Global warming and hurricane intensity and frequency: The debate continues

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ABSTRACT: The recent destruction due to hurricanes and the apparent increase in frequency in the southeastern United States, especially in 2005 season, has prompted many scientists to study possible causes of these changes. Some scientists believe that global warming and increased sea surface temperatures are to blame. Warm water holds more energy to fuel hurricanes and may contribute to the conditions needed for the formation of hurricanes. The increased ocean temperatures may cause a decrease in wind shear and an increase in evaporation and atmospheric water vapor. These factors all contribute to the conditions conducive to formation of hurricanes. Some scientists, however, simply believe that the recent increases are due to normal multidecadal oscillations resulting from currents and Thermohaline Circulation. Whereas others believe that a change in the instrumentation and data collection techniques has led to unreliable data and the creation of trends that do not exist. Although some flaws in the data do exist, global warming and increased sea surface temperatures do appear to have influenced hurricane frequency and intensity. The magnitude, however, of this effect is not yet completely quantifiable. The absence of a single major landfall by a major hurricane in the Gulf and Atlantic region in 2006 season adds yet another source of uncertainty in the currently observed patterns. This paper examines these issues in light of the apparent increase in hurricane frequency and intensity in the North Atlantic basin in recent years.

KEYWORDS: Global warming; hurricanes; wind speed; Atlantic Ocean; uncertainty; risk

1 GLOBAL WARMING

The increase in temperature of both the atmosphere and of the oceans in recent years is an undeniable fact. Many effects of this increase, however, were unknown until recently or are still unknown. Some scientists are now finding a correlation between the increase in sea surface temperature and the increase in hurricane frequency and intensity in the North Atlantic basin. Unless the increase in global temperatures is not stopped or at least slowed down, hurricanes and other natural disasters may have the tendency to continue to grow in strength and duration, threatening communities and their possessions. Therefore, it is important to understand what is causing global warming and how exactly it is affecting the frequency and intensity of hurricanes or if it is at all, which some scientists doubt. It is also crucial to understand how global warming may work together with other factors known to lead to the development of hurricanes.

Anthropogenic factors may be responsible for the warming of the globe and thus of the Atlantic as well. Greenhouse gases released through the use of fossil fuels and from agriculture, as well as many other sources, have led to the greenhouse effect. The greenhouse effect causes the atmosphere to absorb more solar energy but does not allow this heat and radiation out of the atmosphere [1]. The more greenhouse gases in the atmosphere, the more heat and radiation that are trapped and contribute to increases in global temperature [2].

Global warming has had a fairly significant impact on ocean temperatures. In fact, records show an almost 1 degree Fahrenheit (about 0.5 degrees Celsius) warming of the oceans in the past 50 years [3]. Studies in ocean temperature fluctuations show that this type of increase is unprecedented and has not occurred in several thousands of years [1]. In addition to the increase in sea surface temperature that has already occurred, it is predicted that doubling the atmospheric carbon dioxide would lead to an additional temperature increase of 0.5 degrees Celsius [1]. The melting of the polar ice caps also has the potential to raise the sea surface temperatures around the globe and contribute to an increase in the rising of the oceans. In order for hurricanes to form, the sea surface temperature must be above 80 degrees Fahrenheit or 26 degrees Celsius. As the sea surface temperatures reach and exceed this temperature in greater areas and to greater depths, the potential for hurricanes to form and to become stronger increases. The rising of sea surface temperature is especially significant in the North Atlantic Basin because of ocean currents. Warming of the ocean in the tropical North Atlantic has a very substantial effect on sea surface temperatures outside of the tropical North Atlantic causing a change in the entire dynamics of the Atlantic environment.

The future of global warming, however, is uncertain. Future emissions of greenhouse gases and aerosols are unknown and can only be predicted. Therefore, the uncertainty in the future of global warming makes it difficult to predict how hurricane frequency and intensity will be influenced. People have the potential to drastically change their habits either causing many more emissions to occur or less if they become more environmentally conscious. Another unclear aspect involved in global warming is how exactly the environment and specifically climate is affected by global warming. Therefore, it is difficult to quantify future changes in the atmosphere and how exactly it will affect hurricanes. The hurricanes, themselves, also have a significant impact on the atmosphere and the climate, causing even more uncertainty. For example, hurricanes cause significant cooling of the ocean surfaces through mixing in the areas in their tracks.

2 INCREASE IN HURRICANE FREQUENCY IN THE NORTH ATLANTIC BASIN

Global warming has led to increased sea surface temperatures, which combine with normal multidecadal oscillations and currents to produce ideal conditions for hurricanes. Hurricanes are highly organized and many different factors must come together in a very specific and not yet completely understood way for them to form. In recent years, before 2006 season, the rise in sea surface temperatures has made it easier for this organization to occur by changing, making wetter, the environment in which the hurricanes form. In fact, in the past 6 years, a doubling of activity for the North Atlantic basin has occurred as well as an increase in the number of storms that are hitting land [4] while on the other hand, hurricane activity in 2006 season has been considerably low.

Approximately 60% of hurricanes in the Atlantic Ocean develop from winds coming westward from Africa. As these atmospheric waves move across the mid-Atlantic, specifically across the Main Development Region, storms form that have the potential to eventually turn into tropical storms and eventually hurricanes. While approximately 60% of total hurricanes are attributed to African winds, around 85% of major hurricanes are formed from these winds [4]. The African waves combine with normal oscillations and higher sea surface temperatures as well as many other factors to form hurricanes. Warm water fuels the formation of hurricanes and keeps them going once they have formed. Warm sea surface temperatures also decrease atmospheric stability [4]. As water warms, it expands, evaporation increases and the water vapor content in the atmosphere is much higher [5]. The increased water vapor combined with, in many cases, African winds then leads to thunderstorms which can then turn into tropical storms and hurricanes. If the water becomes warmer due to global warming or simply currents and natural temperature oscillations, then more evaporation occurs and more water vapor is in the atmosphere leading to increased rainfall that can then fuel a potential hurricane. Scientists have found a recent and large increase in water vapor over the North Atlantic that is around 15% higher than 30 years ago [5]. The warm water and increased water vapor may even be causing an increase in the length of the hurricane season and the expansion of areas affected by the hurricanes. A report from the Center for Global Development gives the examples of Brazil being struck by the first hurricane ever in the South Atlantic and Canada being hit by Hurricane Juan [5]. While others do not believe that hurricane track is directly affected by the rise in sea surface temperatures, rising temperatures do affect the atmospheric circulation, which in turn affects hurricane tracks [6].

An increase in the duration of hurricane season by about 5.5 days per decade has been reported to be occurring recently [6]. With a longer season, hurricanes have more time to develop and flourish in the North Atlantic Basin. This increase in the season length may be due to the increase in sea surface temperatures. The waters are warmer and the warm water extends deeper into the ocean. Therefore, the ocean waters have greater energy and a greater potential for hurricane formation. Emanuel has also reported that storms in the North Atlantic and western North Pacific have increased in duration by about 60% since 1949 [7].

Another factor besides season length, sea surface temperatures, and atmospheric water vapor that affects the formation of hurricanes is wind shear. Wind shear is the difference in horizontal wind between two points of the altitude, typically 1.5 km and 12 km are used [8]. Even mild to moderate wind shear, the change in the horizontal wind between the upper and lower troposphere, can play a very significant factor in the development of hurricanes. A magnitude for vertical shear equal to or above 8 mps inhibits the development of the very organized structure needed for hurricane formation [4]. The vertical shear, however, is reduced by warmer sea surface temperatures [8]. Vertical shear is increased by the occurrence of the El Niño Southern Oscillation in the Pacific Ocean. This explains why hurricane frequency is much lower in the years in which El Niño is occurring in the Pacific. El Niño is known to be occurring in 2006-2007 which explains a very calm hurricane season during the 2006 season.

Data from all of the oceanic basins show that the North Atlantic Basin is the only one with noticeable trends when it comes to sea surface temperature and hurricane frequency [9]. What makes this basin different than the others? The North Atlantic Basin may be the only ocean basin that has had fairly reliable data for hurricanes over the last several decades. Other basins have some data records but due to changes in instrumentation and classification, they are less reliable. For example, some basins only use satellite imagery to determine when hurricanes occurred and how intense they were. Satellites, however, were not completely reliable which will be discussed later. Other basins, such as the North Atlantic Basin, used aircraft reconnaissance as well as satellite imagery, making the data from these basins more reliable.

Some scientists argue that natural climate oscillation is the only reason that hurricane frequency has increased in recent years. These scientists argue that the North Atlantic is currently in a warm phase and will be for several more years or even decades. One well-documented oscillation is the Atlantic Multidecadal Oscillation (AMO) that is controlled by Thermohaline Circulation (THC). The AMO is a long period (50-70 year) oscillation of the Atlantic Ocean currents [8]. THC is one of the major processes by which warm water is circulated from the tropics to the north in the Atlantic. The water in the tropics becomes warmer and then is moved north on the surface of the ocean by the Gulf Stream and North Atlantic Current. Once it gets more north, the water cools down and sinks deeper into the ocean, which allows more warm water to flow above and release more heat into the atmosphere and then sink itself [2]. This process causes the North Atlantic to become warmer and enter into a warm phase. Warm phases correspond with more frequent hurricanes and more intense hurricanes [2]. Warmer phases increase the THC. These natural cycles make it difficult to directly connect rising sea surface temperatures from global warming to increased hurricane frequency. Scientists are trying to determine whether THC is indeed affected significantly by global warming and rising sea surface temperatures. Most likely, both anthropogenic global warming and natural cycles are working together to increase the ocean temperatures [10]. It is important, therefore, to determine how much of the global warming can be attributed to each.

The increase in activity could also simply be due to changes in the instrumentation used to measure the intensity of the storms and thus used to classify the storms as hurricanes or major hurricanes. The data from the North Atlantic basin, however, seems to be fairly reliable due to several methods of determining hurricane intensity. The increase could also be due to a long period oscillation that we have not yet been able to detect because records do not date back more than a few decades [9]. Hurricane frequency could have been much higher previous to the records. Since reliable records of hurricane wind speeds go back to only the 1950s, there is currently no completely accurate way to be sure that there were not more frequent storms before then [1]. Researchers are looking for ways to determine when hurricanes occurred and how frequently before records were available. For example, a study from the University of Tennessee is examining tree rings to determine when hurricanes occurred [11].

3 INCREASE IN HURRICANE INTENSITY IN THE NORTH ATLANTIC BASIN

Many scientists have found that the increased sea surface temperatures affect not only hurricane frequency, but also hurricane intensity. As greenhouse gases in the atmosphere cause an increase in global warming, the wind speeds in hurricanes will rise. It is estimated that doubling the carbon dioxide content will cause a 5% increase in the wind speed and an 18% increase in hurricane rainfall [11]. The limit of intensity that a hurricane can reach increases with the amount of greenhouse gas in the atmosphere, but the magnitude of this increase is, as of now, unknown [1].

How intense a hurricane will become is determined by many different factors. Some of these factors are warmer sea surface temperatures, low wind shear, and high humidity in the atmosphere. As the humidity increases due to rising atmospheric and sea surface temperatures, moist air rises and condenses causing rain. As the air rises, air pressure near the ocean's surface decreases allowing more water to evaporate and ultimately condense as rain [12]. This cycle leads to the creation of many of the factors needed for hurricane formation. Continuation of this cycle due to warmer surface water is what causes a hurricane to become stronger and last longer.

The intensities of hurricanes are measured by the maximum surface wind speed, which occurs at the eyewall of the hurricane. Aircraft reconnaissance and satellites have been used to measure these wind speeds [9]. Aircraft reconnaissance is a much more reliable way to detect the wind speed but was not always available for use in the areas where the hurricanes were occurring. The Dvorak Technique was employed which used satellites to measure the maximum surface wind speed using differences in temperature and pressure between the eye of the storm and the area surrounding the eye. The technique, however, was not a completely reliable technique before the 1980's. The technique and instrumentation has been continually revised so it is difficult to use the data to develop reliable trends in all of the basins. In 1984, an infrared method based on the Dvorak Technique was developed. This new method again used the temperature difference between the eye and the eyewall of the hurricane to estimate the surface wind, but used better satellites with higher resolution to do so [13]. Before the 1980s the resolution for the satellites was not very high and thus, the resulting maximum wind speed estimates were not the most reliable. The data from the North Atlantic Basin, however, is more reliable because the trends are supported by the data gathered through aircraft reconnaissance. Aircraft reconnaissance yields more accurate information but was only available in certain basins. The North Atlantic Basin is the only basin with continual aircraft reconnaissance data with which to verify trends in intensity from the Dvorak Technique [9].

The Dvorak Technique uses the knowledge that the strength of the hurricane is directly dependent on the temperature and pressure difference between the eye of the hurricane and outside of the eye. The warmth of the ocean during the tropical storm or hurricane determines how much thermodynamic potential is available to keep the internal air column warm and thus increase the intensity of the hurricane [8]. Therefore, as global warming increases sea surface temperatures, the potential for more destructive hurricanes to form is enhanced.

In order to have a uniform way to determine the intensities of hurricanes, a power-dissipation index (PDI) has been introduced by Emanuel, which takes into account not only the maximum wind speed, but also the life span of the storm [11]. The PDI is the cube of the maximum sustained wind speed at 10 m integrated over the lifetime of the storm [7]. The PDI is then an estimate of the total energy usage of the storm. Emanuel has found, after applying his index to past storms, that the PDI has cycled up and down since 1930 but has rapidly increased in the past 30 years. In fact, Emanuel found that the PDI has doubled over the past 30 years in the North Atlantic basin when global warming has been a factor in the rising of sea surface temperatures [3]. He has also found a 15% increase in speed as well as a 60% increase in duration [1]. Another index used to compare hurricane intensities is the Accumulated Cyclone Energy (ACE) index which is proportional to the kinetic energy of the storm. The ACE index is the sum of the squares of the maximum sustained wind velocity taken every six hours. It is similar to PDI and has a very high correlation with it [14]. The ACE index also indicates an increase in hurricane energy in the North Atlantic basin. This increase in intensity is most likely occurring because the oceans have more energy to offer the hurricanes with warmer waters that extend deeper into the ocean. Both PDI and the ACE index can be related to the destruction potential of the hurricanes as well as the intensity.

A study at the University of Wisconsin used satellite images of Atlantic hurricanes past and present to come up with a uniform way to determine intensity. Since all hurricanes would be analyzed in the exact same way, it is easy to determine whether the apparent increase in intensity is due to analysis techniques or an actual increase in intensity. Using this technique, it has been noted that this analysis agreed with other analysis techniques and that energy released per season by hurricanes has, in fact, increased. The conclusions of both this study and that of Emanuel arrived at the exact same conclusion: that storm intensity has increased markedly and the energy released by storms has doubled [15].

Cold water acts as a braking mechanism for the hurricanes, as does high wind shear and strong winds in general. Destructive power of hurricanes has increased because braking mechanisms are not working as well because the warm water penetrates deeper so cool water is less able to calm the storm. If the warm upper layer is not very deep then the storm will not have enough energy (heat) to become extremely intense. High wind shear and strong winds churn up cold water which decreases the energy going into the storm and can destroy the organization needed for formation of a coherent vortex [12].

Since the factors that diminish or prevent hurricanes are slowly decreasing and the conditions that intensify hurricanes are increasing, hurricanes are able to increase their wind speeds and durability. Webster et al. (2005) have found a sizeable increase, an almost doubling, in the proportion of hurricanes in all oceanic basins that are able to reach categories 4 and 5 (storms with wind speeds of 56 to 67 mps and greater than 67 mps respectively) and thus be classified as major hurricanes. The maximum intensities of these higher category hurricanes, however, have stayed fairly constant and do not seem to be increasing significantly [9]. The North Atlantic had approximately 10 hurricanes of categories 4 and 5 from 1986-1995, whereas 1996-2005 had 25 hurricanes of categories 4 and 5 [14]. Klotzbach (2006) reported an important relationship between sea surface temperatures, the Accumulated Cyclone Energy index, and category 4-5 hurricanes [14]. A study at the Geophysical Fluid Dynamics Laboratory predicts a one-half category increase in intensity and an 18 percent increase in the amount of rain over 80 years of build-up of 1%/year of carbon dioxide [16].

The increase in hurricane intensity and the rainfall associated with hurricanes means that areas further inland than before have the potential to be affected. A more intense storm is more difficult to abate once it has begun. The hurricane needs a great deal of energy to persist once it is over land. However, the hurricane is carrying a great deal of energy itself that must be dissipated before the storm terminates. Hurricanes with higher intensities, therefore, are able to persist for a longer period of time over land. Also, the areas closest to the coast could be hit by higher storm surges originating from the rising sea level [12].

Some scientists do not believe that an increase in hurricane intensity has occurred at all. Records of hurricane wind speeds only go back to the 1950s and records up to the 1980s are not extremely reliable considering the changes in instrumentation and data collection that occurred. The increase in the number of major hurricanes recently could have occurred because storms in earlier years were not accurately categorized because of poor instrumentation. The PDI uses past data from these various types of instrumentation and uses correction factors that have the potential to cause controversy about the resulting data [11]. Therefore, in order for any theories about hurricane frequency and intensity to become widely accepted, the reliability of data collection and hurricane categorization must be improved. Understanding of hurricane genesis in general must be increased and knowledge about atmospheric circulation and oscillations in the ocean temperatures must be expanded. With better background knowledge, it would be easier to understand how exactly global warming and sea surface temperatures affect hurricane formation, duration, and intensity.

Computer simulations are increasingly being used to get a better understanding of hurricane formation. The simulations are very limited however due to the fact that they need to have small enough scales to be able to track the formation of the hurricane but must be large enough to take atmospheric variables into account [11]. It is important to understand how global warming and increased sea surface temperatures interact with normal oscillations to make hurricane intensity and frequency as it is right now. Global warming may have very little impact compared to the other oscillations but the impact is important nonetheless.

Many people around the world believe that hurricanes have become more destructive recently. While hurricanes may be increasing in intensity, the increase in monetary damage is more likely due to the movement of people and their goods and dwellings to the coasts. As more buildings, homes, and people are putting themselves at risk to hurricanes the potential for damage increases [17,18]. Therefore, while global warming and understanding of climate is important to knowledge of the world we live in, the best way to prevent hurricane damage and deaths is to move out of harms way or build structures that will be more resistant to the flooding and winds associated with hurricanes. In addition, people must be aware of how their actions are affecting the climate. Destroying natural wetlands and other geographical barriers makes people more vulnerable to the environment. In addition, dispersing greenhouse gases into the atmosphere is affecting our world now with no telling what kind of destruction the gases have the potential to cause in the future. Even though we do not totally understand the environment in all of its intricacies, it is important not to take the environment fore granted because before long it could be ruined.

4 IPCC-AR4 PERSPECTIVE

The 2007 Fourth Assessment report [19] of the Intergovernmental Panel on Climate Change (IPCC-AR4) in their summary presents the following scenarios concerning frequency and intensity:

*Frequency***:** On a global scale there is no clear trend in the annual numbers of tropical cyclones, however, the frequency has increased in the North Atlantic, which is a subject of debate. Despite the apparent statistical linkage between frequency increase and global warming the search for an underlying mechanism is underway.

Intensity: The report rates the probability of the link between global warming and increase in the frequency of hurricanes as "more likely than not" that there is human contribution to the observed trends of hurricane activity since 1970. It is also reported that it is likely (better than 2 to 1 odds) that future tropical storms will intensify with higher wind speeds and precipitation associated with increasing sea surface temperature.

5 UNCERTAINTIES AND RISK

Any impact of climate change requires that a careful consideration of the level of understanding concerning all major issues in light of the inherent uncertainties is made. These uncertainties entail: incomplete or imperfect observations (sampling uncertainties); incomplete conceptual framework (modeling); chaotic climate behavior, i.e., sensitivity to initial conditions; lack of predictability (randomness) [20]. It is important to draw distinction between: the probability of events and confidence of these estimates; subjective and objective assessment of uncertainty; assignment of uncertainty to observational and model based results [21].

6 CLOSING REMARKS

The increase in sea surface temperature due to global warming, ocean currents, and multidecadal oscillations has been recently believed by some to have had an impact on hurricane intensity and frequency, though the magnitude of this impact is not yet known. The lack of consistent records makes the development of trends very difficult and potentially unreliable. An increase in intensities of hurricanes, however, does appear to coincide with an increase in sea surface temperatures. Trends in frequencies are more difficult to distinguish, although an increase in frequency does appear to be occurring recently. However, a lack of any significant hurricane activity this year in the Atlantic basin has dampened the sustenance of this trend. Model based simulations help to make predictions for the future possible, but until these models are improved, the results may not be widely accepted.

With the projected future trends in population growth and increasing developments in the coastal regions the damage will escalate regardless of global warming, it is likely that it will be exacerbated in the event global warming realizes changes in the intensity and frequency of tropical activity. Therefore, the structural engineering community needs to assess these developments and their impact on the potential future damage situations and decide on what steps can be taken now to minimize the consequences and cost to society of these projected changes. In some circles it is now being considered to plan our communities and design our buildings and civil infrastructure better. It is interesting that a similar observation was arrived at in the early nineties at a workshop at MIT on the Potential Impact of Climate-Induced Natural Disasters on the Construction Industry, The World at Risk: Natural hazards and Climate Change. These included adoption of more efficient building codes that are attentive to the measures to reduce energy consumption; development of more efficient building envelopes, cladding and curtain walls to cut down heating and cooling demands and institution of measures to reduce pavement surfaces and replace them with green surfaces [18]. At the very least, simply improving current structures to resist current climatic extremes would go long ways in ameliorating the potential impact of theorized climate change induced effects.

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