CAUSES OF THE UNUSUALLY DESTRUCTIVE 2004 ATLANTIC BASIN HURRICANE SEASON

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The very active and destructive 2004 Atlantic basin hurricane season is attributed to two primary features: a strong Atlantic equatorial trough and steering currents that caused hurricanes to track westward across the U.S. coastline.

The 2004 Atlantic basin hurricane season will be remembered for the hurricane-spawned destruction that it produced. It is estimated that destruction in the United States totaled more than $40 billion, which is more than the damage of Hurricane Andrew (1992; National Climatic Data Center 2004). Five of the six intense or major (Saffir–Simpson category 3, 4, or 5; Simpson 1970) hurricanes of 2004 formed in the low-latitude central Atlantic. Four of these six major hurricanes had long low-latitude westerly tracks across the Atlantic and impacted the Caribbean and the southeast United States (Fig. 1). This is to be contrasted with the previous nine years where most major hurricanes recurved before reaching the U.S. coastline (Fig. 2).

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DOI:10.1175/BAMS-87-10-1325

In final form 6 May 2006

According to best-track data from the National Hurricane Center (2004), the 2004 Atlantic basin hurricane season had 14 named storms (NS), 9 hurricanes (H), and 6 intense or major hurricanes (IH). In addition, 22.25 intense or major hurricane days (IHD) occurred during the year. All 22.25 intense hurricane days occurred during the months of August and September, which is 5.4 times the August–September 1950–2000 average. Table 1 displays a summary of tropical-cyclone statistics for the 2004 season along with definitions of these statistics. Note that we do not count Subtropical Storm Nicole in our seasonal statistics, as it was never classified as a tropical cyclone by the National Hurricane Center. Bell et al. (2005) discuss the 2004 Atlantic basin hurricane in some detail. In this paper, we go into greater detail discussing the physics behind why 2004 was as active and destructive as it was.

Utilizing an aggregate seasonal tropical-cyclone activity measure known as net tropical-cyclone (NTC) activity (Gray et al. 1994), 2004 ranked as the most active hurricane season since 1950, and no season since reliable records were established in the mid-1940s (including the record-breaking 2005 season) had more activity during August–September than did the 2004 season. The 2004 season accumulated 215 NTC units, of which 206 units

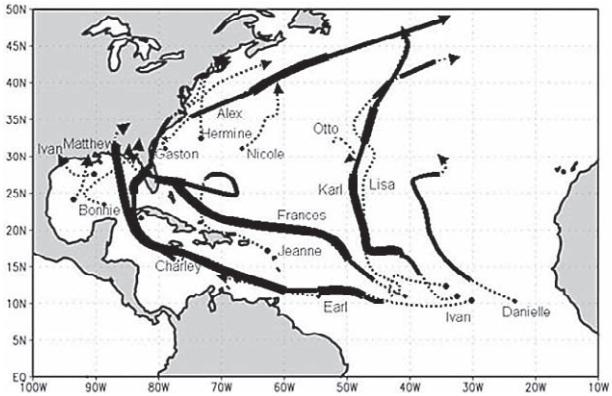

Fig. 1. Atlantic basin tropical-cyclone tracks for the 2004 season. Dotted lines represent tropical storm strength, thin solid lines represent hurricane strength, and thick solid lines represent intense or major hurricane strength.

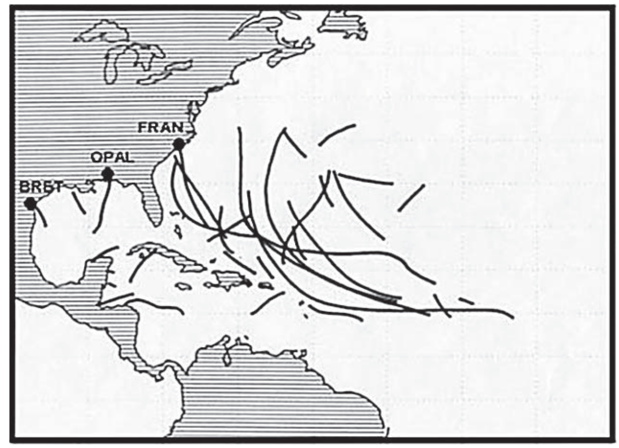

Fig. 2. Atlantic basin major hurricane tracks for the 1995–2003 seasons.

occurred during August and September. It should also be noted that the recently completed 2005 season shattered all previous NTC records, accruing approximately 260 NTC units. However, the August–September period of 2004 was much more active than the August–September period of 2005 and the August–September period of 1950. During 1950, only 170 of the 235 NTC units that were accumulated occurred during August–September; during 2005, only 110 of the 274 NTC units that were accumulated occurred during August–September. The average full season from 1950 to 2000 had 100 NTC units, and the average August–September had 76 NTC units. Table 2 contrasts 2004 Atlantic basin hurricane activity with that of the average season for the past 11 years (1995–2005), the previous 25 years (1970–94), and the 51-yr climatological average (1950–2000). Note how active the 2004 season was, especially with regard to major hurricane activity.

The 2004 season was also notable for its near-continuous midseason concentration of tropical-cyclone activity. From 25 August to 3 October (40 days), the National Hurricane Center was continually issuing tropical-cyclone advisories. However, the rest of the season was very inactive. June and July witnessed no tropical-cyclone activity, and only two weak tropical storms formed during the month

Table 1. Tropical-cyclone statistics for the 2004 season. The 1950–2000 climatological average value for each of these statistics is given in parentheses. We calculated 1950–2000 climatological average values using the raw data from the best-track database per the recent findings of Landsea (2005). The earlier suggested bias correction for intense hurricanes (e.g., Landsea 1993) is no longer used. Definitions for these statistics are as follows: NS are tropical cyclones with maximum surface winds > 17 m s^{-1}; H are tropical cyclones with maximum surface winds > 32 m s^{-1}; IH are tropical cyclones with maximum surface winds > 49 m s^{-1}; named-storm days (NSD) are four 6-h periods during which a tropical cyclone is observed to have attained tropical storm–force winds; hurricane days (HD) are four 6-h periods during which a tropical cyclone is observed to have attained hurricane-force winds; and IHD are four 6-h periods during which a tropical cyclone is observed to have attained intense hurricane-force winds. NTC activity is defined as in Gray et al. (1994) and is an aggregate measure of the following six parameters normalized by the percentage of their climatological averages: NS, NSD, H, HD, IH, and IHD.

Tropical-cyclone statistic	2004 observed value
Named storms (9.6)	14.0
Named-storm days (49.1)	90.25
Hurricanes (5.9)	9.0
Hurricane days (24.5)	45.5
Intense hurricanes (2.5)	6.0
Intense hurricane days (5.8)	22.25
Net tropical-cyclone activity (100)	215.0

of October. A weak tropical storm formed the last day of November.

The 2004 season also had an unusual number of long-lived intense hurricanes. Hurricane Ivan was a major hurricane for 10 consecutive days, the longest period on record. The 22.25 major hurricane days during the season are the most observed in a single season since reliable hurricane records became available around the mid-1940s.

We attribute the very active August–September of 2004 to two basic conditions: 1) an unusually strong Atlantic equatorial trough or intertropical convergence zone (ITCZ) and 2) an arrangement of near-stationary midlatitude ridge and trough patterns that inhibited recurvature of most of the westward-moving low-latitude tropical cyclones until they reached the longitudes of the United States.

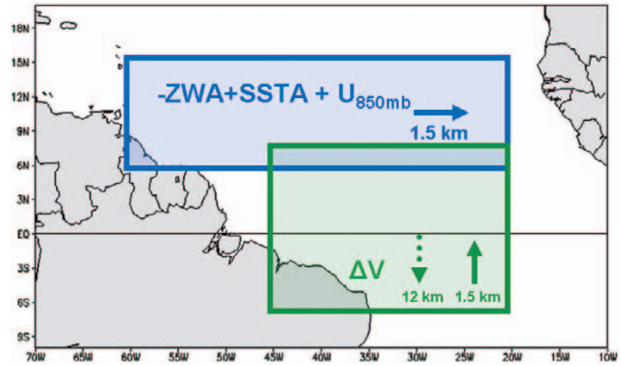

Fig. 3. Location of the atmospheric and oceanic fields utilized to define the Atlantic basin GP. Symbol definitions and longitude–latitude regions are listed in the text.

ENHANCED ATLANTIC EQUATORIAL TROUGH. Figure 3 displays the Atlantic regions that we associate with the strength of the equatorial trough during August–September. We evaluate conditions in August–September 2004 and compare these 2004 measurements with August–September periods from 1950 to 2005. Since we have just experienced record activity during the 2005 season, we have included values from the 2005 season for reference. The August–September period of 2004 was noteworthy because of the unusually strong Atlantic equatorial trough or ITCZ. We estimated this trough strength from a combination of three parameters that we define as the genesis parameter (GP),

Table 2. Comparison of 2004 and the last 11 years of Atlantic basin hurricane activity (1995–2005) with the prior quarter-century period (1970–94) and with climatology (1950–2000).

Year	NS	NSD	H	HD	IH	IHD	NTC
2004	14.0	90.25	9.0	45.5	6.0	22.25	215
11-yr average (1995–2005)	14.8	79.7	8.5	36.5	4.1	10.8	161
25-yr average (1970–94)	8.6	38.7	5.0	16.0	1.5	2.5	69
51-yr climatology (1950–2000)	9.6	49.1	5.9	24.5	2.5	5.8	100

$$GP = \Delta V + U_{850mb} + SSTA, \qquad (1)$$

where ΔV is the average August–September meridional wind component at 850 hPa minus the meridional wind component at 200 hPa in the green box (7.5°S–7.5°N, 20°–45°W), U_{850mb} is the average August–September 850-hPa zonal wind component in the blue box (5°–15°N, 20°–60°W), and SSTA is the average August–September sea surface temperature anomaly (SSTA) in the blue box (5°–15°N, 20°–60°W). We have used the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) to make calculations of the August–September values of each term of Eq. (1) for the 56 years between 1950 and 2005. The higher the value of the GP, the more intense the Atlantic equatorial trough, and the more favorable the tropical Atlantic for tropical-cyclone development and intensification.

Table 3 gives quantitative values of the GP based on the sum of the three terms in Eq. (1). Column 1 is a measure of the strength of the cross-equatorial flow, as derived from the difference between the 850- and the 200-hPa meridional winds between 7.5°S–7.5°N and 20°–45°W. Positive values indicate a stronger wind blowing into the trough at low levels and a stronger wind blowing away from the trough at upper levels. Such wind features provide more favorable conditions for tropical cyclogenesis by enhancing upward vertical motion within the trough and help-

Table 3. Comparison of Aug–Sep values of the GP. All values are listed in standard deviations. Years 2004 and 2005's rank with respect to each of the last 56 Aug–Sep periods (1950–2005) is given in parentheses.

	Column 1	Column 2	Column 3	Column 4	Column 5
Period	850- minus 200-hPa V anomaly (7.5°S–7.5°N, 20°–45°W	850-hPa U anomaly (5–15°N, 20°–60°W)	SSTA (5°–15°N, 20°–60°W)	GP: Combined columns 1 + 2 + 3	Annual Aug–Sep named storm formations south of 25°N
1950–69	−0.1	0.8	0.0	0.3	4.7
1970–94	−0.5	−0.8	−0.4	−0.7	3.3
1995–2003	1.3	0.4	0.9	1.2	5.4
2004	2.5 (2)	0.5 (18)	1.8 (4)	2.2 (3)	9.0 (1)
2005	2.3 (4)	0.6 (15)	2.6 (1)	2.5 (1)	7.0 (T-5)

ing to lower surface pressures of the passing easterly waves (Gray 1968). The 2004 season had the second highest values of this parameter.

Column 2 is a measure of the strength of the 850-hPa zonal-wind anomaly region 5°–15°N and 20°–60°W. When zonal winds have westerly anomalies, the trade winds are weaker, implying weaker tropospheric vertical wind shear and more favorable conditions for tropical-cyclone development and intensification (DeMaria 1996). Also, when the ITCZ in the tropical Atlantic is stronger than normal, the cross-equatorial wind flow tends to be anomalously strong out of the southwest. Hence, anomalous low-level westerly flow implies a stronger ITCZ. During August–September of 2004, zonal wind anomalies were 0.5 standard deviations from the west, implying favorable genesis conditions and a stronger ITCZ.

Column 3 is a measure of SSTAs within the region 5°–15°N and 20°–60°W. When Atlantic sea surface temperatures are warmer than normal, conditions are more favorable for tropical-cyclone genesis. Higher SSTAs provide increased latent and sensible heat flux from the ocean surface and consequently lower sea level pressure (Shapiro and Goldenberg 1998). These lower surface pressures in the tropical Atlantic thereby enhance low-level cross-equatorial flow into the Northern Hemisphere and consequently strengthen the ITCZ. Sea surface temperatures were 1.8 standard deviations above normal during August–September of 2004. This ranked as the fourth warmest of the last 55 years. It should be noted that according to the NCEP–NCAR reanalysis, the 2005 hurricane season had the warmest Atlantic sea surface temperatures over the entire 56-yr period.

When all three parameters are summed, the Atlantic GP was found to be the third highest on record since 1950, trailing only the very active seasons of 2003 and 2005. The total number of August–September named storm formations south of 25°N bears this out. Nine named storms formed south of this latitude during August–September of 2004. No season witnessed more named storm formations south of 25°N during August–September. When the highest 10 (of 56) August–September values of the GP are compared with the lowest 10 (of 56) August–September values of the GP, it was found that 58 named storms formed south of 25°N during the highest 10 GP periods compared with only 21 named storms forming south of 25°N during the lowest 10 GP periods. We believe that the GP is a very useful tool for evaluating conditions that are favorable for low-latitude Atlantic tropical-cyclone formation. Additional evidence for the utility of the GP is seen with the 2005 season. The GP was the highest on record, and seven named storms formed south of 25°N during August–September, which is well above the 1950–2005 average of 4.3 named storm formations per year. Figure 4 displays the GP and the number of August–September named storm formations south of 25°N for 1950–2005. In general, years with high values of the GP have many more named storm formations in the Tropics.

During each Atlantic hurricane season, easterly waves develop in the trade wind region over eastern and central North Africa. These easterly waves are noted to form and move westward every 2–3 days across the tropical Atlantic from July to September, with wave activity showing fairly small year-to-year variability (approximately 50–60 systems per year; Frank 1970). If the Atlantic equatorial trough is strong, a higher percentage of these waves will encounter favorable winds and thermodynamic conditions for tropical-cyclone formation and intensification. If the Atlantic equatorial trough is weak, fewer waves will develop. About 80% of all Atlantic basin major hurricanes form from such easterly waves (Landsea 1993). In seasons like 2004, when the Atlantic equatorial trough is unusually strong, 8–10 of these easterly waves may develop into named tropical cyclones; whereas, when the equatorial trough is weak, as few as 0–2 of these African waves may develop.

Although the Atlantic equatorial trough was very strong during the 2004 season, it has tended to also be quite strong since 1995. NCEP–NCAR reanalysis data have shown that North Atlantic sea surface temperatures have warmed considerably since 1995. Associated with this increase in North Atlantic SST has been an increase in Atlantic basin tropical-cyclone activity, particularly for major hurricane activity. This decadal increase has been noted in the literature and has been referred to as the positive phase of the Atlantic multidecadal mode (Goldenberg et al. 2001). In general, when the Atlantic multidecadal mode is in its positive phase; North Atlantic sea surface temperatures are warmer, sea level pressures are lower, vertical wind shear through the troposphere is weaker, and Atlantic hurricane seasons are enhanced. Recent-year enhancement of Atlantic-basin tropical-cyclone seasons is clearly evident. From 1970 to 1994, the average season witnessed 1.5 major hurricanes; whereas, from 1995 to 2005, the average season witnessed 4.1 major hurricanes. The last 11 years have therefore seen a 275% increase in Atlantic major hurricanes as compared with the earlier 25-yr period.

We believe that this increase in North Atlantic sea surface temperatures is associated with an increase in the strength of the Atlantic Ocean thermohaline circulation (THC); although there is some scientific question as to whether the circulation has been strengthening or weakening over recent decades. Bryden et al. (2005), in an observational study, claim that the meridional overturning circulation, a proxy for the THC, has weakened by approximately 30% since 1957. They caution, however, that their findings are close to the margin of error in their measurements. In contrast, two modeling studies (Latif et al. 2004; Knight et al. 2005) find that when the Atlantic Ocean thermohaline circulation is strong, salinity in the North Atlantic tends to be higher, and sea surface temperatures over the North Atlantic are warmer, similar to what has been observed since 1995 (Goldenberg et al. 2001). We theorize that the enhanced Atlantic equatorial trough, weaker tropospheric vertical wind shear and enhanced tropospheric horizontal wind shear, lower sea level pressure, and warm Atlantic sea surface temperatures all derive from a change to a positive phase of the Atlantic multidecadal mode and a strengthening of the Atlantic thermohaline circulation.

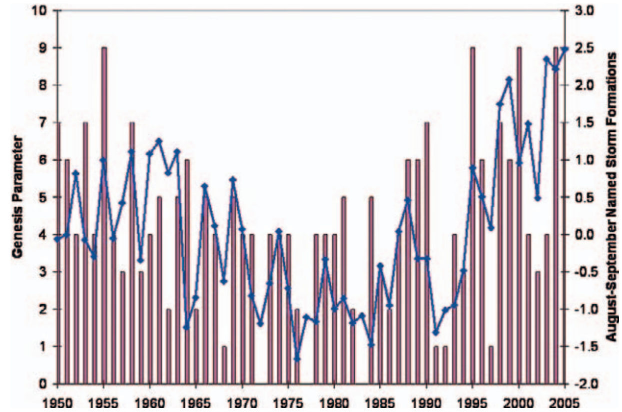

Fig. 4. The GP and Aug–Sep named storm formations south of 25°N for 1950–2005; GP is the blue solid line, and named storm formations south of 25°N are the red columns. Note that, in general, more named storm formations occur when GP values are above average.

FAVORABLE STEERING CURRENTS FOR U.S. HURRICANE LANDFALL. The four destructive hurricanes that made landfall in Florida and Alabama in 2004 distinguish this season from the other active hurricane seasons between 1995 and 2003 (1995–96, 1998–2001, 2003). During August–September 2004, a quasi-stationary ridge of high pressure was present in the midtroposphere (~500-hPa level) over eastern Canada and the northeast United States. Saunders and Lea (2005) observe that when high pressure is present over the eastern United States and Canada during August–October, the U.S. accumulated cyclone energy (ACE) index, a measure of hurricane landfall intensity, tends to be above average. Associated with these eastern North American ridge conditions was the presence of similar quasi-stationary upstream and downstream troughs of low pressure over the western United States and the east-central Atlantic. Figure 5 displays this predominant quasi-stationary ridge–trough pattern that was present during much of August–September 2004. These northeastern U.S.–eastern Canada upper-air ridge conditions caused the western side of the Bermuda

Table 4. Combined genesis-intensification-westward track (defined as the LP during Aug–Sep periods). All values are listed in standard deviations. Years 2004 and 2005's rank with respect to each of the last 56 Aug–Sep periods (1950–2005) is given in parentheses.

	Column 1	Column 2	Column 3	Column 4	Column 5
Period	GP	Intensification: Negative of 200-hPa U (5°–15°N, 20°–60°W)	Westward-track motion: 500-hPa ht (40°–50°N, 65°–75°W) – (50°–60°N, (20°–30°W) – (40°–50°N, 100°–110°W)	Total U.S. TC LP: Combined columns 1 + 2 + 3	Aug–Sep U.S. hurricane landfall
1950–69	0.3	1.1	0.0	0.7	1.4
1970–94	–0.7	–0.7	0.1	–0.7	1.0
1995–2003	1.2	–0.5	–0.4	0.2	1.0
2004	2.2 (3)	–0.4 (32)	1.3 (5)	1.5 (2)	6.0 (1)
2005	2.5 (1)	–0.5 (34)	0.3 (22)	1.2 (9)	3.0 (T-4)

high to be strengthened and extend further westward than in an average year. Since hurricanes are steered by their surrounding midlevel (~500 hPa) height and wind fields (George and Gray 1976), such a pattern favors landfall along Florida and the eastern U.S. coastline. The quasi-stationary upper-air ridge conditions caused a high percentage of the hurricanes that formed at low latitudes in the central Atlantic to move on long westward tracks toward the United States. This is in contrast to the typical major hurricane tracks of 1995–2003, which tended to recurve into the middle-latitude westerlies before reaching the longitudes of the United States. During the nine years of 1995–2003, only 3 of the 32 major hurricanes that developed in the Atlantic basin made landfall in the United States (Fig. 2). By contrast, three of the six major hurricanes that formed in 2004 made U.S. landfall as category 3 or greater storms, and four of the seven major hurricanes that formed in 2005 made U.S. landfall as category 3 or greater storms. The twentieth-century average of U.S. major hurricane landfall versus the number of Atlantic basin major hurricanes is approximately 1 to 3.5.

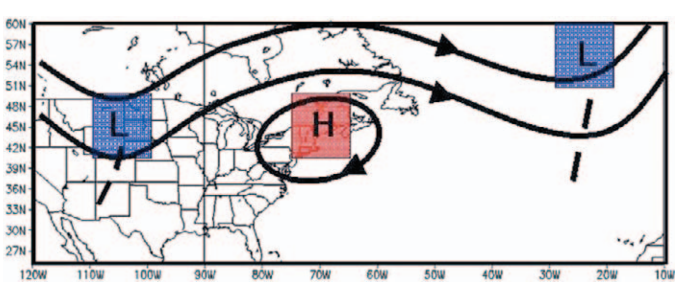

Fig. 5. Prevailing upper-level height pattern during Aug–Sep 2004 in the northern part of the Western Hemisphere with 500-hPa regions shown in colored boxes. The red box with an H indicates an anomalous upper-level high or ridge, and the blue boxes with an L indicate an anomalous upper-level low or trough.

Table 4 displays a genesis-intensification-westward track U.S. landfall parameter (LP), which is defined as follows:

$$LP = GP + ZWA + SC, \quad (2)$$

where GP is the genesis parameter as defined in Table 2, ZWA is the negative of the average August–September 200-hPa zonal wind component within 5°–15°N, 20°–60°W, and SC is the steering current and is defined as the average August–September 500-hPa heights within 40°–50°N, 65°–75°W, minus the average August–September 500-hPa heights within 40°–50°N, 100°–110°W, minus the average August–September 500-hPa heights within 50°–60°N, 20°–30°W.

This parameter was calculated from the NCEP–NCAR reanalysis data. Column 1 is the same Atlantic basin GP as derived in Table 2. Column 2 is a measure of 200-hPa zonal wind anomalies within 5°–15°N, 20°–60°W. When these winds are anomalously from the east, tropospheric vertical wind shear is reduced, and conditions are more favorable for tropical-cyclone development and intensification (DeMaria 1996). In general, the 1950s and 1960s witnessed strong anomalous easterly winds. This accounts for why most seasons during these two decades were quite active, although thermodynamic features in the 1950s and 1960s such as Atlantic sea surface temperatures were not as favorable as they have been during the past decade. In 1997, although the equatorial trough was strong, vertical wind shear was also quite strong and inhibited low-latitude tropical-cyclone development. Column 3 is a measure of potential westward-track motion or the intensity of the northeastern U.S. ridge versus that of the troughs to the west and to the east. To measure the stationarity of this pattern, we difference the 500-hPa heights in the area of 40°–50°N, 65°–75°W (East Coast ridge) from the 500-hPa heights at 50°–60°N, 20°–30°W (north of Azores Islands trough), and the 500-hPa heights are 40°–50°N, 100°–110°W (western U.S. trough). High values of this parameter indicate easterly steering flow, which causes the cyclones to track farther westward. August–September of 2004 had the fifth highest values (of 56 years) for this potential westward-movement parameter. Column 4 gives a sum of these three (genesis, intensification, and westward movement) components as defined in Eq. (2). The year 2004 was the second-highest value of the sum of these three U.S. LP components. It is no surprise that the United States experienced eight landfalling named storms and six landfalling hurricanes during August–September 2004 as shown in column 5: Charley (two landfalls, first in Florida and then in South Carolina), Frances, Gaston, Ivan, and Jeanne. The LP was also well above average in 2005 (ninth highest value of the past 56 years), and three hurricanes made landfall during August–September: Katrina (two landfalls, first in Florida and then in Louisiana) and Rita. Figure 6 displays the LP and the number of August–September hurricane landfalls for 1950–2005. In general, years with high values of the LP have more U.S. hurricane landfalls.

The LP is given more evaluation in Table 5. When the highest 10 values of the LP (from 1950 to 2005) are compared with the lowest 10 values, there is a 13-to-2 difference for landfalling hurricanes. For landfalling hurricanes, this ratio is 22 to 4, and for landfalling named storms, the ratio is 33 to 10.

The unusual combination of factors that led to the generation of so many intense hurricanes in the central tropical Atlantic and at the same time led to the establishment of near-ideal westerly steering currents at the climatological peak of the hurricane season is a very-low-probability event. However, as was mentioned earlier, the northeastern United States tended to have upper-level trough conditions from 1995 to 2003 (as evidenced by the negative SC values seen in column 3 of Table 5), which inhibited landfall despite the large number of Atlantic basin major hurricanes. Regardless of whether ridge or trough conditions dominate steering currents along the East Coast in the coming seasons, we should expect to see increased amounts of damage from landfalling hurricanes, as evidenced by the phenomenally destructive 2004 and 2005 hurricane seasons. With the ever-increasing U.S. and Caribbean coastal populations and the increases in wealth per capita that have occurred over the past four to five decades (Pielke and Landsea 1998), it seems inevitable that we will likely see unprecedented amounts of hurricane-spawned destruction in the coming years. It should be noted that none of the four hurricanes that devastated the United States during the 2004 season made landfall in a heavily populated area. If Charley, Frances, Ivan, or Jeanne had made landfall near a major metropolitan area (as Katrina did in 2005), it is likely that damage would have been 3–5 times greater.

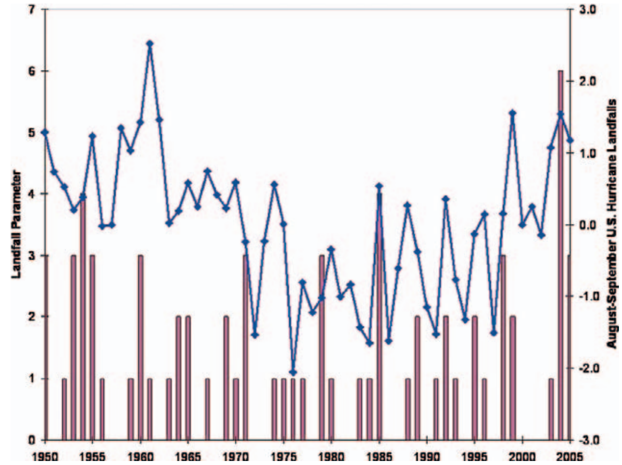

FIG. 6. The LP and Aug–Sep U.S. hurricane landfalls for 1950–2005 LP are the blue solid line, and Aug–Sep U.S. hurricane landfalls are the red columns. Note that, in general, more landfalls occur when LP values are above average.

DISCUSSION AND SUMMARY. In the aftermath of the destructive 2004 hurricane season, many individuals queried whether the landfall of four destructive hurricanes in such a short period of time was related to human-induced climate change brought on by increased greenhouse gas emissions. The Center for Health and Global Environment at the Harvard Medical School held a news conference in the wake of the four storms and indicated that humans were likely to be somewhat responsible for these damaging cyclones (Center for Health and

TABLE 5. Ratio of named storms, hurricanes, and intense-hurricane landfall events for the 5, 10, and 25 highest Aug–Sep values of the U.S. LP versus the 5, 10, and 25 lowest Aug–Sep values of the U.S. LP.

Ratio	Number of named storms	Number of hurricanes	Number of intense hurricanes (category 3–4–5)
Highest 5/lowest 5	19/5	12/3	7/1
Highest 10/lowest 10	33/10	22/4	13/2
Highest 25/lowest 25	60/44	42/18	27/6

Global Environment 2004). Two papers in 2005 indicated a large increase in power dissipation index (PDI) for the northwestern Pacific and North Atlantic basins since the 1970s (Emanuel 2005) and a nearly 50% increase in global category 4–5 hurricanes since the mid-1970s, respectively (Webster et al. 2005). However, other papers question the validity of these findings due to potential bias-correction errors in the earlier part of the data record for the Atlantic basin (Landsea 2005). Also, while major hurricane activity in the Atlantic has shown a large increase since 1995, global tropical-cyclone activity, as measured by the accumulated cyclone energy (ACE) index (Bell et al. 2000), has decreased slightly during the past 16 years (1990–2005; Klotzbach 2006).

We attribute the heightened Atlantic major hurricane activity of the 2004 season as well as the increased Atlantic major hurricane activity of the previous nine years to be a consequence of multidecadal fluctuations in the strength of the Atlantic multidecadal mode and strength of the Atlantic Ocean thermohaline circulation. Associated with a positive phase of the Atlantic multidecadal mode are warm North Atlantic sea surface temperatures, low tropical Atlantic sea level pressures, reduced tropospheric vertical wind shear, and increased Atlantic major hurricane activity. Historical records indicate that positive and negative phases of the Atlantic multidecadal mode and thermohaline circulation last about 25–30 years (typical period ~50–60 years; Gray et al. 1997; Latif et al. 2004). Since we have been in this new active thermohaline circulation period for about 11 years, we can likely expect that most of the next 15–20 hurricane seasons will also be active, particularly with regard to increased major hurricane activity. Due to the increased coastal population and wealth, the U.S. coastline can expect hurricane-spawned damage and destruction in the coming few decades to be on a scale much greater than has occurred in the past. It is the landfalling major hurricanes that should be expected to show the largest percentage increases. Although major hurricanes account for only about 25% of all U.S. landfalling tropical cyclones, they account for about 80%–85% of all hurricane-spawned damage when normalization is made for coastal population, inflation, and wealth per capita (Pielke and Landsea 1998).

ACKNOWLEDGMENTS. We would like to thank Eric Blake, John Knaff, and Chris Landsea for many helpful discussions during the 2004 hurricane season. We thank the reviewers and editor for helpful comments that considerably improved the quality of the manuscript. This work was supported by the National Science Foundation and by AIG-Lexington Insurance Company.

REFERENCES

Bell, G. D., and Coauthors, 2000: Climate assessment for 1999. *Bull. Amer. Meteor. Soc.,* **81,** 1328.

——, S. Goldenberg, C. Landsea, E. Blake, R. Pasch, M. Chelliah, and K. Mo, 2005: Atlantic hurricane season. *Bull. Amer. Meteor. Soc.,* **86,** S26–29.

Bryden, H. L., H. R. Longworth, and S. A. Cunningham, 2005: Slowing of the Atlantic meridional overturning circulation. *Nature,* **438,** 655–657.

Center for Health and the Global Environment, cited 2004: Hurricanes and global warming news conference. [Available online at www.ucar.edu/news/record/transcripts/hurricanes102104.shtml.]

DeMaria, M., 1996: The effect of vertical shear on tropical cyclone intensity change. *J. Atmos. Sci.,* **53,** 2076–2088.

Emanuel, K. E., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature,* **436,** 686–688.

Frank, N. L., 1970: Atlantic tropical systems of 1969. *Mon. Wea. Rev.,* **98,** 307–314.

George, J. E., and W. M. Gray, 1976: Tropical cyclone motion and surrounding parameter relationships. *J. Appl. Meteor.,* **15,** 1252–1264.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nuñez, and W. M. Gray, 2001: The recent increase in Atlantic hurricane activity: Causes and implications. *Science,* **293,** 474–479.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.,* **96,** 669–700.

——, C. W. Landsea, P. W. Mielke, and K. J. Berry, 1994: Predicting Atlantic basin seasonal tropical cyclone activity by 1 June. *Wea. Forecasting,* **9,** 103–115.

——, J. D. Sheaffer, and C. W. Landsea, 1997: Climate trends associated with multi-decadal variability of Atlantic hurricane activity. *Hurricanes: Climate and Socioeconomic Impacts,* H. F. Diaz and R. S. Pulwarty, Eds., Springer-Verlag, 15–52.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Klotzbach, P. J., 2006: Trends in global tropical cyclone activity over the past 20 years (1986–2005). *Geophys. Res. Lett.,* **33,** L10805, doi:10.1029/2006GL025881.

Knight, J. R., R. J. Allan, C. K. Folland, M. Vellinga, and M. E. Mann, 2005: A signature of persistent natural thermohaline circulation cycles in observed climate. *Geophys. Res. Lett.,* **32,** L20708, doi:10.1029/2005GL024233.

Landsea, C. W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.,* **121,** 1703–1713.

——, 2005: Hurricanes and global warming. *Nature,* **438,** E11-13, doi:10.1038/nature04477.

Latif, M., and Coauthors, 2004: Reconstructing, monitoring, and predicting multidecadal-scale changes in the North Atlantic thermohaline circulation with sea surface temperature. *J. Climate,* **17,** 1605–1614.

National Climatic Data Center, cited 2004: Climate of 2004 Atlantic hurricane season. [Available online at www.ncdc.noaa.gov/oa/climate/research/2004/hurricanes04.html.]

National Hurricane Center, cited 2004: 2004 Atlantic hurricane season. [Available online at www.nhc.noaa.gov/2004atlan.shtml.]

Pielke, R. A., Jr., and C. W. Landsea, 1998: Normalized hurricane damage in the United States: 1925–95. *Wea. Forecasting,* **13,** 621–631.

Saunders, M. A., and A. S. Lea, 2005: Seasonal prediction of hurricane activity reaching the coast of the United States. *Nature,* **434,** 1005–1008.

Shapiro, L. J., and S. B. Goldenberg, 1998: Atlantic sea surface temperatures and tropical cyclone formation. *J. Climate,* **11,** 578–590.

Simpson, R. H., 1970: The hurricane disaster potential scale. *Weatherwise,* **27,** 169, 186.

Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang, 2005: Changes in tropical cyclone number, duration and intensity in a warming environment. *Science,* **309,** 1844–1846.