ATLANTIC BASIN HURRICANES: INDICES OF CLIMATIC CHANGES

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Abstract. Accurate records of basinwide Atlantic and U.S. landfalling hurricanes extend back to the mid 1940s and the turn of the century, respectively, as a result of aircraft reconnaissance and instrumented weather stations along the U.S. coasts. Such long–term records are not exceeded elsewhere in the tropics. The Atlantic hurricanes, U.S. landfalling hurricanes and U.S. normalized damage time series are examined for interannual trends and multidecadal variability. It is found that only weak linear trends can be ascribed to the hurricane activity and that multidecadal variability is more characteristic of the region. Various environmental factors including Caribbean sea level pressures and 200mb zonal winds, the stratospheric Quasi–Biennial Oscillation, the El Niño–Southern Oscillation, African West Sahel rainfall and Atlantic sea surface temperatures, are analyzed for interannual links to the Atlantic hurricane activity. All show significant, concurrent relationships to the frequency, intensity and duration of Atlantic hurricanes. Additionally, variations in the El Niño–Southern Oscillation are significantly linked to changes in U.S. tropical cyclone–caused damages. Finally, much of the multidecadal hurricane activity can be linked to the Atlantic Multidecadal Mode – an empirical orthogonal function pattern derived from a global sea surface temperature record. Such linkages may allow for prediction of Atlantic hurricane activity on a multidecadal basis. These results are placed into the context of climate change and natural hazards policy.

1. Introduction

The United Nation's Intergovernmental Panel on Climate Change (IPCC) has speculated that climate change due to increasing amounts of anthropogenic "greenhouse" gases may result in increased tropical sea surface temperatures (SSTs) and increased tropical rainfall associated with a slightly stronger intertropical convergence zone (ITCZ) (Houghton et al., 1990, 1992, 1996). Because tropical cyclones extract latent and sensible heat from the warm tropical oceans and release the heat in its upper tropospheric outflow to fuel

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the storm's spin up, early work of the IPCC expressed concern that warmer SSTs will lead to more frequent and intense hurricanes, typhoons and severe tropical cyclones. These concerns prompted the IPCC (Houghton et al. 1990) to suggest in 1990 that:

> There is some evidence from model simulations and empirical considerations that the frequency per year, intensity and area of occurrence of tropical disturbances may increase [in a doubled carbon dioxide world], though it is not yet compelling.

However, any changes in tropical cyclone activity are intrinsically also tied to large–scale changes in the tropical atmosphere. As a result, SSTs by themselves cannot be considered without corresponding information regarding the moisture and stability in the tropical troposphere. What has been identified in the current climate as being necessary for genesis and maintenance for tropical cyclones (e.g. SSTs of at least 26.5°C – Gray 1968) would change in an enhanced CO_2 world because of possible changes in the moisture or stability. It is quite reasonable that an increase in tropical and subtropical SSTs would be also accompanied by an increase in the SST threshold value needed for cyclogenesis because of compensating changes in the tropospheric moist static stability (Emanuel 1995).

In addition to the thermodynamic variables, changes in the tropical dynamics also play a large role in determining changes in tropical cyclone activity. For example, if the vertical wind shear over the tropical North Atlantic moderately increased during the hurricane season in an increased CO_2 world – as what is typically seen during El Niño–Southern Oscillation warm phases (El Niño events), then we would most likely see a significant decrease in tropical cyclone activity. This is due to the Atlantic basin having a marginal climatology for tropical cyclone activity because of its sensitivity to changes in vertical wind shear and lack of an oceanic monsoon trough (Gray et al. 1993). In other less marginal tropical cyclone basins, changes in the vertical shear profile typically result in alterations in the preferred location of development (e.g. Nicholls 1979, Chan 1985, Revell and Goulter 1986, and Lander 1994).

These complications along with conflicting global circulation modeling (GCM) runs compelled the 1995 IPCC (Houghton et al. 1996) to express greater uncertainty about the nature of tropical cyclones in an enhanced CO_2 environment:

> The formation of tropical cyclones depends not only on sea surface temperature (SST), but also on a number of atmospheric factors. Although some models now represent tropical storms with some realism for present day climate, the state of the science does not allow assessment of future changes.

Most recently, Henderson–Sellers et al. (1998) addressed a few of the tropical cyclone–greenhouse warming problems. The first is that "there is no evidence to suggest any major changes in the area or global location of tropical cyclone genesis in greenhouse conditions." This conclusion is based upon Holland's (1997) thermodynamic tropical cyclone model which does show that in a greenhouse–warmed climate there is an upward alteration in the minimum SST from 26.5 to 28°C needed for tropical cyclogenesis. The additional conclusion from Henderson–Sellers et al. (1998) suggests "an increase in [maximum potential intensity] MPI of 10%–20% [in central pressure or 5%–10% in maximum sustained winds] for a doubled CO_2 climate but the known omissions (ocean spray, momentum restriction, and possibly also surface to 300 hPa lapse rate changes) all act to reduce these increases." This second finding is also based upon the thermodynamic models of Emanuel (1986) and Holland (1997), which also appears to corroborate similar findings for Northwest Pacific typhoons from a "downscaled" GCM to mesoscale model approach by Knutson et al. (1998). Henderson–Sellers et al. (1998) do not provide guidance for possible changes in tropical cyclone frequency, mean intensity, or area of occurrence.

Because of the enormous impacts that tropical cyclones have today (e.g. in 1995 total mainland U.S. hurricane damages averaged the order of $5 billion annually – Pielke and Landsea 1998), it is essential that detailed studies be made of observed tropical cyclone activity. An understanding of such activity plays an important role in both public and private policy decisions. Additionally, tropical cyclone activity has rather large interannual and interdecadal variations which are extremely important for their own sake and which could turn out to have a greater impact relative to changes forced by greenhouse warming, as suggested by Lighthill et al. (1994). A reliable assessment of what the future holds for tropical cyclone activity would also have significant policy utility.

This paper documents the long–term variations in tropical cyclone activity of the Atlantic basin (e.g. the North Atlantic Ocean, the Gulf of Mexico and the Caribbean Sea) from instrumental records and corresponding climatic fluctuations responsible for variability, on annual and longer timescales. Section II provides definitions of various tropical cyclone indices and acknowledges the datasets utilized. Section III reviews previous work on the physical mechanisms of interannual through multidecadal timescales that influence tropical cyclones in the Atlantic basin. Section IV analyzes indices of Atlantic basin tropical cyclone activity for both all–basin and landfalling cyclones and their quantitative relationship to various climatic forcing. Section V is a discussion of Atlantic hurricanes as measured through these indices and their relevance to policy issues. The final section summarizes and discusses our key findings.

2. Tropical Cyclone Definitions and Datasets

"Tropical cyclone" is the generic term for a non–frontal, synoptic scale, "warm–core" low-pressure system that develops over tropical or sub–tropical waters with organized convection and a well–defined closed cyclonic surface wind circulation. It derives its energy primarily from latent and sensible heat flux from the ocean which is enhanced by strong winds and lowered surface pressure. These energy sources are tapped through condensation in convective clouds concentrated near the cyclone's center (Holland 1993).

The tropical cyclone designation is a broad term under which various strength systems in the Atlantic basin are divided into:

- **Tropical Storm:** Maximum sustained (1 min mean) surface (10 m) wind speed 18 to 32 m s^{-1}
- **Hurricane:** Wind speed at least 33 m s^{-1}
- **Intense (or Major) Hurricane**: Wind speed at least 50 m s^{-1}. These are the category 3, 4 or 5 hurricanes on the Saffir–Simpson (Simpson 1974) Hurricane Scale (Table I)

The Atlantic basin is usually active during the months of June through November, comprising the traditional "hurricane season" (Neumann et al. 1993). However, the large majority of intense hurricanes occur in just the three months of August, September and October (Landsea 1993).

Tropical storms and hurricanes here are collectively referred to as **named storms** [in deference to the fact that since 1950 all tropical cyclones that were of at least tropical storm force were given a name for identification (Neumann et al., 1993), although some cyclones were determined to be of tropical storm strength after the fact and thus lack a formal name].

When considering the variations in named storms, subtropical storms are also to be included in such analyses. **Subtropical storms** are non–frontal low pressure systems comprising initially baroclinic circulations developing over subtropical waters with sustained one minute surface winds of at least 18 ms^{-1} (National Oceanic and Atmospheric Administration 1997). Such nomenclature has been utilized since 1968, though it is likely that these systems were designated and included in the database as tropical storms previously. Thus, failure to include the subtropical storms into the climate record examined would introduce an artificial bias into the database (Neumann et al. 1993).

Subsets of these tropical cyclone designations are also useful. For example, Gray (1968) showed distinctly differing environmental conditions for tropical cyclogenesis in subtropical latitudes versus those forming closer to the equator. Ideally, we would wish to stratify Atlantic tropical cyclones

Table I. Maximum sustained wind speed, minimum surface pressure, storm surge, and general damaging effects for the five Saffir–Simpson (Simpson 1974) Hurricane Scale values. The last column provides a relative value for median of normalized U.S. hurricane damages per category. A Category 1 hurricane – scaled a "1" in the table – had a median damage of $33 million (Pielke and Landsea 1998). Note how in the table the median damages go up enormously with increasing category of hurricane.

Saffir–Simpson Category	Maximum Sustained Wind Speed (m s^{-1})	Minimum Surface Pressure (mb)	Storm Surge (m)	Relative Value and Damaging Effects
1	33 to 42	≥ 980	1.0 to 1.7	1 – Minimal
2	43 to 49	979 to 965	1.8 to 2.6	10 – Moderate
3	50 to 58	964 to 945	2.7 to 3.8	50 – Extensive
4	59 to 69	944 to 920	3.9 to 5.6	250 – Extreme
5	> 69	< 920	> 5.6	500 – Catastrophic

into those forming from easterly waves and developing without impacts by middle and upper tropospheric troughs versus those with some baroclinic component, as is done in Hess et al. (1995). However, such categorization is extremely subjective and may not be reliable as even today debates occur as to the influence that upper lows play in tropical cyclone development. This uncertainty is due both to the paucity of over–ocean data and to the incompleteness of intensification theories (e.g., Elsberry et al. 1992). As an alternative that is not as physically based, but more defensible is to stratify the named/subtropical storms time series into those forming poleward (**northern named/subtropical storms**) and equatorward (**southern named/subtropical storms**) of 23.5°N.

Additionally, of significant societal concern is the number of hurricanes which affect the people of the Caribbean. Reading (1989) and Gray (1990) showed that there are substantial interdecadal variations on the number of hurricanes striking this region. Thus a time series of **Caribbean hurricanes** is constructed and analyzed based upon the presence of hurricanes within the the Caribbean Sea and hurricanes directly affecting the land masses which surround the Caribbean (e.g. Central America [including the eastern Yucatan coast of Mexico], Cuba, Jamaica, Hispaniola, Puerto Rico, the Lesser Antilles, northern Venezuela and northern Colombia).

One objective method for determining the seasonal amount of tropical cyclone activity is through the summed duration of each storm. This partially removes the subjectivity involved in categorizing the intensity of tropical cyclones. A seasonal total of **hurricane days** is the amount of days in which a hurricane existed (two hurricanes existing simultaneously for 24 hours count as two days). The computations count days in six hour increments.

In addition to these indices, two additional time series were created: the **peak intensity** – the strongest sustained winds reached by the strongest hurricane each hurricane season – and **mean intensity** – the average of the strongest winds for all of the named and subtropical storms for a season. These indices are independent of frequency variations and only measure changes in intensity.

While records are available for the entire Atlantic basin for hurricanes back to the late 1800s (Jarvinen et al. 1984) and for landfalling hurricanes along the United States coastline back to the 16th Century (Ludlum 1989), reliably knowing the intensity of such systems extends for a much briefer period of time. For the whole Atlantic basin, reliable intensity measures exist back to the commencement of routine aircraft reconnaissance in 1944 (Neumann et al. 1993), but even these data have been arbitrarily corrected to remove an overestimation bias in the winds of intense hurricanes during the 1940s through the 1960s (Landsea 1993). The winds of strong hurricanes from 1944 through 1969 have been reduced 2.5–5 m s^{-1} as a first order bias removal[1]. No estimate of the true occurrence of all–basin intense hurricanes is attempted for the era before the mid 1940s because of the lack of reliable data on the strong inner core of the hurricanes except for very infrequent measurements conducted by unfortunate ships' crews. Thus 1944 marks the beginning of all of the all–basin time series analyzed here.

For U.S. landfalling hurricanes, observations of minimum central pressure provide accurate records back to 1899 for nearly all hurricanes (Jarrell et al. 1992). Before this year, records of intensity at landfall are incomplete and can only provide rough estimates of a hurricanes' strength. Thus 1899 is the first year utilized for U.S. landfalling hurricane data.

Lastly for tropical cyclone–related datasets, Pielke and Landsea (1998) have developed a normalized mainland U.S. hurricane damage time series that takes into account inflationary, coastal county population and wealth changes. This index, independent of tropical cyclone data itself, extends from 1925 through 1996 and is an estimate of how much damage would be caused if landfalling cyclones of the past struck in 1996.

All Atlantic tropical cyclone records are presented with respect to a long–term average (1950–1990) to allow for consistent comparisons amongst indices despite differences in length of record.

A variety of environmental parameters such as Atlantic and Pacific SST, African rainfall, sea level pressures, 200 mb zonal winds and 50 mb stratospheric winds are compared with the preceding tropical cyclone records. The

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[1] This is only a temporary solution, however. What is needed is a "reanalysis" of all available data – primarily aircraft reconnaissance – with today's analysis techniques to create an updated data set. Such efforts are currently underway (Neumann and McAdie 1997).

SST data sets are those of the 1856–1991 reconstruction of historical ship-based data of Kaplan et al. (1998). SST data from the optimally interpolated product of Reynolds and Smith (1994) for the years from 1992 to 1996 are appended to the Kaplan dataset. Box averages as well as cubic splines were used to interpolate the 1.0° Reynolds and Smith data to the Kaplan 5.0° grid. The Reynolds and Smith SST anomalies were calculated using the Kaplan as well as the Reynolds and Smith SST climatology. The smaller root mean squared difference between the two globally averaged SST anomaly time series for the common period (November 1981 to December 1991) was obtained when the Reynolds and Smith SST anomalies were calculated using the the Reynolds and Smith SST climatology. Both interpolation methods gave very similar results and we decided to utilize the cubic splines for this analysis. The El Niño–Southern Oscillation (ENSO) is represented by SSTs during August–October (ASO) in the region 5°N – 5°S and 120–170°W (the "Niño 3.4" index) as suggested by Barnston et al. (1997) as having the strongest concurrent link to Atlantic hurricanes. After Saunders and Harris (1997), we utilize ASO tropical North Atlantic SST anomalies for the region 5–25°N and 15–55°W to examine local SST effects on Atlantic hurricane activity.

To analyze the relationship of tropical cyclones with Atlantic SST anomalies in a way that is independent of the separately analyzed ENSO relationship, it is convenient to first account for and remove the teleconnected effects of ENSO on the Atlantic Ocean. Enfield and Mestas-Nuñez (1998) have done this by computing global SST anomaly modes after first extracting the global ENSO variability represented by a complex empirical orthogonal function (EOF) mode. An EOF analysis is a multivariate statistical technique that gives the most efficient representation of the variability in a data set. The main advantage of EOF analysis is that it generally allows one to capture most of the variance in the data in the first few modes. However, it is important to note that the EOFs do not necessarily represent physical modes. Each mode is comprised of a spatial pattern and an associated time series. Enfield and Mestas-Nuñez' third non–ENSO mode represents interannual to multidecadal SST variability, primarily in the Atlantic, with the multidecadal component being strongest.

The African rainfall dataset is a five station index of June–September (JJAS) 1899 through 1996 rainfall for the Western Sahel region, updated from that reported in Landsea et al. (1992). A Caribbean/Gulf of Mexico eleven station sea level pressure index was developed using the same stations and methodology as Knaff (1997) but for ASO 1950 through 1996 from the original dataset of Vose et al. (1992). For an index of Caribbean 200 mb zonal winds, data from Shea et al. (1994) for twelve stations (Table II) were compiled for the August–October 1950 through 1996 time period. ASO Caribbean 50 mb stratospheric winds were provided from the dataset collected and updated at Colorado State University (Gray 1984a, Gray et al. 1992a) for the years 1950 through 1996.

Table II. Summary of the twelve upper-air stations used for the August through October index of 200 mb zonal winds for the Caribbean. Listed along with the World Meteorological Organization (WMO) number is the station name and coordinates.

WMO number	Station	Latitude	Longitiude
76644	Merida, Mexico	21.0°N	89.5°W
78367	Guantanamo, Cuba	19.9°N	75.2°W
78384	Roberts Field, Grand Cayman	19.3°N	81.3°W
78397	Kingston, Jamaica	17.9°N	76.8°W
78501	Swan Island	17.4°N	83.9°W
78526	San Juan, Puerto Rico	18.4°N	66.0°W
78806	Balboa, Canal Zone	8.8°N	79.6°W
78866	St. Martin	18.1°N	63.1°W
78954	Seawell, Barbados	13.1°N	59.5°W
78970	Piarco, Trinidad	10.6°N	61.4°W
78988	Curacao	12.2°N	69.0°W
80001	San Andres Island, Columbia	12.6°N	81.7°W

3. Climatic Forcing of Atlantic Tropical Cyclones

Understanding tropical cyclone variability on interannual to interdecadal timescales is hampered by the relatively short period over which accurate records are available. Figure 1 presents the various observational platforms available for analyzing tropical cyclone occurrences in the Atlantic basin. Changes in the tropical cyclone databases due to observational platform improvements (and sometime degradations) can often be mistaken as true variations in tropical cyclone activity. Thus caution is urged in interpretations of quantitative tropical cyclone indices. For studies of climatic changes it is strongly suggested that one not utilize incomplete data collected prior to the dates indicated in the previous section. With these caveats in mind, some studies have had successes in the fields of interannual and longer time scales for Atlantic hurricanes, some of which are detailed below.

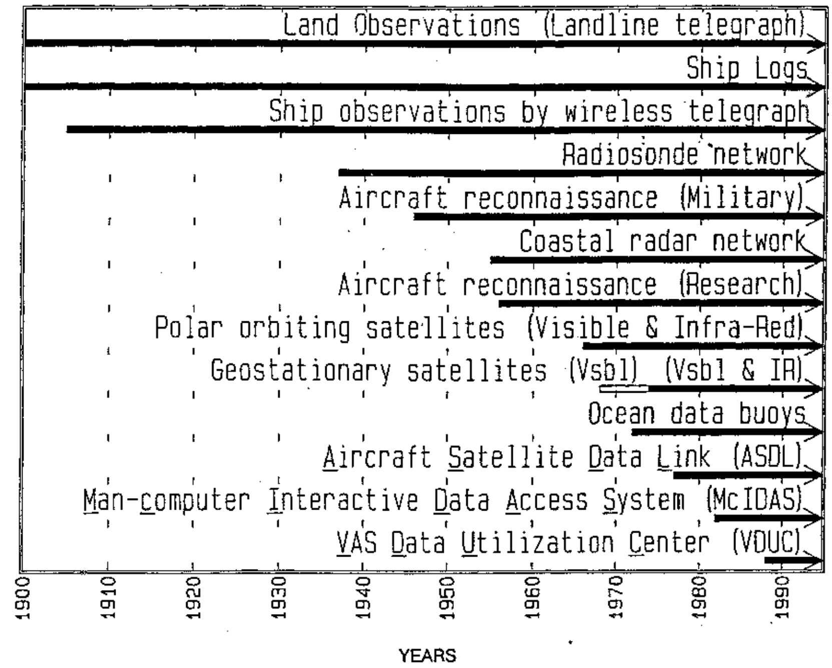

Figure 1. Technical advances in systems for observing tropical cyclones in the Atlantic basin, 1900 through the mid 1990s – from Neumann et al. (1993).

3.1. INTERANNUAL CHANGES

Globally, tropical cyclones are affected dramatically by the El Niño–Southern Oscillation (ENSO). ENSO is a fluctuation on the scale of a few years in the ocean–atmospheric system involving large changes in the Walker and Hadley Cells throughout the tropical Pacific Ocean region (Philander 1989). The state of ENSO can be characterized, among other features, by the SST anomalies in the eastern/central equatorial Pacific: warmings in this region are referred to as El Niño events and coolings as La Niña events. During El Niño events when convective activity in the equatorial Pacific is shifted to the east, the tropospheric vertical shear increases due to a pickup of the climatological westerly winds in the upper troposphere, primarily from 10 to 20°N between Africa and the Americas (hereby known as the "main development region" after Goldenberg and Shapiro 1996). In contrast, reduced 200mb westerlies and shear have been observed during La Niña events (Gray 1984a, Shapiro 1987, Goldenberg and Shapiro 1996). Strong vertical wind shear disrupts the incipient tropical cyclone and can prevent genesis, or, if a tropical cyclone has already formed, strong vertical shear can weaken or destroy the tropical cyclone by interfering with the organization of deep convection around the cyclone center (DeMaria 1996). Thus the larger (smaller) vertical shear accompanying El Niño (La Niña) events lead directly toward decreased (increased) numbers of Atlantic hurricanes. Gray (1984a) demonstrated that the United States is more at risk during non–El Niño years: a 3–to–1 difference in the frequency of landfalling intense hurricanes.

In addition to ENSO, the Atlantic basin shows systematic alterations of tropical cyclone frequency by the stratospheric Quasi-Biennial Oscillation (QBO – Gray 1984a, Shapiro 1989), an east–west oscillation of stratospheric winds that encircle the globe near the equator (Wallace 1973). Atlantic hurricane activity is enhanced during the west phase of the QBO and diminished in the east QBO years. This relationship may be due to alterations in the static stability and dynamics near the tropopause (Gray et al. 1992b, Knaff 1993).

Interannual variations in the Atlantic basin tropical cyclones have also been linked to more localized, basin–specific features such as sea level pressures, local SSTs and West African rainfall. Additional environmental factors may also be important for interannual Atlantic tropical cyclone variability – such as low level moisture availability (Landsea et al. 1998), tropospheric moist static stability (Pasch et al. 1998), and lower tropospheric jet characteristics (Molinari et al. 1997). An examination of these environmental forcings should be considered in future analyses.

Sea level pressures (SLPs) act to directly impact the strength of the vertical wind shear. In the Atlantic basin because of a relatively invariant sea level pressure field near the equator, above (below) average SLP in the main development region tightens (loosens) the local pressure gradient and strengthens (weakens) the easterly tradewinds by 1 to 3 m s^{-1}, thereby contributing to increased (decreased) vertical shear (Gray et al. 1993, 1994). Additionally, Gray et al. (1993) have suggested that below average SLP indicates a poleward shift and/or a strengthening of the ITCZ. Both situations contribute to less subsidence and drying in the main development region through which easterly waves move. Knaff (1997) indicates that low SLP is accompanied by a deeper boundary layer, a weakened tradewind inversion, a more moist middle troposphere, and weaker 200mb westerly winds (and vertical shear). Moreover, an enhanced ITCZ provides more large–scale, low level cyclonic vorticity to incipient tropical cyclones, thereby creating an environment that is more conducive for tropical cyclogenesis (Gray 1968). In contrast, above average SLP tends to be associated with opposite conditions which are unfavorable for tropical cyclogenesis.

Sea surface temperatures in the genesis regions of tropical cyclone basins have a direct thermodynamic effect on tropical cyclones through their influence on moist static stability (Malkus and Riehl 1960). SSTs also indirectly alter the vertical shear through a strong inverse relationship with surface pressures (Shapiro 1982, Gray 1984b). In particular for the Atlantic basin, warmer than average waters are usually accompanied by lower than average surface pressures, and thus, weaker tradewinds and reduced shear.

Cooler than average waters are usually accompanied by higher pressure, stronger tradewinds and increased shear (Knaff 1997). Somewhat surprisingly, interannual SST variations have relatively small contributions toward altering the total named storm frequency in the Atlantic basin (Raper 1992, Shapiro and Goldenberg 1998). However, Saunders and Harris (1997) provide substantial evidence that both preceding and during the hurricane season that Atlantic SSTs in the main development region contribute a large percentage of the variance explained (over 30% during the height of the season) with the number of hurricanes generated in that area. Indeed they argue through a partial correlation analysis that these Atlantic SSTs are the dominant physical modulator of tropical Atlantic hurricanes. The discrepancies between these studies need to be understood.

One aspect of interannual variability that has recently been uncovered is the association of the Atlantic tropical cyclone basin with the monsoon of West Africa. June through September monsoonal rainfall in Africa's Western Sahel has shown a very close association with intense hurricane activity (Reed 1988, Gray 1990, Landsea and Gray 1992, Landsea et al. 1992). Wet years in the Western Sahel (e.g. 1988 and 1989) are accompanied by dramatic increases in the incidence of intense hurricanes, while drought years (e.g. 1990 through 1993) are accompanied by a decrease in intense hurricane activity. Variations in tropospheric vertical shear and African easterly wave intensity have been hypothesized as the physical mechanisms that link the two phenomena (Gray 1990, Landsea and Gray 1992), although Goldenberg and Shapiro (1996) have demonstrated that changes in the vertical shear probably dominate. They note that wet (dry) years are associated with reduced (increased) wind shear, due to both weaker (stronger) than average lower tropospheric tradewinds and upper tropospheric westerlies throughout the main development region.

3.2. INTERDECADAL CHANGES

Gray (1990) and Landsea et al. (1992) described large multidecadal variations in the Atlantic intense hurricanes while the total number of named storms remained more constant from decade to decade. Overall, they found that the late 1920s to the 1960s were very active and 1900s to the mid 1920s as well as the 1970s to the mid 1980s were quiescent. Landsea et al. (1996) showed evidence that the quiet period of the 1970s and 1980s continued through at least the early 1990s.

These multidecadal intense Atlantic hurricane variations are attributed by Gray (1990) to changes in the Atlantic SST structure. Warmer (cooler) than average conditions in the Atlantic north of the equator coupled with cooler (warmer) than average SSTs in the South Atlantic favor increased (decreased) intense hurricane activity. Such a dipole structure of the Atlantic

SSTs also forces drought and wet periods in the North Africa's Western Sahel (e.g. Folland et al. 1986), which at least partially explains why there is a strong concurrent link between the year–to–year Sahel rainfall variations and intense Atlantic hurricanes described in the previous section. The SST dipole pattern appears to alter the overlaying tropospheric circulation such that warm North/cold South Atlantic conditions correspond to reduced vertical wind shear in the main development region favoring the formation and intensification of tropical cyclones (Gray et al. 1997). In contrast, a cool North/warm South Atlantic acts in concert with enhanced tradewind easterlies and upper tropospheric westerlies and thus increased tropospheric vertical wind shear. Additionally, these SST variations likely play a direct role in providing changes of the heat input available to the incipient tropical cyclone by changing the boundary layer moist enthalpy values (Saunders and Harris 1997, Landsea et al. 1998).

It has been hypothesized (Gray et al. 1997) that these multidecadal oceanic temperature, intense hurricane and Sahel rainfall changes are regulated by the strength of the thermohaline circulation and North Atlantic deep water formation – portions of the global “Great Ocean Conveyor” (Broecker 1991). Kushnir's (1994) analysis agrees with Gray et al. in suggesting that the thermohaline circulation is the cause of these multidecadal SST variations. Deser and Blackmon (1993), however, suggest that fresh water flux in the Labrador region alters oceanic deep water production on shorter (about 10 year) periods. Presently, the exact cause of these variations has yet to be confirmed.

4. Indices of Atlantic Basin Hurricanes

4.1. ALL–BASIN ACTIVITY

Examination of the record for the Atlantic numbers of named and subtropical storms shows substantial yearly variability, but no significant trend (Fig. 2). In contrast, the numbers of intense hurricanes (Fig. 3) have gone through pronounced multidecadal changes: active during the late 1940s through the mid 1960s, quiet from the 1970s through the early 1990s, and then a shift again to busy conditions again during the extraordinarily active years 1995 and 1996. The Atlantic hurricanes (Fig. 4) share characteristics of both of the previous time series with only a moderate interdecadal change, but substantial interannual variability. In comparison with hurricane frequency, hurricane days (Fig. 5) show a much more substantial interdecadal variability, indicating that duration of such systems is more sensitive to forcing on these timescales than is the total number of events.

Concurrent with these frequency and duration changes, Figure 6 shows that there have been periods of strong mean intensity of the Atlantic trop-

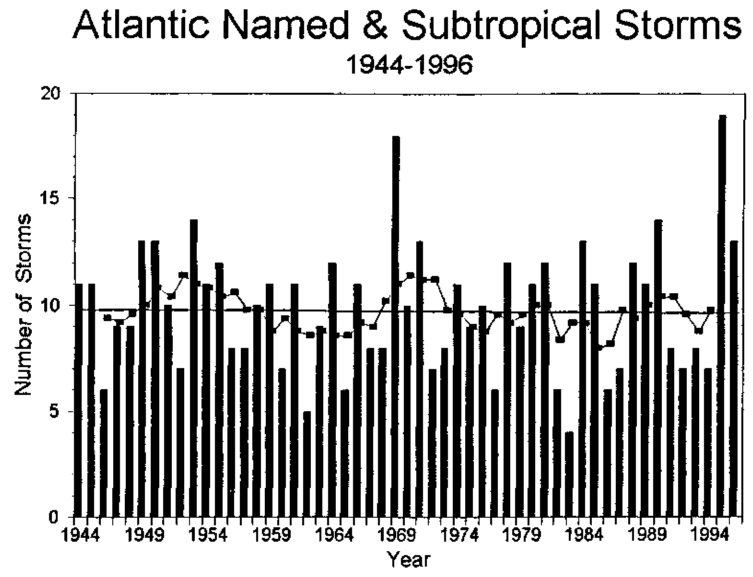

Figure 2. Annual number of named and subtropical storms over the Atlantic basin for the period of reliable record from 1944 to 1996. The long term (1950–90) average of 9.8 per year (solid line) as well as a five year running mean (light curve) are superimposed on the time series.

ical cyclones (mid 1940s–1960s and 1995–1996) and weak mean intensity (1970s–early 1990s). These long–term variations in mean intensity are primarily driven by decreases in the numbers of intense hurricanes (Fig. 3), while the total frequency of named and subtropical storms remains relatively constant (Fig. 2). Perhaps somewhat surprisingly, the time series of peak intensity (Fig. 7) reached by the strongest hurricane each year shows no significant trend or interdecadal fluctuations. However, there is evidence of more interannual variability during the 1970s through the 1990s compared with the more constant period of the 1940s to the 1960s. However, the bias–correction employed for the strong hurricane intensities (e.g. Landsea 1993) may cause an artificial smoothing of the peak intensities in the earlier decades. Thus this change in interannual variability characteristics is suspect. It is hoped that the aforementioned hurricane re–analysis effort will allow this issue to be addressed in more detail in the future.

While the named and subtropical storms have shown no trend or even any substantial multidecadal fluctuations over the last five decades, the same does not hold true when the data are categorized by latitude of formation. Figure 8 shows the annual counts of storms forming north and south of the 23.5°N latitude line. Both generally display multidecadal swings with mirroring variations: high (low) numbers of south (north)–forming storms in

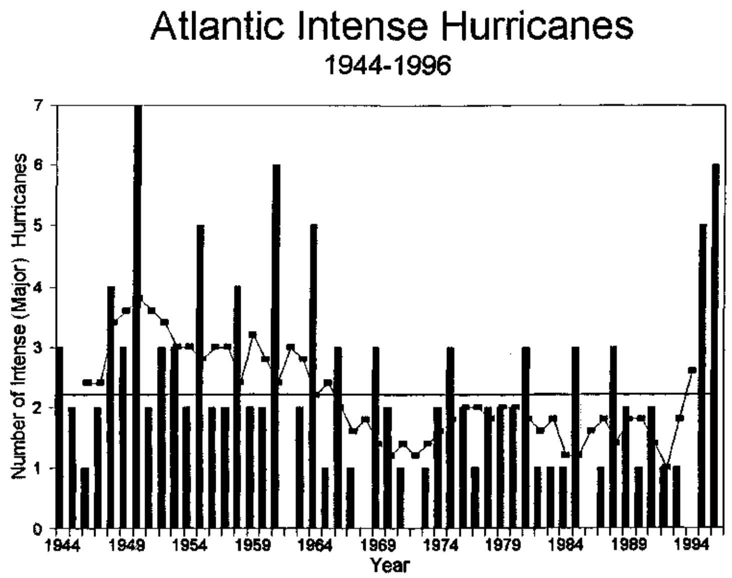

Figure 3. Annual number of intense hurricanes over the Atlantic basin for the period of reliable record from 1944 to 1996. The data for the years 1944–1969 have been revised downward to take into account the overestimation of intensities during these years. See Landsea (1993) for details. The long term (1950–90) average of 2.2 per year (solid line) as well as a five year running mean (light curve) are superimposed on the time series.

the 1940s to the 1960s and a switch to reduced (increased) values during the 1970s through the early 1990s. The southern tropical/subtropical storms match the fluctuations of the intense hurricanes, while the northern forming tropical/subtropical storms are the only class of Atlantic tropical cyclones that appears to have been at higher than usual levels during the 1970s through the early 1990s.

Little can be said of quantitative value for the all–basin tropical cyclone activity before the mid 1940s because of lack of observational networks over the open ocean. However, Fernández–Partagás and Diaz (1996) estimate that the overall Atlantic tropical storm and hurricane activity for the years 1851–1890 was 12% lower than the corresponding forty year period of 1951–1990, though nothing can be said regarding the intense hurricanes. They base this assessment upon a constant ratio of U.S. landfalling tropical cyclones to all–basin activity, which is likely a valid assumption for the multidecadal timescale even though it does not hold for year to year variations. This also assumes that Fernández–Partagás and Diaz were able to uncover all U.S. landfalling tropical cyclones back to 1851, which may be a somewhat less valid contingency.

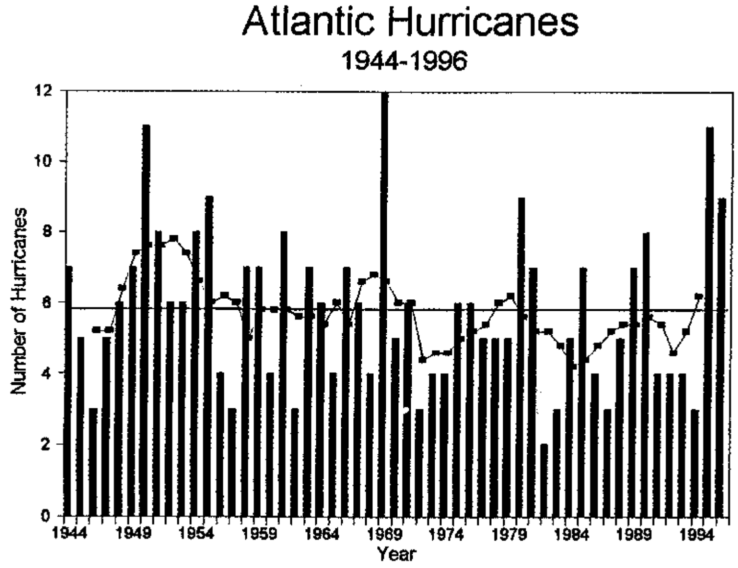

Figure 4. Annual number of hurricanes over Atlantic basin for the period of reliable record from 1944 to 1996. The long term (1950–90) average of 5.8 per year (solid line) as well as a five year running mean (light curve) are superimposed on the time series.

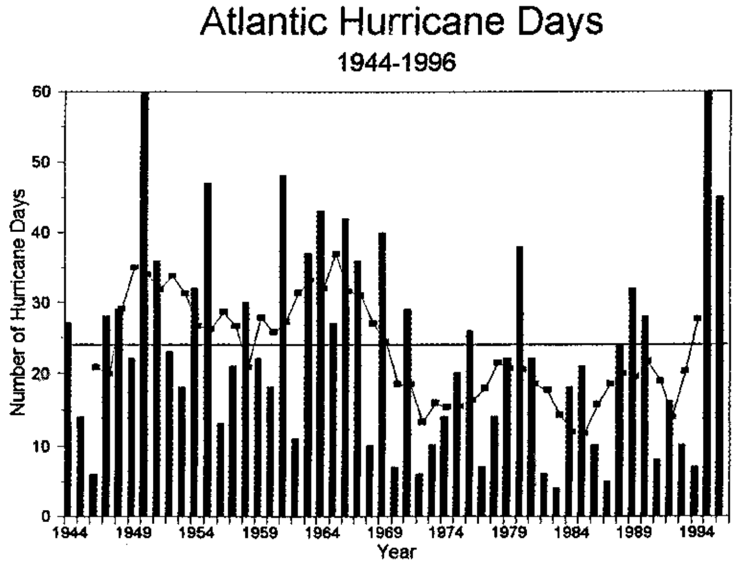

Figure 5. Annual number of hurricanes days over Atlantic basin for the period of reliable record from 1944 to 1996. The long term (1950–90) average of 23.7 days per year (solid line) as well as a five year running mean (light curve) are superimposed on the time series.

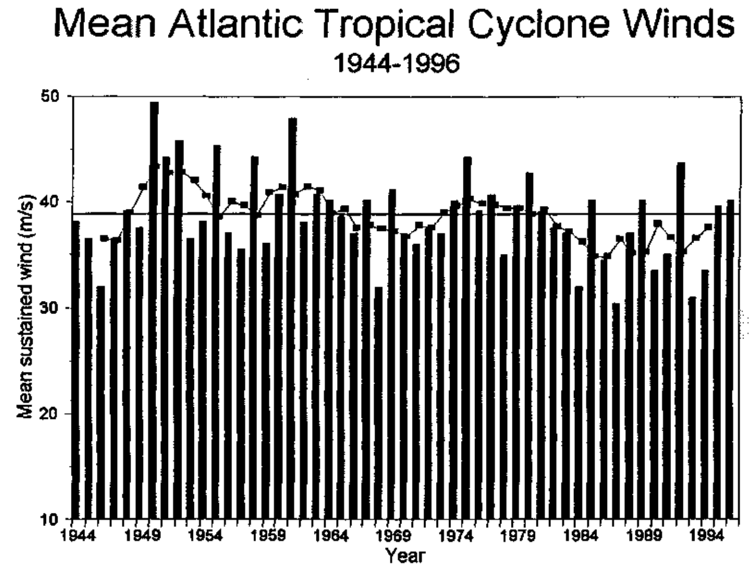

Figure 6. Time series of the Atlantic basin mean intensity – average of the highest sustained surface winds achieved by all of the storms for each year – for the period of reliable record from 1944 to 1996. The long term (1950–90) average of 39.0 ms^{-1} (solid line) as well as a five year running mean (light curve) are superimposed on the time series.

Most of these figures appear to emphasize the dominance of interdecadal fluctuations rather than linear trends, especially for the stronger tropical cyclone records. However, knowing what linear trends – if any – are contained in the data can also be a useful quantity. Table III presents the temporal correlations and the resulting regression coefficients. Note that only five tropical cyclone indices show statistically significant trends: intense hurricanes, hurricane days, mean intensity, and north–forming named and subtropical storms, and Caribbean hurricanes. All of these parameters, except for the north–forming named and subtropical storms, show significant trends toward **less** activity in recent decades.

4.2. LANDFALLING HURRICANES

The dominance of large multidecadal variations for the entire Atlantic basin is shared by many of the indices for hurricanes striking land. In particular, the region of the Caribbean Sea has shown dramatic changes in hurricane activity – averaging around 1.5 per year during the 1940s through the 1960s dropping to near 0.5 per year in the 1970s to the early 1990s (Figure 9). This is followed by the unprecedented (in this five decade time series) six hurricanes afflicting the region in 1996.

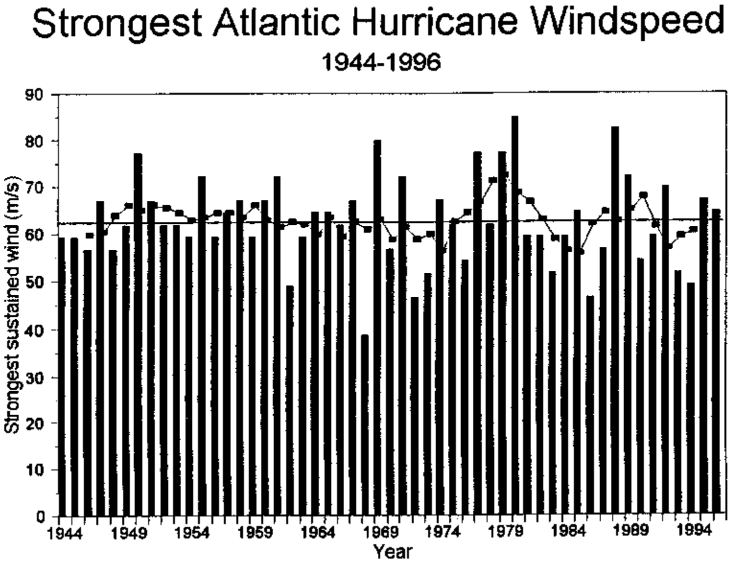

Figure 7. Time series of the Atlantic basin peak intensity – the highest sustained surface winds for the strongest hurricane each year – for the period of reliable record from 1944 to 1996. The long term (1950–90) average of 63.1 ms^{-1} (solid line) as well as a five year running mean (light curve) are superimposed on the time series.

In contrast to the Caribbean, U.S. landfalling hurricanes show a relatively small multidecadal variability in the time series with only the 1940s (active) and the 1970s (quiet) having distinctly different values than the long term average (Figure 10). This is similar to the behavior seen in the all–basin hurricane record. Few multidecadal variations are found in of the named and subtropical storms which struck the U.S. (not shown).

Where one does observe a strong multidecadal fluctuation in the United States tropical cyclones is with intense hurricanes, especially those that hit the East Coast from the Florida peninsula up to New England (Fig. 11). In this case, the quiet period in recent decades was so inactive that not a single East Coast intense hurricane made landfall from 1966 through 1984. This is in extreme contrast to the nineteen years previous (1947–1965) when fourteen intense hurricanes struck. Only in the last few years does it appear that this extremely quiescent period may be ending. This recent quiet period – well matched by the all–basin intense hurricanes described earlier – is similar to, but more extreme than, an inactive period during the first two decades of this century. In contrast, a subset of the Atlantic basin consisting of the U.S. Gulf Coast from Texas to the Florida panhandle (Fig. 12) has observed much weaker multidecadal variability in intense hurricane strikes, with sub-

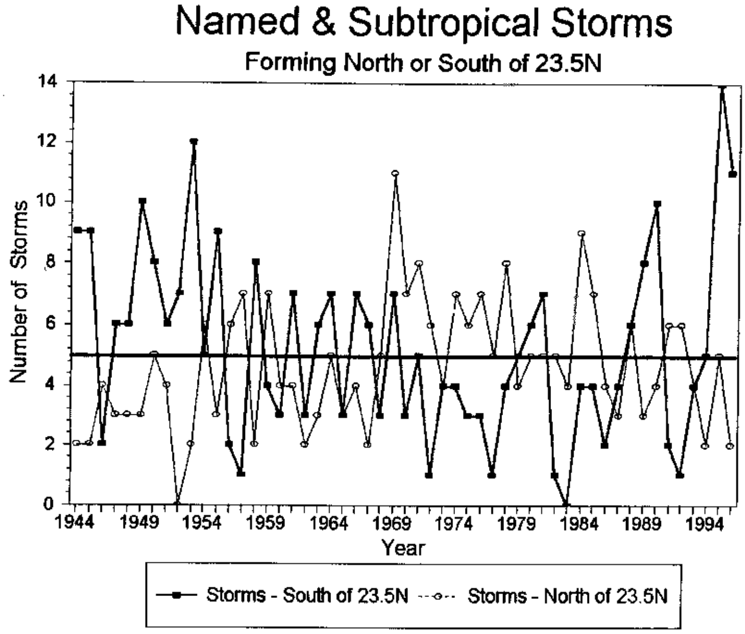

Figure 8. Annual number of Atlantic basin named and subtropical storms forming south (dark line) and north (light line) of 23.5°N for the period of reliable record from 1944 to 1996. The long term (1950–90) average of 4.9 per year (thick line) – valid for both time series – is also shown.

stantially more active conditions than average occurring only in the 1910s and quiet conditions only in the late 1940s and early 1950s.

Finally, hurricane–caused damage in the United States – when properly normalized – can also provide an independent indication of multiyear changes in tropical cyclone activity. Figure 13 shows the time series of damage normalized in terms of changes in inflation, wealth and coastal county population changes are taken into account (Pielke and Landsea 1998). Note the extreme destruction in 1926 (due to the near worst case scenario of a large Category 4 hurricane striking first the populous Miami–Ft. Lauderdale region in Florida, then striking Pensacola, Florida and Mobile, Alabama as a Category 3 hurricane), lowered values of damage in the early and mid 1930s followed by $3–7 billion damage per year for nearly every five year period from the late 1930s until the late 1960s. During the 1970s and 1980s, the normalized damage in the United States was substantially smaller ($1–3 billion per year) than in earlier decades. During the first part of the 1990s, damage again returned to higher levels due to the destructiveness of Hurricane Andrew in 1992.

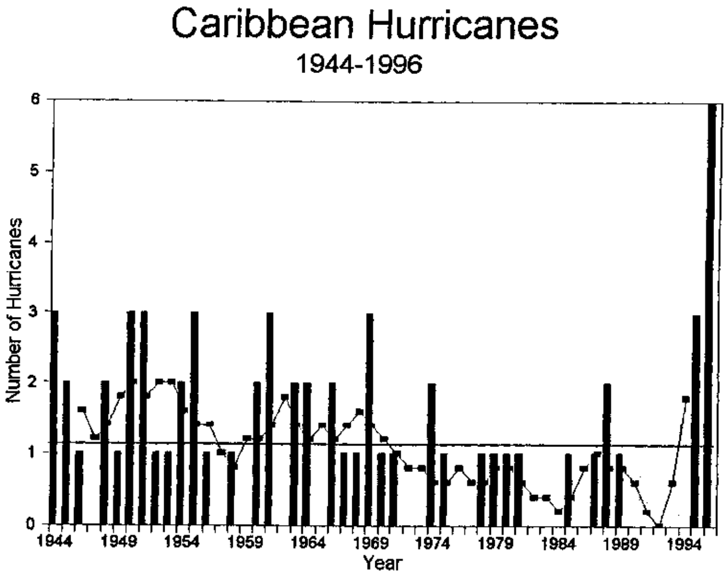

Figure 9. Time series of Caribbean Sea hurricanes for the period of reliable record from 1944 to 1996. The long term (1950–90) average of 1.1 per year (solid line) as well as a five year running mean (light curve) are superimposed on the time series.

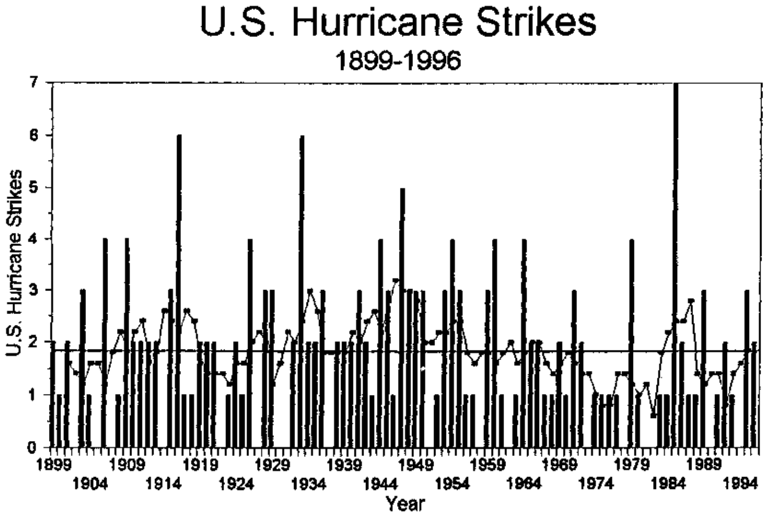

Figure 10. Annual number of hurricanes making landfall along the continental United States coastline for the period of reliable records of 1899–1996. The long term (1950–90) average of 1.66 per year (solid line) as well as a five year running mean (light curve) are superimposed on the time series.

Table III. Trends in Atlantic all–basin tropical cyclone indices. Trends calculated for the years 1944–1996 for the all–basin activity and the Caribbean hurricanes, 1899–1996 for the U.S. landfalling hurricanes, and 1925–1996 for the normalized U.S. tropical cyclone damages. Trends significant at the 0.01 level are indicated by "***", at the 0.05 level by "**", and at the 0.10 level by "*".

Tropical Cyclone Index	Linear Correlation Coefficient (r)	Regression Coefficient
Named/Subtropical Storms	+0.02	+0.04 per decade
Hurricanes	–0.11	–0.17 per decade
Intense Hurricanes	–0.23 **	–0.23 per decade
Hurricane Days	–0.18 *	–1.63 days per decade
Mean Intensity	–0.26 **	–1.34 ms^{-1} per decade
Peak Intensity	-0.04	–0.45 ms^{-1} per decade
Northern Named/Subtropical Storms	+0.25 **	+0.34 per decade
Southern Named/Subtropical Storms	–0.15	–0.30 per decade
Caribbean Hurricanes	–0.19 **	–0.15 per decade
U.S. Hurricanes	–0.07	–0.04 per decade
U.S. East Coast Intense Hurricanes	–0.02	0.00 per decade
U.S. Gulf Coast Intense Hurricanes	–0.06	–0.01 per decade
U.S. Normalized Tropical Cyclone Damage	–0.14	–$728 Million per decade

4.3. RELATIONSHIP TO CLIMATIC FORCINGS

Tables IV and V provide detailed comparisons of how the various Atlantic basin tropical cyclone indices are modulated by concurrent variations of individual environmental factors. These two tables – quartile differences and linear correlation coefficients, respectively – document the controls on interannual variability, though not much can be inferred here about causes on the interdecadal timescale.

The El Niño–Southern Oscillation, as represented by the Niño 3.4 SST anomalies, induces moderate–sized changes in the frequency and intensity of Atlantic tropical cyclones. La Niña events cause 36% more named/subtropical storms than El Niño events with mean intensities that are 6% stronger. ENSO's effect extends throughout the entire basin, though the effect is larger in the more southerly forming systems. The Caribbean region and the United States also see a large modulation of hurricane strikes, though the changes are only weakly significant for the U.S. Gulf Coast intense hurricanes.

Table IV. Quartile mean (median for U.S. normalized damages) differences (top 25% versus the bottom 25%) of a variety of environmental factors versus Atlantic tropical cyclone activity indices. The first value listed (or only value if just one is provided) shows the quartile differences for the period of 1950–1996 to allow a comparison of all factors based upon the same time period. Differences significant at the 0.01 level are indicated by "***", at the 0.05 level by "**", and at the 0.10 level by "*". Significance levels are adjusted to account for any serial correlation (Reid et al. 1989).

Tropical Cyclone Index (1950–1990 Mean)	ASO Niño3.4 SSTs (La Niña/El Niño)	ASO Caribbean 200 hPa Zonal Winds (Easterlies/Westerlies)
Named/Subtropical Storms (9.8)	11.6/8.5 ***	11.2/7.9 ***
Hurricanes (5.8)	6.7/4.9 ***	7.3/4.2 ***
Intense Hurricanes (2.2)	3.2/1.3 ***	3.6/1.2 ***
Hurricane Days (23.7)	29.9/19.1 ***	35.0/13.1 ***
Mean Intensity (39.0)	39.7/37.3 ***	40.5/37.1 ***
Peak Intensity (63.1)	65.4/58.8 ***	62.8/59.8 ***
Northern Named/Subtropical Storms (4.9)	5.8/5.1 *	4.2/4.8
Southern Named/Subtropical Storms (4.9)	5.8/3.4 ***	7.0/3.1 ***
Caribbean Hurricanes (1.1)	1.7/0.8 ***	2.0/0.5 ***
U.S. Hurricanes (1.7 [1899–1996: 1.8])	2.0/1.1 *** (1899–1996: 2.4/1.0 ***)	2.2/1.3 ***
U.S. East Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	0.58/0.08 *** (1899–1996: 0.33/0.04 ***)	0.58/0 ***
U.S. Gulf Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	0.33/0.25 (1899–1996: 0.45/0.28 **)	0.17/0.42 ***
U.S. Normalized Damage ($361 [1925–96: $1,065])	$2,358/$691 (1925–96: $3,526/$1,049 **)	$1,680/$1,418

Tropical Cyclone Index (1950–1990 Mean)	ASO Stratospheric QBO (West Phase/East Phase)	ASO Caribbean Sea Level Pressures (Low/High)
Named/Subtropical Storms (9.8)	11.8/8.8 ***	12.4/7.9 ***
Hurricanes (5.8)	7.3/5.1 ***	8.2/4.3 ***
Intense Hurricanes (2.2)	3.6/1.7 ***	3.7/1.1 ***
Hurricane Days (23.7)	35.2/17.2 ***	39.1/13.3 ***
Mean Intensity (39.0)	41.0/38.1 ***	41.5/37.0 ***
Peak Intensity (63.1)	68.4/59.8 ***	68.9/58.1 ***
Northern Named/Subtropical Storms (4.9)	5.8/4.8 **	4.0/5.0
Southern Named/Subtropical Storms (4.9)	6.0/4.0 ***	8.4/2.9 ***
Caribbean Hurricanes (1.1)	1.6/1.1 *	2.4/0.4 ***
U.S. Hurricanes (1.7 [1899–1996: 1.8])	2.5/1.7 **	2.2/1.1 ***
U.S. East Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	0.33/0.33	0.50/0.17
U.S. Gulf Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	0.58/0.25 ***	0.25/0.42 *
U.S. Normalized Damage ($361 [1925–96: $1,065])	$2,712/$2,256	$3,250/$902 *

Tropical Cyclone Index (1950–1990 Mean)	ASO Tropical North Atlantic SSTs (Warm/Cool)	JJAS West Sahel Rainfall (Wet/Dry)
Named/Subtropical Storms (9.8)	11.3/8.2 **	10.7/8.1 ***
Hurricanes (5.8)	7.2/5.1 **	7.5/4.2 ***
Intense Hurricanes (2.2)	3.0/1.7 **	3.2/0.9 ***
Hurricane Days (23.7)	31.9/21.0 *	34.8/10.8 ***
Mean Intensity (39.0)	39.9/38.9	42.8/36.5 ***
Peak Intensity (63.1)	66.1/62.4	68.0/55.8 ***
Northern Named/Subtropical Storms (4.9)	3.3/5.3 ***	4.2/5.4
Southern Named/Subtropical Storms (4.9)	8.0/3.7 ***	6.4/2.7 ***
Caribbean Hurricanes (1.1)	1.8/0.8 *	1.9/0.2 ***
U.S. Hurricanes (1.7 [1899–1996: 1.8])	1.5/1.8 (1899–1996: 1.8/1.7)	2.2/1.0 ** (1899–1996: 2.0/1.3 ***)
U.S. East Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	0.33/0.42 (1899–1996: 0.46/0.29)	0.83/0.08 ** (1899–1996: 0.62/0.12 ***)
U.S. Gulf Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	0.25/0.42 (1899–1996: 0.42/0.17)	0.33/0.25 (1899–1996: 0.46/0.29 **)
U.S. Normalized Damage ($361 [1925–96: $1,065])	$541/$1685 (1925–96: $1453/$1534)	$5,092/$232 * (1925–96: $1,996/$682)

Table V. Linear correlation coefficients (r) of a variety of environmental factors versus Atlantic tropical cyclone activity indices. The first value listed (or only value if just one is provided) shows the correlation for the period of 1950–1996 to allow a comparison of all factors based upon the same time period. Correlations significant at the 0.01 level are indicated by "***", at the 0.05 level by "**", and at the 0.10 level by "*". Significance levels are adjusted to account for any serial correlation (Reid et al. 1989).

Tropical Cyclone Index (1950–1990 Mean)	ASO Niño3.4 SSTs	ASO Caribbean 200 hPa Zonal Winds
Named/Subtropical Storms (9.8)	–0.33 **	–0.45 ***
Hurricanes (5.8)	–0.30 **	–0.56 ***
Intense Hurricanes (2.2)	–0.40 ***	–0.62 ***
Hurricane Days (23.7)	–0.28 **	–0.60 ***
Mean Intensity (39.0)	–0.30 **	–0.38 ***
Peak Intensity (63.1)	–0.25 *	–0.25 *
Northern Named/Subtropical Storms (4.9)	–0.14	0.15
Southern Named/Subtropical Storms (4.9)	–0.24 *	–0.57 ***
Caribbean Hurricanes (1.1)	–0.29 **	–0.47 ***
U.S. Hurricanes (1.7 [1899–1996: 1.8])	–0.15 (1899–1996: –0.30 ***)	–0.24 *
U.S. East Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	–0.22 (1899–1996: –0.20 **)	–0.25 *
U.S. Gulf Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	–0.16 (1899–1996: –0.16)	0.11
U.S. Normalized Damage ($361 [1925–96: $1,065])	0.00 (1925–96: –0.04)	0.00

Tropical Cyclone Index (1950–1990 Mean)	ASO Stratospheric QBO	ASO Caribbean Sea Level Pressures
Named/Subtropical Storms (9.8)	0.42 ***	–0.56 ***
Hurricanes (5.8)	0.41 ***	–0.62 ***
Intense Hurricanes (2.2)	0.39 ***	–0.59 ***
Hurricane Days (23.7)	0.46 ***	–0.64 ***
Mean Intensity (39.0)	0.17	–0.41 ***
Peak Intensity (63.1)	0.23	–0.44 ***
Northern Named/Subtropical Storms (4.9)	0.15	0.06
Southern Named/Subtropical Storms (4.9)	0.33 **	–0.62 ***
Caribbean Hurricanes (1.1)	0.19	–0.54 ***
U.S. Hurricanes (1.7 [1899–1996: 1.8])	0.14	–0.27 *
U.S. East Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	–0.10	–0.10
U.S. Gulf Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	0.24 *	0.03
U.S. Normalized Damage ($361 [1925–96: $1,065])	–0.23 *	–0.03

Tropical Cyclone Index (1950–1990 Mean)	ASO Tropical North Atlantic SSTs	JJAS West Sahel Rainfall
Named/Subtropical Storms (9.8)	0.42 ***	0.30 **
Hurricanes (5.8)	0.38 ***	0.51 ***
Intense Hurricanes (2.2)	0.29 **	0.52 ***
Hurricane Days (23.7)	0.33 **	0.59 ***
Mean Intensity (39.0)	0.05	0.52 ***
Peak Intensity (63.1)	0.16	0.35 **
Northern Named/Subtropical Storms (4.9)	–0.32 **	–0.21
Southern Named/Subtropical Storms (4.9)	0.56 ***	0.45 ***
Caribbean Hurricanes (1.1)	0.24	0.45 ***
U.S. Hurricanes (1.7 [1899–1996: 1.8])	0.02 (1899–1996: 0.07)	0.28 * (1899–1996: 0.21 **)
U.S. East Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	0.00 (1899–1996: 0.11)	0.40 *** (1899–1996: 0.23 **)
U.S. Gulf Coast Intense Hurricanes (0.32 [1899–1996: 0.36])	–0.10 (1899–1996: 0.07)	–0.03 (1899–1996: 0.09)
U.S. Normalized Damage ($361 [1925–96: $1,065])	–0.04 (1925–96: 0.07)	0.07 (1925–96: 0.07)

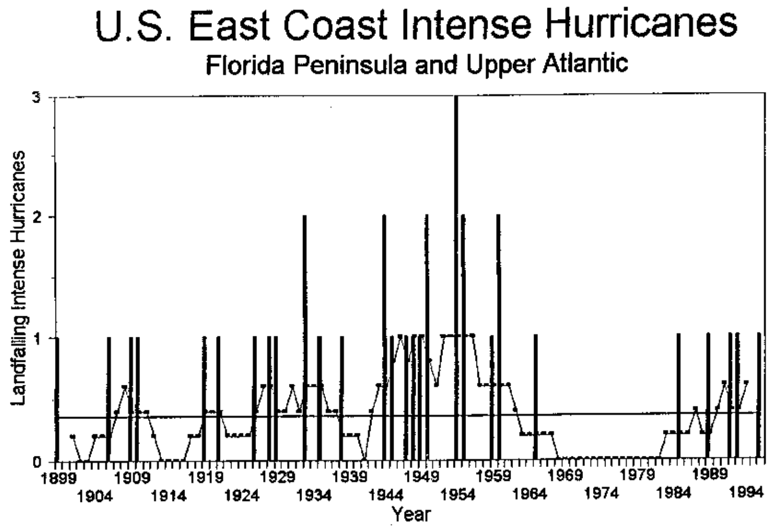

Figure 11. Annual number of intense hurricanes that have made landfall along the U. S. East Coast from the Florida peninsula to the Upper Atlantic (from Georgia to New England) for the period of reliable records of 1899–1996. The long term (1950–90) average of 0.32 per year (solid line) as well as a five year running mean (light curve) are superimposed on the time series.

The Caribbean 200 hPa zonal winds and the sea level pressures both exert a similar, very strong influence on the frequency and intensity of tropical cyclones. Easterly wind anomalies and low pressures are associated with an increase of 42% and 57% more named/subtropical storms, respectively, than in the years of westerly wind and high pressure anomalies. The mean intensity of such systems is also dramatically altered with correspondingly stronger systems by 9% and 12% for the years of easterly wind and low pressure anomalies. However, in the northerly latitudes these effects are reversed with favored formation occurring in the years of westerly wind anomalies and higher pressure, though these reversed alterations are weaker than what occurs to the southern tropical cyclone formations. The wind and pressure changes correspond to large variations in the landfalling Caribbean and U.S. hurricanes, though the U.S. Gulf Coast intense hurricanes respond to the reversed effect with more strikes in Caribbean high pressure and west wind years.

The stratospheric QBO appears to primarily have a moderate effect on the frequency of Atlantic tropical cyclones forming anywhere in the basin, but only a weak signal in the intensity of systems. The west phase of the QBO is linked to a 34% increase in total storms over the number seen in the QBO

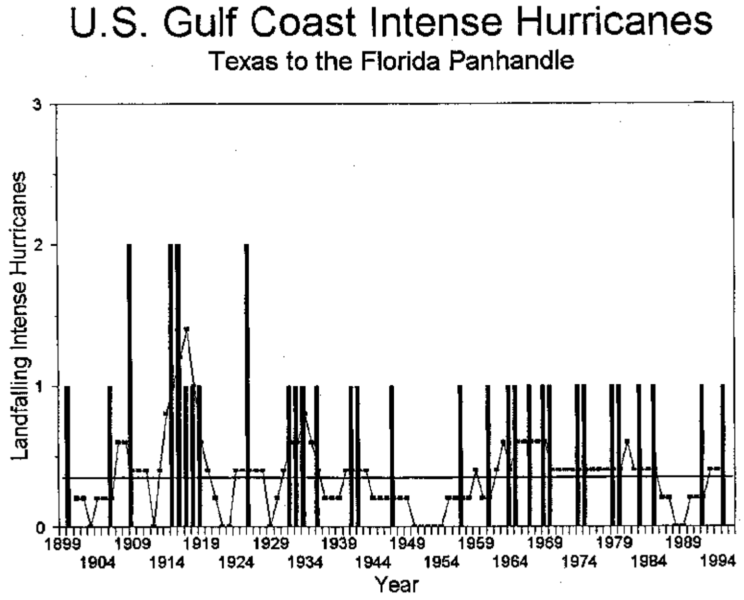

Figure 12. Annual number of intense hurricanes that have made landfall along the U. S. Gulf Coast from Texas to the Florida panhandle for the period of reliable records of 1899–1996. The long term (1950–90) average of 0.32 per year (solid line) as well as a five year running mean (light curve) are superimposed on the time series.

east years. The mean intensity, however, is not significantly correlated to the QBO phase. The landfalling hurricanes in the Caribbean and U.S. are all significantly modulated by the QBO, though the effects are relatively weak.

The tropical North Atlantic SSTs appears to have the largest influence on the spatial distribution of the total number of named and subtropical storms. There is a over a two–to–one difference in southern forming storms during warm versus cold Atlantic SST years; this is nearly reversed for the northerly latitude forming storms. However, as more intense categories of tropical cyclones are considered, the tropical North Atlantic SSTs effects are diminished on this interannual timescale. Thus Atlantic SST impact upon the frequency of U.S. landfalling hurricanes is negligible and only marginally observed for Caribbean hurricanes.

Finally, the West Sahel rainfall difference appear to play a moderate role in the total frequency and have a very large impact on intensity. There is a 32% increase in named and subtropical storms in the wet Sahel years compared with the dry years, though partially this is somewhat reduced because of a compensating decrease in the number of formations in northerly latitudes. The intensity of the mean storm is strengthened by 17% in the wet versus the dry years. These alterations cause big changes in the Caribbean and U.S. hurricanes, again primarily along the U.S. East Coast intense hurricanes.

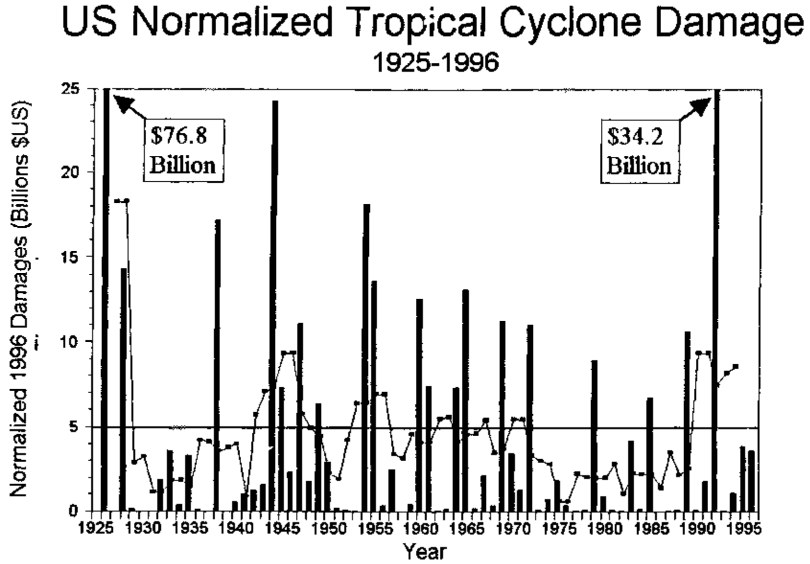

Figure 13. Time series of annual normalized tropical cyclone damage for the U.S. East and Gulf Coasts. The long–term (1950–90) average of $3.5 billion per year (solid line) as well as a five year running mean (light curve) are superimposed on the time series. Damage is normalized to 1996 dollars by inflation, coastal county population changes, and an index of personal property amounts.

In a comparative analysis, the frequency of named/subtropical storms is most strongly altered by sea level pressure variations followed by 200mb zonal winds, the stratospheric QBO and Atlantic SSTs. However, the total frequency of events distorts large regional differences based upon latitudinal variations. For southerly latitude formations the primary interannual forcing is due to sea level pressure and Atlantic SST variations. These effects are followed by changes associated with Western Sahel rainfall and 200mb zonal winds. The same factors – with the exception of Atlantic SSTs – also appear to strongly modulate Caribbean hurricane strikes. Only two factors were found that had a homogeneous, basinwide effect. ENSO and the stratospheric QBO both show reduced activity throughout the Atlantic basin during warm events and east phases, respectively. However, effects were most pronounced in the southern portion of the basin. Opposite effects between tropical cyclones forming in the southerly and northerly portion of the basin are seen most strongly for the Atlantic SSTs and the West Sahel rainfall, with a weaker signal present in the sea level pressure anomalies. Along the U.S. coastline, the factors of sea level pressures, ENSO and West Sahel rainfall have the largest effects on number of hurricane strikes. Again, this is dependent upon location, however. For the East Coast, interannual variations of intense hurricane strikes are best related to ENSO, West Sahel rainfall and 200mb zonal winds. For intense hurricane strikes along the Gulf Coast, the single largest factor is the phase of the QBO followed by the 200mb zonal winds and sea level pressure anomalies both in an opposite sense where westerly winds and high pressures in the Caribbean favor more strikes. Interannual variations in normalized U.S. damages are only well related to ENSO, with significantly less damage during El Niño events and more during La Niña events, and just marginally associated with Caribbean sea level pressures and West Sahel rainfall. These relationships show up more clearly in the composite analyses since the linear correlation analyses have difficulty in identifying a coherent signal in the rather noisy distribution of normalized U.S. damages.

Independent of frequency, mean and peak intensities of Atlantic tropical cyclones are most strongly linked to West Sahel rainfall followed by changes in Caribbean sea level pressures and 200mb zonal winds. Likewise, duration of hurricanes is nearly equally strongly associated with variations of these three previously mentioned parameters with longer lived hurricanes during years of wet West Sahel seasons, easterly 200mb zonal wind anomalies and low sea level pressures.

After investigating the interannual aspects of Atlantic tropical cyclones and their environmental controls, an analysis of multidecadal relationships of Atlantic tropical cyclones to Atlantic SSTs was attempted. Figure 14 presents the "Atlantic Multidecadal Mode" EOF time series from Enfield and Mestas–Nuñez (1998) in the bottom panel. The top panel of Fig. 14 is the correlation between the time series of the EOF and the actual SST data at every grid point. This has very similar spatial structure to the actual EOF spatial pattern and gives a measure of the local fractional variance (squared temporal correlation) accounted at every grid point. The dominant spatial relationships – in the positive phase – have warm SSTs in the tropical North Atlantic between 5 and 25°N, the far North Atlantic between 40 and 70°N, and cool SSTs in the South Atlantic. There are also secondary signals seen with warm conditions in the North Pacific and cool conditions in the Indian Ocean, the South Pacific and along the U.S. New England coastal waters. This mode, likely the same as has been previously identified by Folland et al. (1986) and Kushnir (1994), operates primarily with the most power in the multidecadal mode with distinct multiple decades of warm North/cold South Atlantic and vice versa. Mestas–Nuñez and Enfield (1998) further show that under a varimax rotation, variability outside the North Atlantic separates into distinct rotated modes; only the North Atlantic rotated mode retains the multidecadal temporal signature seen in Fig. 14, while the North and South Atlantic rotated modes are independent of each other. It is concluded that the Multidecadal mode seen in Fig. 14 is primarily a representation of North Atlantic SST variability after accounting for the ENSO influence. The duration of these various modes can approximately be broken down into the following years since 1857 when the analysis starts:

- 1857 to 1868 - Indeterminate
- 1869 to 1893 - Warm North Atlantic (25 years)
- 1894 to 1925 - Cold North Atlantic (32 years)
- 1926 to 1970 - Warm North Atlantic (45 years)
- 1971 to 1994 - Cold North Atlantic (24 years)
- 1995 to 1996 - Indeterminate

The recent change of the mode in 1995 and 1996 may signify a return to a multidecadal period of the warm North Atlantic phase, but there is not enough evidence yet to be conclusive. For the following analysis, 1971 to 1994 will be considered as part of the cold North Atlantic phase and 1995 to 1996 will be considered indeterminate.

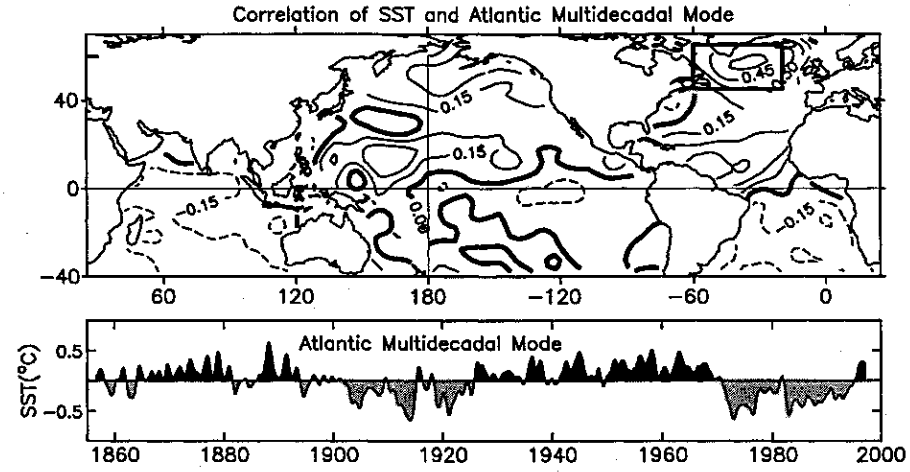

Figure 14. Top) Distribution of correlations for the years 1857 to 1996 between local monthly SST anomalies versus the third EOF "Atlantic Multidecadal Mode"; Bottom) Temporal realization of the Atlantic Multidecadal Mode computed from temporal amplitude time series and the area-average spatial loadings over the rectangular area in the North Atlantic.

Table VI presents differences in Atlantic tropical cyclone activity based upon the phase of the Atlantic Multidecadal Mode. Variations based upon these SST differences are similar to, but generally stronger than, the interannual changes shown in Table V. Decades of the warm North Atlantic phase show little change in total frequency of storms, primarily because there is a nearly compensating decrease in northerly latitude formations compared with those forming in the southerly portion of the basin. Intensity of tropical cyclones are modulated strongly with 80% more intense hurricane occurring in the warm North Atlantic years over the cold North Atlantic decades. These impacts are strongly felt in the Caribbean basin with 200% more intense hurricanes occurring in the warm North Atlantic decades and for intense hurricanes striking the U.S. East Coast with an increase of 165%. Differences for the U.S. Gulf Coast intense hurricanes appear insignificant. Consequently, normalized damage for the U.S. is also dramatically altered with a median value of $1,747 million per year in the warm North Atlantic regime versus only $317 million per year in the cold North Atlantic decades. Figure 15 provides a spatial comparison of intense hurricane activity throughout the whole basin for the two multidecadal regimes. Note how frequencies of intense hurricane are decreased throughout the entire basin with the exception of the Gulf of Mexico during the cold North Atlantic decades in comparison with the warm North Atlantic decades.

Table VI. Mean (median for U.S. normalized damage) values for Atlantic tropical cyclone activity based upon Atlantic Multidecadal Mode variations. Differences between warm North Atlantic (all years) and cold North Atlantic (all years) are tested for significance in the last column. Differences significant at the 0.01 level are indicated by "***", at the 0.05 level by "**", and at the 0.10 level by "*".

Tropical Cyclone Index (Years available)	Cold North 1899–1925	Warm North 1926–70	Cold North 1971–94	Warm North All Years	Cold North All Years	Significance
Named/Subtropical Storms (1944–94)	–	9.9	9.2	9.9	9.2	
Hurricanes (1944–94)	–	6.2	5.0	6.2	5.0	**
Intense Hurricanes (1944–94)	–	2.7	1.5	2.7	1.5	***
Hurricane Days (1944–94)	–	27.7	16.5	27.7	16.5	***
Mean Intensity (1944–94)	–	39.5	37.4	39.5	37.4	*
Peak Intensity (1944–94)	–	62.5	62.0	62.5	62.0	
Northern Named/Subtropical Storms (1944–94)	–	4.0	5.3	4.0	5.3	**
Southern Named/Subtropical Storms (1944–94)	–	5.9	3.9	5.9	3.9	***
Caribbean Hurricanes (1944–94)	–	1.5	0.5	1.5	0.5	***
U.S. Hurricanes (1899–1994)	1.7	2.1	1.4	2.1	1.6	*
U.S. East Coast Intense Hurricanes (1899–1994)	0.22	0.53	0.17	0.53	0.20	**
U.S. Gulf Coast Intense Hurricanes (1899–1994)	0.41	0.36	0.29	0.36	0.35	
U.S. Normalized Damage (1925-94)	$0	$1,747	$528	$1,747	$317	

5. Policy Relevance

Indices of Atlantic basin hurricane activity underlie important policy decisions in the public and private sectors. For example, insurance and reinsur-

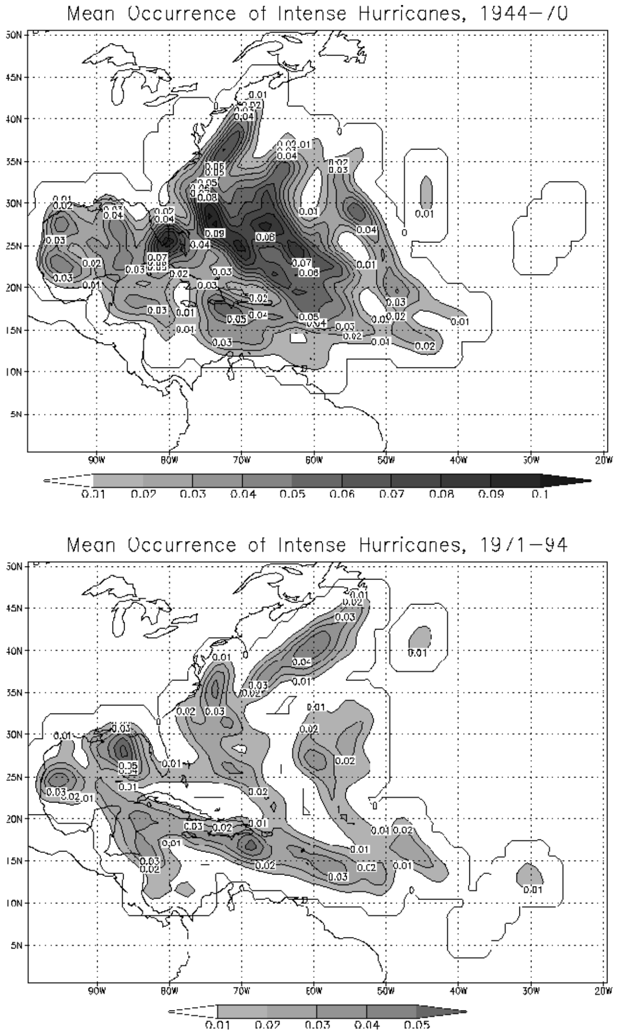

Figure 15. Observed annual frequency of intense hurricanes in a 1.0 by 1.0 latitude/longitude grid field smoothed with a nine point binomial filter twice for (top) 1944-70 (warm North Atlantic) and (bottom) 1971-94 (cold North Atlantic)

ance companies evaluate risk, in part, based on their interpretation of the historical record. More broadly, public attention and resources are directed to the hurricane problem based upon assessments of past tropical cyclone incidences and impacts (Pielke and Pielke 1997a). In recent years, some in the media and in policy positions have identified hurricane activity as a signal of human-induced climate change (Pielke 1997). Consequently, an examination of past trends in hurricane incidence is directly relevant to both climate change policies and natural hazards policies.

5.1. CLIMATE CHANGE POLICY

In 1996, Working Group III of the IPCC estimated increased worldwide damages and loss of life related to hurricane impacts in a doubled CO_2 world at $630 million and 8,000 additional lives lost (Watson et al. 1996). Working Group III concluded that these economic losses and lives lost would be prevented with the adoption of emissions reductions policies. There is an obvious inconsistency between the projections by IPCC Working Group III of increased impacts and the conclusions of Working Group I, which stated that "the state of the science does not allow assessment of future changes" in tropical cyclone indices.

Setting aside for the moment this inconsistency, the logic of the IPCC Working Group III is fundamentally flawed. Even if there were valid theoretical reasons to expect more tropical cyclones in the future related to human–caused climate change, the climatological record gives no indication that society can modulate hurricane impacts through energy policies. That is, as atmospheric CO_2 levels have increased, "there is currently no evidence that there has been systematic changes in the observed tropical cyclones around the globe" (Landsea 1998). The suggestion by the IPCC that a reduction in greenhouse gas emissions will lead to less or less intense tropical cyclones and therefore less impacts to society begs several further questions of relevance to the policy community which have thus far gone unasked and unanswered:

- Can the scientific community reliably differentiate future hurricane frequencies and magnitudes based on the various scenarios of greenhouse gas emissions and concentrations (i.e., IS92a–f from Houghton et al. 1992)?

The analysis of climatological information presented in this paper suggests that for many decades to come, detection of a human–forced signal in the tropical cyclone record will be extremely difficult to detect because of both the relatively modest size of the predicted changes in MPI and the rather large apparently natural multidecadal variability (cf. Henderson–Sellers et al. 1998). Therefore, it is unrealistic for policy makers to expect in the near term (i.e., in the next few years) that the scientific community will be able to reliably predict future hurricane incidences differentiated by various emissions scenarios. Henderson–Sellers et al. (1998) noted that "global and mesoscale model-based predictions for tropical cyclones in greenhouse conditions have not yet demonstrated prediction skill."

- Is there reason to believe that policy makers should expect the policy actions now being contemplated (e.g., the Kyoto Accord to the Framework Convention on Climate Change) will reduce the number of and intensities of future hurricanes that will impact society?

There is no evidence to suggest that society can intentionally modulate tropical cyclone frequencies and magnitudes through energy policies[2]. Therefore, policy responses to hurricanes ought to focus on the reduction of society's vulnerability to hurricanes, rather than on prevention of the storms themselves (Pielke and Pielke 1997b). For instance, in the context of insurance, Henderson–Sellers et al. (1998) recommend a focus on "appropriate reserves and restrictive underwriting" rather than on accurate predictions, or by extension, on controlling future hurricane incidences.

Answers to these questions do not exclude the possibility that an anthropogenic forcing might lead to changes (Henderson-Sellers et al. 1998). They do strongly suggest that reliable prediction of future hurricane indices (much less societal impacts) differentiated by various emissions scenarios is beyond the capabilities of the scientific community. Further, if a policy objective is to reduce society's vulnerability to hurricane impacts, then decision makers would be wiser to consider better adapting to documented variability, rather than preventing storms from occurring (Pielke 1998)[3].

5.2. NATURAL DISASTER POLICY

One of the most striking features of the information presented in section four of this paper are the 19 years which passed between intense hurricane landfalls on the U.S. East Coast from 1966 through 1984. These decades saw much of the population growth and development of coastal communities. Overall, the 19 years prior to 1966 saw 14 intense hurricanes strike the U.S. East Coast. Most of the historical economic losses are the result of storms striking the U.S. East Coast rather than the Gulf Coast (Table VII). Consider also that over the seven year period 1944 to 1950, the state of Florida saw \$44.2 billion (normalized to 1995 values, see Pielke and Landsea 1998) in losses, or more than \$6 billion per year, while the 46 year period 1951 to 1997 saw a similar total amount of normalized damages, \$49.3 billion or about \$1.1 billion per year. Most of the damages of the latter period were the result of Hurricane Andrew in 1992.

The review of indices for hurricane climatic changes reveals that from the perspective of societal impacts, recent decades are indeed anomalous. But

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[2] This is not to say that energy policies CANNOT affect hurricanes, only that there is no proof that society can purposely modulate hurricane activity via energy policies. See Pielke (1998) for a broader discussion of the Kyoto Protocol.

[3] A more comprehensive discussion of mitigation and adaptation in the context of global climate policy is found in Pielke (1998).

Table VII. Correlations of normalized U.S. hurricane damages versus indices of Atlantic basin hurricane activity. Correlations are calculated for the years 1944–1996 for the all–basin activity and the Caribbean hurricanes and 1925–1996 for the U.S. landfalling hurricanes. Correlations significant at the 0.01 level are indicated by "***", at the 0.05 level by "**", and at the 0.10 level by "*". Significance levels are adjusted to account for any serial correlation (Reid et al. 1989).

Tropical Cyclone Index	Linear Correlation Coefficient (r)
Named/Subtropical Storms	0.00
Hurricanes	+0.12
Intense Hurricanes	+0.08
Hurricane Days	+0.15
Mean Intensity	+0.26 **
Peak Intensity	+0.21 *
Northern Named/Subtropical Storms	0.00
Southern Named/Subtropical Storms	+0.02
Caribbean Hurricanes	+0.16
U.S. Hurricanes	+0.51 ***
U.S. East Coast Intense Hurricanes	+0.61 ***
U.S. Gulf Coast Intense Hurricanes	+0.29 ***

contrary to conventional wisdom of some in the media, public, and policy communities, recent decades are unique because of the relative infrequency of U.S. landfalls of strong hurricanes, and not because of any upsurge in strong storms (cf. Landsea et al. 1996). Hurricanes arguably are the natural hazard with the greatest potential for economic disruption in the United States, and further, the potential for a large loss of life related to a hurricane's landfall is increasing with coastal development (Pielke and Pielke 1997a). Because the nation's hurricane policies have been typically developed in the immediate aftermath of a disaster (Birkland 1997, Simpson 1998), it would be prudent for the policy community to assess whether or not the lack of hurricane impacts in recent decades has led to an atrophying of the nation's hurricane policies. Some questions to consider include:

- Are national, state, and local hurricane policies supported by public and private decision makers in a manner commensurate with the documented vulnerability of society?

- How prepared is the U.S. east coast for 14 intense hurricanes in 19 years as occurred in the 1940s–1960s?
- How prepared is the nation, and Florida specifically, for a recurrence of the hurricanes of the late 1940s?
- Is the time ripe for the United States to develop a national hurricane policy?

Asking and answering questions like these are important steps in reducing the nation's vulnerabilities to hurricane impacts. One benefit of past hurricane impacts is that society has learned many lessons. These lessons provide a basis of experience on which to reduce the nation's vulnerability to hurricane impacts (Pielke and Pielke 1997a). What seems to be lacking is awareness of whether the nation's risk is matched by its response.

6. Discussion and Summary

Atlantic hurricane variability can be characterized as having a lack of strong linear trends, but comprised of robust multidecadal variations. Such decade to decade changes are not evident when examining the entire named/subtropical storm database over the last five decades, but such variability becomes evident upon stratification by latitudinal regime and by intensity of the tropical cyclones.

In particular, we found that the hurricanes, especially those reaching sustained winds of 50 ms^{-1} – the intense hurricanes – were very common in the 1940s through the 1960s and much reduced in occurrence from the 1970s through the early 1990s. The years of 1995 and 1996 showed an intriguing return to high levels of activity more reminiscent of the earlier, active decades. The duration of hurricanes also showed similar variations with longer–lived (around 25–40 days per year) systems in the 1940s through the 1960s and rather short–lived hurricanes (around 10–25 days per year) in the decades since.

Such variability was not uniform throughout the basin. In fact, for the named/subtropical storms forming north of 23.5°N, the 1970s to the early 1990s actually showed an increase of activity, while there was a nearly equal decrease in formations south of that latitude. It is quite possible that some of this increase in named/subtropical storms in the northern latitudes was due to the availability of geostationary satellite imagery starting in the mid 1960s, as suggested by Elsner et al. (1996). However, it does appear that the decrease in activity in the southern latitudes is a real change. Inhabitants the Caribbean and the U.S. East Coast, in particular, were quite fortunate during the last few decades as these regions experienced many fewer damaging hurricanes than in earlier decades. Consequently, normalized hurricane damages in the U.S. were substantially lower in the 1970s and 1980s than in previous decades.

The one region with accurate enough records to extend the analysis back to the turn of the century – the U.S. East and Gulf Coasts – shows that the quiet period of recent decades is similar to the first two and a half decades of the century, though this is more true for the East Coast than the Gulf Coast which shows less multidecadal variability.

Analyses were also performed to contrast the impact that various environmental factors have upon Atlantic tropical cyclone variability. Figure 16 provides a schematic summarizing these interannual and interdecadal forcings of Atlantic tropical cyclones. The largest interannual variations appear to be associated with Caribbean sea level pressures and 200mb zonal winds: years of low pressures and easterly 200mb wind anomalies corresponded with more frequent and more intense tropical cyclones. Of course, the existence of more tropical cyclones will naturally directly contribute toward lower surface pressures and easterly wind anomalies. However, Knaff (1997) showed that the direct impact on the sea level pressures was small and that these SLP changes did not significantly alter the correlations derived. Additionally, Landsea et al. (1998) showed that, for at least the hurricane season of 1995, the lowered sea level pressures and 200mb easterly anomalies preceded the hurricane activity by several months and thus in this case could not have been caused by the hurricanes themselves.

The other environmental factors considered here – El Niño–Southern Oscillation, the stratospheric Quasi–Biennial Oscillation, West Sahel rainfall and Atlantic sea surface temperatures – also showed moderate to strong influences on Atlantic tropical cyclone activity, confirming previous studies. A new finding is that some of the environmental factors including the Caribbean sea level pressures (consistent with Knaff 1997), Atlantic SSTs and West Sahel rainfall did induce a weakly, opposite forcing of increased activity in the northerly portion of the basin during years of high pressure, cool SSTs and dry West Sahel seasons. In contrast, two of the environmental factors appeared to cause consistent basinwide alterations – ENSO and the QBO – in particular, though their effects in the southerly latitudes were strongest. Thus the hypothesis from Goldenberg and Shapiro (1996) that there is an "out–of–phase" relationship between the southerly and northerly latitude storm formations because of vertical shear proves true in the case of West Sahel rainfall, but not for ENSO. In addition, the key dependency of the QBO on the U.S. Gulf Coast intense hurricanes mirrors the findings of Lehmiller et al. (1997) in their scheme for forecasting Gulf of Mexico intense hurricane activity by 1 August.

Results in this study may be able to somewhat resolve the aforementioned discrepancies regarding the influence of Atlantic SSTs on interannual basinwide tropical cyclones. It was found here that the SSTs appear to ex-

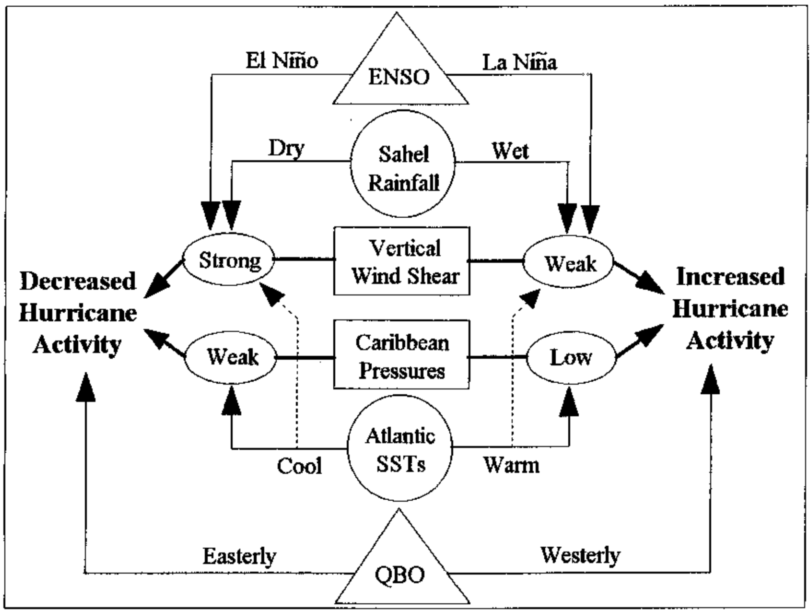

Figure 16. Schematic of environmental forcings of Atlantic tropical cyclones on primarily interannual (triangles) and interdecadal (circles) timescales. The rectangles indicate the physical factors directly responsible for tropical cyclone variations.

ert the most dominant "dipole" type signal in Atlantic tropical cyclones with more (fewer) storms forming in the southern (northern) latitudes during warmer than usual years. However, this signal is diluted when the entire tropical cyclone dataset is considered as a whole. Additionally, the relationship weakens as more intense tropical cyclones are considered. Thus Saunders and Harris (1997) are correct that Atlantic SSTs are the dominant mechanism when analyzing formations just in the eastern tropical North Atlantic. However, when looking at the entire basin and for more intense hurricanes, Raper (1992) and Shapiro and Goldenberg (1998), respectively, are also correct that the Atlantic SSTs play a weaker interannual role. The key is that the dataset of tropical cyclones must be broken down into spatial location and by intensity when doing the analysis.

The analysis here is not meant to imply that these various environmental factors independently affect Atlantic tropical cyclones, without interacting with one another. Indeed, Knaff (1997) demonstrated that the Caribbean SLP variations were strongly linked and were possibly due to a feedback with the tropical upper tropospheric trough and the strength of the associated 200 mb westerlies. However, of the six environmental factors considered here, only five pairs (out of 15 possible) have a covariance exceeding 25% of the variability: West Sahel rainfall and Caribbean SLPs (27%), Caribbean SLPs and Caribbean 200 mb zonal wind anomalies (29%), West Sahel rainfall and Caribbean 200 mb zonal wind anomalies (32%), tropical North Atlantic SSTs and Caribbean 200 mb zonal wind anomalies (34%), and West Sahel rainfall and tropical North Atlantic SSTs (38%). The remaining ten pairs of combinations had relationships explaining less than one–fifth of the variance between the two environmental factors. While most of these relatively small values of co–variability suggest that the environment factors may be independently related to Atlantic tropical cyclones, further study is certainly warranted in investigating the interdependence of these conditions.

While the Atlantic SSTs were a quite weak interannual environmental factor for intense hurricanes, the multidecadal mode of Atlantic SSTs in contrast corresponds strongly to the observed decade to decade changes in Atlantic intense hurricanes. In particular, the quiet regimes of 1899–1925 and 1971–94 are well related to an SST regime of cold North Atlantic conditions. The years of 1926–70, which were distinctly warm in the North Atlantic, correspond to active conditions for Atlantic hurricanes. There is an 80% increase in intense hurricanes during the warm North Atlantic decades compared with the cold North Atlantic years. These changes have direct impacts on the hurricanes which strike the Caribbean islands as well as the United States, especially intense hurricanes making landfall from the Florida peninsula to New England. The U.S. normalized damages between the two SST regimes are striking, with a factor of four increase in median damages during the warm North Atlantic decades.

The discrepancy between the interannual and interdecadal response of Atlantic tropical cyclones to Atlantic SSTs may be explained by the SSTs relationship to the other environmental controls. On the interdecadal timescale, Gray (1990) showed that there are long–term variations in the vertical wind shear amounts, which are in phase with the Atlantic SST mode: reduced vertical shear during the warm North Atlantic decades favoring more intense hurricane activity and increased vertical shear during the cold North Atlantic years inhibiting strong hurricanes. In contrast to this, the influence of Atlantic SSTs is occasionally not in phase with the overlying tropospheric circulation on the interannual timescale. A good example of this occurred in 1997 with very warm tropical North Atlantic SSTs, yet the intense hurricanes were much reduced from preceding years because of the strong vertical shear induced by the 1997 El Niño event (Bell and Halpert 1998).

The lack of a distinct multidecadal variation of intense hurricanes in the Gulf of Mexico is likely due to local conditions that dominate over these basinwide SST changes (Landsea et al. 1992). Since 1967 when satellite monitoring made it possible, all of the U.S. East Coast intense hurricanes were spawned from easterly waves. In contrast, baroclinically–initiated tropical cyclones (e.g. stationary frontal boundaries or upper–tropospheric cutoff lows) occasionally have developed into intense hurricanes that make landfall along the U.S. Gulf Coast. Hurricane Alicia, which struck the Texas coast in 1983, is a notable example of this latter phenomena. Additionally, vertical shear changes in the Gulf are not correlated highly with variations of ENSO or West Sahel rainfall, unlike the main development region (Goldenberg and Shapiro 1996).

The years of 1995 and 1996 showed at least a temporary return of warm North Atlantic SST conditions, and with it, a return to numerous intense hurricanes. An analysis is currently underway to evaluate whether this change is likely one of a multidecadal nature. If so, this holds the potential of providing a reliable multidecadal forecast of Atlantic hurricane activity.

Knowledge of future incidences of hurricanes holds the promise of economic benefits and enhanced response. Nevertheless, decision makers do not need to know the future with certainty to begin to stimulate improved responses to hurricanes, they need only to understand and appreciate the past. An understanding of trends in hurricane indices is an important step in that direction.

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