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A Sigh of Relief: Respiratory Illness In Areas Recently Affected By Hurricanes

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Abstract

This report investigates what physical, biological, and political mechanisms contribute to the observed increase in respiratory illness following the passage of a hurricane. No primary data was collected for this study, and all data presented in it was previously published by accredited scientific sources. The data used for this study is representative of large geographic and temporal scales, but a significant amount of the data comes from the Gulf Coast of the Southeastern United States during the 2005 hurricane season. Additionally, in this study, respiratory illness is generally classified in one of three ways, Acute Respiratory Infection (ARI), Upper Respiratory Symptoms (URS), and Lower Respiratory Symptoms (LRS). This report first establishes a positive link between hurricanes and respiratory disease and then offers several potential ways to minimize the increase in respiratory disease following future storms.

Preface

To begin, I wish to offer my indefatigable gratitude to the many people who aided me throughout the various stages of my thesis project. First, the members of my committee: Dr Darin Toohey, Dr Dale Miller, and Dr Jill Litt. Each of them was absolutely invaluable in the process of creating, researching, writing, and editing my project, and I can say with full confidence that this project would not have been at all possible without their combined efforts. Additionally, I would like to extend thanks to my father, Dr Christopher Healey, for his assistance in the process of writing and editing my project, and for gladly accepting the rather significant burden of financing the project.

My inspiration for this project came during the midwinter of my junior year as an undergraduate, when I fell victim to pneumonia. During my recovery, I became curious as to what caused pneumonia and how it could be transmitted, and the idea for my project was born. I have always had a fascination with hurricanes and other extreme weather events, and memories of a favorite TV show from childhood made me curious about epidemiology, and so I decided to combine the two and investigate whether there were significant patterns of pneumonia incidence and prevalence in areas hit by hurricanes. However, my initial research turned up little in the way of useful information. With the guidance of my committee, I began to reshape my research to be more comprehensive in some areas and more restrictive in others.

My research question appeared to be almost completely novel in its scope and purpose, and the thought that I could be investigating something that had never been examined before appealed to me greatly, and was a driving force in my decision to prepare and defend an honors thesis. I have always felt a deep passion for science, and this project represents, by and far, the most significant achievement to date of my career as a scientist, and it is my hope that this project will serve to prepare me for a future dedicated to identifying problems and scientifically solving them for the good of humanity.

Introduction

Hurricanes are notorious for the trail of death and destruction that they leave in their wake as they make their way off of the Atlantic Ocean and through the Southeastern portion of the United States. They are capable of destroying entire cities, shutting off power for weeks on end, and killing hundreds or even thousands of people. Behind the readily observable and immediately destructive forces of storm surge, high-speed winds, and flooding lies the less perceptible but equally formidable adversary of infectious disease. When politicians and researchers discuss the death toll of a hurricane, nearly all of the consideration goes to the forms of bodily harm that manifest their effects immediately, namely drowning and traumatic injury. In this project, I intend to elucidate an extremely prevalent but commonly overlooked public health threat that arises in the days and weeks following a hurricane: respiratory illness. It is my objective to create an intellectual foundation that will allow me to conclusively answer the question "What physical, biological, and political mechanisms contribute to the observed increase in respiratory illness following the passage of a hurricane?"

Respiratory illness is consistently among the most prevalent of all public health concerns that face hurricane victims, and yet it is still often completely overlooked when creating hurricane and public health-related legislation and policy. While the increase in incidence and prevalence of respiratory disease is principally brought about by scientific and natural mechanisms, it is also partially brought about, and exacerbated by, public policy problems. There is considerable evidence that existing hurricane and public health policy is largely insufficient and ineffective at both preventing the transmission of respiratory illnesses and providing the necessary care and treatment to hurricane victims who exhibit symptoms of respiratory illness, regardless of severity. It is my objective to not only summarize and analyze the findings of the pertinent scientific research that has been previously conducted, but also to consider existing hurricane and public health policies and discuss where and why they fall short. In addition to this, I will suggest actions that can be taken and policies that can be put in place in the future to better prevent the propagation of disease and allow victims of hurricane-related respiratory illness to access the healthcare and medication that they need.

The information that makes up this thesis project is presented in a three-tiered manner, with one section pertaining to natural scientific (mainly biological and physical) processes, another discussing public policy and political processes, and another section in which I will suggest several actions that could be taken in the future that could potentially limit the effects of respiratory illness. I have separated these sections to assist in showing that the observed increase in respiratory illness cannot likely be attributed entirely to either natural processes or political processes, but rather a combination thereof. The three-tiered approach is employed in an effort to increase the comprehension and understanding of the information and data presented, and one of the objectives of this project is to instill in the readers a comprehensive understanding of why respiratory disease is so rampant following hurricanes. My intention for this project is to compile data and present solutions in a fashion that could someday be used to create policies and medical practices that would save lives, and for this, a comprehensive understanding of the underlying mechanisms of disease propagation is essential.

The first of the aforementioned sections will be a comprehensive review of literature and statistics published by research professionals and government agencies including, but not limited to, the Centers for Disease Control and Prevention (CDC), the National Weather Service (NWS), the National Oceanographic and Atmospheric Administration (NOAA), and the National Institute of Environmental Health Services (NIEHS). This section will provide data presented in an array of forms and synthesize that data into a single aggregate body of evidence.

The second section will be an analysis and discussion of existing hurricane and public health policies, including how they are insufficient or ineffective and how some of these insufficiencies can be strategically eliminated in a cost-effective and timely manner. The policies discussed in this section will include emergency aid distribution and funding, evacuation procedures, emergency stockpiles, and other political problems that arise following a hurricane. One of the greatest challenges that face emergency response workers and healthcare professionals is managing the flow of information across local, state, and regional boundaries, and there have in the past been many issues with states sharing epidemiological and disease surveillance data between themselves.

Due to the astounding array of public health issues that arise following a hurricane, not all issues relating to the respiratory system could be included in this project for the sake of time and maintaining uniformity of data. One of the most relevant public health concerns in the days and weeks following a hurricane, but one not considered in this project, is how to track and provide ongoing care to patients of chronic illnesses such as tuberculosis (TB), and Acquired Immune Deficiency Syndrome (AIDS), especially when large numbers of victims have been displaced or evacuated by the storm. Studies have shown that as many as one in five patients that receive care for a chronic illness quit the treatment after a hurricane. (MMWR, 2006)

The relatively large geographic and time scales of this project and the standardized manner in which the research and conclusions are presented will allow it to appeal to both professional and amateur scientists alike. It is my hope that this project will be read by my peers as well as being read by professionals who may either consider my suggestions or use the compiled research as a starting point for a more in-depth study. While many studies have been conducted that are somewhat pertinent to my research question, there have been no other quantitative surveys of respiratory symptoms following hurricanes. Many different public health and safety publications were used in compiling the research and data that are presented in this project, and I found the Morbidity and Mortality Weekly Report and similar publications to contain a wealth of valuable information.

Background

Hurricanes

A hurricane is an extraordinarily powerful type of tropical cyclone, and tropical cyclones are among the most powerful and destructive of all natural phenomena. Tropical cyclones are low-pressure storm systems that form over the warm surface ocean waters of the equatorial oceans, both Pacific and Atlantic. While the tropical waves from which hurricanes form are quite common, with one occurring roughly every four to five days, only a few storms ever strengthen enough to be considered hurricanes. Hurricanes can present many forms of danger to both coastal and inland areas, including extremely heavy rains, flooding, storm surge, extreme winds, and even tornadoes.

Tropical waves of low pressure that can eventually strengthen into hurricanes occur over low latitude oceans, and tend to be pushed westward by equatorial tradewinds until they either spin out over the open ocean or intensify into a more severe storm. When conditions are just right, tropical cyclones can intensify as they track across the ocean, and a tropical cyclone can exist in one of four different stages of intensity from tropical disturbance to hurricane. The initial low-pressure waves that begin the intensification process often form severe thunderstorms, which provide the initial lifting mechanisms for hurricanes to strengthen. Air rushing in from all directions collides in the low-pressure center of these thunderstorms and is then lifted from the surface. The Coriolis effect, or the apparent deflection of moving objects caused by Earth's rotation, causes the winds rushing toward the center to rotate counter-clockwise as they go. As the warm and moist surface air is lifted, it expands and cools, eventually reaching the dew point temperature. When a parcel of air reaches its dew point temperature, the moisture contained in the air condenses from a gaseous form into a liquid form and releases enormous amounts of energy in the form of latent heat in the process. This latent heat energy is what fuels tropical cyclones as they intensify and move over warm ocean waters.

As previously stated, a tropical cyclone can belong to one of four classes depending on its intensity and size. A distinct group of clouds, showers, and thunderstorms that maintains its identity for at least one day is a called a tropical disturbance, and the tropical waves that sometimes form hurricanes are a type of tropical disturbance. When the storm strengthens enough to have closed circulation (counter-clockwise winds around the central low pressure) and have one-minute sustained winds of 33 knots (38 miles per hour) or less, it is classified as a tropical depression. When sustained winds reach 34 knots (39 mph), the storm is given a name by the National Weather Service and jumps to the category of tropical storm. A storm only becomes a hurricane when the one-minute sustained winds reach speeds of 64 knots (74 mph), though peak winds in a hurricane have been known to reach 155 knots (180 mph) or more.

A hurricane will either intensify or weaken depending mostly on whether the hurricane is over warm water, cold water, or land. In a situation similar to Hurricane Katrina, where a hurricane sits atop very warm waters for several days, the storm is capable of strengthening enough to jump several categories in intensity, sometimes even going from a category one storm to a category five storm in just a matter of days. Conversely, if a hurricane sits atop cooler oceans or land, then the storm will decrease in intensity and weaken until it simply spins itself out. Once the winds of a storm reach hurricane-strength speeds, they are classified according to the Saffir-Simpson scale, which divides hurricanes into five categories based on the maximum sustained wind speed measured in the storm. A Category One hurricane has one-minute sustained winds of 74-95 mph, a Category Two hurricane has winds of 96-110 mph, a Category Three of 111-129 mph, a Category Four of 130-156 mph, and to be considered a Category Five storm, sustained winds must reach 157 miles per hour or greater. Hurricanes that reach a classification of Category Three or higher are considered major hurricanes because of the potential damage and loss of life that they present, and on average one major hurricane hits the United States per year.

After tropical cyclones make their way westward at low latitudes, they often begin to follow a more northward track across the Caribbean, and they sometimes strengthen even more as they go. While the general trends of hurricane paths are well understood and modeled, it is still nearly impossible to predict exactly where and when a hurricane will make landfall, and this unpredictability is a major contributor to the dangers that hurricanes pose to people living in coastal areas. The NWS issues forecasts for when, where, and with what intensity hurricanes will hit land, but unfortunately these forecasts and the evacuation orders that accompany them are all too often ignored.

Many different graphical representations of hurricane forecasts are issued by the National Hurricane Center and the Central Pacific Hurricane Center, but these graphics reflect the high levels of uncertainty present in storm forecasting. Graphics issued usually include relative probabilities that a certain degree of severity will hit a certain area, and forecasts may include landfall locations, storm surge levels, rainfall accumulations, and gusts and sustained wind speeds.

A hurricane can damage coastal and inland areas in many different ways, some more immediate and others lasting longer. These may include flooding due to heavy rains and storm surge, extreme winds, lightning, tornadoes, and formation of rip tides in waters near the coast. These destructive forces, and many more, can combine to kill hundreds or thousands of people and cause many billions of dollars worth of damage. It is often difficult to adequately prepare for hurricanes because of the unpredictability of their tracks and the relatively short timescale on which they develop and strengthen, as well as the array of threats they pose.

As a hurricane approaches land, it causes water to pile up between the storm and the coastline, and this 'pile' of water, known as storm surge, can be among the most destructive threats posed by a hurricane. As the hurricane moves closer to land, the storm surge continues to pile up until the center of the storm moves onto land and pushes the water with it. The rise in water level is fairly slow at first, but as the center of the hurricane get closer to land, the water continues to rise higher and higher and is capable of reaching levels of 25 feet or greater above mean sea level. The severity of storm surge experienced fluctuates largely depending on the size and intensity of the storm, and its direction of travel relative to the coastline. The most destructive hurricanes often travel nearly perpendicular to the coastline, and when this happens, the forward motion of the storm combined with its rotational motion cause extreme levels of storm surge in the front right quadrant of the storm.

Another variable that can greatly influence the severity of storm surge is the naturally occurring cycle of tides. If a hurricane makes landfall at a time that corresponds with high tide, then storm surge rises even higher and is known as storm tide. The combination of high winds, storm tide, and battering waves can be deadly and cause tremendous property damage along areas of coastline hundreds of miles wide. The astounding volume of water capable of being pushed ashore by storm surge can be extremely destructive when combined with hurricane-force winds. With a single cubic yard of water weighing nearly 1700 pounds, the stability of even the best-engineered structures can quickly become compromised when large volumes of water are moved quickly. In addition to the destruction of buildings and other structures, storm surge can erode beaches and demolish bridges and roads in coastal areas, putting enormous restrictions on transportation and necessitating millions of dollars worth of repairs.

Hurricanes can contain tornadoes, both far away from the center of the storm in the rain bands and close to the eyewall, and these tornadoes can cause damage in addition to that caused by the main storm. While tornadoes spawned by hurricanes are often relatively weak and short-lived, some can be extremely powerful. The frequency of occurrence and severity of these tornadoes is highly variable from storm to storm and is therefore quite difficult to forecast with any degree of accuracy.

Another of the significant threats posed by a hurricane are the torrential rains. Hurricanes are capable of dumping six or more inches of water in a short period of time, and this volume of rain falling in such a short period of time is often enough to trigger massive flooding that can last for arrive in moments in the form of flash floods, but can also persist for days along rivers and streams. Flooding caused by rain is one of the greatest threats to inland communities that are hit by hurricanes. This is partially because the amount and location of rains can be difficult to accurately predict, as rains are influenced by factors such as storm intensity, direction of storm movement, and the topography of the land.

Infectious Disease and Respiratory Illness

Disease can be defined as a disorder of structure or function in a human that produces specific signs or symptoms and is not the direct result of a physical injury. Infectious diseases are a group of conditions that are caused by certain types of microorganisms present among those that live and colonize on and in the human body. While many different types of microorganisms can be found both on and in the body, including bacteria, viruses, parasites, and fungi, only certain types are human pathogens (harmful to people). Interestingly, a significant number of the organisms that cause disease in humans are only capable of affecting humans. The immune system, or the body's natural defense mechanism against disease, is sufficient so that some pathogens are only threatening when conditions are perfect for them to rapidly reproduce and manifest their effects on the body.

Different types of infectious disease are caused by different pathogens, and the symptoms of a disease are the result of the interplay between the pathogenic microorganism and the body's defenses. Even though relatively few microorganisms are pathogenic in humans, there are still enough unique types to cause a dazzling array of symptoms, and signs and symptoms common to infectious disease include heightened internal temperature (fever), loss of appetite, fatigue, and muscle aches. Infectious diseases can be transmitted from person to person in numerous distinctive ways, and each disease-causing pathogen has its own preferred method of transmission.

Infectious microorganisms are commonly classified according to the state of the host's immune defenses when the disease is contracted, and this leads to two general classifications, primary pathogens and opportunistic pathogens. Primary pathogens are those that cause disease as a result of their presence or activity in an otherwise healthy host. Opportunistic pathogens, however, are those that cause disease only in a host with depressed defenses, and immune defenses can be depressed by genetic defects, exposure to antimicrobial drugs or immunosuppressive chemicals such as chemotherapy, and as a result of an immunosuppressive infectious disease such as HIV.

Infectious diseases can be transmitted from host to host by a diversity of unique mechanisms, and understanding the method of transmission is fundamental to understanding the biology of the pathogen and the disease that it causes. Each different type of pathogen has a method of transmission that is most effective, and the preferred type of transmission often corresponds to area or function of the body that is most affected by the disease. It is not uncommon for the symptoms of a disease to facilitate in the transmission of the pathogen to other hosts, such as in cases of respiratory infection, where an infected person's coughing and sneezing aerosolizes the pathogen and aids in its transmission from person to person.

A very common mechanism of disease transmission is through direct contact with an infected individual, and this contact may take several forms. The mechanism by which infectious disease is most frequently spread is direct human to human to contact. The direct transfer of pathogens from one person to another can occur when an infected person kisses, touches, coughs near, breathes on, or sneezes on another person. Additionally, disease transmission can occur through direct contact with bodily fluids, which often occurs as a result of sexual contact or blood transfusion. The infected person need not show any outward signs or symptoms of the disease they carry, they can be a carrier of a dormant form of the disease and still transmit it to another person.

Another common form of direct contact that is sufficient to allow for transmission of infectious diseases is human to animal contact. If a person is bitten or scratched by an infected animal or an animal that carries the pathogen on it, the disease can easily be transmitted from the animal to the person. Handling infected animal waste can also lead to infection, even if no direct physical contact has occurred with the animal itself. Yet another type of direct contact by which disease can be transmitted is mother to unborn child, as a mother can inadvertently pass disease to her unborn child through the umbilical cord or through the placenta.

Another mechanism of infectious disease transmission is indirect contact with an infected individual, often through contact with a surface or object contaminated by the infected person. Pathogens can linger and live on fomites (foreign objects such as doorknobs, coins, or faucet handles that are capable of becoming contaminated with a pathogen and serving in its transmission), and if a human touches a fomite and then touches their eyes, mouth, or nose without washing their hands, disease transmission can occur.

A mechanism of disease transmission that is especially prevalent in the days and weeks following a hurricane is the consumption of or contact with contaminated food and water. Infectious diseases can be transmitted to a large number of people in a short amount of time if common food and water sources become contaminated by pathogens. Pathogens that are often transmitted in this fashion include *Escherichia coli* (E coli), bacteria belonging to the genus *Salmonella*, and many others.

Another mechanism of disease transmission is vector-borne transmission, which can be further categorized as mechanical or biological. An example of a mechanical vector could be a housefly that lands on infected feces and contaminates its appendages, and then lands on a person's food, thus contaminating the food. Conversely, a biological vector harbors the pathogens within it, instead of on the outside. Transmission of the disease takes place when an infected insect bites a person and passes the pathogen to a human host. Biological vectors can include arthropods (insects) such as mosquitoes, fleas, ticks, and lice, but may take on other forms as well. Pathogens that rely on biological vectors to transport them from host to host are often completely dependent on the vector, and are unable to carry on their life cycle without it. Well-documented vector borne diseases include malaria, dengue fever, and West Nile Virus (transmitted by mosquitoes), and Lyme disease (transmitted by ticks).

Epidemiology, or the study of the patterns, causes, and effects of health and disease conditions within a population, is crucial to understanding disease transmission and creating effective public health policies. Epidemiologists examine the times and locations of disease outbreaks and determine if the disease outbreak was sporadic (random/occasional occurrence), endemic (common to the region in which the outbreak occurred), epidemic (unusually high numbers of infection in a region), or pandemic (a worldwide epidemic). Disease surveillance and screening practices are often conducted for the sake of gathering data for epidemiological studies, and will be discussed in greater detail later in this project.

This project focuses on infectious diseases that manifest themselves in the human respiratory system and are therefore classified as respiratory diseases. Respiratory diseases are extremely common across the world, and according to the World Health Organization (WHO), lower respiratory infections are consistently the leading cause of mortality (death) due to infectious disease worldwide. The frequency at which humans breathe and the amount of potentially contaminated outside air that must be brought into the body causes the respiratory system to naturally lend itself to attack by pathogens, resulting in infection and disease transmission.

The human respiratory system refers to the organs and tissues that allow for gas exchange to take place, and include the mouth, nose, sinuses, windpipe (trachea), airways (bronchi and bronchioles) and air sacs (alveoli). When pathogens find their way into a person's respiratory system, they are capable of manifesting their effects in both the upper respiratory system (nose, throat, sinuses, and trachea) and the lower respiratory system (lungs: bronchi, bronchioles, and alveoli), and are often initially categorized according to which region of the respiratory system they affect.

Most of the data that was used in this project measured prevalence and incidence of respiratory illness defined as upper respiratory symptoms (URS), lower respiratory symptoms (LRS), or acute respiratory infections (ARI).

Classification	Common Examples
Acute Respiratory Infection (ARI)	Common Cold, Pharyngitis, Laryngitis, Bronchitis, Pneumonia
Upper Respiratory Symptoms (URS)	Common Cold, Tonsillitis, Laryngitis, Sinusitis
Lower Respiratory Symptoms (LRS)	Pneumonia, Tuberculosis, Bronchitis

Acute respiratory infections (ARI) are a classification of infectious respiratory disease that include the common cold, pharyngitis, laryngitis, bronchitis, and pneumonia. ARI pose a significant threat to public health, as they are some of the most prevalent infectious diseases on Earth, and they often have high mortality rates and are associated with high economic costs. Though prevalence and mortality rates are highly variable between and within continents, ARI accounts for more than six percent of total worldwide mortality, and over 75% of worldwide deaths associated with ARI can be attributed to pneumonia. While ARI can on occasion be fatal to a healthy person, most mortality associated with them is in people with compromised immune response systems, namely young children and old people. Upper respiratory infections are often relatively less severe than lower respiratory infections, and examples of common upper respiratory infections include the common cold, tonsillitis, laryngitis, and sinusitis. Lower respiratory infections are quite common worldwide, both in developing and developed countries, and can become severe or even life threatening if left unchecked. Frequently seen examples of lower respiratory infections include pneumonia, tuberculosis, and bronchitis.

Methods

Research

Restrictions on the amount of time and money available for this project caused me to be unable to actually conduct any of my own experimentation or data collection, and therefore I have no experimental subjects of my own to report on, nor do I have any primary data that required statistical analysis. This project relies entirely on the work of other scientists for data and statistical analysis, and because of this, my methods section will elucidate the research and construction process, as well as giving some light onto the methodology used in the studies cited for this project.

Due to the large scientific scale of my research question, the research contained in this project comes from a variety of different sources, most of which are either peer-reviewed scientific publications or government health and safety publications. The severity of hurricanes and the amount of press that they tend to generate allowed me relatively easy access to general information on hurricanes, often from news publications or websites, but in an attempt at maintaining objectivity, I tried to only include and cite sources of information that were published by reputable and objective sources.

I used many different research methods to find the studies that I included in the creation of this project, but a majority of the research utilized the online Academic Search Premier function provided by the University of Colorado library. The multifaceted nature of my idea necessitated the use of an array of search keywords to find the studies and data used to create this project, and some of the more commonly used ones included ‘pneumonia’, ‘respiratory illness’, ‘respiratory symptom’, ‘respiratory infection’, ‘hurricane’, ‘tropical cyclone’, ‘disease surveillance’, ‘disease transmission’, and ‘natural disaster’.

Though numerous somewhat-related studies exist, I attempted to only use studies that pertained specifically to the topics I was researching. In cases when I was unable to locate or access applicable data or studies, I would look to my committee members and other helpful resources, such as the Government Publications specialist at the University of Colorado library, and through those I was able to access data and studies that would have otherwise proven very difficult or impossible to get.

The most commonly cited sources in this project are publications that are put out by the CDC and other government agencies, and include the Morbidity and Mortality Weekly Report (MMWR), the Journal of the American Medical Association (JAMA), the Journal of General Internal Medicine (JGIM), the American Journal of Public Health (AJPH), and Public Health Reports (PHR). Of these publications, some were far more applicable to my field of study than others (such as the MMWR), and those are where a majority of my data and graphics come from.

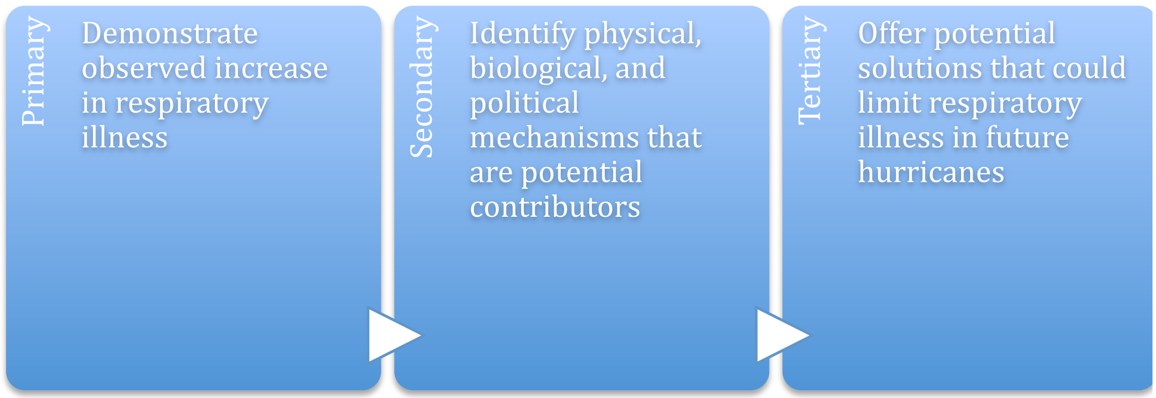
In particular, the MMWR tended to have studies that gave data that was extremely useful both in what was being measured and the manner in which it was presented.

In addition to the aforementioned publications, information used specifically to compile my background section comes from a wider variety of sources than just scientific and governmental publications, including reputable health science centers such as National Jewish Health Center and the Mayo Clinic. The National Weather

Service's National Hurricane Center website and the Weather Channel's Storm Encyclopedia both proved very helpful in describing the formation and life cycle of hurricanes in layman's terms.

To begin research, I first set out looking for studies that would help me definitively demonstrate that there is, in fact, a measurable increase of respiratory illnesses following a hurricane, and from there the scope of my research continued to narrow and narrow. The next step in research was to identify and investigate different variables that could potentially contribute to the observed increase in respiratory disease, and this led to a great deal of further investigation of a few physical variables such as flooding, mold growth, demolition/rebuilding efforts, and air quality, as well as several political variables such as emergency response policy and inter-state cooperation with relief efforts.

I set out to accomplish three distinct levels of goals with this project, with each new level building on the information presented in the previous level. First, I needed to provide evidence that would demonstrate that there is, in fact, an increase in the incidence and prevalence of respiratory illness. After this had been accomplished, I sought to identify several physical, biological, and political mechanisms that could potentially contribute to the observed increase. Finally, I offered a number of actions that could be taken to potentially limit the increase in respiratory illness seen in the aftermath of future hurricanes.



Analysis

The various forms of data that I used to create this project, while similar in their scope and method of presentation, often had minor differences in either what they investigated or how they reported their findings. To account for this, I grouped the studies generally by what symptoms they investigated (ARI, LRS, URS, CO poisoning, asthma) and, when possible, by geographical or temporal relativity. Hurricane Katrina, for instance, generated massive amounts of publicity and press coverage, which led to significantly higher numbers of scientific investigations than less severe storms, and therefore a significant amount of the data and studies cited relate to Hurricane Katrina and the Gulf Coast, with specific emphasis on New Orleans and other areas of the American southeast.

While data that quantifies respiratory illness in the wake of a hurricane is fundamental to this project, it is only put into context when juxtaposed with pre-hurricane statistics to be used for comparative reference. When possible, I have presented my research in a manner that will not only illustrate rates of respiratory disease incidence and prevalence but also provide insight into how the given rates compare to averages in times when hurricanes are not present.

Findings

Incidence and Prevalence of Respiratory Disease

Studies have proven that both prevalence (number of individuals affected at a certain point in time) and incidence (number of new cases reported in a certain elapsed time, i.e. a year) of respiratory illnesses tend to increase immediately following a hurricane and remain elevated for up to six months after the passage of the storm. (Cummings, et al. 2008, Rath, et al. 2011) The following studies have been grouped by which particular form of respiratory disease they investigate or quantify, although there is inevitably some overlap between categories.

The hurricane season of 2005 was anomalously severe in many different ways, and for that reason a majority of the data presented will be from storms of that season, namely Hurricanes Katrina and Rita. The 2005 Atlantic hurricane season saw the formation of fifteen hurricanes, four of which (Emily, Katrina, Rita, and Wilma) recorded sustained winds of 156 miles per hour or greater, thereby earning them Category Five status on the Saffir-Simpson scale. Previous to 2005, the worst hurricane season on record (1969) had recorded twelve hurricanes, and two different years (1960 and 1961) had recorded two Category Five hurricanes in one season, but there had never been four in a single season. Furthermore, three of the ten strongest Atlantic hurricanes ever recorded occurred in 2005, and one of them, Hurricane Wilma, set a record for the lowest barometric pressure (and therefore the most intense cyclone) ever measured in the Atlantic Basin. A normal reading for barometric pressure at sea level would be approximately 1013 mbar, and at its peak intensity, sea level pressure in the center of Hurricane Wilma was measured at 882 mbar, with one-minute sustained winds reaching a maximum of 185 miles per hour. 2005 saw the formation of not only the most intense Atlantic hurricane ever recorded, but also one of the deadliest and costliest hurricanes ever recorded in Hurricane Katrina. Estimates of storm-related deaths range from around 1,250 to over 1,800, and the approximately $81 billion in damage done made Katrina the costliest hurricane in United States history.

The first category of respiratory illness that I will discuss (and the most commonly reported) is Acute Respiratory Infections (ARI), and these include the common cold, pharyngitis, laryngitis, bronchitis, and pneumonia. In the days following the passage of Hurricanes Katrina and Rita in 2005, the CDC, the American Red Cross (ARC), and the Louisiana Department of Health and Hospitals (LDHH) implemented a variety of disease surveillance measures in an effort to track injury and illness in areas most affected by the storm. The results of this widespread surveillance effort proved conclusively that respiratory illness is rampant after a hurricane has passed, and respiratory disease is consistently among the most commonly reported injuries or illnesses, regardless of the population being surveyed.

One sector of the surveillance program implemented by the LDHH following the passage of Hurricane Katrina consisted of four hospitals and ten non-hospital health care centers spread throughout four parishes in and around New Orleans. In the two weeks following Katrina, this particular sector recorded 7,508 total health events, and of those, 4,169 (55.6%) were illness-related (not injury-related). A total of 505 patients were seen for ARI, including numerous members of a single National

Guard battalion, and the proportion of patients seen for ARI increased over time from September 8 to September 25, suggesting a correlation to the effects of the hurricane. Although ARI was the second most commonly reported illness, it was not often very severe, with only 23 (4.6%) of the patients seen for ARI exhibiting symptoms severe enough to warrant hospitalization. (Williams, et al. 2005)

The ARC and LDHH enacted a similar disease surveillance system intended to survey hurricane victims temporarily residing in evacuation centers (EC) throughout the southeast, and it found ARI and flu-like symptoms to be the most commonly reported affliction among those surveyed. (MMWR, 1/2006) For this program, approximately 500 evacuation centers across Louisiana with populations ranging from 10 to 7,000 persons were identified, and emergency workers at these EC were given surveillance forms that could be used to record the numbers of complaints of various infectious diseases reported at that EC. These surveillance forms were then to be filled out and then returned via fax, telephone, or email if available, but the number of responses was limited by phone and power outages. Though it does provide important insight, this study is not entirely representative of actual complaint numbers in EC because of a number of limitations, including that only roughly one third of the EC population was under surveillance at any given time. Other limitations to this surveillance system will be discussed at greater length in later sections pertaining to disease surveillance and emergency response policy.

Another part of the disease surveillance efforts during the 2005 hurricane season was a system that monitored eight hospitals and 19 acute-care clinics across the urban New Orleans area, and the results tallied by this system confirm those from others. The most common single affliction reported in this system was ARI, with ARI accounting for 14.5% of total illness cases reported. Interestingly, this survey identified whether the person being surveyed was a resident, a relief worker, or someone of unknown status, and the percentage of relief workers that experienced ARI symptoms was nearly twice that of residents. (MMWR, 1/2006)

Additional categories of respiratory illness that are commonly surveyed and reported after hurricanes are Upper Respiratory Symptoms and Lower Respiratory Symptoms (URS and LRS, respectively). URS can include common cold, tonsillitis, laryngitis, and sinusitis, amongst others, and are often relatively less severe than LRS. Examples of LRS would be pneumonia, tuberculosis, and bronchitis, and LRS can develop into severe or even life-threatening situations if left untreated.

A post-Katrina study of 1,243 children in New Orleans healthcare facilities conducted by Tulane University found that the rates of both URS and LRS were markedly increased after the hurricane. Before Katrina, approximately 22% of participants reported URS and 9% reported LRS, while after Katrina, 76% of participants reported URS and 36% reported LRS. Percentages of children living in residences that experienced multiple environmental exposures were identified in this study, including roof/glass/storm damage (50%), outside mold (22%), dust (18%), and flood damage (15%), and roof/glass/storm damage was associated with both URS and LRS, while mold growth was associated with only LRS. (Rath, et al. 2011)

The *Journal of the American Medical Association* published a study in 2006 that recorded illness and injury in the aftermath of Hurricane Katrina, and it also reported high levels of respiratory illness relative to other health complaints. This survey recorded cases of illness and injury that were reported by emergency departments (ED), disaster emergency medical assistance teams (DMAT), and outpatient clinics (OC) in Hancock, Harrison, and Jackson Counties, three coastal Mississippi counties that had been affected by Katrina. The study reported a combined total of 27,135 visits from ED, DMAT, and OC, and of these, nearly 10% reflected respiratory illness in the form of URS or LRS. There were 1,769 cases in which URS were reported and 761 in which LRS were reported, which represents approximately 6.5% and 2.7%, respectively, of the total number of reports. (McNeill, et al. 2006)

The severe and widespread flooding that was brought on by Hurricane Katrina caused visible mold growth in approximately 44% of New Orleans area homes, which presented a serious health risk to residents of the area. (Solomon, et al. 2006) In an effort to quantify this, the CDC conducted a population-based survey of 600 randomly selected homes in the New Orleans area shortly after Hurricane Katrina, and the surveys showed a surprisingly high number of respondents reporting respiratory illness. Approximately 23% of respondents reported one URS, 20% reported two URS, and 22% reported three URS, for a total of 65% of total respondents reporting at least one URS. Similarly, 20% of respondents reported one LRS, 13% reported two LRS, 7% reported three LRS, and 4% reported seven out of seven possible LRS, for a total of 44% of total respondents reporting at least one LRS. (Cummings, et al. 2008) A main goal of this study was to investigate the correlation between water-damaged home clean up and respiratory illness, and the two were found to be strongly correlated. This is consistent with a growing body of scientific evidence that correlates exposure to indoor mold and dampness and respiratory illnesses. Perhaps the strongest evidence that supports my assertion that rates of respiratory illnesses increase in the aftermath of a hurricane is contained in this study:

> Although we know of no other population-based surveys of respiratory symptoms following hurricanes, these findings are consistent with previous investigations using hospital-based surveillance, which have generally found respiratory illnesses to be among the most common diagnoses reported post-disaster, including Hurricanes Katrina and Rita. (Cummings, et al. 2008)

Approximately 27,000 evacuees from New Orleans sought refuge in the Houston Astrodome, and infectious disease transmission and health of evacuees was an immediate concern. A disease surveillance system was rapidly developed and implemented to track disease transmission in the mega-shelter, and the results of this study are consistent with previously discussed results. Surveillance efforts were maintained until the approach of Hurricane Rita (approximately seventeen days), and during this period, nearly 30,000 interviews were conducted, with an average of 35% of the shelter population interviewed on any given night. Of all symptoms reported, cough and runny nose were consistently the two most common, and levels of both rose steadily over the course of the surveillance period. (Murray & Kilborn, 2009)

Evacuees from New Orleans went not only to Houston and other nearby areas, but also to areas further from the coast such as Colorado. In the Hurricane Katrina evacuation centers in Colorado, respiratory illness was the second most commonly reported symptom, with 18% of respondents reporting breathing problems and nearly 17% reporting a cough. Though most respiratory illnesses that affected evacuees were discovered in time to allow for adequate treatment, one man who evacuated to Colorado died of pneumonia, though it was later determined that he passed away as a result of refusing care for his pneumonia. (MMWR, 3/2006)

Respiratory illness tends to increase not only in the immediate aftermath of a hurricane, but also to remain elevated for a significant time after the storm. One previously mentioned study published by the *American Journal of Public Health* in 2008 found rates of respiratory illness to still be elevated at the time of the survey (approximately six months after Hurricane Katrina), and a later study conducted by a separate scientific team found the same thing, but a year later. (Cummings, et al. 2008) A survey of the health of Medicare enrollees (generally lower income and socioeconomic status) one year after Hurricane Katrina found a slight increase in mortality (4.9% at time of survey, 4.3% before Katrina) and a significant increase in morbidity, which increased 12.6% for the overall survey population and 15.9% for non-whites residing in New Orleans parishes. (Burton, et al. 2009)

Although the 2005 hurricane season was particularly devastating and destructive, other seasons have produced hurricanes had the same effects on the incidence and prevalence of respiratory disease. For instance, on September 13, 2008, a category two storm hit the Texas coast near Galveston, and caused widespread damage, flooding, and power outages in nearby Houston. A Houston Department of Health and Human Services survey of 440 homes in the Houston area showed that respiratory disease was an issue there as well, with 58 (13.2%) households reporting new respiratory illnesses. (MMWR, 10/2009)

Severe weather events such as hurricanes can cause power outages for large geographic areas that can last for weeks at a time, and this leads to the next form of respiratory illness that shows a significant increase in the aftermath of a hurricane: Carbon Monoxide (CO) poisoning. Residents of areas experiencing blackouts brought on by a hurricane often resort to use of small portable generators to provide them with enough electricity to perform necessary daily tasks, and all too often the safety warnings on the generators are ignored or misunderstood. Trends of CO poisoning nearly always show a spike in the days following hurricanes, and this pattern is consistent from storm to storm. A majority of cases involving CO poisoning are seen between the hours of 5:00 AM and 10:00 AM, and the time of exposure has been usually been identified as overnight. Trends regarding the placement of the generator are also fairly consistent from hurricane to hurricane, with about a third of incidents being attributed to a generator operated outdoors, a third being attributed to a generator operated in a garage, and the remainder of incidents involving a generator operated inside of a home or on a porch or patio.

In the wake of Hurricane Katrina, the Alabama Department of Public Health and the Texas Department of State Health Services asked the CDC to assist in investigating the extent and causes of CO poisoning in counties affected by hurricanes. Their efforts found a total of 27 separate incidents of CO poisoning that resulted in 78 non-fatal cases and 10 deaths, and nearly all of the incidents were related to improper use of gasoline-powered generators. (MMWR, 3/2006) While in most of the incidents of CO poisoning the gasoline-powered generator in question was placed outside of the house, it was often left near the home to power window air-conditioning units or to connect to central electrical panels, and therefore exhaust fumes containing CO were able to seep or be sucked back into the place of residence. A similar investigation into areas of Texas affected by Hurricane Ike turned up 54 cases of CO exposure of enough significance to be considered a poisoning, seven of which resulted in the death of the victim. This study estimated that approximately 85% of the identified cases of CO poisoning were caused by improper use of a portable generator, despite widespread efforts to educate the public on the dangers of running a portable gasoline-powered generator without proper ventilation. (MMWR, 8/2009)

Four major hurricanes struck Florida between August 13 and September 25, 2004, and as a result, millions of people found themselves without power. During this period, 51 separate Carbon Monoxide exposure incidents were identified that resulted in 167 non-fatal cases of CO poisoning and 6 fatal cases. In approximately 96% of the incidents identified in this study, information regarding the source of the CO was available, and in approximately 96% of these cases, improper use of a portable gasoline-powered generator was to blame. In this study, as in the aforementioned studies, a vast majority of incidents involved a place of residence that did not have a working CO detector or alarm. (Sniffen, et al. 2005)

Potential Explanations of Observed Increase in Respiratory Illness

The previous section presented a strong case demonstrating that incidence and prevalence of respiratory illnesses consistently tend to increase in the aftermath of a hurricane, both in short-term (days) and long-term (months) surveys. In this section, I will present an assortment of possible explanations for the observed increase in respiratory illness, via mechanisms of a biological or physical nature. There are many different possible explanations available, and this project documents each explanation but does not attempt to prove that one explanation is more or less viable than any other. It is highly likely that no single explanation is solely responsible, and that all factors contribute slightly to the problem, with the combined effects of each mechanism being what brings about the increased rates of respiratory illness in hurricane-affected areas.

Biological Mechanisms

Hurricanes often cause widespread flooding through the combined effects of heavy rain and storm surge, and the extremely high winds can move floodwaters a significant distance from their place of origin. While flooding is a physical mechanism, it leads to very prevalent mold growth in and around homes, and is therefore worthy of mention in this section. For example, a CDC survey of post-Katrina New Orleans found 46% of homes to have visible mold, with flooded regions of the city showing more than twice the mold concentrations of non-flooded regions. (Bloom, et al. 2009) Another study published in the *Annals of Internal Medicine* reported that New Orleans area doctors suggested that mold and dust that had aerosolized and begun to circulate the city was responsible for the increased numbers of respiratory illnesses being reported in local emergency rooms. (Wilson, 2006)

The effects of the presence of mold and indoor dampness on respiratory health have been well documented in recent scientific studies, and are therefore presented as a potential explanation for the observed increase in respiratory illness following a hurricane. One of these studies was a 2010 study published by the journal *Environmental Health* that quantitatively investigated the possible association between residential dampness and mold and increases in respiratory infections (ARI), including bronchitis. This study found residential dampness and presence of mold in the home to be associated with a substantial and statistically significant increase in ARI, and suggested that if the aforementioned association could be proven as causal, then a substantial proportion of respiratory diseases could be prevented. (Fisk, et al. 2010) The previous study was built upon the findings of several qualitative investigations of the possible association between the presence of indoor dampness and mold and increases in ARI, which included studies by the Institute of Medicine of the Academy of Sciences (IOM) and the World Health Organization (WHO). Chronologically speaking, the first of the two studies was the one conducted by the IOM, and it documented an association between respiratory symptoms such as coughing, wheezing, asthma, and several URS and the presence of indoor dampness and mold. The later WHO study built upon the findings of the IOM study, and expanded the associations with indoor dampness and mold to include other respiratory infections, dyspnea (shortness of breath), asthma development, and current asthma. In addition, the WHO study concluded that excessive levels of indoor dampness and mold growth were an important public health problem, and one of enough severity and prevalence that it merited prevention and remediation measures. (Fisk, et al 2010)

In addition to bringing on new cases of respiratory illness, mold growth and dampness can lead to exacerbation of existing respiratory symptoms or diseases, including asthma. A 2007 survey of 526 asthmatic children found that children who had been exposed to indoor mold or dampness tended to experience respiratory symptoms nearly three times as often as children that had no such exposure. Even after adjustment of the results to account for other contributing factors such as gender, age, parental smoking, parental education, and pet ownership, the results were still conclusive, with approximately 42% of children with dampness or mold exposure reporting respiratory symptoms, compared to approximately 16% for children without exposure. (van den Berg, et al. 2007)

The extreme dangers posed by hurricanes often warrant the issuing of evacuation orders for large urban areas, and mass evacuations pose another significant health threat to hurricane victims, and thus are presented as the next possible biological explanation for the observed increase in respiratory illness that follows a hurricane. When hurricanes cause the displacement of hundreds of thousands or even millions of people, overcrowding in shelters presents a serious health threat to evacuees, and many studies have shown that displaced populations are at an increased risk of ARI and a variety of other communicable diseases, such as viral infections such as influenza and tuberculosis. Crowding, poor ventilation, and prolonged exposure often experienced by displaced populations are risk factors for ARI, and ARI are consistently among the leading causes of morbidity and mortality in populations displaced by natural disasters all over the world. (Toole & Waldman, 1997)

In an effort to prevent unnecessary exposure and transmission of infectious diseases in evacuation shelters, the WHO has recommended minimum space requirements per EC resident, and when these requirements are not met, the amount of ARI cases seen tends to increase, even in otherwise healthy individuals. Regardless of the type of natural disaster involved, ARI are consistently a leading cause of morbidity and mortality in displaced populations, especially three to five days after the emergency. (Robinson, et al. 2011) Rates of illness in displaced populations that can be attributed to ARI are especially high in children less than 5 years of age, and also tend to initially show lower levels immediately after the emergency that increase steadily over time. For example, in the aftermath of Hurricane Mitch in 1998 in Nicaragua, reported incidence of ARI was nearly four times higher at the end of the survey period (30 days after the storm) than at the beginning of the survey period, which began immediately after the hurricane. (Watson, et al. 2007)

Physical Mechanisms

While there are several potential explanations for the observed increase in respiratory illness following a hurricane that rely on biological mechanisms as their method of disease transmission, there is an even greater array of physical mechanisms that could also be contributing to the problem. Such physical mechanisms include transport of water-borne pathogens in floodwaters, aerosolization of particles during demolition and rebuilding efforts, changes in air quality (usually in the form of increased air pollution), the misuse of portable gasoline-powered generators, and the physical destruction of healthcare facilities and equipment. Physical mechanisms of disease transport are almost certainly a contributor to respiratory illness increases that follow a hurricane, and have therefore been investigated as a part of this study.

The direct transport and transmission of water-borne pathogens by floodwaters has been proposed as a physical means of disease transmission that may be responsible for increases in respiratory illness, and is hence the next mechanism which will be examined. (Robinson, et al. 2011) Floodwaters can be transported great distances from their area of origin when subjected to the forces of a hurricane, and if floodwaters become contaminated, then pathogens can be transported with the water. If the flooding is severe and widespread (which it often is in the case of a hurricane), then water-borne pathogens can be transported to large geographic areas in relatively short periods of time, and this leads to increased risk of illness. While the pathogens that tend to be transported and transmitted through contaminated floodwater are quite varied, they are not necessarily the types of pathogens that manifest their effects on the respiratory system. Pathogens that cause gastrointestinal infections such as E. coli and giardia are far more likely to be transported in floodwaters; however, there are pathogens that cause respiratory illnesses that can be spread through movement of contaminated floodwater.

A 2010 investigation of floodwater contamination after natural disasters (Hurricane Katrina was one of several natural disasters considered in this study) found conclusively that urban floodwaters are often contaminated. The combined effects of heavy rain and storm surge can lead to flooding in urban areas that often is extensive enough that it overwhelms and mixes with local sewer systems, which can lead to fecal contamination of floodwater. Samples of floodwater from several different natural disasters that were analyzed consistently contained a high level of human pathogens. (ten Veldhuis, et al. 2010) Additional studies of hurricanes and other natural disasters have also suggested contaminated floodwater as a possible means of pathogen transport and disease transmission. (Knowlton, et al. 2011)

A similar survey of victims of flooding emergencies found ARI to be quite common, and attributed the relatively high levels to a variety of mechanisms. Cases have been reported that involved the direct aspiration of contaminated floodwaters or the inhalation of aerosolized materials in the post-storm demolition and clean-up phase. A variety of pathogens can cause pneumonia or other ARI, and certain regions have certain gram-negative bacilli and other pathogens that can present themselves as respiratory illnesses when they find their way into a human host. (Allworth, 2011)

The aerosolization of harmful substances during demolition and rebuilding efforts is a potential physical mechanism of disease transmission that is well documented in recent studies. The demolition of homes and other buildings that is often necessary to rebuild after a hurricane can cause the release and aerosolization of enormous amounts of particulates and other substances that are harmful when inhaled. Government emergency management agencies and aid organizations regularly attempt to warn citizens of the dangers of conducting demolition and clean up operations without using proper respiratory protection, but these warnings are often overlooked. When warnings are not heeded and demolition and clean up efforts are conducted without the use of sufficient protective equipment, both respiratory and other types of illnesses can result.

Studies have shown that inhalation of toxic or biologically active particles, toxic fumes, and smoke aerosolized during demolition and clean up efforts can lead to increased rates of respiratory illness. (Robinson, et al. 2011) A survey of water-damaged homes in New Orleans after Hurricane Katrina showed a strong correlation between respiratory symptoms and whether or not the respondent had participated in the clean up of a water-damaged home. Not surprisingly, rates of respiratory illness were significantly lower in cases in which a respirator had been worn while clean-up efforts were being conducted. (Cummings, et al. 2008) As previously mentioned, there has been proven to be a statistical correlation between exposure to roof, glass, or other home damage as a result of a hurricane and an increase in reported respiratory symptoms, particularly URS. (Rath, et al. 2011)

The next mechanism of a physical nature that could potentially explain the increase in respiratory disease after a hurricane is air pollution. Concentrations of airborne pollutants can have significant effects on public health, and changes in air quality and increased concentrations of pollutants after a hurricane can be a serious threat to storm victims. Increased concentrations of organic and particulate airborne pollutants such as NO_3, CO, O_3, SO_2, and PM_{10} have been proven to be strongly associated with increases of asthma, pneumonia, and other respiratory diseases, and these pollutants are often at heightened levels following the passage of a hurricane. (Cheng, et al. 2007) A variety of symptoms can be caused by exposure to heightened levels of airborne pollutants, including asthma, lightheadedness, nausea, vomiting, headaches, and many others. The respiratory system is the system most affected by exposure to airborne pollutants, as airborne pollutants enter the body through the lungs during the respiration process, and the lungs can exhibit symptoms almost immediately following exposure.

Several different post-Katrina surveys of air quality in New Orleans documented increased levels of a variety of airborne pollutants known to be associated with respiratory illness. These surveys measured and compared pre- and post-Katrina concentrations of particulate pollutants (including asbestos), bioaerosols, and volatile organic compounds (VOC), and concentrations of pollutants of all three types were found to be heightened after the storm. (Chung, et al. 2009, Ravikrishna, et al. 2010) Exposure to pollutants of all three types can lead to respiratory illness, especially in individuals more susceptible to illness, including asthmatics and elderly people. Interestingly, air sample analysis found that concentrations of nitrous oxides in the New Orleans area decreased in the immediate aftermath of Hurricane Katrina, likely due to the decrease in power production and oil refining operations. (Yoshida, et al. 2010) A further EPA analysis of air samples from New Orleans found that one in four areas had concentrations of benzene that were at twice the safe level or higher. (Twombly, 2006)

Perhaps the most well documented physical mechanism that is responsible for post-hurricane increases in respiratory illness is the improper use of portable gasoline-powered generators in and around homes. Gasoline powered generators emit Carbon Monoxide (CO) as a by-product of the combustion process that produces power, and when generators are left indoors or left in poorly ventilated areas, CO can accumulate and be breathed in by individuals in the area. Carbon Monoxide permanently binds with hemoglobin molecules in the blood when inhaled, resulting in lowered concentrations of oxygen in the blood as oxygen molecules are unable to be transported from the lungs to other areas of the body. When excessive amounts of CO are inhaled and concentrations of oxygen in the blood drop, CO poisoning can be a result, and symptoms of CO poisoning can include headache, nausea, vomiting, and in severe cases, even death.

CO poisoning can be brought on by many things, but it is most commonly associated with a portable gasoline-powered generator that was placed indoors or in a poorly ventilated area such as a patio or garage and left running overnight. Warnings often only say to use generators in outdoor areas, but placing the generator outside of the place of residence does not guarantee safety. Generators are commonly placed outdoors, but near doors or windows so that they can power window air conditioning units and connect to central electrical panels. Also, generators are commonly placed indoors or near windows to keep them dry, as many generators have stickers that warn against exposing the unit to moisture. Many cases of CO poisoning have been documented in which the generator was placed outside of the residence, but still in close enough proximity to a window or door that CO-rich exhaust could seep into the building, leading to CO poisoning.

A vast majority of cases of Carbon Monoxide poisoning that are documented in the aftermath of a hurricane can be directly attributed to the improper use or ventilation of a portable gasoline-powered generator, though the exact proportions vary from storm to storm.

FIGURE. Number of carbon monoxide poisoning cases reported by hyperbaric oxygen facilities after Hurricane Katrina — Alabama, Louisiana, and Mississippi, August 29–September 24, 2005

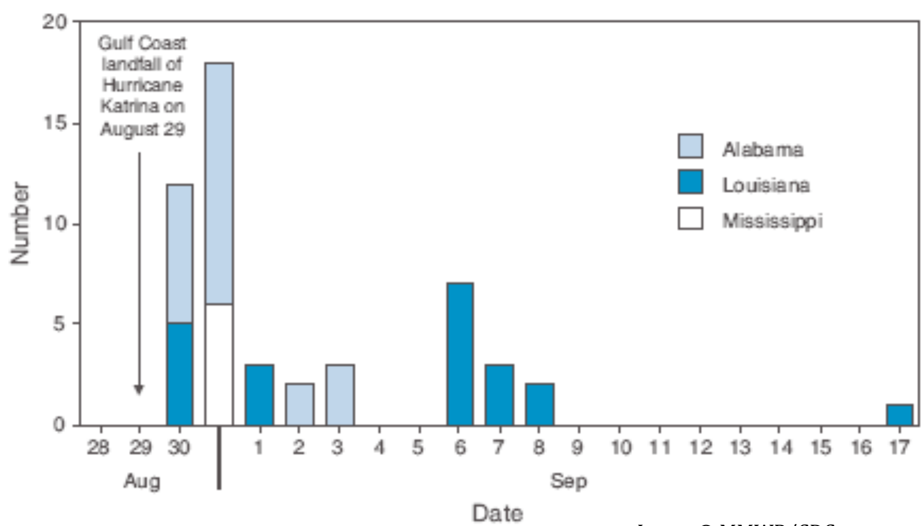


Image © MMWR/CDC

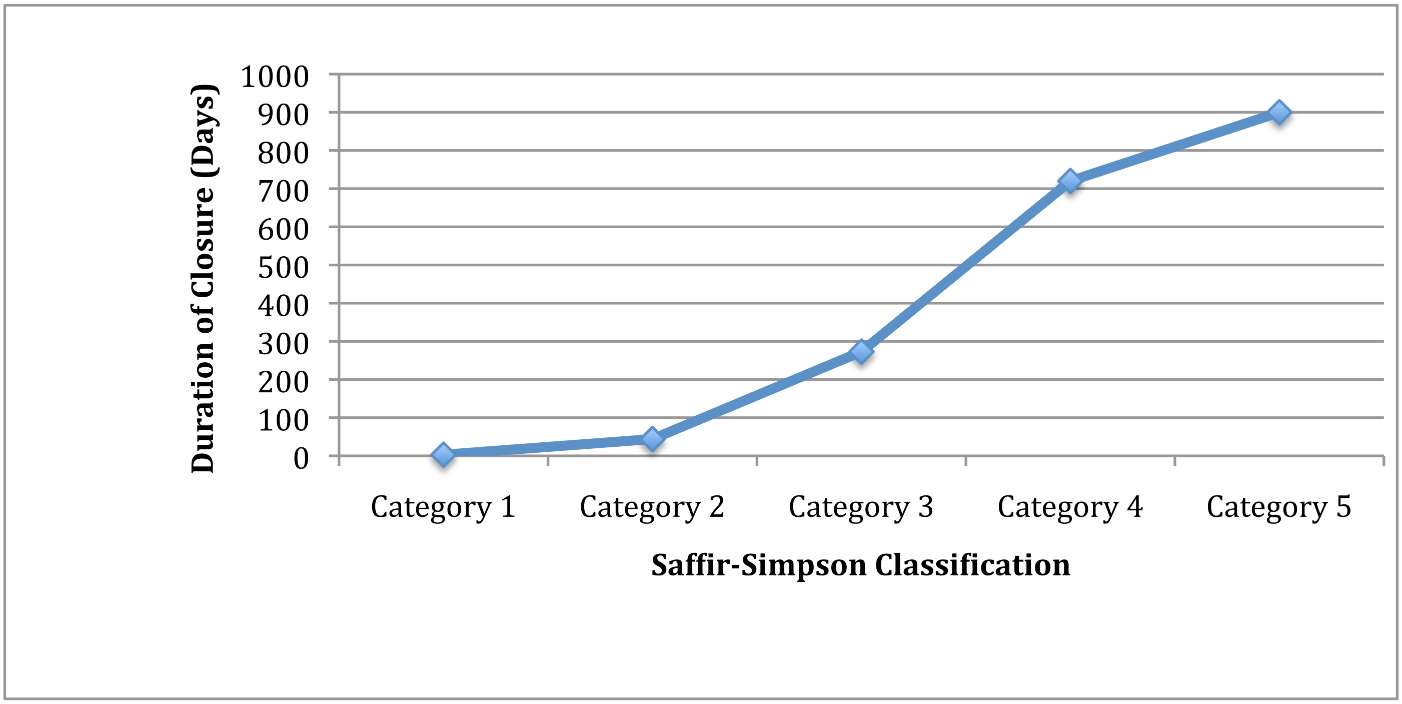
Approximately 96% of the 167 CO poisonings reported in Florida hospitals during the 2004 hurricane season were found to be directly related to the misuse of a generator, and other storms have reported similar trends. (Sniffen, et al. 2005) In the case of Hurricane Katrina and Hurricane Rita, nearly all cases of CO poisoning were attributed to improper use of a generator, while in the case of

Hurricane Ike (a relatively less severe storm), only approximately one in five cases of CO poisoning was generator-related. (MMWR, 8/2009)

Carbon Monoxide poisoning is not only well documented because the mechanism that brings it about it well understood, but also because it causes a significant number of fatalities compared to other post-hurricane respiratory health risks. Nearly all major hurricanes that strike the US result in at least one CO poisoning-related fatality, and the more severe a storm, the more likely it is to cause CO poisoning deaths. Hurricanes Katrina and Rita (2005) resulted in ten fatal cases of CO poisoning, Hurricane Ike (2009) resulted in seven fatal cases, and the 2004 hurricane season in Florida resulted in six fatal cases. (MMWR, 3/2006)

The final potential explanation I will offer for the observed increase in respiratory illness following a hurricane is the effects of a hurricane on heath care facilities, equipment, and staff. In a hurricane, winds in excess of 100 miles per hour combined with heavy rains and storm surge can flood large geographic areas and cause the destruction of buildings and downing of power and phone lines. All of these things can lead to compromised or non-existent opportunities for victims of hurricanes to access health care. Additionally, when mass evacuation orders are issued, health care professionals are often evacuated, leaving a woefully insufficient health care system, especially during the heightened need for care in the aftermath of a hurricane. Evacuation or other storm-related loss of health care professionals can represent a serious threat to public health, especially in cases documented in poorer second and third world nations where the health care system is not as widespread or lacks the infrastructure necessary to respond properly. Even when there are enough health care professionals in a hurricane-affected area to see patients, they are often not able to provide certain types of care, such as those that rely on electricity and computers to function properly. Furthermore, loss of electricity and Internet communication caused by a hurricane can present significant obstacles to doctors and other medical professionals that are attempting to care for victims.

In 2009, a study was published in *The American Surgeon* in which the effects of a hurricane on a coastal healthcare campus were modeled on a computer, and then the model was run for each different category of hurricane. The model was built to take variables such as winds, flooding, and loss of power into consideration when computing the duration of closure of the campus necessary to return to normal functions. When the model was run, a Category One hurricane resulted in a three-day closure of the campus, a Category Two hurricane resulted in a 44 day closure of the campus, a Category Three hurricane resulted in a 273 day closure of the campus, and Category Four and Five hurricanes were determined not to be survivable on the campus. In the case of a Category Four or Five hurricane, all staff would have to be evacuated, which would increase the closure of the campus significantly, resulting in closures of 720 days and 900 days for Category Four and Five hurricanes, respectively. (Tran, et al. 2009) Clearly, hurricanes can have a significant effect on the functions of healthcare facilities, presenting hurricane victims with another obstacle.



Disease Surveillance Programs and Methods

Proper and accurate disease surveillance after a hurricane is fundamental to efforts to combat disease transmission, and many strategies exist for how to properly measure and track disease after a hurricane. Many obstacles exist to obvious disease surveillance strategies, with loss of power and Internet communication being among the most common. This section will discuss several disease surveillance strategies enacted in the aftermath of past hurricanes and will also discuss potential shortcomings of these strategies. Tactics that could potentially be enacted in the future to allow for more rapid, accurate, and accessible surveillance data will be also be discussed, but in a later section.

As previously mentioned, disease surveillance strategies were implemented by the American Red Cross and the Louisiana Department of Health and Hospitals, Office of Public Health in evacuation centers (EC) throughout Louisiana following the passage of Hurricanes Katrina and Rita. Because power for computers was largely unavailable, this surveillance system consisted of one-page forms preprinted with instructions for recording and returning that were given to volunteers at various EC. These forms recorded reports of fever (>100.4 °F), watery diarrhea, bloody diarrhea, vomiting, Flu and other ARI, chronic medical conditions, and assorted other ailments. Once completed, these forms were to be returned via fax, telephone, or email for analysis and recording. (MMWR, 1/2006) A similar disease surveillance program was implemented to survey Hurricane Katrina evacuees taking shelter in the Houston Astrodome, and in it paper surveillance forms had to be used because of storm-related power and phone outages. Rather than only recording patients that sought care for a specific complaint, this program sent volunteers out to conduct nightly "cot surveys", in which evacuees were asked a series of questions regarding the health of them and their families. (Murray & Kilborn, 2009)

While the information gathered in the aforementioned surveillance programs was quite valuable and offered public health officials important insight on what diseases were most prevalent, there were also significant limitations to each potential strategy. For instance, in many cases disease surveillance forms are filled out by volunteers, and in a majority of situations, these volunteers have not been properly trained on recognition and definition of the symptoms and syndromes listed on the forms. Additionally, because short-term volunteers largely staff EC, there is a very high turnover rate for workers at EC, which can lead to further miscommunication and incorrect reporting.

Even in cases where there are sufficient amounts of volunteers and they have all received proper training, power and phone outages often make it quite difficult to communicate the results of the survey to a central agency or location where the data can be analyzed and translated into a useable format. Additionally, in the previously mentioned surveillance programs that surveyed evacuee populations, reporting of injury and illness was encouraged, but was not compulsory. If for some reason an evacuee was not comfortable reporting their injury or illness, they could simply refuse the survey, which could lead potentially lead to skewed results and data that is not completely representative of the survey population. Furthermore, in both of the aforementioned disease surveillance programs, an average of roughly one-third of the population of the EC was interviewed or surveyed, meaning that the reported trends may have a significant discrepancy from the actual trends of the entire EC population. (Murray, et al. 2009)

Public Health and Policy Concerns

A primary goal of emergency management policy is to identify what mechanisms lead to loss of life and property in the aftermath of natural disasters such as hurricanes, and minimize them in such a manner that the social and monetary cost to society is limited. Current emergency management policy is insufficient to successfully carry out this goal, and this insufficiency is apparent in a variety of areas, the most prominent of which will be examined in this report. My formal educational training has been almost entirely scientific in nature, and as so I am less qualified to offer an opinion on the public policy of hurricanes than I am to offer an opinion on the science of hurricanes. In the course of my scientific research, however, I encountered many a study that included brief mentions or sections that discussed related policy, and several policy-related problems were common enough that I deemed them worthy of mention in this report.

The first policy-related problem that will be examined is emergency preparedness, or more specifically, the lack of existing sufficient emergency preparedness policy. Hospitals and other care centers that have not implemented emergency preparedness strategies and created stockpiles of post-disaster necessities have historically found themselves in dire straits in a number of ways. Take for example Hurricane Andrew in 1992, where field hospitals reported total depletion of antibiotic stores within 24 hours of the passage of the storm, or in Hurricane Katrina when Charity Hospital (the only level one trauma center for the entire Gulf Coast) was left devastated and dysfunctional by the storm. (Robinson et al. 2011, Rosenbaum, 2006) Clearly, a better disaster management strategy could have prevented these situations, and it is cases such as these that have made the lack of existing emergency management strategies a significant problem with public policy designed to ensure safety of citizens in the aftermath of natural disasters such as hurricanes.

When Hurricane Katrina struck the Gulf Coast in 2005, neither the City of New Orleans nor the State of Louisiana had a coherent evacuation policy in place, which led to significant complications in the evacuation process. (Taras, 2007) The poor evacuation strategies led to initial evacuation orders being issued with less than 48 hours before landfall, and mandatory evacuation orders being issued with less than 24 before landfall, which is far too little time to evacuate an entire city. (Shughart, 2011) Another shortcoming of evacuation policy in Hurricane Katrina was its failure to provide adequately for the carless portion of the population, who was largely left unable to evacuate when public transit systems were shut down. Studies and computer models have shown that total evacuation time can be reduced by up to 45% by implementing transit-based evacuation during lulls (overnight/non-peak) in auto-based evacuation and by up to 14% by simply rerouting buses off of major arterial roadways. (Naghawi, et al. 2010)

Another noteworthy problem with post-disaster policy is existing limits to flow of post-disaster necessities between jurisdictional vicinities, usually states. Mutual aid, or an agreement between authorities to lend assistance across jurisdictional boundaries, had not been planned for any hurricanes previous to the 1992 season, and this presented a serious problem. In 1992, the Emergency Management Assistance Compact (EMAC) was enacted, and its primary goal was to allow for the flow of relief workers, equipment, and supplies between states in areas affected by natural disasters and other emergencies, and in this sense, it was successful. However, the EMAC was commonly thought to be inadequate in its allowance for the flow of epidemiological information and laboratory data that could be advantageous in efforts to prevent the spread of infectious disease. (Knowlton, et al. 2011) Healthcare information is considered extremely confidential in modern America, and because of this, there are often legal restrictions on access to data regarding illness and injury.

Even when state and federal governments allot significant sums of money to disaster relief efforts, there tend to be problems with the distribution of relief funding. Studies have shown that all other things being equal, (including severity of damaged caused by storm) that federal relief funds tend to be distributed more to states with more electoral votes and less to states with less electoral votes. (Shughart, 2011)

Perhaps the most significant problem with hurricane-related public policy is the issue of insurance. When Hurricane Katrina hit, nearly three out of four Mississippi Gulf Coast residents did not have federal flood insurance, and those who did were temporarily unable to obtain payments of their claims when funds ran out. (Shughart, 2011) The lack of mandatory flood insurance for residents of high-risk areas combine with federal disaster relief programs to change people's behavior in terms of risk-taking. When people are aware that they have a safety net like federal relief, they are more likely to build in high-risk areas, even when replacing property that had just been destroyed by a disaster. Population densities in coastal areas are nearly twice what they were before federal flood insurance programs were created, and this has been suggested many times as a reason that hurricanes are becoming more and more costly as we move into the future. (Shughart, 2011)

Suggestions For Future

It is my sincere hope that the information that I have compiled and presented in this project will be reviewed by someone in the future and used in the creation of scientific or political solutions that will limit the increase of respiratory illness in the aftermath of a hurricane. To that end, I will now offer a few suggestions that I believe could potentially alleviate the aforementioned respiratory health threats. These suggestions address the biological, physical, and political mechanisms that contribute to the increased rates of respiratory illness that follow a hurricane and represent a variety of potential solutions.

One of the previously mentioned contributors to post-hurricane respiratory illness was the aerosolization of harmful particles and gases during demolition and clean up efforts. I suggest that emergency relief agencies and aid organizations make protective equipment such as respirators and masks readily available in areas where demolition and clean up is taking place, and for free or as little cost as possible. If most or all people that took part in post-hurricane demolition or clean up activities were to have access to respirators and other protective respiratory equipment, then a significant proportion of respiratory illness caused in that manner could be instantly eliminated. Additionally, this would occur at a cost that would be relatively low when compared to the cost to society of healthcare provided to remediate the respiratory illnesses brought on by inhalation of harmful particles and gases.

Yet another simple and cost-effective way that post-hurricane respiratory illness could be prevented is by creating portable gasoline-powered generators that can be used in moist conditions without hazard of electrocution. As previously stated, hurricanes indirectly cause a significant number of cases of Carbon Monoxide poisoning when people turn to portable gas-powered generators to provide power during post-hurricane blackouts, and a significant number of these cases could easily be prevented. Studies have shown that a primary reason that generators are placed in unsafe areas is because the generators have large warning labels on them that describe the risk of electrocution if the generator is placed in a wet or moist area (Smith, 2003). Many people place generators in or near the home in an effort to keep them dry and functioning properly, and generators in a poorly ventilated space in or near homes cause the majority of post-hurricane CO poisonings. If generators could be made to be safe even in moist or wet conditions, then users of portable gas-powered generators would likely be more comfortable placing the generator a safe distance from windows and doors, and as a result, rates of hurricane related CO poisonings would likely decrease.

The mechanisms that are mainly of a political nature, including the evacuation of healthcare professionals, contribute a significant amount to the increase in respiratory illness following a hurricane. It is my opinion that if a type of program were to be established that would offer financial or other economic incentives to healthcare professionals who would agree to remain in place despite evacuation orders, that some post-hurricane respiratory illness could be prevented. If there were more doctors, nurses, paramedics, and other healthcare professionals present in the aftermath of a hurricane, then the spread of disease would likely be limited as patients would receive more accurate diagnoses and prompt, effective care than they are currently able to receive with the limited healthcare staff available. Even if healthcare facilities and equipment have been destroyed or otherwise rendered useless by a storm, it would almost certainly be beneficial simply to have more healthcare professionals available to provide care.

An additional political measure that could be taken to minimize the prevalence of respiratory disease after a hurricane is to increase the amount of time and money that go into evacuation planning and policy measures. When hundreds of thousands or even millions of people are evacuated on extremely short notice (as is the case under current evacuation plans), many problems can arise. If the flow of evacuees could be better managed and the need for 'megashelters' such as the Houston Astrodome could be eliminated, then overcrowding, a major mechanism of disease transmission, could be reduced significantly.

As previously mentioned, disease surveillance programs are essential to tracking, monitoring, and preventing disease outbreaks, especially in displaced populations, and the loss of power and phone communications caused by hurricanes often makes accurate and timely disease surveillance an intricate task. Cellular phones, which connect to a network via a wireless connection rather than through surface-borne phone lines, would be more likely to be available for use once the storm had passed, and this leads to my next suggestion.

Many Americans today are owners of smartphones that are capable of downloading and running applications, and if an application could be developed that could be used to upload real-time reports of illness and injury, then disease surveillance efforts could reach more people and could produce more accurate results. Such an application would need to be very user-friendly, with clear and simple instructions on what symptoms to look for when identifying certain illnesses and injuries, and would need to offer users the opportunity to report one or more cases of injury or illness. Reports of injury and illness on the application would include the ability to select the observed symptoms from a list of possible symptoms that are likely to be experienced in the aftermath of a hurricane. In addition to this, the application could also request information such as age, gender, or location that could be potentially useful to epidemiology teams. Suggestions for what actions or medicines could be taken to prevent worsening of existing injuries and illnesses according to the symptoms being experienced by the user could also be very easily and cost-effectively distributed by the application.

This application would then transmit the information from the injury and illness reports to a central database where it could be analyzed and stored for future use. Even in the physical absence of healthcare professionals, accurate identification of illnesses could decrease the incidence of new cases, as people would be more prone to recognize their illness and attempt to isolate themselves if such an application existed. Additional benefits of such an application would be the relatively low cost of creation and maintenance, especially when compared to the financial and temporal cost of printing, filling out, and transporting tens or hundreds of thousands of disease surveillance forms from evacuation centers spread across large geographic areas.

Hurricanes are among the most powerful and destructive forces of nature, and their occurrence poses many different threats to individuals that live in their paths, especially those in coastal areas. Although the hurricane itself is often responsible for significant amounts of injury and physical damage, the end of the storm does not by any means represent the end of the danger. Perhaps the most prevalent of the long-term threats to human health posed by a hurricane is the increased risk of infectious disease following a storm. Diseases of many types, including respiratory, all have potential to be at elevated rates in the aftermath of a hurricane, and many different mechanisms are potentially responsible for the increase. In conclusion, it is my sincere hope that this project will someday be useful in the creation and implementation of successful public policies and scientific studies that will prevent suffering and loss of life due to respiratory illness. ∞

Proposed Solution	Mechanism Targeted
Distribution of free or reduced cost protective respiratory equipment	Participation in demolition/clean up efforts of water/storm damaged homes
Development of waterproof portable gasoline-powered generators	Carbon Monoxide Poisoning as a result of improper use/ventilation of portable gasoline-powered generators
Establishment of incentive program for healthcare professionals	Evacuation of healthcare personnel resulting in insufficient healthcare availability
Development of disease surveillance smartphone application	Difficulty with disease surveillance efforts due to loss of power, internet, and land-line telephone connections

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