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Effects of a Hurricane on Fish Parasites

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Abstract. Hurricanes, also called tropical cyclones, can dramatically affect life along their paths, including a temporary losing or reducing in number of parasites of fishes. Hurricane Katrina in the northern Gulf of Mexico in August 2005 provides many examples involving humans and both terrestrial and aquatic animals and plants. Fishes do not provide much of an indicator of hurricane activity because most species quickly repopulate the area. Fish parasites, however, serve as a good indicator of the overall biodiversity and environmental health. The reasons for the noted absence or reduction of parasites in fishes are many, and specific parasites provide indications of different processes. The powerful winds can produce perturbations of the sediments harboring intermediate hosts. The surge of high salinity water can kill or otherwise affect low salinity intermediate hosts or free-living stages. Both can introduce toxicants into the habitat and also interfere with the timing and processes involved with host-parasite interrelationships. All these have had a major influence on fish parasite populations of fishes in coastal Mississippi, especially for those parasites incorporating intermediate hosts in their life cycles. The length of time for a parasite to become re-established can vary considerably, depending on its life cycle as well as the associated biota, habitat, and environmental conditions, and each parasite provides a special indicator of environmental health.

Key words: bioindicator, hurricane, monitor, fish, parasites, microbial agents

Introduction

Hurricanes, tropical cyclones, reflect the power produced by the sea and atmosphere! When someone hears about a natural disaster, especially one involving the sea, that person usually thinks about how it negatively affects humans. This presentation deals primarily with a hurricane's effects on the parasites of fishes but also mentions some examples involving the effects on human diseases and the presence of terrestrial organisms because all three aspects have features in common. It will focus on Hurricane Katrina in August 2005.

Hurricane Katrina spawned in the eastern North Atlantic over the Bahamas on 23 August 2005 as Tropical Depression 12. Based on data from the National Oceanic and Atmospheric Administration (NOAA), the weather condition quickly became Tropical Storm Katrina on 24 August and made a first landfall in South Florida as a category 1 hurricane on the Saffir-Simpson Hurricane Scale. It then entered the Gulf of Mexico, gained strength rapidly, partially because of the passage over the warm water of the Loop Current, and attained category 5 intensity (sustained winds at 280 km/h and 902 mbar, gusts recorded from research plane at 433 km/h, 866 mbar). On 29 August, it was downgraded to a category 3 hurricane but the effect of the earlier category 5 wind speeds on Gulf waters and the massive size of the storm combined to create devastating storm surge conditions for coastal Mississippi, Louisiana, and Alabama. The surge reached 8.2 meters high where I live in Jackson County, with higher and lower surges in other areas of coastal Mississippi depending on the location and geographic configuration; it penetrated 20 km inland along bays, rivers, and bayous. Preliminary estimates placed complete destruction at 90% of all structures within 0.8 km of the coastline. The surge in Louisiana was highest in Plaquemines Parish (4.3 meters), but it was equally destructive to the structures there. Following initial landfall, a progression of storm-induced breeches in the New Orleans levee system resulted in catastrophic flooding of about 80% of New Orleans, located about 4.5 meters below sea level. The city received about 3 meters of flood water in some areas (about 34 billion liters on 30 August). Recent advances in early warning technology resulted in fewer than 2,000 human lives lost from Florida to Louisiana, but the stress, diseases, and other factors in conjunction with pre-existing health conditions caused many more indirect human deaths for the next year or two, especially in Mississippi and Louisiana. The devastation caused by Hurricane Katrina covered a land mass of about 235,000 square kilometers, similar to the size of Great Britain. A portion of this impact to the geography, animals, and people was intensified and the affected area enlarged by the added effects of Hurricane Rita, which struck along the Louisiana-Texas border on 24 September 2005. It was also a category 5 hurricane, and it had sustained winds of 285 km/hr with a pressure as low as 895 mbar with an effect on the coastal marine life in Mississippi as well as further west.

Major human health concerns that gained national notoriety involved potential or actual increases in human diseases transmitted by various mosquitoes and

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contaminated water. Predicted large scale epidemics never culminated (Manuel, 2006; Sinigalliano *et al.*, 2007). Of about 50,000 people in Louisiana evacuation centers, a little fewer than half underwent surveillance at least every few days for the 49-day study period. Influenza-like illness, having a 4.7 average daily incidence per 1,000 persons with the largest cluster containing 47 individuals, and a rash reported by a 2.7 daily incidence were the two most commonly reported communicable disease syndromes. Skin infestation by arthropods in a cluster of 60 cases was the largest reported disease cluster; however the majority of large clusters resulted from over-reporting (CDC, 2006). Of reported illnesses, 25.5% of relief workers and 14.8 % of residents in the New Orleans area had acute respiratory infections and 8.8 and 9.9 %, respectively, had skin or wound infections (CDC, 2006). *Vibrio* cases, including two cases of toxigenic vibrio cholerae O1 (serotype Inaba, biotype El Tor), were confirmed, but no epidemic of cholera developed, and the agent is endemic in the area. Soon after the storm, 22 cases of non-choleragenic *Vibrio* illness were detected in Louisiana and Mississippi. More disease was anticipated because people along the coastal counties and parishes had no electricity, gas, running water, working toilets, telephone service (not even cell phones), or garbage removal for periods of weeks to months, with many still not having some of those services after almost 2 years.

Alterations in the flora, fauna, and geologic perspective in the terrestrial habitats were quite apparent to people losing their homes and living in trailers, tents, or damaged homes and coming into direct contact with the environment. In addition to adding water to breeding grounds for mosquitoes, the hurricane cleared berms and vegetation from most areas near the coast, often several km from the beach. In addition to destroying numerous invasive plants and animals, it created a different, denuded habitat, allowing other invasive species to arrive or to invade further and become better established. Especially notable introduced species that flourished included a variety of weeds, two fire ants, and a widow spider. During the previous 36 years, I had seen about a half dozen specimens of the brown widow spider, *Latrodectus geometricus*, initially introduced from Africa soon after World War II. The spider was less common in coastal Mississippi pre- and post-Katrina than the native southern black widow, *Latrodectus mactans*, and the northern black widow, *Latrodectus variolus*, with all three occurring much more commonly after the storm. For example, after the houses and landscape along a few hundred-meter swath adjacent to the East Belle Fountaine Road just east of Ocean Springs along the beach were devastated and cleared by the storm, a perfect habitat for the neurotoxic venomous spiders was created. My former graduate student Ash Bullard lived in a trailer provided by the Federal Emergency Management Agency (FEMA) on the slab for his prior house that was entirely broken up and washed away. On his lot, he noted black widow spiders abundant anywhere a board or other object covered dirt and the brown widow spider not as abundant but still very numerous in leaf litter, trash cans, and hollow spaces in cinder blocks. They also occurred elsewhere in abandoned buildings, under railings and porches, in mailboxes, under flower pots, and in woodpiles. All the widows reached a peak about mid September 2006, and none was seen by Bullard on 2 March 2007, a couple weeks after fire ants had become abundant. In May 2007, my graduate student Joshua Cook noted that the spiders were less prevalent around his trailer, but a few adults and numerous egg cases were still abundant around many FEMA trailers and woodpiles even after two years post-Katrina. Media shows on gardening still recommend wearing gloves as a preventive measure against the widows. Fire ants, both black and red species, are also introduced and compete with native ants; they were provided an advantage over the native ants by the storm.

Physical differences in the terrestrial habitat as well as direct influence of storm water resulted in a different biotic community; also a gain or loss in some components of the biota helped alter hosts for acquiring parasites. As a human example, in the aftermath of Katrina, a loss of the nine-banded armadillo (*Dasypus novemcinctus*), the primary vertebrate host for the flagellate *Trypanosoma cruzi*, and an increase in human dwellings of the reduviid (kissing bug) intermediate host *Triatoma sanguisuga* prompted a human source for blood-meals. Ten of the 18 tested bugs were positive for *T. cruzi* by PCR and therefore considered responsible for the cited case of human Chagas disease and a health risk until the armadillo population could become reestablished (Dorn *et al.*, 2007).

Life in the sea and coastal rivers and bayous for many species was altered more spectacularly than it was on land, but observations were not as evident to the general public as those involving humans and terrestrial biota. This report separates the factors into four major environmental influences, which did or could have a major impact on parasites as well as other animals in the aquatic environment. These deal with perturbations of the sediments, introduction of high salinity water into the freshwater or low salinity habitats, release and introduction of toxicants into the ecosystem, and disruption of the seasonal dynamics of the host-parasite relationships. Parasites of fishes provide an exceptional indicator for assessing these perturbations, even when maintained in captivity where they also can be affected, either directly or indirectly.

Perturbations of the sediments

Sediments on shore, near shore, and offshore in specific areas exhibited disruption during Hurricane Katrina. Benthos turned over and islands eroded. Footprints of the Mississippi barrier islands were reduced by 25%, but the elevations of the islands were reduced to near sea level with vegetative cover reduced by at least 50% (e.g., Carter et al., 2007). The islands provided unique habitats to numerous plants and animals as well as a buffering first line of defense against hurricanes and related storm events. In their current condition, they are poorly equipped to serve either function (Barbour, 2006). Clay and sandy sediments were lost from some areas and added to others (Otvos and Carter, 2007). Commercial oyster beds in Mississippi Sound became covered by a considerable amount of sediments. A year after Katrina, the harvestable oyster stock was estimated by the Mississippi Department of Marine Resources to be reduced by more than 90%.

One region hard hit by Katrina was offshore from Southwest Pass where the Mississippi River empties into the Gulf of Mexico, a considerable distance south of New Orleans; it was shown by D. Reide Corbett (East Carolina University, Greenville, North Carolina, personal communication) that Katrina's energy was most influential to coastal sediments at an offshore depth of 25-30 meters, where 1 meter of sediments was scoured from the bottom and resuspended, with its corresponding loss of polychaetes, bivalves, and other infauna. Sediments were removed from the delta and added to the continental shelf. Hurricanes Katrina and Rita within one month resuspended, mobilized, and deposited about five times the amount of material normally deposited from the Mississippi River over a one-year period. About 30 cm of deposited sediments settled within a month at a depth of 50 meters off Southwest Pass. Analysis was conducted by looking at pre- and post-hurricane core samples for relative values of ^{7} beryllium, ^{234} thorium, and ^{210} lead, showing the influence of land input, marine input, and time, respectively. Prior studies on Hurricane Ivan off the Gulf coast of Florida showed an absence of macrofauna from the top 15 cm for at least a year.

Fish parasite populations are altered by this perturbation of sediments, and trematodes provide an especially good indication of the macrofauna and environmental health. Since all trematodes have a molluscan first intermediate host other than the exception of a few inshore blood flukes with polychaete first intermediate hosts, completion of a life cycle can be difficult following any perturbation. When the sediments are perturbed, the first intermediate host may be killed, eliminated, or inhibited from reproducing. The sediments may become altered in such a way that the host can not live in them and recruitment is delayed until the conditions are again conducive for habitation and growth of the mollusk. Even when the host species is re-established, it has to acquire an infection, and the trematode has to undergo asexual development to produce infective stages necessary to repopulate the species in the fish host. Depending on the specificity of the digenean species and the various hosts in the cycles, repopulation of the digenean can take from several months to several years.

The Atlantic croaker, *Micropogonias undulatus*, uses the estuary as a nursery ground, and its digeneans, especially those acquired when it feeds in Mississippi Sound as opposed to when it feeds in the bayous, provide a good example of loss of parasites resulting from sediment disruption. *Diplomonorchis leiostomi* is a very common monorchiid trematode requiring two bivalves in its cycle and locally infecting both the Atlantic croaker and the spot, *Leiostomus xanthurus*, a related sciaenid. The monorchiid did not re-occur post-Katrina in Mississippi until February 2006 when some immature specimens were recovered from spot but not croaker. In spite of examining numerous collections of both fishes every few months, it did not show up again until January 2007 in spot and March 2007 in croaker, and, when it did, it occurred in low prevalence and mean intensity of infection. About March 2007, other locally common monorchiids also started showing up in local fishes. For example, *Lasiotocus glebulentis* occurred in the striped mullet, *Mugil cephalus*, and *Lasiotocus* cf. *minutum* occurred in the Gulf killifish, *Fundulus grandis*, (from a low salinity clam).

Unlike being transmitted by a buried clam, the adult hemiuroid trematode *Lecithaster confusus*, adult nematode *Spirocamallanus cricotus* from the intestines and the juvenile nematode *Hysterothylacium* sp. from the mesentery were all probably transmitted to the croaker by copepods. Infections of those three helminths showed up in croaker during March 2006 as did some presumably copepod-transmitted (or by chaetognath or fish paratenic hosts that fed on infected copepods or other infected hosts) tetraphyllidean juvenile cestodes in the spot in February 2006. None of these occurred in most collections; most individuals of these two fishes as well as most of the many fish species in inshore Mississippi harbored few if any parasites. Also, helminths that do not incorporate intermediate hosts like the monogenean *Macrovalvitrematoides micropogoni* that reproduces on the croaker did not reappear as quickly as one might expect. That worm was recorded post-Katrina first in March 2007, when it was relatively abundant.

Seatrouts, fishes related to the croaker, include the spotted seatrout (*Cynoscion nebulosus*), which spends its entire life in Mississippi Sound and adjacent waters and the sand seatrout (*Cynoscion arenarius*), which lives in the Sound and offshore from it. They commonly harbor numerous similar parasites, including several trematodes (Blaylock and Overstreet, 2003), most of which are probably acquired near the barrier islands. However, they exhibited no trematode and few other parasites except some cestode juveniles until August 2006, when the spotted seatrout constituted most of the samples and acquired the acanthocolpid *Stephanostomum interruptum*. By January 2007, the seatrout was infected by the bucephalids *Bucephalus cynoscion* and *Prosorhynchoides caecorum*, which are transmitted by bivalves followed by fish second intermediate hosts; these infections continued to be prevalent and were followed by the snail-crustacean transmitted *Opecoeloides fimbriatus* in May 2007.

In freshwater fishes, species of *Phyllodistomum* infected the urinary bladder of catfishes, centrarchids, and *Fundulus* spp. These gorgoderid trematodes were most likely transmitted from sphaeriid clams buried in the muddy sand and common in the fish hosts before Katrina, but none of the trematodes reappeared until April-May 2007 and then they were rare.

Other freshwater and marine parasites also incorporate members of the infauna in their life cycles. Hosts other than gastropods and bivalve mollusks can host both digeneans and other parasites, and these, not all infauna, include but are not limited to a range of crustaceans from ostracods to decapods (especially copepods, isopods, and amphipods), insects, oligochaetes, echinoderms, chaetognaths, cephalopods, amphibians, and other fish species.

Introduction of high salinity water into freshwater or low salinity habitats

The typical tideland fauna in beaches, marshes, bayous, and lower reaches of the rivers in coastal Mississippi is neither consistent in composition from year to year not from season to season. The dynamics of variation in temperature, salinity, and other conditions result in considerable variation in the prevalence and abundance of most organisms/inhabitants. When the area receives an abundance of rain and the winter and spring weather fronts cause winds to blow toward the south, then the resulting salinity is low, and the low salinity (e.g., 2-6 ppt) populations of gastropods and bivalves are abundant. The coastal salinity preceding Katrina was low, approximating 5 ppt along the coastal marshes. Katrina brought in a surge of high salinity (perhaps 32 ppt) water. An exceptionally warm year and a subsequent drought for several months kept salinity in the bayous relatively high (e.g., > 15 ppt through December 2005) as well as caused wide-scale mortalities of a large portion of the surviving trees as well as fishes from oxygen depletion in restricted areas. This fluctuation in salinity probably influenced biodiversity in these areas more than sediment disruption because the substratum was not scoured as much as in Mississippi Sound and offshore from the barrier islands. We recorded low values of 5-8 ppt in the first portions of both 2006 and 2007.

Fishes and some invertebrates are motile and the estuarine species can usually tolerate or avoid rapid changes. These animals were either not affected, or, after their habit recovered, the animals rapidly returned to their specific habitat or other members were recruited into those habitats. The population sizes of many returned to the same high levels, and in some cases members attained a size larger than average. June 2007 television reports on recreational fishing professed great abundances of most sports fish. The parasites of these fish and invertebrates rather than the fish and invertebrates themselves provide a more "complete" indicator of the biodiversity because the entire series of hosts in each cycle all have to become established and the parasites have to develop. In some cases this takes over three years, and the presence of all the parasites represents the entire biodiversity, including both meiofauna and macrofauna, related to the life histories as well as to the abiotic health of the ecosystem.

Basically, the young fish recruited post-Katrina into the general Mississippi estuary had either no parasites or few parasites that did not require an intermediate host. Larger specimens of fish, those individuals occurring pre-Katrina, had an abundance of parasites, but the species had a longevity over a year. For example, the acanthocephalan *Dollfusentis chandleri*, which lives over a year in the fish, occurred in many large Atlantic croaker many months after the storm, but no young individual or fish born after the storm has exhibited any infection though the present time (June 2007). Monogeneans were prevalent within a year post-Katrina (*Macrovalvitrematoides micropogoni* on the Atlantic croaker, *Gyrodactylus stephanus* on the western mosquitofish, and *Gyrodactylus* spp. on killifishes) as were trichodinids on the gills, but none was in high numbers that would have indicated a stressed condition.

Haploporid trematodes in local mullets, especially the striped mullet, which when young prefers low salinity habitats, were abundant and conspicuous pre-Katrina. The life cycles of the two common species, *Culuwiya beauforti* and *Dicrogaster fastigata*, involve the fish and low salinity gastropods. There is no second intermediate host; the metacercariae of both encyst on algae or substrata that the mullet eat. Post-Katrina, those and other parasites were absent from young fish and decreasing in numbers in large fish present pre-Katrina. In July 2006, a few specimens of each were recovered in mullet from a specific location but not prevalent along the coast until March 2007. This period was again followed by their absence until at least June 2007. Other haploporids in non-mullet hosts have not re-occurred, but some are still present in neighboring states to Mississippi and Louisiana.

In contrast, another mullet haploporid, *Intromugil mugicolus*, perhaps using a relative high salinity snail, had not been seen in local mullet for a few years preceding Katrina and was considered rare in our area. However, numerous irregular samples of mullet post-Katrina revealed the species to be common starting from March 2007. Also, monogeneans, trichodinids, and copepods, none of which use intermediate hosts also were more prevalent at that time than before the storm.

The striped mullet, Atlantic croaker, Gulf killifish, and poeciliid western mosquitofish, *Gambusia affinis*, have been monitored for parasites from various locations in Mississippi for several years. The normal parasite fauna of the three fishes has yet to reappear, has been represented by few species in few locations only, or has recently started to reappear, responding to an elongated period of low salinity. For example, the Atlantic croaker typically has a high species richness, but the first parasites to show up were *Metadena spectanda* and *Opecoeloides fimbriatus*, but they did not reappear until July 2006 and then just in specific locations. A few other species have been seen in low numbers in the croaker periodically since then.

Cyprinodontiforms are extremely good intermediate hosts for a variety of bird and mammal heterophyids and a couple of echinostomatids. Both the fundulid Gulf killifish in moderate salinity and the poeciliid western mosquitofish, *Gambusia affinis*, in freshwater or low salinity were monitored to determine when they started to acquire infections. In June 2006, the Gulf killifish contained a few individual juvenile specimens (encysted metacercariae) of *Phagicola diminuta* and *Ascocotyle angrense*, two of the several heterophyid trematodes that normally infect it and were present in large individual fish when first examined after the storm. Most heterophyid metacercariae can remain infective in the killifish for over a year. Also in June 2006, *Ascocotyle tenuicollis* and *Echinochasmus schwartzi* occurred in the mosquitofish. By February and March 2007, bucephalid metacercariae were also present in juvenile killifish and *Ascocotyle mcintoshi* occurred in juvenile mosquitofish. In June 2006, juveniles of the poeciliid sailfin molly, *Poecilia latipinna*, exhibited *Ascocotyle leighi* and *Echinochasmus schwartzi*, and the sheepshead minnow, *Cyprinodon variegatus*, had heavy infections of *Ascocotyle pachycystis*. As of now, June 2007, I have seen no other heterophyids post-Katrina in these or other cyprinodontiforms. Few other parasites occurred, but the viviparous *Gyrodactylus* spp. on the skin and *Myxobolus funduli* (transmitted by an oligochaete) in gills were common in the Gulf killifish.

In August 2006 in Waveland, Mississippi, where there was less buffering from the barrier islands and most structures were totally destroyed, infections of the coccidian *Calyptospora funduli* first occurred as light intensity of unsporulated stages in young Gulf killifish. High intensity of infections occurred there with sporulated stages in fish present before storm. In August 2006, they also showed up in fish from the east in Halstead Bayou, Ocean Springs, where the liver was over 90% involved with unsporulated stages. This parasite uses a grass shrimp as the intermediate host (Solangi and Overstreet, 1980; Fournie *et al.*, 2000).

Ponds on Horn Island continue to maintain a high post-Katrina salinity, so the snails in the typically low salinity habitats have not repopulated. Consequently, the normal parasites in the fishes have not recovered even through the euryhaline fishes thrive.

In freshwater rivers still in the coastal counties, numerous collections of centrarchids, catfishes, catastomids, fundulids, and other fishes yielded numerous trematode species pre-Katrina, but not until August 2006 did any fish exhibit a trematode. A single channel catfish (*Ictalurus punctatus*) was infected with *Crepidostomum ictaluri*, but with the exception of a clinostome metacercaria in September 2006, no other trematode has been seen. A special attempt was made to obtain specimens of the previously abundant *Plagiocirrus loboides* from fundulids without success (e.g., Curran *et al.* In press).

Salinity changes can also produce bacterial and fungal infections, especially when the fish hosts, just like their human counterparts, become trapped in non-optimal habitats. For example, fishes normally in low salinity develop lesions, typically with *Vibrio* spp. both systemic and in skin lesions, whereas fishes normally in mid- to high salinity develop systemic infections of *Aeromonas hydrophila* and fungal strains of *Saprolegnia* (e.g., Overstreet, 1997).

In contrast with the inshore parasite populations, those in fishes that migrate through the area, remain well south of the barrier islands, and migrate from offshore to inshore, the infections of most did not indicate any influence from Katrina. For example, the bucephalid (acquired from feeding on a fish intermediate host) *Prosorhynchoides ovatus* in the Atlantic tripletail, *Lobotes surinamensis* (Lobotidae), was abundant inshore or offshore both before and after the storm.

Release and introduction of toxicants

Many toxicants remain undisrupted in sediments for years, causing no harm to the organisms in the water or surface of the sediments. Once disrupted by storm activity, dredging, or other actions, the toxicants are resuspended in the water and can affect most hosts and parasites. Some compounds can kill one or more hosts in a cycle, can kill the free living stage of a parasite such as a miracidium, cercaria, or a juvenile nematode, and others can affect the resistance of a host to parasitic infection (e.g., Overstreet, 1993). Action can be direct or it can alter water conditions such as the pH, which in turn could affect the infections. Also, the fish may exhibit either more or fewer parasites than before the storm. Local examples are the acetylene production waste and high aliphatic hydrocarbon levels (825 ppm dry sediment weight) in Lake Yazoo near the mouth of the East Pascagoula River. Lytle and Lytle (1985) showed that suspended sediment from that site can kill entire samples of the mysidacean, amphipod, and fish (*Cyprinodon variegatus*) bioassay animals exposed to either the soluble component or the soluble and sedimentary material. The pH perturbation from the carbide residues measured consistently above 11. Another example is the polychlorinated biphenyls (Aroclor), which leak, get resuspended in the northern Gulf of Mexico, can kill fish (Hansen *et al.* 1974), can make the fish more susceptible to parasitic infection, or possibly kill the parasite but not the host (e.g., Overstreet, 1993).

In addition to lead, arsenic, and, in some cases, chromium in the New Orleans floodwater exceeded drinking water standards, but only lead was greater than in typical stormwater (Pardue *et al.*, 2005). Moreover the high fecal coliform bacterial count (1.4 x 105 MPN/100 ml) and low oxygen concentration (<0.02 mg/L at the bottom of the water column in mid-city after 9 days) was also typical of stormwater. What was distinguishable in New Orleans was the large volume and extensive human exposure rather than the actual toxic levels. Perhaps a close analogy is the "Prague" flood of 2002, with its massive flooding of the Elbe River basin resulting in release of dibenzodioxins and furans into the watershed after the flooding of Spolana chemical plant (Stachel *et al.*, 2004). Levels such as those in New Orleans are highly toxic to fish, whereas those in Mississippi were probably much higher but not a longstanding risk for human exposure; fish that died in large numbers were usually restricted to confined areas and suffocated from lack of oxygen. Most toxicants were short-lived in the water column.

A hurricane such as Katrina also has high winds that produce turbulent mixing in the water column of both volatile and persistent organic and inorganic compounds introduced through spills and through the atmosphere in a poorly understood dynamic (e.g., Jurado *et al.* 2007). When one considers the additional rapid dispersion resulting from the surge, there is little way to assess it, especially when no person is in a physical position to determine the immediate concentrations of toxicants or the fate and effects contributed by the toxicants. Nevertheless, one can still assume that an enormous quantity of all sorts of persistent pollutants was released from the sediments and much more than that amount of persistent and non-persistent pollutants were introduced. A lack of a published reference data base for fish tissue quality in near-coastal areas of the Gulf of Mexico restricts an assessment of the environmental significance of point source contaminants or general contamination. Lewis *et al.* (2002), however, has provided levels of inorganic and organic contaminant concentrations in edible tissue of fish collected from eight coastal areas in the northern Gulf of Mexico receiving wastewater discharges and from two reference locations. Some indeterminable amount of the decreased biodiversity of fish parasites results from the effects of the toxicants on the various hosts.

The parasites in a sample of 30 histologically sectioned specimens of the western mosquitofish, *Gambusia affinis*, taken from near Back Bay of Biloxi 12-months post-Katrina were evaluated from a monitoring station continuously contaminated with three heavy metals and some organic compounds to determine if infections were similar to that reported pre-Katrina (Overstreet, 1997) and later, more strongly affected by possible additional contamination, or less affected, perhaps because of dilution of the contaminated water and sediments. The high salinity surge water from Katrina appeared to flush out and remove the heavy metal and perhaps affect the freshwater intermediate hosts, at least temporarily, from the habitat. Only one harmful parasite was seen, a myxosporidian that appeared to rapidly reproduce throughout various host tissues and overpower the host defenses. Previously, this parasite was experimentally demonstrated to kill a large portion of the fish stock from that location and occurred in relatively high prevalence, even though apparently absent from samples in several other localities. Four parasite species were present, including the introduced Asian fish tapeworm (*Bothriocephalus acheilognathi*) in two individuals and an acanthocephalan cystacanth in the liver of one individual, neither of which was present in earlier samples and both of which were acquired from feeding on crustaceans. Two individuals contained a diplostomoid metacercaria that was present previously. In all, 80% of the fish showed no parasite in two examined slides per fish compared with 7% of similar pre-Katrina samples.

Disruption of seasonal dynamics of host-parasite interactions

Infectious stages of parasites typically co-occur seasonally with their susceptible hosts. For example, the haploporid trematodes *Culuwiya beauforti* and *Dicrogaster fastigata* discussed above from *Mugil cephalus* first reappeared in July 2006. Then no infected fish was seen in most areas until March 2007 but finally absent again until at least June 2007. High prevalence and mean intensity of infections typically occur in the spring, summer, and autumn months. Apparently, infected snails have not become re-established along the coast in the two years following the storm. Perhaps not enough snails were present or infected in the general area, only snails from few specific locations were infected in 2006, snail populations had not reached their normal levels (we have not seen the snails in some typical locations), or there is some other inconsistency. We experienced low salinity waters in the bayous of 5-8 ppt in January-March of 2006 and 2007, but the snails hosting the above and other trematodes have not returned and some of the higher salinity (e.g., 15 ppt) snail species have become established at low salinities, at least temporarily, and are apparently replacing the low salinity species (Heard *et al.*, 2002). This shift definitely influences the helminth populations.

Some parasitic stages live in their intermediate or final hosts for several years. This serves as a good means to maintain a parasite population even though environmental condition might temporarily interrupt the life cylc. In the case where a hurricane eliminates a species rather than reduces it, the cycle could be broken for several years, especially when seasonal salinity and temperature conditions do not mesh synchronously with the parasitic stage.

Oligochaetes host some myxosporans and nematodes. Many tubificids live for a few years and production of infective myxosporan stages is seasonal and, as such, few infections have re-appeared. The nematode *Eustrongylides ignotus* occurred abundantly in fish intermediate and paratenic hosts in specific low salinity localities in Mississippi. The Gulf killifish has been an exceptional host, and some large fish with large worms were seen for about a year after the storm. It has not been seen in any fish that could represent a post-Katrina infection.

Captive conditions can stress fish

In most cases, facilities which housed fish, whether they were commercial ponds, public displays, research facilities, or personal aquaria, lost all or most of the captive stock. In many cases, the storm washed away both the facilities and inhabitants and in others it flooded them. In all cases, the power was lost and the remaining fish, if any, died from oxygen depletion over the several-week period. In most places electricity was not restored for weeks, and all generators were ruined or inoperable. Perhaps following the storm, resurrected facilities were more vulnerable. Spotted seatrout in our Gulf Coast Research Laboratory research culture facility all died during the storm, but the restocked fish did acquire an infection of *Amyloodinium ocellatum* several weeks after being re-established. Whereas this outbreak could not be attributed directly to the hurricane, *A. ocellatum* in wild fish appeared to be especially prevalent locally (Reg Blaylock, personal communication), making contamination of the systems easy.

In contrast with fishes, most specimens of the bottlenose dolphin (*Tursiops truncatus*) were placed in swimming pools distant from the beach immediately pre-Katrina and not crowded, like fish are in both production and display facilities. The dolphin remaining in a destroyed local oceanarium swam out to sea but came back after the storm subsided to obtain food and attention from their handlers. A series was then transferred to some well-filtered portable circular raceways and maintained for a lengthy period by veterinarians, regular trainers, and qualified US Navy personnel. None died. We examined eight dolphins, all of which had been administered high daily doses of the fungicide fluconazole (Diflacan, Pfizer Pharmaceuticals). Nine fungal species, four of which are mammal pathogens, still could be cultured. Species richness was greatest, seven, from blowhole isolates, with four from lesions and filters and filtrate, and none from the blood (Kennedy *et al.*, 2006). Most parasites of captive dolphin, such as dysteriid ciliates (Ma *et al.*, 2006), apparently do not harm their hosts. Once the dolphins were transferred to less-confined spaces in the Bahamas, their infections apparently cleared.

General aspects

Hurricane Katrina caused an apparent lack of many parasite species for a long period, at least two years as of this report. A loss of intermediate hosts resulting from lost habitat or altered ecological conditions halted new infections of parasites. However, when a fish undergoes local migratory activity, it can acquire some parasites, producing a lower intensity of infection than typical. The freshwater cestode *Bothriocephalus acheilognathi* constitutes the only post-Katrina introduced aquatic parasite of which I am aware, and it had occurred pre-Katrina several kilometers to the east in the adjacent Escatawpa River system. It, however, is known to cause mortalities in cultured carp in Mexico and in other fishes where it has been introduced.

Recovery of parasites usually depends on recovery of the intermediate hosts. Re-establishment differs for each parasite. For example, the eastern oyster (*Crassostrea virginica*), first or second intermediate host for a few trematodes, develops from a spat attached to the shell of another oyster or some other hard substratum. Management of this commercially important product can speed up the process by depositing recent or fossil shells of *Rangia cuneata*, pieces of oyster shells, or other material over old oyster reefs that had been covered by storm-deposited sediments so that new spat could have an optimal-sized hard substratum on which to attach and develop without competition. In contrast, most bivalves may take much longer to have optimal sediments in which to develop. The trematode *Diplomonorchis leiostomi* of spot, Atlantic croaker, and other sciaenids requires two such bivalves, and it has yet to re-establish in the fishes.

When the presence of a parasite species after a hurricane or other dramatic activity occurs in atypically low or unexpected numbers, there are several possible reasons. They may have low specificity, with a variety of intermediate or final hosts, and one of those hosts may maintain the parasite population. Also, when an intermediate host occupies a multitude of habitats or geographic localities, those from one habitat or location can maintain the parasite population. Habitat alterations can support atypical hosts for a specific geographic locality, resulting in different or unexpected parasites.

To properly assess changes in parasite populations after a hurricane, which by definition is a rare event, fish recruited after the storm, typically young-of-the-year individuals, should be examined for the parasites. Since some parasites, whether adult or juvenile, can survive for several years in a host, attention has to be directed toward the life histories of the parasites used as indicators. Also, migratory fishes entering a perturbed area usually do not show an absence or low number of parasites, unless the host acquires the parasite in the perturbed area and the cycle is restricted to that area of investigation.

Re-establishment of parasites that disappear after a hurricane seems to take one, two, and perhaps a few more years, depending on the species and situations as indicated by the "short-term-loss" examples provided. When specific substratum that is unique for a specific parasite becomes disturbed, that parasite might be a "long-term-loss" and may require many years to become re-established. Such a long-term loss might also occur when one of the necessary hosts in the parasite cycle is replaced or its population drastically reduced.

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