5B.7 THE ROLE OF SALINITY AS THE PRIMARY DRIVER FOR THE ATLANTIC OCEAN'S MULTI-DECADAL PARAMETER VARIATIONS

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1. INTRODUCTION

The North Atlantic undergoes large multi-decadal variations of SST (Figures 1 and 2), Sea Level Pressure Anomaly (SLPA), hurricane frequency and intensity (Figures 3 and 4) and many other meteorological features. The author hypothesizes that the primary cause of these multi-decadal variations is a result of alteration in North Atlantic salinity content. Salinity changes cause a variation in the strength of the Atlantic's upper ocean poleward moving current. This current moves faster than average when salinity is high and slower when it is lower. This paper discusses the likely physical processes associated with these salinity driven multi-decadal poleward variation of ocean current which has been designated the Atlantic thermohaline circulation (THC).

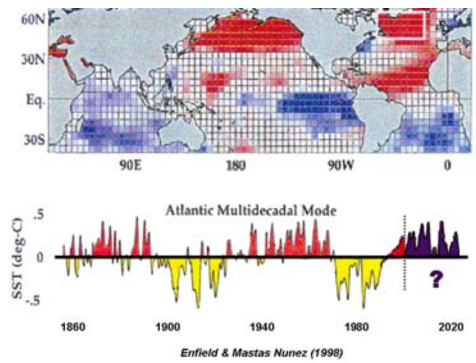

Figure 2. EOF analysis of the global ocean sea surface temperature anomaly (SSTA) which illustrates the strong multi-decadal variability and the opposite changes of the northern vs. southern hemisphere SSTA patterns (Enfield and Mastas Nunez, 1998).

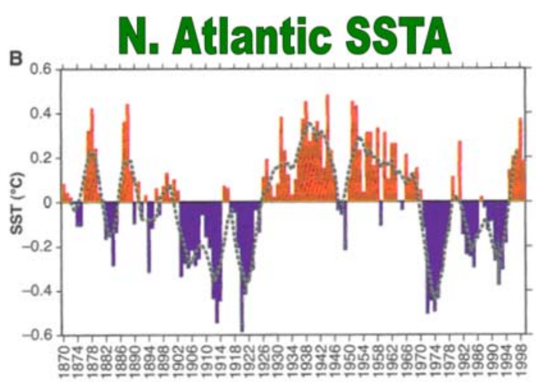

Figure 1. Sea surface temperature anomaly (SSTA) of the North Atlantic 50-60^{o}N; 60^{o}W-10^{o}W (1870-1998). Note the back-and-forth multi-decadal changes.

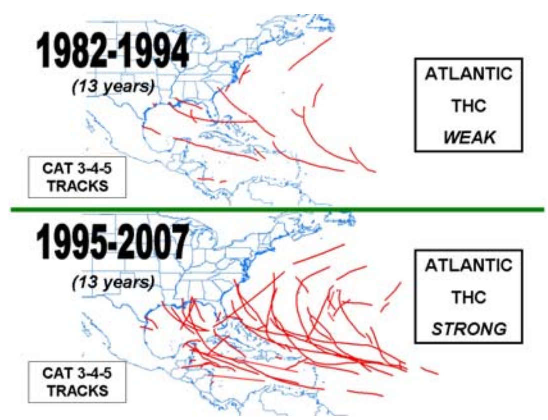

Figure 3. Number of major hurricane tracks in the 13-year period between 1982-1994 and the last 13-year period of 1995-2007.

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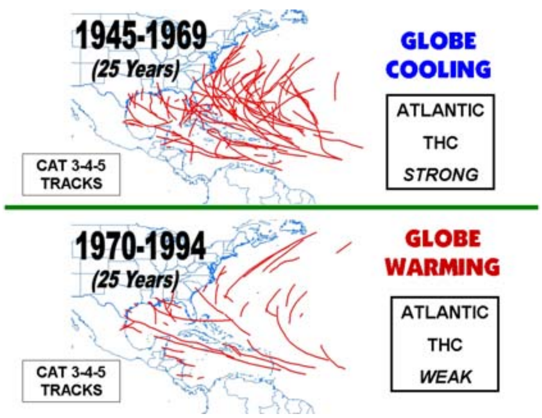

Figure 4. Major hurricane tracks during two 25-year periods, the top period (1945-1969) when the globe was undergoing a modest cooling period and the 25-year period of 1970-1994 when the globe was undergoing a warming period.

2. SPECIAL CHARACTERISTICS OF THE ATLANTIC

The Atlantic Ocean basin is largely land-locked except on its far southern margin. It has the highest salinity of any of the ocean basins and especially of its high north latitude ocean water (Figure 5). Saline water has a higher density than fresh water. The North Atlantic is the primary global location for the subsidence of upper ocean water to deep levels. This can occur only if the upper ocean water can become denser than the water at deep levels. The ocean fully ventilates itself every 1 to 2 thousand years through a polar region (mainly the North Atlantic) subsidence and a compensating upwelling of less dense water primarily in the Southern Hemisphere tropics (Figure 6). 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 sinks because of its higher salinity induced density. The deep water so formed then returns to the Atlantic's southern fringes and mixes with the higher latitude water of the S. Hemp. circumpolar ocean current. The Atlantic portion of this circulation feature has been designated the Thermohaline Circulation (THC). It is part of the Great Ocean Conveyor Belt of Figure 6.

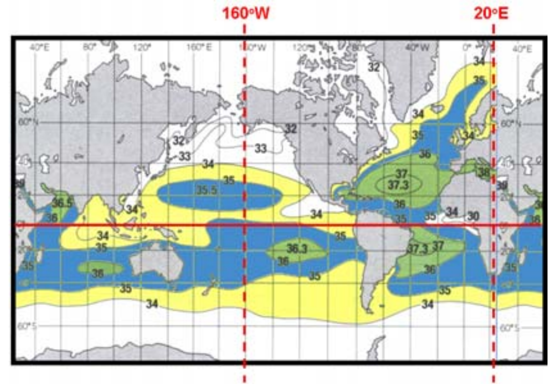

Figure 5. Average surface salinity of the global oceans. Notice the North Atlantic's especially high salinity values at northerly latitudes.

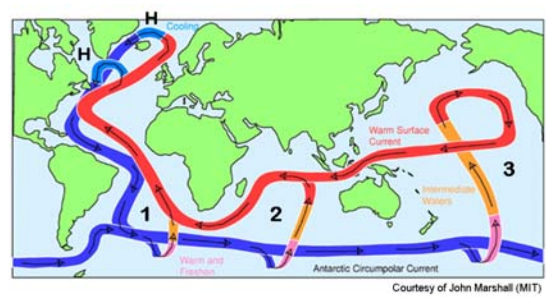

Figure 6. A more recent portrayal of the ocean's deep water circulation as portrayed by Marshall (2006). Note upwelling of water in the Southern Hemisphere tropics as a primary response to the North Atlantic's deep water formation.

The strength of the THC varies on multi-decadal time scales due to the nature of the Atlantic's naturally occurring multi-decadal salinity time scale variations. When the THC is stronger than normal the North Atlantic's upper-ocean water becomes warmer and saltier than usual and other 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 Atlantic thermohaline circulation (THC) has been significantly stronger than average since 1995 and during the period of the 1930s through the 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 its unique Atlantic Ocean geometry. The earth's most recent period of ice ages commenced about 2-3 million years ago and is associated with the time of middle America 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 and Arctic Oceans have since been pretty much of a closed ocean basin.

This sequestering of the Atlantic-Arctic Oceans has brought about special Atlantic climate conditions that were not present when the Atlantic and Pacific Oceans were connected. Before the land rise and filling-in of the Isthmus of Panama, it was possible for ocean waters to flow freely between the Atlantic and Pacific. This isolation of the Atlantic together with the net energy deficit of the Western Hemisphere (in comparison with the Eastern Hemisphere) have 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 subtropical rainfall. But sub-tropical surface winds and evaporation rates (~1.2 meters of water/year) remain quite high. From 30^{o}S to 40^{o}N latitude 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 percent. Such large positive values of evaporation minus precipitation (E - P) are not found in any other large and isolated oceanic area. The Atlantic's unique geometry allows for the development and sustaining of such high and unique salinity conditions.

Salinity has a strong positive influence on water density. The higher salinity content of the North Atlantic upper water enables it to sink (if it also has been cooled) to deep (or bottom) ocean levels where it then flows southward. Upper level poleward moving North Atlantic water that is able to retain high salinity values and cool to temperature values near 4^{o}C (maximum density of fresh water) is dense enough to sink to deep levels. North Atlantic upper level cold and high salinity water is the globe's most dense water. Such high density North Atlantic upper water is able to sink to Deep Water levels (NADW). 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.

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) [1Sv = 10^6 m^3 s^{-1}]. This is equivalent to a yearly mass evacuation of Atlantic upper water occupying a volume of 1000 km by 5000 km to a depth of 100 meters. The poleward advecting and cooling of this water is 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 this THC circulation can undergo significant yearly, decadal and century changes in strength.

3. VARIATION IN STRENGTH OF 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 to the upper water flowing into the North Atlantic due to Arctic and the Labrador Sea currents, the fresh water of the rivers, and the amounts of high latitude Atlantic rainfall, etc (Figure 7). There must not be too much salinity diminution during the upper ocean's advection from sub-tropical to high latitude 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 large quantities of water to deep levels.

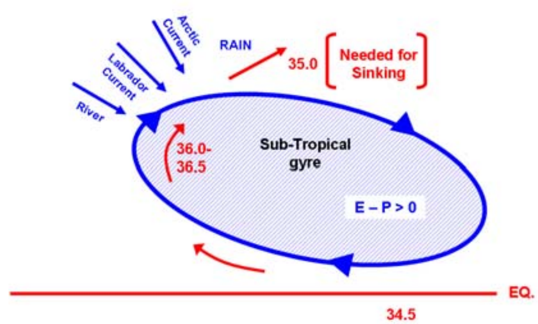

Figure 7. Idealized portrayal of North Atlantic sub-tropical upper ocean gyre circulation conditions where salinity is continuously accumulating on the west side of the gyre. This high salinity water is then advected poleward where salinity diminution occurs due to its mixing with lower salinity water and reductions from fresh water of rivers and rainfall. If salinity can be maintained at values as high or higher than ~ 35 gm/kg, then NADWF can occur.

When the THC is stronger than normal larger amounts of saline water are being exported out of sub-tropical gyre that are beyond what the sub-tropical gyre can replenish through positive amounts of evaporation minus precipitation (E – P). In time, there will then have to be a gradual reduction in the thermohaline circulation.

In the opposite sense, when the THC is weaker than normal there is more time for salinity to increase within the sub-tropical ocean gyre through positive (E-P). There will then come a time (a decade or two later) when salinity has increased to the point where the THC is activated to become strong again. Atlantic salinity and the strength of the THC thus tend to vary inversely with each other as shown in Figure 8. There are also periods when Arctic ice flow and/or an enhanced Labrador current discharge may so dilute the THC with fresh water that it is weakened beyond the ability of the sub-tropical gyre to furnish enough salinity to keep itself going.

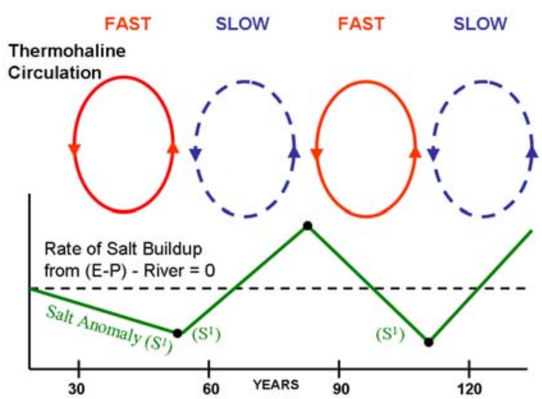

Figure 8. Ilustrating how North Atlantic salinity values (green curve at bottom) are hypothesized to go up-and-down in response to the varying strength of the THC.

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 (NAO and AO increase). A strong THC typically brings about warmer high latitude North Atlantic and weaker westerly winds (i.e., the NAO and AO become weaker). It must be remembered that in a mechanical sense the atmosphere dissipates its kinetic energy at a rate of about 10 percent per day. The maintenance of the THC for long periods in a strong or weak mode cannot be thought of to be a consequence of the wind fields. The ocean THC is a more dominant feature than the atmospheric wind circulation. The THC is more of a steady feature. Once established with sufficient salinity, it is possible for the THC to maintain itself for years at a time. By contrast, the westerly wind currents, due to their rapid frictional 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 and river run-off) which the poleward moving ocean current can ingest and still be dense enough to sink to bottom levels. The strength of the high latitude Atlantic 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 must ingest from mixing and from fresh water sources. The temperature of the poleward flowing water is less of a factor for density variation than is salinity.

4. STORAGE OF WEST ATLANTIC SUB-TROPICAL SALINITY

There can be a substantial storage of salinity in the western sub-tropic Atlantic down to 500-600 m depth. This depth of high salinity water is aided by the subtropical gyre winds causing 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 have a large salt storage capacity and to maintain a strong THC circulation 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 more steady and varies percentage wise much less than the outward advection of salt by the THC.

Assuming that salinity is reduced by about 1-2 gm/kg, 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 long period average 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 75 percent 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, of strength 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 percent greater than would be required for salinity maintenance. Salt content would then gradually increase within the gyre and some years later the THC would have to begin to increase in strength.

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 part of the Atlantic gyre for the maintenance of a strong THC for many years beyond the gyre's ability to replenish itself. 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 a continuous equivalent amount of upwelling water to balance the North Atlantic deep water (NADW) formation. This is possible through deep water mixing of less dense water and the development of positive upwelling buoyancy. There are likely times when favorable upwelling conditions in the Indian and Pacific Ocean basins are not present. The status of upwelling conditions in the Pacific and Indian Oceans are likely also an important factor as to the strength of the THC. These eastern hemispheric influences likely feed back to cause the strength of the THC to be altered from that specified by North Atlantic upper water density conditions alone.

Figure 9 shows that the North Atlantic SST and the surface salinity are highly correlated. This is to be expected. A stronger Atlantic poleward advection of lower latitude water will simultaneously cause both warmer and more saline water to move into the North Atlantic.

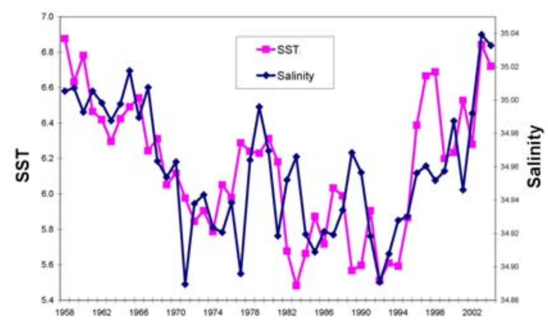

Figure 9. Illustrating how changes in North Atlantic (50-65^{o}N; 50^{o}W-10^{o}W) SST (pink) and salinity (navy) are strongly correlated with each other. A strong THC causes more warm and higher salinity water to be advected poleward. A weak THC leads to lower SST and salinity values. The THC was strong in the early and late periods of this graph and weak in the middle periods.

5. SUMMARY

It is not possible to directly measure the strength of the THC. We think we can infer the THC's strength from proxy measurements of the North Atlantic SST and Salinity Anomalies (SA) in the area 50-65^{o}N; 50^{o}W-10^{o}W minus the SLPA over the broad Atlantic (0-50^{o}N; 70^{o}W-10^{o}W). When the Atlantic THC is strong the Atlantic atmospheric and ocean sub-tropical gyres are weaker than normal. When the Atlantic THC is weaker than average the gyres are stronger than normal. Our estimate of the deviation of the strength of the NTC from its average value (NTC*) is given by the following formula:

$$NTC^* \propto [(SSTA + SA) - SLPA] \quad \textbf{(1)}$$

With regards to multi-decadal variations of Atlantic hurricane activity it is possible to give a sequence of physical arguments (Figure 10) for how a year or a multi-decade period with stronger or weaker than normal THC will have Atlantic basin tropical conditions with positive or negative tropical Atlantic SSTAs, low or high SLPAs, weak or strong trade winds, and smaller or larger values of tropospheric vertical wind shear; all factors required for enhanced or reduced Atlantic basin hurricane activity.

Atlantic hurricane activity is not significantly impacted by CO_2 increases or by global mean surface temperature changes. Atlantic hurricanes are, however, strongly impacted by Atlantic meteorological parameter alterations associated with the changing strength of the Atlantic Ocean thermohaline circulation (THC).

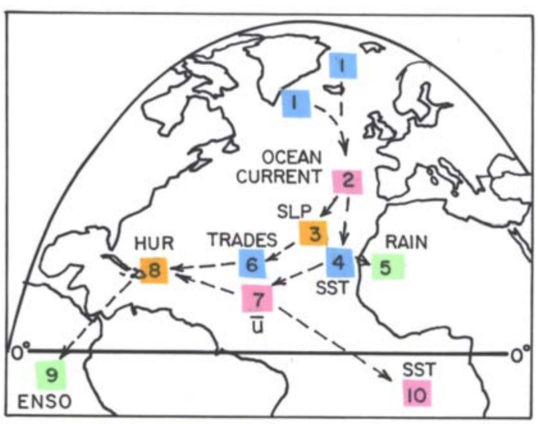

Figure 10. Illustration of how changes in THC induce North Atlantic subsidence in areas 1 cause ocean current changes in area 2 which lead to SLP (3), SST (4) and rain (5) changes which, in turn, cause changes in the strength of the trade winds (6), upper tropospheric westerly winds (7) and other factors which lead to more or less hurricanes.

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