CLIMATE TRENDS ASSOCIATED WITH MULTI-DECADAL VARIABILITY OF ATLANTIC HURRICANE ACTIVITY

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William M. Gray[1], John D. Sheaffer[1] and Christopher W. Landsea[2]

[1]Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523, U.S.A.

[2]Hurricane Research Division
NOAA/AOML
4301 Rickenbacker Causeway
Miami, Fl 33149, U.S.A.

Abstract

Anomalous long term variations of ocean heat transport offer an attractive and intuitively creditable explanation for many long term climate trends. Multi-decadal variations of intense Atlantic hurricane activity are but one manifestation of an extensive array of regional and global climate trends which appear to be linked to variations of heat transport by the Atlantic thermohaline circulation. In addition to influencing Atlantic tropical cyclones and the closely associated West African monsoon, Atlantic thermohaline variability appears to be linked to global SST variations and related trends occurring throughout the global climate system. Consequently, understanding decadal trends in hurricane activity may be critically dependent on understanding the somewhat broader issue of decadal variations of the

major ocean circulations.

The net transport of warm surface layer water to high latitudes by the so-called "Atlantic conveyor belt" (i.e., thermohaline) circulation is sensitive to surface layer salinity anomalies in the ``deep water" formation areas of the North Atlantic. A major decrease of surface layer salinity appeared over portions of these areas during the late 1960s which reduced ocean water density and slowed the surface water sinking process associated with deep water formation. This trend, in turn, lead to diminished northward heat transport by the ocean hence, to cooling of ocean surface temperatures in much of the North Atlantic and warming of SSTs in much of the South Atlantic. These regional Atlantic SST anomalies initiated the atmospheric circulation anomalies associated with the long running Sahel drought and the associated decrease of intense Atlantic hurricane activity in recent decades.

At approximately the same time, the ocean surface also cooled in much of the North Pacific while strong SST warming occurred in much of the Southern Hemisphere Atlantic, Indian and Pacific Ocean areas. This global distribution of altered ocean surface temperatures has been directly linked to altered patterns of Atlantic and West African surface pressure and monsoon circulations. These global climate changes also include the energetics of ENSO and related variables in the tropical Pacific and Indian Oceans and numerous ``teleconnected" interactions between the tropical Pacific, the North Pacific, North America and Europe.

At present there are few long term observational data for making reliable direct estimates of trends in the net Atlantic Ocean conveyor transport. Consequently, no such information is available for detecting and further anticipating forthcoming decadal trends in hurricane activity. Needed research is suggested which includes surveys and the synthesis of additional trend data for the specification of plausible and physically consistent global interactions linking the Atlantic conveyor circulation and other decadal trend associations in the global climate system. In this way, some of these global data may yield factors which are potentially useful for forecasting the onset and termination of new decadal trends of hurricane activity. This prospect is examined in data for the most recent 50-year period and in prior realizations of similar concurrent climate trends in earlier historical data.

2.1 Background

The development of intense hurricanes occurs only with a very favorable set of atmospheric and oceanic conditions. As the tropical Atlantic region is typically only moderately accommodating to hurricane development, rather modest climatological deviations in this region can strongly alter the amount of intense hurricane activity (Gray 1979; Gray et al. 1993). Because seasonal trends in some key ocean-atmosphere conditions in the tropical Atlantic are predictable months in advance, we enjoy a surprising degree of seasonal predictability for Atlantic hurricane activity (see Gray et al. 1984a,b and Gray et al. 1992, 1993, 1994). The discussion in this chapter centers on a comparative review and synthesis of recent multi-decadal trends of Atlantic hurricane activity and the multiple, concurrent and apparently related regional and global climate trends during the past 50-100 years. As most large scale decadal and longer-term climate trends are in some way linked to variations of the oceanic thermohaline circulations, we argue that these observed decadal variations of hurricane activity and most of the concurrent trends in global climate are likely all linked to multi-decadal scale variations of the Atlantic thermohaline circulation.

Comparative multi-decadal distributions of hurricane tracks are shown in Fig. 1 for the tropical West Atlantic-Caribbean area during two recent 24-year periods. The results in Fig. 1provide a basic perspective on the nature of recent decadal trends in the incidence of hurricanes. It is unlikely that the extent of the climatic processes responsible for the obvious and persistent differences shown in Fig. 1 are restricted to the tropical Atlantic. Hence, we seek to interpret these changes in terms of additional regional and global climate trends which are approximately coherent with recent observed multi-decadal changes of hurricane activity. To this end, we present a summary of some of the more interesting recent multi-decadal climate trends which suggest the presence of global mode of climate variability which is related to recent variations of hurricane activity and modulated by long term variations of the global ocean circulations. A partial depiction of some of these widely spaced and diverse climate trends, both in the Atlantic region and in more remote locations as well, is shown in Fig. 2. These global climate trends include anomalous excursions in both Pacific and Atlantic Basins and in teleconnections extending between tropical areas and into the middle and high latitudes. Although detailed data for many of these scattered climate indices exist for only the last 50 years or so, those with a hundred or more years of data also indicate prior realization of multi-decadal climate covariability with Atlantic hurricane activity. A more complete discussion of these global climate trends is given below in part four of this chapter.

Strong northward transport of heat occurs in the ocean surface layer throughout the Atlantic Ocean basin. This transport circulation is associated with a net evaporative loss of water from the ocean surface along the north-south extent of the Atlantic. This net evaporation leads to the creation of relatively salty surface water conditions in the North Atlantic. As salinity dominates temperature in determining the density of sea water, chilling of this comparatively saline water in open areas of the far North Atlantic leads to the formation of very dense water which can sink to great depths in the ocean; this process is termed ``deep water formation". Extensive sinking of surface water in the North Atlantic maintains a net northward moving compensation circulation of comparatively warm and salty surface layer water. This northward circulation is often termed the ``Atlantic conveyor belt" (Broecker, 1991). The basic features of this long recognized circulation process are illustrated in the two maps shown in Fig. 3, taken from early work by Stommel (1957). The circles plotted on each map in Fig. 3 represent terminus points for the transport streamlines for upper (U) and lower (L) level circulation features.

Reduced salinity or "freshening" dramatically lowers ocean surface water density which can, in turn, inhibit deep convective overturning in the ocean for extended periods. Significant freshening of the ocean surface can occur in various ways including anomalous melting of pack ice, precipitation and advection (see Walsh and Chapman, 1990). Various data suggest that repeated multi-decadal episodes of weakening net northward heat transport to the far North Atlantic may be linked to freshenings of the upper surface layer and decreased deep water formation in the high latitude Atlantic region (Bjerknes, 1964; Broecker, 1991; Bryan and Stoffer, 1991; Weaver et al. 1994). A freshening event of this sort, termed the "Great Salinity Anomaly" (or GSA), appeared during the mid-1960s (Lazier, 1980) and has persisted for several decades, in rough concurrence with the observed recent 25-year change in intense hurricane activity. The GSA event has been qualitatively linked to the concurrent and apparently ongoing cooling of Northern Hemisphere Sea Surface Temperatures (SST) and warming of SSTs in much of the Southern Hemisphere oceans in recent decades (Street-Perrott and Perrott, 1990). Climate records indicate that a similar North Atlantic freshening event may have occurred during the early part of this century (Dickson et al. 1990; Kushnir, 1994; Hurrell, 1995). Paleo-climate data also suggest similar but comparatively more massive freshenings have occurred on multi-century scales in the North Atlantic and may be implicated with millennium-scale climate trends during the glacial-interglacial transitions (see Gordon 1986; Broecker 1991).

The precise rate of net northward heat transport to high latitudes by the Atlantic "conveyor" process varies with latitude and is not accurately known for any location. However, consensus estimates for ocean conveyor transport across 40^{o}N range from 15 to 30 percent of the total northward heat transport by the atmosphere at the latitude for the entire Northern Hemisphere (see OUCT, 1989). Therefore, significant alterations of poleward heat transport by the Atlantic ``conveyor" immediately imposes significant compensating adjustments on the atmospheric heat transport process and eventually on the remainder of the ocean thermohaline circulation as well. The amplitude, timing and duration of the decreased Atlantic conveyor transport inferred to have occurred due to the GSA provides ample basis for suggesting that, in addition to hurricane variability, other regional and global climate trends occurring during the past century (eg., "global warming") may also be largely due to the GSA and closely related effects (see Gray 1993). The nature and causes of the latter are proper issues for close study.

The following discussion reviews evidence for linkages between alterations of hurricane activity, ocean conditions in the North Atlantic and concurrent global climate events. We begin with a description of recent trends in hurricane activity and related climate trends in the tropical Atlantic. This is followed by a more extensive description of the Atlantic and global thermohaline circulation. A synthesis of these ideas is then attempted in the context of a global summary of recent concurrent climate variations. Emphasis is given to the close association between the recent 25-year decrease of intense Atlantic tropical cyclones and the concurrent long term West African (Sahel) drought. In doing these analyses, we have focused on the need to anticipate future trends in hurricane activity. Neither new measurements nor reliable long term indices of Atlantic conveyor transport are available for this purpose at present. Meanwhile, there is significant need to determine when the specific regional and/or global climate control features which have been inhibiting intense hurricane activity for 25 years will again trend toward conditions typical of the prior, more active mode of hurricane activity which occurred during the mid-1940s through the mid-1960s.

2.2 Decadal Climate Trends in the Tropical Atlantic

2.1 Decadal Variability of Atlantic Hurricane Activity

Table 1 provides a detailed summary of four measures of seasonal intense Atlantic hurricane activity. The hurricane categories referred to in Table 1 are based on the Saffir-Simpson (SS) scale of tropical cyclone intensity (see Simpson, 1974; Saffir, 1977). A summary of the SS storm characteristics, including central pressure, maximum sustained wind, storm surge height and estimates of the potential for coastal destruction are given in Table 2 for each of the five SS intensity categories. The exponential rise in estimated hurricane destruction potential for each intensity class, as indicated in the last column on the right of Table 2, reflects the observation that wind and storm surge destruction by hurricanes increases very sharply with increased SS intensity category (see Landsea, 1993).

The total seasonal incidence of the most intense category 3, 4 and 5 hurricanes generally exhibits the greatest climatic variability, both for year-to-year and for multi-decadal time frames. The decadal variability illustrated by Fig. 1 is also apparent in the data summary in Table 1 and in additional track composites shown in Fig. 4. The analysis of intense hurricane landfall at higher latitudes on the US East Coast in Fig. 4 complements the analysis for all classes of hurricanes in low latitude areas of the deep tropics shown in Fig. 1. Time series which show the long term trends of seasonal hurricane activity are given in
Fig. 5. The data series in Fig. 5 illustrate the important differences in the seasonal incidence of total (i.e., both weak and strong tropical cyclones) activity versus the seasonal occurrence of intense (category 3-4-5) hurricanes only. Note in Table 1 how the ratios of earlier versus later period hurricane activity are greatest for the more intense storm activity parameters.

The category termed "named storms" in Table 1 and Fig. 5 is inclusive of all tropical storms with sustained winds greater than 34 knots. Whereas little long term trend can be inferred for the seasonal incidence of total named storm activity in the Atlantic, shown in the left panel of Fig. 5, a sharp decrease of intense (category 3-4-5) hurricane activity can be inferred to have begun during the late 1960s from the right panel of Fig. 5. Inspection of Table 1 and Figs. 1, 4 and 5 (plus additional results given below) reveals that, in general, decadal variability is most pronounced for (1) the most intense classes of hurricanes and (2), for hurricanes originating in the deeper tropics, south of 25°N latitude. The latter point is clearly shown by the composites of hurricanes in the deep tropics in Fig. 2.1.

Intense hurricane activity was significantly greater during the 1950s and 1960s, in comparison with the 1970s and 1980s and the first half of the 1990s except, as discussed below, during 1988, 1989 and very recently during 1995. However, as noted in Fig. 5, little or no decadal scale trend was observed in the total frequency of named storms during this period (see also Gray 1990; Landsea 1991; Landsea and Gray 1992). Satellite detection of a few weaker storms in remote areas during recent years may bias these results slightly. Because the total incidence of Atlantic tropical cyclones, including tropical storms and weak and strong hurricanes, has been relatively constant during recent decades, little notice has been given to the marked decrease of the intense hurricanes and, therefore to the parallel trend in hurricane related destruction which also began to decrease during the late 1960s. The large multi-decadal variations become evident only when analyzed in terms of the seasonal totals of SS category 3-4-5 hurricanes, as shown in Figs. 1 and 4. Obvious differences in Figs. 1 and 4 are noticeable for intense landfalling hurricanes striking the US East Coast and Peninsular Florida. However, these differences are less apparent for landfalling intense hurricanes along the remainder of the Gulf of Mexico Coast (not shown, see Landsea et al. 1992). We believe that decadal differences are less distinct in the Gulf because a somewhat smaller percentage of Gulf hurricanes develop from easterly wave disturbances originating in West Africa. Since the advent of satellite monitoring in 1967, all intense hurricanes striking the US East Coast have developed from African waves whereas some intense Gulf hurricanes have developed from local frontal boundaries and related circulations (eg., Hurricane Alica in 1983). Consequently, there is less of a link to decadal changes in West African rainfall and related oceanic and atmospheric conditions in the deep tropical Atlantic region.

2.2 Covariation of Intense Hurricane Activity and West African Rainfall

The "Sahel" is an extended east-west zone in North Africa wherein generally marginal and highly variable rainfall occurs. This area lies between the Sahara Desert to the north (see map in Fig. 6) and the transitional grasslands and rainforest areas further south. Rainfall variations in much of the Sahel tend to closely parallel variations of seasonal Atlantic hurricane activity. The sense of this association is that intense Atlantic hurricane activity tends to be enhanced during summers when the Western Sahel has above average precipitation and vice versa. This association holds for both year-to-year variations and for longer-term, decadal time frames (Landsea and Gray 1992; Landsea et al. 1992). Consequently, long term regional circulation anomalies tied to Sahel rainfall can also be related directly to variable hurricane activity; in recent decades this association has linked drought to a decrease of intense hurricanes. This covariability can also be used to make qualitative links between both of these trends and variable Atlantic thermohaline transport.

Given that the tropical Atlantic lies immediately west and downwind (in the tropical easterlies) of West Africa and that the majority of Atlantic hurricanes develop from easterly waves moving westward from West Africa, it is not surprising that variable aspects of summer monsoon rainfall in West Africa and trends in intense Atlantic hurricane activity are related. But it is surprising that they are so well related, both on seasonal and longer term time scales. Indeed, there is also a good predictive link between early season West African rainfall (prior to August) and subsequent late summer (August, September, October) hurricane activity.

Precursor signals for seasonal hurricane activity can also be observed in West African rainfall during the late summer and fall of the prior year. This latter association presumably involves more vigorous vegetation cover and soil moisture processes early on in the following year which enhance *in situ* recycling of monsoon moisture to the atmosphere (see Gray et al. 1992). Regardless, this precipitation-hurricane association is a reflection of the strength and position of (1) the West African monsoon trough and (2) the Atlantic (Bermuda) summer center of high pressure as these two features become established during June and July. A strong summer monsoon at an anomalously high latitude position in June-July is conducive to continued abundant West African rainfall and comparatively vigorous Atlantic easterly wave systems during the remainder of the summer (see Gray 1990).

There is adequate continuous meteorological data coverage of the Western Sahel to provide reliable rainfall information back to the 1890s (see Nicholson 1989; Landsea 1991; Landsea et al. 1992). The precipitation data series in Fig. 7 show variations of a Western Sahel rainfall index during the last 50 years. The persistent, decades long drought which began about 1970 in West Africa and the concurrent trend to reduced intense hurricane activity evident in Fig. 5 appear to be closely associated manifestations of a single large-scale climate forcing factor (see Gray 1990; Gray and Landsea 1993). Presumably, as stated above, both of these trends are related to a decrease in the net northward ocean heat transport throughout much of the Atlantic basin beginning in the late 1960s. The precipitation time series in Fig. 7 contrasts the greater amounts of rainfall which occurred in the Western Sahel throughout most of the 50-year period between roughly 1920 to 1970 versus the somewhat deficient totals especially during the recent 25-year period between 1970-1994. Shinoda and Kawamura (1994) have shown that the drought conditions in the Sahel from the late 1960s to the late 1980s were primarily due to a strong reduction in the total amount of rainfall within the West African monsoon. An equatorial shift of the rainbelt, while helping to account for the Sahel drought in the years 1968, 1973, 1985 and 1987, was in general a secondary component in comparison to the monsoon-wide rainfall reduction. It will be shown in the following section that both wet and dry rainfall variations in West Africa during the early decades of this century were also closely concurrent with complementary (increased/decreased) trends in hurricane activity and the inferred mode of the Atlantic conveyor circulation.

Inferred weakening of the Atlantic Ocean conveyor circulation during recent decades appears to have contributed to important changes in the regional configuration of SST anomalies (both warming and cooling) which are especially evident in areas just off the northwest African Coast. The distribution of SST differences for 1950 to 1964 minus 1970 to 1984 are shown in Fig. 8. The areas of positive SST difference in Fig. 8 were warmer during 1950 to 1964 and areas of negative difference were cooler. Hence, an area of appreciable cooling occurred during 1970 to 1984 along the African coast south of about 15°N latitude and east of about 30° W longitude (positive differences) whereas coastal areas north of 15°N warmed (negative differences).

As illustrated in Fig. 9, the concurrent development of these surface temperature anomalies has caused collocated anomalies of surface pressure but which tend to vary in opposite directions; that is, anomalously high temperatures are associated with low surface pressures and vice versa (see Hastenrath 1990). Consequently, the long term ocean cooling trend on the Northwest African coast has led to a gradual rise in surface pressure over parts of the subtropical Atlantic where conditions in adjacent coastal areas are directly influenced by the ocean. The resulting gradual increase of surface pressure differences due to higher pressure at Nouadhibou, Mauritania (21° N, 17° W) along the West African coast and lower pressure at the interior station at Dori, Niger (14° N, 0° W) in Fig. 9 illustrates this effect. The 4 mb pressure gradient change during this 35-year period is the equivalent of a geostrophic wind change of about 10 m/s. This very large change of the pressure gradient is likely an important contributor to the observed major changes in West Africa monsoon moisture advection in recent decades and hence, is likely responsible for the large decadal decrease in Sahelian summer monsoon rainfall.

The protracted Western Sahel drought relented briefly during 1988 and 1989; rainfall then was more typical of seasonal values during the 1950s and early 1960s. This increased rainfall was accompanied by the development of a total of five category 4 and 5 Atlantic hurricanes during these two seasons.

Similarly, the five category 4-5 hurricanes which occurred in 1988 and 1989 generated a total of 18.75 intense hurricane days (9.0 and 9.75 for 1988 and 1989, respectively) which is well above the long term average of 2.1 intense hurricane days observed during the 25-year period of 1967-1991 (excluding 1988 and 1989). Following the 1989 hurricane season it seemed reasonable to infer that the long running multi-decadal Sahel drought might be ending with far reaching implications for increased hurricane destruction during the following years. We now see that the drought did not totally end in 1988 and 1989 as drought conditions returned to West Africa during 1990 through 1993. Enhanced Sahel rainfall during 1994 and 1995 again indicates that we may now be seeing the onset of comparatively wet longer-term conditions in the Sahel and more Atlantic intense hurricane activity. The exceptionally active 1995 hurricane season (5 intense hurricanes, 11.5 intense hurricane days) is entirely consistent with this inference.

The two year 1988-1989 interruption of the Sahel drought appears to have been due largely to a teleconnected response to the unusually cold Equatorial Pacific Ocean SST (La Niña) conditions which developed during these two years. La Niña conditions of comparable magnitude had not occurred since the middle 1950s. Teleconnected effects due to these cold SSTs contributed to weakening the upper tropospheric westerly winds within the lower Caribbean Basin and their eastward extension into the tropical Atlantic. When this upper-level circulation anomaly occurs, reduced upper tropospheric westerly winds over the tropical Atlantic become associated with the establishment of stronger upper tropospheric easterlies over West Africa and a general enhancement of the West African monsoon rainfall (Gray 1990; Landsea and Gray 1992). Decadal trends in the mode of ENSO activity also appear to be linked to Atlantic thermohaline variability. We will briefly touch on this topic again in Section 4.

2.3 The Nature and Variability of Atlantic Ocean Thermohaline Transport

The idea of an Atlantic "conveyor" provides a useful conceptual model for understanding the influence of variations in the Atlantic thermohaline circulation. This conveyor circulation is driven by the broad scale distribution of evaporation and surface layer salinity and temperature along the north-south extent of Atlantic Ocean. A simplified rendering of the Atlantic conveyor process and its likely global linkages is shown in Fig. 10 (cf., Fig. 2). Whereas the actual global thermohaline circulation is immensely more complex (see Schmitz 1995), Fig. 10 shows the key linkages to be considered here. Continuous north-south continental land areas flank the relatively narrow and enclosed Atlantic Ocean basin from 35° S northward to the open Arctic Ocean areas east of Greenland. This enclosed ocean configuration is unique in that it causes a large net evaporative loss of water vapor for the Atlantic Basin as a whole. Air entering the basin at high latitudes occurs mostly as westerlies which are dried during passage over the western highlands of both North and South America. Similarly, most incoming tropical air arrives as very dry easterlies out of Africa while tropical air exits the basin as moist westward moving trade winds passing over the relatively narrow and low areas of Central America. The resulting net excess of evaporation over precipitation in the Atlantic Basin creates large surface salinity values in comparison with the other large ocean areas.

A net northward transport of heat as warm upper surface layer water in the Atlantic, as noted in the chapter introduction, is engendered by the sinking of massive quantities of this comparatively high salinity water as it is chilled in the very high latitude areas of the North Atlantic. Related deep water formation processes in the Antarctic region are of lesser magnitude and are less spatially confined occurring through brine rejection during sea ice formation in several areas along the perimeter of the continent, primarily in the Ross and Weddell Seas (Schmitz 1995; Toggweiler 1994). The chilled, high salinity North Atlantic surface water descends to the deep ocean levels and moves southward, out of the basin and gradually becomes incorporated into the deep Southern Hemisphere circumpolar currents.

A more detailed view of present knowledge on the mean surface layer circulation in the North Atlantic Ocean is shown in Fig. 11 (from Schmitz and McCartney 1993). The numerous currents and recirculation features (gyres) shown in Fig. 11 represent the recent consensus regarding the best known Atlantic circulation features while smoothing over numerous lesser eddies. The circled numbers in Fig. 11 give estimated flow values expressed in Sverdrups (Sv; one Sv is a volume flux of 10^6 cubic meters per second). The dashed lines in the northern portion of the domain indicate comparatively warm high latitude circulations. The boxes at the ends of these high latitude flow elements designate areas of subsidence and the numbers in boxes are estimated subsidence flux values in Sv. The estimates of net volume sinking in Fig. 11 indicate that this process is concentrated (7 Sv) in the Davis Straight east of Newfoundland and in the Norwegian Sea (3 Sv).

Major alterations of the strength of the Atlantic thermohaline circulation in the recent 10 to 50 thousand year time frame have been hypothesized as a key factor influencing the rates of onset and retreat of glaciation during the most recent ice-age. Abrupt discharges of fresh water from the collapse of huge pools of glacial melt over North America provide a plausible mechanism for large ocean freshenings causing extended Atlantic conveyor shut down periods observed in paleoclimate data (Broecker 1991). Although processes linked to the onset and retreat of the ice-ages represent very large variations of the thermohaline circulation on time scales of thousands of years, observations indicate that weaker, shorter term variations also occur, as shown in Fig. 12. The oxygen-isotope record of the Greenland ice core in Fig. 12 provides a proxy profile of regional North Atlantic temperature changes during the last ten thousand years. Note in Fig. 12 that since the final warming at the end of the last ice age (~ 10,000 B.P.), North Atlantic temperatures have remained comparatively steady but with many small multidecadal or century length temperature fluctuations of a few degrees Celsius occurring throughout the record. These smaller multi-decadal and century scale ocean temperature fluctuations are likely linked to similar but comparatively weak variations of the ocean thermohaline circulations. These smaller variations appear to be analogous to trends observed during the present century, the notable recent consequences of which have been manifest during the last 20-25 years when the North Atlantic cooled (see Kushnir 1994; Hurrell 1995).

Direct observational evidence of persistent large-scale freshening of the ocean surface layer in the far North Atlantic during the late 1960s is shown in Fig. 13; this is the so called GSA event mentioned previously. Weather ship "Bravo", as noted in the caption to Fig. 13, was located in the area of the Labrador Sea near the "7 Sv" subsidence area shown in Fig. 10 where considerable deep water formation normally takes place. The effects of the GSA event in slowing the conveyor system have imposed small but nevertheless significant changes on the climate of the North Atlantic. Anomalously cold SST values due to diminished northward conveyor heat transport have altered the surface heat balance over very large areas and, thereby, have altered the large-scale atmospheric circulation. These atmospheric effects appear to include changes in (1) the regional North Atlantic-Western Europe air temperature, winds, surface pressure and precipitation distribution (see Deser and Blackmon 1993; Kushnir 1994; Hurrell 1995), (2) in the distribution of surface-500 mb thickness over much of the Northern Hemisphere (see Shabbar et al. 1990), (3) in the land-sea monsoon circulations over northwest Africa shown previously in Fig. 9 and (4) the vertical variability (shear) of east-west (zonal) winds throughout the deep tropics of the Atlantic and Caribbean region; these among numerous others. As discussed in greater detail below, we believe these effects are likely related to the recent quarter century Sahel drought and concurrent reduction of Atlantic Basin intense hurricane activity, as well as numerous additional closely concurrent climate trends in more remote areas.

Extensive research is showing that several such variations of the Atlantic conveyor likely occurred during this century. Another weak conveyor episode appears to have occurred prior to about 1915.

Reduced salinity (Dickson et al. 1990), colder SSTs and lower surface pressure (Kushnir 1994; Hurrell 1995) were observed in the far North Atlantic and accompanied reduced hurricane activity and Sahel drought during this period. An inferred stronger conveyor circulation transferred more energy into the high latitude North Atlantic region between 1920 and 1965, followed by the present weak conveyor environment with significantly less northward ocean heat transport since the late 1960s. The upper layer freshening (salinity decrease) leading to the most recent diminished mode of the Atlantic conveyor (i.e.,Fig. 13) was apparently caused by the anomalous advection of relatively thick Arctic pack ice (comprising a large fresh water component) through the Fram Straight (between Greenland and Spitsbergen) into the North Atlantic via the Greenland and Labrador Seas during the mid 1960s (Walsh and Chapman 1990). Melting of these positive sea ice anomalies significantly lowered observed surface salinity values in the Labrador Sea area which eventually spread to much of the far North Atlantic.

Additional considerations relate to the eventual recycling of ocean deep water. As was suggested in Fig. 10, there are numerous potential paths whereby North Atlantic deep water (NADW) can eventually make its way back into the ocean surface layer of the South Atlantic and become reincorporated into the northward Atlantic conveyor flux. At present, the process is thought to involve various extended loops around the bottom and intermediate levels of the Indian and North Pacific Ocean basins while slowly diffusing upward into the surface layer. This surface layer water eventually becomes reincorporated into the upper water of the tropical Indian Ocean and the South Circumpolar Currents (Schmitz 1995). Note in Fig. 10 that the estimated rate of resupply of upper layer ocean water into the South Atlantic occurs as about 10 Sv of relatively cold, low salinity water entering from the South Pacific through the Drake Passage and about 4 Sv of comparatively warm, saline water which moves westward from the Indian Ocean (Schmitz, op.cit).

Data on the average age of global ocean deep water suggests mean recycling times on the order of 600 years (Toggweiler 1994). However, observations indicate that vertical diffusion processes in the deep ocean are far too slow to accommodate this rate of recycling. This disparity has led to suggestions of deep upwelling of weakly stratified south circumpolar water as a major deep water removal-recycling process (Toggweiler 1994). This additional upwelling appears to be accomplished primarily by west wind driven pumping processes centered in areas of the South Atlantic just east of the Drake Passage. Hence, deep water recycling rates may also involve variable aspects of high latitude Southern Hemisphere winds.

Another important consideration is that variable amounts of warm and salty upper-level water from the South Indian Ocean enter the South Atlantic in the area west of the Cape of Good Hope. This westward transfer occurs primarily as large "retroflection rings" or eddies which break off the Agulhas Current where it turns sharply eastward to join the south circumpolar flow. Consequently, significant alterations of the upper layer salinity may occur in the South Atlantic due to variable rates of wind driven upwelling and of variable inflow of warm, saline Indian Ocean water. These trends have the potential to alter salinity of water entering the conveyor and thus, to eventually alter deep water formation rates in the North Atlantic and northward heat transfer on time scales of decades, centuries and longer.

Figure 14 gives a schematic summary view of four primary processes which likely influence the Atlantic portion of the global thermohaline circulation. Because of the potential associations with diverse climate trends including hurricane activity, the nature and causes of variable Arctic sea ice advection and South Atlantic upwelling and advection processes influencing North Atlantic salinity have become very important research questions. Some studies are focusing on variable precipitation and ice formation feedback processes within the arctic basin. Studies by Walsh and Chapman (1990), Mysak et al. (1990) and Serreze et al. (1992) present data and plausible hypotheses for 15 to 80 year ice pack oscillations driven by variable interactions involving high latitude albedo and land surface hydrology processes and regional Arctic Ocean circulations. Recent data presented by Aagaard (1995) shows that average ice thickness and, thereby, net flux of fresh water passing southward through the Fram Straight and into the North Atlantic has recently been steadily decreasing (since 1991). This latter trend poses the immediate prospect of gradually increasing ocean surface layer salinity in high latitudes of the North Atlantic leading to an increased thermohaline conveyor flow. Note however, that the currently unknown effects and functional time scales of variable inputs of anomalously warm, saline water from the Indian Ocean versus relatively cold, fresh water from the South Pacific into the upper surface layers of the South Atlantic complicates the overall problem of anticipating multi-decadal change.

2.4 Discussion and Review of Additional Related Multi-decadal Climate Trends

2.4.1 Discussion

Climatic events lasting several centuries (eg. the "climate optimum" of the late middle ages and the more recent "Little Ice Age") are also likely related to ocean conveyor variability, but wherein multi-century modes of inter-basin ocean circulations are implicated (see Gordon et al. 1992). Regardless, the GSA - diminished conveyor transport scenario offers a plausible explanation for how the North Atlantic and much of the Northern Hemisphere became cooler in comparison with the Southern Hemisphere during the last 20-25 years. Significant cooling of the North Atlantic region began during the late 1960s and encompassed much of the Northern Hemisphere within a few years. The observed concurrent warming of much of the Southern Hemisphere Oceans and the tropical West Pacific are illustrated in Fig. 15. The spatial distribution of a major mode of global SST variability during the last 100 years is shown (Fig. 15, upper) along with a time series (solid line in Fig. 15 lower) showing the time variations of the sign and amplitude of this pattern during the period (from Folland et al. 1991; also see Barnett 1984). Manabe and Stouffer (1988) obtained quite similar global SST anomaly distributions when simulating an active versus inactive Atlantic conveyor in a coupled ocean-atmosphere model. The dashed time series in Fig. 15 lower shows concurrent variations of Sahel rainfall. Measured rainfall variations over Northwest Africa during the last 100 years (eg. Fig. 15 lower) and inferred for the last few centuries (Nicholson 1989) indicate that drought periods in the Sahel typically last 10-30 years, punctuated by wet periods of somewhat longer duration. The dry period prior to 1915 in Fig. 15 lower was similar in magnitude but not so long as the recent 1970 to present (1995) drought.

The temperature pattern in Fig. 15 upper represents the distribution of global SST variability extracted from an 87 year (1901-1987) data set using Empirical Orthogonal Function (EOF) analysis. The pattern is the third most powerful mode of variability (hence, EOF No. 3), following variability associated with the annual cycle and El Niño - Southern Oscillation (ENSO). Note in Fig. 15 upper that SST cooling associated with weak conveyor transport after 1970 also occurs over much of the North Pacific in parallel with cooling in the North Atlantic while much of the Southern Hemisphere ocean areas become warm (and vice versa when the conveyor is strong between 1920 and 1970). Very similar global difference patterns are observed as composite anomaly differences obtained by Nitta and Yamada (1989) for the 1950s versus the 1970s in a more recent (1950-1985) global SST data set.

On the basis of the time series in Fig. 15 lower, we may infer that the conveyor was relatively weak prior to about 1915 and after about 1965 but with a more active 1920-1964 period in between. In this context, we review other studies of regional and global data which also reflect the effects of these inferred decadal variations of the conveyor circulation. The climate record contains numerous examples of such climate trends. Notably, Kushnir (1994) used wintertime North Atlantic SST, air temperature and sea level pressure (SLP) data to specify four 15-year periods during the last 100 years which had fairly distinct climate trends and which allow two sets of composite active, versus inactive conveyor differences.

Kushnir found that the periods 1900 to 1914 and 1970 to 1984 were similar in having anomalous distributions of cold SSTs and low SLP (see also Hurrell 1995) over the North Atlantic whereas 15-year periods 1925 to 1939 and 1950 to 1964 were selected as the best cases of the opposite conditions (i.e., comparatively warm SSTs and high North Atlantic SLP at high latitudes). Dickson et al. (1990) reported evidence of diminished surface layer salinity in the far North Atlantic during 1900-1915 which is consistent with salinity during the recent (1970-1984) GSA cold period.

Composite differences for the mean annual distribution SSTs in the North Atlantic for 1925 to 1939 (warm) minus 1900 to 1914 (cold) are shown in Fig. 16. A similar spatial pattern of SST differences during the summer months for 1950 to 1964 minus 1970 to 1984 SSTs was shown in Fig. 8 (cf. Fig. 15 upper and see Kushnir 1994).

Inspection of the time series data in Fig. 15 lower shows that the Western Sahel was dry between 1900-1914 and wet between 1924 to 1939. Similarly, trends in the Sahel during more recent periods (cf, Fig. 7) include wet during 1950-1964 versus dry during 1970-1984. Noting that the sign of the eigenvector coefficient on the right axis of Fig. 15 lower is reversed, similar inferences can be drawn for global SSTs time series; that is, that the North Atlantic is generally warm when the Sahel becomes wet and vice versa. Hence, these results show the pre-1915 and post-1964 periods to have multiple similarities in Atlantic SST and salinity and Sahel rainfall which contrast with conditions during the intervening 50 years. Recent work by Hurrell (1995) generally verifies Kushnir's results and extends these results to long term alterations in the Northern Hemisphere mid-latitude storm track and to resulting broadscale precipitation differences over Northern Europe.

Details of the physical processes linking the Sahel drought with diminished hurricane activity are presented in Gray (1990), Gray et al. (1992, 1993, 1994); Gray and Landsea (1991), Landsea and Gray (1992) and Landsea et al. (1992). Basically, the reconfiguration of Atlantic SST anomalies in recent decades due to effects of the GSA weakened the summertime West African monsoon trough. As the West African monsoon is the source of Atlantic easterly waves, it is in large part responsible for initiating nearly all intense hurricane activity in the deep tropics (Landsea, 1993). Figures 17 and 18 extend the prior analysis (i.e., Figs. 1 and 4) to comparative composites of landfalling intense hurricane tracks for the two 15-year early 20th century periods (Fig. 17) and for the two more recent (Fig. 18) 15-year periods identified by Kushnir (1994).

The analyses in Fig. 17 were restricted to landfalling storms on the mainland or major islands so as to minimize any possible tendency for underreporting of storms in remote areas which remained at sea during either of these two early periods. As during 1950-64, considerably greater hurricane activity occurred during the 1925-39 inferred active conveyor (and warm North Atlantic and wet Sahel) period than during 1900-1914. The comparison of hurricane tracks shown in Fig. 18, is for intense (class 3-4-5) hurricanes forming in the deep tropics east of 60° W longitude during 1950-64 versus 1970-1984. The region selected for this comparison emphasizes storms likely to have formed from African waves and thereby, helps to establish the association between hurricanes and African drought discussed previously.

A more expansive summary of the differences in hurricane activity which were illustrated in Figs. 17 and 18 is given in Tables 3 and 4. Table 3 shows the total number of landfalling intense hurricanes for Peninsular Florida and for the remainder of the US East Coast during two 47-year periods. These two periods include 47 years of inferred strong conveyor conditions (1921-1967) versus 47 weak conveyor years comprised of two periods spanning 1900-1920 plus 1968-1992. A similar tabular summary is presented in Table 4 but for hurricanes in the Caribbean basin during two recent 24 year periods of comparatively weak (1970-1993) versus strong (1944-1967) conveyor conditions. The inferred strong conveyor versus weak conveyor differences for intense hurricane activity are consistently greater than two-to-one in these areas and approach a four-to-one difference for Peninsular Florida.

As noted previously in the discussion of Figs. 1 and 4, the incidence of landfalling hurricanes on the US Gulf (of Mexico) Coast shows decidedly less decadal variability (see Landsea et al. 1992). This diminished decadal variability in the Gulf likely occurs because many of these hurricanes develop from disturbances which form locally within the Gulf. This is especially true for storms developing early (June, July) and late (October) in the season. As a result, a smaller percentage of the intense hurricanes which landfall in the Gulf form from African waves so that the incidence of intense Gulf hurricanes is less strongly influenced by variable Atlantic conveyor transport.

4.2 Recent Multi-Decadal Climate Variability in the Pacific and Indian Ocean Regions

The "warm pool" region of the equatorial West Pacific, Indonesia and the Eastern Indian Ocean is the primary ocean heat reservoir for ENSO and the associated teleconnected global climatic variability. For this reason, ENSO variability in relation to Atlantic conveyor variability, is of significant interest. As noted previously, the first two decades after 1900 appeared to have experienced climatic trends similar to those observed during the recent GSA linked periods. ENSO (and hence warm pool) linked data presented by Enfield (1989) also reflect these differences, most notably in the amount of year-to-year variability of Central and East Pacific SSTs and of the Southern Oscillation (pressure) Index (SOI; see also Trenberth 1994). During the inferred slow conveyor periods of 1900 to 1915 and 1970-present [vis-a-vis Kushnir's (1994) analysis], the amplitude of this variance in Enfield's data is consistently a factor of two greater than what occurred during the generally active conveyor period of 1920-1965. These same differences are discussed by Ramage (1983) and by Brown and Katz (1991) who noted how the significance of Sir Gilbert Walker's studies of the Southern Oscillation (eg. Walker and Bliss 1937) was lost for 60 years, in large part because the frequency and intensity of El Niños subsided dramatically during the 1920-1965 period.

A recent trend to more and stronger El Niño events in the tropical Pacific Ocean and overall tropical Pacific and Southern Hemisphere SST warming has been observed since about 1970 (Enfield 1989; Shabbar et al. 1990). These trends may be postulated to be part of a complex sequence of global adjustments to the redistribution of ocean heat energy owing to diminished Atlantic conveyor transport and related changes in Northern Hemisphere atmospheric circulation. This hypothesis allows that some changes may occur almost immediately with the appearance of the GSA whereas other trends may not develop until several years or more later. North Atlantic variability can thus be viewed as a factor contributing to altered modes of ENSO variability in recent decades (see Trenberth 1994). Related decadal effects also appear to include the strong concurrent surface cooling trends in parts of the central and eastern North Pacific and warming in the equatorial and sub-tropical Northwest Pacific (eg., Fig. 15a). A reconfiguration of the temporal and spatial variability of ENSO-linked equatorial SST anomaly patterns and changes in the well known tropical-mid latitude teleconnections has also been observed. In the latter, we consider trend-like changes in the so called Pacific North America (PNA) pattern which links atmospheric variability in the equatorial Pacific to seasonal climate anomalies in the western North America and the Canadian Arctic (see Shabbar et al. 1990).

Michaelsen and Thompson (1992) studied various ENSO proxy indices for the last 100 years (i.e., tree ring data, O_{18} isotope ratios and Line Island precipitation) in comparison with standard ENSO SLP and SST indices. A listing (their Table 17.5) identifies all years since 1900 during which at least one of these indices indicated the presence of a strong or very strong El Niño. During the 30 total years identified by Kushnir (1994) as proxy "active" conveyor periods (i.e., 1925-1939 and 1950-1964), only six years (hence one year in five) are identified by Michaelsen and Thompson (1992) as having at least one index indicating a strong El Niño; hence, evidence of some form of El Niño activity. In contrast, of the 30 inactive conveyor years identified by Kushnir (1900-1914 and 1970-1984), 15 years (or, half of all inactive conveyor years) have at least one ENSO index indicating a strong El Niño. Clearly this evidence suggests that El Niño-like conditions appear to become more pervasive during the inferred ïnactive" conveyor periods. Gray (1984a) noted that teleconnected effects of El Niños are a major factor for diminished hurricane activity. Therefore, the observed trends in all the above (i.e., in ENSO activity plus North Atlantic SSTs and SLP, Sahel rainfall and global SSTs) are all broadly compatible trends and are closely coherent with observed decadal trends of Atlantic hurricane activity during the past century.

Enfield (1989) noted that strong El Niño events seem to have become more frequent in recent decades. Others have pointed out that the overall character of the development of El Niños has also changed (see Barnett 1991; Trenberth 1994). In the latter case, a distinct tendency for warm SSTs to spread eastward across the Central Pacific, somewhat in advance of the development of strong warm anomalies along the West Coast of South America, has occurred during the onset of the most recent three (1982, 1986, 1990) ENSO warming events. Gray (1984a) noted that the main feature that seemed to tie El Niños to diminished hurricane activity was enhanced vertical wind shear in the western tropical Atlantic during strong El Niños (see Fig. 19). That the tropical circulation has tended in recent decades to produce more strong El Niños and toward more El Niño-like conditions in general is evidenced by the trend in teleconnected Caribbean area vertical mean wind profiles shown in Fig. 19. The horizontal arrow in Fig. 19 represents the typical propagation speed of a tropical Atlantic wave disturbance moving westward into the Caribbean area. Note the much greater net vertical wind shear which occurs relative to these moving disturbances since 1970. The effect of this greater vertical wind shear is to pull apart developing tropical storms and to either prevent or seriously diminish their intensification.

Recent research has also revealed a wide array of similar decadal scale climate trends occurring concurrently (or very nearly so) in the tropical West Pacific and Indian Ocean warm pool region. Gaffen et al. (1991) and Graham (1990) show upward trends for equatorial West Pacific SSTs, tropospheric temperatures and humidity, beginning in the early 1970s. Regional tropopause heights (Reid and Gage 1993) and tropospheric thickness anomalies (Sheaffer and Gray 1995) in the warm pool area also show a distinct upward trend beginning about 1970, leveling off somewhat after 1985.

Some of these climate trends appear somewhat abruptly and are closely concurrent with the onset of the GSA in the mid 1960s; good examples of these being the trends in Sahel rainfall, intense hurricanes and surface pressure, winds, sea surface and air temperature and precipitation in the North Atlantic (see Hurrell 1995). Other trends seem to have appeared more gradually with an extended transitional onset of five years or more. Examples of the latter delayed or more gradual trends include surface heights of major lakes, including the Great Lakes (Manchard et al. 1988) and the Great Salt Lake (McKenzie and Eberli 1987), sea level pressure-monsoon precipitation associations for the Indian monsoon (Parthasarathy et al. 1991) and conditions in the Pacific warm pool relative to ENSO variability (see Gaffen et al. 1991; Sheaffer and Gray 1995).

We note in this regard that the ``global conveyor" as configured in Fig. 10 should not be viewed as a rigid, lock-step sort of process, periodically starting and stopping uniformly throughout its extent. A simplistic interpretation and synthesis based on such a view could be proposed wherein a disruption and subsequent slowing of the Atlantic conveyor would lead directly to a buildup of accumulated ocean surface heat energy in the warm pool due to slowing of the ``Indonesian Throughflow" conveyor segment (labeled "IT " in Fig. 10) which traverses the warm pool through Indonesia west of New Guinea. Although the Indonesian Throughflow flux is known to be large ($\approx$ 8.5 Sv) and highly variable, trends in this "throughflow" circulation appear to occur as an effect of ENSO variability (Schmitz 1995). Hence, the observed multi-decadal changes of conditions in the warm pool area may more likely be due to the influence of altered atmospheric circulations (eg., trade wind forcing) acting on the subtropical Central and East Pacific Ocean rather than as a "backing up" of impeded tropical warm water flux through the warm pool on a rigid global "conveyor belt". Consequently, slowing of the Atlantic conveyor may well be reflected in the foregoing trends in the condition of Pacific warm pool, but through associations possibly involving several anomalous large scale atmospheric circulations altering patterns of upwelling and ocean transport in remote areas of the Pacific.

4.3 Other Atlantic-Global Teleconnections

Ramage (1983) discusses the transient nature of various interseasonal correlation relationships which have been proposed for seasonal weather forecasting. He suggested that the multiple concurrent changes of many of these interseasonal associations (correlations) in various oceanic and atmospheric climate indices which occurred during the late 1960s should be examined to gain insight on the basic nature of global climate variability. Gray (1990) made accommodation for these effects as they relate to the association between Sahel drought and seasonal incidence of intense Atlantic hurricanes. Barnston and Livezey (1987), Chen et al. (1992), Sheaffer and Reiter (1985) and Namias et al. (1988) also made similar suggestions for accommodating concurrent long term changes in potential seasonal forecast relationships for the tropical and North Pacific and Western North America.

The six data series shown in Fig. 20 provide a small but diverse sampling which is typical of numerous concurrent global climate changes that have been reported in the recent literature. As the data periods represented in Fig. 20 vary somewhat, a prominent arrow has been added to each time series to show the position of the year 1970 on the abscissa. For the purpose at hand, these data series and others like them can be separated into three groups as follows: (1) those trends known to be tied to hurricane variability (i.e., Fig. 20F); (2) trends likely to be linked with hurricane variability (Fig. 20A) and; (3) trends which offer interesting possibilities but require more study (Figs. 20B, C, D and E).

Some specific considerations regarding the data series in Fig. 20 are as follows: Panels 20A (North Atlantic SSTs), and 20F (Sahel rainfall) are similar to the results already discussed in Figs. 9 and 16b. Panel 20B (after Trenberth 1990) shows long term trends in area averaged SLP for the North Pacific, the observed trend being a general lowering of high latitude surface pressures in the North Pacific. Whereas Trenberth (1990) interprets the figure as evidence of a trend in SLP beginning in 1977, these data might also be viewed as showing a trend beginning as early as 1970. Figure 20C shows increasing ocean surface levels in the equatorial Southeast Pacific wherein the effect is inferred to be related to decadal weakening of the Pacific trade winds and a relaxation of the residual (dynamic) westward drift of tropical surface water. Figure 20D shows time series of 300 mb height anomalies at five West Pacific warm pool stations including Koror, Singapore, Darwin, Majuro and Honiara. Excepting Darwin, all the data in Fig. 20D show a slow increase of upper-level heights (atmospheric warming) beginning about 1973. Finally, Fig. 20E relates to the problem of transience in empirical forecasting relationships. In this case, the input data were detrended prior to computing the running ten-year correlation coefficients shown in the figure. The sign of the fall to winter interseasonal correlations reversed sharply about 1970. Further studies and reviews of these types of trends are presented by Nitta and Yamada (1989), Hsiung and Newell (1986) and Barnett (1991), all of whom examined strong trends in Pacific SSTs and related climatic features which are broadly concurrent with the recent Atlantic (conveyor) anomaly.

The inference regarding linkages between the diverse trends in Fig. 20 is that the global atmospheric circulation in the Northern Hemisphere adjusted fairly rapidly to effects of the GSA on Atlantic Ocean heat transport. For example, Knox et al. (1988) noted a sharp change in Northern Hemisphere geopotential height anomalies beginning in the 1960s. The contrasting global ocean-atmosphere trend characteristics inferred for comparatively active versus inactive conveyor periods (eg., Manabe and Stouffer 1988; Folland et al. 1991) appear to be rather systematic such that, when considered separately, both modes likely contain distinct interseasonal relationships which are useful for making simple seasonal forecasts during each mode (i.e., Gray et al. 1993, 1994; also, panel 20E). However, these prospects not withstanding, the more important opportunity may lie in adopting these and similar trends in the global climate for identifying changing decadal modes useful for longer term, decadal-scale forecasting of important climate trends including the incidence of intense hurricanes.

5 Summary and Thoughts for the Future

A review of the most recent 100 years of data shows that variations of hurricane activity in the tropical Atlantic appear to be linked (1) to mode-like variations of regional and global SSTs, and (2) to related trends in global air temperature, pressure anomalies and atmospheric circulations. All of these effects extend well beyond the tropical Atlantic. The preeminent effect which seems to dominate all others as a unifying process for these changes is decadal variations in the Atlantic Ocean thermohaline circulation. Figure 21 presents an overview of the primary regional Atlantic climatic differences associated with comparatively strong (left panel) versus weak (right panel) hurricane activity and inferred thermohaline transport conditions.

A notable decrease of upper layer salinity appeared and spread to large areas of the North Atlantic Ocean during the late 1960s and persisted for at least ten years. This salinity anomaly is presumed to have been caused by anomalous influx of sea ice from the Arctic. One effect of the resulting salinity anomaly was a reduction in the net rate of North Atlantic deep water formation with a collateral reduction of the compensating northward conveyor circulation of warm, salty water in the ocean surface layer (eg., right panel in Fig. 21). The inferred weakening of the net northward Atlantic thermohaline transport during the last 25 years is likely the cause of the cooling of large areas of the North Atlantic Ocean and concurrent warming in much of the South Atlantic. Various observational data presented here and numerous recent numerical studies (eg., Brewer et al. 1993; Weaver et al. 1994; Huang 1994;Weisse et al. 1994, Dickson and Brown 1994; among many others) testify to the feasibility of this concept.

The effects of these changes in the regional distribution of tropical SST anomalies are particularly evident as areas of cooling along the coast of Northwest Africa. This long term ocean cooling has caused a gradual rise in surface pressures along the subtropical Northeast Atlantic and adjacent parts of the Northwest African coast where conditions are directly affected by the ocean. These increased coastal pressure values have created an increased low level pressure gradient between the northwest African Coast and the central Sahel region. In the latter, region surface pressure has been influenced by increasingly hot, dry regional land surface conditions rather than by cooler ocean temperature changes. The combined direct effect of these two complementary changes in the regional surface pressure gradient (as shown in Figs. 8 and 20) has been a decreased southwest monsoonal surface wind circulation (note wind barbs in Fig. 21), a weaker monsoon and less vigorous easterly waves propagating into the tropical Atlantic. Figure 21 also reflects the increased tendency to El Niño conditions (and hence teleconnections) in the tropical Pacific.

It is also likely that regional feedback enhancements associated with persistent dry northeast wind anomalies (emanating out of the Sahara) have contributed to the intensity of the long term Sahel drought. These changes have reduced moisture available for evaporation from the land surfaces, resulting in warmer summertime land surface temperatures. The hydrostatic effects of these temperatures created even lower surface pressures over the interior Sahel land areas which, when added to the positive SST induced pressure anomaly along the African coast, further alter the pressure gradient and thereby further accentuate the dry northeast wind and reduced moist southwesterly flow. Thus, once the ocean induced cooling along the West African coast initiates an increase in dry northeast winds, an interior land feedback response causes a greater enhancement of the effect.

The foregoing sequence of associations offers a plausible interpretation of how the multi-decadal

Sahelian drought and enhanced El Niño has been initiated by anomalously low ocean salinity thousands of miles from either effect in the far North Atlantic and why these effects have persisted so long. As the West African monsoon is the source of Atlantic easterly wave activity, these effects are at least partly responsible for the recent 25 years of greatly reduced Atlantic intense hurricane activity. Trends to more El Niño like conditions throughout the global tropics are also implicated in decreased hurricane activity. The prominent multi-decadal changes in West African rainfall and intense Atlantic hurricane activity thus appear to be a natural consequence of the variable Atlantic thermohaline circulation. The nature of the teleconnected tie to increased El Niño activity needs more study, but historical and geological evidence indicate that similar trends, but of both comparable and greater amplitude and duration have occurred many times in the past. Hence, these multi-decadal changes are not necessarily associated with recent anthropogenic climate alterations.

The rather loosely specified salinity effects to which we have ascribed recent inferred slowing of the Atlantic conveyor circulation are unlikely to continue indefinitely. Rather, we must anticipate that regional conditions governing the conveyor circulation will eventually assume a stronger mode. Although net Atlantic transport has recently been reduced, evaporation and related global processes have continued. Other factors left unchanged, these processes alone will gradually alter distributions of ocean salinity which, in time, will influence the intensity of the Atlantic circulation. Presumably, in this ``salt oscillator'' mechanism, the thermohaline circulation must increase when enhanced net rates of sinking again develop in the North Atlantic and the ``conveyor'' intensifies with an attendant increase in net northward heat transport by the Atlantic Ocean.

The timing of any forthcoming increases in Atlantic conveyor transport, leading to increased West African rainfall and intense Atlantic hurricane activity, remains open to question. There is some evidence from 1994-95 data that the last 25-year mode of atmospheric response may even now be changing. Paleoclimatologists are studying the changes of the conveyor belt circulation on time scales of a century to thousands of years. Shorter, decadal to century time scale conveyor belt changes are also now beginning to receive attention. Hopefully data being collected in new research, most notably NOAA's Atlantic Climate Change Program (ACCP), will identify additional factors which reflect impending changes in the conveyor and closely linked climatic conditions. For now, more study is needed on specific atmospheric and oceanic parameters in the existing observational records which may first signal that alterations in the conveyor circulation are occurring.

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REFERENCES

Aagaard, K., 1995: The fresh water flux through the Fram Straight: A variable control on the thermohaline circulation. Preliminary extended abstracts, ACCP Principal Investigators Meeting, Miami, FL, 1995.

Angell, J. K., 1988: Variations and trends in the tropospheric and stratospheric global temperatures. *Journal of Climate*, **1**, 1296-1313.

Barnett, T. M., 1984: Long-term trends in surface temperatures over the oceans. *Monthly Weather*

Review, **112**, 303-312.

Barnett, T. M., 1991: The interaction of multiple time scales in the tropical climate system. *Journal of Climate*, **4**, 269-285. Barnston, A. and R. E. Livezey, 1987: Classification, seasonality and persistence of low frequency atmospheric circulation patterns. *Monthly Weather Review*, 115, 1083-1126.

Bjerkens, J., 1964: Atlantic air-sea interaction. *Advances in Geophysics*, 1-82.

Brewer, P.G., W.S. Broecker, W.P. Jenkins, P.B. Rhines, C.G. Rooth, J.H. Swift, Takahashi and R.T. Williams, 1983: A climatic freshening of the deep Atlantic North of 50 N over the past twenty years. *Science*, **222**, 1237-1239.

Broecker, W. S., 1991: The great ocean conveyor. *Oceanography*, **4**, 79-89.

Brown, B. and R. Katz, 1991: The use of statistical methods in the search for teleconnections: past, present and future. Chapter 12 in *Teleconnections Linking World Wide Climate Anomalies*, Cambridge University Press, M. Glantz, R. Katz and N. Nicholls, eds.

Bryan, K. and R. Stouffer, 1991: A note on Bjerknes hypothesis for North Atlantic variability. *Journal of Marine Systems*, **1**, 229-241.

Chen, T.-C., H. VanLoon and M.-C. Yen, 1992: Changes in the atmospheric circulation over North Pacific-North America since 1950. *Journal of Meteorological Society of Japan*, **70**, 1137-1146.

Dansgaard, W., S. J. Johnson, H. B. Clausen, and C. C. Langway, 1971: *Climate record revealed by Coup Century Ice Core. In: the late Cenozoic Glacial Ages.* Ed., K. K. Turekian, Yale University Press, New Haven.

Deser, C. and M.L. Blackmon, 1993: Surface climatic variations over the North Atlantic during winter: 1900-1989. *Journal of Climate*, **6**, 1743-1753.

Dickson, R. and J. Brown, 1994: The production of North Atlantic deep water. *Journal of Geophysical Research*, **99**, 12319-12341.

Dickson, R., E. M. Gmitrowicz and A. J. Watson, 1990: Deep water renewal in the North Atlantic. *Nature*, **344**, 848-850.

Enfield, D., 1989: El Niño, past and present. *Review of Geophysics*, **27**, 159-187.

Folland, C., J. Owen, M. Ward and Andrew Colman, 1991: Prediction of seasonal rainfall in the Sahel region using empirical and dynamical methods. *Journal of Forecasting*, **10**, 21-56

Gaffen, D. J., T. P. Barnett and W. P. Elliott, 1991: Space and time scales of global tropospheric moisture. *Journal of Climate*, **4**, 989-1008.

Gordon, A. L., 1986: Interocean exchange of thermocline water. *Journal of Geophysical Research*, **91**, 5037-5046.

Gordon, A. L., S. E. Zebiak and K. Bryan, 1992: Climate variability and the Atlantic Ocean. *EOS*, (April 4, 1992), 163-165.

Graham, N., 1990: Decadal-scale climate variability in the 1970's and 1980's: Observations and results.

Proceedings of the Fifteenth Annual Climate Diagnostics Workshop. Asheville, NE October 29 - November 2, 1990. (US Dept. of Commerce PB90-198573)

Gray, W. M., 1979: Hurricanes: their formation, structure and likely role in the tropical circulation. Supplement to Meteorology Over the Tropical Oceans. Published by RMS, James Glaisher House, Grenville Place, Bracknell, Berkshire, RG 12 1BX, D. B. Shaw, ed., 155-218.

Gray, W. M., 1984a: Atlantic seasonal hurricane frequency: Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Monthly Weather Review*, **112**, 1649-1668.

Gray, W. M., 1984b: Atlantic seasonal hurricane frequency: Part II: Forecasting its variability. *Monthly Weather Review*, **112**, 1669-1683.

Gray, W. M., 1990: Strong association between West African rainfall and U.S. landfalling intense hurricanes. *Science*, **249**, 1251-1256.

Gray, W. M., 1993: Atlantic conveyor belt alterations as a possible cause of multi-decadal global surface temperature change. Preprints, Fourth Conference on Global Change Studies, Anaheim, CA, January.

Gray, W. M. and C. W. Landsea, 1991: Predicting US hurricane spawned destruction from West African rainfall. Paper given at 13th Annual Hurricane Conference, Miami, FL, April 3-5, 40 pp. (Available from Dept. of Atmospheric Science, Colo. State Univ., Ft. Collins, CO, 80523).

Gray, W. M. and C. W. Landsea, 1993: West African rainfall and Atlantic basin intense hurricane activity as proxy signals for Atlantic conveyor belt circulation strength. Preprints, Fourth Conference on Global Change Studies, Anaheim, CA, January.

Gray, W. M., C. W. Landsea, P. Mielke and K. Berry, 1993: Predicting Atlantic basin seasonal tropical cyclone activity by 1 August. *Weather and Forecasting*, **8**, 73-86.

Gray, W. M., C. W. Landsea, P. Mielke and K. Berry, 1994: Predicting Atlantic basin seasonal tropical cyclone activity by 1 June. *Weather and Forecasting*, **9**, 103-115.

Gray, W. and J. Sheaffer, 1991: El Niño and QBO influences on tropical cyclone activity. Chapter 8 in *Teleconnections Linking World Wide Climate Anomalies*, Cambridge University Press, M. Glantz, R. Katz and N. Nicholls, eds.

Hastenrath, S., 1990: Decadal-scale changes of the circulation in the tropical Atlantic sector associated with Sahel drought. *Introduction to the Journal of Climate*, **10**, 459-472.

Hsiung, J. and R. E. Newell, 1986: Factors controlling free air and ocean temperature of the last 30 years and extrapolation to the past. In Abrupt Climate Change, W. H. Berger and L. D. Labeyrie (Eds.), D. Redel Co., 67-87.

Huang R., 1994: Thermocline circulation: Energetics and variability in a single basin model. *Journal of Geophysical Research*, **99**, 12471-12485.

Hurrell, J., 1995: Decadal trends in the North Atlantic oscillation and regional temperature and precipitation. *Science*, 269. 676-679.

Kay, P.A. and H.F. Diaz, 1985: Problems and prospects for predicting Great Salt Lake levels. Kay and Diaz, Eds. (Center for Public Affairs Administration, University of Utah, Salt Lake City, UT, pp 67-91)

Knox, J. L., K. Higuchi, A. Shabbar and N. Sargant, 1988: Secular variation of northern hemisphere 50 kPa geopotential height. *Journal of Climate*, **1**, 500-511.

Kushnir, Y., 1994: Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions. *Journal of Climate*, **7**, 141-157.

Landsea, C. W., 1991: West African monsoonal rainfall and intense hurricane associations. Dept. of Atmos. Sci. Paper No. 484, Colo. State Univ., Ft. Collins, CO, 80523, 280 pp.

Landsea, C. W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Monthly Weather Review*, **121**, 1703-1713.

Landsea, C. W. and W. M. Gray, 1992: Associations of Sahel monsoon rainfall and concurrent intense Atlantic hurricanes. In press *Journal of Climate*, 5, 37 pp.

Landsea, C. W., W. M. Gray, P. W. Mielke, Jr. and K. J. Berry, 1992: Multidecadal variations of Sahel monsoon rainfall and U.S. landfalling intense hurricanes. *Journal of Climate*, ***5***, *1528-1534.*

Landsea, C. W., W. M. Gray, P. W. Mielke, Jr. and K. J. Berry, 1994: Seasonal forecasting of Atlantic hurricane activity. *Weather*, **49**, 273-284.

Lazier, J. N. R.,1980: Oceanographic conditions of weather ship Bravo, 1964-1974. *Atmosphere-Ocean*, **18**, 227-238.

Manabe, S. and R. Stouffer, 1988: Two stable equilibria of a coupled ocean-atmosphere model. *Journal of Climate*, **1**, 841-866.

Manchard, D., M. Sanderson, D. Howe and A. Alpagh, 1988: Climatic change and Great Lakes levels: the impact on shipping. *Climatic Change*, **12**, 107-133.

McKenzie, J. A. and G. P. Eberli, 1987: Indications for abrupt Holocene climatic change: Late Holocene oxygen isotope stratigraphy of the Great Salt Lake, in *Abrupt Climatic Change* (127-136), H. Berger and D. Labeyrie (Eds.), D. Reidel Publishing Comp.

Michaelsen, J. and L.G. Thompson, 1992: A comparison of proxy records of El Niño/ Southern oscillation. Chapter 17 in El Niño, Historical and Paleoclimatic Aspects of the Southern Oscillation. Cambridge University Press. H. F. Diaz and V. Markgraf editors.

Moses, T., G. Kiladis, H. F. Diaz and R. G. Barry, 1987: Characteristics and frequency of reversals in mean sea level pressure in the North Atlantic sector and their relationship to long-term temperature trends. *Journal of Climate*, **7**, 13-30.

Mysak, L. A., D. K. Manak and R. F. Marsden, 1990: Sea-ice anomalies observed in the Greenland and Labrador Seas during 1901-1984 and their relation to an interdecadal Arctic climate cycle. *Climate Dynamics*, **5**, 111-133.

Namias, J., X. Yuan, and D. Cayan, 1988: Persistence of North Pacific SST and atmospheric flow anomalies. Journal of Climate, **1**, 682-703.

Nunez, R. H., J. O'Brien and J. Shriver, 1992: The effects of El Niño rainfall or Chile (1964-1990). Paper submitted to *International Journal of Climatology*. Nicholson, S. E., 1989: African drought characteristics, causal theories and global teleconnections. *Geophysical Monographs*, **52**, 79-100.

Nitta, T. and S. Yamada, 1989: Recent warming of tropical sea surface temperature and its relationship to the Northern Hemisphere circulation. *Journal Meteorological Society of Japan*, **67**, 375-383.

OUCT (Open University Course Team), 1989: Ocean circulation. Pergamon Press, Oxford.

Parthasarathy, B., A. Rupakumar and A. A. Munot, 1991: Evidence of secular variations in Indian monsoon rainfall-circulation relationships. *Journal of Climate*, **4**, 927-938.

Ramage, C., 1983: Teleconnections and the siege of time. *Journal of Climatology*, **3**, 223-231.

Reid, G. C. and K. S. Gage, 1993: Troposphere-stratosphere coupling in the tropics: the role of El Niño and the QBO. Proceedings of NATO advanced study institute on the role of the stratosphere in global change. Canquivannc, France, September, 1992.

Saffir, H. S., 1977: Design and construction requirements for hurricane resistant construction. American Society of Civil Engineers, New York, Preprint Number 2830, 20 pp.

Schmitz, W.J., 1995: On the interbasin -scale thermohaline circulation. *Reviews of Geophysics*, **33**, 151-173.

Schmitz, W. and M. S. McCartney, 1993: On the North Atlantic circulation. *Reviews of Geophysics*, **31**, 29-49.

Serreze, M. C., J. A. Maslanik, R. G. Barry and T. D. DeMaria, 1992: Winter atmospheric circulation in the arctic basin and possible relationships to the great salinity anomaly in the Northern North Atlantic. *Geophysical Research Letters*, **19**, 293-296.

Shabbar, A., K. Higuchi and J. Knox, 1990: Regional analysis of 50KPa geopotential heights from 1946 to 1985. *Journal of Climate*, **3**, 543-557.

Sheaffer, J. D. and W. M. Gray, 1995: Tendency for strong warming of the equatorial lower stratosphere prior to strong El Niños. In revision for *Journal of Geophysical Research*.

Sheaffer, J. D., 1993: Decadal scale trends in Pacific-Western North America teleconnections and implications for seasonal predictability of anomalous precipitation. Preprints, Fourth Conference on Global Change Studies, Anaheim, CA, January 17-22.

Sheaffer, J. D. and E. R. Reiter, 1985: Influence of Pacific sea surface temperatures and seasonal precipitation over the western plateau of the United States. *Archive of Meteorological and Geophysical Bioclimate*, Ser. **A34**, 111-130.

Shinoda, M. and R. Kawamura, 1994: Tropical rainbelt, circulation and sea surface temperatures associated with the Sahelian rainfall trend. *Journal of the Meteorological Society of Japan*, **72**, 341-357.

Simpson, R. H., 1974: The hurricane disaster potential scale. *Weatherwise*, 27, 169-186. Stommel, H., 1957: A survey of ocean current theory. *Deep Sea Research*, **4**, 149-184.

Street-Perutt, F.A. and R.A. Perrott, 1990: Abrupt climate fluctuations in the tropics: the influence of the Atlantic Ocean circulation. *Nature*, **343**, 607-611.

Toggweiler, 1994: The oceans overturning circulation. *Physics Today*, 47, 45-50. Trenberth, K. E., 1990: Recent observed interdecadal climate changes in the Northern Hemisphere. *Bulletin American*

Meteorological Society, **71**, 988-993.

Trenberth, K. E., 1994: The different flavors of El Niño. Proceedings of the 18th Annual Climate Diagnostics Workshop, Nov 1-5, 1993, Boulder, CO. Walker, G. T. and E. W. Bliss, 1937: World Weather. VI. *Memoirs Royal Meteorological Society*, **4**, 119-139.

Walsh, J. E. and W. L. Chapman, 1990: Arctic contribution to upper-ocean variability in the North Atlantic. *Journal of Climate*, **3**, 1462-1473.

Weaver, A., S. Aura and P. Myers, 1994: Interdecadal variability in an idealized model of the North Atlantic. *Journal of Geophysical Research*, **99**, 12423-12441.

Weisse, R., U. Mikolajewicz and E. Maier-Reimer, 1994: Decadal variability of the North Atlantic in an ocean general circulation model. *Journal of Geophysical Research*, **99**, 1241-1242.

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