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Statistical aspects of major (intense) hurricanes in the Atlantic basin during the past 49 hurricane seasons (1950–1998): Implications for the current season

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Abstract. Statistical aspects of major (intense) hurricanes, those of category 3 or higher on the Saffir-Simpson scale (e.g., having a maximum sustained wind speed of ≥50 m s^{-1}), in the Atlantic basin during the interval of 1950–1998 are investigated in relation to the El Niño-Southern Oscillation cycle and to the postulated "more" versus "less" activity modes for intense hurricane activity. Based on Poisson statistics, when the hurricane season is simply classified as "non-El Niño-related" (NENR), the probability of having three or more intense hurricanes is ≈53%, while it is only ≈14% when it is classified as "El Niño-related" (ENR). Including the activity levels ("more" versus "less"), the probability of having three or more intense hurricanes is computed to be ≈71% for the "more-NENR" season, 30% for the "less-NENR" season, 17% for the "more-ENR" season, and 12% for the "less-ENR" season. Because the 1999 hurricane season is believed to be a "more-NENR" season, the number of intense hurricanes forming in the Atlantic basin should be above average in number, probably about 4 ± 1 or higher.

Introduction

Major (or intense) hurricanes in the Atlantic basin (i.e., those of category 3–5 on the Saffir-Simpson hurricane damage potential scale [e.g., *Gray*, 1990]) represent one of Nature's most destructive forces, sometime causing tremendous loss of life and damage reaching into the billions of dollars [*Gray and Landsea*, 1992; *Williams*, 1992; *Pielke and Landsea, 1998*]. These particular tropical cyclones have a central pressure <965 mbar, a maximum sustained wind speed ≥50 m s^{-1}, and an accompanying storm surge ≥2.7 m.

Previous studies [e.g., *Gray*, 1984; *Gray and Sheaffer*, 1991; *Landsea and Gray*, 1992; *Landsea et al.*, 1992; *Gray et al.*, 1992, 1993, 1994, 1997; *Goldenberg and Shapiro*, 1996; *Lehmiller et al.*, 1997] have shown that there exists strong statistical associations between the number of intense U.S. landfalling hurricanes and, in particular, the West African monsoon rainfall, the phase of the stratospheric quasi-biennial oscillation (QBO) of zonal winds at 30 and 50 mbar, and the occurrences/lack of occurrences of El Niño. Also, studies have indicated that a substantial downward trend in the intense hurricane activity is apparent for the past five decades [*Landsea and Gray*, 1992; *Landsea*, 1993; *Landsea et al.*, 1996], where this downward trend is interpreted as being more symptomatic of a two-state ("more" versus "less") mode of activity rather than a simple linear decline [*Gray*, 1990; *Landsea*, 1993; *Goldenberg et al.*, 1997; *Wilson*, 1997, 1998a; *Landsea et al.*, 1997].

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More than 98% of the intense hurricane activity is known to occur after August 1 during a typical hurricane season (June 1–November 30), with the bulk occurring during the months of August–October [e.g., *Gray et al.*, 1993]. Using the bias adjustment described in *Landsea* [1993], on average, about two intense hurricanes are seen during any given season, this value representing not only the mean but also the mode and median of the distribution [*Wilson*, 1998a, b]. While the record of hurricane activity has been tabulated back to 1871 [*Neumann et al.*, 1993], only that portion which dates from about 1944 to the present is considered reliable, owing to the use of routine aircraft monitoring and, more recently, to the use of satellite imagery of the Atlantic basin (although some small degree of noise may yet remain within the data set). Since 1944, the range of annual frequency of intense hurricanes in the Atlantic basin has spanned from zero to seven. From 1944 until the mid 1960s, the mean annual frequency was slightly higher than average, followed by a lower than average period, at least until the 1995–1996 seasons when higher annual frequencies were seen once again [*Kimberlain and Elsner*, 1998; *Landsea et al.*, 1998].

In this paper, the statistical aspects of intense hurricanes in the Atlantic basin for the interval of 1950–1998 (i.e., the past 49 hurricane seasons) are investigated relative to the El Niño-Southern Oscillation cycle and the postulated "more" versus "less" activity modes for intense hurricane activity. This is accomplished in order to evaluate the statistical significance of these specific groupings (thus, useful for any hurricane season) and to estimate the number of expected intense hurricanes during the present season.

Results and Discussion

Figure 1 depicts the annual rate of intense hurricanes for the interval of 1950–1998, taken from *Landsea et al.* [1996] and updated to include the 1996–1998 seasons. The median rate (two per season) is shown by the straight line and the heavy line depicts the 10-year moving average. While it is recognized that the change between the "more" and "less" activity levels probably occurs rather abruptly [e.g., *Goldenberg et al.*, 1997; *Wilson*, 1997], it is convenient to use the 10-year moving average in relation to the median rate to specify the appropriate activity level. In particular, when it is ≥2 (<2), this is taken as an indication that the "more" ("less") active mode is operative. It follows, then, that the observed sequence of 49 seasons can be simply divided into three separate groups: A single "less" active era that spans 25 consecutive seasons and portions of two "more" active eras that span a total of 24 seasons. During the "less" active era, 20 of the 25 seasons have had an annual frequency of intense hurricanes measuring 2 or less (with all measuring 3 or less and more than half <2), while during the "more" active eras, 18 of 24 seasons have had two or more (with nearly half measuring 3 or

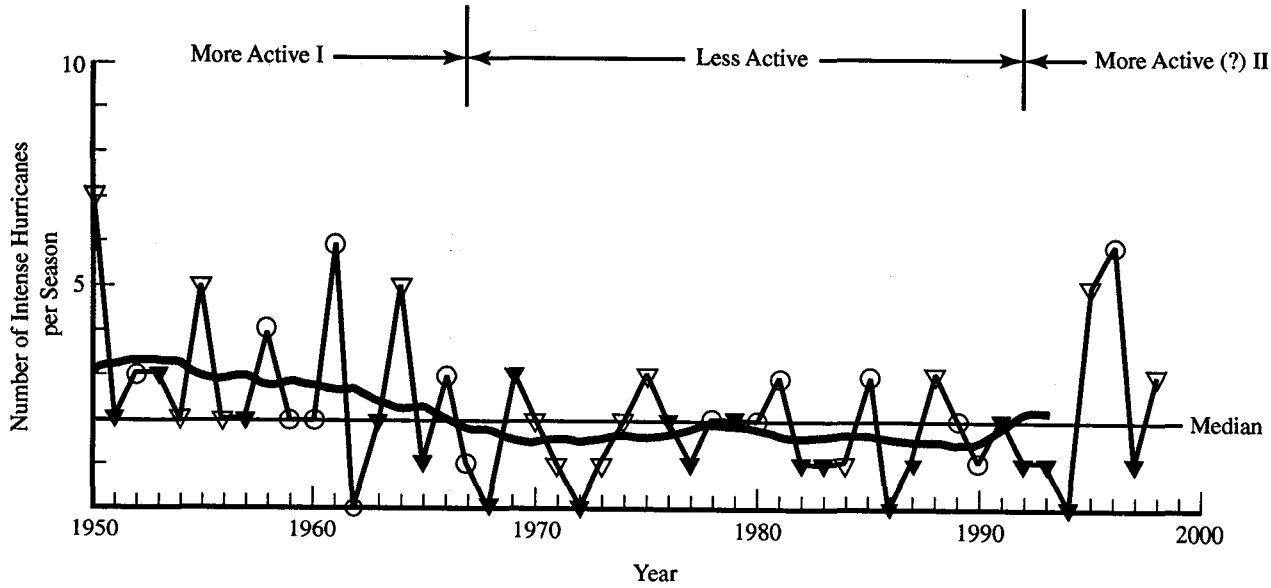

Figure 1. The annual frequency of intense hurricanes forming in the Atlantic basin, 1950–1998. Filled triangles represent seasons that are "El Niño-related" and unfilled triangles and unfilled circles represent seasons that are "non-El Niño-related," where the latter two symbols actually identify "La Niña-related" and "interlude-related" seasons, respectively [see *Wilson*, 1998a]. See text for additional details.

more and seven measuring 4 or more). Comparing the number of ENR and NENR seasons, 20 are described as ENR seasons and 29 as NENR seasons. During the 20 ENR seasons, 18 have had an annual frequency of two or less (with all measuring 3 or less and more than half <2), while during the 29 NENR seasons, 23 have had two or more (with nearly half measuring 3 or more and seven measuring 4 or more).

Table 1 displays the distribution of seasonal rates r of intense hurricanes during the past 49 hurricane seasons (1950–1998). The tabulation is described in terms of several specific groupings: The "ENR-NENR" groupings, the "less-more" activity groupings, the two-tier combination groupings (i.e., "less-ENR," "less-NENR," "more-ENR," and "more-NENR"), and the "combined" grouping (which ignores any categorization). At the bottom are the totals in terms of number of seasons N(S) and number of intense hurricanes N(IH) for the various columnar descriptions and the mean rate (and standard deviation).

Of the various groupings, the one for "ENR-NENR" is the most statistically important ($t = -3.61$), although all have t statistics that are statistically meaningful (i.e., at ≥95% level of confidence), except the ones for less (ENR-NENR) and ENR (less-more). This suggests that when the "less" active mode is operative, there is no significant statistical difference in the seasonal rates of intense hurricanes when comparing ENR and NENR seasons—both typically have r <3 (and, so far, always <4). Also, when the ENR season is in effect, there is no signifi-

Table 1. The Distribution of the Seasonal Rate of Intense Hurricanes for 1950–1998 for Various Selected Grouping Criteria (49 Seasons, 108 Intense Hurricanes)

				Activity		Activity			
						Less		More	
r	ENR	NENR	Combined	Less	More	ENR	NENR	ENR	NENR
0	4	1	5	3	2	3	0	1	1
1	8	5	13	9	4	4	5	4	0
2	6	9	15	8	7	3	5	3	4
3	2	7	9	5	4	1	4	1	3
4	0	1	1	0	1	0	0	0	1
5	0	3	3	0	3	0	0	0	3
6	0	2	2	0	2	0	0	0	2
7	0	1	1	0	1	0	0	0	1
N(S)	20	29	49	25	24	11	14	9	15
N(IH)	26	82	108	40	68	13	27	13	55
Mean Rate	1.3 (0.9)	2.8 (1.7)	2.2 (1.6)	1.6 (1.0)	2.8 (1.9)	1.2 (1.0)	1.9 (0.8)	1.4 (0.9)	3.7 (2.0)

Note: r is the number of intense hurricanes per season; ENR means "El Niño-Related" season; NENR means "Non-El Niño-Related" season.

Table 2. Poisson Distributions $(P(r) = (e^{-m} m^r)/r!)$

				Activity		Activity			
						Less		More	
r	ENR (1.3)	NENR (2.8)	Combined (2.2)	Less (1.6)	More (2.8)	ENR (1.2)	NENR (1.9)	ENR (1.4)	NENR (3.7)
0	0.2725	0.0608	0.1108	0.2019	0.0608	0.3012	0.1496	0.2466	0.0247
1	0.3543	0.1703	0.2438	0.3230	0.1703	0.3614	0.2842	0.3452	0.0915
2	0.2303	0.2384	0.2681	0.2584	0.2384	0.2169	0.2700	0.2417	0.1692
3	0.0998	0.2225	0.1966	0.1378	0.2225	0.0867	0.1710	0.1128	0.2087
4	0.0324	0.1557	0.1082	0.0551	0.1557	0.0260	0.0812	0.0395	0.1931
5	0.0084	0.0872	0.0476	0.0176	0.0872	0.0062	0.0309	0.0111	0.1429
6	0.0018	0.0407	0.0174	0.0047	0.0407	0.0012	0.0098	0.0026	0.0881
7	0.0003	0.0163	0.0055	0.0011	0.0163	0.0002	0.0027	0.0005	0.0466
Sum	0.9998	0.9919	0.9980	0.9996	0.9919	0.9998	0.9994	1.0000	0.9648

cant statistical difference in the seasonal rates whether one is in the "more" or "less" active mode—both typically have $r < 3$ (and, so far, always <4).

Table 2 presents the Poisson distributions for each of the displayed groupings identified in Table 1. 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.

From Figure 1 and Tables 1 and 2 one finds that during the past 49 seasons, there have been only five instances when no intense hurricanes formed in the Atlantic basin, four having occurred during ENR seasons and one during an NENR season (1962). Furthermore, there appears to be only about a 4% chance that more than three intense hurricanes should be expected during a season, given that the season is classified as ENR (actually, as yet, r has never exceeded three during an ENR season), as compared to about a 31% chance, given that the season is classified as NENR. Interestingly, by always using the "combined" group and predicting that the season will have a rate of 2 ± 1 (i.e., close to the average rate), one expects to be correct ≈71% of the time and by simply predicting a rate of three or less one expects to be correct ≈82% of the time.

During the 1998 hurricane season (an NENR season), three intense hurricanes formed in the Atlantic basin ("Bonnie," "Georges," and "Mitch"), this number being slightly higher than the long-term average (=2) and higher by two as compared to the 1997 seasonal rate (=1, an ENR season). As compared to the classes of NENR and "more" active seasons, the 1998 seasonal rate was essentially of average size (=2.8), although as compared to the two-tier, "more active-NENR" seasonal average (=3.7), it was perhaps slightly below average in size (cf. http://tropical.atmos.colostate.edu/forecasts/index.html).

The occurrence of three intense hurricanes during the 1998 season has caused the 10-year moving average to remain unchanged between 1992 and 1993 (=2.20). Because the yearly change in the 10-year moving average usually is quite small (about ±0.05 units 56% of the time), one anticipates that the average for 1994 will be of similar value (i.e., about 2.20±0.05). This implies that during the 1999 hurricane season, one should expect about 4±1 intense hurricanes to form in the Atlantic basin. Obviously, the 10-year moving average for 1994 cannot be below 2.10, because the seasonal rate for 1999 or any year is bounded by r=0. Similarly, because the highest observed seasonal rate over the past 49 seasons has been r=7, it seems unlikely that the 10-year moving average for 1994 will be above 2.45. The importance here is that the 10-year moving average for 1994 will remain >2, inferring that the "more" active mode remains in effect. (While the basis for the prediction is the relative behavior of the 10-year moving average with respect to the median rate, one must acknowledge that the shifts between active states appears rather abruptly, obviously due to decadal-scale changes in climate [*Goldenberg et al.*, 1997].)

Final Comments and Conclusions

About 15 years ago, Professor William Gray first drew attention to the El Niño-Atlantic hurricane activity relationship. In particular, he noted that in most El Niño years there was a dearth of "hurricane days," a decrease in the hurricane/tropical storm seasonal rates, and a diminution of U.S. landfalling class 4–5 hurricanes [*Gray*, 1984]. Subsequent studies have additionally found that fewer intense hurricanes formed in the Atlantic basin since the mid 1960s [*Gray*, 1990; *Landsea and Gray*, 1992], where this decrease is interpreted as being symptomatic of a two-regime level of activity distribution for intense hurricanes [e.g., *Gray*, 1990; *Landsea*, 1993; *Landsea et al.*, 1996; *Landsea et al.*, 1997; *Wilson*, 1997, 1998a, b]. The resurgence of activity in 1995 [*Kimberlain and Elsner*, 1998; *Landsea et al.*, 1998] certainly hints that a return to the more active era probably has already taken place [cf. *Goldenberg et al.*, 1997; *Wilson*, 1998a].

Statistically speaking, it is apparent, following the description presented here using the 10-year moving average in relation to the median rate, that when the "less" active mode has been in effect, the seasonal rate for intense hurricanes has always been $r < 4$, with no significant statistical difference between ENR and NENR seasons (although very real physical differences have been demonstrated to exist [*Goldenberg and Shapiro*, 1996]). While true, the opportunity for $r = 0$ has been much more likely when the season has been further classified as ENR rather than NENR. Additionally, it is apparent that when the "more" active mode has been in fashion, as appears to be the case now, the seasonal rate has been much more dependent upon whether the season was also classified as ENR or NENR. For the former, r typically has been 1–2 events per season (true for 7 of 9 seasons), while for the latter, r typically has been much broader (r=2–6; only 1 of 15 seasons had $r < 2$). When the season is an ENR, typically 2 or fewer (so far, always 3 or fewer) intense hurricanes have formed in the Atlantic basin, while when the season is NENR, typically 2 or more have formed, this being especially true when the "more"

active mode has also been operative. For 1999, because it appears highly likely that it is a "more" active NENR season [e.g., *Wilson*, 1998a, b], one infers that the season rate r will be above average in number (probably about 4 ± 1 or higher).

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