The Recent Increase in Atlantic Hurricane Activity: Causes and Implications

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Persistence of East Coast Trough

Historically, about one-third of the Atlantic major hurricanes make landfall on the continental U.S. coastline. Between 1995-2000, 23 major hurricanes formed in the Atlantic basin, but only three [Opal (1995), Fran (1996), and Bret (1999)] have come ashore as major hurricanes. If the historical one-out-of-three ratio of U.S. major hurricane landfalls to basin-wide major hurricanes had applied during the last six years, then there would have been 7-8 major hurricane landfalls. The U.S. East Coast has been protected by an anomalous mid- and upper-tropospheric trough located offshore during the last six hurricane seasons (e.g., *1*). The persistence of this trough has caused most of otherwise northwest-moving major hurricanes to recurve to the northeast before they reached the U.S. If the position and strength of the trough is related to the changes in the Atlantic multidecadal mode and hurricane activity, then the trough could possibly persist as long as the conducive conditions (warmer SSTs) remain. If the condition of the trough is independent from the other conditions, then the trough could shift while the Atlantic is still favorable and we would subsequently see an increase in East Coast landfalls. Based on previous landfall records for U.S. major hurricanes, it appears probable that the trough and other associated steering patterns are not related to the North Atlantic SST changes, since when conducive conditions were in place during earlier periods, there were also large numbers of U.S. East Coast landfalls. The status of the trough (and other associated steering patterns) seem to vary such that, within active eras, there are shifts of preferred landfall locations -- as shown in the hundred-year record of landfalls for U.S. major hurricanes (*2*). It has been suggested that the shifts in landfall locations are associated with the phase of the North Atlantic oscillation (NAO) (*3*). Additional research needs to be done to examine these relationships.

North Atlantic versus North Pacific Activity

In contrast with the large increase in Atlantic basin activity during the last six years, total tropical cyclone activity for the North Pacific basins (including East, Central and West) has decreased. If one combines Atlantic and North Pacific activity, there is a net downward trend for 1995-2000 (*4*). It has been shown that overall Atlantic activity tends to be negatively correlated with activity in most other basins (*5*). Hence, an interpretation of the recent elevated activity in the Atlantic as a measure of increases in global tropical cyclone activity is not consistent with world-wide experience.

Disasters During Low Activity Years

Even relatively inactive years can produce extreme hurricane disasters. It is not the number of systems that develop that determines the amount of damage, but rather the number that impact land, and where the landfalls occur. When a single major hurricane strikes a heavily populated coast, it causes far more damage than several major hurricanes hitting nearly empty shoreline. For example, Hurricane Andrew in 1992, the only major hurricane during a relatively inactive year (NTC = 66%; see Supplemental Figure 2), caused ~$27 billion in damage, compared with less than $6 billion in damage to the United States during 1995, one of the most active years on record (NTC = 231%). In addition, fresh-water flooding disasters can occur even from weaker systems.

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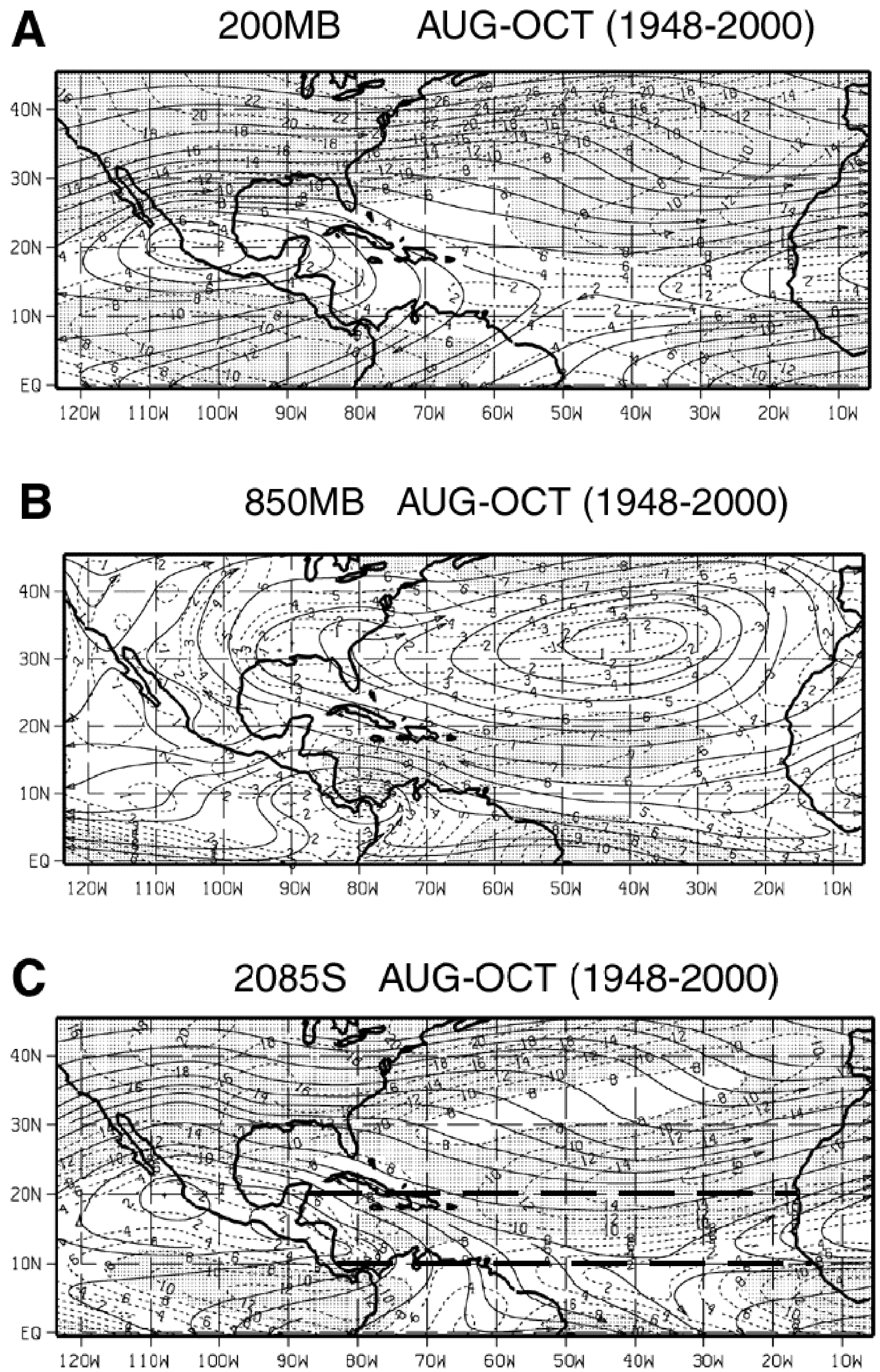
	Warm 1944-1970	Cold 1971-1994	Warm 1995-2000	Warm All	Cold All	Ratio W/C	Ratio W*/C*
Tropical Storms	9.8	8.5	13.1	10.5	8.5	1.24	1.54
Hurricanes	6.2	5.0	8.2	6.6	5.0	1.32	1.64
Major Hurricanes	2.7	1.5	3.8	2.9	1.5	1.93	2.53
Hurricane Days	27.7	16.5	39.5	29.8	16.5	1.81	2.39
NTC (%)	114.3	75.5	164.5	123.4	75.5	1.62	2.18
Caribbean Hurricanes	1.5	0.5	2.5	1.7	0.5	3.40	5.00
Low $|V_z|$ region (%)	70.7	32.6	58.8	68.2	32.6	2.09	1.80

Supplemental Table 1. Mean values and statistical significance of the multidecadal changes in Atlantic tropical cyclone activity and $|V_z|$ parameter (see Fig. 3) based upon Atlantic multidecadal mode (AMM) variations (see Fig. 2B) for various indices of activity that are considered reliable since 1944 (*6*). (Note that the $|V_z|$ data are only available 1948-2000.) Means for individual periods and of "all" warm (1944-1970 and 1995-2000: 33 years) (W) and "all" cold (1971-1994: 24 years) (C) AMM years are shown. The last two columns show ratios between the indices for W versus C years, and for the current warm (1995-2000) (W*) versus most recent cold (1971-1994) (C*) periods. Differences between parameter means for W and C as well as W* and C* are all significant with at least 99% confidence.

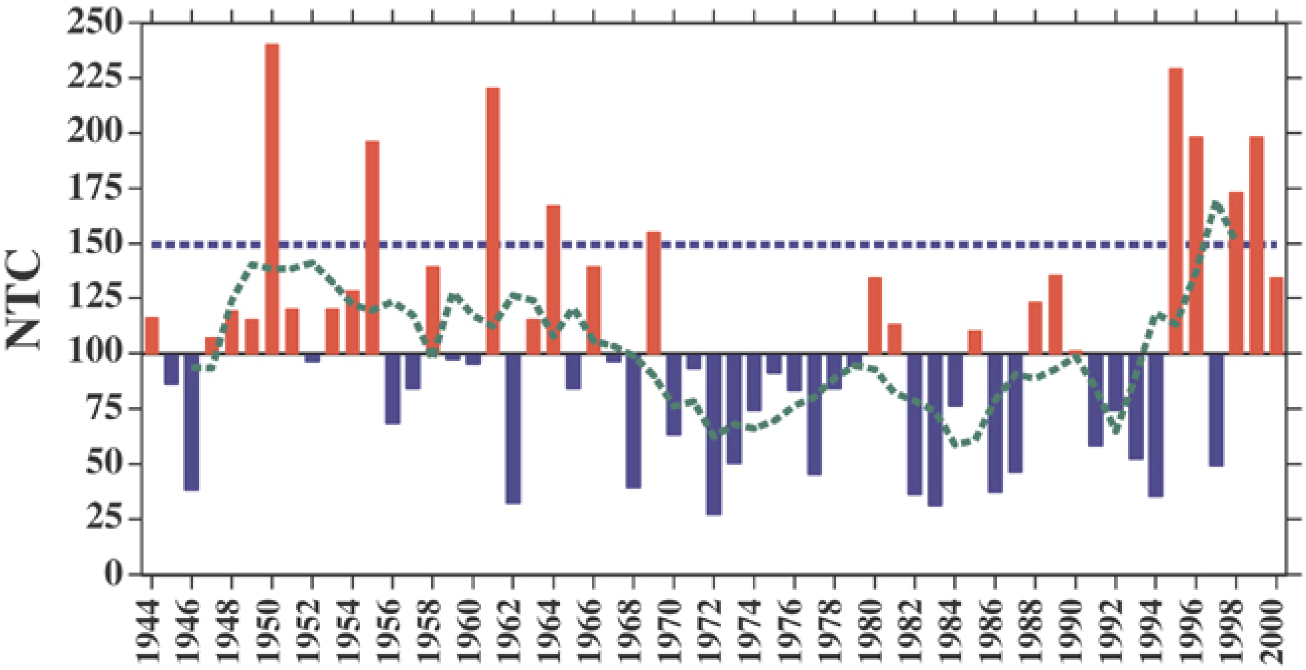
	Warm 1899-1902	Cold 1903-1925	Warm 1926-1970	Cold 1971-1994	Warm 1995-2000	Warm All	Cold All	Ratio W/C	Signif.	Ratio W*/C*	Signif.
U.S. Hurricanes	1.2	1.8	2.1	1.4	2.2	2.0	1.6	1.25	*	1.57	–
U.S. MH	0.50	0.65	0.82	0.42	0.50	0.76	0.52	1.46	*	1.19	–
U.S. Gulf Coast MH	0.25	0.43	0.36	0.29	0.33	0.35	0.36	0.97	–	1.14	–
U.S. East Coast MH	0.25	0.22	0.53	0.17	0.17	0.47	0.19	2.47	***	1.00	–
U.S. Damage ($M)	773	441	2,037	616	3,454	2,113	440	4.80	*	5.61	–
AMM (Annual) (°C)	0.08	-0.24	0.18	-0.20	0.22	0.18	-0.22	–	***	–	***

Supplemental Table 2. Mean values and statistical significance of the multidecadal changes in U.S. landfall frequency [hurricane and major hurricane (MH) strikes], damages and Atlantic multidecadal mode (see Fig. 2B) based upon Atlantic multidecadal mode (AMM) variations. The data used extend back to 1899 since almost complete observations of minimum central pressure at landfall for U.S. strikes exist back to that year (*6*). For the U.S. damages, medians, rather than means, are used. The values for damages (units of millions of dollars) are normalized to 2000 values by considering not only inflation, but also population and wealth changes (*7*). Values for individual periods and combination of periods are shown. The combination of "all" warm AMM years (W) includes 1899-1902, 1926-1970 and 1995-2000 (total of 55 years). The combination of "all" cold AMM years (C) includes 1903-1925 and 1971-1994 (total of 47 years). W* and C* refer to the current warm (1995-2000) and most recent cold (1971-1994) periods, respectively. Ratios between the indices for W and C and for W* and C* are also shown. Differences between parameter means that are significant with at least 90, 95 and 99% confidence are indicated by "*", "**", and "***", respectively. The differences between the various landfall parameters for W versus C are all statistically significant except for U.S. Gulf Coast MH. The increases shown here for various U.S. landfall parameters since 1995 (i.e., W* versus C*), however, are not statistically significant, but the increases in overall numbers of various strengths of systems and for the Caribbean region (Supplemental Table 1) are all significant. The NTC for most of the years since 1988 has been well above average (> 120%) (see Supplemental Figure 2). The years in that period with average or below-average activity are 1990-1994 and 1997, years when SSTs in the Niño 3.4 region (5°N-5°S; 120-170°W) (*8*) were anomalously warm during the peak of the hurricane season. The effects of El Niño are evident in the higher values of $|V_z|$ for all but one (1990) of those years (Fig. 3). Additionally, during 1991-1994, the Atlantic multidecadal mode was still cold (Fig. 2B), contributing to the low activity of those years. Since there is some evidence that a preliminary shift to higher activity started in 1988, both 1988-2000 and 1995-2000 intervals have been used to test the statistical significance of the differences between the recent quiet and active periods. Ratios and statistical significance are shown here and in Supplemental Table 1 only using 1995 as the transition year. Results using 1988 are similar; all of the statistical significance based upon 1995 are also significant based upon 1988. Most of the differences test more strongly when using 1995 as the shift point, however, with the notable exception of U.S. East Coast major hurricanes. This was not significant using the 1995 shift but had a ratio of 5.17 for 1988-2000 versus 1971-1987, statistically significant with at least 95% confidence, mainly due to two devastating major hurricanes during 1988-1994, Hugo (1989) and Andrew (1992).



Supplemental Figure 1. Climatological winds from the NCEP/NCAR Reanalysis (*9*) for 1948-2000 averaged for August-September-October (ASO). Streamlines and isotachs (m s^{-1}) are shown.

(A) Upper-level (200 mb) winds. **(B**) Lower-level (850 mb) winds. **(C)** Vertical shear, V_z (vector difference between 200 and 850 mb winds). Isotach intervals are 2 m s^{-1} for **(A)** and **(C)** and 1 m s^{-1} for **(B)**. Wind speeds >6 m s^{-1} for **(A)** and **(B)** and >8 m s^{-1} for **(C)** are shaded. In **(C)**, heavy dashed lines give north and south boundaries of main development region (MDR). The mean upper-level (200 mb) winds are westerly over most of the Atlantic basin. The lower-level (850 mb) winds are easterly from the equator to ~30°N. Climatological V_z in the MDR during October is much higher than during August and September. Decreased $|V_z|$ is generally caused by upper-level easterly and lower-level westerly anomalies that weaken the climatological upper-level westerlies and lower-level easterlies over the MDR. The inclusion of October in the calculation of the winds shown here tends to skew V_z towards slightly higher values. Even during August and September, however, $|V_z|$ is > 8 m s^{-1} over most of the basin as well as much of the MDR. October is included since the V_z fluctuations in the MDR for that month are still related to changes in major hurricane activity (*10*).



Supplemental Figure 2. Net Tropical Cyclone activity (NTC) in the North Atlantic hurricane basin for 1944-2000. Values above (>100%) and below (<100%) average activity are shown as solid red and blue columns, respectively. Dashed (green) curved line is 5-year running mean. Also shown is the threshold value (150%) for hyperactive years (dashed blue straight line). NTC gives a measure of the *overall* activity in a season by combining information on frequency, intensity and duration. By definition, NTC tends to be weighted somewhat towards the stronger systems. NTC ≡ (%TS+%H+%MH+%TSD+%HD+%MHD)/6, where TS, H, and MH are the number of systems reaching (at least) tropical storm, hurricane and major hurricane status, respectively, TSD, HD and MHD are the cumulative durations (summed for 6-hr intervals) at each status for all storms in a particular season, and "%" for each parameter is the percentage of the 1950 to 1990 climatological mean attained in that season (*4*). If all of the parameters are near their respective long-term means, NTC would be ~100%, i.e., an "average" season. Since 1944, values for NTC have ranged from a minimum of 28% (1972) to a high of 243% (1950). The mean NTC for the years 1971-1994 is only 76% compared with a mean of 114% for 1944-1970 (Supplemental Table 1). Six years (out of 25) during 1971-1994 had above-average activity (i.e., >100%) compared with 15 (out of 26) in the earlier period. Five of the years during 1944-1970 were "hyperactive" (defined as NTC ≥ 150%) while there were no hyperactive years during 1971-1994. The hyperactive year 1995 marked the first since 1969. The mean NTC for 1995-2000 was 165% with four of the years hyperactive. In 2000, during which neutral ENSO conditions prevailed, the season still produced well-above-average activity.