Hurricanes and Global Warming

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November 2011

Video of this presentation

Hurricanes as the Poster-Child for Global Warming

Hurricanes have been depicted as the literal poster-child of the harmful impacts of global warming. Without argument, hurricanes (which also include storms known as "typhoons" in the Northwest Pacific and "severe tropical cyclones" in the Indian and Southwest Pacific) are extremely destructive and often responsible for the deaths of hundreds and occasionally thousands of people. As an example, Hurricane Katrina was responsible for the death of ~1200 and about $108 billion in damages.² The before and after pictures of the home of David and Kimberly King of Waveland, Mississippi show the incredible power of that hurricane's storm surge and winds.
Certainly, if there are any significant effects of global warming on hurricanes either today or in coming decades, these need to be understood and addressed.

**Global Warming is Real**

As a preamble, I definitely agree that global warming has occurred (around a degree F [or half degree C] in the last several decades at the earth's surface).

Also there is substantial evidence - in my view - that mankind has caused a significant portion of this warming through greenhouse gas emissions such as carbon dioxide and methane. I do not know whether the human contribution toward the warming is relatively small (~a quarter) or large (~two-thirds), but do agree that there is quite a bit of evidence that mankind is altering the global climate and will continue to do so in the future.
If the consensus of the various global climate models are to be believed for scenarios of "business as usual" greenhouse gas emissions, then the tropical and subtropical oceans will warm up by 4-6 °F (2-3 °C) by the end of the century. It is assumed here that this is correct. (Such a stance presumes that a quite sizable vicious cycle of warming due to cloud and moisture effects will occur, much beyond what the greenhouse gases are capable of in isolation. While these self-reinforcing cycles are predicted by many global climate models, it is not guaranteed that this will occur and there are credible researchers who have analyzed a substantially weaker vicious cycle from observational data than suggested by these computer models. Thus there remains a large range of the amount of global warming to be expected in the future due to manmade changes in my view.) What does, then, a 1°F (0.5°C) ocean temperature change today and a potential 4-6°F (2-3 °C) warming by the end of the 21st Century mean for hurricanes?

How Should Global Warming Affect Hurricanes?

Hurricanes are natural heat engines. They extract energy from the moist, warm air over the tropical and subtropical oceans, liberate this energy in the process of forming clouds and rainfall, but lose most of this energy in the cold exhaust of the cyclone in the upper part (~8 mi, or ~12 km) of the atmosphere. A very small percentage (less than 1%) of this released energy is used to warm the air within the hurricane, drop the air's density and pressure, and cause the swirling winds to spin faster and faster.

It's also important to point out that ocean temperatures are not the only factor that is crucial in knowing which disturbances will develop into a tropical storm and which systems will intensify to become extremely strong hurricanes. Other physical "ingredients" in the hurricane "recipe" include moist air and numerous thunderstorms, weak vertical wind shear (the difference in winds near the ocean versus the upper part of the atmosphere), and a triggering disturbance (in the Atlantic this is often from an African easterly wave in the atmosphere). Any manmade alterations to the air's moisture, thunderstorm activity, vertical shear, and originating disturbances may be as or even more important that changes to the ocean temperatures themselves. All climate models predict that for every degree of warming at the ocean that the air temperature aloft will warm around twice as much. This is important because if global warming only affected the earth's surface, then there would be much more energy available for hurricanes to tap into. But, instead, warming the upper atmosphere more than the surface along with some additional moisture near the ocean means that the energy available for hurricanes to access increases by just a slight amount. Moreover, the vertical wind shear is also supposed to increase, making it more difficult (not easier) for hurricanes to form and intensify.
The bottom line is that nearly all of the theoretical and computer modeling work suggest that hurricanes may be slightly stronger (by a few percent) by the end of the 21st Century, even presuming that a large global warming will occur.\(^9\)

The climate models are also coming into agreement that the number of tropical storms and hurricanes will not go up and may perhaps even decrease (by around one-fourth fewer) because of the increased vertical wind shear.
With such modest and mixed alterations anticipated several decades away, what does global warming imply for hurricane activity today? The ~1°F (~0.5°C) ocean temperature warming has likely made hurricanes stronger today by about 1%. Thus even for a Saffir-Simpson Hurricane Wind Scale Category 5 hurricane - like Hurricane Katrina over the Gulf of Mexico - the increase in hurricane winds are on the order of 1-2 mph (2-3 kph) today.

It is likely - in my opinion - that manmade global warming has indeed caused hurricanes to be stronger today. However, such a linkage without answering the more important question of - by how much? - is, at best, incomplete and, at worst, a misleading statement. The 1-2 mph change currently in the peak winds of strong hurricane due to manmade global warming is so tiny that it is not measureable by our aircraft and satellite technologies available.
today, which are only accurate to about 10 mph (~15 kph) for major hurricanes.

**What Does the Observed Increase in Hurricane Damages Imply?**

One might argue that the various climate model output and theoretical predictions of global warming may be so seriously flawed that their forecasts are invalid. (It is noted that one might think the effects are overblown, about right, or not severe enough, depending on one's perspective.) Such a line of reasoning might instead focus upon observed parameters in the last few decades like tropical storm and hurricane numbers, maximum winds and direct damages caused by these cyclones. Recent events might appear to support an idea of increased hurricane activity and impacts.

For example, the 2004 hurricane season featured four hurricanes that struck Florida - an unprecedented event, which caused a record amount of damages in the continental United States: $45 billion\(^\text{10}\).

This was immediately followed by the 2005 hurricane season that produced four major landfalling hurricanes in the U.S.: Dennis, Katrina, Rita and Wilma - also an unprecedented event, which broke the one year old record for tropical storm and hurricane damages with $142 billion\(^\text{11}\).

With such extreme impacts, there have been people speculating that global warming is already having a strong
effect on hurricanes. Indeed, I heard Mr. Al Gore in a talk at the University of Miami on 28 February, 2007 as part of his speaking tour for "An Inconvenient Truth" unequivocally state that global warming has already made hurricane damages much worse today.

Such a conclusion can be tested by examining the database of U.S. tropical storm and hurricane damage (direct losses like structural destruction to houses, office buildings, bridges and agricultural losses). NHC maintains a database of such losses for the continental United States that is relatively complete back to 1900\textsuperscript{12}. Inspection of these losses shows that the damages from these cyclones have been going up dramatically, even after adjusting to account for inflation (i.e., a dollar today can't buy as much as it could a few decades ago).

![U.S. Tropical Storm and Hurricane Damages](image)

Perhaps it is not surprising that some folks may conclude that because both raw hurricane losses are going up and ocean temperatures are going up, that global warming may be responsible for both trends.

However, such a quick conclusion fails to consider what other factors may cause damages from hurricanes to go up. Indeed, there are two huge factors that must be considered before making any statements about trends from hurricane damages. The first of which is people in the United States are much wealthier on average than in the past. (Well, perhaps not in 2011 compared with 2007 before the Great Recession.) But in general, we have twice as much wealth - property and possessions - than our parents did when they were our age and about four times as much wealth as our grandparents when they were our age. So when a hurricane strikes the U.S. coast there are bigger homes with multiple cars and lots of stuff in the homes that can and do get destroyed.
Secondly, the population along the U.S. coastline also has dramatically risen, with the number of people living in coastal counties between Texas to Maine increasing from about ten million residents in 1900 to almost 50 million in 2000.

The picture in the background highlights the difficulty of having huge populations living in vulnerable areas along the coast, as evacuations ordered when a hurricane threatens often displace hundreds of thousands or even millions of residents.

So before making any meaningful conclusions about trends in U.S. hurricane damages, these societal effects of more people and more wealth per person have to be addressed. One can normalize the U.S. hurricane damages to estimate how much destruction an historic hurricane would cause if it were to hit today's society. By using indices for inflation, coastal county population changes at the locations where the hurricanes hit, and per capita wealth changes, then it may be possible to see if there have been any true long-term increases in hurricane damages that may be due to global warming\textsuperscript{13}. (Another important factor in U.S. hurricane damage is mitigation and the implementation of stronger building codes. There is considerable evidence that strong building codes can significantly reduce losses.)
However, as strong codes have only been implemented in recent years and only in some locations, their effect on overall losses is unlikely to be large. But in future years, efforts to improve building practices and encourage retrofitting existing structures could have a large impact on losses.)

Some surprising conclusions arise when a more apples-to-apples comparison of historic hurricane damage versus more recent hurricane impacts is conducted. First of which, is that Hurricane Katrina would not be the worst case if each of the U.S. hurricanes during the last century were to hit today's society. Instead, Katrina would be second behind the Great Miami Hurricane of 1926. This hurricane was a Category 4 cyclone (stronger than Katrina) having about the same very large size and made landfall in the Miami-Ft. Lauderdale-Palm Beach metropolitan area. The $100 million of damage in actual 1926 dollars would normalize to about $165 BILLION today if it hit the same stretch of coast with today's population and infrastructure.

This amount of destruction would be much more than that caused by Katrina.

Secondly, the damages - normalized to today's societal conditions - tell a very different story than the raw damage record. U.S. hurricane losses now average about $11 billion per year (about half of this being insured losses).
And instead of a dramatically increasing trend of hurricane damages, destruction from these storms varies on a
decade-to-decade timescale with more damages in the early 1900s, low damages during the late 1900s to early 1920s,
much higher destruction in late 1920s to the early 1960s, and reduced damages from the late 1960s to early 1990s.
Certainly, the U.S. hurricane damages from 1996 to 2005 were quite high, but now it is evident that these were quite
similar to the decade of 1926 to 1935. So after straightforward consideration of the non-meteorological factors of
inflation, wealth increases, and population change, there remains no indication that there has been a long-term pick up
of U.S. hurricane losses that could be related to global warming today. There have been no peer-reviewed studies
published anywhere that refute this. However, this normalized record of damages does provide us with some
indications of hurricane climate variations that likely are unrelated to global warming. More on this topic is provided
later.

Has There Been a Doubling in the Number of Tropical Storms and
Hurricanes?

One could argue - persuasively - that the U.S. hurricane damage record is too noisy, too uncertain and the
normalization process too inadequate to resolve the issue of whether manmade global warming is affecting hurricane
impacts today. Instead, one should just be able to go directly to the Atlantic basin hurricane database - HURDAT\textsuperscript{14} -
and simply count how many tropical storms and hurricanes have occurred over time.

Indeed, this is exactly what some studies have done. For example, one paper\textsuperscript{15} showed a strong relationship
between Atlantic Ocean temperatures and Atlantic basin tropical storm and hurricane counts from 1871 to present.
When the waters were cooler, fewer storms occurred; and when the waters were warmer, more. Of particular note was the huge trend in number of tropical storms and hurricanes, going from 6-8 per year in the 1870s to 14-16 per year in the 2000s. The authors concluded that "this record [of Atlantic tropical storm and hurricane counts] shows a strong, long-term relationship with tropical Atlantic August-October sea surface temperature (SST) The underlying factor appears to be the influence of (primarily anthropogenic) forced large-scale warming."

Another study looked the same data and came to the same conclusions: "Overall, there appears to have been a substantial 100-year trend leading to related increases of over 0.78°C in SST and over 100% in tropical cyclone and hurricane numbers. It is concluded that the overall trend in SSTs, and tropical cyclone and hurricane numbers is substantially influenced by greenhouse warming."

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A natural question should arise in studies that are comparing tropical storms and hurricanes today versus a century ago: Have recent improvements in our ability to detect and monitor these cyclones affected the record and thus the trends obtained? After all, these storms form over the ocean and spend most or all of their life cycle over the ocean. Before the 1960s there were no satellites taking pictures of the earth, and before 1944 there were no aircraft reconnaissance flying into (and looking for) tropical storms and hurricanes. The satellites and aircraft are our most
important monitoring technologies available today. Therefore, many storms may have been missed in earlier decades. Both sets of the studies described above began with the assumption that there were very few missing storms in earlier years and that these would not alter the conclusions that they reached.

How Have the Ways We Measure Tropical Storms and Hurricanes Improved?

Is it reasonable to assume that we have a complete record for over 100 years? Let's compare the ways that we observe tropical storms and hurricanes today versus a century ago. Today, at the National Hurricane Center we are so fortunate to have some amazing technology at our disposal. To begin, we have a wide array of conventional measurements: ships sending weather observations every six hours or more; buoys anchored to the ocean floor providing continuous readings of winds, pressures, temperatures, and waves; and hundreds of coastal weather stations both in the United States and the countries throughout the Caribbean.

During the last decade or so, we've also had access to some unique wind measurements over large swaths of the open ocean from satellite-based scatterometers via NASA's QuikSCAT satellite from 2000 until 2009 and currently via the European ASCAT satellite. In addition to all of these surface measurements, we also have some amazing satellite imagery available. The geostationary satellites
- GOES-West, GOES-East, and METEOSAT - provide the now routine satellite imagery that allows NHC to monitor the whole Atlantic basin at once with updates every half an hour.

Additionally, we have a large variety of low-earth orbiting satellites that allow us to peer through the cloud tops to see the active thunderstorms underneath by monitoring in the microwave spectrum. We literally could not do our job as forecasters without the satellite information: we would be blind at NHC without them.

However, often the satellite imagery is not able to provide the accurate details of what is needed for our forecasts: where precisely is the center of the cyclone, what are the peak winds, and how far do strong winds extend from the center of the system? We are very fortunate that we also have the Hurricane Hunters - the aircraft reconnaissance crews of the U. S. Air Force Reserve's 53rd Weather Reconnaissance Squadron flying C-130s and the NOAA Aircraft Operations Center flying Orion P-3s - that go into the center of tropical storms and hurricanes to obtain this crucial information.

So with these tremendous resources available to the Hurricane Specialists at NHC, if there is a tropical storm or hurricane today, we know about it, advisories are written, and the cyclone winds up in the database after the season.
This hurricane database is a "by-product" of operations that is appended to by the NHC Hurricane Specialists like Dr. Jack Beven based upon observations available at that time and knowledge of hurricanes during that hurricane season.

Now consider the information available about tropical storms and hurricanes one hundred years ago. In 1911, there were no satellites, no aircraft reconnaissance, no radar, no buoys and no automated weather stations. Indeed, it was only two years previous, that the very first ship captain stuck in a hurricane aboard his ship was able to use a two-way radio to let people back at the coast know that a hurricane was out over the ocean. So, if one puts themselves in the place of Dr. Isaac Monroe Cline, the Meteorologist-in-Charge at the New Orleans Weather Bureau Office, he had very crude and primitive tools to make his forecasts of tropical storms and hurricanes.

On a typical day around 1911, Dr. Cline would have in addition to the coastal weather observations a couple of ship reports from the Caribbean, perhaps one in the Gulf of Mexico, several along the mid-Atlantic U.S. Coast and just a few others across the whole Atlantic Ocean.

Forecasting with these extreme limitations was almost hopeless because he could not even answer the basic questions of just where were the tropical storms and hurricanes and how strong were they? It would appear that the hurricane database would have some very large gaps in both numbers of cyclones and their peak winds as one went further back in time.
There are efforts, which I am fortunate to assist with, to reanalyze the hurricane database\textsuperscript{17}. This project's goal is to take another look at historic hurricanes by obtaining all of the raw observations, and then reassessing the track and intensity of the systems using today's understanding and analysis tools. It is hoped that these efforts are improving the hurricane database. Unfortunately, we can't go back to 1911 or the 19th Century with satellite imagery or aircraft reconnaissance. Thus my team and I are also restricted in our efforts to use fairly crude and primitive tools. So "crude and primitive", with apologies to Gieco, that my team and I feel like cavemen trying to figure out what happened a century ago. It would seem to be excessively naïve to believe that the Atlantic hurricane database is complete and reliable with no significant gaps going back a century or more into the past. Even a caveman would not make that mistake.

One way to see if there are sizable gaps in the entire hurricane database is to count just those cyclones that struck land. Comparing the two busiest hurricane seasons on record - 2005 and 1933 - the difference across the ocean between those two years is apparent: there were several tropical storms and hurricanes in the eastern half of the North Atlantic in 2005, while in 1933 there were none. So either this huge gap in 1933 actually occurred, or there were tropical storms and hurricanes in the eastern half of the ocean, but they went unobserved. If one restricts the counting to those tropical storms and hurricanes that hit land in 2005, 17 of the 28 tropical storms and hurricanes made landfall. But in 1933, 19 of the 21 tropical storms and hurricane in that season struck a coast. So by a metric of landfalling cyclones, 1933 was busier than 2005 and much of the long-term upward trend is removed\textsuperscript{18}.

"Shorties" - How Short-lived, Weak Tropical Storms are Affecting our
During the 2007 hurricane season, I was struck by the somewhat contradictory measures of how busy the year was. By a count of 15 tropical storms and hurricanes, this would make it substantially more active than the long-term (1966-2005) average of 11 per year.

Yet, a more comprehensive measure of the hurricane season - the Accumulated Cyclone Energy (ACE) index - that takes into account not only how many cyclones, but also how strong they became, and how long they lasted - suggested a slightly below average season. The reason for this inconsistency is because nine of the 15 named storms in 2007 were very short-lived (less than 36 hours) as a tropical storm and mostly quite weak. I hypothesized that this was due to improved monitoring capabilities that allow us to better identify, to write advisories on, and to include into the hurricane database weak, short-lived cyclones that perhaps even a decade or two ago would not have been identified as such. New instruments such as the Advanced Microwave Sounding Unit (AMSU) and scatterometers from low-earth orbiting satellites, new methods for interpreting geostationary satellite imagery such as the Advanced Dvorak Technique, new observation techniques such as the Stepped Frequency Microwave Radiometer aboard the Hurricane Hunter aircraft and more oceanic moored buoys providing continuous measurements, and new diagnostic methods such as the Cyclone Phase Space analysis all have contributed - in my opinion - toward increased numbers of weak, short-lived tropical storms.19

So, I went back into the records for the 2007 and 2008 seasons and was able to identify at least six weak, short-
lived tropical storms that I considered would be very unlikely to have been "named" previously.

These short-lived cyclones - with peak lifetime winds of only about 45 mph (70 kph) - were indeed tropical storms and thus did deserve forecast advisories being written by the National Hurricane Center and for inclusion into the hurricane database. But how would counting such "shorties" affect the climate record of tropical cyclone frequency?

Taking a look at the long-term changes in the number of these shorties should be instructive.

This graph shows that there were very few shorties - only 12 in the first 44 years of the 20th Century - the time period when oceanic tropical storms could only be monitored from ships. Beginning in the mid-1940s, the number of shorties jumped to about 1 per year, coincident with the advent of aircraft reconnaissance missions. These missions also included flights out of Antigua in the Lesser Antilles, where they would fly eastward toward West Africa looking for potential tropical storms and hurricanes. (Such missions are not needed any longer, due to the geostationary satellite imagery providing routine coverage over the open Atlantic Ocean.)

Beginning in the 1960s, the National Hurricane Center began getting routine satellite pictures via polar orbiting
sateails. Coincident with this technological advance, the number of shorties again jumped to about two per year. Finally, during the last decade or so, the frequency of shorties has shot up again to about four per year, coincident with the newest technology and analysis techniques mentioned above. So over a century the number of short-lived, generally very weak tropical storms has increased dramatically. It is my opinion that this big increase is primarily or entirely due to technology changes - now we can see, advise on, and record the shorties. (It is worth noting that quite similar trends of a very large increase in the number of weak tornadoes in the United States has also been attributed toward enhanced observational networks, including - in the tornado case - the Weather Surveillance Radar-1988 Doppler (WSR-88D) radar network.)

Furthermore, a rigorous statistical study has demonstrated that the huge increase in shorties is very likely to be artificial. While it is my opinion (and is substantiated by this paper) that the increases of these short-lived, weak tropical storms are just an artifact of better technology, it is possible that there are some true climate signals embedded within them. Regardless, let's throw out the shorties and see what is left over, as the longer-lived, stronger cyclones are the ones of much more societal significance anyways. In doing so, the original graph of all tropical storm and hurricane numbers goes from this image to the "mouseover" image after removing the shorties.

In these graphs, the yearly numbers are plotted in red, the black lines show the decade and longer variations (with a five year centered average), and the blue lines indicate the long-term (late 19th Century to today) linear trend. The most important aspect at this point to notice is that the trend which is very large in the whole tropical storm and hurricane frequency database - going from 7 to 12 cyclones per year - is reduced down by ~80% to just a small trend of 7 to 8 cyclones per year after removal of the shorties.

But this adjustment still neglects the fact that there were medium duration tropical storms and hurricanes (~2-4 days) that did not strike land and were not recorded in the pre-satellite era. Fortunately, some recent innovative work provides a way to quantitatively estimate the number of "missed" tropical storms and hurricanes. This method takes the amount of actual ship traffic over the Atlantic Ocean, Gulf of Mexico and Caribbean Sea each year during the last century in combination with the locations/sizes of cyclones today and estimates the number that likely occurred but just never recorded. For example, early in the 20th Century there were only two main shipping lines - one between the U.S. mid-Atlantic coast and Europe and one from Europe southward along the west coast of Africa.
These ship locations meant that very large portions of the Atlantic basin had almost no measurements. After the opening of the Panama Canal in 1914, substantially more ships were routed from the United States or Europe to the western Caribbean. But even by the middle part of the 20th Century, there still remained about half of the tropical and subtropical Atlantic Ocean that had almost no ship traffic. (The adage about whether a tree falling in the forest with no one around would cause a sound is appropriate here as well: If a tropical storm treks across the Atlantic with no ships encountered, would that mean that the storm did not exist?)

Using this methodology, my colleagues and I calculated the rough number of missed tropical storms and hurricanes that lasted at least two days, but did not hit land or encounter a ship.

This shows that about 2-3 medium-to-long lived storms were missed during the 1880s, about 1-2 in the 1900s, and down to about 1 per year in the 1950s. (The spikes in the late 1910s and early 1940s were due to the effect of World Wars I and II reducing the amount of ship observations recorded, and thus more missed storms.)
Move the mouse over the image to see the trend after adding the estimated number of missed medium-to-long lived storms.

So removing the shorties and adding in the estimated number of missed medium-to-long lived storms reveals quite a different picture regarding the long-term changes: instead of a doubling in the number, the frequency of these storms is flat over the time period of a century as seen in the blue trend line.

What remains is now a much more prominent active and quiet swing: active from the late 1870s to ~1900, quiet from the 1900s to the 1920s, active during the 1930s to 1950s, quiet from the 1960s to 1994, and active from 1995 onward.

How Have the Numbers of Hurricanes and Major Hurricanes Changed?

Further work extending the methodology of estimating the amount of missed cyclones to the number of hurricanes shows very similar results: a large trend in the original hurricane database to essentially no long-term changes (or perhaps even a slight reduction in hurricane numbers).
What remains are periods of busy-quiet-busy-quiet that last 25-40 years each.

While no such study has yet been done for the major hurricanes - Category 3, 4, or 5 on the Saffir-Simpson Hurricane Wind Scale - the raw record is still instructive. After all, major hurricanes account for about 85% of the U.S. tropical storm and hurricane damages, even though they only account for about a quarter of all landfalls\textsuperscript{25} - these are the cyclones that by far are the most destructive and most fatal. Starting in 1944 (the first year of aircraft reconnaissance), it was active during the late 1940s to the 1960s, quiet in the 1970s to 1994, and busy since 1995.

Preliminary work\textsuperscript{26} is indicating that some of the major hurricanes monitored by the rudimentary aircraft reconnaissance during the 1940s and 1950s were overestimated in their intensity and may not have been Category 3 or stronger. On the other hand, major hurricanes over the central or eastern North Atlantic - such as 2009's Hurricane Fred\textsuperscript{27} and 2010's Hurricane Julia\textsuperscript{28} - very likely would not have been "counted" as a major hurricane in the pre-satellite era of the 1940s to 1960s (and may have been even missed completely, given their locations). The bottom line is that the current very active period since 1995 is indistinguishable from the 1940s to the 1960s - it is busy now, but it was just as active in the mid-20th Century.

What does the United States Hurricane Landfall Record Show?

Finally, one can go back further in time with reliable estimates of numbers of hurricanes and major hurricanes by only evaluating those that made landfall. For the United States, current records extending back to 1851\textsuperscript{29} show no trend in either the number of U.S. hurricanes or the number of major U.S. hurricanes.
However, before 1900 there were stretches of the coast - such as parts of Florida, Louisiana, and Texas - where too few people lived to know what the strongest winds were to strike or even IF a hurricane occurred. Thus it is possible that there were more hurricanes or major hurricanes to strike the United States in the late 19th Century than is shown here. Again, instead of a long-term increase, what remains are periods of increased activity like the 1870s-1890s, 1930s-1950s, and the 2000s interspersed by quiet periods during the 1850s-1860s, 1900s-1920s, and 1960s-1990s.

What is the Cause of these Multi-year Swings in Hurricane Activity?

What might be the cause of these multi-year swings - on the time scales of roughly 25-40 years each of active and quiet? The best answer in my opinion is a phenomenon called the Atlantic Multidecadal Oscillation. This is a natural fluctuation driven by the Atlantic Ocean, which experiences distinct warm and cool periods that are not tied to the long-term global warming signal. When the Atlantic is in a warm phase, not only are the waters warmer by ~1/2°F (~1/4°C), but the atmosphere has more moisture, less wind shear to tear incipient hurricanes apart, and more vigorous and plentiful thunderstorms that fuel the cyclones. Conversely, in the cool phase of the Atlantic Multidecadal Oscillation, the waters are slightly cooler and the atmosphere is drier, has more inhibiting wind shear, and cannot sustain the thunderstorm activity as readily. The warm phase of the Atlantic Multidecadal Oscillation occurred during the 1870s to the early 1900s, the late 1920s to the late 1960s, and from 1995 onward. Conversely, the cool phase occurred during the 1850s and 1860s, the mid-1900s to the mid-1920s, and the early 1970s to 1994.
These multi-year swings in ocean temperature are nearly an exact match to the adjusted number of tropical storms, adjusted hurricanes, U.S. hurricanes, and normalized U.S. hurricane damages. When stratified by the Atlantic Multidecadal Oscillation, there is a doubling in the number of major hurricanes, a 50% increase in the frequency of U.S. landfalling major hurricanes, and over three times as many Caribbean hurricane strikes between the warm and cool phases.

Paleo-climatologists examining corals, ocean sediment cores, and tree-ring data also tell us that such cycles have been going on for centuries. Thus these hurricane changes being seen on a decade-by-decade scale are very likely to be natural in origin.

How May Hurricane Activity Change in the Future?

Again, all of this is not to say that manmade global warming is not real, nor unimportant. My reading of the research does suggest to me that there has been and should continue to be warming of the earth's climate due to the greenhouse gases of carbon dioxide and methane. And that there should be changes to hurricanes caused by this manmade global warming. But as described earlier, simply linking hurricanes to global warming is not sufficient. Quantifying the changes is critical for understanding how such alterations will affect mankind and coastal ecosystems.
My interpretation of the climate change research suggests the following - assuming that there is a significant 2-3°C (4-6°F) global warming due to business-as-usual emissions (which is not a guarantee):

**Overall Tropical Storm and Hurricane Changes Due to Global Warming by 2100**

- **Frequency:** Numbers may see a moderate decrease (~25%)
- **Wind (Intensity):** Small increase (~3% stronger)
- **Storm Surge:** Small increase (~3% higher) produced by the hurricane (but also must add on additional amount from overall sea level rise)
- **Rainfall:** Moderate increase per cyclone (~10% within ~325 km [200 mi]), but reduced overall numbers may offset increase per cyclone
- **Genesis Location/Track:** Somewhat uncertain, but no indications of large changes

These overall changes that may occur are relatively tiny and are several decades away, in my opinion. These conclusions are similar, though slightly smaller, than those indicated by a review panel of the topic of hurricanes and global warming that was recently published in Nature Geophysics in which I participated.33

What is much more important is the massive population buildup along the U.S. coastline and in countries of the Caribbean and Central America. Such increases in coastal inhabitants (not global warming) make mankind dramatically more vulnerable to hurricanes today than in the past with thousands at risk of injury or death along with damage totals in the tens of billions of dollars when a strong hurricane strikes. As an example, this figure shows the combination of Florida's coastal county population along with major hurricane strikes by decade during the 20th Century.35

![Florida Population and Major Hurricanes](image)

Move the mouse over the image to see the actual number of landfalling major hurricanes

This shows the dramatic increases in population for this state (in red) along with the extremely variable number of major hurricanes to strike during each decade (the small hurricane images). At the same time that the number of inhabitants dramatically went up in the 1970s to the 1990s, the number of strong hurricanes dropped way down. Bill Gray and I predicted in this 2002 Miami Herald op-ed piece that Florida was likely to experience a renewed jump in major hurricane strikes during the 2000s and 2010s. Now that the first decade of the 21st Century has completed, we see that indeed Florida did have very busy period of major hurricane strikes (Charlie, Ivan, and Jeanne in 2004, Dennis and Wilma in 2005).
Such impacts are likely to continue in the near future - not because of global warming - but instead because of the warm phase of the Atlantic Multidecadal Oscillation. Knowing, however, when the cold phase of the Atlantic Multidecadal Oscillation will occur - and a distinct drop in major hurricane numbers - is unknown, but likely within the next decade or two\textsuperscript{36}. Is global warming a concern? Yes. We're conducting an uncontrolled experiment where we really don't completely know what the consequences will be. I've been particularly shocked about the drastic changes going on in the Arctic, with the huge ice cover loss in the summertime that may very well be related to manmade global warming. The biggest immediate worry I have is with the huge population increases of vulnerable coastal communities both in Florida, elsewhere in the U.S., and to our neighbors in the Caribbean. Such jumps in coastal residents are causing massive damage increases and, unfortunately, large losses of life such as the 10,000 deaths in Honduras and Nicaragua from 1998's Hurricane Mitch\textsuperscript{37} and the 1200 people that drowned from Katrina in Mississippi and Louisiana. The confluence of more people and infrastructure with the current busy period for Atlantic hurricanes has me quite concerned today. But - in my opinion - the overall impact of global warming on hurricanes is currently negligible and likely to remain quite tiny even a century from now\textsuperscript{38}.

Footnotes:

1 Christopher W. Landsea is the Science and Operations Officer at the National Weather Service's National Hurricane Center in Miami, FL. Chris's responsibilities at NHC include hurricane and marine weather forecasting, training, outreach, and transitioning research results into operations. He also leads efforts in reanalyzing the historical hurricane records to provide a more complete, reliable database. Before joining NHC in 2005, he had previously worked for ten years at the Hurricane Research Division also in Miami. While at HRD, Chris participated in the annual Hurricane Field Program flying into and around 15 hurricanes aboard the Aircraft Operation Center's Orion P-3 and Gulfstream IV aircraft, as well as conducting research into the seasonal and climate variations of hurricanes. Much of his career within NOAA (the National Oceanic and Atmospheric Administration, of which NHC, NWS, HRD, and AOC are a part) has focused upon research into how hurricanes have changed over the historical record and how this relates to manmade global warming. Chris has published 33 peer-reviewed papers on the topics of the Atlantic hurricane database, hurricane changes over time, and the effects of man-made global warming on hurricanes. (It should be noted that the following discussion is Chris Landsea's opinion only and is not representing any official policy of NHC, NWS or NOAA in general. Various scientists within NOAA have differing opinions about global warming's impact on hurricanes and there is no official NOAA policy on the topic. Varying ideas on an issue often mean that it is a science in progress with no definitive answers. That is certainly the case with regards to global warming and hurricanes.)

2 Eric Blake and colleagues, 2011 in The Deadliest, Costliest, and Most Intense United States Tropical Cyclones From 1851 to 2010 (and other Frequently Requested Hurricane Facts)

3 Intergovernmental Panel on Climate Change, 2007


5 Kerry Emanuel, 1988, Journal of Atmospheric Sciences
Kerry Emanuel, 1998, Weather

6 Bill Gray, 1968, Monthly Weather Review

7 Tom Knutson and Bob Tuleya, 2004, Journal of Climate

8 Gabe Vecchi and Brian Soden, 2007, Geophysical Research Letters

10 James Franklin and colleagues, 2006 in Monthly Weather Review

11 Jack Beven and colleagues, 2008 in Monthly Weather Review

12 Eric Blake and colleagues, 2011 in The Deadliest, Costliest, and Most Intense United States Tropical Cyclones From 1851 to 2010 (and other Frequently Requested Hurricane Facts)

13 Roger Pielke, Jr. and colleagues, 2008, in Natural Hazard Review

14 Colin McAdie and colleagues, 2009, Tropical Cyclones of the North Atlantic Ocean, 1851-2006

15 Michael Mann and Kerry Emanuel, 2006, in EOS

16 Greg Holland and Peter Webster, 2007, in Philosophical Transactions of the Royal Society A

17 Re-analysis Project

18 Chris Landsea, 2007 in EOS

19 Chris Landsea and colleagues, 2010 in Journal of Climate


21 Gabriele Villarini and colleagues 2011, in Journal of Geophysical Research


23 Chris Landsea and colleagues, 2010 in Journal of Climate

24 Gabe Vecchi and Tom Knutson 2011, in Journal of Climate

25 Roger Pielke, Jr. and colleagues 2008, in Natural Hazards Review

26 Andrew Hagen and colleagues 2011, submitted to Journal of Climate.


28 Jack Beven and Chris Landsea 2011, on-line report.

29 Eric Blake and colleagues, 2011 in The Deadliest, Costliest, and Most Intense United States Tropical Cyclones From 1851 to 2010 (and other Frequently Requested Hurricane Facts)
Stan Goldenberg and colleagues, 2001, in Science
Jim Kossin and Dan Vimont, 2007, in the Bulletin of the American Meteorological Society

Dave Enfield and Luis Cid-Serrano, 2010, in International Journal of Climatology


Tom Knutson and colleagues, 2010 in Nature Geoscience

Roger Pielke, Jr. and colleagues, 2003 in Natural Hazards Review

Chris Landsea and Bill Gray, 2002 in the Miami Herald

Dave Enfield and Luis Cid-Serrano, 2006 in International Journal of Climatology

Richard Pasch and colleague, 2001 in Monthly Weather Review

For more information, my papers on hurricanes are available here