TROPICAL CYCLONE LANDFALL IN THE UNITED STATES 1960–1989

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Abstract

All tropical cyclones which originated in the North Atlantic Basin (including the Gulf of Mexico and Caribbean Sea) and made landfall within the United States during the period 1960-1989 are analyzed. The cyclones are divided into categories based on formation area (six distinct regions), month of cyclogenesis, maximum strength the cyclone achieved (using the Saffir-Simpson scale), and landfall location (nine distinct zones). In order to identify climatological patterns and trends, statistical procedures are used with each of the stated variables.

This study differs from others on tropical cyclone climatology through methodology. Here, only tropical cyclones which made landfall within the U.S. during the study period are examined. By incorporating this methodology, a greater understanding of the associated trends and climatological interactions of cyclones which pose danger to U.S. citizens is gained. The study aids in delineating the time period during which a tropical cyclone is expected, the extent of the area likely to experience a tropical cyclone, and the likely severity of the tropical cyclone.

Results indicate that landfall zones along the Gulf Coast are primarily affected during the early portion of the hurricane season by tropical cyclones which form in the Gulf of Mexico. As the hurricane season progresses, the cyclones form in the Caribbean and usually make landfall within the state of Florida. During the time of greatest cyclone frequencies (August and September), the cyclogenesis area shifts to its farthest eastern extent, near the Cape Verde Islands. These tropical cyclones typically make landfall along the western Gulf Coast, Florida, or along the East Coast north of 34°N. Late season cyclogenesis reverts back to the Gulf of Mexico and once again plagues the Gulf Coast landfall zones.

1. Introduction

It has long been speculated that the recognized tropical cyclone formation regions go through cycles (Vega and Binkley 1991), thus affecting different landfall areas at various times in history. This may be the reason for a distinct lull in tropical cyclone activity along the eastern seaboard of the United States during the past 30 years (Garstang 1990). This lull may partially explain the apparent lack of concern over massive urbanization of coastal properties in that area (Pracher 1990). Recent activity (i.e., Hurricanes Hugo and Andrew) has focused renewed attention on tropical cyclone climatology and potential impacts in the US (Rogers and Davis 1993; Stone et al. 1993; Gray and Landsea 1992; and Gray 1990), especially along the eastern seaboard (Gray and Sheaffer 1991; and Vega 1990).

Frank (1985) states that the annual number of tropical cyclones in the North Atlantic Basin is highly variable, with annual totals over the last century ranging between 1 and 21, and that no long-term trends are evident within the recent past. Reading (1989), however, shows that long-term trends in frequency do exist for the North Atlantic during the past 100 years. By examining decadal frequencies, Reading shows that a lull in activity appears from 1900 through the 1920s. A sharp and significant rise in storm frequencies occurs during the 1930s and lasts until the 1950s at which time cyclone frequencies climbed to 138% above the mean value of 72 storms per decade. However, since the 1960s, decadal tropical cyclone frequencies dwindle to just below the mean value but still remain higher than the frequency troughs of the 1870s, 1910s and 1920s. Reading also shows that cyclone frequencies are highest along the eastern US coast before the 1920s with few tropical cyclones penetrating to the west. The majority of cyclones recurved north and eastward over the Caribbean or eastern Gulf of Mexico during that time. Therefore, higher cyclone frequencies are recorded along the central to eastern Gulf Coast and the east coast.

It has been suggested that the lower frequencies since the 1960s are attributable to the equatorward displacement of the average tropical cyclone track (Walsh 1977). Spencer and Douglas (1985) show that the frequencies decline in a west and northwest to south migration pattern. This is in agreement with Reading (1989) who argues that the lull results from a decrease in Cape Verde type cyclones. Gray (1990), and Landsea and Gray (1992), attribute the decline to drought conditions in the Sahel of western Africa which effectively reduce the number of strong easterly wave seedlings in the Atlantic Ocean and present circulation features which are not conducive to tropical cyclone formation. Vega (1990) suggests that changes in the global circulation regimes, especially the Intertropical Convergence Zone (ITCZ) and the Bermuda High (also see Coleman 1988; and Coleman 1982), are responsible as interactions between the two account for all previously mentioned phenomena.

From this it is apparent that long-term trends in tropical cyclone frequencies do exist but are not fully understood due to the relatively short climatic record. Also, interactions between tropical cyclones and other associated climatological phenomena have not been fully explored (Gray and Sheaffer 1991; and Vallee 1990), thereby inhibiting complete understanding. Furthermore, many tropical cyclone trends become difficult to examine as cyclone tendencies and interactions become lost in the sheer number of events (Lawrence 1989).

This study incorporates a methodology which utilizes only those tropical cyclones which have made landfall within the conterminous United States. By arranging cyclones in this manner, a greater understanding of the recent trends and climatolog-
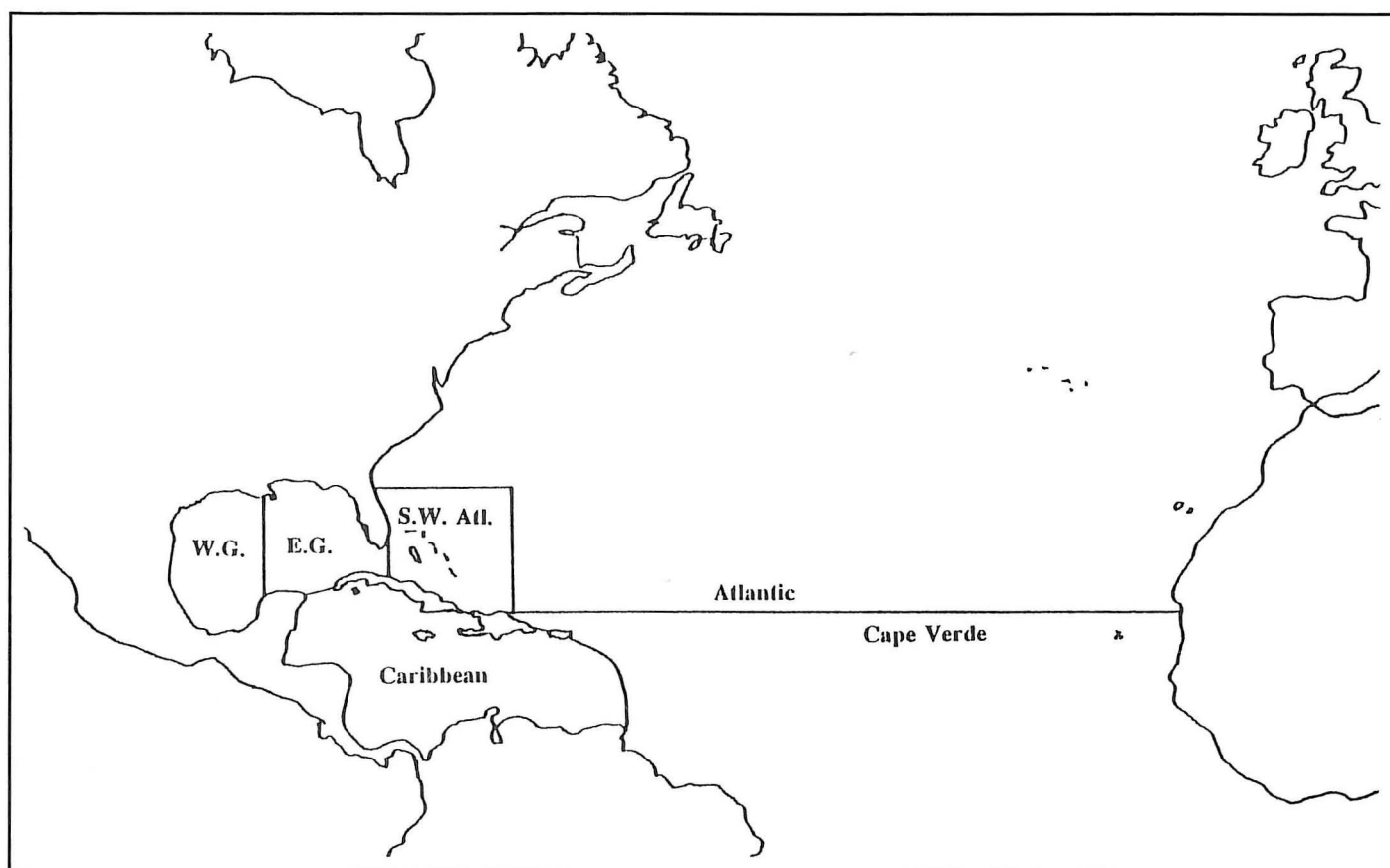
Fig. 1. North Atlantic Basin tropical cyclone formation areas.

ical interactions of cyclones which pose danger to US citizens may be gained. Furthermore, this study aids in delineating the time period during which a tropical cyclone may be expected, the extent of the area likely to experience a tropical cyclone and the likely severity of the tropical cyclone.

2. Methodology

This study concerns all tropical cyclones which formed in the North Atlantic Basin and made landfall in the United States during the period, 1960–1989. The implementation of weather satellite tracking contributes to the chosen study period. Therefore, the exact location of cyclone formation and landfall is better ensured. Tropical cyclone data is taken from *Tropical Cyclones of the North Atlantic Ocean, 1870–1986* (Neumann et al. 1987) as well as the February 1988–1990 issues of *Weatherwise* (Case 1990; Lawrence 1989; and Case 1988). From this data, the highest intensity a storm reaches on the Saffir-Simpson Hurricane Intensity Scale (Simpson and Riehl 1981) is used to classify the storm. This criteria establishes the potential threat of a severe cyclone to a particular landfall area. It is acknowledged that cyclones may change intensity during their lifetime, however, it is believed that the potential intensity of a particular cyclone is regulated through climatic conditions which correspond to particular formation regions.

The first area in which a tropical cyclone eye crosses onto the US mainland is used as the point of landfall for that cyclone. Multiple strikes by the same tropical cyclone are not examined which further eliminates the number of events. This methodology ensures the proper evaluation of favorable first strike conditions. The date at which the reference materials (hence the

National Hurricane Center) first record the cyclone is used as the date of formation and the corresponding location is used as the cyclone formation point.

a. Formation

Six regions of tropical cyclone formation are identified and used in this study. Initial formation areas are based upon recognized formation areas as identified by Neumann et al. (1987), Chaston (1988), and Reading (1989). However, the formation areas are further expanded, redefined and given set boundaries through track analysis (Vega and Binkley 1993). The six formation regions are graphically represented in Fig. 1.

b. Landfall

The coast of the United States from the Texas-Mexican border to the Maine-Canadian border is divided into nine *a priori* landfall zones in which tropical cyclones from the North Atlantic Basin may strike (Fig. 2). These landfall zones are:

Zone 1: Brownsville, Texas to Houston, Texas;
Zone 2: Houston to New Orleans, Louisiana;
Zone 3: New Orleans to Apalachicola, Florida;
Zone 4: Apalachicola to Tampa Bay, Florida;
Zone 5: Tampa Bay to Key West, Florida;
Zone 6: Key West to Jacksonville, Florida:
Zone 7: Jacksonville, to Charleston, South Carolina;
Zone 8: Charleston to Cape Hatteras, North Carolina; and,
Zone 9: Cape Hatteras to the Maine-Canadian border.

This landfall system effectively divides the Gulf and eastern coast into nine zones with approximately similar area (except for area 9) and meeting the prescribed criteria (area, upper-
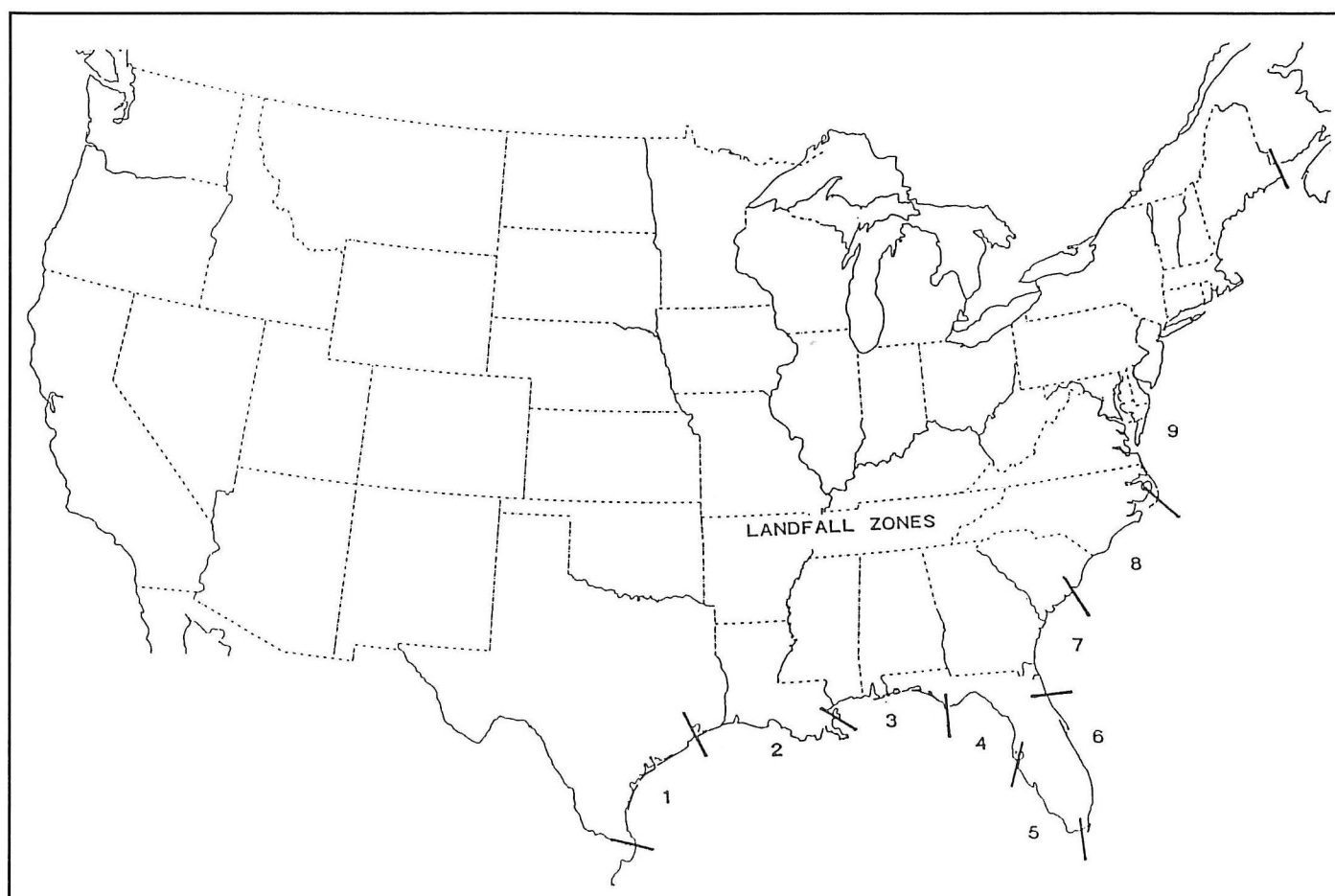
Fig. 2. Landfall zones along the Gulf and Atlantic Coasts.

air observation site, and a National Weather Service forecast office—so that more specific future evaluations may be carried out). Coastline geography is also a determining factor in the boundaries of each landfall zone as natural breaks in the coastline are utilized. These natural breaks result from complex geomorphological conditions, many of which arise from air-sea interactions (i.e., currents). Therefore, coastal configuration may affect the area of tropical cyclone landfall (Rogers and Davis 1993). This methodology differs from other studies which utilize arbitrary (in nature) state or county boundaries. It is recognized that the last zone (9) has a much greater area than the other zones. However, due to its higher latitude, it is expected to receive much lower tropical cyclone landfall frequencies.

The point of landfall used in this study is the point at which the official best track (central position of the storm eye) crosses onto the continental US. Multiple strikes by a single tropical cyclone are not included, as only the first landfall area in which the eye passes is considered the landfall point for that storm. Some slight discrepancies may exist where cyclones breach the border between two landfall zones, however, consistency in grouping is maintained as closely as possible.

c. Statistics

A statistical approach is used to identify relationships between the tropical cyclone formation areas, landfall zones, intensities and the months of the hurricane season (June–November). Chi-square analysis and analysis of variance, incorporating the Scheffe Contrast test (Dowdy and Wearden 1991),

are used to identify and determine trends between the stated variables. It is noted that the statistical computations are based upon a relatively low number of storms so that in some aspects of the study, the statistical analysis may be biased through assumption violation.

3. Analysis

a. Temporal variation

A Bartlett-Box observed chi-square test is used to determine whether one five-year period during the study period produces higher cyclone frequencies than any other. In agreement with Frank (1985), no statistically significant differences are detected [probability value (P) = 0.15] indicating that the frequency of storms is relatively even throughout the study period.

An intra-annual approach is utilized by dividing the hurricane season (June–November) into separate months for analysis. August and September prove to be the dominant months for tropical cyclogenesis as 25 and 26 cyclones (which made landfall) formed respectively (Fig. 3). The frequency drops dramatically during the next highest month of cyclone activity, June (10 storms). The months of July and October follow as 9 and 6 cyclones formed respectively. Finally, November proves to be the month of least activity as one tropical cyclone (making landfall) formed during this time.

A chi-square goodness of fit test is used to determine statistical significance, assuming that the formation of cyclones is equal across all months of the hurricane season. A probability
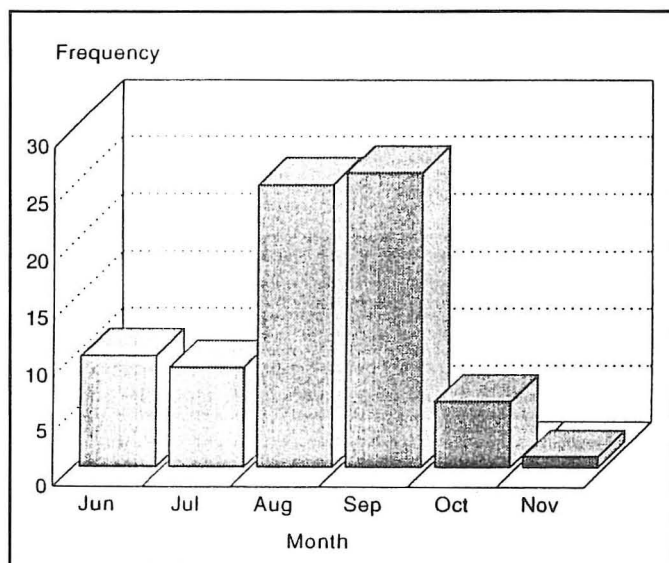
Fig. 3. Monthly frequencies of tropical cyclones which made landfall in the United States, 1960–1989.

value is calculated (P = 0.04) which indicates significance at an alpha level of 0.05. The Scheffe Contrast test indicates that a significantly higher number of cyclones formed during the months of August and September as compared to all other months.

b. Landfall zones

To determine whether any one landfall zone receives significantly stronger tropical cyclones than any other, a one-way analysis of variance is used. The cyclones are divided by the respective points of landfall (the nine landfall zones) and analyzed. Actual wind speeds of the tropical cyclones are used in this aspect of the analysis with a mean wind speed calculated for each landfall zone. No statistically significant differences are detected (P = 0.70) among the means. Therefore, all landfall zones are affected by tropical cyclones of approximately similar intensity.

1) Landfall zone 1

The tracks of all tropical cyclones which made landfall within landfall zone 1 are depicted in Fig. 4. The cyclone tracks vary but are mainly from the south and southeast indicating some Subtropical High (STH) control. The Western Gulf of Mexico is the primary formation region which affects this landfall zone (Table 1). This is expected given the close proximity between the formation regions and the landfall zone. However, it is somewhat surprising that the next most active formation regions with regard to this zone are the Caribbean and Cape Verde. This is indicative of the STH influence on storms which form in this region during the peak months of the hurricane season (August and September). The STH attains maximum strength during this time (Sahsamanoglou 1990), which causes storms to steer across the entire Atlantic Ocean and Gulf of Mexico, whereby recurvature occurs in its lee. It is during the recurvature stage that landfall typically occurs.

It is expected that the Eastern Gulf formation region be better represented given the proximity to the landfall zone. The Southwest Atlantic and the Atlantic formation regions are not represented in the distribution as cyclones formed within these waters typically make landfall along the eastern seaboard.

Statistically, no one formation region is a dominant producer of storms (P = 0.11) with regard to this landfall zone. The null hypothesis states that a landfall region should be affected by an equal number of storms from each formation region. Here, a fairly even distribution (statistically) results.

The monthly frequency distribution indicates that tropical cyclones may affect this landfall zone at any time during the hurricane season, with the exception of November (Table 2). The first four months of the hurricane season represent the times of greatest cyclone frequency; July, August, and September record equal frequencies. Such a pattern closely resembles the pattern of mean sea surface temperatures (SSTs) in that the Gulf of Mexico typically heats sooner and retains heat longer than the larger and deeper Atlantic Ocean (Gordon 1986). Therefore, both early and late season cyclones form within the Gulf as a result of high SSTs. The chi-square statistical analysis proves the evenness of the temporal distribution as no month produces a significantly greater number of storms as compared to all others (P = 0.26).

The vast majority of tropical cyclones which strike landfall zone 1, are of relatively low intensity (Table 3). However, a few storms of high intensity during their lifetime (category 3–5) make landfall within the region. These storms form mainly during the months of peak oceanic SSTs (August and September) and typically originate within the Cape Verde formation region. Chi-square analysis indicates that the higher number of tropical storms is statistically significant (P < 0.001) assuming an equal frequency of all intensity levels.

2) Landfall zone 2

Track analysis of cyclones which made landfall in zone 2 proves that cyclones typically affect this area during recurvature (Fig. 5). Although the initial movement of many storms is from the south, the tendency is for cyclones to recurve at landfall. The latitude of the zone is responsible as cyclones enter the transition (approximately 30°N) between the global easterlies and the global westerlies. This transition combines with the cyclones own inertia and resulting Coriolis deflection (Hsu 1988) which causes cyclones to briefly slow and recurve over the landfall zone.

As with zone 1, the Western Gulf formation region produces the greatest number of storms which affect this zone (Table 1). This relationship is proven statistically significant (P = 0.02) through chi-square analysis. As expected, the Eastern Gulf formation region is also very active in relation to this zone due to proximity. The barotropic atmosphere in lee of the STH is conducive to cyclone formation from either of the two Gulf regions and subsequent landfall within this zone. The Cape Verde formation region is also well represented as is the Caribbean.

A slight shift is seen in the temporal record of cyclones associated with this landfall zone as compared to zone 1 (Table 2). Here, there is a definite peak in cyclone activity during August and September. Also, the frequency distribution proves that early and late season cyclones are not as threatening to this zone as is the case with zone 1. The temporal pattern adequately reflects overall higher SSTs in both the Gulf of Mexico and the Atlantic Ocean during months with peak cyclone frequencies. Statistical significance is detected using the chi-square procedure (P = 0.02) indicating significantly higher frequencies during these times.

The distribution of cyclone intensities is heavily weighted in the low end of the Saffir-Simpson scale (Table 3). It is interesting to note that more Category 1 hurricanes made landfall than did tropical storms. This implies a longer average

Table 1. Frequency of Tropical Cyclones by Formation Region and Landfall Zone.

	W.G	E.G.	S.W.A.	Car.	C.V.	Atl.
Zone 1	5	2	0	3	2	0
Zone 2	6	4	0	2	4	0
Zone 3*	1	0	0	5	2	2
Zone 4	0	2	0	4	0	0
Zone 5	0	3	0	4	2	0
Zone 6	0	0	7	0	2	0
Zone 7	0	0	0	1	2	0
Zone 8	0	0	3	0	1	0
Zone 9	0	0	3	0	2	0

* Does not include one storm formed in the Pacific Ocean.

Table 2. Frequency of Tropical Cyclones by Month and Landfall Zone.

	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Zone 1	2	3	3	3	1	0
Zone 2	1	3	5	6	1	0
Zone 3	2	1	3	4	0	1
Zone 4	3	1	2	0	0	0
Zone 5	2	1	3	0	3	0
Zone 6	0	0	5	4	0	0
Zone 7	0	0	1	1	1	0
Zone 8	0	0	2	2	0	0
Zone 9	0	0	1	4	0	0

Table 3. Frequency of Tropical Cyclones by Maximum Intensity and Landfall Zone.

	TS	1*	2	3	4	5
Zone 1	5	3	0	2	2	0
Zone 2	4	7	0	1	2	2
Zone 3	4	1	0	3	1	2
Zone 4	2	3	0	1	0	0
Zone 5	3	5	0	0	0	1
Zone 6	4	2	0	0	2	1
Zone 7	1	1	0	0	0	1
Zone 8	2	0	1	0	1	0
Zone 9	3	0	0	1	1	0

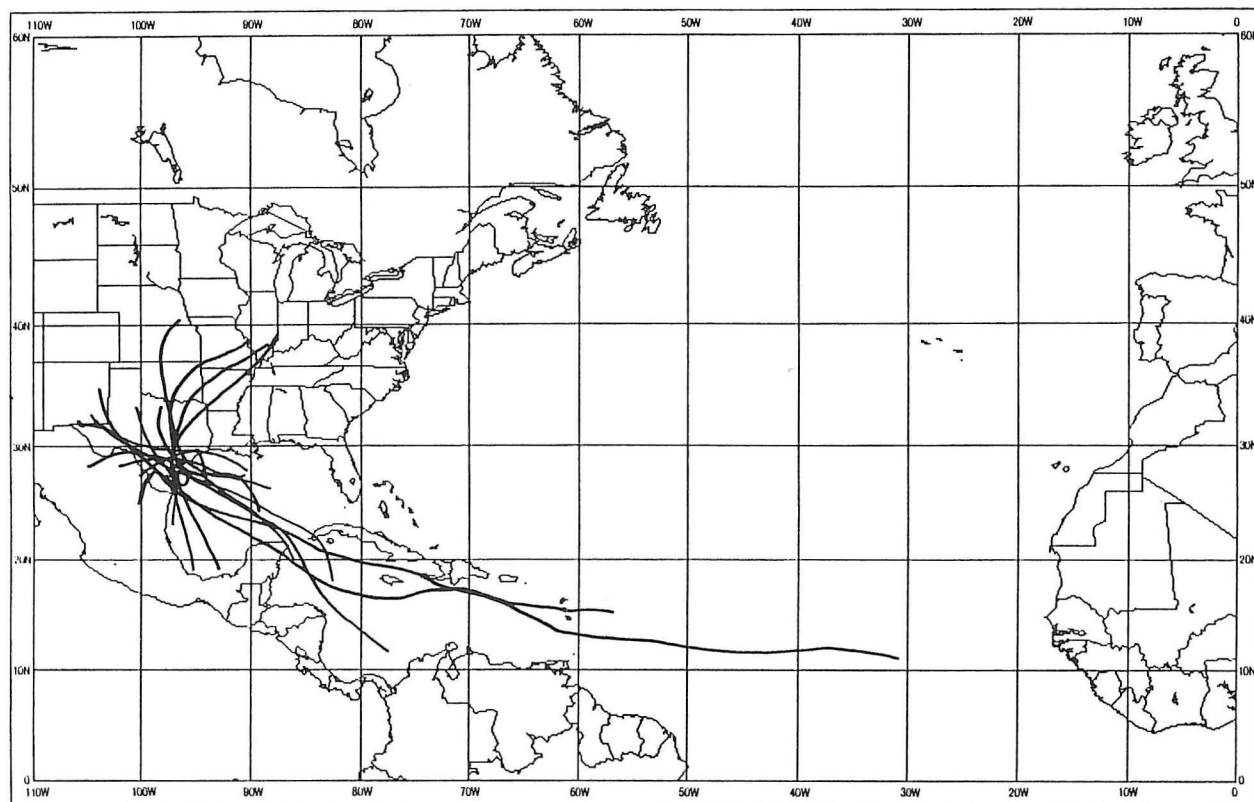* Saffir–Simpson Hurricane Intensity Scale (categories 1–5)

Fig. 4. Tracks of tropical cyclones (1960–1989) which made landfall in zone 1.
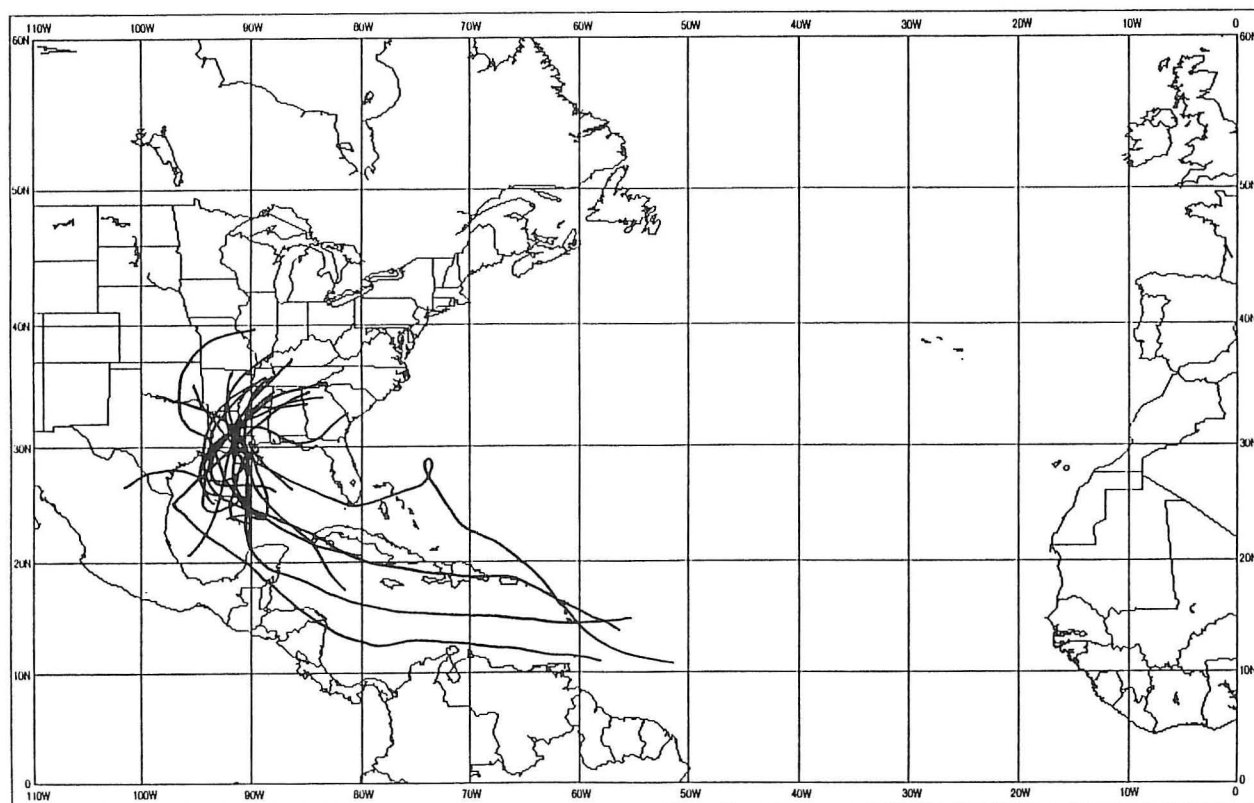

Fig. 5. Tracks of tropical cyclones (1960–1989) which made landfall in zone 2.

cyclone trajectory before landfall than is evident in zone 1. A slight bimodal distribution is prevalent indicating a small influx of storms late in the hurricane season. These cyclones typically form in the Caribbean and Cape Verde formation regions. The chi-square goodness of fit test indicates that the prevalence of tropical storms and Category 1 hurricanes is statistically significant (P = 0.03).

3) Landfall zone 3

Cyclones which strike landfall zone 3 typically track from the south and southeast (Fig. 6) into the landfall zone. A more parabolic track is associated with these cyclones, indicating STH influence in steering the cyclones to the west where they recurve into the global westerlies.

The prevalence of Gulf of Mexico tropical cyclogenesis all but diminishes with regard to this landfall zone (Table 1). Here, the Caribbean is the dominant producer of cyclones, followed equally by the Cape Verde and Atlantic formation regions. It is very interesting that the Atlantic region produced two zone 3 cyclones as this represents the entire production of landfall striking cyclones from this formation region. The low latitude of the Atlantic cyclones combines with STH interaction to support the prevailing storm tracks. Furthermore, one tropical cyclone originates within the Pacific Ocean near southern Mexico (not shown in Fig. 6). Although the cyclone is included in the temporal and intensity analysis, it is excluded in the formation region analysis. Chi-square analysis confirms the fact that no one formation region produced a statistically significant number of cyclones (P = 0.07).

Given the frequency distribution of the formation regions, the even temporal distribution is a bit surprising (Table 2). With the diminishment of Gulf tropical cyclogenesis, one would expect a preponderance of mid- to late-season cyclones. This is not the case, the distribution suggests that early and late season cyclones form within the Caribbean and Cape Verde regions. The Caribbean is shallow as compared to the Atlantic and is at a lower latitude than the Gulf, therefore, tropical cyclone formation is highly plausible both early and late in the hurricane season. In addition, peak cyclogenesis is divided fairly evenly between the months of August and September. The chi-square test confirms the even distribution as no month produces a significantly greater number of cyclones than any other (P = 0.49).

Cyclones which strike landfall zone 3 are distributed across the entire Saffir-Simpson scale (Table 3). This reflects the temporal distribution previously discussed. Early and late season cyclones tend to be of relatively low intensity while mid-season tropical cyclones tend to be of higher intensity. No statistically significant trends are detected in association with cyclone intensities (P = 0.55).

4) Landfall zone 4

The tracks of cyclones which strike landfall zone 4 are primarily northward and recurvature typically takes place after landfall (Fig. 7). The cyclones typically parallel the eastern seaboard after landfall as they move into higher latitudes. In addition, many of these cyclones undergo reintensification over the baroclinic region of the Gulf Stream.

Cyclones associated with this zone form exclusively in the Eastern Gulf and Caribbean formation regions (Table 1), with the Caribbean the dominant cyclogenesis area. The Western Gulf formation region is not represented due to the shearing apart of northeastward tracking cyclones in this area (Hebert 1993). Chi-square analysis proves the two formation zones to be significantly related to the landfall zone (P = 0.01).

The cyclones are equally distributed across the early portion of the temporal record (Table 2), however, no statistical significance is detected within the distribution (P = 0.63). The low total numerical value of cyclones associated with this zone may influence the statistic, however, given a higher number of storms it is doubtful that a clear pattern would emerge. The most notable feature of the temporal record is that no cyclones are represented during the month of September. Given this, and the fact that only two cyclones affect the area during the month of August implies a physical control associated with shifting formation regions.

The intensity of tropical cyclones which strike this zone are mainly low on the Saffir-Simpson scale (Table 3). This is in keeping with the tendency for early season cyclones to pass over the area. The proximity of the genesis area and the landfall zone effectively prohibits the storms from reaching and maintaining extremely high wind speeds. However, no statistical significance is attributed to cyclone intensities associated with this zone (P = 0.55).

5) Landfall zone 5

Longer cyclone trajectories are associated with landfall zone 5, as compared to landfall zone 4 (Fig. 8). The storms either track due north and recurve after landfall or track to the northwest and recurve into the landfall zone. The latter represents the parabolic track most often associated with tropical cyclones.

The distribution of cyclogenesis regions associated with this landfall zone is very similar to that of landfall zone 4 (Table 1). The main differences are the number of storms involved (9 compared to 6) as well as the infusion of Cape Verde storms. In addition, the Eastern Gulf is slightly better represented with this landfall zone as compared to zone 4. No statistical trends are detected (P = 0.15) indicating a distribution equally representative of all formation regions.

The temporal record also proves to be rather evenly distributed as no peaks in frequency are evident (Table 2). The month of June produced two storms which affected this zone and both August and October produced three. The distribution is somewhat erratic as compared to the typical pattern of SSTs for the North Atlantic Basin. Therefore, cyclones may affect this zone from any formation region during any month of the hurricane season as no dominant patterns are found through statistical analysis (P = 0.49).

The intensities of tropical cyclones which strike this landfall zone are almost exclusively low during the study period (Table 3). Of these, the majority (5) are of Category 1 intensity while only three tropical storms are present. Also, one storm which originated in the Cape Verde region attained Category 5 status. The slightly longer storm tracks associated with this zone, as opposed to those previously discussed, probably aids the intensification of tropical storms into hurricanes but does not allow intensification to reach severe stages. The chi-square procedure proves the preponderance of Category 1 hurricanes to be statistically significant (P = 0.03).

6) Landfall zone 6

Many of the landfall cyclones of zone 6 track to the northwest and make landfall before recurvature (Fig. 9). This is associated with the low latitude of the landfall zone, in that the cyclones are still influenced by the global easterlies upon impact. Also, the influence of the STH is noted in the group of cyclone tracks as many are forced into peninsular Florida in lee of the high pressure cell. The cyclones typically travel to the northeast along the eastern seaboard after landfall where a second landfall often occurs.
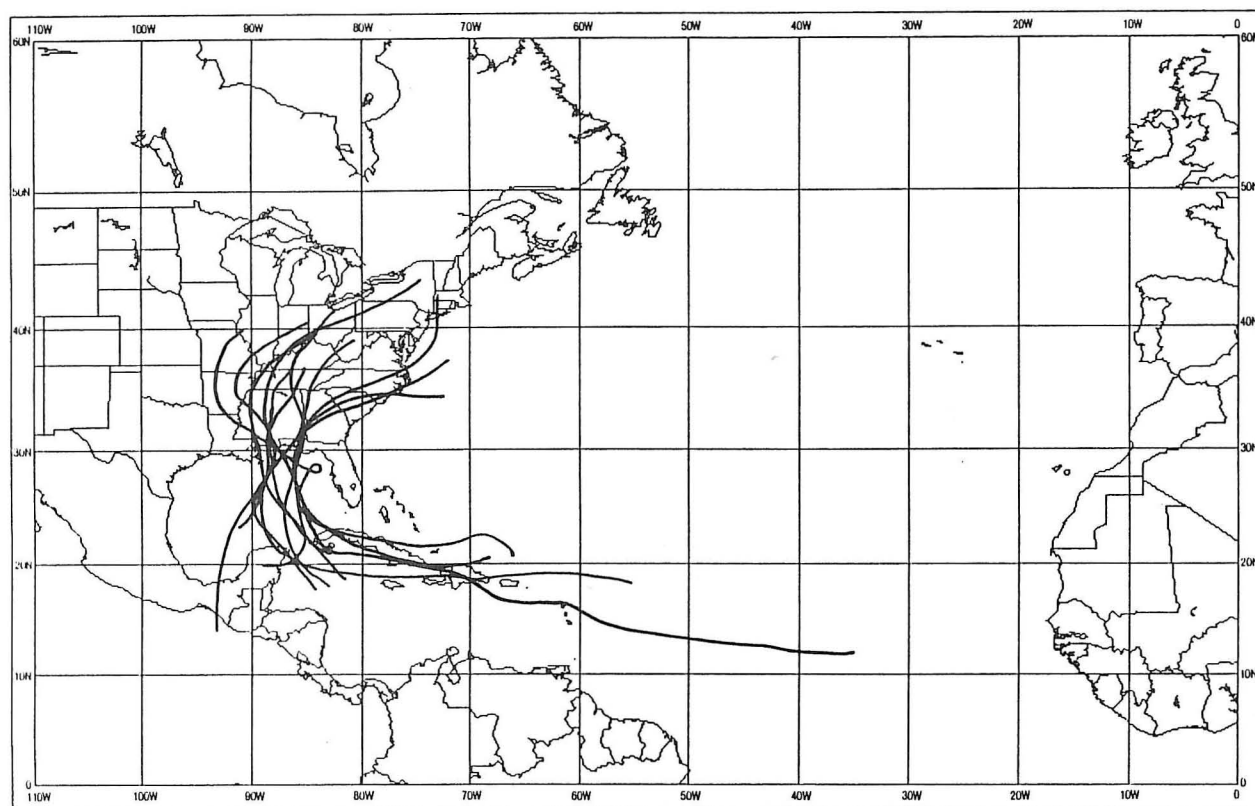
Fig. 6. Tracks of tropical cyclones (1960−1989) which made landfall in zone 3.
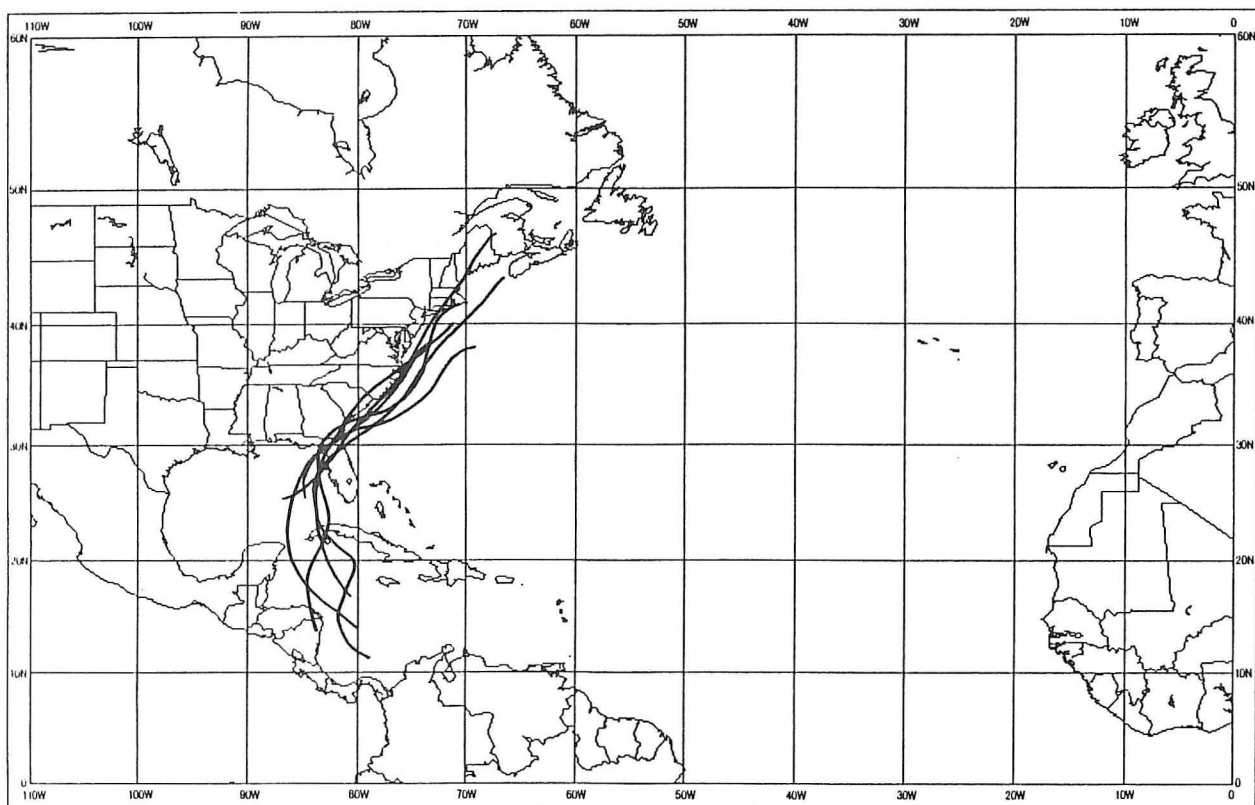

Fig. 7. Tracks of tropical cyclones (1960−1989) which made landfall in Zone 4.
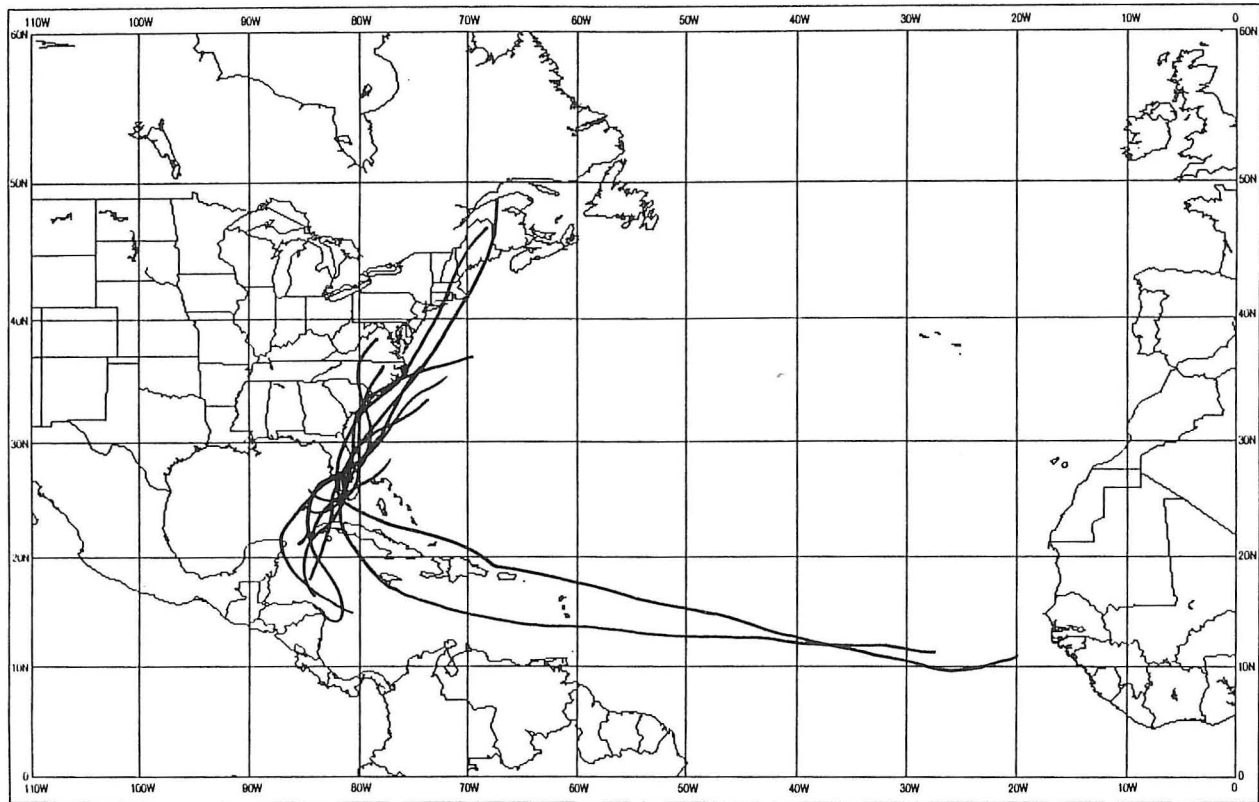
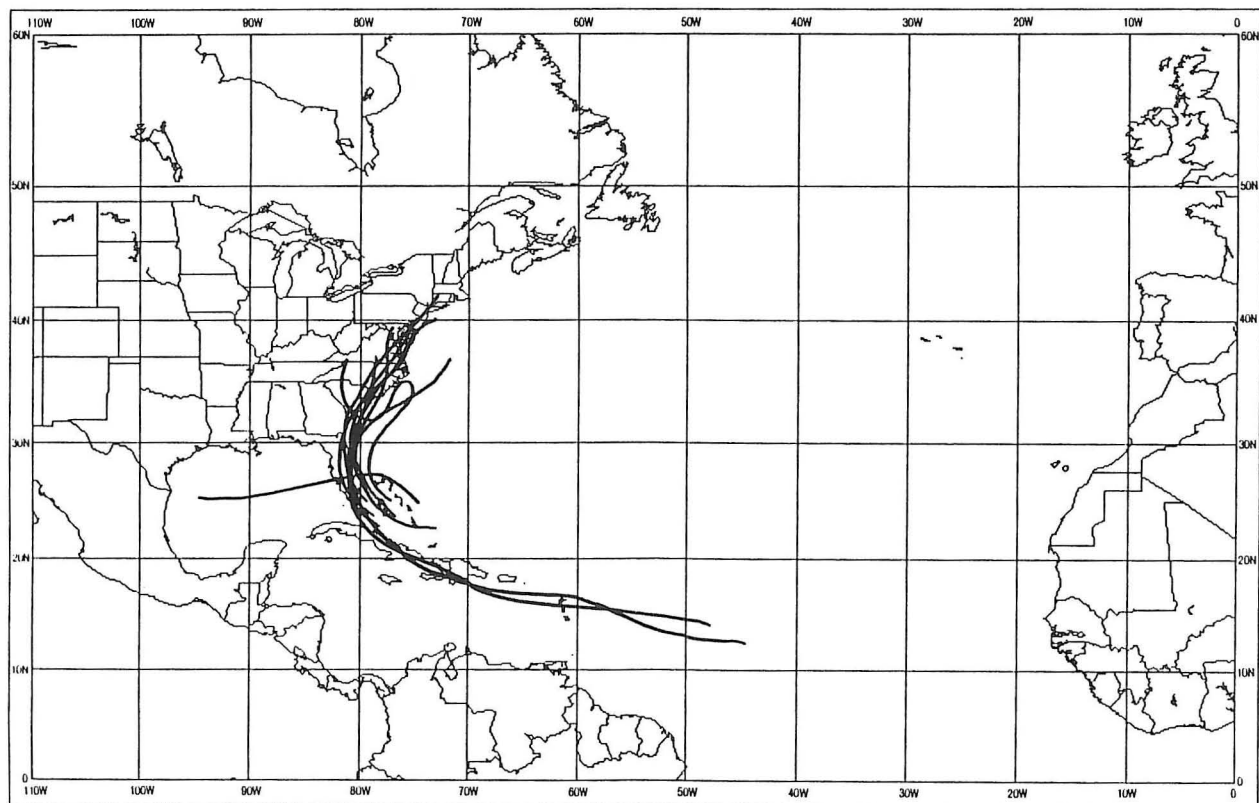Fig. 8. Tracks of tropical cyclones (1960–1989) which made landfall in zone 5.

Fig. 9. Tracks of tropical cyclones (1960–1989) which made landfall in zone 6.

Only two formation regions are associated with this landfall zone (Table 1). Of these, the Southwest Atlantic contributes the greatest number of cyclones to this zone as the Cape Verde region produced only two storms which affected the area during the study period. It is expected that this formation region, as well as the Atlantic formation region, be better represented due to proximity and typical track characteristics. The chi-square procedure proves that a significant relationship exists between the Southwest Atlantic formation region and the landfall zone (P < 0.001).

The formation of landfall cyclones occurs only during the months of August and September with regard to this zone. These are the months of highest SSTs in the formation regions associated with this zone (Table 2). This is attributed to the depth of the formation basins as well as the complex interchange of deep waters (Gordon 1986). Therefore, a gradual shift of the formation regions to the east occurs throughout the early to mid-hurricane season, so that only during times of maximum SSTs do cyclones which affect this landfall zone form within these regions. Not surprisingly, statistical analysis shows considerable significance (P < 0.001) with regard to the two months.

The intensity distribution of storms which strike this landfall zone shows a wide range but somewhat anchored in the low end of the Saffir-Simpson scale (Table 3). This is due to the proximity of the landfall zone relative to the primary formation region as many of the cyclones are not able to gain higher wind speeds before landfall. Two of the three intense cyclones which did strike the area formed within the Cape Verde region. The wide distribution is augmented statistically (P = 0.28).

7) Landfall zone 7

Although only three tropical cyclones made landfall within zone 7, all three crossed a large expanse of ocean from the southeast only to make landfall during recurvature (Fig. 10). Overall, these cyclones exhibited the typical parabolic track with slight variations.

The Cape Verde formation region is responsible for two of the three storms, the other formed in the Caribbean (Table 1). Interestingly, all of the cyclones occurred during the last five years of the study period (1985, 1988, and 1989). With the addition of Hurricane Andrew in 1992, the ending of the long-term inactive cycle along the east coast may be represented. If this cycle has truly ended, the eastern seaboard may experience more frequent intense hurricanes reminiscent of the 1930–1960 time period (Gray 1992). Statistically, no significant differences among the frequencies of the formation regions is found (P = 0.22), however, the low number of cyclones may bias the statistic.

All three cyclones are distributed across the mid to late portion of the hurricane season (Table 2). This substantiates the fact that the Atlantic Ocean does not heat sufficiently in the early portion of the hurricane season to produce east coast threatening cyclones. This is not to say that tropical cyclones cannot affect this landfall zone during June and July, only that it is unlikely based upon this analysis. Statistically, no significant differences are detected among the months of the hurricane season (P = 0.85).

The intensity levels of the three cyclones are a bit unusual in that two are of low level while one is a Category 5 (Table 3). Given the formation regions, the time of cyclogenesis, and the length of the storm tracks, one would expect much higher intensities overall. Localized atmospheric interactions and the distribution of SSTs along the cyclone tracks may be key determinants of such an intensity distribution. As expected, no statis-

tically significant trends are found with regard to the intensities (P = 0.70).

8) Landfall zone 8

Like landfall zone 7, a small number of cyclones are associated with zone 8 (Fig. 11). All of the storms exhibit a northerly track component and recurve to the northeast after landfall. Interestingly, one cyclone shows a rather anomalous track which exhibits two loops. STH interaction appears critical to the confinement of the storms to the east coast thereby prohibiting recurvature until a sufficiently high latitude (> 35°N) is achieved.

Three of the four cyclones formed within the Southwest Atlantic formation region (Table 1). It is expected that both the Atlantic and the Cape Verde formation regions be better represented. The underlying climatic controls which prohibit the Atlantic region and many Cape Verde region cyclones from making landfall within this zone must be further investigated. Statistical analysis confirms the importance of cyclogenesis in the Southwest Atlantic to landfall within this zone (P = 0.01).

Only the months of August and September produce tropical cyclones which affect this region (Table 2). Cyclone frequency is divided equally between the two months which represent times of greatest oceanic SSTs. The chi-square probability value (0.06) indicates no statistical significance at an alpha level of 0.05, however, the low number of storms bias the statistic.

Intensities of the cyclones which made landfall within this zone are staggered throughout the Saffir-Simpson scale (Table 3). Therefore, no clear patterns emerge which is confirmed through the statistical analysis (P = 0.41).

9) Landfall zone 9

Cyclone tracks of tropical cyclones associated with landfall zone 9 exhibit very little recurvature (Fig. 12). This is not surprising given the latitude of the zone as well as the coastal configuration. Storms which do recurve normally either drift into the open waters of the North Atlantic without making landfall, or simply make landfall at a lower latitude. Therefore, this zone is affected only by storms which possess an anomalous north to northwesterly track component throughout the life cycle.

The only formation regions represented with regard to this zone are the Southwest Atlantic and the Cape Verde, with the Southwest Atlantic the primary cyclogenesis region (Table 1). This is not unusual given the formation regions of cyclones which affect other east coast landfall zones. Statistical significance is applied to the Southwest Atlantic and Cape Verde regions as a chi-square probability value (P) of 0.01 is calculated.

As with zone 8, the months of August and September are the only months of cyclogenesis with regard to this landfall zone (Table 2). This further confirms the temporal shift of the formation regions and the corresponding SSTs throughout the hurricane season. Southwest Atlantic and Cape Verde cyclones, which form mainly during these months, seem to be the only cyclones which affect the entire east coast of the US. No other months (with the exception of one October storm) or formation region produces tropical cyclones which affect the US north of 34°N. This may be a phenomena related to this relatively short study period, however, further investigation is warranted. Consequently, a statistically significant relationship is found between these two months and landfall zone 9 (P = 0.01).

Again, the frequency distribution of cyclone intensities provides no clear pattern (Table 3). Both tropical storms as well as intense hurricanes are almost equally represented. Given the
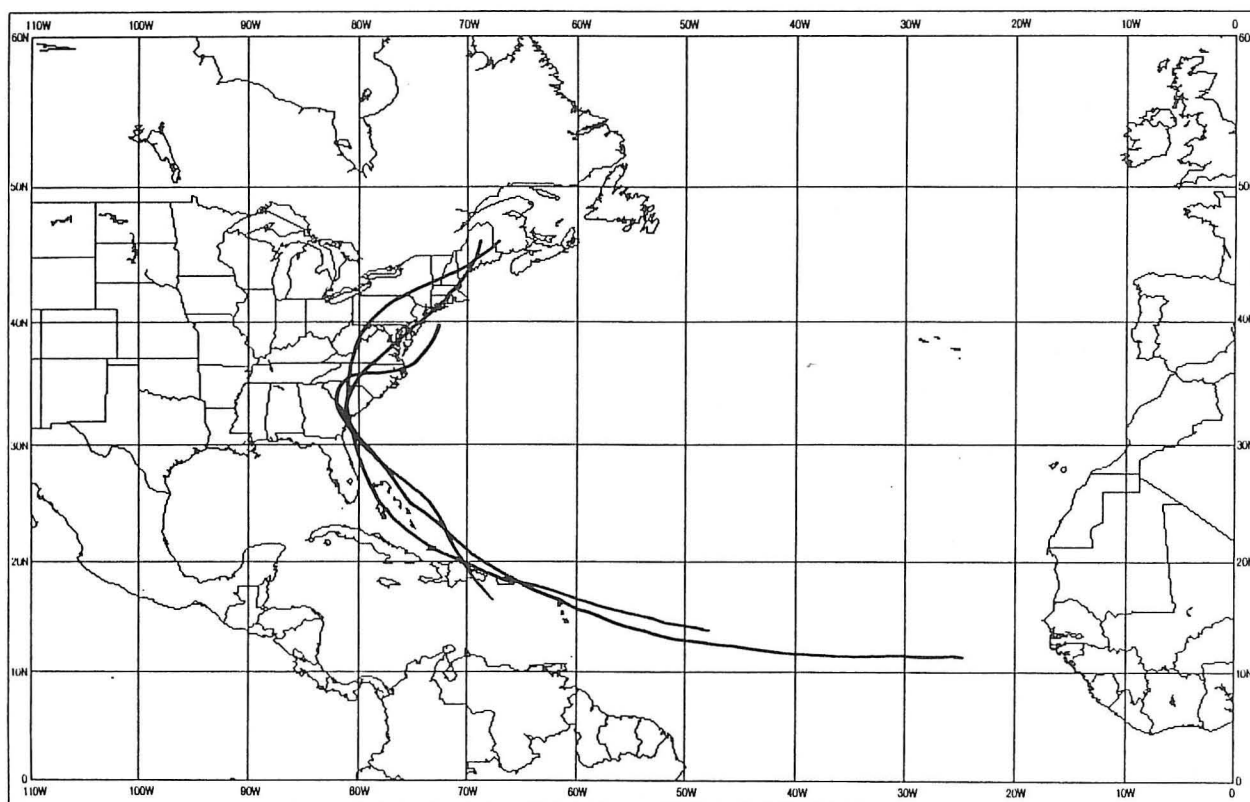
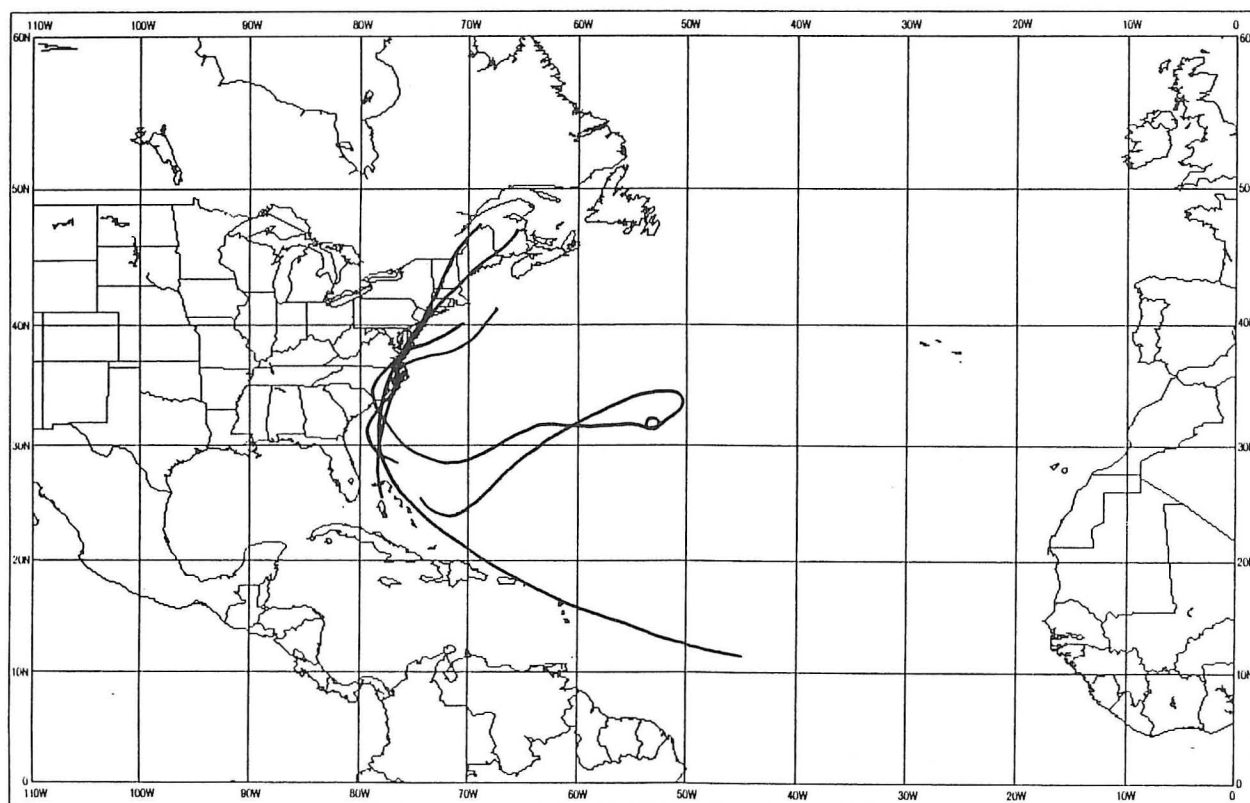Fig. 10. Tracks of tropical cyclones (1960–1989) which made landfall in zone 7.

Fig. 11. Tracks of tropical cyclones (1960–1989) which made landfall in zone 8.
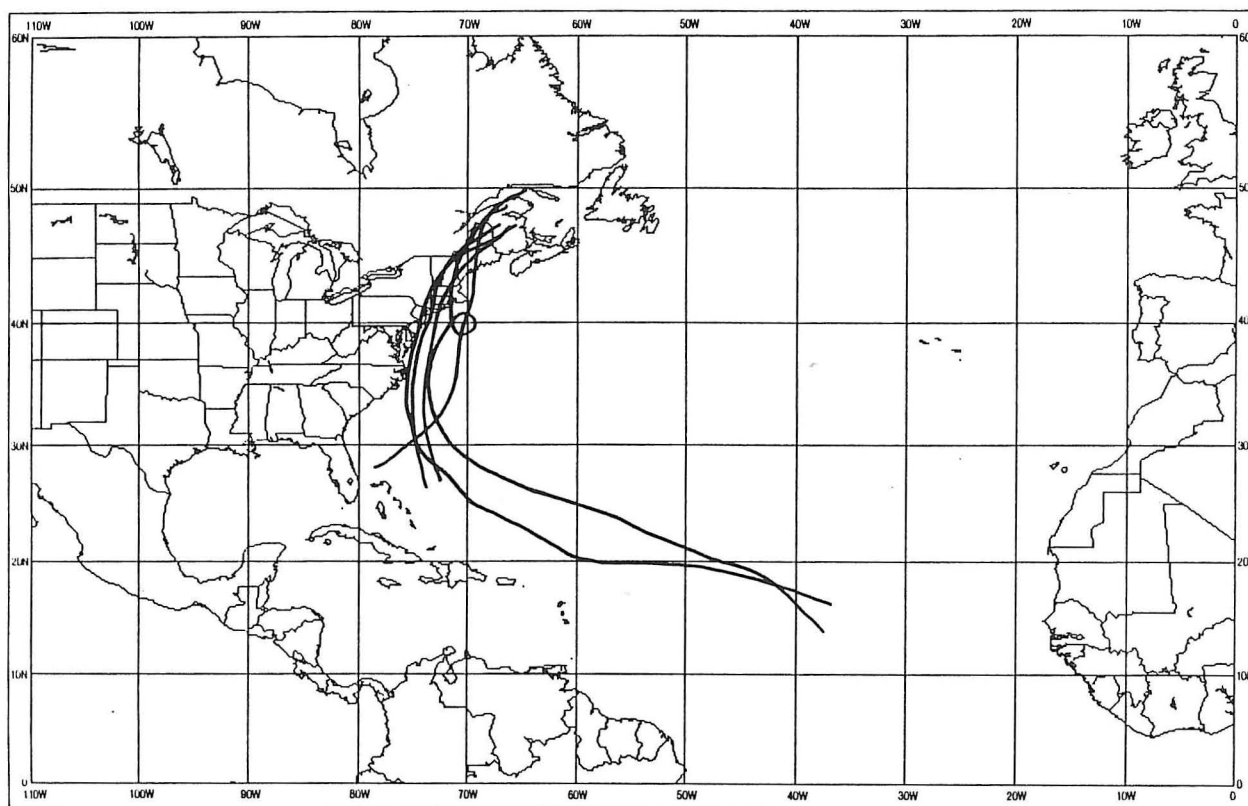
Fig. 12. Tracks of tropical cyclones (1960–1989) which made landfall in zone 9.

track lengths, it is thought that SSTs and STH interactions greatly influence the development of individual cyclones which affect this area.

4. Conclusions

The purpose of this study was to examine tropical cyclone landfall along the Gulf and Atlantic Coast of the United States from 1960–1989. The study attempted to discern relationships between tropical cyclone landfall, cyclogenesis areas, and cyclone intensities. The research supports the generally regarded fact that, due to variations in time and formation region, the paths and landfall areas of tropical cyclones vary. Cyclone formation regions shift with global circulation and SST patterns so that the subsequent cyclone tracks also shift. Cyclones will, therefore, be produced and strike different areas of the US during preferred times of the hurricane season.

Early and late season cyclones typically develop in areas which are first affected by the vertical declination of the sun. The Gulf of Mexico and the Caribbean Sea both heat sooner and retain heat longer than the Atlantic Ocean, due primarily to size and depth. Therefore, landfall zones affected during these times are; 1, 2, 3, and 4, all of which are located along the Gulf Coast. As the formation areas shift to the east during the middle of the hurricane season, zones 5, 6, and 7, are affected. It is during this time (August and September) that the largest number of tropical cyclones form as all formation regions are active. The introduction of the Southwest Atlantic

and Cape Verde formation regions contribute cyclones which mainly strike the east coast. All landfall cyclones for zones 7, 8 and 9, form during August and September (with one exception) and form within these two formation regions (again with one exception). Late in the hurricane season, cyclones once again return to the Gulf Coast as the formation regions revert back to those of the early season.

Perhaps the most surprising aspect of this research deals with the intensity of the tropical cyclones. The majority of cyclones which strike every landfall zone are of low intensity (TS to Category 2). In addition, the stronger cyclones are not scattered among all landfall zones, but rather confined to specific areas. The cyclones with high intensity, Categories 3–5, primarily strike landfall zones 1–3 (between the Texas-Mexican border and Apalachicola, Florida). This is an indication that those cyclones which primarily form in the Cape Verde formation region and have the longevity to traverse the entire Atlantic obtain these highest levels of intensity. However, recent strong hurricanes (Hugo and Andrew) suggest a possible trend toward stronger east coast hurricanes.

The interaction between the storms, SSTs and the STH seems to be critical with regard to the resulting track. Also, these key interactions may affect the intensity of storms as well as disrupting emerging patterns especially with regard to storms which affect the east coast. Here, the variability of both the SSTs and the STH is greater than in the smaller formation basins of the Gulf of Mexico and the Caribbean Sea. Therefore, climatological patterns are better defined within those basins.

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