U.S. HURRICANE DAMAGE —

CAN RISING LEVELS OF CO₂ BE ASSOCIATED WITH SANDY’S MASSIVE DESTRUCTION?

by William M. Gray and Philip J. Klotzbach
Department of Atmospheric Science
Colorado State University

NOVEMBER 2012
ABSTRACT

Atlantic basin hurricane activity undergoes large yearly and multi-decadal variability. A large portion of this variability, particularly the variability of the major or Category 3-4-5 hurricanes, is directly related to the strength of the Atlantic Thermohaline Circulation (THC) or the Atlantic Multi-decadal Oscillation (AMO). On a long-period normalized basis, major hurricanes cause about 80-85 percent of US tropical cyclone destruction. There has been a downward trend in US landfalling hurricane activity over the last 50 years. This goes opposite to the upward trend of atmospheric CO₂ levels over the last 50 years.

Our hurricane research extending over many years indicates that Atlantic hurricane variability is driven almost exclusively by natural changes. The potential influence of human-induced CO₂ increase on Atlantic hurricane frequency and intensity is likely to be negligible. As extensive and tragic as Sandy’s 2012 destruction has been, it and other destructive hurricanes in recent decades are not beyond the range of what is known to be the natural variability of the atmospheric-ocean system. What is more amazing than Sandy’s tragic and extremely damaging flooding, at least from an intellectual point-of-view, is the number of knowledgeable people and prominent government and private citizens who have concluded that Sandy’s destruction was largely the result of human-induced climate change resulting from our over-abundant use of fossil fuels. Our analysis of Atlantic hurricane activity variations over the last century does not support such a conclusion.

1. BACKGROUND

The U.S. landfall of major hurricanes Dennis, Katrina, Rita and Wilma in 2005 and the four Southeast landfalling hurricanes of 2004 – Charley, Frances, Ivan and Jeanne, raised questions about the possible role that global warming played in those two unusually destructive seasons for the U.S. In addition, three (Category 2) hurricanes (Dolly, Gustav and Ike) pummeled the Gulf Coast in 2008 causing considerable devastation. Some researchers have tried to link the rising CO₂ levels with SST increases during the late 20th century and say that this has brought on higher levels of hurricane intensity.

These speculations have been given much media attention; however, we believe that they are not valid, given current observational records of Atlantic hurricane activity over the last century. The long manuscript by Gray (2011) goes into extensive detail describing why a significant relationship between increased CO₂ and increased Atlantic hurricane activity is not valid.

There has, however, been a large increase in Atlantic basin major hurricane activity in the last eighteen years (since 1995) in comparison with the prior 18-year period of 1977-1994 (Figure 1) as well as the prior quarter-century period of 1970-1994. It has been tempting for many who do not have a strong background of hurricane information to jump on this recent increase in major hurricane activity as strong evidence of a human influence. It should be noted, however, that the last 18-year active major hurricane period of 1995-2012 has not been more active than the earlier 18-year period of 1947-1964 when the Atlantic Ocean circulation conditions were similar to what has been observed during the last 18 years. These earlier active conditions occurred even though atmospheric CO₂ amounts and global SSTs were lower during this earlier period.
Figure 1: Tracks of major (Category 3-4-5) hurricanes during the 18-year period of 1995-2012 when the THC was strong versus the prior 18-year period of 1977-1994 when the THC was weak. Note that there were approximately 2.5 times as many major hurricanes when the THC was strong as when it was weak.

Table 1 shows how large Atlantic basin hurricane variations can be between strong and weak THC periods. Note especially how large the ratio is for major hurricane days (3.7) during strong vs. weak THC periods. Normalized U.S. hurricane damage studies by Pielke and Landsea (1998) and Pielke et al. (2008) show that landfalling major hurricanes account on average for about 80-85 percent of all tropical cyclone-related destruction. This occurs even though these major hurricanes make up only 15-20 percent of named storms. This would give a general relative potential destructive difference between strong versus weak THC periods of about 15 to 1.

Table 1: Comparison of Atlantic annual basin hurricane activity in two 18-year periods when the Atlantic Ocean THC (or AMO) was strong versus an intermediate period (1970-1994) when the THC was weak.

<table>
<thead>
<tr>
<th>THC</th>
<th>SST (10-15°N; 70-40°W)</th>
<th>Avg. CO₂ ppm</th>
<th>NS</th>
<th>NSD</th>
<th>H</th>
<th>HD</th>
<th>MH</th>
<th>MHD</th>
<th>ACE</th>
<th>NTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1947-1964 (18 years) Strong</td>
<td>27.93</td>
<td>319</td>
<td>9.9</td>
<td>53.9</td>
<td>6.4</td>
<td>29.8</td>
<td>3.7</td>
<td>9.2</td>
<td>119</td>
<td>131</td>
</tr>
<tr>
<td>1970-1994 (25 years) Weak</td>
<td>27.60</td>
<td>345</td>
<td>9.3</td>
<td>41.9</td>
<td>5.0</td>
<td>16.0</td>
<td>1.5</td>
<td>2.5</td>
<td>68</td>
<td>75</td>
</tr>
<tr>
<td>1995-2012 (18 years) Strong</td>
<td>28.02</td>
<td>373</td>
<td>15.2</td>
<td>77.1</td>
<td>8.0</td>
<td>31.6</td>
<td>3.7</td>
<td>8.6</td>
<td>140</td>
<td>152</td>
</tr>
<tr>
<td>Annual Ratio Strong/Weak THC</td>
<td>Δ 0.35°C</td>
<td>~0</td>
<td>1.3</td>
<td>1.5</td>
<td>1.4</td>
<td>1.9</td>
<td>2.5</td>
<td>3.7</td>
<td>1.9</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Although global surface temperatures increased during the late 20\textsuperscript{th} century, there is no reliable data to indicate increased hurricane frequency or intensity in any of the globe’s other tropical cyclone basins since 1972. Global Accumulated Cyclone Energy (ACE), defined as the sum of the square of a named storm’s maximum wind speed (in 10\textsuperscript{4} knots\textsuperscript{2}) for each 6-hour period of its existence, shows significant year-to-year and decadal variability over the past forty years but no increasing trend (Figure 2). The red arrows of this figure, in fact, indicate a downward trend over the last 20 years. Similarly, Klotzbach (2006) found no increasing trend in global TC activity during the period from 1986-2005.

Figure 2: Northern Hemisphere and global Accumulated Cyclone Energy (ACE) over the period from December 1971-October 2012. Figure has been adapted from Ryan Maue.

\textbf{2. UP SWING IN ATLANTIC MAJOR HURRICANE ACTIVITY SINCE 1995}

The Atlantic Ocean has a strong multi-decadal signal in its hurricane activity which we attribute to multi-decadal variations in the strength of the THC (Figure 3). The oceanic and atmospheric response to the THC is often referred to as the Atlantic Multi-decadal Oscillation (AMO). We use the THC and AMO interchangeably throughout the remainder of this discussion. The strength of the THC cannot be measured directly, but it can be diagnosed, as we have done, from the magnitude of the SST anomaly (SSTA) in the North Atlantic (Figure 4) combined with the sea level pressure anomaly (SLPA) in the Atlantic between the latitude of the equator and 50°N (Klotzbach and Gray 2008).

The THC (or AMO) is strong when there is an above-average poleward advection of warm and saline low-latitude waters to the high latitudes of the North Atlantic. This salty, dense water can then sink to deep levels when it reaches the far North Atlantic in a process known as deep water formation. The water then moves southward at deep levels in the ocean. The amount of North Atlantic water that sinks is proportional to the water’s density which is determined by its salinity content as well as its temperature. Salty water is most dense at water temperatures near freezing. There is a strong association between North Atlantic SSTA and North Atlantic salinity (Figure 5). High salinity implies higher rates of North Atlantic deep water formation (or subsidence) and thus a stronger flow of upper level warm water from lower latitudes as replacement. See the papers by Gray et al. (1999), Goldenberg et al. (2001), and Grossmann and Klotzbach (2009) for more discussion.
Figure 3: Illustration of strong (top) and weak (bottom) phases of the THC or AMO.

Figure 4: Long-period portrayal (1870-2011) of North Atlantic sea surface temperature anomalies (SSTA). The red (warm) periods are when the THC (or AMO) is stronger than average and the blue periods are when the THC (or AMO) is weaker than average.
3. **Thermohaline Circulation (THC) Responsible for Hurricane Variations – Not CO₂ Changes**

Theoretical considerations do not support a close relationship between SSTs and hurricane intensity. In a global warming world, the atmosphere’s upper air temperatures will warm or cool in unison with longer-period SST changes. Vertical lapse rates will thus not be significantly altered in a somewhat warmer or somewhat cooler tropical oceanic environment. We have no plausible physical reasons for believing that Atlantic hurricane frequency or intensity will significantly change if global or Atlantic Ocean temperatures were to rise by 1-2°C, without corresponding changes in many other basic features, such as vertical wind shear or mid-level moisture, little or no additional TC activity should occur with SST increases.

**Confusing Time Scales of SST Influences.** A hurricane passing over a warmer body of water, such as the Gulf Stream, will often undergo some intensification. This is due to the sudden lapse rate increase which the hurricane’s inner core experiences when it passes over warmer water. The warmer SSTs cause the hurricane’s lower boundary layer temperature and moisture content to rise. While these low-level changes are occurring, upper tropospheric conditions are often not altered significantly. These rapidly occurring lower- and upper-level temperature differences cause the inner-core hurricane lapse rates to increase and produce more intense inner-core deep cumulus convection. This typically causes an increase in hurricane intensity. Such observations have led many observers to directly associate SST increases with greater hurricane potential intensity. This is valid reasoning for day-to-day hurricane intensity change associated with hurricanes moving over warmer or colder patches of SST. But such direct reasoning does not hold for conditions occurring in an overall climatologically warmer (or cooler) tropical oceanic environment where broad-scale global and tropical rainfall conditions are not expected to significantly vary. During long-period climate change, temperature and moisture conditions rise at both lower and upper levels. Lapse rates are little affected.
Any warming-induced increase in boundary layer temperature and moisture will be (to prevent significant global rainfall alteration) largely offset by a similar but weaker change through the deep troposphere up to about 10 km height. Upper-tropospheric changes are weaker than boundary layer changes, but they occur through a much deeper layer. These weaker and deeper compensating increases in upper-level temperature and moisture are necessary to balance out the larger increases in temperature and moisture which occur in the boundary layer. Global and tropical rainfall would be altered significantly only if broad-scale lapse rates were ever altered to an appreciable degree.

Thus, we cannot automatically assume that with warmer global SSTs that we will have more intense hurricanes due to lapse-rate alterations. We should not expect that the frequency and/or intensity of major hurricanes will necessarily change as a result of changes in global or individual storm basin SSTs. Historical evidence does not support hurricanes being less intense during the late 19th century and the early part of the 20th century when SSTs were lower than they are today.

**Discussion.** We have no plausible physical reasons for believing that Atlantic hurricane frequency or intensity will change significantly if global ocean temperatures were to continue to rise. For instance, in the quarter-century period from 1945-1969 when the globe was undergoing a weak cooling trend, the Atlantic basin experienced 80 major (Cat 3-4-5) hurricanes and 201 major hurricane days. By contrast, in a similar 25-year period from 1970-1994 when the globe was undergoing a general warming trend, there were only 38 Atlantic major hurricanes (48% as many) and 63 major hurricane days (31% as many) (Figure 6). Atlantic SSTs and hurricane activity do not follow global mean temperature trends. Figure 7 shows our analysis of the strength of the Thermohaline Circulation (THC) between 1945-2012. Note the two distinctive periods of strong THC conditions between 1945-1969 and 1995-2012 versus the intermediate period of 1970-1994 when we diagnosed the THC as being weak.

We derive the strength of the THC from a combination of the standard deviation (SD) of the Sea Surface Temperature Anomaly (SSTA) in the region 50°N-60°N; 50°W-10°W minus the SD of the Sea Level Pressure Anomaly (SLPA) in the region of 0°-50°N; 70°W-10°W. Figure 8 shows the areas we use to measure SST and SLP anomalies for our THC calculations.
Figure 6: Tracks of major (Category 3-4-5) hurricanes during the 25-year period of 1945-1969 when the globe was undergoing a weak cooling versus the 25-year period of 1970-1994 when the globe was undergoing a modest warming. CO₂ amounts in the later period were approximately 18 percent higher than in the earlier period. Major Atlantic hurricane activity was less than half as frequent during the latter period despite warmer global temperatures.

Figure 7: Portrayal of our proxy for the strength of the THC from 1945-2012.
Figure 8: Parameter values used to estimate the strength of the Atlantic Thermohaline Circulation (THC).

Figures 9 and 10 display the influence of the THC strength on major hurricane (MH) activity. Figure 9 shows the tracks of major hurricanes during the 25-year period of 1970-1994 when the THC was weak versus the two THC periods of 1945-1969 (25 years) and 1995-2012 (18 years) when the THC was strong.

Note the large ratios of major hurricane (MH) numbers (2.1 and 2.4) and of the ratio differences of major hurricane days (3.2 and 3.4) between the two strong versus the weak THC periods. Figure 10 gives similar information of Figure 9 for the differences in major hurricane numbers and major hurricane days for the 15 highest versus the 15 lowest THC years between 1945 and 2012.
Figure 9: Major hurricane (Cat 3-4-5) tracks during strong (1945-1969 and 1995-2012) versus weak (1970-1994) THC periods. The ratio of the average of the number of major hurricanes (MH) and major hurricane days (MHD) to the normalized activity of 1970-1994 is given on the right.

Figure 10: The tracks of major (Cat 3-4-5) hurricane tracks of the 15 strongest versus 15 weakest THC years between 1945-2012. There were 2.6 times more major hurricanes during the highest versus the lowest two 15-year periods and 4.4 times as many major hurricane days.
**How the varying strength of the THC acts to cause alterations in hurricane activity.** Through a progression of associations the strength of the THC is hypothesized to bring about alterations of the tropospheric vertical wind shear, trade wind strength, SSTs, middle-level water vapor, and other conditions in the Atlantic Main Development Region (MDR – 7.5-22.5°N; 20-75°W). The favorable changes of SST in the MDR are a consequence of a combination of the ocean’s THC influences on a variety of parameters in the Atlantic’s MDR. A stronger than average THC causes more ocean sinking in area 1. This in turn reduces the strength of the Atlantic gyre. There is then a change in all of the other conditions shown in Figure 11 to bring about more favorable parameters in the MDR for TC formation and intensification. This figure illustrates how the changing rate of southward advection of colder water in the east Atlantic (2) brings about alterations of SLP (3), SST (4), and rainfall (5). These changes in turn lead to changes in trade wind strength (6) and 200-mb zonal wind (7). Changes in hurricane activity follow (8). These changing conditions bring about weaker trade winds and reduced evaporation which typically acts to increase SST. It is also found that in periods with a strong THC, El Niño frequency and intensity is typically reduced (9) and Atlantic hurricane activity, particularly major hurricane activity, is enhanced.

While the THC typically remains in an above-average or in a below-average stage for periods of 25-35 years, there can be monthly, seasonal or longer breaks up to a year or two within these longer periods when the AMO (or THC) conditions of features such as SST, salinity, pressure, wind, and moisture become substantially weaker in positive phases or stronger during negative phases. During these periods where the multi-decadal signal is interrupted, we sometimes observe below-average TC activity during a positive phase (e.g., 1962 and 1968) or above-average TC activity during a negative phase (e.g., 1988 and 1989).

![Figure 11: Schematic showing the large number of parameters that are closely related to the strength of the Thermohaline Circulation (THC).](image)

**Semi-century downward trends in US landfall tropical storms and hurricanes.** The most reliable long-period hurricane records we have are the measurements of US landfalling TCs since 1900 (Table 2). Although global mean ocean and Atlantic SSTs have increased by about 0.4°C between the two 57-year periods (1899-1955 compared with 1956-2012), the frequency of US landfall numbers actually shows a weak downward trend for the later period. This downward trend is particularly noticeable for the US East Coast and Florida Peninsula where the difference in landfall of major (Category 3-4-5) hurricanes between
the 47-year period of 1919-1965 (26 landfall events) and the 47-year period of 1966-2012 (7 landfall events) has been especially large (Figure 12). For the entire United States coastline, 42 major hurricanes made landfall during the earlier 47-year period (1919-1965) compared with only 22 major hurricanes for the latter 47-year period (1966-2012). This occurred despite the fact that CO₂ averaged approximately 370 ppm during the latter period compared with 310 ppm during the earlier period.

We should not read too much into the four very active hurricane seasons of 2004, 2005, 2008 and 2010. The activity of these years was unusual but well within natural bounds of hurricane variation.

Table 2: U.S. landfalling tropical cyclones by intensity during two 57-year periods.

<table>
<thead>
<tr>
<th>YEARS</th>
<th>Named Storms</th>
<th>Hurricanes</th>
<th>Major Hurricanes (Cat 3-4-5)</th>
<th>Global Temperature Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1899-1955 (57 years)</td>
<td>216</td>
<td>119</td>
<td>46</td>
<td>+0.4 °C</td>
</tr>
<tr>
<td>1956-2012 (57 years)</td>
<td>185</td>
<td>89</td>
<td>34</td>
<td></td>
</tr>
</tbody>
</table>

Figure 12: Contrast of tracks of East Coast and Florida Peninsula major landfalling hurricanes during the 47-year period of 1919-1965 versus the most recent 47-year period of 1966-2012

What made the 2004, 2005, and 2008 seasons so destructive was not the high frequency of major hurricanes but the high percentage of hurricanes that were steered over the US coastline. The US hurricane landfall events of these years were primarily a result of the favorable upper-air steering currents present during these years.
Although 2005 had a record number of TCs (28 named storms), this should not be taken as an indication of something beyond natural processes. There have been several other years with comparable hurricane activity to 2005. For instance, 1933 had 20 named storms in a year when there was no satellite or aircraft data. Records of 1933 show all 20 named storms had tracks west of 60°W where surface observations were more plentiful. If we eliminate all of the named storms of 2005 whose tracks were entirely east of 60°W and therefore may have been missed given the technology available in 1933, we reduce the 2005 named storm total by seven (to 21) – one more than the number observed in 1933.

Utilizing the National Hurricane Center’s best track database of hurricane records back to 1875, six previous seasons had more hurricane days than the 2005 season. These years were 1878, 1893, 1926, 1933, 1950 and 1995. Also, five prior seasons (1893, 1926, 1950, 1961 and 2004) had more major hurricane days. Although the 2005 hurricane season was certainly one of the most active on record, it was not as much of an outlier as many have indicated.

We believe that the Atlantic basin remains in an active hurricane cycle associated with a strong THC. This active cycle is expected to continue for another decade or two at which time we should enter a quieter Atlantic major hurricane period like we experienced during the quarter-century periods of 1970-1994 and 1901-1925. Atlantic hurricanes go through multi-decadal cycles. Cycles in Atlantic major hurricanes have been observationally traced back to the mid-19th century. Changes in the THC (or AMO) have been inferred from Greenland paleo ice-core temperature measurements going back thousands of years. These changes are natural and have nothing to do with human activity.

4. CO₂’S MINISCULE ENERGY INFLUENCE ON TC ACTIVITY

The first author has been performing extensive data analysis with the International Satellite Cloud Climatology Project (ISCCP) and the National Center for Environmental Prediction (NCEP) Reanalysis data sets. We have used this data to make an annual average of the global tropical (30°N-30°S; 0-360°) energy budget (Figure 13) for the years from 1984-2004. Note that the various surface (459 Wm⁻², 402 Wm⁻², 215 Wm⁻²) and top of the atmosphere energy fluxes (399 Wm⁻², 355 Wm⁻², 254 Wm⁻²) are very large. For the tropical surface, for instance, there are 637 Wm⁻² net units of downward incoming solar and infrared (IR) energy. This downward energy flux is largely balanced by an upward surface energy flux of 615 Wm⁻² which is due to upward energy transfer from IR, evaporated liquid water, and sensible heat.

It has been estimated that a doubling of CO₂ (from the pre-industrial period) without any feedback influences would result in a blockage of IR (or OLR) to space of about 3.7 Wm⁻². The currently-measured value of CO₂ in the atmosphere is about 390 parts per million by volume (ppmv). If we take the background pre-industrial value of CO₂ to be 285 ppmv, then our globe should currently be emitting (from CO₂ increases alone up to now) about (105/285)*3.7 = 1.4 Wm⁻² less IR (or Outgoing Longwave Radiation – OLR) energy flux to space than was occurring during the mid-19th century at the beginning of the Industrial Revolution.
Figure 13: Vertical cross-section of the annual tropical energy budget as determined from a combination of ISCCP and NCEP Reanalysis data over the period of 1984-2004. Abbreviations are IR for longwave infrared radiation, Alb for albedo and OLR for outgoing longwave radiation. The tropics receive an excess of about 44 Wm\(^{-2}\) radiation energy which is exported to latitudes poleward of 30\(^\circ\). Estimates are that about half (22 Wm\(^{-2}\)) of this export is transported by the atmosphere and the other half is transported by the oceans. Note, on the right, how small has been the OLR blockage that has occurred up to now due to CO\(_2\) increases (~1.4 Wm\(^{-2}\)) and how generally small is the blockage of 3.7 Wm\(^{-2}\) that will occur from a doubling of CO\(_2\) by the end of this century.

This reduced IR energy flux of 1.4 Wm\(^{-2}\) is very small in comparison with most of the other tropical energy budget exchanges. Slight changes in any of these other larger tropical energy budget components could easily negate or reverse this small CO\(_2\)-induced OLR blockage up to now.

The 1.4 Wm\(^{-2}\) reduction in OLR we have experienced since the mid-19\(^{th}\) century is very small in comparison with the overall 399 Wm\(^{-2}\) of solar energy impinging on the top of the tropical atmosphere or the mostly compensating 356 Wm\(^{-2}\) of OLR and albedo energy which the tropics radiates back to space. This 1.4 Wm\(^{-2}\) energy gain (0.39% of the net energy returning to space) is much too small to allow a determination of its influence on TC activity. Any such potential CO\(_2\) influence on TC activity would be deeply buried as turbulence within the tropical atmosphere's many other larger energy components.

It is possible that future higher atmospheric CO\(_2\) levels may cause a small influence on global TC activity. Any such potential influence would likely be too small to ever be able to be reliably detected. Even if such a small influence were ever detected it would be swamped by the many other larger natural processes which are always at work to cause natural variations of TC activity. At the present time, we can only measure TC intensity to an accuracy of about 5 mph.
5. **Superstorm Sandy’s Special Characteristics**

Superstorm Sandy’s landfall of October 29-30 was an unusual (but not unprecedented) low probability weather event which resulted from the infrequent merging of a warm-core tropical cyclone and a strong middle-latitude cold-core cyclone system. Such merging occurs every few years but seldom in such a highly populated and vulnerable location, the northeast US coastline.

Sandy’s extra-large sized cyclonic vortex was the primary reason why the system was as destructive as it was (Figure 14). The large radius of outer winds drove a high ocean surge and brought heavy rainfall over an unusually broad area of the northeast US coastline. Sandy moved from the south into an area with a high pressure ridge to its north side. This caused it to begin tracking towards the northwest and then west onto the southern New Jersey coastline. Sandy’s track and strong outer winds produced an ocean surge which drove high ocean water toward the narrowing and land-funneling coastal sections of greater New York City (Figure 15). A high tide and full moon near the time of highest surge acted to further enhance the coastal flooding.

![Figure 14: Numerical forecast from the GFS model from Thursday, October 25, indicating a large hybrid TC approaching the mid-Atlantic/Northeast United States four days in the future. This was a remarkably accurate forecast.](image)

A broad coastal area from southern New England to the Maryland coast was impacted by a large storm tide. Sandy’s broad wind profile and slow motion before and after landfall acted to prolong the period of high water, wind, and rainfall.
Figure 15: Illustration of the funneling of storm surge (yellow arrows) into the surrounding high population areas (in red) of New York City and Long Island by Sandy’s easterly driven winds to the north of its landfall center (green arrow) in southern New Jersey (courtesy of NASA).

Sandy’s simultaneous merging of two notable weather events (a tropical cyclone and a mid-latitude cyclone) with a high pressure system to its north side caused an atypical high latitude westerly track. Such a track is extremely unusual but within nature’s complex climate variability. A very similar high water driven storm surge enveloped New York in 1821. There have also been several tropical cyclones that have barely missed New York City since records began nearly 400 years ago. Similar tropical cyclone and mid-latitude cyclone merger events have occurred many times in the past, but very few have occurred at such a highly vulnerable location as near the New York City metropolitan area.

Figures 16-19 show tracks of TCs in the past when:

1. Notable hurricanes and tropical cyclones passed over New York City (Figure 16),

2. Notable hurricanes impacted Long Island (Figure 17),

3. Hurricanes and strong tropical cyclones at higher latitudes (>35°N) had a westward track component (Figure 18).

4. Notable early American hurricanes impacted the northeast US coastline during the 17th – 19th centuries (Figure 19).
Figure 16: Notable cyclones with direct impacts on New York City.

Figure 17: Destructive tropical cyclones directly impacting Long Island.
Figure 18: US landfalling tropical cyclones making western track turns about 35°N.

Figure 19: Notable early American hurricanes that influenced the northeast US coastline as reported by D.M. Ludlum (1963).
Characteristics of Superstorm Sandy’s Lifespan. Sandy’s unprecedented destruction resulted from a merging of a northward-moving Category 1 hurricane off the US East Coast and an easterly moving strong cold front and upper-trough approaching from the Midwest. As the cold front and associated trough moved further eastward, its southern portion split off to form a large upper-level cold-core cyclone. This cut-off southern portion of the trough then moved around Sandy’s southern fringe and acted to greatly enhance Sandy’s outer-core southern circulation. While this was happening, a high pressure area to the north of Sandy was building. This acted to greatly broaden and increase Sandy’s easterly winds on its poleward side. Figures 20, 21, and 22 give an idealized 3-stage portrayal of the progression of the merging of these two separate cyclones which led to the unusually large event that emerged along the NJ and NY shorelines.

Figure 20: First of three consecutive idealized mid-tropospheric (500 mb – 5 km ht.) flow patterns showing the beginning of the merging of the long north-south trough (in red) with the poleward moving Category 1 Hurricane Sandy (green). The trough then splits, with its northern branch moving northeastward, while the southern part of the trough is advected around Sandy's southern flank. This acts to greatly enhance Sandy's upper-level wind strength.
Figure 21: Continued progression of the merger of Sandy with the upper-level trough. The southern part of the trough has been advected around Sandy which enhances the broad outer-core circulation of the developing superstorm.

Figure 22: Idealized 500-mb flow pattern near the period of Sandy's landfall in southern New Jersey. At this point, Sandy was generating its maximum wind driven ocean surge around New York City.
The maximum sustained winds of Sandy at landfall were only about 60 mph with gusts 10-20 mph higher. These winds were substantially lower than would normally be expected with Sandy's central pressure as low as 943 mb. Despite its low central pressure near landfall, Sandy was not judged to have sustained winds of hurricane strength when most of its destruction occurred. It had already been reclassified as an extra-tropical cyclone before landfall.

What caused Sandy to be so destructive was:

1. An extraordinary large outer-wind structure such that the landfall of its center in southern New Jersey could cause catastrophic flooding in and around New York City.

2. Its storm structure near such a vulnerable location where storm surge could be maximized from inward land funneling in and around New York City. The special funneling of surge-driven water into New York Harbor just to the north of Sandy Hook is a very rare geographic arrangement. Such narrowing inlets like New York Harbor and Long Island Sound cause ocean currents to converge and to mechanically force water to a higher level.

3. The westerly motion of Sandy at landfall in southern NJ brought in the storm surge around New York from an easterly direction. This meant that the height of the storm surge could be enhanced by the cyclone's winds in combination with the cyclone's motion. This also allowed the time period of the highest wind and surge induced water level to last longer than it would have if Sandy had come, like most other tropical cyclones affecting New York City, from the south.

4. Ocean surge was also maximized by Sandy’s higher surge driven water occurring near high tide and at full moon.

6. Human-Induced CO₂ Increases are not Responsible for Sandy

Since the start of extensive human-induced CO₂ production associated with the Industrial Revolution began (~1850) there has been a gradual build-up of long-wave infrared (IR) blockage of radiation to space to the current value of about 1.4 Wm⁻². This is equivalent to a current energy imbalance of only about 0.4% of the continuous net in-and-out global radiation flux. This very small gradual rate of growing energy imbalance could easily be compensated for by very small changes in IR and albedo fluxes to space brought about by other global circulation processes such as variations of precipitation, cloudiness, global ocean current changes, etc. which is stronger than anything changing amounts of CO₂ could accomplish. Naturally driven changes of the radiation budget at the top of the atmosphere from a variety of natural processes can typically overwhelm any changes larger than the radiation changes with human-induced CO₂ increases would be able to bring about.

New York City and the New Jersey coast may not see another such massively destructive super-storm like Sandy for another one to two hundred or more years, or it is remotely possible that another Sandy type cyclone could occur next year or the year after. But the probability of a super-cyclone like Sandy occurring in the next few years is very low. The possibility of a Sandy-type event has always been present.

As extensive and tragic as Sandy’s spawned destruction has been, it is not beyond the range of what is known about the variability of rare but extreme cyclone events.
For instance, the longest recorded period of no major (Cat 3-4-5) hurricane landfall in the US occurred during the last seven years (2006-2012). We have also had 20 fewer major hurricane landfall events in the more recent 47-year period (1966-2012) than compared with the earlier 47-year (1919-1965) period when CO₂ levels have been rising (Figure 23).

We conclude that Sandy, while being a rare and devastating superstorm along the mid-Atlantic and Northeast coasts, was almost exclusively due to natural variations in the chaotic atmosphere/ocean system.

Figure 23: Illustration of how US landfalling major hurricane numbers have been trending downward while CO₂ values are increasing.
7. Citations and Additional Reading


