FA P1.23 CLIMATOLOGICAL AND SYNOPTIC CHARACTERISTICS OF RAPIDLY INTENSIFYING TROPICAL CYCLONES IN THE NORTH ATLANTIC BASIN

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1. INTRODUCTION

Tropical cyclone (TC) intensity forecasting has proven to be considerably less skillful than has TC track prediction. An analysis of operational TC track and intensity forecasts in the Atlantic performed by DeMaria (1997) showed that while track forecasts exhibit statistically significant skill relative to climatology and persistence out to 72 h, TC intensity forecasts are not skillful beyond 36 h. Moreover, DeMaria (1997) showed that even during the first 36 h when operational intensity forecasts had skill that was statistically significant, the forecasts were still only about half as skillful as the TC track forecasts. The limited operational intensity forecasting skill for the Atlantic basin is a direct result of the lack of accurate TC intensity forecasting guidance. Currently, the only operational TC intensity forecast models employed by the National Hurricane Center (NHC) that are not based solely on climatology and persistence are the GFDL and SHIPS models; however, neither of these models has yet to demonstrate statistically significant skill relative to climatology and persistence for an entire hurricane season.

While the forecasting of TC intensity change in general has been quite difficult, the forecasting of rapid TC intensification has been particularly challenging as was underscored by the unexpected rapid intensification of Hurricane Opal (1995). Although both the operational intensity forecast models and the official National Hurricane Center (NHC) forecast correctly indicated that Opal would intensify, none of the aforementioned sources anticipated that Opal would strengthen so rapidly from a minimal category 2 to a strong category 4 hurricane on the Saffir/Simpson scale in just 18 hours. Fortunately, Opal weakened dramatically after this period of rapid intensification and made landfall as a minimal category 3 hurricane. Nevertheless, the unexpected rapid intensification of Opal so close to the United States underscores the need for improving our understanding of TC intensification, especially the rapid intensification process.

In the only previous comprehensive study of rapid intensification, Holliday and Thompson (1979), hereafter referred to as HT79, examined the climatological characteristics of rapidly intensifying TCs in the Northwest Pacific basin for the period 1956-1976.

Some of the important findings of their study were that rapid intensification was only observed when a sufficiently deep layer of warm water was present, and that rapid intensification was more prevalent during the nighttime than during the daytime. More recently, an analysis of the climatological and synoptic characteristics of rapidly intensifying TCs observed from 1989-1992 was performed during the development of a statistical hurricane intensity prediction scheme (SHIPS) for the Atlantic basin by DeMaria and Kaplan (1994). The results of this analysis indicated that rapid intensification occurred in TCs that were over warmer than average sea-surface temperatures (SSTs) consistent with the results from HT79 for the Northwest Pacific basin. Another important finding of this study was that the rapidly intensifying storms were typically embedded in regions where the 850-200 mb vertical shear (SHR) of the wind was substantially lower than the sample average. In contrast, however, this study found that the 200 mb fluxes of relative eddy angular momentum (REAM) for these cases was not substantially different than the sample mean. This is interesting since some previous research (Molinari and Vollaro 1989) has indicated that large positive fluxes of REAM may be associated with rapid intensification.

In this paper, the climatological characteristics of TCs that underwent rapid intensification (RI) in the Atlantic basin during the period from 1975-1996 will be investigated using NHC best track data as well as climatological SST and mixed-layer depth estimates obtained from Levitus (1982). This time period was chosen since some form of the Dvorak (1975) satellite classification scheme has been used for this entire period, and several significant improvements in the Dvorak scheme were first employed during the 1975 Atlantic hurricane season. The goal of this paper is to define what RI is for the Atlantic basin using methodology that is very similar to that used in HT79 for Northwest Pacific typhoons. The mean climatological characteristics of these rapid intensifiers will also be examined to determine if they differ substantially from those of the entire TC sample.

The large-scale characteristics (e.g., SHR, REAM fluxes) for TCs from 1989-1996 will also be examined to try and identify the large-scale physical mechanisms favorable for rapid TC intensification. This period was chosen since the observed magnitude of a variety of synoptic characteristics could be obtained for all named TCs during this time period from the data base used to develop the SHIPS intensity forecast model. The results of this analysis will be presented at the conference.

2. DATA AND ANALYSIS

The primary data used to analyze the climatological and synoptic characteristics of North Atlantic TCs were obtained for the period from 1975-1996 from the

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HURDAT file maintained by NHC (Jarvinen et al. 1988). The HURDAT file consists of 6-h estimates of position, central pressure (CP), and maximum sustained surface wind speed (MSSW) for all named Atlantic TCs from 1886 to the present. Since NHC often requests aircraft reconnaissance (recon) for TCs that are west of ~50° W, aircraft reconnaissance data were likely available for use in constructing the HURDAT file for many of the TCs during this time period. Nevertheless, there were undoubtedly occasions when recon data were unavailable to construct the HURDAT file. During these time periods, the HURDAT positions and intensity estimates would have been determined by employing satellite and ship data. While, these estimates are not likely to be as accurate as those determined using aircraft recon data, Gaby et al. (1980) found fairly good agreement between TC position and intensity estimates obtained using the Dvorak (1975) scheme and those in the final HURDAT file when evaluations were performed during periods when aircraft recon data were available. Specifically, their study showed that Dvorak estimates of MSSW were within 8 kt of those contained in the final HURDAT file although the Dvorak scheme tended to underestimate the MSSW by ~5 kt. Gaby et al. (1980) also showed that the TC position estimates obtained using the Dvorak scheme were typically within 30 km of those in the final HURDAT file. While these results are encouraging, one noteworthy weakness of the Dvorak (1975) scheme is that it places constraints on the rate at which the estimated intensity can increase. Although the Dvorak constraint that the 24 h pressure change can not exceed ~50 mb does place an artificial limit on the TC intensifcation rate, it still appears to be sufficiently large for the purpose of this study. In summary, despite any weaknesses that the Dvorak (1975) scheme may have, the period from 1975 to the present when both the Dvorak (1975) scheme and recon data were used to determine TC positions and intensities is believed to be sufficiently accurate to perform the analysis described below.

3. RESULTS

The maximum 24 h pressure fall (ΔPfall$_{24}$) observed during the lifetime of each named storm in the Atlantic basin for the period 1975-1996 was computed. The quantity ΔPfall$_{24}$ was evaluated to permit comparisons to be made between the results of this study and those from HT79, since the authors of HT79 employed this quantity when defining RI for the Northwest Pacific typhoon. Only TCs for which the HURDAT file contained pressure values every 6 h were used in this study, since the use of storms with missing 6 h pressure values would likely lead to underestimation of the ΔPfall$_{24}$ computed for these TCs. Moreover, named storms that began as subtropical cyclones were also excluded from the current study. The decision to exclude subtropical cyclones was made because the physical structure of these systems may have been different than the structure of cyclones whose origin was tropical in nature.

When examining RI in the Northwest Pacific basin, HT79 only employed TCs that reached typhoon intensity which they defined as TCs that had pressures≤980 mb. Consequently, we defined a stratification comprised of only Atlantic TCs that attained hurricane intensity; however, we also created another stratification that included all named Atlantic storms. The criterion that we employed to determine if an Atlantic TC reached hurricane intensity was selected based upon the MSSW rather than the CP as HT79 employed. This decision was reached for a few reasons. First, the pressure wind relationships for the Northwest Pacific and the Atlantic basins differ with Atlantic TCs having higher MSSWs than Northwest Pacific TCs for the same pressure. For example, in the Atlantic basin the Dvorak (1975) pressure-wind relationship for a CP of 980 mb which HT79 cited as the cutoff for typhoon intensity (MSSW≥65kt) yields a MSSW of ~76 kt. Although a CP of 987 mb, which by the Dvorak (1975) scheme yields a MSSW of 65 kt, could have been used as the cutoff for hurricane intensity in the Atlantic basin, the pressure wind relationships employed at NHC have changed over the years. Therefore, the cutoff for hurricane intensity was assumed to be 65 kt in the Atlantic for this study.

Figure 1 shows the distribution of ΔPfall$_{24}$ stratified by the basin of formation as well as the maximum intensity reached during the lifespan of each TC. The three stratifications are : 1) Northwest Pacific typhoons (PACTYP), 2) Atlantic named storms (ATLNST),and 3) Atlantic named storms that reached hurricane intensity (ATLHUR). It is important to note that the data used to construct the ΔPfall$_{24}$ distribution for the PACTYP stratification shown in Fig. 1 were obtained directly from HT79. Figure 1 indicates that the overall shapes of the distribution of ΔPfall$_{24}$ computed for the PACTYP and ATLHUR stratifications are quite similar, although the distribution of ΔPfall$_{24}$ for the ATLHUR stratification is skewed toward smaller pressure falls. The figure also shows that the ΔPfall$_{24}$ distribution for the ATLNST

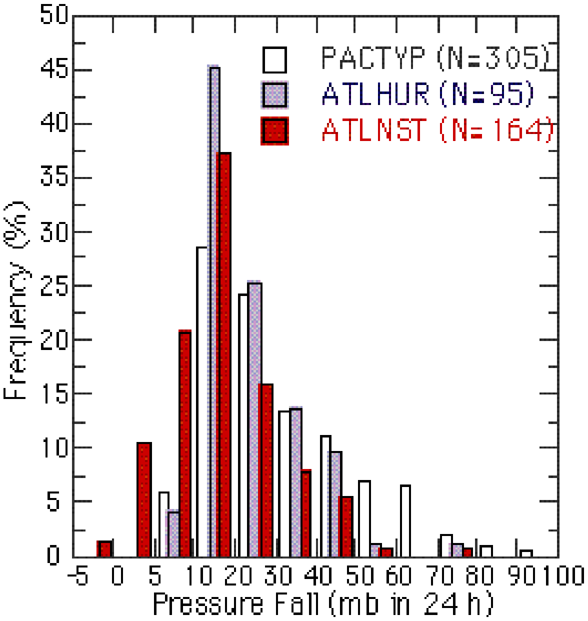

Fig. 1. Frequency distribution of ΔPfall$_{24}$ for the PACTYP, ATLNST, and ATLHUR stratifications.

stratification is skewed toward the smallest $\Delta\mathrm{Pfall}_{24}$ values of the three stratifications. It is interesting to note that despite the differences in the $\Delta\mathrm{Pfall}_{24}$ distributions observed for the various samples, the pressure fall class from 10-19 mb is the most frequently observed class for all three stratifications.

Table 1 shows some sample statistics for the three stratifications used in Fig. 1. The table indicates that the maximum $\Delta\mathrm{Pfall}_{24}$ observed in the Northwest Pacific basin is considerably larger than is observed for the Atlantic basin. This may be due, in part, to the existence of far fewer cases for the Atlantic basin. However, the median $\Delta\mathrm{Pfall}_{24}$ obtained for the ATLHUR stratification is also ~28% less than that obtained for the PACTYP stratification suggesting that, on average, higher $\Delta\mathrm{Pfall}_{24}$ are observed for the Northwest Pacific basin. Table 1 also shows that the standard deviation (S.D.) for the PACTYP stratification is ~50% greater than the S.D. computed for either the ATLHUR or ATLNST stratifications, indicating that there is considerably more variability in the intensification rates observed for the Northwest Pacific basin.

Figure 2 is a cumulative frequency diagram of the $\Delta\mathrm{Pfall}_{24}$ for the three stratifications. The figure shows that while the frequency distributions of the PACTYP and ATLHUR stratifications are quite similar below the 20th percentile, they become quite different at the higher percentiles. HT79 defined RI for the Northwest Pacific basin as being any typhoon whose $\Delta\mathrm{Pfall}_{24}$ was within the upper 25% (e.g. 75th percentile) of the sample. Thus, any typhoon with a $\Delta\mathrm{Pfall}_{24} \geq 42$ mb/day was classified as undergoing RI in their study. Interestingly, employing the 75th percentile as the cutoff for RI in the Atlantic basin, yields $\Delta\mathrm{Pfall}_{24}$ of ~30 mb/day and ~22 mb/day for the ATLHUR and ATLNST stratifications, respectively. It is worth noting that a $\Delta\mathrm{Pfall}_{24}$ of 42 mb/day which HT79 defined as being the lower limit for RI for the Northwest Pacific basin, corresponds with roughly the 90th percentile for the ATLHUR stratification.

The finding of higher intensification rates for the Northwest Pacific basin than the Atlantic basin appears consistent with the results of Gray (1968). Gray (1968) showed that, on average, three times as many TCs of tropical storm intensity develop in the Northwest Pacific than develop in the Atlantic. His results indicated that the Northwest Pacific basin is generally a more favorable basin than the Atlantic for TC formation due mainly to the combined affects of higher potential buoyancy in the lower troposphere and lower SHR. Presumably, the existence of these favorable conditions result not only in more TCs developing, but also are reflected in higher rates of intensification being observed in the TCs that due develop.

Table 1. The number of observations (N), minimum (Min), maximum (Max), average (Avg), median (Med), and standard deviation (S.D.) of the $\Delta\mathrm{Pfall}_{24}$ for the PACTYP, ATLHUR, and ATLNST stratifications. All statistics were computed using the $\Delta\mathrm{Pfall}_{24}$ data from Fig. 1. Positive values of $\Delta\mathrm{Pfall}_{24}$ represent pressure falls while negative values denote pressure rises. The units are mb/24 h.

Stratification	N	Min	Max	Avg	Med	S.D.
PACTYP	305	5	95	29.7	24.0	18.4
ATLHUR	95	5	72	23.2	19.7	12.5
ATLNST	164	-4	72	16.6	14.3	12.5

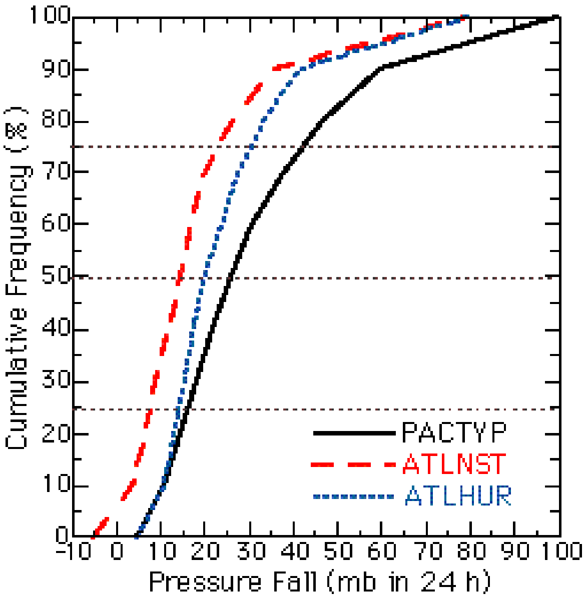

Fig. 2. Cumulative frequency distribution of $\Delta\mathrm{Pfall}_{24}$ for the PACTYP, ATLNST, and ATLHUR stratifications.

To investigate whether there were any identifiable differences in the climatological characteristics of hurricanes that underwent RI, the mean characteristics of the entire ATLHUR sample were computed and compared to those obtained for the rapidly intensifying ($\Delta\mathrm{Pfall}_{24} \geq 30$ mb/day) Atlantic hurricane (RIATLHUR). This was accomplished by computing the mean values of each of the climatological parameters at the start of the period of $\Delta\mathrm{Pfall}_{24}$ of each storm for both the ATLHUR and the RIATLHUR samples and these values are shown in Table 2. These procedures were also employed for the ATLNST stratification; however, we will only discuss the results obtained for the ATLHUR stratification since this stratification was more similar to the PACTYP sample employed in HT79.

Inspection of Table 2 indicates that there is not much variation in the Julian day (September 8 vs 11) or time of day (9.3 UTC vs 9.0 UTC) between the means computed for the ATLHUR stratification and the RIATLHUR samples. Moreover, since the time of the observations employed in this study were either 0,6,12 or 18 UTC, the mean time of day of ~9 UTC shown in Table 1 indicates that, in general, there is no preference for a TC to intensify more rapidly either early or late in the day. This is in agreement with the composite results of Frank (1977) who did not find any appreciable diurnal variation in CP or maximum wind in his study of

Table 2. Mean climatological characteristics for the ATLHUR and RIATLHUR samples.

Characteristic	**ATLHUR**	**RIATLHUR**
Julian Day	252	254
Time (UTC)	9.3	9.0
Latitude (°N)	22.8	20.4
Longitude (°W)	67.4	66.7
MSSW (kt)	56	75.0
CP (mb)	994	982
SST (°C)	27.4	28.0
Mixed-layer depth (m)	40.2	43.0
Storm heading (°)	319	303
Storm speed (kt)	9.9	10.8

Northwest Pacific typhoons. However, this result is in contrast with the results of HT79 which found that 66% of the rapidly intensifying Northwest Pacific typhoons commenced RI during the nighttime. HT79 hypothesized that diurnal variations in upper-tropospheric temperatures may be responsible for the observed preference for RI to occur at night in their study. Since the HT79 study utilized observations at 3,9,15, and 21 UTC, some of the differences in the two studies may be the result of their ability to employ observation times that are better suited to capturing any potential diurnal variations in intensity.

Table 2 indicates that the mean position of the RIATLHUR is only slightly southeast of the position computed for the mean ATLHUR. However, one significant difference between the RIATLHUR and the ATLHUR samples is that the RIATLHUR sample has a significantly higher mean intensity than the average ATLHUR as measured by both the MSSW and CP. This finding seems reasonable since stronger TCs generally exhibit a more organized inner core structure. The observation of higher SSTs for the RIATLHUR sample is consistent with the results of HT79 who found that the vast majority of TCs that experienced RI in there sample had SSTs≥28°C. Table 2 shows that the RIATLHUR tends to have a more westward motion than the sample mean ATLHUR. This result seem reasonable since a more westward heading would tend to keep the hurricane further south where the SHR tends to be lower, and DeMaria and Kaplan (1994) have shown that low SHR is conducive to RI. Finally, Table 2 shows that RI tends to occur for TCs that have higher translational speeds and are over regions of climatologically higher than average mixed-layer depths. While these differences are fairly small, both factors would tend to minimize the amount of upwelling of cool water from below the sea surface which has been shown to have a detrimental impact on TC intensity (Schade 1995).

4. SUMMARY

The climatological characteristics of TCs that underwent RI in the Atlantic basin during the period 1975-1996 were examined using the NHC HURDAT file and climatological SST and mixed-layer depth information from Levitus (1982). The NHC HURDAT file was employed to compute $\Delta Pfall_{24}$ for each named Atlantic TC during the above time period. These $\Delta Pfall_{24}$ were employed to enable comparisons to be made between the results of this study and those from HT79. HT79 analyzed intensification rates of Northwest Pacific typhoons and determined that typhoons whose $\Delta Pfall_{24}$ was in the top 25% of the sample, met the criterion for RI. Employing this definition for the Atlantic sample, yielded thresholds for RI of 30 mb/day and 22 mb/day for the ATLHUR and ATLNST stratifications, respectively. These rates of RI are significantly lower than the $\Delta Pfall_{24}$ rate of 42 mb/day that HT79 determined was the cutoff for RI in the Northwest Pacific basin. The finding of higher rates of intensification for the Northwest Pacific basin appears to be consistent with the results of Gray (1968) who showed that the Northwest Pacific basin is a more favorable basin than the Atlantic for tropical storm formation.

An analysis of the mean climatological characteristics of the entire ATLHUR and RIATLHUR samples was performed to investigate the climatological conditions that are conducive to RI. This analysis showed that the mean RIATLHUR was stronger than the mean ATLHUR and was also situated over warmer than average SSTs and deeper than average mixed-layers. The mean RIATLHUR was also moving faster and more westward than the average ATLHUR. While not all the differences between the mean climatological characteristics computed for the ATLHUR and RIATLHUR were particularly large, they do suggest that more favorable climatological conditions existed for hurricanes in the RIATLHUR sample.

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