TESTIMONY OF

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BEFORE THE
COMMITTEE ON SCIENCE
ENVIRONMENT, TECHNOLOGY, AND STANDARDS SUBCOMMITTEE
UNITED STATES HOUSE OF REPRESENTATIVES

October 11, 2001

Good morning, Mr. Chairman and members of the Committee. Thank you for inviting me to discuss potential implications of the recent increase in Atlantic hurricanes and the evidence that this is the beginning of a multidecadal pattern that could have major implications for coastal communities in coming years. Understanding the historical patterns and the present conditions that have led to this increase in Atlantic hurricanes is crucial for developing a management strategy.

I am Chris Landsea, Research Meteorologist with the Hurricane Research Division of the Atlantic Oceanographic and Meteorological Laboratory in Miami, Florida. The Atlantic Oceanographic and Meteorological Laboratory is one of twelve laboratories administrated by the Office of Oceanic and Atmospheric Research of the National Oceanic and Atmospheric Administration (NOAA). The Hurricane Research Division conducts basic and applied research which directly benefits hurricane track and intensity forecasting which is a direct contribution to NOAA's mission of environmental prediction.

Progress in predicting and understanding weather has been one of the greatest success stories in science. Hurricanes pose a major threat to our Nation's coastal communities which points to a critical need for enhanced predictive capabilities. The impacts of hurricane winds, storm surge and inland flooding remain major threats to the Nation's coastal communities. Inland flooding after hurricane landfall is becoming more devastating as Americans continue the trend of building new homes and businesses in low-lying flood plains. Accurate and early forecasts of hurricanes give emergency managers and people time to prepare for the possibility of disastrous affects that are coming, including possible evacuations. Understanding the location and severity of hurricane landfall is the key to planning long before the event. Well-orchestrated responses in the years, months, days, hours and even minutes before hurricane landfall can limit the loss of human lives and property damage.

NOAA's Office of Oceanic and Atmospheric Research strives to improve the reliability, accuracy, timeliness, and specificity of predictions of hazardous weather, such as hurricanes, to help society cope with these phenomena. Research results from the Hurricane Research Division, in conjunction with the National Weather Service modernization efforts, have helped to improve our hurricane prediction capabilities. Over the last 30 years, the improvement in forecast error has averaged about 1% per year, largely due to an increased understanding of hurricane dynamics, improvements in computing and technology and more data in the region around the hurricane. However, more accurate predictions with greater lead times are becoming increasingly more important with the onslaught of increasing coastal population and infrastructure coupled with the increased likelihood of severe hurricanes over the next couple of decades.

The following information details the current Atlantic hurricane situation and attempts to relate the increased hurricane activity to an increased potential for storm-related damage caused by hurricanes and their associated flood and wind-related conditions.

The years 1995-2000 experienced the highest level of North Atlantic hurricane activity ever measured. Compared with the previous 24 years (1971-94), there were twice as many hurricanes in the Atlantic, including two and a half times more major hurricanes. Major hurricanes are those reaching Category 3 strength with winds exceeding 110 mph and most of the deadliest and costliest Atlantic tropical cyclones are major hurricanes. In this same period, more than five times as many hurricanes impacted the Caribbean Islands. Today, major hurricanes account for just over 20% of the landfalling United States tropical storms and hurricanes but cause more than 80% of the damage. Overall, the United States has experienced about five times greater average damages from tropical storms and hurricanes during the warm (high activity) than during the cold (low activity) phases of the Atlantic multidecadal mode.

Based upon changes in oceanic and atmospheric conditions, we think this increased activity is due to a natural cycle called the Atlantic Multidecadal Mode, a north Atlantic and Carribean sea surface temperature shift between warm and cool phases that each last 20 to 40 years. The data suggest that we are in a warm Atlantic phase; thus, an active Atlantic hurricane era may be underway, similar to that last seen from the late 1920s to the late 1960s. Further, our results suggest that the record amount of hurricane activity could possibly be caused by a combination of the multidecadal ocean temperature changes plus a small contribution from the long-term warming trend. Known cycles of natural variability are high. However, inadequacies in the data record make long-term warming a difficult issue to resolve because model variability studies are inconclusive.

The North Atlantic hurricane season officially lasts from June 1 to November 30. The tropical storms that can turn into hurricanes and threaten the east and Gulf coasts of the United States form in the Gulf of Mexico, Caribbean Sea, and Atlantic, many developing from easterly waves moving off the west coast of Africa. Hurricanes are fueled by warm water as they travel across the ocean. An abundance of warm water provides more energy allowing the storm to increase in strength. However, we have found that the warm water alone was not enough. The winds between the upper and lower troposphere (the first seven miles of our atmosphere starting from the ground or ocean and going upwards) also play a major role. Strong vertical shear (i.e. a large difference in the speed and direction of the wind between the lower and upper troposphere) in the wind inhibits the formation or intensification of tropical cyclones whereas, weak wind shear encourages them.

Evidence from our research, recently published in Science, suggests that many of the hurricane seasons in the next two or three decades may be much more active than they were in the 1970's through the early 1990's. The present high level of hurricane activity is likely to persist for an additional 10-40 years. Warmer sea surface temperatures….are expected to contribute to conditions that foster more hurricanes over this period. Thus, we should prepare for a busy period of hurricane activity.

Consistent with experience since the active phase began in 1995, there would be a continuation of significantly increased numbers of hurricanes (and major hurricanes) affecting the Caribbean Sea, and basin-wide numbers of major hurricanes. The Gulf of Mexico, however, is expected to see only minor differences. Tragic impacts of the heightened activity have already been felt, especially in the Caribbean. In addition, an increase in major hurricane landfalls affecting the U.S. East Coast is anticipated.

An active hurricane season does not necessarily mean more storms making landfall. In 1992, Hurricane Andrew became the costliest disaster in U.S. history and was the only hurricane to make landfall that year. While anticipating generally high activity during the hurricane seasons for the next few decades, we do not expect every year to be hyperactive. Nonetheless, rapidly increased population and development means that hurricane damage will be far more than previously experienced by coastal residents. Years with a low level of activity can produce disasters because even weak storms can cause devastating flooding.

Although increased activity during a particular year does not automatically mean increased storm-related damages, years with high activity have a greater overall potential for disaster than years with low activity. Increased occurrence combined with dramatic coastal population increases during the recent lull, add up to a potential for massive economic loss. In addition, there remains a potential for catastrophic loss of life in an incomplete evacuation ahead of a rapidly intensifying system. Government officials, emergency managers, and residents of the Atlantic hurricane basin should be aware of the apparent cyclical changes and evaluate preparedness and mitigation efforts in order to respond appropriately in a regime where the hurricane threat is much greater than it was in the 1970s through early 1990s.

The primary goal of the U.S. Weather Research Program (USWRP) is to increase the accuracy and lead time of hurricane forecast predictions. The USWRP is a well-organized, multi-agency collaborative program. NOAA cooperates with NASA, NSF, the Navy, and the university community to conduct weather research that will improve forecasts of the location and intensity of hurricanes in advance of their arrival. NOAA's Hurricane Research Division provides many observational contributions to the Hurricane Program within the USWRP. As the likelihood of hurricane frequency and severity along the Atlantic coastline increases, the need for accurate prediction capabilities will continue to grow if we are to provide timely warnings for our coastal residents.

I would like to express my appreciation again to you Mr. Chairman and members of the Committee for this opportunity to explain the multidecadal increase in hurricanes of the Atlantic basin and the far-reaching implications this increase has for our country. I look forward to future milestones and improvements in hurricane research and to the many contributions NOAA can continue to make in this important area. Through NOAA's leadership, our understanding of hurricanes and subsequent improvements in operational hurricane predictions have improved. We have come a long way but still have much to accomplish before all U.S. citizens will reap the benefits of our weatherproofing efforts. Thank you again for the invitation today. I hope this summary has been useful. My testimony for the record will include an attachment of the full text, including figures, from my recent *Science* magazine article providing more specific technical data which served as the basis for my remarks today. I would be happy to address any questions you may have.

Appendix I.

The Recent Increase in Atlantic Hurricane Activity: Causes and Implications

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Please Note: This revised manuscript is in the format of the final submission to *Science*. Numerous editorial and several minor content changes where made prior to publication.

The manuscript appears in the July 20th, 2001 issue of *Science*.
Vol. 293, pp. 474-479.

Supplemental material is found on the web at:
Posted at ***Science*** **Online** at: **www.sciencemag.org/cgi/content/full/293/5529/474/DC1**

The years 1995-2000 experienced the highest level of North Atlantic hurricane activity in the reliable record. Compared with the generally low activity of the previous 24 years (1971-94), the last six years have seen a doubling of overall activity for the whole basin, a 2.5-fold increase in major hurricanes (= 50 m s^{-1}) and a five-fold increase in hurricanes affecting the Caribbean. The greater activity results from simultaneous increases in North Atlantic sea-surface temperatures and decreases in vertical wind shear. Because these changes exhibit a multidecadal time scale, the present high level of hurricane activity is likely to persist for an additional ~10-40 years. The shift in climate calls for a reevaluation of preparedness and mitigation strategies.

During 1970-87, the Atlantic basin experienced generally low levels of overall tropical cyclone activity. The relative lull was manifested in major hurricane (*1*) activity (Fig. 1), major hurricane landfalls on the U.S. East Coast, and overall hurricane activity in the Caribbean. A brief resurgence of activity in 1988 and 1989 made it appear that the Atlantic basin was returning to higher levels of activity similar to the late 1920s through the 1960s (*2*). This notion was later discarded when the activity returned to lower levels from 1991-94 (*3*), due in part to the long-lasting (1990-95) El Niño event (*4*). This event ended in early 1995 and was followed later that year by one of the most active Atlantic hurricane seasons on record (*5*). Activity has been well-above average each year since 1995, except for 1997. Here we address the question of whether or not the increase in activity reflects a long-term climate shift, as suggested by previous studies (*6-9*), and provide evidence that confirms this suggestion based upon changes in oceanic and atmospheric conditions.

The North Atlantic basin (including the North Atlantic Ocean, Caribbean Sea and Gulf of Mexico) exhibits substantial interannual and interdecadal variability of tropical cyclone activity. This variability is especially pronounced in major hurricane activity. Interdecadal major hurricane fluctuations occur in both landfall locations (*10*) and overall activity (*11-13*). Most of the deadliest and costliest Atlantic tropical cyclones (*10*) are major hurricanes. Major hurricanes account for just over 20% of the landfalling United States tropical storms and hurricanes but cause more than 80% of the damage (*14*).

Most Atlantic tropical cyclones form from atmospheric easterly (African) waves that propagate westward from Africa across the tropical North Atlantic and Caribbean Sea primarily between 10° and 20°N [termed the "main development region" (MDR) (*15, 16*) (see Fig. 2A)]. The Atlantic tropical cyclones not spawned by African waves usually form poleward of 25°N. African waves account for ~60% of the Atlantic basin tropical storms and non-major hurricanes but ~85% of major hurricanes (*17*). Almost all major hurricanes formed from African waves begin development (i.e., attain tropical depression status) in the MDR (*15*) and thus are more sensitive to climatic fluctuations in the tropics.

Although the number of easterly waves in the tropical Atlantic is fairly constant from year to year, the fraction that develops into tropical cyclones varies substantially (*18*, *19*). The key to understanding the fluctuations on interannual and interdecadal scales is the MDR. The climatic forcing that affects that region can be separated into local and remote factors. In combination, these factors influence the number of waves that develop into tropical cyclones during each hurricane season. Local factors occur in the actual region and have a direct thermodynamic or dynamic connection to development. Remote factors occur away from the MDR, but are associated (via teleconnections) with conditions in that region. All factors vary on disparate temporal and spatial scales, and there is considerable interdependence between some of them. The extremely active 1995 season, for example, resulted from the juxtaposition of virtually all of the factors known to favor development (*5*). Among the local tropical Atlantic factors are the lower stratospheric Quasi-Biennial Oscillation (*20, 21*), sea-level pressure (*5, 20, 22*), lower tropospheric moisture (*5*), sea-surface temperature (SST) (*23-25*), and vertical shear of the horizontal environmental wind (*15, 26*). The two local factors addressed here are SST and vertical shear.

In general, when looking for long-term variability, it is necessary to look at the oceans because their large thermal and mechanical inertia provide long-term memory and predictability (*27*). The oceans are the primary energy source for tropical cyclones. Localized SSTs play a direct role in providing moist enthalpy to power incipient tropical cyclones (*5, 25*). Warmer SSTs decrease atmospheric stability which increases the penetration depth of a vortex thus making developing tropical cyclones more resistant to vertical wind shear (*28*). Local SST > 26.5°C is usually considered to be a necessary condition for tropical cyclone development (*26*), and higher SST can increase overall activity (*23-25*). Multidecadal variations in major hurricane activity have been attributed to changes in the SST structure in the Atlantic (*2, 12, 13*) as tropical North Atlantic SSTs correlate positively with major hurricane activity. Although North Atlantic SSTs directly impact tropical cyclone activity as a local thermodynamic effect, it appears unlikely that this is their only physical link to hurricane activity. For influencing activity on interannual time scales, this local effect plays either a negligible role (for major hurricanes) or at best a secondary role (for all hurricanes) (*24*).

The dominant local factor for tropical cyclone activity is the magnitude of the vertical shear of the horizontal wind between the upper and lower troposphere, vertical wind shear. Strong Vertical wind shear inhibits the formation and intensification of tropical cyclones (e.g., *15, 26*), primarily by preventing the axisymmetric organization of deep convection. Local vertical wind shear > ~8 m s^{-1} is generally unfavorable for development (*29*). The climatological mean vertical wind shear, Vertical wind shear, for August-September-October (ASO), the peak three months of the Atlantic hurricane season during which virtually all major hurricanes form, is westerly with a magnitude, vertical wind shear, greater than 8 m s^{-1} over much of the basin (*15, 16*). Climatologically high values for vertical wind shear are one of the main reasons why conditions in the Atlantic basin are not especially conducive to tropical cyclone development. The tropical North Atlantic SST appears to act in concert with the overlying tropospheric circulation such that warmer SSTs correspond to reduced vertical wind shear in the MDR (*12, 24*).

A key remote factor is SST variability in the central and eastern equatorial Pacific Ocean associated with El Niño/Southern Oscillation (ENSO). Positive Pacific SST anomalies associated with warm-phase ENSO (El Niño) have been linked to increased vertical wind shear over the MDR, and conversely for cool-phase ENSO (La Niña) (*15, 20*, *30*). Another remote factor that has been linked to interannual and multidecadal variability in Atlantic basin tropical cyclone activity is rainfall variability over the western Sahel (*2*, *31*), with positive rainfall anomalies associated with reduced vertical wind shear over the MDR (*15*).

The most obvious indicator of a possible long-term shift is the changes in the tropical cyclone activity itself. The total number of tropical storms and non-major hurricanes in the North Atlantic basin has remained fairly constant from decade to decade (*13*). The numbers of major hurricanes and of Caribbean hurricanes, however, exhibit strong multidecadal variability. The late 1920s to the 1960s were very active, while both the 1900s through mid-1920s and the 1970s through the early 1990s were quiescent (*2, 12, 13*).

The events of each year reflect a combination of temporal scales. Interannual fluctuations in activity occur in both high and low activity periods (Fig. 1). Inhibiting influences during relatively inactive multidecadal periods, however, set a limit on the possible level of activity. During 1944-70 (the portion of the previous active multidecadal period shown in Fig. 1), the average number of major hurricanes per year was 2.7 (*32-34*). Six of the years produced four or more major hurricanes. In contrast, the average for the quieter period of approximate equal duration, 1971-94, was only 1.5, with no years having >3 major hurricanes. The quieter period's threshold of three major hurricanes was then exceeded in 1995 for the first time since 1964. The average number of major hurricanes for 1995-2000 is 3.8 (*34*). Three of those years had four or more. The Net Tropical Cyclone activity

(NTC) for the North Atlantic, another measure of activity (*8*), shows a similar combination of interannual and multidecadal fluctuations (*35*). The only year since 1995 with below-average activity was 1997, when the Atlantic hurricane activity was suppressed by the strongest El Niño event of this century (*36*). Even with 1997 included, the mean number of major hurricanes and mean NTC for 1995-2000 are the highest of any consecutive six years in the 1944-2000 record. While this recent period spans only six years, it clearly belongs to a different low-frequency climate regime than the previous 24 years (1971-94).

Studies of global SSTs using empirical orthogonal function (EOF) analysis (e.g., *37*) have shown that the primary source of interannual SST variability is the ENSO region. To analyze the relationship of Atlantic tropical cyclone activity with Atlantic SST anomalies in a way that is independent of ENSO, it is helpful to first remove the teleconnected effects of ENSO on the Atlantic Ocean (*38*). The first rotated non-ENSO SST mode (*39*) represents interannual to multidecadal variability (Fig. 2). Because the mode's temporal variability is dominated by multidecadal-scale fluctuations (Fig. 2B) with the largest amplitudes in the Atlantic, we refer to it as the "Atlantic multidecadal mode". The positive phase of the mode's spatial pattern (Fig. 2A) has warm SSTs in the tropical North Atlantic from 0° to 30°N (which includes the MDR) and in the far North Atlantic from 40° to 70°N. This mode is not local to the MDR; it is instead a large-scale feature that, because it is also present in the MDR, affects Atlantic tropical cyclone activity. The primary region for SST anomalies that would affect tropical cyclones directly would be in and just north of the MDR, i.e., ~10-25°N (*24, 40*).

These multidecadal-scale fluctuations in SSTs closely follow the long-term fluctuations in Atlantic tropical cyclone activity (*13*). The time series for the Atlantic multidecadal mode (Fig. 2B), major hurricanes (Fig. 1) and NTC (*35*) all show similar multidecadal-scale shifts. Ignoring interannual fluctuations, major hurricane activity is high from 1944 through at least ~1964 (Fig. 1), NTC is high through ~ 1969 (*35*) and the Atlantic multidecadal mode is predominately warm until ~ 1970 (Fig. 2B). Then, major hurricane activity and NTC are mostly below average and the Atlantic multidecadal mode colder from the early 1970s through the early 1990s. All three quantities have increased dramatically since 1995. Note also that the two busiest periods in the 1970s and 1980s, 1979-81 and 1988-90 (*35*), coincide with two short warming periods, 1979-81 and 1987-90 (see Fig. 2B), indicating the possibility of significant relationships on shorter (decadal) time scales. The correlations between the 5-year running mean of the Atlantic multidecadal mode with the major hurricane and NTC running means are 0.72 and 0.81, respectively (*41*).

It has been hypothesized that multidecadal changes in oceanic temperatures, major hurricane activity and Sahel rainfall are related to fluctuations in the intensity of the thermohaline circulation in the North Atlantic (*12, 42*). A faster thermohaline circulation is suggested to be associated with warmer SSTs in the North Atlantic and colder SSTs in the South Atlantic. These conditions would enhance Sahel rainfall and decrease vertical wind shear in the MDR. In other words, the decadal-scale SST fluctuations affecting Atlantic hurricane (particularly major hurricane) activity would likely produce the connection via changes in the upper- and lower-level zonal atmospheric circulations over the MDR (*40*). It is also possible, but less likely, that the changes in atmospheric circulation are forcing the SST changes. It is doubtful, however, that long-term increased tropical cyclone activity could cause warmer North Atlantic SSTs since hurricanes result in a cooling of SSTs through vertical mixing and upwelling (e.g., *43*).

Figure 3 shows the fluctuations in vertical wind shear averaged for ASO for the south-central portion of the MDR where the strongest correlations between vertical wind shear and major hurricanes occur (*15, 16*). Although there is substantial interannual variability in vertical wind shear, primarily associated with ENSO, this is being modulated by the obvious multidecadal-scale fluctuations. These fluctuations show a switch from conducive (high percentages of low vertical wind shear) to suppressed (low percentages of low vertical wind shear) conditions in 1970, almost coincident with the shift in major hurricanes (Fig. 1), NTC (*35*) and SSTs (Fig. 2B). In Fig. 3, however, the switch back to conducive conditions appears to start in 1988 (*44*), seven years earlier than the switch for the other parameters. Even though 1991 through 1994 exhibit a short-term return to less conducive values, 1988 through 1990 had the most favorable values since 1969. Figure 2 shows some evidence of North Atlantic SST warming for a few years around 1988 followed by several cooler years in the early 90's before the major warming in 1995. The warming around 1988 is much more evident in the Atlantic multidecadal mode values for ASO and in the actual ASO SSTs for the MDR (not shown). Nonetheless, the dominant shift to warmer values clearly takes place in 1995, which is when occurrences of >3 major hurricanes and hyperactive years [NTC = 150%; (*35*)] resumed.

For almost every measure of tropical cyclone activity, the differences between the warm and cold phases of the mode are statistically significant (*34, 44*). The single exception is the number of U.S. Gulf Coast landfalling major hurricanes. This is because the Gulf of Mexico activity does not have a significant relationship with vertical wind shear fluctuations in the MDR (*11, 12, 15*) or to the multidecadal North Atlantic SST fluctuations (Fig. 2A). The greatest differences (ratios) are for major hurricanes, hurricane days, U.S. East Coast major hurricane landfalls, and especially Caribbean hurricanes and U.S. damage. The Caribbean Sea has shown dramatic changes in hurricane activity -- averaging 1.5 occurrences per year during the warm periods compared to only 0.5 per year during the cold period (*34*). The current warm period has produced an average of 2.5 occurrences per year with an unprecedented (since 1944) six hurricanes in the region during 1996. These multidecadal changes are illustrated in Fig. 4, which clearly shows the enhancement of overall Caribbean hurricane activity during warmer periods. Not only is the entire Caribbean region much less active during the colder period (Fig. 4A), but the only hurricanes that developed during that period in the Caribbean Sea east of ~73°W formed during the two intermittent short warming periods (1979-81 and 1987-90) discussed earlier. Large multidecadal fluctuations of major hurricane landfalls are especially evident for the U.S. East Coast from the Florida peninsula to New England and are illustrated in Fig. 5. No major hurricanes made landfall from 1966-83. This relatively quiet period was similar to, but more extreme than, the low activity period during the first two decades of the 20th Century. In contrast, during 1947-65, 14 major hurricanes struck the East Coast (*13*). Overall, the United States has experienced about five times as much in median damages from tropical storms and hurricanes during the warm (high activity) than during the cold (low activity) phases of the Atlantic multidecadal mode (*44*).

The Atlantic tropical cyclone record, which (except for U.S. landfall data) is not considered reliable before 1944 (*33*), shows less than one complete cycle of the multidecadal signal. The record for the SST signal represented by the Atlantic multidecadal mode (Fig. 2B), however, which has demonstrated a robust relationship with the observed activity, shows about two complete cycles -- with some proxy records extending back several additional cycles (*42*). In addition, U.S. landfall data are able to show almost two periods of the signal (*13, 44*). Because of the multidecadal scale of the Atlantic SST variability portrayed here, the shift since 1995 to an environment generally conducive to hurricane formation -- warmer North Atlantic SSTs and reduced vertical wind shear -- is not likely to change back soon (*45*). This means that during the next 10-40 years or so, most of the Atlantic hurricane seasons are likely to have above average activity, with many hyperactive, some around average, and only a few below average. Furthermore, consistent with experience since the active phase began in 1995, there would be a continuation of significantly increased numbers of hurricanes (and major hurricanes) affecting the Caribbean Sea, and basin-wide numbers of major hurricanes. The Gulf of Mexico, however, is expected to see only minor differences. Tragic impacts of the heightened activity have already been felt, especially in the Caribbean [e.g., Hurricanes

Georges and Mitch (*46*)]. In addition, an increase in major hurricane landfalls affecting the U.S. East Coast is anticipated, but has not yet materialized (*47*).

Some have asked whether the increase in activity since 1995 is due to anthropogenic global warming. The historical multidecadal-scale variability in Atlantic hurricane activity is much greater than what would be "expected" currently from a gradual global temperature increase attributed to global warming (*5*). There have been various studies investigating the potential effect of long-term global warming on the number and strength of Atlantic-basin hurricanes. The results are inconclusive (*48*). Some studies document an increase in activity while others suggest a decrease (*49*). Tropical North Atlantic SST has exhibited a warming trend of ~0.3˚C over the last 100 years (*38*); whereas Atlantic hurricane activity has not exhibited trend-like variability, but rather distinct multidecadal cycles as documented here and elsewhere (*12, 13, 17*). The extreme activity in 1995 has been attributed in part to the record-warm temperatures in the North Atlantic (*25*). The possibility exists that the unprecedented activity since 1995 is the result of a combination of the multidecadal-scale changes in Atlantic SSTs (and vertical shear) along with the additional increase in SSTs resulting from the long-term warming trend. It is, however, equally possible that the current active period (1995-2000) only appears more active than the previous active period (1926-70) due to the better observational network now in place. During the previous active period, only 1966-70 had continual satellite coverage (*33, 50*). Further study is essential to separate any actual increase from an apparent one due to more complete observations.

Although increased activity during a particular year does not automatically mean increased storm-related damages (*51*), years with high activity have a greater overall potential for disaster than years with low activity. Increased occurrence combined with dramatic coastal population increases during the recent lull, add up to a potential for massive economic loss (*13*). In addition, there remains a potential for catastrophic loss of life in an incomplete evacuation ahead of a rapidly intensifying system. Government officials, emergency managers, and residents of the Atlantic hurricane basin should be aware of the apparent shift in climate and evaluate preparedness and mitigation efforts in order to respond appropriately in a regime where the hurricane threat is much greater than it was in the 1970s through early 1990s.

References and Notes

1. The stages of a tropical cyclone [tropical system (warm core) with "closed" surface circulation and organized deep convection] include tropical depression [maximum sustained (1-min. mean) surface wind < 18 m s^{-1}], tropical storm (18 to 32 m s^{-1}) and hurricane (= 33 m s^{-1}). Hurricanes that have attained a maximum sustained surface wind speed = 50 m s^{-1} are referred to as major (or "intense") hurricanes (*17*), corresponding to categories 3, 4 or 5 on the Saffir-Simpson scale (*53*). The data source used to calculate the tropical cyclone parameters used in this study is the best track file for the Atlantic basin (*54*) compiled by the National Hurricane Center (NHC) of the Tropical Prediction Center (TPC) /National Atmospheric and Oceanic Administration (NOAA).
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synoptic meteorology is to use the term "vertical shear", *Vertical wind shear*, for the difference in velocity between the upper (200 mb) and the lower (850 mb) troposphere without dividing by the distance between the levels, so that the units of *Vertical wind shear* are (m s^{-1}) rather than (s^{-1}) or (m s^{-1} km^{-1}).

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32. Landsea (*17*) documented that strong hurricanes in the 1940s to the 1960s were assigned slightly higher maximum sustained surface wind speeds for a particular minimum central surface pressure than hurricanes from 1970-1991 with the same central pressure. This bias is as high as 5 m s^{-1} for category 4 and 5 hurricanes. At the threshold value for major hurricanes of 50 m s^{-1}, the bias appears to be ~2.5 m s^{-1}. Therefore, consistent with his bias adjustment, 52 m s^{-1} is used for the present study as the threshold for major hurricanes from 1944-69. This bias adjustment effectively lowers the number of major hurricanes for certain years before 1970 (e.g., the number of major hurricanes for 1969 is reduced from five to three) and reduces the values for other parameters that utilize major hurricane data.
33. Although these data are available since 1851, only the data for the years since 1944, when routine aircraft reconnaissance of Atlantic tropical cyclones began, are considered very reliable. The greatest reliability starts around the mid-1960s when operationally satellite detection of Atlantic tropical cyclones began (*50*). Before satellite coverage, a portion of the lifetimes of many systems had probably been missed.
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35. See Web figure 2 in supplemental material (*55*).
36. G.D. Bell, M.S. Halpert, *Bull. Amer. Meteor. Soc.* **79**, S1 (1998).
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analysis is a multivariate statistical technique commonly used in climate studies. It allows one to capture the main spatial and temporal variability of climate variables as a few "empirical modes". These modes, however, do not always represent physical modes.

38. D.B. Enfield, A.M. Mestas-Nuñez, *J. Climate* **12**, 2719 (1999). They represented ENSO as the leading complex EOF of global 1856-1991 SST anomalies in the interannual (1.5 - 8 yr) band. Contrary to conventional EOF analysis, complex EOF analysis allows accounting for phase propagation in a single mode. The ENSO mode and a linear trend were then removed from the SST anomalies and an EOF analysis was used to study the residual (non-ENSO) variability.

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44. See Web table 2 in supplemental material (*55*).

45. Instrumental and proxy data (1650 A.D. to present) as well as model simulations suggest that Atlantic multidecadal variability deviates significantly from a simple stochastic process (*42*). This evidence also indicates that the signal is broad band (30-70 years) and not a single peak in the spectrum. With a broad-band signal it is difficult to predict when sign changes will occur. Due to its multidecadal nature, however, it is reasonable to say that if the signal has recently changed sign, it will probably not change back soon.

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55. Supplemental material is available at : **www.sciencemag.org/cgi/content/full/293/5529/474/DC1**.

56. We thank H. Willoughby, F. Marks, J. Gamache, A. Barnston, L. Shapiro, P. Reasor, R. Rogers, R. Burpee and M. Finke for comments on the manuscript and helpful discussions, S. Feuer and J. Harris for assistance in processing the wind data, D. Enfield for assistance with

SST data and helpful suggestions, N. Dorst and S. Murillo for other technical support, S. Taylor, R. Simon, and B. Goldenberg for editing assistance, and D. Lewis for additional helpful support. In addition, we wish to thank M. DeMaria and an anonymous reviewer for their insightful comments and N. Ward for suggestions that helped initiate this study. Partial funding for this research comes from the NOAA Office of Global Programs (Pan-American Climate Studies).

Biography

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Christopher W. Landsea is a Research Meteorologist at the Hurricane Research Division (HRD) in the Atlantic Oceanographic and Meteorological Laboratory (AOML) of the National Oceanic and Atmospheric Administration (NOAA) located in Miami, Florida, U.S.A. Dr. Landsea received his Master's Degree and Doctorate in Atmospheric Science from Colorado State University (1991, 1994). His graduate work was under Dr. Bill Gray, one of the world's leading experts on hurricanes and tropical meteorology.

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He has published over 30 book chapters and articles in the journals Bulletin of the American Meteorological Society, Climatic Change, EOS, Geophysical Research Letters, Journal of Climate, Journal of Insurance Regulation, Meteorology and Atmospheric Physics, Monthly Weather Review, Science, Tellus, Weather and Weather andForecasting. Dr. Landsea is a member of the American Meteorological Society (AMS), the National Weather Association and the American Geophysical Union.

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