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Effects of Hurricane Ivan on Water Quality in Pensacola Bay, Florida

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ABSTRACT: Pensacola Bay, Florida, was in the strong northeast quadrant of Hurricane Ivan when it made landfall on September 16, 2004 as a category 3 hurricane on the Saffir-Simpson scale. We present data describing the timeline and maximum height of the storm surge, the extent of flooding of coastal land, and the magnitude of the freshwater inflow pulse that followed the storm. We computed the magnitude of tidal flushing associated with the surge using a tidal prism model. We also evaluated hurricane effects on water quality using water quality surveys conducted 20 and 50 d after the storm, which we compared with a survey 14 d before landfall. We evaluated the scale of hurricane effects relative to normal variability using a 5-yr monthly record. Ivan's 3.5 m storm surge inundated 165 km^2 of land, increasing the surface area of Pensacola Bay by 50% and its volume by 230%. The model suggests that 60% of the Bay's volume was flushed, initially increasing the average salinity of Bay waters from 23 to 30 and lowering nutrient and chlorophyll *a* concentrations. Additional computations suggest that wind forcing was sufficient to completely mix the water column during the storm. Freshwater discharge from the largest river increased twentyfold during the subsequent 4 d, stimulating a modest phytoplankton bloom (chlorophyll up to 18 μg l^{-1}) and maintaining hypoxia for several months. Although the immediate physical perturbation was extreme, the water quality effects that persisted beyond the first several days were within the normal range of variability for this system. In terms of water quality and phytoplankton productivity effects, this ecosystem appears to be quite resilient in the face of a severe hurricane effect.

Introduction

On September 16, 2004, Hurricane Ivan made landfall approximately 70 km west of Pensacola, Florida, as a category 3 hurricane on the Saffir-Simpson scale with maximum sustained winds of 193 km h^{-1} (105 kt; Sallenger et al. 2006). Offshore, Ivan repeatedly attained category 5 status (Stewart 2005) and generated some of the largest waves ever recorded (Wang et al. 2005). Pensacola Bay, located just outside the eye wall in the strong northeast quadrant of the storm, received the full force of the storm, including a storm surge of 3 to 5 m above mean low water (MLW; FEMA unpublished data). Ivan generated 14 cm of rainfall at Pensacola Regional Airport and 20 cm at inland locations in the Pensacola Bay watershed (e.g., Brewton, Alabama; NOAA 2004a,b). As the storm moved slowly inland, high winds caused extensive damage to forests in the watershed, including economic losses of $740 million (Alabama Forestry Commission 2004; Stewart 2005; Florida Department of Forestry unpublished data).

We are not aware of any studies documenting the effect of hurricanes on estuaries in the northern Gulf of Mexico despite 18 hurricanes, including 7 major hurricanes (category 3 or higher on the Saffir-Simpson scale), making landfall between 1950 and 2005 along the coast from Appalachicola, Florida, to Lake Pontchartrain, Louisiana (NOAA/NHC unpublished data). When hurricane effects on coastal systems have been documented, the focus has usually been the effects of rainfall and subsequent river flooding (e.g., Chesapeake Research Consortium 1976; Mallin et al. 1999; Peierls et al. 2003). Effects resulting from storm surge and waves have been documented less frequently (e.g., Florida Bay: Tabb and Jones 1962; Waquoit Bay: Valiela et al. 1998).

We examined the short-term effects of Hurricane Ivan on water quality in Pensacola Bay, with an emphasis on the relative effects of freshwater inflow and the tidal surge associated with the storm. The analysis is based on a tidal prism flushing model and two water quality surveys conducted in the weeks and months following the storm, which we compared with a survey collected shortly before the storm and with a 5-yr baseline data set collected during 2000 to 2004. We also comment on other aspects of hurricane effects on the coastal ecosystem.

Study Site

Pensacola Bay is a river-dominated estuarine complex located in northwestern Florida (Fig. 1). It encompasses 370 km^2, has a mean depth of 3.5 m,

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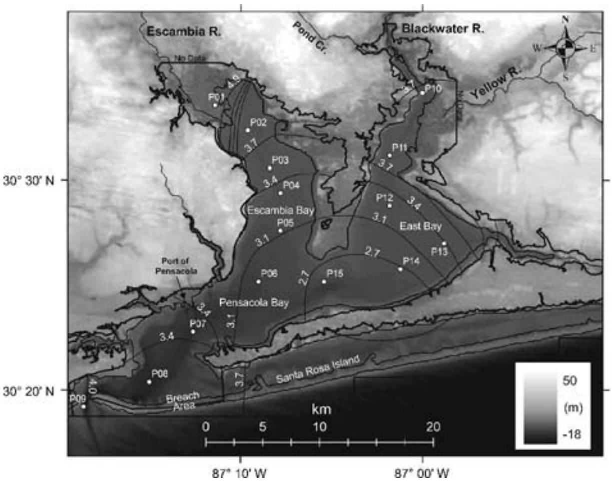

Fig. 1. Map of the Pensacola Bay system illustrating the mean low water shoreline of the Bay (thin line), the maximum extent of storm surge inundation (thick line), and the estimated height of the storm surge (contours, labels in meters). Water quality sampling locations are labelled P01 to P15. Underlying shading is from a NOAA digital elevation model, which describes bathymetry and land elevations (NOAA NGDC unpublished data). The storm surge inundation area is a GIS coverage generated by the Federal Emergency Management Agency and was derived from shoreline surveys of high water marks. These surveys did not describe flooding in the Escambia, Yellow, and Blackwater River floodplains. Breach area indicates an area of Santa Rosa Island that was eroded to below sea level, leaving a shallow inlet.

and has diel, low-amplitude (0–50 cm) tides. Annual mean discharge of the Escambia River is 200 $m^3 s^{-1}$ and accounts for 65% of total freshwater inputs. Pensacola Bay opens to the Gulf of Mexico through a single narrow pass. The watershed covers 18,318 km^2 and receives 165 cm of rainfall annually, among the highest in the United States. Hypoxia occurs commonly in portions of the Bay, reflecting frequently strong stratification, but anoxia is uncommon (EPA 2005).

Methods

Water Quality Surveys

Water quality surveys were conducted monthly during 2000–2004 at up to 15 sites located along two transects within the Pensacola Bay system (Fig. 1). The final of 48 surveys prior to Ivan occurred on September 1, 2004, 15 d before the storm. Post-Ivan surveys were conducted on October 6 and November 5, 20 and 50 d after the storm, respectively. Hydrographic data were collected at each station using a Seabird SBE25 CTD measuring water temperature, salinity, dissolved oxygen, PAR, chlorophyll *a* fluorescence, and turbidity. Profile data were binned at a 0.25-m interval. Surface and bottom water samples were collected with either a Van Dorn bottle or a low pressure submersible pump. Samples for dissolved nutrients were filtered in the field using a syringe filter system with combusted GF/F filters. Additional 2-l water samples were collected in a clean polyethylene bottle and processed for chlorophyll *a* and particulate carbon and nitrogen in the laboratory within 2 to 3 h. Nutrients (NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, SiO_2) were analyzed using standard methods (APHA 1989); dissolved inorganic nitrogen (DIN) denotes the sum of NH_4^+, NO_2^-, and NO_3^-. Method detection limits (MDL) were 0.4, 0.47, and 0.03 μM for NH_4^+, $NO_2^- + NO_3^-$, and PO_4^{3-}, respectively. Values below MDL were replaced with MDL/2. Chlorophyll *a* samples were extracted in methanol, sonicated, and analyzed fluorometrically (Jeffrey et al. 1997). Vertical profiles of chlorophyll *a* were computed from in vivo (CTD) fluorescence using a field calibration derived from extracted chlorophyll *a* values ($r^2 = 0.5$ to 0.9).

Freshwater Inputs, Tide Heights, and Surge Volume

River flow data were obtained from U.S. Geological Survey gauging stations on the Escambia River at Molino, Florida, Blackwater River near Baker, Florida, Yellow River near Milligan, Florida, and Big Coldwater Creek near Milton, Florida, accounting for 74% of the watershed area. Runoff from ungauged watershed areas adjacent to Pensacola Bay was computed from the discharge per unit of watershed area in the Pond Creek watershed, a small gauged watershed immediately adjacent to Pensacola Bay (Fig. 1).

The extent of inundated land and the maximum height of tidal surge were estimated by directly observing the locations and heights (referenced to NAVD88) of high water marks around the perimeter of Pensacola Bay (FEMA 2004). These data were summarized (FEMA 2005) and also released as a Geographic Information Systems (GIS) coverage (FEMA unpublished data). The area inundated by the storm surge (A_i) includes the surface area of the Bay at mean lower low water (A_{mllw}) and the area of inundated land, including the area north of the midline of Santa Rosa Island. The surge volume was computed as an irregular trapezoid using $(A_{mllw} + A_i)H/2$, where H is the average height of the surge above mean lower low water, MLLW (in Pensacola, NAVD88 = 0 is presently 0.085 m above MLLW).

A time series of sea surface elevation (H) above MLLW was recorded by the National Oceanic and Atmospheric Administration (NOAA) gauging station in Pensacola for the period prior to Hurricane Ivan until shortly after 23:00 on September 15, 2004, when the gauge was destroyed. A continuing timeline for H was approximated from verbal accounts of water levels inside bayside homes, which were correlated with the NOAA tide gauge record.

A tidal prism model was used to estimate the magnitude of exchange associated with the storm surge. The fraction of Bay water flushed by the surge was computed as $fV_s/(fV_s + V_{mllw})$ where V_s is the volume of the surge, V_{mllw} is the MLLW volume, and f is the fraction of the surge water that mixed with Bay waters before retreating. Average salinity in the Bay immediately following Ivan was estimated via $(fV_s s_o + V_{mllw} s_i)/(fV_s + V_{mllw})$, where s_o is the salinity of the inflowing storm surge water and s_i is the average salinity within the Bay prior to the storm. The maximum extent of flushing was estimated assuming complete mixing ($f = 1$); alternative scenarios with $0 < f < 1$ were also evaluated.

Results

Magnitude of Storm Surge, Freshwater Inflow, and Flushing

Hurricane Ivan caused water levels to rise continuously for 31 h, peaking at 0200 central daylight time (CDT) on September 16, 2004 according to personal accounts (Litzinger and Harvey personal communication; NOAA/NOS/CO-OPS unpublished data). The NOAA water level station in Pensacola was destroyed sometime after 2300 CDT on September 15, 2004, at which time water levels were rising at 18 cm h^{-1} and had reached 2 m above MLW. Water levels must have increased at c. 45 cm h^{-1} during the next 3 h to reach the estimated maximum surge elevation at Pensacola of 3.35 m (Fig. 1). The average surge elevation for the Bay as a whole was 3.5 m, whereas the surge in northern Escambia Bay reached nearly 5 m. Santa Rosa Island was overtopped in many places. A particularly low-lying stretch was eroded to below sea level, leaving several shallow inlets. Based on the time series of water levels in the Bay, we computed that the cross-section average current velocity through Pensacola Pass increased steadily to 140 cm s^{-1} shortly before midnight as Ivan approached. An improbable increase to 600 cm s^{-1} was needed to account for the more rapid water level rise in the Bay. Most likely, the barrier island was breached at this time, allowing significant flow over the top and facilitating the much more rapid flooding of the Bay. Estimates based on personal accounts indicate that water levels retreated rapidly at first after the storm passed and then slowed to reach 2 m above MLW 10 h after peak levels were reached.

Ivan's storm surge inundated 165 km^2 of land, increasing the Bay's surface area by 50% and its volume by 230% (Fig. 1). The maximum storm surge volume, 1.6 km^3, was 9 times larger than the tidal prism associated with the largest normal tides. Ivan's storm surge was twofold larger than that associated with Hurricanes Erin (1995), Opal (1995), and Dennis (2005), all of which made landfall in the Pensacola Bay area (NOAA/NHC unpublished data). Based on the tidal prism model, the surge flushed a maximum (i.e., assuming $f = 1$) of 60% of the Bay's water out to sea as it retreated, and proportionately smaller amounts assuming $f < 1$. Such a massive flushing event would have increased salinity in the Bay substantially. As of 1 September, mean salinity within the Bay was 23.4. Salinity at Pensacola Pass on 1 September, an initial estimate for the salinity of the surging water, was 30.9. Salinity up to 32.4 was observed within the Bay on 6 October, suggesting that the surge water had a higher salinity. Archived output from a U.S. Navy real-time data-assimilating hydrodynamic model for the Gulf of Mexico (Ko et al. 2003; Naval Research Laboratory unpublished data) indicated that Ivan's approach intensified a westward coastal current that increased salinity offshore of Pensacola Bay to 34.5 as the storm made landfall. Using the Navy model's estimate of offshore salinity in our tidal prism model (for s_o), we compute that Ivan's surge abruptly increased the mean salinity of the Bay from 23.4 to as high as 30. Transient exposure to higher salinities most likely occurred during the storm in seaward portions of the estuary.

Freshwater discharge from the Escambia River increased twentyfold from 68 $m^3 s^{-1}$ the day before Ivan to a peak of 1,588 $m^3 s^{-1}$ four days later. Flow then decreased, stabilizing at 112 $m^3 s^{-1}$ by early October. Flow from smaller basins in the watershed responded more rapidly and more intensely, but recovered to pre-storm levels more rapidly. Although flow levels following Ivan were strongly elevated, they are not unusual or record setting for this region. Higher peak flow on the Escambia River was associated with Hurricane Georges in 1998 (2,944 $m^3 s^{-1}$), which generated threefold more rain than Ivan. The record flow on the Escambia River, 3,200 $m^3 s^{-1}$, followed heavy spring rains in March 1990.

The salinity distribution on the transect from Escambia River to Pensacola Pass 20 d after Ivan reflects both the storm surge and elevated freshwater inflow (Fig. 2). Relative to before Ivan, salinity in bottom water increased slightly, while surface salinity decreased near the river mouth and near Pensacola Pass. After Ivan, bottom water salinity in the central basin of Pensacola Bay was higher than offshore, a vestige of the high salinity surge. The sharp and deepened halocline in the upper Bay is a characteristic response to high flow. We computed that the volume of freshwater in the Bay increased

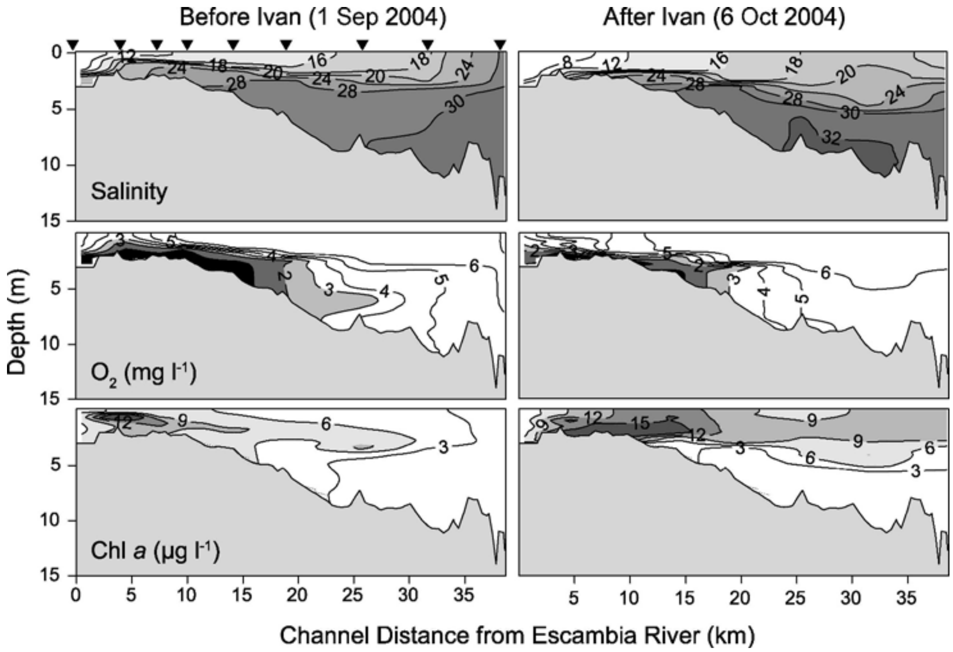

Fig. 2. Contour plots illustrating spatial distributions of salinity, dissolved oxygen, and chlorophyll *a* before Ivan (September 1, 2005) and after Ivan (October 6, 2005) along the transect from the Escambia River to Pensacola Pass. Station locations (P01 to P09, ▼) are indicated on the upper left panel. Black shading on the middle panels indicates $O_2 \leq 1.0$ mg l^{-1}.

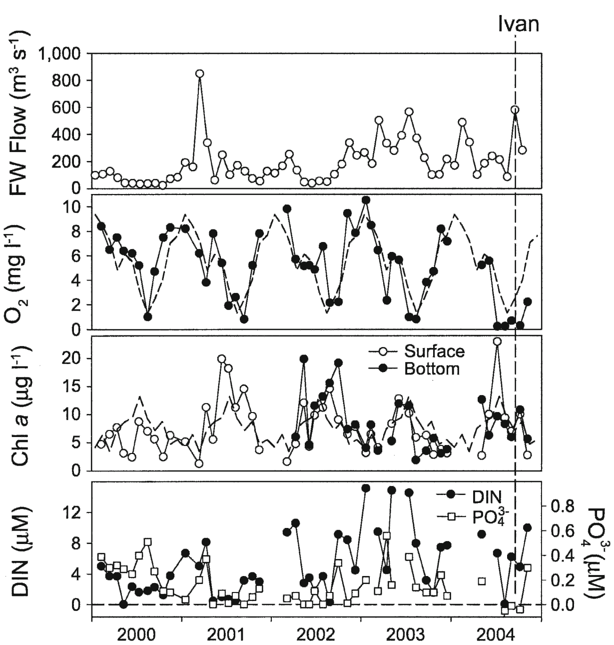

Fig. 3. Time series of monthly average freshwater inflow from the Escambia River, bottom water O_2 at station P04, surface and bottom water chlorophyll *a* concentration at station P04, and surface water dissolved inorganic nitrogen (DIN) and dissolved phosphate (PO_4^{3-}). Dotted lines indicate the 2000–2004 average seasonal pattern of bottom O_2 or surface chlorophyll *a* at P04.

by 0.27 km^3 between September 16 and October 6 and that cumulative freshwater inflow could have accomplished this within 3 d after Ivan. Subsequent cumulative flow by October 6 was eightfold larger, suggesting that the salinity distribution on 6 October reflected a relatively well-developed equilibrium between freshwater inflow and seaward exchange flow.

Water Quality Effects

Because of the intensity of Hurricane Ivan it probably had a massive, transient effect on water quality in Pensacola Bay, mainly due to mixing of the water column and erosion and resuspension of sediments by waves and currents. The approximate magnitude of wind driven currents and vertical mixing can be illustrated via a few computations, which suggest that wind forcing was by itself sufficient to mix the water column during the hurricane. Based on equations from Noble et al. (1996), minimal hurricane force winds (33 m s^{-1}) would generate 13 dyn cm^{-2} of stress on the surface of the Bay. Wind stress computed very conservatively using winds at Pensacola Regional Airport was between 6 and 10 dyn cm^{-2} for 5 h. On Mobile Bay, another shallow, stratified estuary, 16 cm s^{-1} of vertical current velocity shear was observed to result from 1 dyn cm^{-2} of wind stress (Noble et al. 1996). Applying this empirical observation to Pensacola

Bay, wind-forced current shear associated with Ivan may have been greater, or even much greater, than 100 cm s^{-1} (= 16 × 6). Given the vertical salinity structure observed before Ivan (Fig. 2), we can use this estimate to compute a gradient Richardson number (Ri). Applying Ri for each case in the formula $\varepsilon_v = \varepsilon_0(1 + 3.33\mathrm{Ri})^{3/2}$ (Munk and Anderson 1948, cited in Fisher et al. 1979), we can estimate that the magnitude of wind-forced vertical mixing during Ivan was at least 50 times greater than on a normal but windy day (9 m s^{-1}). Such a large increase in wind mixing would be expected to rapidly decrease stratification, leading to complete mixing of the water column during the storm. Vertical mixing would contribute to increased flushing by the storm surge and would temporarily eliminate hypoxia. Also using arguments related to wind stress, Valiela et al. (1998) concluded that Hurricane Bob may have mixed the water column of Waqoit Bay within minutes. Water quality effects associated with mixing events can be temporary, since estuaries can often restratify quickly. Borsuk et al. (2001) observed that when water temperature is high, hypoxia can re-develop within several days after stratification.

More persistent effects probably resulted from the tidal surge, which replaced Bay waters with low-nutrient, well-oxygenated, oligotrophic Gulf waters. Prior to Ivan, DIN and PO_4^{3-} were below detection limits in lower Pensacola Bay and at the pass, but increased to 15–20 and 0.25 µM, respectively, along gradients to the head of Escambia and Blackwater Bays. Surface chlorophyll *a* was 1.1 µg l^{-1} at the pass but 5 to 9 µg l^{-1} inside the Bay. Immediately after Ivan, as a result of the massive flushing, we expect that both dissolved nutrient concentrations and plankton community biomass was lower. Hypoxia was unusually severe in summer 2004 (Fig. 3), and before Ivan affected a 20-km stretch of bottom waters in Escambia Bay (Fig. 2) and all the bottom waters in Blackwater-East Bay. In the hours immediately after the surge retreated, we expect that bottom waters were well oxygenated, reflecting strong wind mixing and flushing of the Bay with seawater.

The post-Ivan water quality survey found water quality conditions that mainly reflected the effects of the flow event. The hypoxia present before Ivan was observed again, with minimum O_2 = 0.15 mg l^{-1} along an 18-km stretch of bottom waters in Escambia Bay. Hypoxia was also present in several places in the Blackwater River and East Bay (minimum O_2 = 0.99 mg l^{-1}). On November 5, despite strong winds (9 m s^{-1}), O_2 remained at unseasonably low concentrations in Escambia Bay (Fig. 3) and Blackwater River and Bay (1 mg l^{-1}). Stronger than normal stratification caused by the storm surge followed by the flow pulse probably contributed to the persistence of hypoxia.

The freshwater pulse associated with Ivan generated a strong but transient response in the phytoplankton community. On October 6, surface and bottom chlorophyll *a* in Escambia Bay was twofold greater than before Ivan (Fig. 2). Concentrations up to 20 µg l^{-1} were present in a mid depth maximum in Escambia Bay. Chlorophyll *a* was elevated to a lesser extent throughout Pensacola Bay. By November 5, both surface and mid depth chlorophyll *a* decreased to values consistent with long-term trends.

The distributions of dissolved nutrients before and after Ivan suggest that flushing due to the storm surge and internal nutrient dynamics had a greater influence on nutrient distributions than elevated freshwater inputs. Nutrient concentrations in the Bay after Ivan were within a normal seasonal range (Fig. 3). Most remarkable was a decrease in NO_2^- + NO_3^- concentration in mid Bay bottom waters, which probably resulted from surge flushing, and a nearly twofold increase in bottom water NH_4^+ in upper Escambia Bay. A spatial correlation between elevated bottom water NH_4^+ and hypoxia implies reduced sediments, possibly enriched with storm-related organic debris. By November 5, O_2 increased in the area and NH_4^+ decreased.

Discussion

The physical perturbation of Pensacola Bay associated with Hurricane Ivan's storm surge was large, but the documented effects of the surge and pulse of freshwater inflow were within the range of normal variability. Post-storm freshwater input stimulated an increase in phytoplankton biomass consistent with the effects of flow pulses we have monitored in the past. Increased phytoplankton biomass persisted for several weeks. Hypoxia was also intensified relative to the seasonal norm. We hypothesize that the small and transient effect of the flow pulse relates to the frequent recurrence of such pulses, low human disturbance in the watershed, and moderate water residence time in the system. Extensive wind damage to forests raises the question of whether nutrient export to coastal waters could increase in the future. Our qualitative observations suggest that damage to seagrass beds, salt marshes, and other coastal wetlands was minimal. A few studies have attempted to characterize the effects of hurricanes on fish and fisheries (e.g., Tabb and Jones 1962). Other studies have simply reported what is qualitatively apparent, such as the presence or lack of significant numbers of dead animals (e.g., Valiela et al. 1998). We did not have any quantitative data to address this potentially important consequence of Hurricane Ivan on

Pensacola Bay. Hurricanes are probably an important factor structuring the long-term ecological characteristics of Gulf coastal systems, in the same sense that fires and other infrequent disturbances influence forest ecology (Foster et al. 1998), but they are not necessarily a threat. Evidence that human occupation and modification of the coast has significantly increased hurricane effects, as is apparent in North Carolina (Bales 2003) and the Mississippi River delta (Ko and Day 2004), appears to be lacking here. Human residents of Pensacola appear to have suffered the most, continuing a nearly 500 year tradition that began when ''The Great Tempest'' of 1559 destroyed over half the fleet of Spaniard Tristan de Luna in Pensacola Bay, delaying attempts to colonize the area for another 164 years (U.S. Air Force unpublished data).

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