spatially. Not only is wind strength important, but also the path that the winds take over the watershed can prove crucial in their impact. To analyze hurricane impacts more systematically, a simple classification system is proposed that accounts for the three main forcing functions or drivers that can significantly change estuaries.

The first driver emanates from the storm's precipitation and consequent runoff, which can cause massive flushing of the watershed and a freshet in the upper reaches of an estuary. Winds and waves, which can alter shorelines and disrupt normal estuarine stratification processes, constitute the second driver. The third driver is the surge associated with low-pressure systems as these systems move over the Bay, potentially transporting oceanic organisms far up the Bay, overwhelming wetlands, and spilling salt water into normally non-saline uplands. By categorizing each of the drivers into high, medium, and low impacts for hurricanes, three main categories of storms are shown to have affected the Chesapeake Bay in the 20th century with as many as 27 different combinations of wind, storm surge, and precipitation. For example, Isabel is a storm in which winds and runoff remained comparatively weak, but surge was high, particularly in the upper portions of the estuary. This situation differs sharply from hurricanes or tropical storms, such as Agnes, which had high precipitation and runoff in the upper watershed but weak winds and storm surge. Such differences highlight the need for additional analyses of historical storms.

INTRODUCTION

Along with the New World, Christopher Columbus made another startling discovery: hurricanes. He appears to have encountered his first hurricane in 1493, with an additional three during his Caribbean voyages. The Spanish were the first to introduce the Caribbean Indian word for the severe tropical storms to Europe, but it took the English a century to understand fully the fury of these storms.

Hurricanes have captured our imagination and terror at least since 1609 when the wreck of the *Sea Venture* off Bermuda inspired William Shakespeare to write *The Tempest*. In a more scientific context, hurricanes are extreme high-energy events. While such storms are generally rare in a given area, they can obliterate structures in their path and profoundly affect estuarine ecosystems. One of the earliest well-documented hurricanes in Chesapeake Bay occurred in 1667 when a huge storm with 12-ft (3.7-m) surge was noted in a dispatch from Virginia to London [1]:

Sir, having this opportunity, I cannot but acquaint you with the relation of a very strange tempest which hath been in these parts with us called a hurricane which had began August 27th *and continued with such violence, that it overturned* *many houses, burying in the ruines much goods and many people, beating to the ground such as were any wayes employed in the fields, blowing many cattle that were near the sea or rivers, into them, whereby unknown numbers have perished, to the great afflication of all people, few having escaped who have not suffered in their persons or estates, much corn was blown away, and great quantities of tobacco have been lost, to the great damage of many, and utter undoing of others. Neither did it end here, but the trees were torn up by the roots, and in many places whole woods blown down so that they cannot go from plantation to plantation. The sea, by the violence of the wind, swelled twelve feet above its usual height drowning the whole country before it, with many of the inhabitants, their cattle and goods, the rest being forced to save themselves in the mountains nearest adjoining, while they were forced to remain many days together in great want.*

It now appears likely that this was the same hurricane that eight days before passed over Barbados and left most houses standing [2]. The damage was so extensive in Virginia, however, that the Secretary of State of the Colony, Thomas Ludwell, who lived at Rich Neck on Archer's Creek, related the following in a letter to Lord Berkeley of Stratton, a favorite of King Charles II [3]:

this poore country is now reduced to a very miserable condition by a continental course of misfortune. On the 27th of August followed the most dreadful Hurry Cane that ever the Colony groaned under. It lasted 24 hours, began at North East and went around northerly till it came to west and so it came to Southeast where it ceased. It was accompanied with a most violent rain but no thunder. The night of it was the most dismal time I ever knew or heard of, for the wind and rain raised so confused a noise, mixed with the continued cracks of failing houses…The waves were impetuously beaten against the shores and by that violence forced and as it were crowded into all creeks, rivers and bays to that prodigious height that it hazarded the drowning of many people who lived not in sight of the rivers, yet were then forced to climb to the top of their houses to keep themselves above water. The waves carried all the foundations of the Fort at Point Comfort into the river and most of furnished and garrison with it… The nearest computation is at least 10,000 houses blown down, all the Indian grain laid flat on the ground, all the tobacco in the fields torn to pieces and most of that which was in the houses perished with them. The fences about the corn fields were either blown down or beaten to the ground by trees which fell upon them.

The description indicates that the storm could have been a Category 3 or even possibly a 4 on the Saffir-Simpson scale when it hit the lower Chesapeake. Curiously, there appears to be no direct mention of the 1667 event in the official records of colonial Maryland [4]. The only 17th-century reference to a hurricane in Maryland notes another hurricane, which apparently occurred in 1670 [5]. In fact, the 1667 hurricane may have headed inland, missing tidewater Maryland and then recurving sharply eastward, since a severe storm was noted on Manhattan Island shortly thereafter.

Whatever the exact track of the storm, Maryland planters eventually benefited because the storm devastated production in Virginia. Consequently, the price of tobacco, which had been slumping, rose for a brief period. This differential response is due in part to the localized area of high winds that occurs around the inner eye wall, as well as localized surge and rainfall that may differ dramatically over a 200-mile-long ecosystem, such as Chesapeake Bay.

The differences in precipitation, wind, and surge not only vary based on the intensity of hurricanes (now classified by the Saffir-Simpson scale), but also due to the direction that such storms approach the Bay. Obviously, hurricanes that approach an estuarine system from the seaward side have a higher probability of surge than hurricanes that approach from the landward direction. In addition, because of the counter-clockwise circulation patterns of hurricanes in the northern hemisphere, the area on the right side of the approaching storm is more likely to have a higher storm surge.

Table 1. The ten heaviest rains in Virginia from tropical cyclones and their remnants.

Total Rainfall	Dates	Location
27.00" (68.58 cm)	8/19 —20/1969	Nelson County
19.77" (50.22 cm)	11/02 —07/1985	2 NE Montebello
18.13" (46.05 cm)	9/14 —16/1999	Yorktown
16.57" (42.09 cm)	9/14 —16/1999	Newport News
16.00" (40.64 cm)	6/17 —24/1972	Chantilly
14.30" (36.32 cm)	9/14 —16/1999	James City
14.30" (36.32 cm)	9/05 —09/1996	Tom's Branch
14.18" (36.02 cm)	6/17 —24/1972	Centreville
14.17" (35.99 cm)	9/05 —09/1996	Luray 5 SE
13.60" (34.54 cm)	6/17 —24/1972	Big Meadows

Despite the many subtle facets that make each hurricane a distinctive event in a given area, we hypothesize that three primary driving forces—precipitation, wind speed, and storm surge—can be used to construct a storm classification that may prove useful to the environmental community in describing major storm events.

PRECIPITATION

The amount and intensity of rainfall associated with hurricanes is often extraordinary and account for various impacts beyond those associated with wind and wave damage or even surge damage. The classic case of a high-precipitation hurricane/tropical storm in Chesapeake Bay is Agnes in 1972 in which a deluge occurred not only in the northern Bay watershed, but also in many parts of Virginia. Indeed, three of the highest precipitation amounts of the top ten in Virginia were associated with Agnes from 16–17 June 1972 (Table 1). Table 1 suggests that three classes can be used for the proposed hurricane classification system: P Class A = 0–10 ft (0–25.4 cm), P Class B = 1–20 ft (25.4–50.8 cm), and P Class C >20 ft (>50.8 cm).

WIND

Since the Saffir-Simpson scale is now widely used to describe the potential impacts of hurricanes and tropical storms, the same cut-off points are used for the proposed classification, while condensing them into three classes (Table 2).

Mercifully, the Chesapeake Bay has not yet experienced any recorded hurricanes in the W Class C range. This lack of extremely strong storms is due to the relative protection afforded from the south by the North Carolina landmass and the fact that storms approaching more directly from the east usually have less energy because they have passed over cooler Mid-Atlantic water before moving ashore. Temperatures of the North Atlantic Ocean have been rising faster than any other ocean since the mid-1950's [6], however, increasing the probability that the Bay will experience a W Class C hurricane in the future. Such a hurricane could literally reach catastrophic proportions, particularly if accompanied by high storm-surge levels.

STORM SURGE

The very low atmospheric pressures associated with hurricanes often cause elevated sea states, termed storm surge. Particularly if a hurricane comes ashore at high tide, storm surge

Table 2. The Saffir-Simpson hurricane classification compared to a three-class system.

Tropical Storms Wind <74 mph	**Class A** Wind <95 mph (119 km$\cdot$hr^{-1})
Category 1 Wind 74 —95 mph	
Category 2 Wind 96 —110 mph	**Class B** Wind 96 —130 mph (154 — 209 km$\cdot$hr^{-1})
Category 3 Wind 111 —130 mph	
Category 4 Wind 131 —155 mph	**Class C** Wind >130 mph (>209 km$\cdot$hr^{-1})
Category 5 Wind >155 mph	

can become a significant factor in changing shoreline dynamics. On barrier islands, surge (combined with waves) is capable of cutting new inlets that result in massive changes in estuarine circulation. A classic example of this occurred during the August 1933 storm, which severed Assateague Island south of Ocean City, Maryland. The cutting of that inlet and subsequent stabilization by the U.S. Army Corps of Engineers has led to a more complex altered circulation in Chincoteague Bay and much more saline water in the Maryland Coastal Bays from Sinepuxent northward. A more recent example of inlet creation occurred during Hurricane Isabel; a new inlet was cut in a low point along the Outer Banks south of Cape Hatteras. The maximum surge recorded in Chesapeake Bay was in the range of 2 m during the hurricane of August 1933 [7], but a few hurricanes that have hit the North American coast had surges that exceeded 8 m (e.g., Camille, discussed below). The scale we propose would place surges <2 m into S Class A, 2–4 m in into S Class B, and >4 m into Class C.

STORM CLASSIFICATION

The traditional classification of hurricanes by wind strength typified by the Saffir-Simpson scale has limitations when assessing the impacts of such storms on large and complex estuaries such as Chesapeake Bay due to its unique geography. Given the great length of the Bay and its relative narrowness, storms can have either baywide effects or be restricted in their impact to only part of the system based on the track, intensity, and speed of the storm. By examining the tracks and types of tropical storms that characterized the Chesapeake region during the 20th century (Figure 1), it is possible to delineate as many 27 different combinations of the effects of storm surge, precipitation, and wave processes to classify tropical storms based on their effects in the Bay. When viewed in aggregate, however, two main categories of storms become evident:

1) Backdoor Storms - Backdoor storms either originate in the Gulf of Mexico or are Atlantic hurricanes that make landfall in Georgia or South Carolina and move considerably inland before reaching the middle Atlantic Coast. Their general effects are likely to be high precipitation with large levels of runoff. They can become baywide events if their tracks cross the upper Bay.

2) Outer Banks Landfall - These storms fall into two general groups: *Lower Outer Banks* storms that tend to track along the lower Virginia Eastern Shore with storm surge and waves affecting the lower Bay; and *Upper Outer Banks* storms that generally track northwest, paralleling the main axis of the Bay and producing storm surges and waves that affect the upper and middle Bay (the exception is Hurricane Connie in 1955).

The backdoor storms most often originate as major hurricanes that make landfall adjacent to the Gulf of Mexico, move northeast across the lower Ohio Valley, and then turn east toward the Mid-Atlantic region. Generally, by the time such storms reach the Chesapeake Bay, they have weakened to tropical storm strength in terms of sustained wind speeds, but can pack a considerable punch in terms of precipitation nevertheless. Indeed, two of the most severe floods the Chesapeake region has experienced in the last 35 years were produced by Gulf of Mexico hurricanes—namely hurricanes Camille and Agnes. Because storms of this magnitude are often large and can track over the Appalachian Highlands, catastrophic flooding can occur over a wide area before these storms reach the main Bay. In 1972, Tropical Storm Agnes (born as Hurricane Agnes) produced rainfall amounts in the upper Susquehanna Basin that resulted in unparalleled levels of runoff and discharge into the upper Chesapeake Bay [8]. Three years earlier, remnants of Hurricane Camille, the strongest hurricane to have made landfall in the continental United States in the 20th century, yielded a 27-foot storm surge in Biloxi, Mississippi and produced severe flooding in the lower Bay, especially in the James River.

Backdoor storms, by the very nature of their origin and track as well as their relatively low peak winds and weakening center of circulation, would appear to be unlikely candidates for significant storm surges or winds. Moreover, since most cross

Figure 1. Mid-Atlantic hurricanes in the Chesapeake Bay region during the 20th century. The solid arrow indicates the track of backdoor storms; the dotted arrow shows the general track of lower Outer Banks storms; the dashed arrow gives the general track of upper Outer Banks storms. Modified figure of the Coastal Services Center of NOAA (*www.noaa.gov*).

the Bay's main stem at right angles (i.e., the least favorable direction for significant fetch in this long and relatively narrow estuary), substantial wave activity across the Bay is likely restricted to the storm's vicinity.

The same cannot be said for hurricanes and even strong tropical storms making landfall on the Outer Banks. The storms coming ashore just south of the Chesapeake Bay have constituted some of the strongest and most damaging storms (many Category 2 and some Category 3 on the Saffir-Simpson scale and Category 2 on the simplified scale presented here) affecting the estuary in the last century. The relative impact of the Outer Banks depends on where these storms make landfall since this influences their track across the Bay. Storms that make landfall on the lower Outer Banks tend to follow tracks that lead over the Tidewater area of Virginia and the lower Virginia Eastern Shore. Apart from storm surges (depending on the central pressure in the eye), waves generated by these winds from the southwest quadrant generally produce flooding in the peninsula down through Virginia Beach. If the storm tracks along the Virginia Eastern Shore, close to the Bay stem, the York and Rappahannock rivers could also come under the influence of storm tides (i.e., waves). Hurricane Brenda (1960) and Hurricane Doria (1971) typify this category of storm.

Perhaps the most dangerous storms in terms of baywide effects are those that make landfall on the upper Outer Banks, just south of the Virginia state line. These storms drive waves into the Bay from the northeast quadrant that flood Tidewater Virginia (in addition to the storm surge), and then track north-northwest paralleling the Bay. This situation contrasts with the lower Outer Banks storms, which tend to drive winds (and waves) to the southwest (Figure 2). By the time these storms reach the latitude of the mid-Bay, they have often moved as far west as West Virginia, but by this point, their effects can reach well into the upper Bay.

With winds coming from the south-southeast across the main axis of the Bay for several hours as they move north, these storms can produce substantial "wind tides," piling up water in the middle and upper Bay. Although the phenomenon is often associated with open coast nor'easters and hurricanes, it is possible that such storms create the conditions for significant wave setup. This phenomenon occurs when waves break on a beach, with the surf progressively increasing the nearshore water level. The longer the waves break at the shoreline, with wave crests parallel or sub-parallel to the trend of the shoreline, the greater the setup. Field measurements taken during storms indicate that a setup of 1 m is possible [9], with the potential for shifting the effective shoreline considerably inland depending on the coastal profile. On the lowlying Eastern Shore, such a setup would translate to extensive flooding.

Like the catastrophic flooding during the Great New England Hurricane of 1938, which could be accounted for by storm surge elevations alone, wave setup probably explains a good deal of the flooding that occurred in the middle and upper Bay from Hurricane Isabel and the notorious "Storm King" Hurricane of 1933. Both storms followed very similar tracks, staying close to the western

Figure 2. Directions of winds from lower Outer Banks storms that track to the northeast across the lower Delmarva Peninsula and upper Outer Banks storms that track to the north-northwest, paralleling the western shore of the Bay.

shore of the Bay until reaching the latitude of Maryland. With hurricane-force winds for almost 4 to 5 hours pushing up the axis of the Bay, the situation in each case was ripe for wave setup. In a highly irregular coast like that of the Chesapeake, however, not all areas in the upper and middle Bay receive waves approaching directly onshore—the most ideal condition for wave setup.

Though analysis of storms over the last 150 years indicates that the occurrence of storms such as Isabel is comparatively infrequent, two trends are converging to make the future impact of large tropical storms in the Chesapeake Bay greater than ever before. Development around the Bay's shore has burgeoned in the last two decades, far beyond any expectations of a few generations ago. Even though shoreline development has probably reached saturation in some areas (such as Annapolis), with approximately 6,000 miles (9654 km) of tidal shoreline many areas remain that can reasonably be considered undeveloped. Estimates for the growth of county populations in some of these areas predict figures anywhere from 50% to 100% higher by the year 2020 [10]. Upper Bay tributaries, such as the Sassafras, could look substantially different in terms of shoreline development within a generation.

Concurrently, sea level rise is projected to increase significantly over this century [11] and will heighten the flood risk. Moreover, as the waters of the Chesapeake Bay deepen with increasing sea level, the capacity of waves to produce greater damage will be significantly enhanced. Because most of the Bay is relatively shallow (generally averaging between 4.5 and 6 m), any increase in its average water depth will disproportionately influence wave power. Figure 3 shows how much the increase in the average depth of the Bay over approximately the past 60 years (~0.3 m) has affected wave power from the same, very moderate storm with winds of 40 $km \cdot hr^{-1}$. For a 4-sec wave, wave power increases by 40% (Figure 3) with a substantial increase in the likelihood of higher rates of shore erosion, wave damage to shore structures, and coastal flooding.

ECOLOGICAL EFFECTS OF HURRICANE TYPES

The ecological effects of tropical storms on mid-latitude complex estuaries such as the Chesapeake Bay have mostly been examined from the standpoint of flooding impacts. Wave and wind effects are less well understood. In the Chesapeake Bay, there are good reasons for this relative lack of information on wave and wind impacts from tropical storms. Foremost among them is the passage of 50 years without a significant hurricane traversing the main stem of the Bay. Unfortunately, when the eye of Hurricane Connie crossed the Bay in 1955, the quality of the instrumentation was primitive compared to current devices. More importantly, the spatial distribution of monitoring stations at the time was quite limited. Though

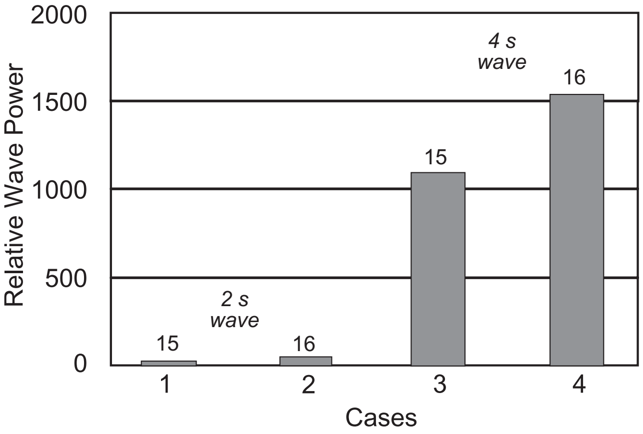

Figure 3. The increase in wave power associated with increasing average water depth in Chesapeake Bay from 4.5–4.8 m, with winds of 40 km·hr^{-1} and a fetch of 15 km.

Connie may have generated waves with heights of perhaps 6 m off Tangier Island [16], little evidence is extant in the literature concerning the effects of waves on the Bay ecosystem.

The other principal reason for the information gap, still true today, is the lack of an adequate baywide wave model, especially for areas such Tangier Sound where an archipelago of islands creates the potential for complex wave refraction patterns. Tangier Sound, coincidentally, is an area of extensive seagrass beds, fringed by some of the largest coastal marshes in the Bay. Both ecosystems would presumably be severely affected by large waves causing subtidal and shore erosion as well as by littoral transport of large volumes of sand (sand makes up most of the shallow shoreface of the sound).

Certainly, a major hurricane making landfall in the Chesapeake Bay and following a track similar to Hurricane Connie (i.e., an upper Outer Banks storm) could be expected to cause locally substantial erosion, both subtidally and at the shore (Figure 4). Moreover, in areas where annual longshore transport is high (such as Calvert Cliffs [17]), severe disruption of benthic communities by unprecedented sand transport could occur.

The impact of backdoor storms, which are mainly precipitation/flooding events, rests on more solid evidence. The existing literature on the ecological effects of hurricanes in Chesapeake Bay has been largely influenced by Tropical Storm Agnes in 1972. This storm, in the classification proposed here, clearly belongs to the backdoor category though its track across the upper reaches of the Susquehanna River was different from more classic backdoor storms, such as Camille. In addition, Tropical Storm Agnes occurred in June, as opposed to August or July. Nonetheless, this storm serves as an example of how an extreme precipitation event can affect the ecology of the Bay.

Peak flooding from Tropical Storm Agnes in the Chesapeake Bay occurred from 21–24 June 1972. The initial effects of the storm were a dramatic reduction in salinity (especially in the upper and middle Bay) along with tremendous flushing of the Bay system overall [18]. Due to the exceptional runoff, suspended concentrations reached unprecedented levels [19].

Tropical Storm Agnes was also associated with high sediment concentrations and high nutrient loads. The precipitous drop in salinities and high flushing rates particularly affected the plankton communities. In the Virginia portion of the mainstem Chesapeake Bay, Grant et al. [20] reported much lower than normal zooplankton biomass (89 mg·m^{-3} in August of 1972 compared to 269 mg·m^{-3} the previous August). This difference is largely reflected the decimation of Cladocerans following the flood. However, sampling at seven

Figure 4. Shore and subtidal erosion from the 1933 “Storm King” hurricane at the Chesapeake Biological Laboratory. Photo courtesy of the Calvert Marine Museum.

stations by Heinle et al. [21] off of Calvert Cliffs revealed little change in the usually dominant euryhaline copepod *Acartia tonsa* population, compared to *Oithona brevicornis*, which disappeared after Agnes. The latter species does not tolerate low salinity (which was ~1.0 psu in the surface layer there on 28 June 1972).

Agnes also disrupted benthic communities, particularly clam and oyster populations, for which mortality varied greatly depending on location [22]. Generally, clam and oyster beds in the upper parts of the tributaries were hardest hit; there was also a marked decline in the occurrence of submersed aquatic vegetation (SAV) baywide by about two-thirds. Later interpretations attributed the seagrass decline to elevated nutrients introduced by high runoff [23].

Overall, the impacts of Tropical Storm Agnes—especially those resulting from the massive sediment accumulation and excessive nutrient loading including the increase in phytoplankton and the decline of SAV—persisted into subsequent years [23, 24]. Arguably, Agnes can be viewed as the turning point at which the Chesapeake Bay shifted from a benthic to planktonic system, in terms of productivity.

Tropical storms in the Chesapeake Bay can also affect the coastal wetlands. Studies [25] indicate that much of the loss in the extensive marshes on the lower Eastern Shore resulted from storm waves eroding the edges of large interior ponds. It follows that hurricanes (or large nor'easters) with peak winds of 180 km·hr^{-1} would cause massive edge erosion in interior ponds; even winds of 40 km·hr^{-1} can cause substantial erosion [15]. Such potentially massive marsh erosion in some areas of the Eastern Shore brings enormous concentrations of suspended solids, much of it organic carbon [26], into the estuary in amounts that easily dwarf the quantity of suspended sediments contributed by river runoff. In this respect, the impacts of a hurricane or large tropical storm could spread far beyond the marshes and associated loss of habitat for wading birds and invertebrates, ultimately influencing estuarine turbidity.

SUMMARY

More detailed classifications of hurricane characteristics, tracks, and wave generation, as attempted in this paper, could prove helpful to the scientific and management communities in assessing the impacts of past storms and providing a better understanding for planning. The public is keenly aware of the destructive power of hurricanes in terms of societal impact. Hurricanes and other tropical storms are not totally without benefit, however, and this or other classification schemes might help identify when and where such storms could yield positive changes in the natural system. For example, cleaner ocean water brought in to estuaries may dilute the normally high nutrient waters now present in U.S. coastal environments. In addition, studies of hurricanes on marsh accretion in Louisiana [12], as well as extratropical storms in Florida [13] and Delaware [14], indicate that high accretion rates result from storms and suggests that they play an important role in the long-term maintenance of marsh systems, which need to keep up with rising sea levels. Others have argued that while some events may help subsidize the sediment budget of some tidal marshes, other events can be quite erosive [15]. Clearly, more study of key processes in estuaries in relation to various types of hurricanes should be undertaken. A fully developed hurricane classification system could potentially aid such research.

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