Have Increases in CO$_2$ Contributed to the Recent Large Upswing in Atlantic Basin Major Hurricanes Since 1995?

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1. **INTRODUCTION**

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. 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 that hurricane intensity has increased in partial response to human activity have been given much media attention and was supported by the recent IPCC-AR4 report. Observational data do not support such an assessment.

Because there has been such a large increase in Atlantic basin major hurricane activity since 1995 in comparison with the very inactive prior 16-year period of 1979–1994 (Fig. 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 on these systems. It should be noted, however, that the last 16-year active major hurricane period of 1995–2010 has not been more active than the earlier 16-year period of 1949–1964 when the Atlantic Ocean circulation conditions were similar to what has been observed over the last 16 years. These earlier
active conditions occurred even though atmospheric CO₂ amounts were lower than now.

Table 1 shows how large were the Atlantic basin hurricane variations 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% of all hurricane-related destruction even though these major hurricanes make up only 20–25% of named storms.

Although global surface temperatures increased during the late 20th century, there are no reliable data to indicate increased hurricane frequency or intensity in any of the globe’s other tropical cyclone basins since 1979. Global Accumulated Cyclone Energy (ACE) shows significant year-to-year and decadal variability but a distinct decreasing trend during the last 20 years (Fig. 2). Similarly, Klotzbach (2006) found no significant change in global TC activity during the period from 1986 to 2005.

2. CAUSES OF THE UPSWING IN ATLANTIC BASIN MAJOR HURRICANE ACTIVITY SINCE 1995

The Atlantic Ocean has a strong multi-decadal signal in its hurricane activity which is due to multi-decadal variations in the strength of the THC (Fig. 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

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**TABLE 1** Comparison of annual Atlantic basin hurricane activity in two 16-year periods when the Atlantic Ocean THC was strong vs. an intermediate period (1970–1994) when the THC was weak

<table>
<thead>
<tr>
<th>THC (or AMO)</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>1949–1964 (16 years) Strong</td>
<td>27.93</td>
<td>319</td>
<td>10.1</td>
<td>54.1</td>
<td>6.5</td>
<td>29.9</td>
<td>3.8</td>
<td>9.5</td>
<td>121</td>
<td>133</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>1995–2010 (16 years) Strong</td>
<td>28.02</td>
<td>373</td>
<td>14.6</td>
<td>74.1</td>
<td>7.8</td>
<td>32.0</td>
<td>3.8</td>
<td>9.4</td>
<td>140</td>
<td>153</td>
</tr>
<tr>
<td>Per year ratio Strong/weak THC</td>
<td>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>
throughout the remainder of this discussion. The strength of the THC can never be directly measured, but it can be diagnosed, as we have done, from the magnitude of the sea surface temperature anomaly (SSTA) in the North Atlantic (Fig. 4) combined with the sea level pressure anomaly (SLPA) in the Atlantic between the latitudes of the equator and 50 °N (Klotzbach and Gray, 2008). Background information on the nature of the THC and its variations can be found in papers by Broecker (1991), Bjerknes (1964), Curry and McCartney (2001), Hurrell (1995), and van Loon and Rogers (1978).

FIGURE 2 Northern Hemisphere and global Accumulated Cyclone Energy (ACE) over the period from 1971 to November 2010. Figure has been adapted from Ryan Maue, Center for Ocean-Atmospheric Prediction Studies, Florida State University.

FIGURE 3 Illustration of strong (top) and weak (bottom) phases of the THC or AMO.
The THC (or AMO) is strong when there is an above-average poleward advection of warm low-latitude waters to the high latitudes of the North Atlantic. This water can then sink to deep levels when it reaches the far North Atlantic in a process known as North Atlantic Deep Water Formation (NADWF). 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 denser than freshwater especially at water temperatures near freezing. There is a strong association between North Atlantic SSTA and North Atlantic salinity as calculated from the Simple Ocean Data Assimilation (SODA) reanalysis (Fig. 5). High salinity implies higher rates of NADWF (or subsidence) and thus a stronger flow of upper-level warm water from lower latitudes as replacement. See the papers by Gray et al. (1996), Goldenberg et al. (2001), and Grossmann and Klotzbach (2009) for more discussion.

3. WHY CO₂ INCREASES ARE NOT RESPONSIBLE FOR ATLANTIC SST AND HURRICANE ACTIVITY INCREASES

Theoretical considerations do not support a close climatological 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 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.

3.1. Confusing Time Scales of SST Influences

A hurricane passing over a warmer body of water, such as the Gulf Stream, will often undergo 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 a rapid 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 (Fig. 6).

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 if broad-scale lapse rates were ever to be altered to an appreciable degree.

Thus, we cannot automatically assume that with warmer global SSTs that we will necessarily have more intense hurricanes due to lapse-rate alterations. We should not expect that the frequency and/or intensity of Category 4—5 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 slightly lower.

3.2. CO2 Influence on Hurricane Activity

We have been performing research with the International Satellite Cloud Climatology Project (ISCCP) and the NOAA National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) 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 (Fig. 7) for the years from 1984 to 2004. Note that the various surface and top of the atmosphere energy fluxes are very large. For the tropical surface, for instance, there are 637 W m$^{-2}$ units of downward incoming solar and infrared (IR) energy. This downward energy flux is largely balanced by an upward surface energy flux of 615 W m$^{-2}$ which is due to upward fluxes from IR radiation, evaporated liquid water, and sensible heat. Similar large energy fluxes are present at the top of the atmosphere and within the troposphere.

It has been estimated that a doubling of CO$_2$ (from the pre-industrial period) without any feedback influences would result in a blockage of OLR to space of about 3.7 W m$^{-2}$. The currently-measured value of CO$_2$ in the atmosphere is 385 parts per million by volume (ppmv). If we take the background pre-industrial value of CO$_2$ to be 285 ppmv, then by theory we should currently be having (from CO$_2$ increases alone) about \((100/285) \times 3.7 = 1.3\) W m$^{-2}$ less OLR energy flux to space than was occurring in the mid-19th century.

This reduced OLR of 1.3 W m$^{-2}$ is very small in comparison with most of the other tropical energy budget exchanges. Slight changes in any of these other

![Figure 7](image-url) 

**FIGURE 7** Vertical cross-section of the annual tropical energy budget as determined from a combination of ISCCP and NCEP/NCAR reanalysis data over the period from 1984 to 2004. Abbreviations are IR for longwave infrared radiation, Alb for albedo, and OLR for outgoing longwave radiation. The tropics receives an excess of about 44 W m$^{-2}$ radiation energy which is convected and exported as sensible heat to latitudes poleward of 30°. Estimates are about half (22 W m$^{-2}$) of this excess is transported by the atmosphere and the other half is transported by the oceans. Note, on the right, how small an OLR blockage has occurred up to now due to CO$_2$ increases (~1.3 W m$^{-2}$) and the blockage of 3.7 W m$^{-2}$ that will occur from a doubling of CO$_2$ by the end of this century.
larger tropical energy budget components could easily negate or reverse this small CO$_2$-induced OLR blockage. For instance, an upper-tropospheric warming of about 1 °C with no change in moisture would enhance OLR sufficient that it would balance the reduced OLR influence from a doubling of CO$_2$. Similarly, if there were a reduction of upper-level water vapor such that the longwave radiation emission level to space were lowered about 6 mb (~120 m) there would be an enhancement of OLR (with no change of temperature) sufficient to balance the suppression of OLR from a doubling of CO$_2$. The 1.3 W m$^{-2}$ reduction in OLR that we have experienced since the mid-19th century (about one-third of the way to a doubling of CO$_2$) is very small when compared with the overall 399 W m$^{-2}$ of solar energy impinging on the top of the tropical atmosphere and the mostly compensating 356 W m$^{-2}$ of OLR and albedo energy going back to space. This 1.3 W m$^{-2}$ energy gain (0.37% of the net energy returning to space) is much too small to ever allow a determination of its possible influence on TC activity. Any such potential CO$_2$ influence on TC activity is deeply buried as turbulence within the tropical atmospheres’ many other energy components. It is possible that future higher atmospheric CO$_2$ levels may cause a small influence on global TC activity. But any such potential influence would likely never be able to be detected, given that our current measurement capabilities only allow us to assess TC intensity to within about 5 mph.

4. CONTRAST OF THEORIES OF HURRICANE ACTIVITY CHANGES

4.1. Theory of Human-Induced Increases Due to Rising CO$_2$ Levels

Those who think CO$_2$ increases have in the past and will in the future cause significant increases in hurricane activity believe that the physics of the CO$_2$-hurricane association is directly related to radiation changes as indicated in Fig. 8. They view CO$_2$ as blocking OLR to space. This acts to warm SSTs and add moisture to the boundary layer just above the ocean surface. These changes cause an increase in lapse rates (the lower levels warm while upper levels do not change much) which lead to more deep cumulonimbus (Cb) convection. More Cb convection leads to a higher percentage of tropical disturbances forming into tropical cyclones and a greater spin-up of the inner-core of those systems which do form.

This physical argument is too simplistic. It has no empirical verification in any other global TC basin except for the Atlantic where SST changes are primarily a result of ocean circulation changes. Table 2 shows the correlation of ACE with late summer-early fall SSTs in the Main Development Regions of the Northeast Pacific, the Northwest Pacific and the Southern Hemisphere. Note the low (or even negative) correlations between ACE and SST in each of these three
TC basins. It is obvious that other physical processes besides SST are primarily responsible for differences in hurricane activity in these basins.

### 4.2. Theory of the THC (OR AMO)

We do not view seasonal hurricane variability in the Atlantic as being directly related to changes in CO₂-induced radiation forcing or to SST changes by themselves. For the Atlantic, we view long-period tropical cyclone variability primarily as a result of changes in the strength of the THC (or AMO). We hypothesize that these changes act as shown in Fig. 9. THC changes result in alterations of tropospheric vertical wind shear, trade-wind strength, and SSTs in the Main Development Region (MDR) of 10°–20°N; 20°–70°W in the tropical Atlantic. A large component of the SST increase in this area is not a direct result of radiation differences but rather the combination of the effects of reduced southward advection of colder water in the east Atlantic and reduced trade-wind strength. Weaker trade winds reduce upwelling and evaporation and typically act to increase SST.

### TABLE 2 Correlation of ACE with late summer-early fall SSTs in three TC basins from 1980 to 2009

<table>
<thead>
<tr>
<th></th>
<th>Yearly mean ACE</th>
<th>ACE vs. SST correlation (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast Pacific</td>
<td>134</td>
<td>0.01</td>
</tr>
<tr>
<td>Northwest Pacific</td>
<td>310</td>
<td>−0.30</td>
</tr>
<tr>
<td>Southern Hemisphere</td>
<td>205</td>
<td>0.23</td>
</tr>
<tr>
<td>Globe (SST 20°N–20°S)</td>
<td>769</td>
<td>−0.08</td>
</tr>
</tbody>
</table>
The influence of the warmer Atlantic SST, as previously discussed, is not primarily to enhance lapse rates and Cb convection but rather as a net overall positive influence on lowering the MDR’s surface pressure and elevating mean upward tropospheric vertical motion and reducing vertical shear. This causes an increase in tropospheric moisture content. It is this combination of factors which brings about more TC activity.

5. DISCUSSION

In a global warming or global cooling world, the atmosphere’s upper air temperatures will warm or cool in unison with the SSTs. Vertical lapse rates will not be significantly altered. 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 to 1969 when the globe was undergoing a weak cooling trend, the Atlantic basin experienced 80 major (Category 3-4-5) hurricanes and 201 major hurricane days. By contrast, in a similar 25-year period from 1970 to 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) (Fig. 10). Atlantic SSTs and hurricane activity do not follow global mean temperature trends or amounts of CO₂.

5.1. US Landfall Observations

The most reliable long-period hurricane records we have are the measurements of US landfalling TCs since 1900 (Table 3). Although global mean ocean and Atlantic SSTs have increased by about 0.4 °C between two 55-year periods (1901–1955 compared with 1956–2010), the frequency of US landfall numbers actually shows a slight downward trend for the latter 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 45-year period of 1921–1965 (24 landfall events) and the 45-year period of 1966–2010 (7 landfall events) was especially large (Fig. 11). For the entire United States coastline, 39 major hurricanes made landfall during the earlier 45-year period (1921–1965) compared with only 26 major hurricanes for the latter 45-year period (1966–2010). This occurred despite the fact that CO$_2$ averaged approximately 365 ppm during the latter period compared with 310 ppm during the earlier period.

**TABLE 3**

<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>1901–1955</td>
<td>210</td>
<td>115</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>(55 years)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1956–2010</td>
<td>180</td>
<td>87</td>
<td>34</td>
<td>+0.4°C</td>
</tr>
<tr>
<td>(55 years)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 21 named storms in a year when there was no satellite or aircraft data. Records of 1933 show all 21 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) — the same number as was observed to occur 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 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.
6. IPCC-IV’S TROPICAL CYCLONE MIS-STATEMENTS

We completely disagree with the large number of papers written right after the time of the flurry of landfalling US major hurricanes during 2004–2005. We strongly disagree on how these authors interpreted the hurricane data to imply that rising levels of CO₂ were likely a significant contributing influence to the large amounts of hurricane destruction during those 2 years.

A number of these papers served as the basis for the IPCC-AR4 (2007) report concerning tropical cyclones of which one paragraph of the Executive Report (page 239) will be quoted:

“Intense tropical cyclone activity has increased since about 1970. Globally, estimates of the potential destructiveness of hurricanes show a significant upward trend since the mid-1970s, with a trend towards longer lifetimes and greater storm intensity, and such trends are strongly correlated with tropical SST. These relationships have been reinforced by findings of a large increase in numbers and proportion of hurricanes reaching categories 4 and 5 globally since 1970 even as total number of cyclones and cyclone days decreased slightly in most basins. The largest increase was in the North Pacific, Indian and southwest Pacific Oceans.”

It is unfortunate indeed that, the IPCC-AR4 report, which shared a Noble Prize for science, would report this information which had already been rebutted by several studies at the time of its issue.

7. SPECIAL CHARACTERISTICS OF THE ATLANTIC OCEAN HURRICANE BASIN

The Atlantic Ocean basin is largely land-locked except for on its far southern margin. It has the highest salinity of any of the ocean basins and the highest upper-ocean density (due to the combination of high salinity and cold ocean temperatures) at its far northern latitudes (Fig. 12). Saline water has a higher density than freshwater at temperatures near freezing. The North Atlantic is the primary global location for the subsidence of upper-ocean water to deep levels in a process known as deep water formation. This can occur only if the upper-ocean water of the North Atlantic becomes denser than the water at deep levels. The global ocean fully ventilates itself every 1–2 thousand years through polar region (mainly the North Atlantic) subsidence to bottom levels of cold, dense, salty water and a compensating upwelling of less dense water in the Southern Hemisphere tropics (Figs. 13, 14). Ocean bio-life depends on this deep ocean ventilation.

The Atlantic Ocean is unique for having a continuous northward flow of upper-level water that moves into the polar region, cools, and then sinks because of its higher salinity-induced density. The deep water that is formed then returns to the Atlantic’s southern fringes and mixes with the higher latitude water of the Southern Hemisphere. The Atlantic portion of this circulation feature has
FIGURE 12  Average surface salinity of the global oceans. Notice the North Atlantic’s high salinity values at northern latitudes.

FIGURE 13  Modified view of the global ocean’s deep circulation as originally portrayed by Wally Broecker, personal communication. Red arrows show upper-ocean circulation and blue arrows show deep ocean circulation.
been designated the Atlantic Thermohaline Circulation (THC). It is part of the Great Ocean Conveyor Belt or the Meridional Overturning Circulation (MOC).

The strength of the THC varies on multi-decadal time scales due to the nature of the Atlantic’s naturally occurring multi-decadal salinity variations. When the THC is stronger than normal, the North Atlantic’s upper-ocean water becomes warmer than usual and other tropical Atlantic meteorological parameter changes occur to cause more hurricane activity. The opposite occurs when the THC is weaker than average.

We have diagnosed that the THC has been significantly stronger than average since 1995 and during the period of the 1930s through 1960s. It was distinctly weaker than average in the quarter-century periods between 1970—1994 and 1900—1925.

The THC appears to be a product of the unique geometry of the Atlantic basin. The earth’s most recent period of ice ages commenced about 2—3 million years ago and is associated with the time of Central American plate tectonic changes which lead to a rise of the Isthmus of Panama and the isolation of the Atlantic Ocean from the Pacific except at its southern margin. The Atlantic has since been mostly a closed ocean basin.

This sequestering has brought about special Atlantic climate conditions that were not present when the Atlantic and Pacific Oceans were connected. Before the filling in of the Isthmus of Panama, it was possible for ocean waters to flow freely between the Atlantic and Pacific. The isolation of the Atlantic together with the net energy deficit of the Western Hemisphere (in comparison with the Eastern Hemisphere) has acted to cause the development of especially large and strong surface high (or anticyclones) pressure systems in the Atlantic subtropics. These high pressure systems cause a strong suppression of Atlantic Basin sub-tropical

**FIGURE 14** A more recent portrayal of the ocean’s deep water circulation Figure courtesy of John Marshall. Note upwelling of water in the tropics south of the equator as a response to the North Atlantic and Antarctic deep water subsidence.
rainfall. However, sub-tropical surface winds and evaporation rates (~1.2 m of water/year) remain quite high. From 30°S to 40°N, the Atlantic Ocean’s net rate of surface evaporation ($E$) is substantially larger than the net rate of precipitation ($P$) by amounts as high as 30–40%. Such large positive values of evaporation minus precipitation ($E - P$) are not found in any other large areas of the global oceans. The Atlantic’s unique geometry allows for the development and sustenance of high salinity conditions not experienced by the other ocean basins.

Salinity has a strong positive influence on water density. The higher salinity content of the cold water in the North Atlantic upper water enables it to sink to deep (or bottom) ocean levels where it then flows southward to the south Atlantic. Upper-level poleward moving North Atlantic water that is able to retain high salinity values and cool to temperature values near 4 °C (maximum density of freshwater) is dense enough to sink to deep levels. High salinity North Atlantic upper-level cold water is some of the globe’s densest water. Such high density North Atlantic upper water is able to sink to deep levels forming NADWF. This deep water then flows southward to mix with the circumpolar vortex of the Southern Hemisphere and eventually to upwell in the Southern Hemisphere tropics. Figures 15 and 16 display some of the unique characteristics of the North Atlantic.
It is estimated (Schmitz, 1996) that the average strength of the Atlantic THC or the amount of water which sinks from upper to lower levels in the North Atlantic is about 14 Sverdrup (Sv) \[1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}\]. This is equivalent to a yearly mass evacuation of Atlantic upper water occupying a volume of 1,000 km by 5,000 km to a depth of 100 m. The poleward advecting and cooling of this water are accomplished by ocean to atmosphere energy transfer and by the mixing of colder high latitude water. This causes a significant warming of the high latitude Arctic atmosphere and a decrease in high latitude westerly winds. It is estimated that the strength of the THC can undergo significant yearly, decadal, and century changes.

8. VARIATIONS IN STRENGTH OF THE THC

The Atlantic THC can vary due to a number of factors, such as the rate of buildup of Atlantic sub-tropical salinity, the salinity content of the South Atlantic water flowing into the North Atlantic, the rate of Atlantic evaporation over precipitation \((E - P)\), the amount and salinity reduction of upper water flowing into the North Atlantic due to Arctic and Labrador Sea current mixing, the amount of freshwater carried by rivers emptying into the North Atlantic, and the amount of high latitude Atlantic rainfall (Figs. 17–19). There must not be too much salinity diminution during the upper-ocean’s advection from sub-tropical to high latitudes if a strong THC is to be maintained. If salinity is reduced too much, the upper ocean cannot maintain a high enough density to be able to sink in large quantities to deep levels.

When the THC is stronger than normal and higher amounts of saline water are being exported out of the sub-tropical gyre that are beyond what the sub-tropical gyre can replace through positive amounts of evaporation minus

\[\text{FIGURE 16}
\text{Portrayal of the typical latitudinal variation of North Atlantic upper water density due to variations in both ocean temperature (blue) and salinity (red). Their combined effect is given in purple. It is only in the high latitudes from approximately 55–70°N of the Atlantic that upper-ocean water is able to become dense enough to sink to bottom ocean levels and form NADW.}\]
precipitation \((E - P)\), then there will, in time, be a gradual reduction in the strength of the THC.

In the opposite sense, when the THC is weaker than normal, there is more time for salinity within the sub-tropical ocean gyre to gradually increase.
through evaporation being greater than rainfall. This allows salinity to gradually increase. There will then come a time (a decade or two later) when salinity has increased to the point where the THC becomes strong again. Atlantic salinity and the strength of the THC thus tend to vary inversely with each other as shown in Figs. 20, 21. There are also periods when Arctic ice flow and/or enhanced Labrador currents may so dilute the THC with freshwater that it is weakened.

When the THC is weak, the high latitude Atlantic and the atmosphere above it receive significantly less ocean-induced thermal energy than when the THC is strong. A weak THC causes the high latitude Atlantic ocean and atmosphere to cool and the westerly winds to strengthen (e.g., an increase in polarity of the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices). A strong THC typically brings about a warmer high latitude North Atlantic Ocean and atmosphere and weaker westerly winds (i.e., the NAO and AO decrease). It must be remembered that in a mechanical sense the atmosphere dissipates its kinetic energy at a rate of about 10% per day. The maintenance of the THC for multi-decadal periods, in a primary way, cannot be thought of as a consequence of the wind fields. The THC is a more dominant feature than the atmospheric wind circulation. The THC is a steady feature that once established, can maintain itself for years at a time. By contrast, the westerly wind currents, due to their rapid dissipation, must be fully regenerated on a time scale of 8—10 days.

The higher the salinity values coming out of the Atlantic subtropics, the greater is the amount of freshwater (from lower salinity water melting, rain,
FIGURE 20  Idealized portrayal of how the THC has decadal variability from strong (red) to weak (black) and back to strong again in response to altering salinity patterns and deep water formation. Ice flows from the Arctic (upper right of figure) can sometimes disrupt or greatly alter these multi-decadal THC patterns.

FIGURE 21  Illustration of how North Atlantic salinity values (green curve at bottom) are hypothesized to go up-and-down in response to the varying strength of the THC.
and river run-off) which the poleward moving ocean current can ingest and still be dense enough to produce NADW. The strength of the THC is thus related to the amount of poleward salinity advection from the south minus the amount of salinity diminution which the poleward moving water ingests from mixing with less saline ocean water and from river and rainfall freshwater inputs. The temperature of the poleward flowing water is less of a factor for density variation than is salinity. Variations of upper-ocean temperature around 4 °C cause very little variations in density as compared with salinity.

9. STORAGE OF WEST-ATLANTIC SUB-TROPICAL SALINITY

There can be a substantial storage of salinity in the sub-tropical Atlantic down to 500–600 m depth (Fig. 22). This depth of high salinity water is aided by the sub-tropical anticyclonic gyre having high values of $E - P$ that continually raises salt content. Also, the sub-tropical gyre winds cause a strong Ekman type of mechanically-forced ocean subsidence. This gradually drives upper ocean high salinity water to even deeper levels.

It is possible for the salt content of the subtropics to maintain a strong THC even when the rate of salt buildup is less than the rate of salt being advected poleward. It is necessary, however, that the THC not be too strong for too long a period so that it depletes too much of the sub-tropical salt gain from evaporation. The sub-tropical buildup of salt by evaporation over precipitation is a steadier feature than the strength of the THC.

Assuming that salinity is reduced by about 1–2 g kg$^{-1}$, as the Atlantic THC water moves from the high salinity region of the west-Atlantic anticyclone to the North Atlantic where it sinks, then with an estimated THC of 14 Sv it is possible to continually maintain the THC and the high values of salinity within the sub-tropical high. On the long-period average, salinity buildup from evaporation minus precipitation ($E - P$) must be balanced by salinity loss through poleward advection of higher salinity water.

If the THC is stronger or weaker than its average value of about 14 Sv, then salinity in the sub-tropical Atlantic would be decreased or increased by an amount approximately equivalent to the percentage alteration of the THC strength from 14 Sv. Thus, if the THC were 20 Sv in strength rather than 14 Sv there would be a gradual reduction in the rate of the Atlantic’s sub-tropical gyre salinity buildup equivalent to about 25% of that required for steady state. Salt content in the sub-tropical gyre would thus be gradually reduced and some years later (if this reduction continues), the THC would begin to weaken. If the THC were, by contrast, to have a strength of 10 Sv rather than 14 Sv, there would be a rate of salinity increase within the Atlantic sub-tropical gyre that would be about 30% greater than would be required by salinity maintenance. Salt content would then gradually increase within the gyre, and some years later the THC would begin increasing in strength.
FIGURE 22  Salinity content of the global oceans at 500 m depth. Note the very high salinity contents of the western Atlantic sub-tropical region.
Such salinity variations and THC strength changes would be hard to detect within the Atlantic subtropics unless they persisted for a number of years. This is because the west-Atlantic subtropics maintain such a massive amount of high salinity which is continuously stored to deep levels. THC changes required to raise or lower significant amounts of salinity are, by comparison, small.

This large reservoir of high salinity water residing within the western Atlantic subtropics would require 20–30 years to deplete if the THC were to flow at its average strength with no replacement of salt from evaporation minus precipitation.

It is thus possible to store large amounts of salinity in the western North Atlantic subtropics for the maintenance of a strong THC for many years beyond the rate of its buildup replacement. Or oppositely, it is possible to maintain a weakened THC for many years despite steady salt buildup.

Another factor in determining the strength of the THC are the conditions on the opposite side of the globe in the Southern Hemisphere which allow for the mass compensating upwelling water to rise. It is required that there be an equivalent amount of upwelling water to balance NADW formation. This is possible through deep, high salinity, water mixing with less dense water and the development of positive upwelling buoyancy. There are likely times when favorable upwelling conditions in the Indian Ocean and Pacific basins are not present. The status of upwelling conditions is likely also a fundamental component of the MOC. They likely feed back to cause the strength of the THC to be altered from that specified solely by North Atlantic water density conditions alone.

10. SUMMARY

It is not possible to directly measure the strength of the THC. We think we can infer its strength from proxy measurements of the North Atlantic SST and salinity anomalies (which are directly related to each other) minus the SLPA over the broad Atlantic (0–50°N; 70°W–10°W). When the THC is strong the Atlantic atmospheric and oceanic sub-tropical gyres are weaker than normal. When the Atlantic THC is weaker than average, the gyres are stronger than normal (Figs. 23, 24).

With regards to multi-decadal variations of Atlantic major hurricane activity, it is possible to give a sequence of physical arguments (Fig. 25) for how a year or a multi-decadal period with a stronger than normal THC will have tropical Atlantic conditions associated which are more favorable for Atlantic basin major hurricane activity. Among these conditions are positive tropical Atlantic SSTAs, lower tropical Atlantic SLPAs, weaker trade winds, and smaller values of tropospheric vertical wind shear.

There is no evidence that Atlantic hurricane activity is significantly impacted by CO₂ increases or by global mean surface temperature changes. This myth should be put to rest. It is the natural variability of the Atlantic’s meteorological parameters that we must be most concerned about.
FIGURE 23  Atlantic regions from which we diagnose the strength of the THC. We assume that the higher the SSTA plus salinity anomaly (SA) and the lower the SLPA, the stronger the THC. Our proxy for the THC is thus THC = [(SSTA + SA) − SLPA]. This proxy deviation is composed of the North Atlantic SSTA plus SA in the regions (50°–65°N; 50°W–10°W) minus the SLPA anomaly in the region (0–50°N; 70°W–10°W). Positive anomalies indicate a stronger than normal THC and negative values indicate a weaker than average THC.

FIGURE 24  Portrayal of our THC proxy value from 1950 to 2006. Our THC proxy equation is given in Fig. 23.
REFERENCES


FIGURE 25 Illustration of how changes in the THC induce NADWF changes in area 1, causing ocean current changes in area 2 which lead to SLP (3), SST (4), and rain (5) changes which, in turn, cause changes in the strength of the trade winds (6), upper-tropospheric westerly winds (7), and other factors which lead to more or fewer hurricanes (8).