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Decadal Trends of Atlantic Basin Tropical Cyclones (1950–1999)

Robert M. Wilson
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TABLE OF CONTENTS

1. INTRODUCTION 1

2. RESULTS 2

3. DISCUSSION AND SUMMARY 16

REFERENCES 19

LIST OF FIGURES

1. (a) The seasonal rate (*r*) of NS for 1950–1999. Each season is identified as ENR by filled triangles or as NENR by unfilled triangles (La Niña-related) and unfilled circles (interlude-related). (b) The distribution of 10-yr moving average first difference (*fd*) values for the number (*N*) of named storms, *N*(NS). The tabular insert gives corresponding 10-yr moving averages (for 1995) and *fd* values (for 1994) for selected seasonal rates for the year 2000 season. See text for additional details 2

2. Same construction as employed in figure 1 except now it is for tropical storms, where *N*(TS) is the number of tropical storms 4

3. Same construction as employed in figure 1 except now it is for hurricanes, where *N*(H) is the number of hurricanes 5

4. Same construction as employed in figure 1 except now it is for major (or intense) hurricanes, where *N*(MH) is the number of major hurricanes 6

5. (a) Histograms of the percentages of seasons for the number of named storms per calendar month (May–December) for the combined data set and for even-odd, ENR-NENR, and less-more differentiated data sets. (b) Same construction as panel (a) except now they are histograms of the percentages of the total number of named storms. 13

6. (a) Histograms of the percentages of the total number of named storms for ENR and NENR seasons during even-more and odd-more years. (b) Same construction as panel (a) except now they are histograms of the percentages of the total number of hurricanes 15

LIST OF TABLES

1. The distribution of the seasonal rate of selected groupings of Atlantic basin cyclones for 1950–1999 and the associated Poisson distributions for the combined data set 7

2. The distribution of the seasonal rate of selected groupings of Atlantic basin cyclones for 1950–1999 and the associated Poisson distributions for ENR seasons 8

3. The distribution of the seasonal rate of selected groupings of Atlantic basin cyclones for 1950–1999 and the associated Poisson distributions for NENR seasons 9

4. The distribution of the seasonal rate of selected groupings of Atlantic basin cyclones for 1950–1999 and for selected climatic conditions and the associated Poisson probability distributions 10

5. The distribution of seasonal rates of selected groupings of Atlantic basin cyclones for 1950–1999 and the more-NENR climate condition, differentiating even and odd years 11

6. The distribution of the seasonal rate of selected groupings of Atlantic basin cyclones for 1950–1999 and for the more-ENR climate condition, differentiating even and odd years 12

LIST OF ACRONYMS AND SYMBOLS

ENR	El Niño related
H	hurricane
ma	moving average
MH	major hurricane
NENR	non-El Niño related
NS	named storm
QBO	quasi-biennial oscillation
S	storm
TS	tropical storm

NOMENCLATURE

fd	first difference
i	index for summation
m	mean rate
N	number
n	number of individual storms
P	probability
r	rate
sd	standard deviation
t	time

TECHNICAL PUBLICATION

DECADAL TRENDS OF ATLANTIC BASIN TROPICAL CYCLONES (1950–1999)

1. INTRODUCTION

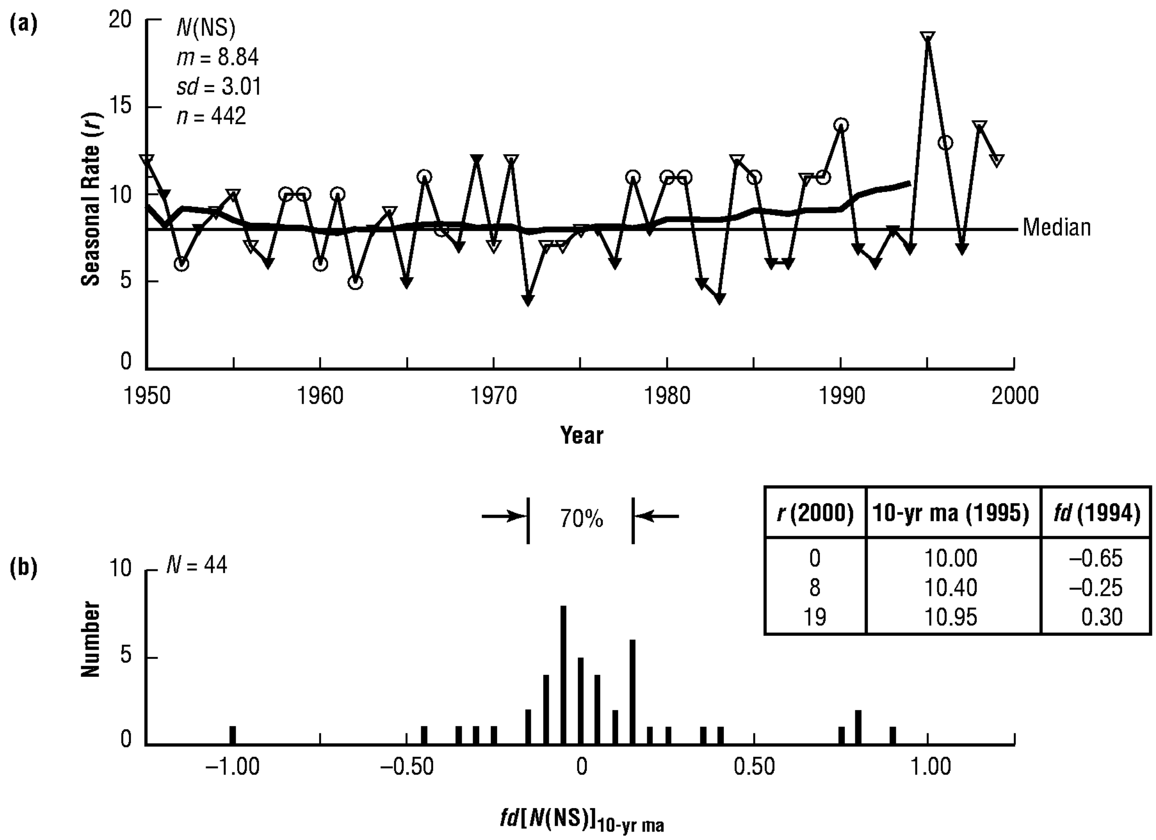
Atlantic basin tropical cyclones have been reported since the time of the explorations of Columbus.[1,2] These large-scale cyclonic weather systems form over the warm tropical waters of the North Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea, often posing a hazard to maritime shipping, island populations, and coastal and inland populations of the continental United States (from Texas to Maine), Mexico, and Central America. On occasion, they have been associated with tremendous loss of life and damage reaching into the tens of billions of U.S. dollars.[3–6]

Classification of Atlantic basin tropical cyclones depends strictly on the maximum sustained wind speed near the center of circulation. For example, a tropical depression is one having a maximum sustained wind speed <17 m sec^{-1}, a tropical storm is one having a maximum wind speed of 17 to <33 m sec^{-1}, and a hurricane is one having a maximum wind speed of at least 33 m sec^{-1}. Major (or intense) hurricanes have a maximum wind speed of at least 50 m sec^{-1} and refer to those of category 3–5 on the Saffir-Simpson hurricane damage potential scale,[7–9] the most destructive of hurricanes.

In this study, the decadal trends of Atlantic basin tropical cyclones, in particular, those “named” systems,[2,4] including tropical storms and hurricanes, are investigated for the 50-yr interval of 1950–1999. Examined are the 10-yr moving averages and associated Poisson probability distributions for various groupings of storms and for differing climatic conditions. As such, this investigation represents an expansion of Wilson[10] who previously examined the 10-yr moving averages and Poisson probability distributions associated with major hurricanes (only) in the Atlantic basin. (Decadal variability in the climate system has received considerable attention in recent years.[11–26])

2. RESULTS

Figure 1(a) displays the seasonal rate (r) of "named" storms (NS) occurring in the Atlantic basin over the past 50 yr (1950–1999). Each season is denoted El Niño-related (ENR), by the filled triangles, or non-El Niño-related (NENR), by the unfilled triangles and circles, where these latter two groupings refer specifically to La Niña- and interlude-related seasons, respectively.[24,27] The thin horizontal line spanning the time series is the median rate, equal to 8, while the thick heavy line is the 10-yr moving average. (Moving averages are often employed in time series data in order to reduce the effect of random movements.[28])



r (2000)	10-yr ma (1995)	fd (1994)
0	10.00	−0.65
8	10.40	−0.25
19	10.95	0.30

Figure 1. (a) The seasonal rate (r) of NS for 1950–1999. Each season is identified as ENR by filled triangles or as NENR by unfilled triangles (La Niña-related) and unfilled circles (interlude-related). (b) The distribution of 10-yr moving average first difference (fd) values for the number (N) of named storms, N(NS). The tabular insert gives corresponding 10-yr moving averages (for 1995) and fd values (for 1994) for selected seasonal rates for the year 2000 season. See text for additional details.

Inspection of figure 1 shows that the 10-yr moving average of named storms was relatively flat until about 1978. Since then, however, it has steadily increased in value, so that its last known value (in 1994) equals 10.65, measuring ≈2.65 units higher than the long-term median rate and being the highest value yet recorded (over the past 50 yr). While the increase may reflect a real change in the Earth's climate system, perhaps related to normal climate variability (or, speculatively, to global warming[23,29,30]), in contrast, it may be due simply to having a more complete record of tropical cyclones, owing to greater use of weather satellites. Many of the tropical cyclones, especially, those that do not reach hurricane status, may occur far from land over the open ocean where one must rely exclusively on qualitative methods based on satellite imagery to gauge the intensity. Still, because (1) the record of tropical cyclone activity is considered reliable from 1944 when routine aircraft reconnaissance of the Atlantic basin began;[2] (2) the recent years of 1990, 1995, 1996, and 1998 are the 4 yr having the highest seasonal rates yet observed (14, 19, 13, and 14, respectively) over the entire 50-yr interval; (3) the trend in the seasonal rates for ENR years (from 1982) appears to be directed upward; and (4) all NENR years (since 1978) have had seasonal rates of ≥11 (measuring 12 in 1999, an NENR year), one cannot escape the notion that the present epoch is indeed one of enhanced activity.

Plotted in figure 1(b) is the spread of *fd* values of the10-yr moving average, where the first difference is defined as the following year's 10-yr moving average minus the present year's 10-yr moving average. One finds that 70 percent of the time, the *fd* value for the number of NS equals ±0.15 units. Hence, because the last known 10-yr moving average equals 10.65 (for 1994), one expected the next value (for 1995) to be ≈10.65 ± 0.15. Such a range plainly indicated that the number of NS's for the year 2000 hurricane season should be 10 or more (≈13 ± 3), providing, of course, that the year 2000 season was not a statistical outlier. Furthermore, it strongly suggested that the year 2000 season should be an NENR season, which is now known to be true.

Following is a computational example showing exactly how the above-stated seasonal rate was determined. Recall that, by definition, the 10-yr moving average of the seasonal rate (r) is the average of two consecutive 10-yr sequences. Mathematically, it is computed as twice the sum of the 9 innermost values (r's) in a sequence of 11 values (i.e., $2 \times \Sigma r_i$ for $i = -4$ through 4) plus the two end values (r_{-5} and r_5) and the total quantity divided by 20. To compute the expected seasonal rate (r) for the next season, one notes that it is equal to 20 times the expected 10-yr moving average minus two times the sum of the incremented (by 1 yr) seasonal rates (i.e., the new r_i for $i = -4$ to 4) minus the rate for the new r_{-5}. As applied to the year 2000 season, its rate is computed as $(20 \times 10.65) - (2 \times 93) - 14$, where 10.65 is the expected 10-yr moving average for 1995, 93 is the new sum of seasonal rates between 1991 and 1999, and 14 is the rate for 1990. Hence, the expected seasonal rate for the year 2000 season was 13. The ±3 results from the observed statistical spread found for the first difference in the 10-yr moving averages, $fd[N(\text{NS})]_{10\text{-yr ma}}$. (This same technique will be employed in the following discussions of tropical storms, hurricanes, and major hurricanes.)

Figure 2(a) illustrates the variation of the seasonal rate (r) for tropical storms (TS), constructed similarly to that of figure 1. Clearly, there has been a general upward progression with time of the seasonal rate, such that now the 10-yr moving average is about twice what it was in the 1950's. Since 1988, the observed seasonal rate for tropical storms has exceeded the median rate every year except 1992, and 7 of the past 9 yr have had a seasonal rate of exactly 4, whether the season was categorized as NENR or ENR.

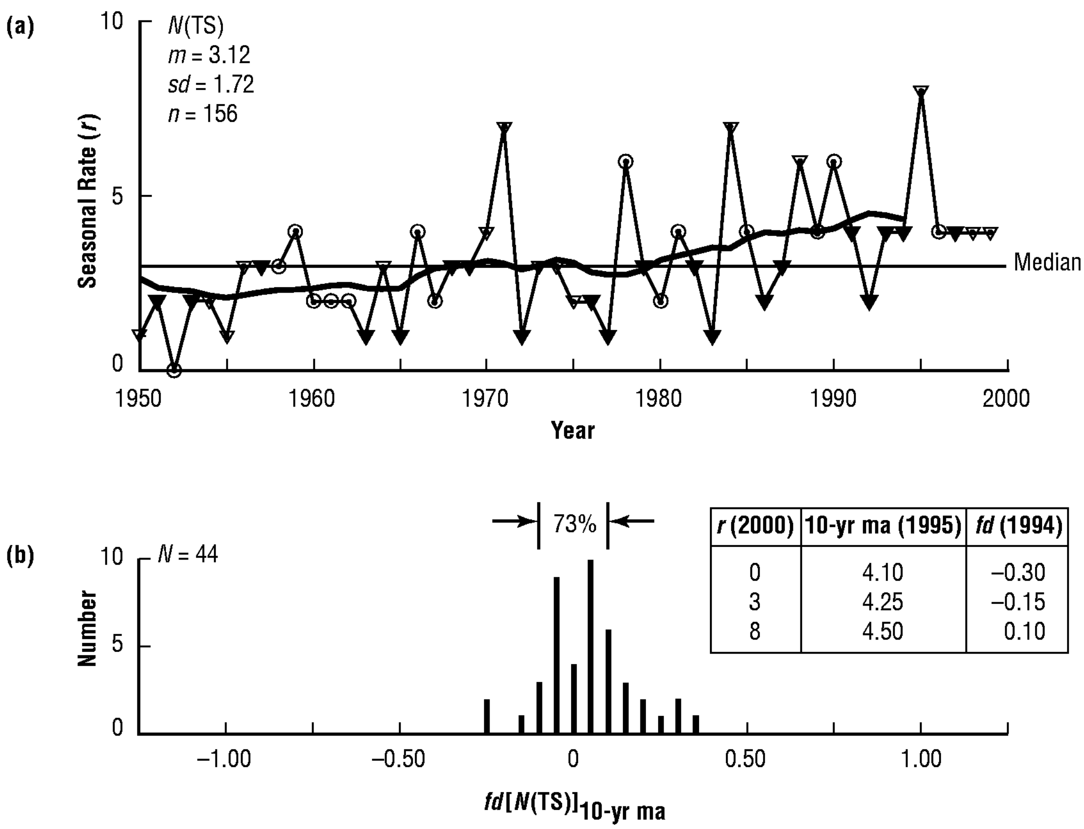


Figure 2. Same construction as employed in figure 1 except now it is for tropical storms, where *N*(TS) is the number of tropical storms.

Figure 2(b) shows the spread of *fd* for tropical storms. One finds that 73 percent of the time, the 10-yr moving average for the following year has been within ±0.10 units of the last known value. Hence, the 10-yr moving average for 1995 was expected to be ≈4.40 ± 0.10, indicating that *r* for the year 2000 season should be ≥4 (≈6 ± 2).

Figure 3(a) similarly exhibits the seasonal rate (*r*) for hurricanes (H). From 1950 through the mid-1960’s, the 10-yr moving average was above the long-term median rate (5.5), while from the mid-1960’s until about 1992, it was below the median rate. The 10-yr moving average rose once again above the long-term median rate about 1992, although its last known value (6.25 in 1994) falls short of the previous high (6.85 in 1951). Perhaps, this is an indication that the 10-yr moving average for hurricanes will continue to grow (see below). Interestingly, 11 of the last 11 ENR seasons have had a seasonal rate below the long-term median rate (actual seasonal rates measuring 2–5), while 9 of the last 11 NENR seasons have had a seasonal rate of ≥7 (actual seasonal rates measuring 5–11).

Figure 3(b) shows the spread of *fd* for hurricanes. One finds that 68 percent of the time, the 10-yr moving average for the succeeding year has been within ±0.15 units of the last known year’s value. Hence, the 10-yr moving average for 1995 was expected to be ≈6.25 ± 0.15, indicating that *r* for the year 2000 season should be ≥4 (≈7 ± 3).

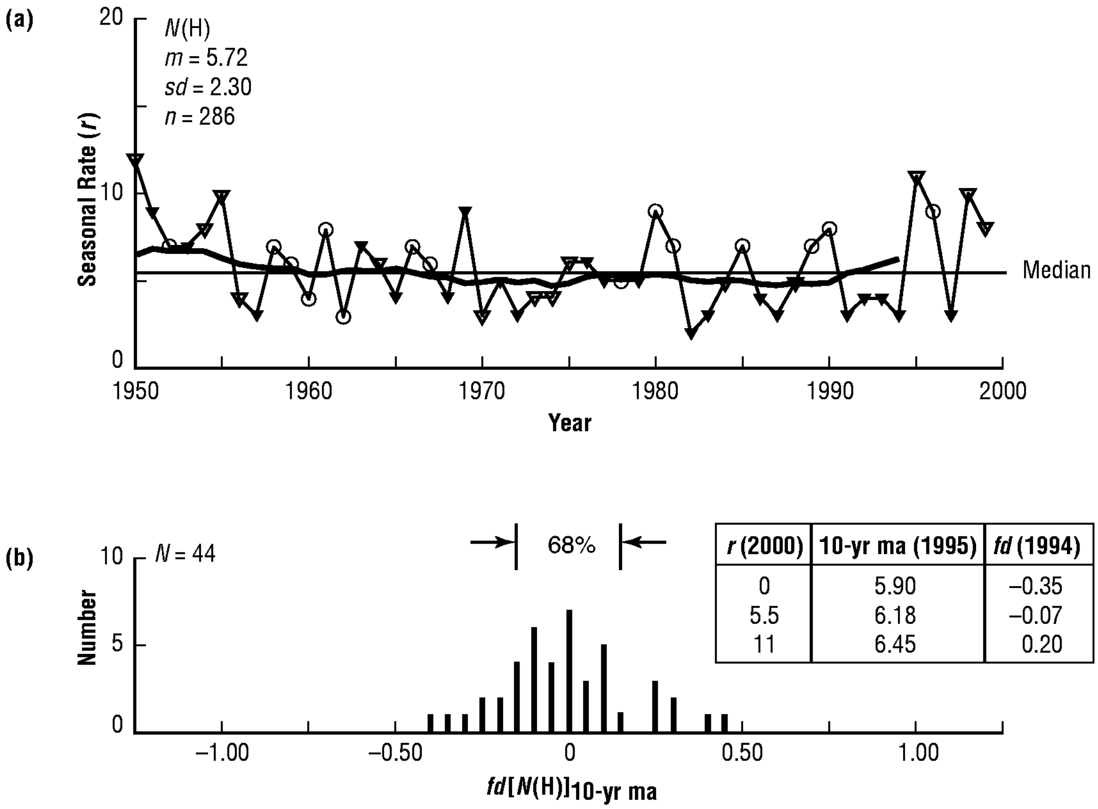
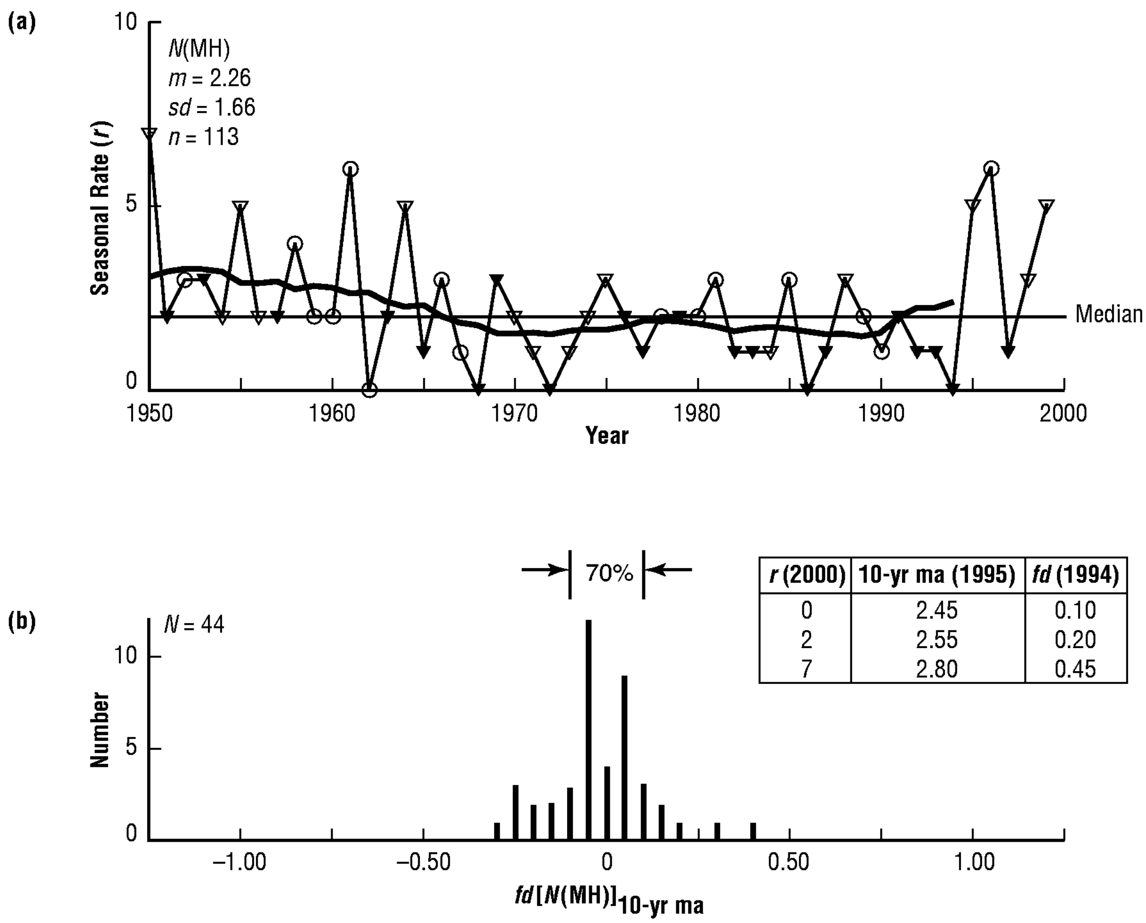


Figure 3. Same construction as employed in figure 1 except now it is for hurricanes, where N(H) is the number of hurricanes.

Figure 4(a) plots the seasonal rate (r) for major (or intense) hurricanes (MH), those of category 3–5 on the Saffir-Simpson hurricane damage-potential scale, the most destructive of hurricanes. The behavior of the 10-yr moving average is found to mimic that for the combined set of all hurricanes, shown previously in figure 3. Namely, a peak is observed to have occurred in the early 1950's, followed by a relatively steady decline[31,32] to values below the median rate beginning about the mid-1960's. The values continued below the median rate until about 1992 when they once again were found to exceed it (in response to the seasonal rate recorded in 1995). On the basis of the relative behavior of the 10-yr moving average to the long-term median rate (equal to 2), Wilson[10] described the behavior of major hurricanes in terms of "intervals of persistent activity." Specifically, he divided the record into portions of two "more" active intervals separated by a single "less" active interval that lasted ≈25 yr.[32–34] As yet, a peak in the 10-yr moving average for the second, more active interval has not been seen, nor is the largest observed value (equal to 2.35) commensurate with that of the first, more active interval (equal to 3.30). Hence, it may be that higher than median rate values will continue for some time into the future before beginning a downward trek, with actual seasonal values being modulated by the random occurrences of El Niño.[18,35] (The two-tiered classification scheme for hurricanes, specifically, major hurricanes, employed in Wilson[10] and herein, a scheme based upon whether the 10-yr moving average is above or below the long-term median rate, is largely arbitrary; yet, clearly, it serves as a convenient descriptor for differentiating seasonal rates[32] and the t-statistic indicates that such a division is statistically important.)



r (2000)	10-yr ma (1995)	fd (1994)
0	2.45	0.10
2	2.55	0.20
7	2.80	0.45

Figure 4. Same construction as employed in figure 1 except now it is for major (or intense) hurricanes, where *N*(MH) is the number of major hurricanes.

Figure 4(b) shows the spread of *fd* for major hurricanes. One finds that 70 percent of the time, the 10-yr moving average for the following year has been within ±0.10 units of the last known year's value. Hence, the 10-yr moving average for 1995 was expected to be ≈2.35 ± 0.10. This range, however, was expected to be exceeded on the positive side (i.e., >0.10) because a rate of 2.45 for 1995 implied a seasonal rate of zero for the year 2000 season (see tabular insert). While a zero rate is possible for any given season, such a rate has occurred only once during the past 50 yr when the season was classified as NENR. More often than not, when the season has been classified as a "more active" NENR season, clearly one expects the seasonal rate for major hurricanes to be ≥3.[10] Presuming this to be the case, one expected the 10-yr moving average for 1995 to be ≥2.60 (although <2.80, since such a rate implied that the seasonal rate for the year 2000 season would be 7, the highest seasonal rate yet observed; as it turned out, the actual 10-yr moving average for 1995 measured 2.60).

Table 1 compares the observed seasonal rate distributions, obtained from figures 1–4, against the associated Poisson probability distributions using the combined data set (i.e., not differentiating between various climatic conditions). The Poisson distribution is quite useful for measuring the probability of occurrence in positively skewed discrete distributions, where knowledge of the mean number of random events that occur within a given time interval is plainly known.[36] (In tables 1–6, the terms denoted *N*(S), *n*, and *m* refer to the number of seasons, the number of individual storms, and the mean rate, respectively.)

Table 1. The distribution of the seasonal rate of selected groupings of Atlantic basin cyclones for 1950–1999 and the associated Poisson distributions for the combined data set.

	***N*(NS)**		***N*(TS)**		***N*(H)**		***N*(MH)**	
r	**Obs**	***P*(*r*)**	**Obs**	***P*(*r*)**	**Obs**	***P*(*r*)**	**Obs**	***P*(*r*)**
0	0	0.0001	1	0.0442	0	0.0033	5	0.1044
1	0	0.0013	7	0.1378	0	0.0188	13	0.2358
2	0	0.0057	12	0.2149	1	0.0537	15	0.2665
3	0	0.0167	11	0.2235	9	0.1023	9	0.2008
4	2	0.0368	13	0.1743	9	0.1463	1	0.1134
5	3	0.0652	0	0.1088	6	0.1674	4	0.0513
6	7	0.0960	3	0.0566	7	0.1595	2	0.0193
7	8	0.1212	2	0.0252	7	0.1304	1	0.0062
8	7	0.1339	1	0.0098	4	0.0932	0	0.0018
9	2	0.1316	0	0.0034	4	0.0592	0	0.0004
10	5	0.1163	0	0.0011	1	0.0339	0	0.0001
11	7	0.0935	0	0.0003	2	0.0176	0	0.0000
12	5	0.0689	0	0.0001	0	0.0084	0	0.0000
13	1	0.0468	0	0.0000	0	0.0037	0	0.0000
14	2	0.0296	0	0.0000	0	0.0015	0	0.0000
15	0	0.0174	0	0.0000	0	0.0006	0	0.0000
16	0	0.0096	0	0.0000	0	0.0002	0	0.0000
17	0	0.0050	0	0.0000	0	0.0001	0	0.0000
18	0	0.0025	0	0.0000	0	0.0000	0	0.0000
19	1	0.0011	0	0.0000	0	0.0000	0	0.0000
N(S)	50		50		50		50	
n	442		156		286		113	
m	8.84		3.12		5.72		2.26	

As an example, for *N*(NS), the number of named storms, one notes that the fewest number of named storms that has occurred during the 50-yr interval of 1950–1999 is 4, having occurred only twice (1972 and 1983, both ENR seasons during the "less active" interval).[10] Hence, one should always expect that at least 4 named storms will be seen during any given season (the probability of obtaining ≤3 named storms during a season is easily computed to be 2.4 percent, obtained by summing the individual probabilities, *P*(*r*), for *r* = 0, 1, 2, and 3). On average, one expects ≈9 named storms (442 named storms in 50 yr), although, clearly the average rate appears to have risen with the progression of time. Also, one should note that the largest number of named storms that has been seen so far during any given season has been 19, having occurred only once (1995, an NENR season during the second, more active interval). Hence, realistically, one should not anticipate a seasonal rate higher than 19 during a season (the probability of obtaining 20 or more named storms during a season is easily computed to be <0.1 percent, computed as $1 - \Sigma P(r)$ for *r* = 0–19).

Previously, Gray[33] demonstrated that El Niño is one of the strongest climatic factors for determining how active a hurricane season ultimately will be.[10,23,24,34,37–40] Tables 2 and 3 compare the observed seasonal rate distributions against the associated Poisson probability distributions, differentiating between ENR and NENR seasons, respectively. For ENR seasons (table 2), one finds, continuing the example, that *N*(NS) has spanned 4–12, averaging ≈7 per season (138 named storms in 20 ENR seasons). The probability of obtaining ≤3 named storms or of obtaining ≥13 named storms during an ENR season is 8.8 and 2.4 percent, respectively. For NENR seasons (table 3), one finds that *N*(NS) has spanned 5–19, averaging ≈10 per season (304 named storms in 30 NENR seasons). The probability of obtaining ≤4 named storms or of obtaining ≥20 named storms during an NENR season is 2.7 and 0.4 percent, respectively. (Previously, Wilson[10] noted that the differentiation of seasonal rates for major hurricanes on the basis of the "ENR-NENR" criterion was statistically important at >99.9-percent level of confidence, having a *t*-statistic equal to –3.61.)

Table 2. The distribution of the seasonal rate of selected groupings of Atlantic basin cyclones for 1950–1999 and the associated Poisson distributions for ENR seasons.

	N(NS)		*N*(TS)		*N*(H)		*N*(MH)	
r	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)
0	0	0.0010	0	0.0863	0	0.0117	4	0.2725
1	0	0.0070	5	0.2114	0	0.0520	8	0.3543
2	0	0.0240	5	0.2590	1	0.1156	6	0.2303
3	0	0.0552	6	0.2115	7	0.1715	2	0.0998
4	2	0.0952	4	0.1295	5	0.1908	0	0.0324
5	2	0.1314	0	0.0635	2	0.1698	0	0.0084
6	5	0.1511	0	0.0259	2	0.1260	0	0.0018
7	4	0.1489	0	0.0091	1	0.0801	0	0.0003
8	5	0.1284	0	0.0028	1	0.0445	0	0.0001
9	0	0.0985	0	0.0008	1	0.0220	0	0.0000
10	1	0.0679	0	0.0002	0	0.0098	0	0.0000
11	0	0.0426	0	0.0000	0	0.0040	0	0.0000
12	1	0.0245	0	0.0000	0	0.0015	0	0.0000
13	0	0.0130	0	0.0000	0	0.0005	0	0.0000
14	0	0.0064	0	0.0000	0	0.0002	0	0.0000
15	0	0.0029	0	0.0000	0	0.0000	0	0.0000
16	0	0.0013	0	0.0000	0	0.0000	0	0.0000
17	0	0.0005	0	0.0000	0	0.0000	0	0.0000
18	0	0.0002	0	0.0000	0	0.0000	0	0.0000
19	0	0.0001	0	0.0000	0	0.0000	0	0.0000
N(S)	20		20		20		20	
n	138		49		89		26	
m	6.90		2.45		4.45		1.30	

Table 3. The distribution of the seasonal rate of selected groupings of Atlantic basin cyclones for 1950–1999 and the associated Poisson distributions for NENR seasons.

	***N*(NS)**		***N*(TS)**		***N*(H)**		***N*(MH)**	
r	**Obs**	***P*(*r*)**	**Obs**	***P*(*r*)**	**Obs**	***P*(*r*)**	**Obs**	***P*(*r*)**
0	0	0.0000	1	0.0282	0	0.0014	1	0.0550
1	0	0.0004	2	0.1005	0	0.0092	5	0.1596
2	0	0.0020	7	0.1794	0	0.0303	9	0.2314
3	0	0.0069	5	0.2135	2	0.0663	7	0.2237
4	0	0.0175	9	0.1906	4	0.1088	1	0.1622
5	1	0.0354	0	0.1361	4	0.1430	4	0.0940
6	2	0.0598	3	0.0810	5	0.1566	2	0.0455
7	4	0.0866	2	0.0413	6	0.1470	1	0.0188
8	2	0.1096	1	0.0184	3	0.1207	0	0.0068
9	2	0.1234	0	0.0073	3	0.0881	0	0.0022
10	4	0.1250	0	0.0026	1	0.0579	0	0.0006
11	7	0.1151	0	0.0008	2	0.0346	0	0.0002
12	4	0.0972	0	0.0003	0	0.0189	0	0.0000
13	1	0.0757	0	0.0001	0	0.0096	0	0.0000
14	2	0.0548	0	0.0000	0	0.0045	0	0.0000
15	0	0.0370	0	0.0000	0	0.0020	0	0.0000
16	0	0.0234	0	0.0000	0	0.0008	0	0.0000
17	0	0.0140	0	0.0000	0	0.0003	0	0.0000
18	0	0.0079	0	0.0000	0	0.0001	0	0.0000
19	1	0.0042	0	0.0000	0	0.0000	0	0.0000
N(S)	30		30		30		30	
n	304		107		197		87	
m	10.13		3.57		6.57		2.90	

Wilson[10] showed that in addition to El Niño, another important influencing factor, at least for major hurricanes, is an apparent two-tier level of activity (“more” versus “less”), inferred to be inherent in the record of major hurricanes. Prior to the mid-1960’s and subsequent to the early 1990’s, the 10-yr moving average of major hurricanes is found to have always exceeded the long-term median rate, while it was always below the median rate between the mid-1960’s and the early 1990’s. This pattern of behavior, if an inherent characteristic of major hurricanes, suggests that the activity level for major hurricanes may oscillate between two preferred states of activity (“more” versus “less”) every 25 yr or so, inferring an oscillatory period of ≈50 yr, a length that has been associated with climatic regime shifts found over the North Pacific, North America, and tropical oceans.[20] Table 4 compares the observed distributions and associated Poisson probability distributions for the two cases of climatic conditions that should now be in vogue, specifically, the “more-NENR” season and the “more-ENR” season, following the categorization scheme employed in Wilson.[10] (Previously, Wilson[10] noted that the differentiation of seasonal rates for major hurricanes on the basis of the “more-less” criterion was statistically meaningful; specifically, it has a *t*-statistic measuring –2.78, inferring that the division by level of activity is statistically important at >99-percent level of confidence.)

Table 4. The distribution of the seasonal rate of selected groupings of Atlantic basin cyclones for 1950–1999 and for selected climatic conditions and the associated Poisson probability distributions.

	More-NENR (16)								More-ENR (9)							
	N(NS)		*N*(TS)		*N*(H)		*N*(MH)		*N*(NS)		*N*(TS)		*N*(H)		*N*(MH)	
r	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)
0	0	0.0000	1	0.0529	0	0.0007	1	0.0235	0	0.0007	0	0.0773	0	0.0094	1	0.2369
1	0	0.0004	2	0.1554	0	0.0051	0	0.0882	0	0.0053	2	0.1979	0	0.0438	4	0.3412
2	0	0.0019	4	0.2285	0	0.0187	4	0.1654	0	0.0191	3	0.2533	0	0.1022	3	0.2456
3	0	0.0066	3	0.2239	1	0.0451	3	0.2067	0	0.0459	1	0.2162	3	0.1591	1	0.1179
4	0	0.0169	5	0.1646	2	0.0818	1	0.1938	0	0.0829	3	0.1383	3	0.1857	0	0.0424
5	1	0.0344	0	0.0968	0	0.1185	4	0.1453	1	0.1196	0	0.0708	0	0.1735	0	0.0122
6	2	0.0584	0	0.0474	3	0.1432	2	0.0908	2	0.1440	0	0.0302	1	0.1350	0	0.0029
7	1	0.0850	0	0.0199	3	0.1484	1	0.0487	2	0.1485	0	0.0111	1	0.0901	0	0.0006
8	0	0.1082	1	0.0073	2	0.1344	0	0.0228	3	0.1340	0	0.0035	1	0.0526	0	0.0001
9	2	0.1226	0	0.0024	2	0.1083	0	0.0095	0	0.1075	0	0.0010	0	0.0273	0	0.0000
10	4	0.1249	0	0.0007	1	0.0785	0	0.0036	1	0.0776	0	0.0003	0	0.0127	0	0.0000
11	1	0.1157	0	0.0002	2	0.0518	0	0.0012	0	0.0510	0	0.0001	0	0.0054	0	0.0000
12	2	0.0982	0	0.0000	0	0.0313	0	0.0004	0	0.0307	0	0.0000	0	0.0021	0	0.0000
13	1	0.0770	0	0.0000	0	0.0174	0	0.0001	0	0.0170	0	0.0000	0	0.0008	0	0.0000
14	1	0.0560	0	0.0000	0	0.0090	0	0.0000	0	0.0088	0	0.0000	0	0.0003	0	0.0000
15	0	0.0381	0	0.0000	0	0.0044	0	0.0000	0	0.0042	0	0.0000	0	0.0001	0	0.0000
16	0	0.0242	0	0.0000	0	0.0020	0	0.0000	0	0.0019	0	0.0000	0	0.0000	0	0.0000
17	0	0.0195	0	0.0000	0	0.0008	0	0.0000	0	0.0008	0	0.0000	0	0.0000	0	0.0000
18	0	0.0082	0	0.0000	0	0.0003	0	0.0000	0	0.0003	0	0.0000	0	0.0000	0	0.0000
19	1	0.0044	0	0.0000	0	0.0001	0	0.0000	0	0.0001	0	0.0000	0	0.0000	0	0.0000
N(S)	16		16		16		16		9		9		9		9	
n	163		47		116		60		65		23		42		13	
m	10.19		2.94		7.25		3.75		7.22		2.56		4.67		1.44	

Over the past 50 yr, the climatic condition designated "more-NENR" has been experienced 16 times. On average, during more-NENR seasons, there have been ≈10 named storms, including 3 tropical storms and 7 hurricanes, of which slightly more than half were major hurricanes. The observed range has been 5–19 named storms, 0–8 tropical storms, 3–11 hurricanes, and 0–7 major hurricanes. The probability of ≥11 named storms is 44.1 percent, the probability of ≥4 tropical storms is 33.9 percent, the probability of ≥8 hurricanes is 43.9 percent, and the probability of ≥4 major hurricanes is 51.6 percent. Thus, during a typical more-NENR season, one anticipates activity levels that could be significantly higher than average, certainly higher than what was experienced during the 25-yr lull that immediately preceded the current, more active mode.

Likewise, over the past 50 yr, the climatic condition designated "more-ENR" has been experienced 9 times. On average, during more-ENR seasons, there have been ≈7 named storms, including 2–3 tropical storms and 4–5 hurricanes, of which about 1–2 were major hurricanes. The observed range has been 5–10 named storms, 1–4 tropical storms, 3–8 hurricanes, and 0–3 major hurricanes. The probability of 11 or more named storms is only 11.5 percent, the probability of 4 or more tropical storms is only 25.5 percent, the probability of 8 or more hurricanes is only 10.1 percent, and the probability of 4 or more major hurricanes is only 5.8 percent. Thus, during a typical more-ENR season, one anticipates activity levels that are diminished, especially as compared to the typical more-NENR season, with little likelihood of seeing abnormally high seasonal rates.

Tables 5 and 6 give the observed distributions and associated Poisson probability distributions for the more-NENR and more-ENR climatic conditions, respectively, differentiating between even- and odd-numbered years (the basis for an even-odd split is purely arbitrary, yet it serves as another simple and convenient way of differentiating the data, perhaps being an overt manifestation of the quasi-biennial oscillation (QBO).[33,34] While no mechanism is demonstrated here that explains this difference in storm formation between even and odd years, if such a mechanism were demonstrated in future work, this relationship could have predictive ability. Comparing even-more-NENR and odd-more-NENR seasons, surprisingly one finds that even-numbered years comprise the bulk of the more-NENR climatic condition: 11 versus 5 seasons (table 5). Comparing even-more-ENR and odd-more-ENR seasons, again surprisingly, one finds that odd-numbered years comprise the bulk of the more-ENR climatic condition: 7 versus 2 seasons (table 6). Comparing even-more-NENR and even-more-ENR seasons, one finds that even-numbered years are more likely more-NENR seasons than more-ENR seasons: 11 versus 2 seasons. Finally, comparing odd-more-NENR and odd-more ENR seasons, one finds neither grouping to be dominant (i.e., the two groups are more evenly split: 5 versus 7 seasons, respectively). What this seems to suggest is that because the year 2000 season was even numbered, it appeared ≈5.5 times more likely to be a more-NENR season than a more-ENR season. Indeed, the lack of occurrence of El Niño onset in late 1999-early 2000 seemed to substantiate that the year 2000 season would be a more-NENR season,[25,26] and, it was.

Table 5. The distribution of the seasonal rates of selected groupings of Atlantic basin cyclones for 1950–1999 and for the more-NENR climate condition, differentiating even and odd years.

	Even-More-NENR (11)								Odd-More-NENR (5)							
	N(NS)		*N*(TS)		*N*(H)		*N*(MH)		*N*(NS)		*N*(TS)		*N*(H)		*N*(MH)	
r	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)	Obs	*P*(*r*)
0	0	0.0001	1	0.0781	0	0.0012	1	0.0347	0	0.0000	0	0.0224	0	0.0002	0	0.0101
1	0	0.0009	1	0.1991	0	0.0080	0	0.1167	0	0.0001	1	0.0850	0	0.0019	0	0.0462
2	0	0.0040	3	0.2539	0	0.0271	3	0.1961	0	0.0004	1	0.1615	0	0.0079	1	0.1063
3	0	0.0125	3	0.2158	1	0.0607	3	0.2196	0	0.0015	0	0.2046	0	0.0222	0	0.1631
4	0	0.0290	3	0.1376	2	0.1021	1	0.1845	0	0.0046	2	0.1944	0	0.0466	0	0.1875
5	1	0.0537	0	0.0702	0	0.1374	1	0.1240	0	0.0113	0	0.1477	0	0.0784	3	0.1725
6	2	0.0830	0	0.0298	2	0.1542	1	0.0694	0	0.0230	0	0.0936	1	0.1097	1	0.1323
7	1	0.1100	0	0.0109	3	0.1482	1	0.0333	0	0.0402	0	0.0508	0	0.1317	0	0.0869
8	0	0.1274	0	0.0035	0	0.1247	0	0.0140	0	0.0612	1	0.0241	2	0.1382	0	0.0500
9	2	0.1312	0	0.0010	1	0.0932	0	0.0052	0	0.0830	0	0.0102	1	0.1290	0	0.0255
10	1	0.1217	0	0.0003	1	0.0627	0	0.0018	3	0.1013	0	0.0039	0	0.1084	0	0.0118
11	1	0.1025	0	0.0001	1	0.0384	0	0.0005	0	0.1123	0	0.0013	1	0.0828	0	0.0049
12	1	0.0792	0	0.0000	0	0.0215	0	0.0002	1	0.1142	0	0.0004	0	0.0579	0	0.0019
13	1	0.0565	0	0.0000	0	0.0111	0	0.0000	0	0.1072	0	0.0001	0	0.0374	0	0.0007
14	1	0.0374	0	0.0000	0	0.0054	0	0.0000	0	0.0934	0	0.0000	0	0.0225	0	0.0002
15	0	0.0231	0	0.0000	0	0.0024	0	0.0000	0	0.0759	0	0.0000	0	0.0126	0	0.0001
16	0	0.0134	0	0.0000	0	0.0010	0	0.0000	0	0.0579	0	0.0000	0	0.0066	0	0.0000
17	0	0.0073	0	0.0000	0	0.0004	0	0.0000	0	0.0416	0	0.0000	0	0.0033	0	0.0000
18	0	0.0038	0	0.0000	0	0.0001	0	0.0000	0	0.0282	0	0.0000	0	0.0015	0	0.0000
19	9	0.0018	0	0.0000	0	0.0000	0	0.0000	1	0.0181	0	0.0000	0	0.0007	0	0.0000
N(S)	11		11		11		11		5		5		5		5	
n	102		28		74		37		61		19		42		23	
m	9.27		2.55		6.73		3.36		12.20		3.80		8.40		4.60	

Table 6. The distribution of the seasonal rate of selected groupings of Atlantic basin cyclones for 1950–1999 and for the more-ENR climate condition, differentiating even and odd years.

	Even-More-ENR (2)								Odd-More-ENR (7)							
	N(NS)		*N*(TS)		*N*(H)		*N*(MH)		*N*(NS)		*N*(TS)		*N*(H)		*N*(MH)	
r	Obs	*P(r)*	Obs	*P(r)*	Obs	*P(r)*	Obs	*P(r)*	Obs	*P(r)*	Obs	*P(r)*	Obs	*P(r)*	Obs	*P(r)*
0	0	0.0015	0	0.0498	0	0.0302	1	0.6065	0	0.0006	0	0.0880	0	0.0067	0	0.1809
1	0	0.0098	0	0.1494	0	0.1057	1	0.3033	0	0.0044	2	0.2139	0	0.0337	3	0.3093
2	0	0.0318	1	0.2240	0	0.1850	0	0.0758	0	0.0164	2	0.2599	0	0.0842	3	0.2644
3	0	0.0688	0	0.2240	1	0.2158	0	0.0126	0	0.0406	1	0.2105	2	0.1404	1	0.1507
4	0	0.1118	1	0.1680	1	0.1888	0	0.0016	0	0.0753	2	0.1279	2	0.1755	0	0.0644
5	0	0.1454	0	0.1008	0	0.1322	0	0.0002	1	0.1119	0	0.0622	0	0.1755	0	0.0220
6	1	0.1575	0	0.0504	0	0.0771	0	0.0000	1	0.1386	0	0.0252	1	0.1462	0	0.0063
7	1	0.1462	0	0.0216	0	0.0385	0	0.0000	1	0.1471	0	0.0087	1	0.1044	0	0.0015
8	0	0.1188	0	0.0081	0	0.0163	0	0.0000	3	0.1366	0	0.0027	1	0.0653	0	0.0003
9	0	0.0858	0	0.0027	0	0.0066	0	0.0000	0	0.1128	0	0.0007	0	0.0363	0	0.0001
10	0	0.0558	0	0.0008	0	0.0023	0	0.0000	1	0.0838	0	0.0002	0	0.0181	0	0.0000
N(S)	2		2		2		7		7		7		7		7	
n	13		6		7		1		52		17		35		12	
m	6.50		3.00		3.50		0.50		7.43		2.43		5.00		1.71	

Unfortunately, looking ahead to the year 2001 season (an odd-more year), because neither grouping (NENR or ENR) seems to be the more dominant for odd-more years, one must be content to wait and see whether or not El Niño returns during the 2001 hurricane season.[26] (A 2×2 contingency table, not shown, constructed by comparing even-odd years against ENR-NENR seasons, is found to be marginally statistically significant, having a probability of obtaining the observed result, or one more suggestive of a departure from independence, $P = 7.4$ percent; i.e., the likelihood that the result is due entirely to chance is only 7.4 percent.)

Figure 5(a)(1) depicts the percentage of seasons over the past 50 yr that had onsets of named storms during each month of the year (i.e., their genesis or when the storms were first tracked). Although the interval running from June–November is the officially recognized "hurricane season," perhaps surprisingly, one finds that onsets of named storms have actually occurred over the broader interval of May–December. In particular, 5 of the past 50 seasons (10 percent) have had a tropical cyclone to form in the Atlantic basin that attained tropical storm or hurricane status during the month of May and 2 seasons (4 percent) have had onsets in December. During June, the first official month of the hurricane season, 19 of the past 50 seasons (38 percent) have had named storms. This number increases to 25 (50 percent) for July, with the overwhelming bulk of seasons having onsets of named storms during August–October: 48 seasons (96 percent) having had onsets in August, 49 seasons (98 percent) in September, and 38 seasons (76 percent) in October. For November, the number of seasons having a named storm drops to 14 (28 percent). The percentage of seasons having onsets of named storms, differentiating between even- and odd-numbered years, ENR and NENR seasons, and less and more active seasons are plotted in (a), subpanels (2)–(4).

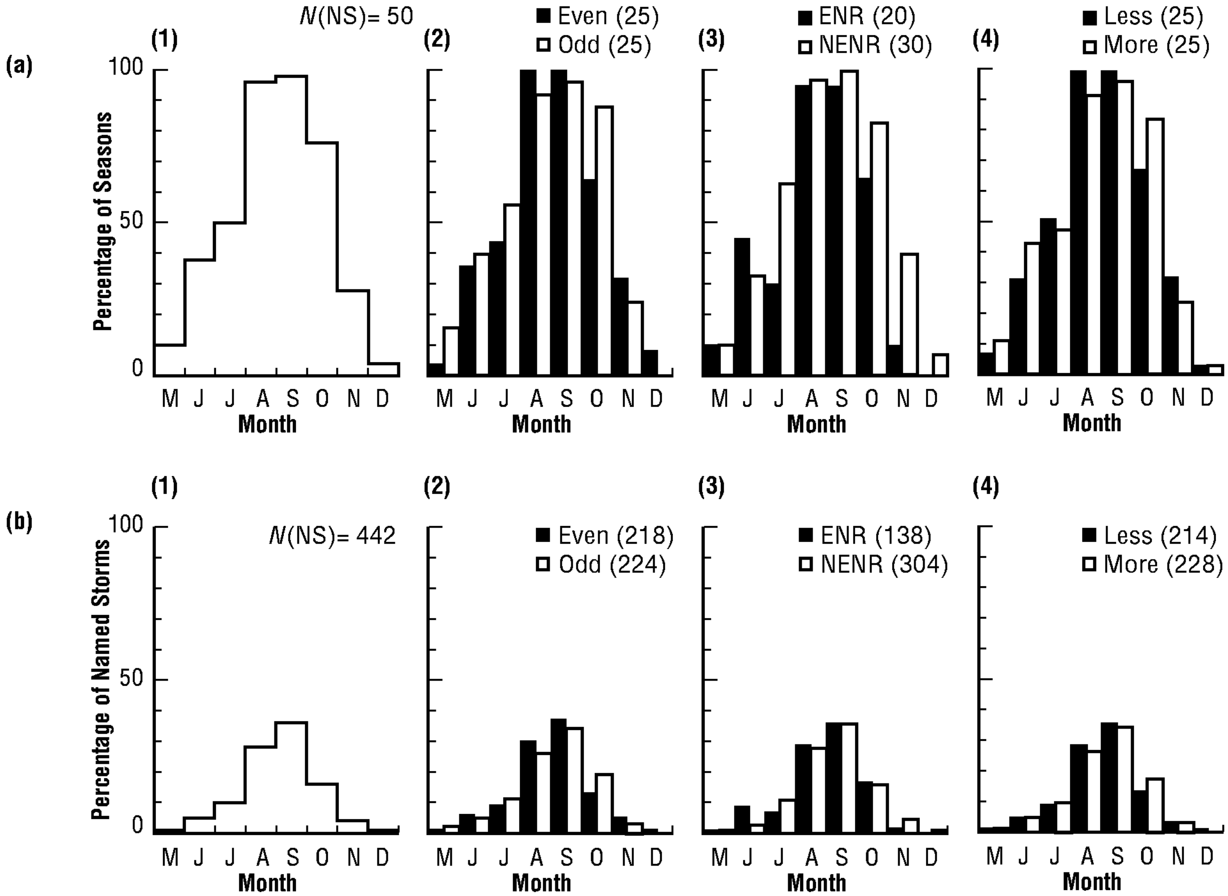


Figure 5. (a) Histograms of the percentages of seasons for the number of named storms per calendar month (May–December) for the combined data set and for even-odd, ENR-NENR, and less-more differentiated data sets. (b) Same construction as panel (a) except now they are histograms of the percentages of the total number of named storms.

Figure 5(b)(1) displays the percentage of named storms that had onsets during each month of the year for the past 50 yr. Thus, while 5 of the seasons had onsets of named storms in the month of May, they only accounted for 5 individual storms (3 tropical storms and 2 hurricanes, or only ≈1 percent of all named storms, 2 percent of all tropical storms, and 0.7 percent of all hurricanes). Similarly, while 2 of the seasons had onsets of named storms in the month of December, these 2 seasons accounted for only 2 individual storms (both hurricanes). For June, one finds 22 individual storms, including 13 tropical storms and 9 hurricanes, or approximately 5 percent of all named storms, 8 percent of all tropical storms, and 3 percent of all hurricanes. For July, one finds 43 individual storms, including 20 tropical storms and 23 hurricanes, or approximately 10 percent of all named storms, 13 percent of all tropical storms, and 8 percent of all hurricanes. In contrast, the months of August–October account for 80 percent of all named storms (353), 74 percent of all tropical storms (116), and 83 percent of all hurricanes (237). November has accounted for only 17 individual storms, including 4 tropical storms and 13 hurricanes, or about 4 percent of all named storms, 2.5 percent of all tropical storms, and 4.5 percent of all hurricanes. The percentage of named storms, differentiating between even- and odd-numbered years, ENR and NENR seasons, and less and more seasons are plotted in (b), subpanels (2)–(4).

Figure 6(a) plots the monthly counts of named storms and (b) plots the monthly counts of hurricanes for even-more and odd-more years, differentiating between ENR (the filled histograms) and NENR seasons (the unfilled histograms). During even-more-NENR seasons, a classification that can be associated with the year 2000 season, 11 of the 13 even-more years have been so described. Furthermore, they accounted for 102 of the 115 named storms and 74 of the 81 hurricanes that occurred during the 13 even-more years. During the 11 even-more-NENR seasons, none had an onset of a named storm in May, although one occurred in December (a hurricane). Only 15 named storms occurred in June and July (including 9 hurricanes). August and September, together, accounted for 66 named storms (including 47 hurricanes), while October and November accounted for 20 named storms (including 17 hurricanes).

During odd-more years, 7 of the seasons were ENR while 5 were NENR. Also, while fewer seasons were denoted NENR during odd-more years, they accounted for the bulk of the named storms and hurricanes, actually having a higher average seasonal rate than was seen during even-more-NENR years (see table 5). The one aspect that seems apparent for odd-more years is that when the season is denoted ENR, the hurricane season appears to abruptly end in October, whereas it continues on for another month when the odd-more season is reckoned as NENR. (The odd-more year is what one expects for the year 2001 season.)

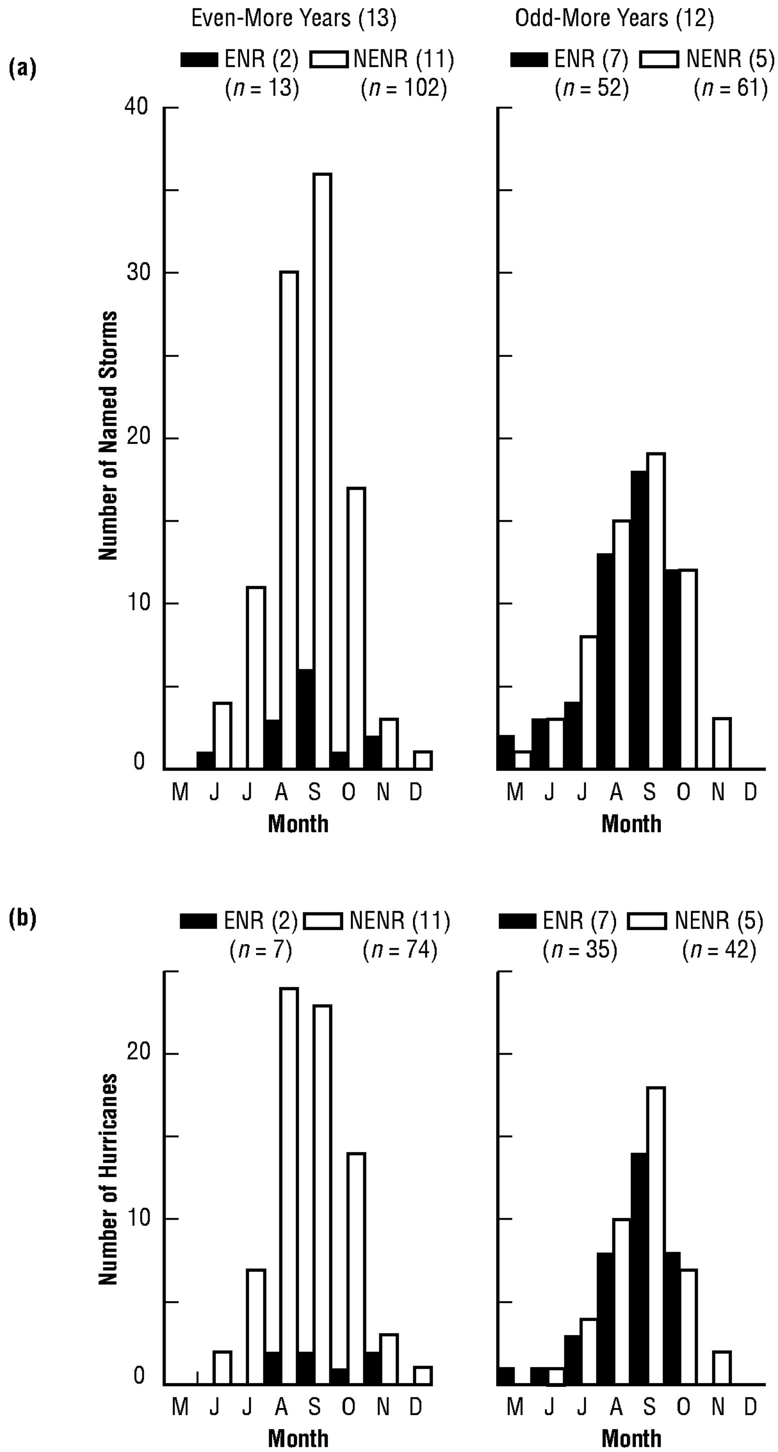


Figure 6. (a) Histograms of the percentages of the total number of named storms for ENR and NENR seasons during even-more and odd-more years. (b) Same construction as panel (a) except now they are histograms of the percentages of the total number of hurricanes.

3. DISCUSSION AND SUMMARY

It can be said that when the water is warm enough and the winds are right (i.e., little or no vertical shear and proper steering currents), one should be especially wary of the heightened potential for the formation of tropical cyclones in the Atlantic basin. These heat engines, once unleashed, should they encounter populous land areas, can literally wreak havoc on the infrastructure of both the prepared and the unprepared.[3,5,6,9,41]

Simulations by Emanuel[42] suggest that once tropical cyclones have reached tropical storm status, their intensity evolution is controlled mostly by the thermodynamic properties of the atmosphere and the upper ocean through which they move.[43,44] How the intensity and frequency of occurrence of tropical cyclones relate specifically to climatic change, however, remains somewhat ambiguous.[30]

Today, there is considerable concern that now, in this present epoch, a change in climate is underway. This change may be a normal fluctuation or, on the other hand, it may be related to the important issues of global warming and the relative frequency of occurrence of El Niño events.[16,25,26,45–52]

In this study, it has been shown that the 10-yr moving averages for named storms, tropical storms, hurricanes, and major hurricanes are all currently at or near record levels. Thus, from the perspective of tropical cyclones in the Atlantic basin, it is quite apparent that the current epoch can be described correctly as one of enhanced activity.

This enhanced level of (persistent) activity may continue for many years to come (perhaps 1–2 decades if indeed it is cyclic, or longer if it is a manifestation of global warming), with actual seasonal rates modulated by the random occurrences of El Niño. Therefore, given that a particular year is ENR or NENR, one can approximately gauge the expected level of activity for that specific season; i.e., whether or not seasonal rates will be below (when El Niño is present) or above average (when El Niño is absent).

For hurricanes and major hurricanes, the change from a less active to a more active (enhanced) environment appears to have occurred rather suddenly. For example, prior to 1995, the seasonal rates for hurricanes and major hurricanes were relatively flat and depressed (generally below their long-term median rates). Then, beginning with the 1995 season, a marked increase in the seasonal rates was seen. Landsea et al.[53] noted that the increase coincided with the return of hurricane activity to the deep tropical latitudes, attributing the increase to the "juxtaposition of virtually all of the large-scale features over the tropical North Atlantic that favor tropical cyclogenesis and development." In fact, except for the 1997 season (which was an ENR season), all seasons from 1995 have been more active than normal, as has been shown in this study,[54–57] strongly indicating perhaps that a return to the more active phase of major hurricanes reminiscent of the1940's and 1950's has taken place.

On the basis of the behavior of the 10-yr moving averages, it was shown that the seasonal rates for named storms, tropical storms, and hurricanes for the year 2000 hurricane season should have been equal to or higher than respective long-term median rates. Also, because the year 2000 was an even-numbered year, statistically, it would likely be an NENR-related season. Both of these perceptions turned out to be true. The year 2000 hurricane season was indeed an even-more-NENR season, accounting for 14 named storms, 6 tropical storms, and 8 hurricanes (of which 3 were major hurricanes). So, the technique appears to have worked rather well for this past season and merits continued consideration (for the year 2001 and future seasons).

For the year 2001 season, it will be categorized as either an odd-more-NENR season or an odd-more-ENR season. As yet, one cannot unequivocally state which designation will apply. If El Niño should clearly manifest itself later this year,[26,58] especially during the year 2001 hurricane season, then plainly the season will be categorized as odd-more-ENR. Presuming this to be true, a slight diminution in the seasonal rates would be expected. On the other hand, if another NENR season proves more likely (certainly not unprecedented), then one should expect a continuation of enhanced activity for all classes of Atlantic basin tropical cyclones in 2001.

On the basis of the past statistical behavior of the 10-yr moving averages, for the year 2001 season one expects approximately 7 ± 3 named storms, 4 ± 2 tropical storms, and 3 ± 3 hurricanes, inferring ≤ 3 major hurricanes. Thus, either the year 2001 season will be a statistical outlier (if seasonal rates equal to or higher than the median rates occur) or it will have diminished rates, probably because El Niño unexpectedly recurs. This makes for an interesting season.

REFERENCES

1. Ludlum, D.M.: *Early American Hurricanes, 1492–1870*, American Meteor. Soc., Boston, MA, 1963.
2. Neumann, C.J.; Jarvinen, B.R.; McAdie, C.J.; et al.: *Tropical Cyclones on the North Atlantic Ocean, 1871–1992*, 4th Rev., National Climatic Data Center, Ashville, NC, November 1993.
3. Gray, W.M.; and Landsea, C.W.: "African Rainfall as a Precursor of Hurricane-Related Destruction on the U.S. East Coast," *Bull. Am. Meteor. Soc.*, Vol. 73, pp. 1352–1364, 1992.
4. Pielke, Jr., R.A.; and Landsea, C.W.: "Normalized Hurricane Damages in the United States: 1925–95," *Wea. Forecasting*, Vol. 13, pp. 621–631, 1998.
5. Williams, J.: *The Weather Book*, Vintage Books, USA Today, New York, NY, pp. 131–149, 1992.
6. Changnon, S.A.; Pielke, Jr., R.A.; Changnon, D.; et al.: "Human Factors Explain the Increased Losses From Weather and Climate Extremes," *Bull. Am. Meteor. Soc.*, Vol. 81, pp. 437–442, 2000.
7. Herbert, P.J.; and Taylor, G.: "Part II: Everything You Always Wanted to Know About Hurricanes," *Weatherwise*, Vol. 32, pp. 100–107, 1979.
8. Simpson, R.H.: "The Hurricane Disaster-Potential Scale," *Weatherwise*, Vol. 27, pp. 169 and 186, 1974.
9. Willoughby, H.E.: "Hurricane Heat Engines," *Nature*, Vol. 401, pp. 649–650, 1999.
10. Wilson, R.M.: "Statistical Aspects of Major (Intense) Hurricanes in the Atlantic Basin During the Past 49 Hurricane Seasons (1950–1998): Implications for the Current Season," *Geophys. Res. Lett.*, Vol. 26, pp. 2957–2960, 1999.
11. Elsner, J.B.; and Schmertmann, C.P.: "Improving Extended Range Seasonal Predictions of Intense Atlantic Hurricane Activity," *Wea. Forecasting*, Vol. 8, pp. 345–351, 1993.
12. Latif, M.; and Barnett, T.P.: "Causes of Decadal Climate Variability Over the North Pacific and North America," *Science*, Vol. 266, pp. 634–637, 1994.
13. Latif, M.; and Barnett, T.P.: "Decadal Climate Variability Over the North Pacific and North America: Dynamics and Predictability," *J. Climate*, Vol. 9, pp. 2407–2423, 1996.
14. Trenberth, K.E.; and Hurrell, J.W.: "Decadal Atmosphere-Ocean Variations in the Pacific," *Clim. Dyn.*, Vol. 9, pp. 303–319, 1994.

15. Hess, J.C.; Elsner, J.B.; and LaSeur, N.E.: "Improving Seasonal Hurricane Predictions for the Atlantic Basin," *Wea. Forecasting*, Vol. 10, pp. 425–432, 1995.

16. Wang, B.: "Interdecadal Changes in El Niño Onset in the Last Four Decades," *J. Climate*, Vol. 8, pp. 267–285, 1995.

17. Wagner, R.G.: "Decadal-Scale Trends in Mechanisms Controlling Meridional Sea Surface Temperature Gradients in the Tropical Atlantic," *J. Geophys. Res.*, Vol. 101, pp. 16,683–16,694, 1996.

18. Goldenberg, S.B.; Shapiro, L.J.; and Landsea, C.W.: "Are We Seeing a Long-Term Upturn in Atlantic Basin Major Hurricane Activity Related to Decadal-Scale SST Fluctuations?" in *Seventh Conf. on Climate Variations*, preprint, American Meteorological Society, Long Beach, CA, pp. 305–310, 1997.

19. Mantua, N.J.; Hare, S.R.; Zhang, Y.; et al.: "A Pacific Interdecadal Climate Oscillation With Impacts on Salmon Production," *Bull. Am. Meteor. Soc.*, Vol. 78, pp. 1069–1079, 1997.

20. Minobe, S.: "A 50–70 Year Climatic Oscillation Over the North Pacific and North America," *Geophys. Res. Lett.*, Vol. 24, pp. 683–686, 1997.

21. Zhang, Y.; Wallace, J.M.; and Battisti, D.S.: "ENSO-Like Interdecadal Variability: 1900–93," *J. Climate*, Vol. 10, pp. 1004–1020, 1997.

22. Kimberlain, T.B.; and Elsner, J.B.: "The 1995 and 1996 North Atlantic Seasons: A Return of the Tropical-Only Hurricane," *J. Climate*, Vol. 11, pp. 2062–2069, 1998.

23. Wilson, R.M.: "Deciphering the Long-Term Trend of Atlantic Basin Intense Hurricanes: More Active Versus Less Active During the Present Epoch," *NASA/TP—1998–209003*, Marshall Space Flight Center, December 1998.

24. Wilson, R.M.: "Statistical Aspects of ENSO Events (1950–1997) and the El Niño-Atlantic Intense Hurricane Activity Relationship," *NASA/TP—1998–209005*, Marshall Space Flight Center, AL, December 1998.

25. Wilson, R.M.: "El Niño during the 1990's: Harbinger of Climatic Change or Normal Fluctuation?" *NASA/TP—2000–209960*, Marshall Space Flight Center, AL, February 2000.

26. Wilson, R.M.: "On the Bimodality of ENSO Cycle Extremes," *NASA/TP—2000–209961*, Marshall Space Flight Center, AL, February 2000.

27. Trenberth, K.: "The Definition of El Niño," *Bull. Am. Meteor. Soc.*, Vol. 78, pp. 2771–2777, 1997.

28. Longley-Cook, L.H.: *Statistical Problems and How to Solve Them*, Harper & Row, New York, NY, pp. 173–201, 1971.

29. Smith, E.: “Atlantic and East Coast Hurricanes 1900–98: A Frequency and Intensity Study for the Twenty-First Century,” *Bull. Am. Meteor. Soc.*, Vol. 80, pp. 2717–2720, 1999.

30. Meehl, G.A.; Zwiers, F.; Evans, J.; et al.: “Trends in Extreme Weather and Climate Events: Issues Related to Modeling Extreme in Projections of Future Climate Change,” *Bull. Am. Meteor. Soc.*, Vol. 81, pp. 427–436, 2000.

31. Landsea, C.W.; Nicholls, N.; Gray, W.M.; et al.: “Downward Trends in the Frequency on Intense Atlantic Hurricanes During the Past Five Decades,” *Geophys. Res. Lett.*, Vol. 23, pp. 1697–1700, 1996.

32. Wilson, R.M.: “Comment on ‘Downward Trends in the Frequency of Intense Hurricanes During the Past 5 Decades’ by C. W. Landsea et al.,” *Geophys. Res. Lett.*, Vol. 24, pp. 2203–2204, 1997.

33. Gray, W.M.: “Atlantic Seasonal Hurricane Frequency, Part I.: El Niño and 30 mb Quasi-Biennial Oscillation Influences,” *Mon. Wea. Rev.*, Vol. 112, pp. 1649–1668, 1984.

34. Gray, W.M.; and Sheaffer, J.D.: “El Niño and QBO Influences on Tropical Cyclone Activity,” in *Teleconnections Linking Worldwide Climate Anomalies: Scientific Basis and Societal Impact*, M.H. Glantz, R.W. Katz, and N. Nicholls (eds.), Cambridge University Press, New York, NY, pp. 257–284, 1991.

35. Elsner, J.B.; Jagger, T; and Niu, X.-F.: “Changes in the Rates of North Atlantic Major Hurricane Activity During the 20th Century,” *Geophys. Res. Lett.*, Vol. 27, pp. 1743–1746, 2000.

36. McElroy, E.E.: *Applied Business Statistics*, 2nd ed., Holden-Day, Inc., San Francisco, CA, pp. 174–176, 1979.

37. Gray, W.M.; Landsea, C.W.; Mielke, Jr., P.W.; et al.: “Predicting Atlantic Seasonal Hurricane Activity 6–11 Months in Advance,” *Wea. Forecasting*, Vol. 7, pp. 440–455, 1992.

38. Gray, W.M.; Landsea, C.W.; Mielke, Jr., P.W.; et al.: “Predicting Atlantic Basin Seasonal Tropical Cyclone Activity by 1 August,” *Wea. Forecasting*, Vol. 8, pp. 73–86, 1993.

39. Gray, W.M.; Landsea, C.W.; Mielke, Jr., P.W.; et al.: “Predicting Atlantic Basin Seasonal Tropical Cyclone Activity by 1 June,” *Wea. Forecasting*, Vol. 9, pp. 103–115, 1994.

40. Saunders, M.A.; Chandler, R.E.; Merchant, C.J.; et al.: “Atlantic Hurricanes and NW Pacific Typhoons: ENSO Spatial Impacts on Occurrence and Landfall,” *Geophys. Res. Lett.*, Vol. 27, pp. 1147–1150, 2000.

41. Glantz, M.H.; Katz, R.W.; and Nicholls, N. (eds.): *Teleconnections Linking Worldwide Climate Anomalies: Scientific Basis and Societal Impact*, Cambridge University Press, New York, NY, 1991.

42. Emanuel, K.A.: "Thermodynamic Control of Hurricane Intensity," *Nature*, Vol. 401, pp. 665–669, 1999.

43. Zhang, Z.; and Krishnamurti, T.N.: "A Perturbation Method for Hurricane Ensemble Predictions," *Mon. Wea. Rev.*, Vol. 127, pp. 447–469, 1999.

44. Bender, M.A.; and Ginis, I.: "Real-Case Simulations of Hurricane-Ocean Interaction Using a High-Resolution Coupled Model: Effects on Hurricane Intensity," *Mon. Wea. Rev.*, Vol. 128, pp. 917–946, 2000.

45. Cane, M.A.; Clement, A.C.; Kaplan, A.; et al.: "Twentieth-Century Sea Surface Temperature Trends," *Science*, Vol. 275, pp. 957–960, 1997.

46. Latif, M.; Kleeman, R.; and Eckert, C.: "Greenhouse Warming, Decadal Variability, or El Niño? An Attempt to Understand the Anomalous 1990's," *J. Climate*, Vol. 10, pp. 2221–2239, 1997.

47. Trenberth, K.E.; and Hoar, T.J.: "El Niño and Climate Change," *Geophys. Res. Lett.*, Vol. 24, pp. 3057–3060, 1997.

48. Hughen, K.A.; Schrag, D.P.; Jacobsen, S.B.; et al.: "El Niño During the Last Interglacial Period Recorded by a Fossil Coral From Indonesia," *Geophys. Res. Lett.*, Vol. 26, pp. 3129–3132, 1999.

49. Hunt, A.G.: "Understanding a Possible Correlation Between El Niño Ocurrence Frequency and Global Warming," *Bull. Am. Meteor. Soc.*, Vol. 80, pp. 297–300, 1999.

50. Rodbell, D.T.; Seltzer, G.O.; Anderson, D.M.; et al.: "An ~15,000-Year Record of El Niño-Driven Alluviation in Southwestern Ecuador," *Science*, Vol. 283, pp. 516–520, 1999.

51. Timmermann, A.; Oberhuber, J.; Bacher, A.; et al.: "Increased El Niño Frequency in a Climate Model Forced by Future Greenhouse Warming," *Nature*, Vol. 398, pp. 694–697, 1999.

52. Collins, M.: "The El Niño-Southern Oscillation in the Second Hadley Centre Coupled Model and its Response to Greenhouse Warming," *J. Climate*, Vol. 13, pp. 1299–1312, 2000.

53. Landsea, C.W.; Bell, G.D.; Gray, W.M.; et al.: "The Extremely Active 1995 Atlantic Hurricane Season: Environmental Conditions and Verification of Seasonal Forecasts," *Mon. Wea. Rev.*, Vol. 126, pp. 1174–1193, 1998.

54. Pasch, R.J.; and Avila, L.A.: "Atlantic Hurricane Season of 1996," *Mon. Wea. Rev.*, Vol. 127, pp. 581–610, 1999.

55. Rappaport, E.N.: "Atlantic Hurricane Season of 1997," *Mon. Wea. Rev.*, Vol. 127, pp. 2012–2026, 1999.

56. Pasch, R.: "Atlantic Hurricanes," *Weatherwise*, Vol. 53, pp. 48–53, 1999.

57. Lawrence, M.; Avula, L.; Beven, J.; et al.: "Atlantic Hurricanes," *Weatherwise*, Vol. 53, pp. 39–43, 2000.

58. Perigaud, C.M.; and Cassou, C.: "Importance of Oceanic Decadal Trends and Westerly Wind Bursts for Forecasting El Niño," *Geophys. Res. Lett.*, Vol. 27, pp. 389–392, 2000.

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Ten-yr moving averages of the seasonal rates for “named storms,” tropical storms, hurricanes, and major (or intense) hurricanes in the Atlantic basin suggest that the present epoch is one of enhanced activity, marked by seasonal rates typically equal to or above respective long-term median rates. As an example, the 10-yr moving average of the seasonal rates for named storms is now higher than for any previous year over the past 50 yr, measuring 10.65 in 1994, or 2.65 units higher than its median rate of 8. Also, the 10-yr moving average for tropical storms has more than doubled, from 2.15 in 1955 to 4.60 in 1992, with 16 of the past 20 yr having a seasonal rate of 3 or more (the median rate). For hurricanes and major hurricanes, their respective 10-yr moving averages turned upward, rising above long-term median rates (5.5 and 2, respectively) in 1992, a response to the abrupt increase in seasonal rates that occurred in 1995. Taken together, the outlook for future hurricane seasons is for all categories of Atlantic basin tropical cyclones to have seasonal rates at levels equal to or above long-term median rates, especially during non-El Niño-related seasons. Only during El Niño-related seasons does it appear likely that seasonal rates might be slightly diminished.

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