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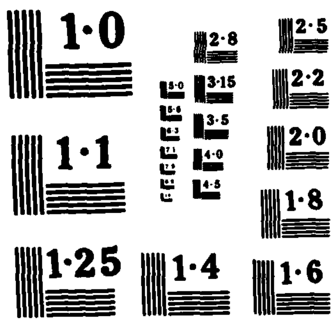
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CLASSIFICATION OF COASTAL ENVIRONMENTS

TECHNICAL REPORT 31

CYCLONE TRACKS AND WAVE CLIMATES AT CAPE HATTERAS, NORTH CAROLINA

U.VA. ONR COASTAL SCIENCES PROGRAM

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DEPARTMENT OF ENVIRONMENTAL SCIENCES
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AUGUST 1985

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ABSTRACT

The tracks of individual tropical and extratropical cyclones are an important determinant of the magnitude and duration of the water waves that will be produced along the mid-Atlantic coast. Based on a data set covering the years 1942 to 1984, an eastward displacement in the mean track of extratropical cyclones associated with increasing wave magnitude and duration is evident. Tropical cyclones show a westward shift in the mean track with increasing wave magnitude, but little change with duration. No temporal pattern could be identified in the frequency of extratropical storms while the number of tropical cyclones has declined over the past fifteen years. The relationship between sea-surface temperatures, the Gulf Stream, and upper latitude blocking and cyclone movement is briefly discussed as possible reasons for the changes in the mean storm tracks.

INTRODUCTION

The waves that coastal storms generate are the primary agent of damage and destruction along the mid-Atlantic coast. The increased frequency of damaging storms along the eastern coast of the United States has been reported by Mather, et al. (1964) and Hayden (1975). This research shows an increase in the frequency of storms that generate deep-water waves of 1.6 m or greater from 1942-67. Hayden concludes that the number, severity and duration of Atlantic coast storms increased between 1942 and 1974. Recent research indicates that this trend is continuing (Hayden, 1985).

Wiegel (1964) defines wave climate as the distribution of wave height, period, and direction averaged over a period of time for a particular location. The generation of an information base covering a sufficient period of time to estimate "stable" wave climate statistics is both difficult and time consuming. Early work (Mather, etal. 1964) focuses on the frequency of cyclones in the offshore zone as a proxy for wave climates. In the research I present here, the actual cyclone tracks (extratropical and tropical) are related to wave climate. Specifically, I sort out the attributes of storm movement, shape, and coastal configuration and quantify the relationship between coastal storms and coastal wave climates.

The test site for this research is the Outer Banks of North Carolina (Fig. 1). I selected this site because synoptic-scale weather systems (hurricanes, tropical storms, and extratropical storms) are the major source of waves and surges along this coast, and because the wave climate data archive for this area is longer there than for anywhere else in the mid-Atlantic coastal region (1942-1984); the record consists of 1349 storms. In addition, the track of each storm is available from published maps.

LITERATURE REVIEW

The patterns of cyclone tracks and cyclone frequencies for the Atlantic coast of the U.S. are well documented (Petterssen, 1950; Klein, 1957; and Klein and Winston, 1958); however, no one has attempted to categorize the storms based on wave climate. The cyclone frequency maximum along the east coast of the United States was presented by Petterssen (1950), extending as far south as Florida. Klein and Winston (1958) attribute this frequency maximum to an Atlantic seaboard cyclone track.

Studies on cyclone tracks along the eastern Atlantic

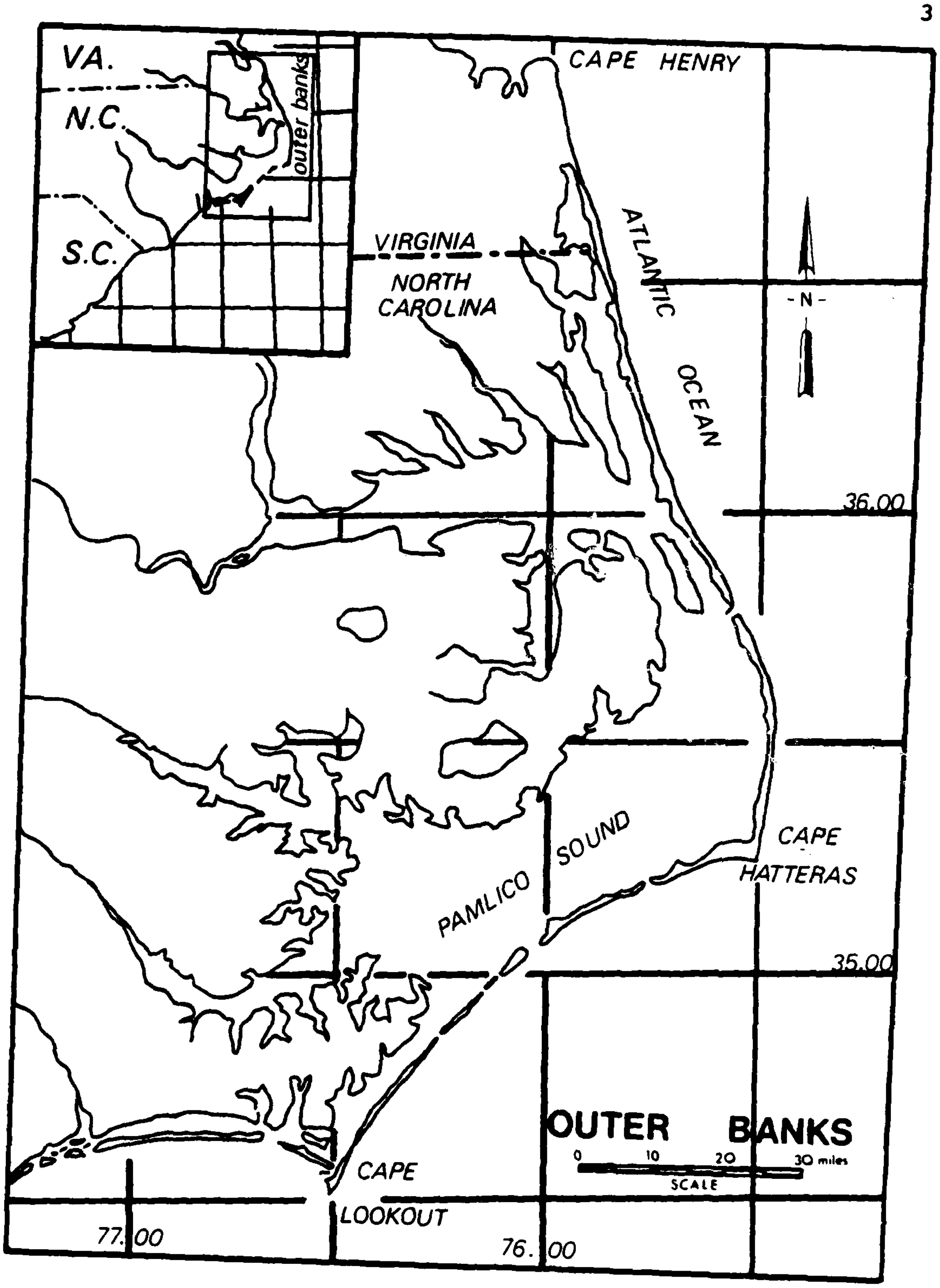

Figure 1. Study area for wave climate data.

coast of the United States have included the stratification of storms in several ways. Klein (1957) interprets the distribution of storms to be a single, broad track and no attempt was made to relate storm tracks to wave activity. Bowie and Weightman (1914), Miller (1946) and Andrews (1963) incorporate cyclogenesis into their classifications of storm tracks. Miller (1946) analyzed cyclogenesis for the mid-Atlantic coastal region and found two distinct cyclone types: Type A which form largely to the north of Cape Hatteras, North Carolina and Type B which form to the south of Cape Hatteras. In work by Dickson and Namias (1976), cyclone movement along the Atlantic coast was attributed to changes in large scale atmospheric conditions. While all of these studies show a dominant cyclone track off the east coast of the U.S., none can directly relate this track to wave action at the coast.

Davies (1980) offers a more global view of wave environments based on the zonal variation in wind energy. Storm wave classes are characterized by a relatively large number of local gale force winds while the swell classes are dominated by the much larger-scale trades. While the results of this study differentiates between several wave environments, Davies did not use actual storms to support the results.

Resio and Hayden (1975) calculate storm-type frequencies for a region off the Atlantic coast for each decade of the 1900's. The results indicate that changes in the track of cyclones relative to the coast give rise to variations in breaker heights and storm surge heights at the coast. The use of actual wave climate data to support these results is not incorporated into the study.

Resio (1974) developed a computer model designed to estimate waves and surges from synoptic-atmospheric phenomena. This model links waves and surges along the mid-Atlantic coast to extratropical cyclones by relating the time-dependent wind-fetch field to storm size, shape, and the rate and direction of movement. While this model provides 23 years of wave climate data, it does not relate individual storms to associated wave climate. Although several of these studies provide cyclone frequencies or wave climates, none incorporate the two into one single analysis.

While the relationship between the large-scale circulation and sea-surface characteristics are described in the literature (Namias, 1955 and Shapiro, 1982), the relationship between tropical cyclone tracks and the wave climates associated with them has not been studied. Dunn and Miller (1960) show that the mean storm track, and to a lesser extent the place of most frequent origin, changes in a logical manner from month to month during the storm season. The relationship between sea surface temperature and tropical storm frequencies and path of movement has been studied by Wendland (1977) and Fischer (1958), indicating that tropical storms tend to track over the warmer water.

Namias (1955) proposed that the vulnerability of coastal regions to hurricanes is directly related to time-averaged planatery wave patterns, and that the prediction of origin and track could be related to large scale pressure patterns. Over a period of a month or a season, it is frequently found that tracks of tropical cyclones cluster about certain preferred axes (Ballenzweig, 1959). Simpson and Riehl (1981) suggest that the difference in coriolis parameter on the north and south sides of a cyclone is chiefly responsible for its poleward displacement, while the interaction between the large subtropical anticyclones and middle-latitude weather systems causes the fluctuations in longitudinal directions.

Bosserman and Dolan (1968) provide the longest (42 years) data record of wave hindcast currently available for the mid-Atlantic coast. Their record includes wave climate data for both tropical and extratropical storms and provides the unique opportunity to combine the record of individual storm tracks with the wave climates associated with those storms. By incorporating the two data sets, a quantitative analysis of the relationship between coastal storms and coastal wave climates is accomplished. This type of analysis has not been done in the past and can not be done with most data sets, including the rich data of Resio (1974).

In summary, previous research (Mather, etal. 1964,; Resio and Hayden, 1975) has focused on the use of cyclone frequencies and cyclone tracks as a substitute for the storm and wave activity along the Atlantic coast. I found the relationship between the frequency of offshore storms and recorded wave climates to be modest (r = .3). Therefore, my objective is to establish the relationship between individual storm tracks and the specific wave climates associated with them.

DATA

The wave climate data for Cape Hatteras was obtained by Bosserman and Dolan (1968) through hindcasting using the Sverdrup, Munk, and Bretschneider (S-M-B) method (CERC, 1984). These data have been periodically updated by Bosserman to provide the current data record of 42 years (1942-1984). The tropical storm data ends in 1973 and thus includes only 30 years. Only cyclones producing waves 1.6 m or greater are considered in this study.

Since the wave climates of individual storms are included in this data set, the data can be stratified in several ways. Bosserman and Dolan (1968) stratified the storms by magnitude, defined as the deep-water significant wave height. These storms were then stratified by the duration of waves produced in each wave height category. Finally, the storms were stratified by a combined duration within magnitude category (Tables 1 and 2).

Pursuant to that work, I isolated the tracks of each storm by height and duration and partioned the statistics on the wave climates acordingly. From monthly charts of the "Tracks of the Centers of Cyclones at Sea Level" published by the Monthly Weather Review and in recent years by Mariners Weather Log, annual totals of cyclones passing through each grid cell recorded. With these totals cyclone frequencies for each year (1942-1984) were tabulated for the 90 2.5° latitude by 5.0° longitude grid cells comprising the study area shown in figure 2. Tropical and extratropical storms are treated seperately and multiple entries of a given storm in a grid cell are ignored.

ANALYSIS

I performed spatial and temporal analysis of the cyclone data by first recording cyclone frequencies on base maps of the study area. To avoid any personal bias in the contouring, I used a computer graphics package from

STORM CHARACTERISTICS

Storms producing waves greater than 1.6 m

MAGNITUDE STRATIFICATION

5.1- 8.0 feet (1.6-2.4 m)
8.1-11.0 feet (2.5-3.4 m)
11.1-14.0 feet (3.4-4.3 m)
14.1-17.0 feet (4.3-5.2 m)
17.1-20.0 feet (5.2-6.1 m)
20.1-23.0 feet (6.1-7.0 m)
Greater than 23.0 feet

DURATION STRATIFICATION

0-5 hours
5-10 hours
10-15 hours
15-20 hours
20-25 hours
25-30 hours
Greater than 30 hours

MAGNITUDE AND DURATION

Less than 5 hours

5.1- 8.0 feet
8.1-11.0 feet
11.1-14.0 feet
14.1-17.0 feet
17.1-23.0 feet

Greater than 30 hours

5.1- 8.0 feet
8.1-11.0 feet
11.1-17.0 feet

Table 1. Data stratification for extratropical cyclones.

STORM CHARACTERISTICS
Storms producing waves greater than 1.6 m

MAGNITUDE STRATIFICATION
5.1- 8.0 feet (1.6-2.4 m)
8.1-11.0 feet (2.5-3.4 m)
11.1-14.0 feet (3.4-4.3 m)
14.1-17.0 feet (4.3-5.2 m)
17.1-20.0 feet (5.2-6.1 m)
20.1-23.0 feet (6.1-7.0 m)
Greater than 23.0 feet

DURATION STRATIFICATION
0-5 hours
5-10 hours
10-15 hours
15-20 hours
20-25 hours
25-30 hours
Greater than 30 hours

MAGNITUDE AND DURATION
Less than 5 hours
5.1- 8.0 feet
8.1-11.0 feet
11.1-23.0 feet

Table 2. Data stratification for tropical cyclones.

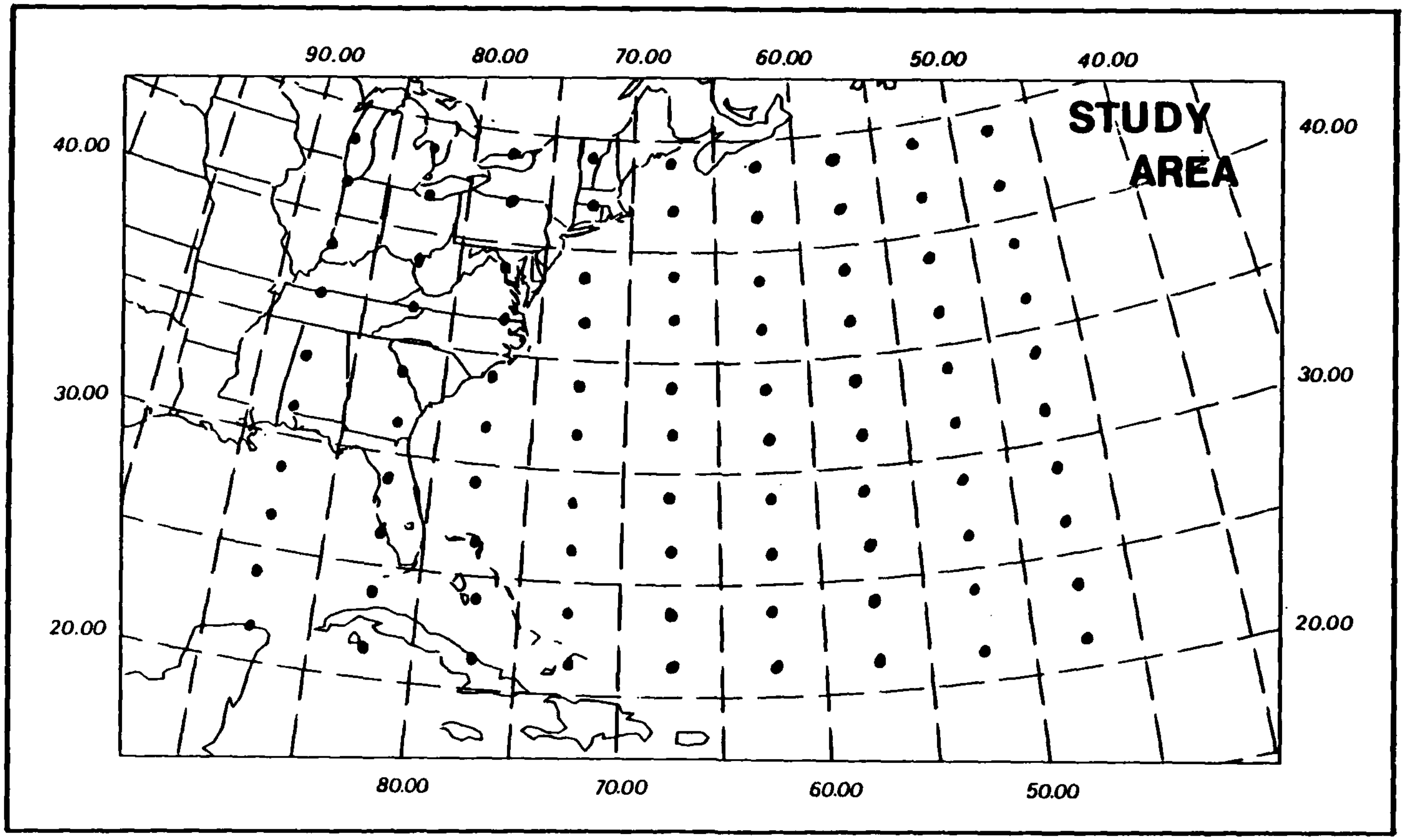

Figure 2: Study area for cyclone frequencies consisting of 90 2.5° latitude by 5.0° longitude grid cells.

the National Center for Atmospheric Research was used (McArthur, 1981). Based on these contours, I defined the mean tracks for each wave height class. I then performed this analysis on all of the stratified data sets treating tropical and extratropical cyclone separately.

The temporal analysis included recording the number of individual storms occuring in each wave height category within a particular year. I plotted these data against time to yield the time series in figures 3a-h and 7a-h). I performed the temporal analysis only on the magnitude stratification of the wave climate data.

RESULTS

Extratropical Storms

Magnitude

Figures 3a-h show the mean cyclone tracks associated with specific wave height categories. The dominant east coast cyclone track described in the early research of Klein (1957) and Klein and Winston (1958) is evident in my mean track for extratropical storms producing waves in all wave height categories (Fig. 3a). Beginning in the Gulf of Mexico, the mean track crosses northern Florida and

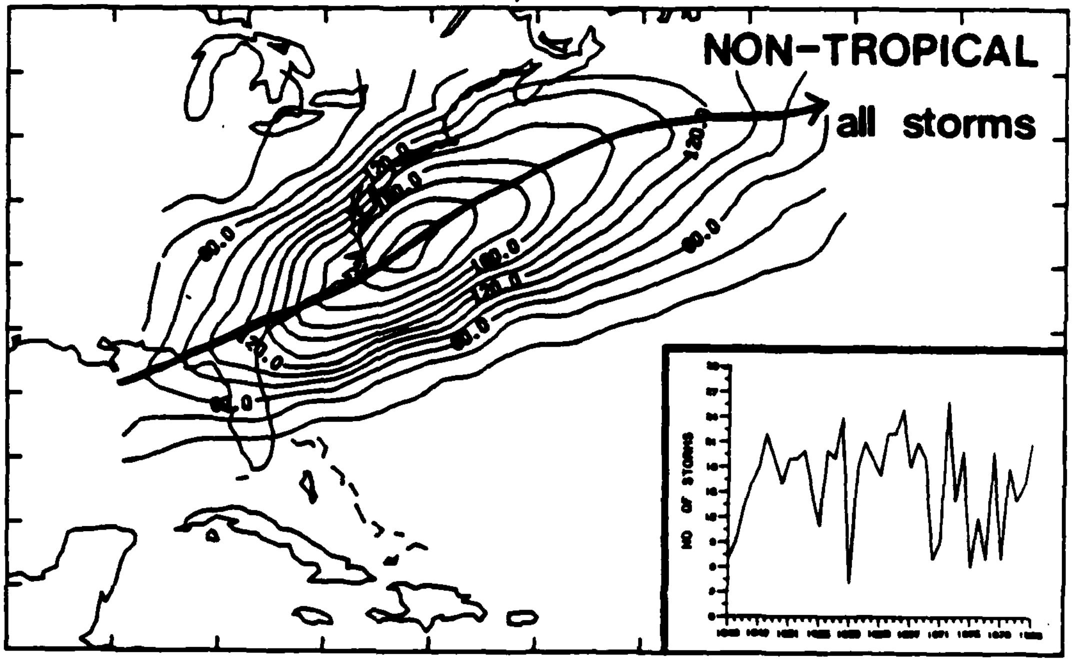

Figure 3a: Mean cyclone track and time series for all extratropical storms producing waves at Cape Hatteras, North Carolina.

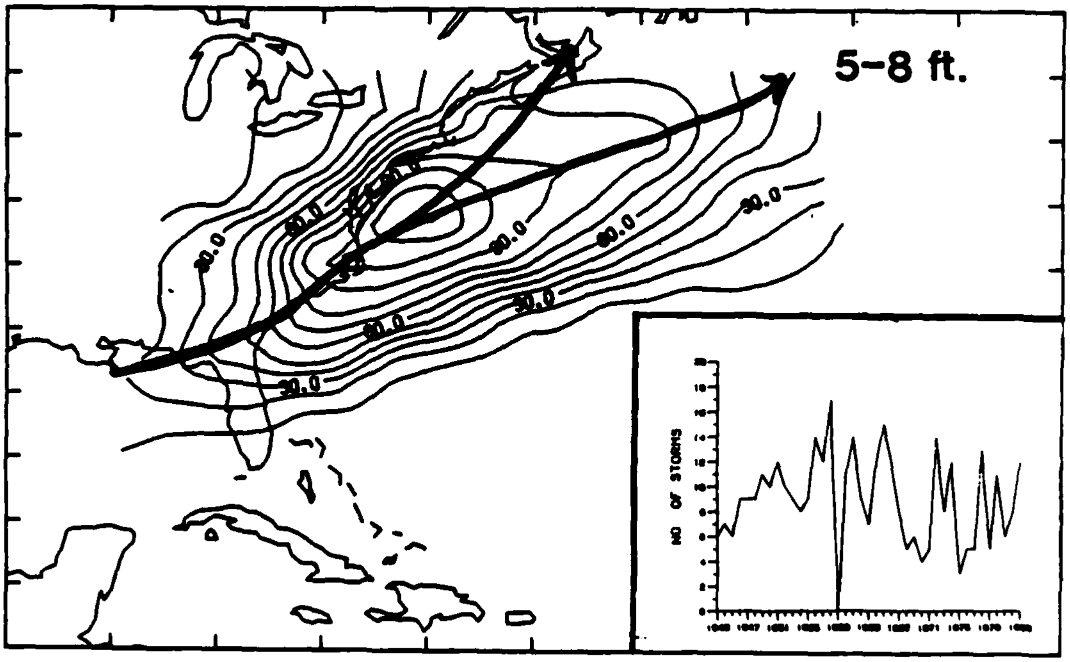

Figure 3b: Mean cyclone track and time series for extratropical storms associated with wave heights of 5-8 feet.

then takes a northerly route along the southeastern coast of the United States. At approximately 38 latitude this track strikes a more northeasterly path away from the coastline. While this is the predominant track for all extratropical cyclones producing deep-water waves at Cape Hatteras of 1.6 m in height, there are significant differences for the various magnitude and duration classes.

The cyclone frequencies for the extratropical storms producing waves in the 5-8 feet category at Cape Hatteras are shown in figure 3b. The mean track passes over the southeastern United States crossing the coastline just north of Cape Hatteras before seperating into two tracks and continuing in north and northeast directions respectively. The divergence of the mean track, located at the area of maximum frequency east of the Virginia coast, is most likely a function of the duration of the storms and is discussed in more detail later. Storms producing waves in the 8-11 feet category follow a similar track (Fig. 3c) crossing over the southeastern U.S. and taking a northeast path from the South Carolina coast with the maximum frequency located northeast of Cape Hatteras. This path persists into the northern Atlantic where a more eastern direction is taken.

The dominant southwest to northeast track of cyclones producing waves in the 11-14 feet category along the

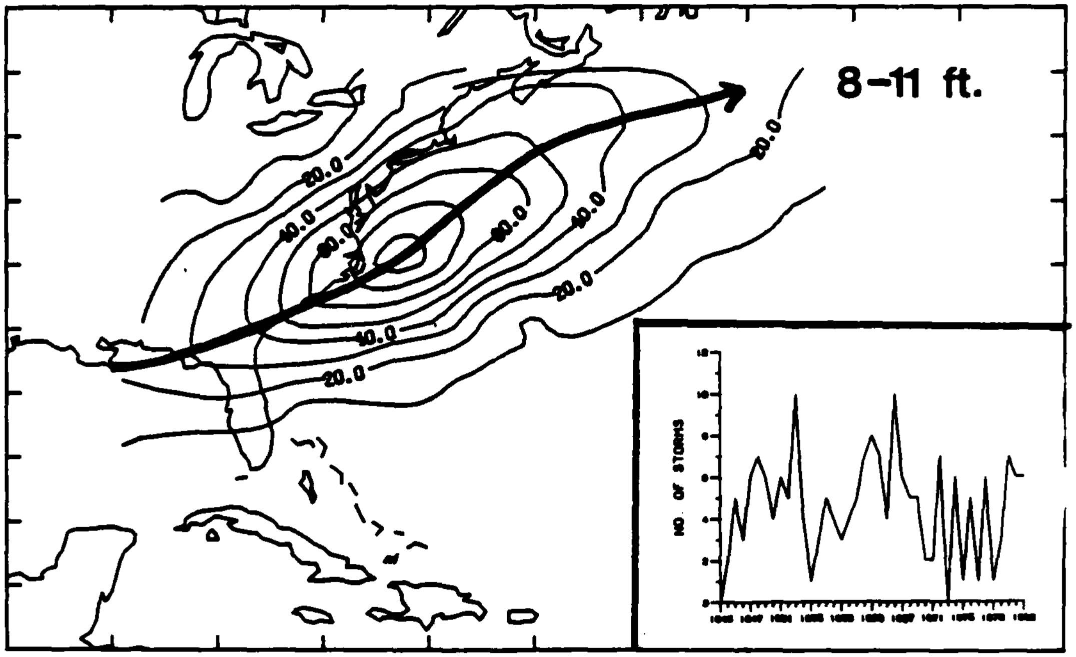

Figure 3c: Same as 3b; 8-11 feet.

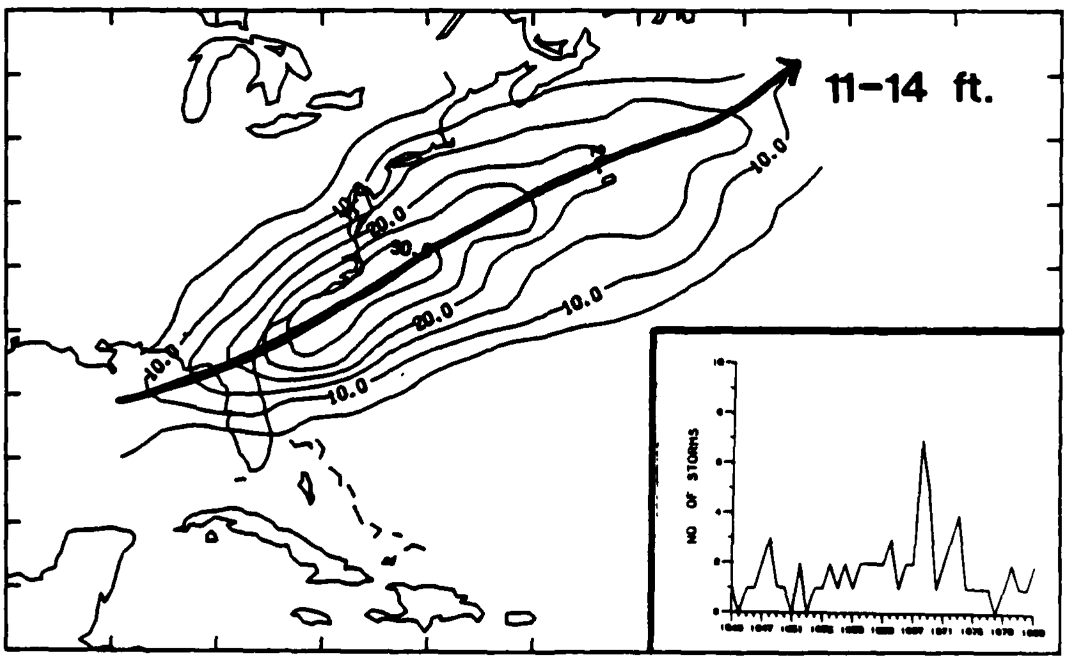

Figure 3d: Same as 3b; 11-14 feet.

Atlantic coast is again evident in figure 3d. The track crosses northern Florida and remains offshore following the maximum frequency along the southeast coast in a northeast direction. Once offshore, a rather straight path at approximately 45 is maintained. Cyclones associated with waves in the 14-17 feet category follow a slightly different path. The mean track originates in the mid-south region of the United States and dips southeast before reaching the coast and turning into a more northeasterly direction (Fig. 3e).

Figure 3f shows the mean track of storms producing waves in the 17-20 feet category. Crossing northern Florida and moving offshore near Georgia, this is similar to previous tracks, taking a northeast route once offshore. The frequency maxima is located south of Cape Hatteras rather than north or northeast as in the others.

The mean tracks of storms that result in waves in the 20-23 feet category and greater than 23 feet are shown in figures 3f and 3g. Because of the relatively small number of such storms a mean track is difficult to determine. Based on the few storms that have occurred a mean track passes through north Florida and moves directly offshore in a northeast direction. The major difference between these tracks and the previous tracks is the distance from the coastline and the southern displacement of the track.

Although the spatial distribution shows a progressive

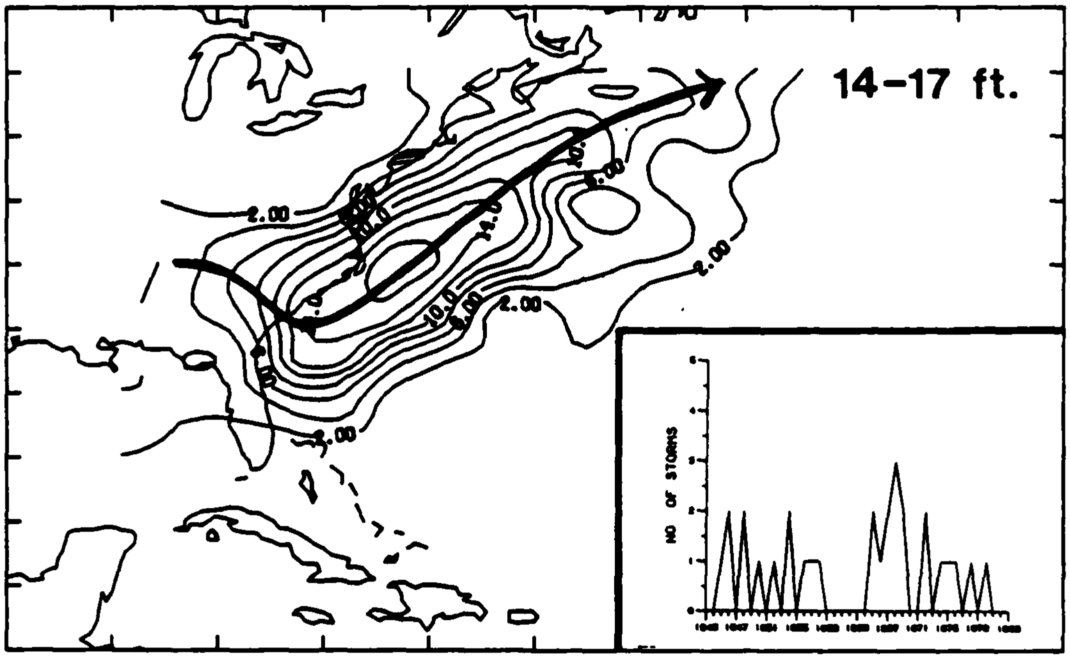

Figure 3e: Same as 3b; 14-17 feet.

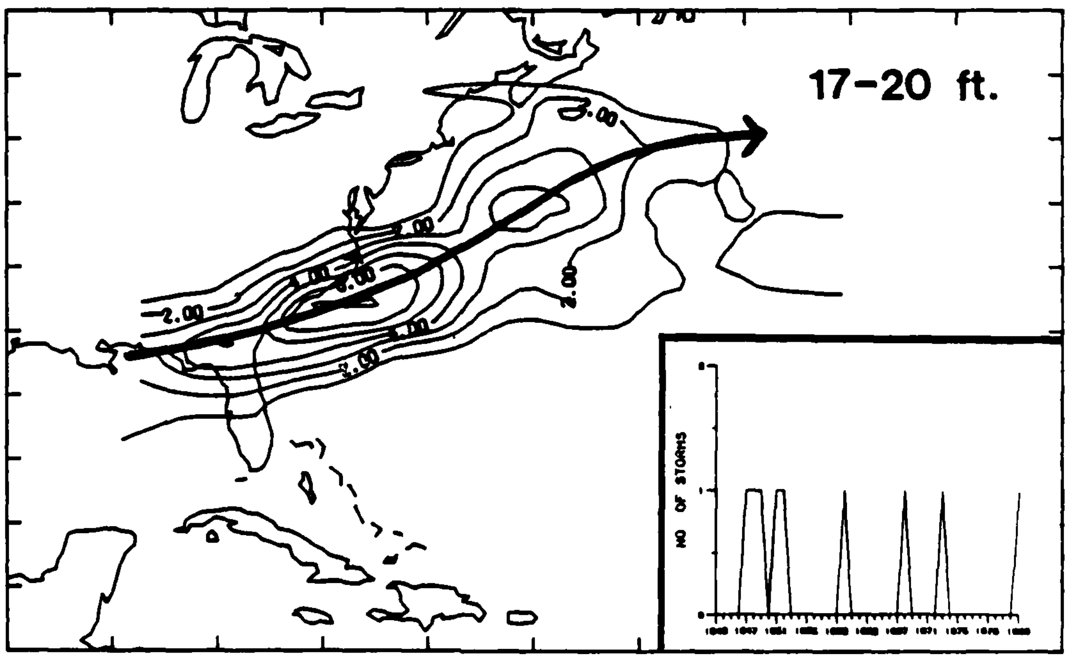

Figure 3f: Same as 3b; 17-20 feet.

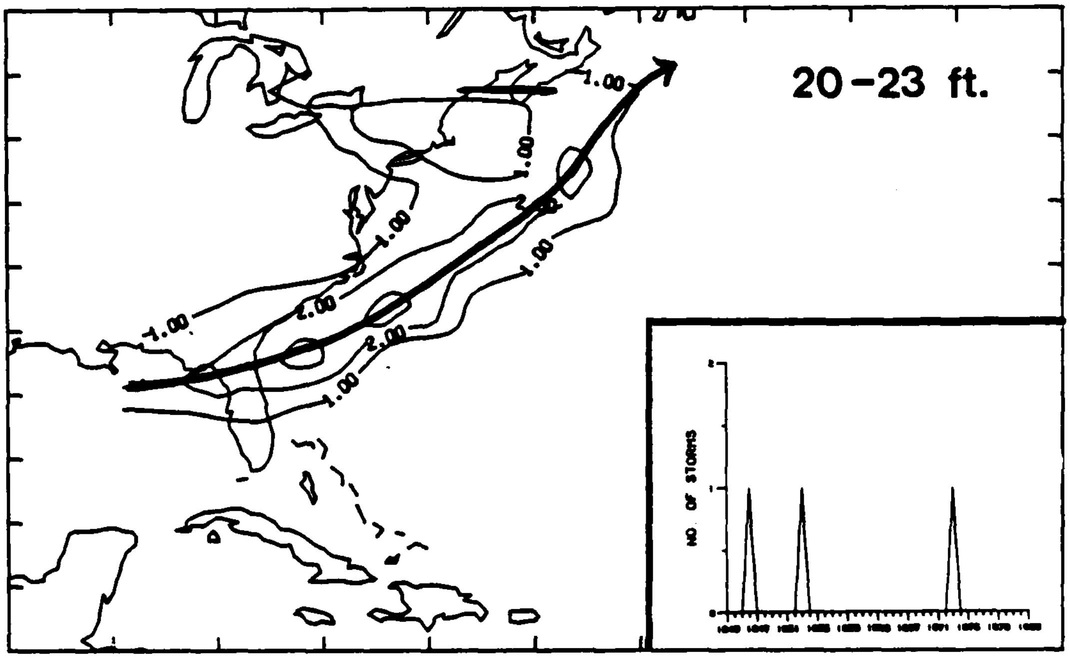

Figure 3g: Same as 3b; 20-23 feet.

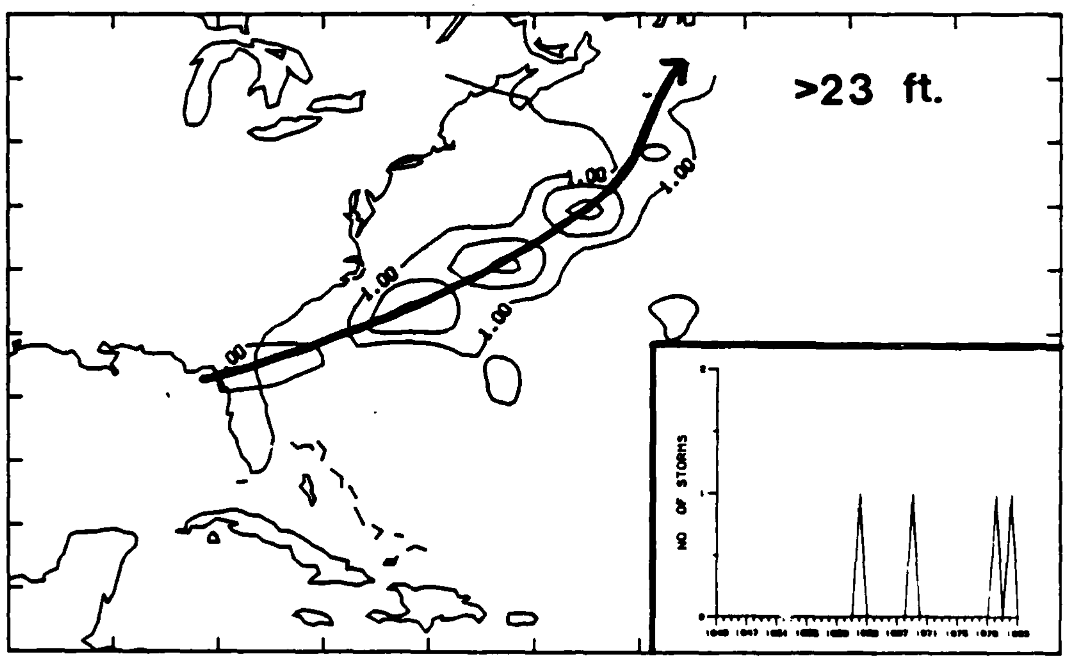

Figure 3h: Same as 3b; Greater than 23 feet.

eastward displacement of the mean track with wave height, the temporal relationship is less clear. For extratropical storms producing waves in all categories the time series shows no definite pattern (Fig. 3a). An increase in storms during the early to mid 1960's and a decrease in the mid 1970's is evident but a pattern cannot be established based on this analysis.

In the 5-8 feet category the increase in storm activity during the 1960's is very evident as is the decrease in the 70's (Fig. 3b). In general, the 1940's are quiet years for storm activity as are the 1950's. The 1960's and late 70's seem to be times of increased storm activity producing waves in the 5-8 feet category. This category corresponds well to the totals shown on the previous map, as one would expected since the small storms occur more frequently than do the larger storms. The time series associated with the 8-11 feet category is similar (Fig. 3c). As before, the 1960's are depicted as relatively stormy years while the 50's and 70's are less active.

The results for the 11-14 feet category (Fig. 3d) indicate that large storms are infrequent at Cape Hatteras. The occurrance of only a few storms during the late 1960's and early 70's coincides with the increase in storm activity associated with the previous category. The storms associated with waves in the 14-17 feet category have been active during the mid 1940's, early 1950's and the middle to late 1960's (Fig. 3e). Again, with so few events a particular pattern cannot be determined.

The remaining three extratropical wave height categories are identified only by the single occurrance of a storm in a particular year. The time series for these categories are given in figure 3f-h. Again, there is no discernable pattern evident. Although the 1970's and 80's are relatively quiet with respect to the 1960's, the frequency of these intense extratropical cyclones is unchanged.

Duration

The cyclone frequencies for the storms associated with waves in any combined category lasting less than 5 hours are shown in figure 4a. The mean track is well north of previous magnitude tracks and crosses the coast near the Chesapeake Bay before moving offshore in a northeast direction. The track actually passes north of Cape Hatteras with a frequency maximum located northeast of Hatteras. This indicates that storms associated with wave heights lasting only a short time track north of Hatteras and close to the coast.

Storms producing waves lasting from 5-10 hours travel along the more dominant east coast track (Fig. 4b). The

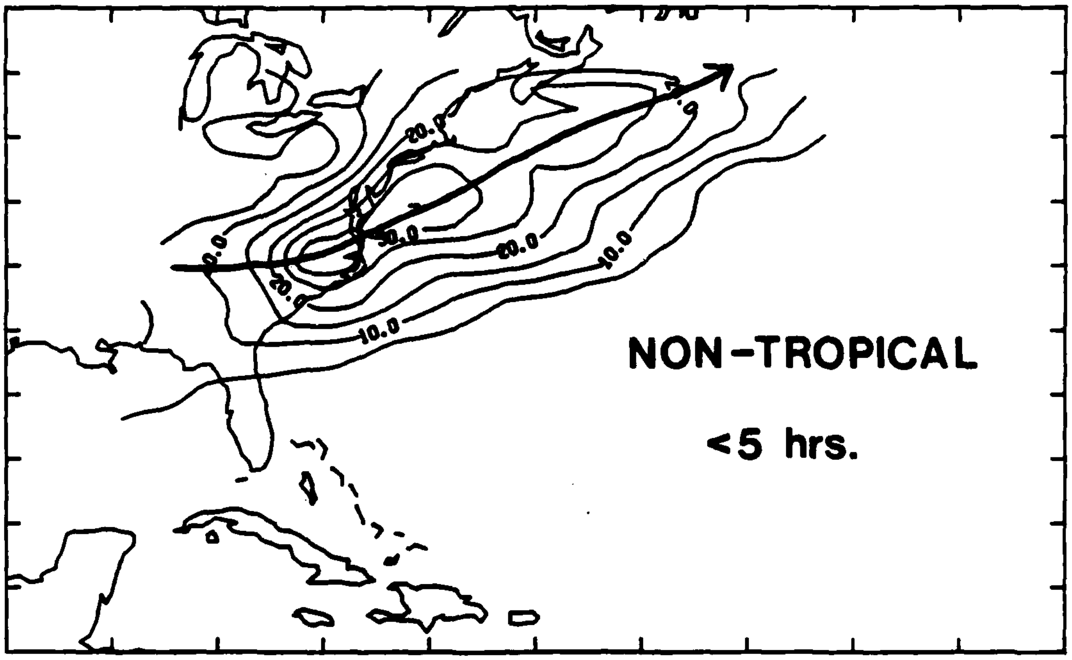

Figure 4a: Mean cyclone track for extratropical storms producing waves with a duration of less than 5 hours.

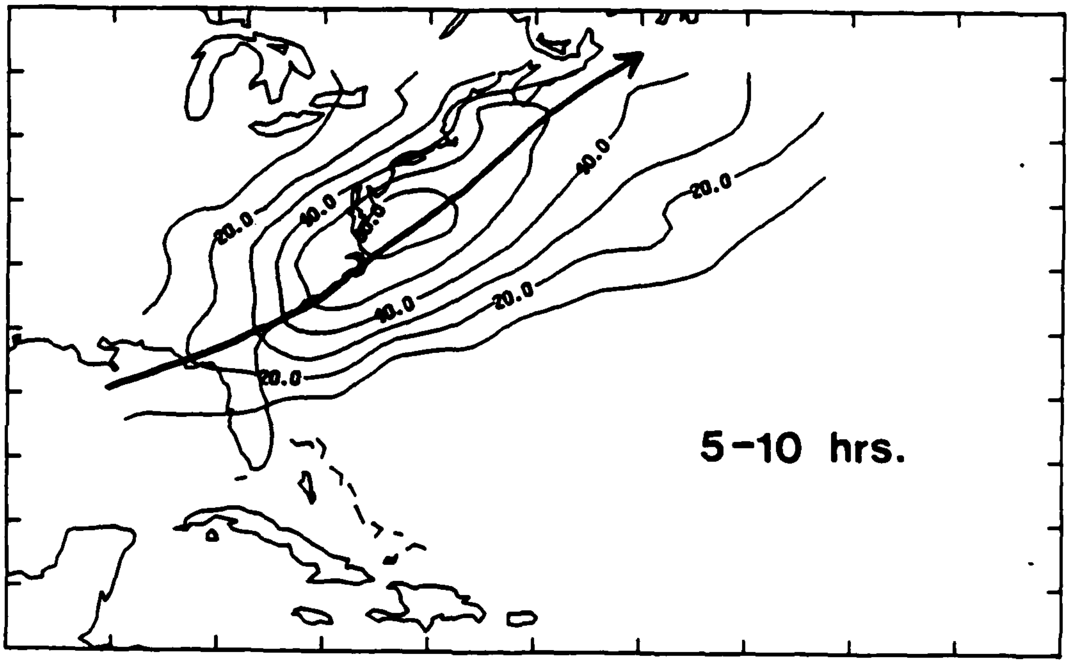

Figure 4b: Same as 4a; 5-10 hours.

mean track moves over northern Florida and remains inland along the coast until just north of Cape Hatteras. These storms have an affinity for land as they parallel the coastline. This appears logical as storms remaining this close to the land weaken and quickly move on. In the 10-15 hour category a similar track occurs in the beginning before a more northeasterly path is followed (Fig. 4c). After paralleling the southeastern coast, the position of the mean track moves offshore north of Hatteras and takes an eastward path. The farther the storms move offshore the better chance they have of maintaining their strength and increasing the duration of wave activity at the shore.

The track along the southeastern Atlantic coast is present in the 15-20 hour category (Fig. 4d). The mean track follows the coastline until reaching Cape Hatteras and then takes on an easterly direction offshore. The categories of 20-25 hours and 25-30 hours show a return to the landward origin of the cyclones (Figs. 4e-f). The mean track associated with these two wave duration categories are similar. Instead of paralleling the southern coast, they move eastward offshore near Georgia and proceed in a northeast direction.

The final duration category accounts for all storms associated with wave heights with a duration greater than 30 hours. The mean track shown in figure 4g, crosses

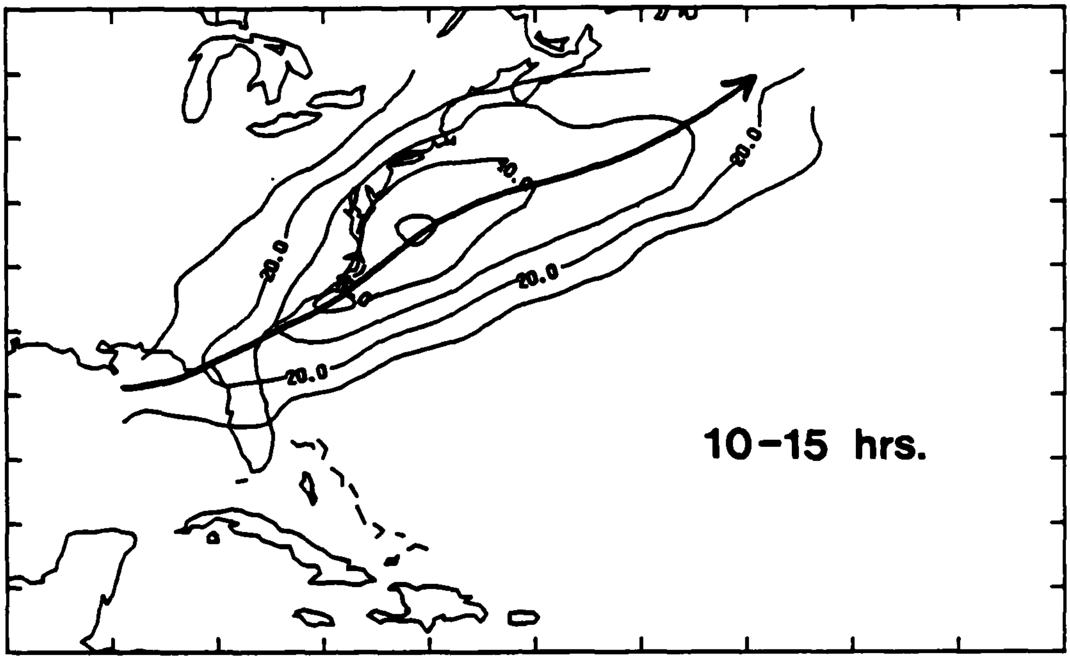

Figure 4c: Same as 4a; 10-15 hours.

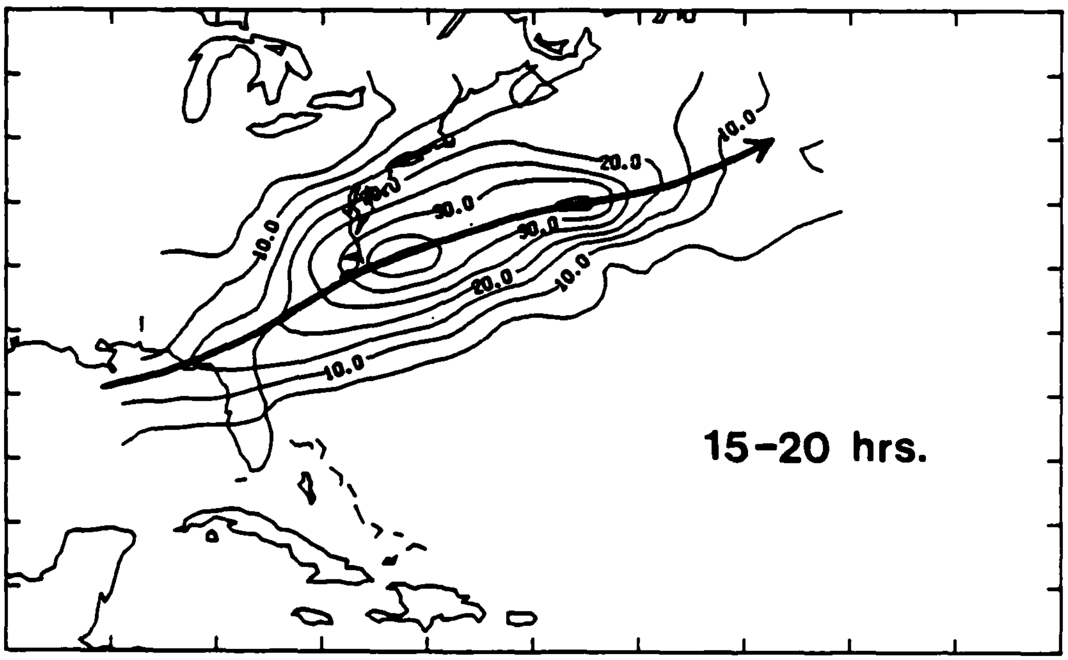

Figure 4d: Same as 4a; 15-20 hours.

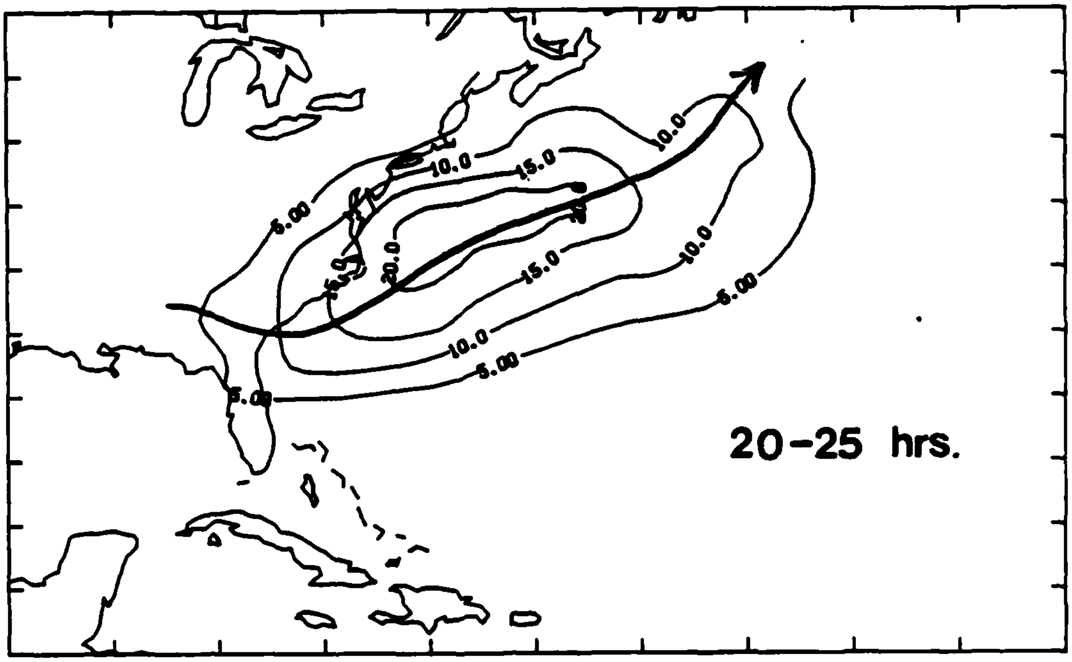

Figure 4e: Same as 4a; 20-25 hours.

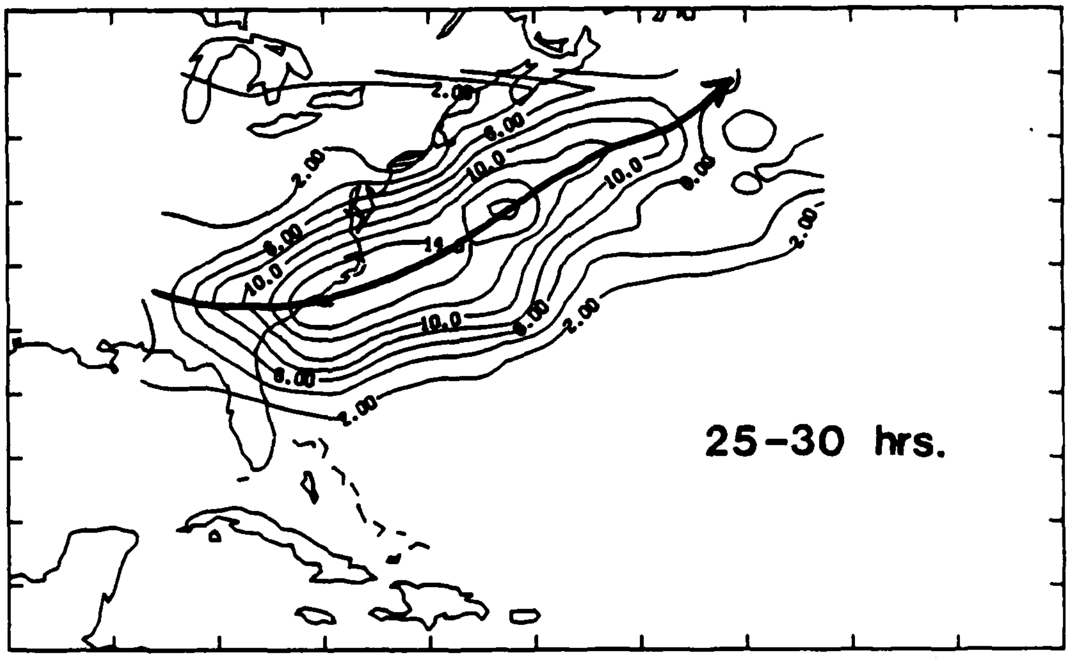

Figure 4f: Same as 4a; 25-30 hours.

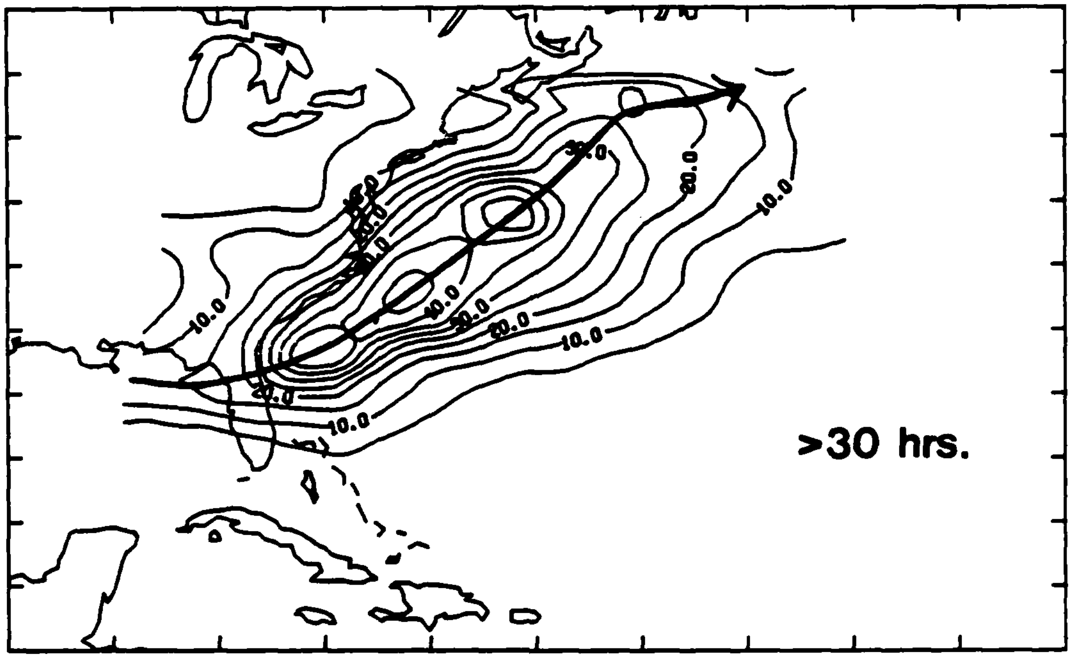

Figure 4g: Same as 4a; Greater than 30 hours.

northern Florida and then directly offshore before taking a northeastern path. The obvious difference between this pattern and the others is its large eastward displacement and southern extension. This displacement coinciding with the lengthy duration can be related to several factors. Blocking by strong anticyclones in the upper latitudes (Rex, 1950) and the position of the upper level jet (Anthes et al., 1981) can cause extratropical storms to stall and remain off the coast for days. Without upper air charts for individual storms it is impossible to determine if these two factors are responsible for the location and duration of the mean track in this particular category.

Duration and Magnitude

In an attempt to delineate between characteristics in the mean cyclone tracks based on duration and those based on magnitude, I merged the categories. The mean track associated with extratropical storms producing waves in the 5-8 feet category and having a duration of less than 5 hours is given in figure 5a. It is identical to the mean track for all storms with a duration of less than 5 hours because the only storms producing wave activity with a duration of less than 5 hours are those in the 5-8 feet category. Any storm associated with wave heights greater

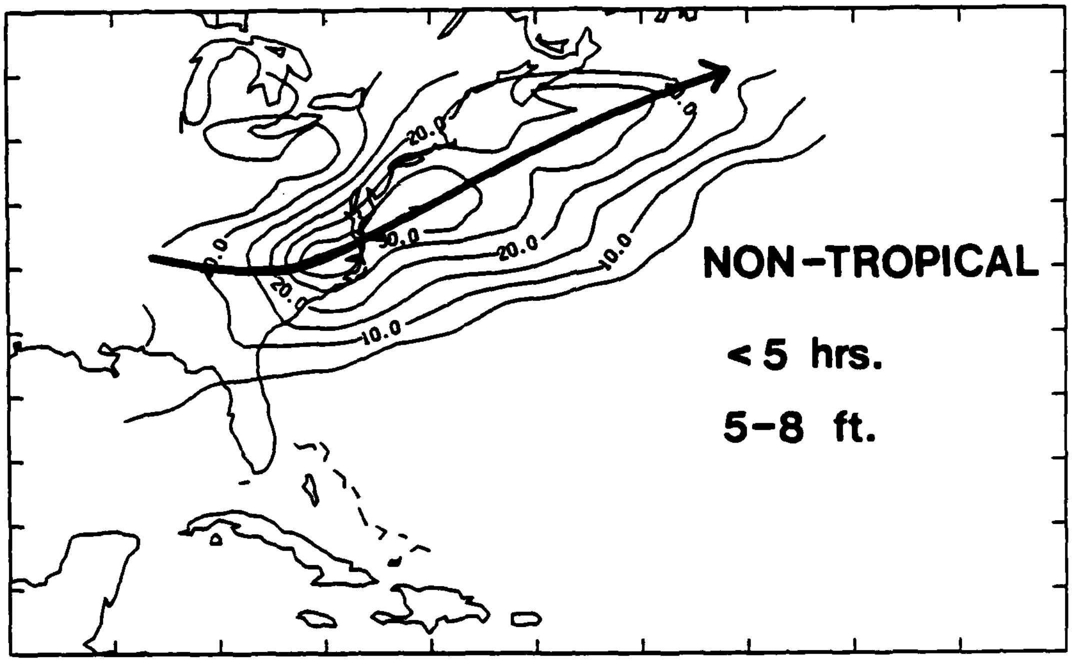

Figure 5a: Mean cyclone track for extratropical storms producing waves with a duration of less than 5 hours and heights of 5-8 feet.

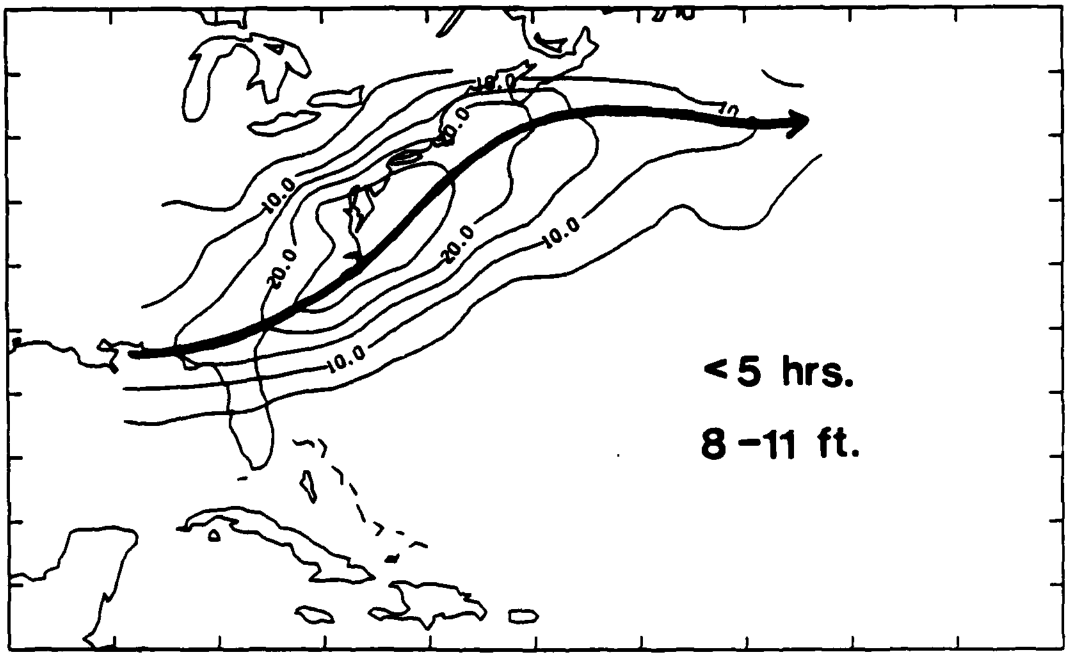

Figure 5b: Same as 5a; 8-11 feet.

than 8 feet results in a duration of greater than 5 hours. Therefore, the storms that take the track north of Hatteras and maintain close proximity to the coast produce relatively small waves at Cape Hatteras.

The cyclone frequencies associated with waves in the 8-11 feet category and lasting less than 5 hours are given in figure 5b. Paralleling the mainland of the southeastern U.S., as in previous presented tracks, the mean track takes on an eastward component upon reaching the higher latitudes. Again, this could be related to blocking patterns in the upper latitudes or shifts in the polar jet. This eastward component results in increased wave height at Cape Hatteras. Otherwise, it is similar to the 5-8 feet track shown in figure 5a.

While the storms with durations less than 5 hours in specific categories all maintain close contact with the southeast Atlantic coast, it is north of Hatteras where the major changes occur. The mean track of the 11-14 feet wave height category with a duration of less than 5 hours is shown in figure 5c. Although it is slightly displaced offshore it is still relatively close to the mainland. North of Hatteras the track takes an easterly path before returning to a northeast direction. In comparison with the previous mean track (Fig. 5b), the eastward route occurs farther south allowing for the increased fetch which leads to the slightly larger waves.

As with the magnitude stratification, the higher wave height categories are associated with fewer storms. Figure 5d shows the mean track for extratropical cyclones producing waves in the 14-17 feet category with a duration of less than 5 hours. While earlier tracks show an affinity for the southeastern coast, this track crosses central Florida and takes a northerly path moving slowly offshore. The lower latitude at which it moves eastward increases the fetch and enables the storms to produce larger waves. With only a few storms comprising the remaining categories, I combined the categories. The mean track of cyclones associated with waves in the 17-23 feet category and lasting less than 5 hours is given in figure 5e. The parabola shaped track is evident here with the offshore displacement being the most notable aspect.

The duration of a storm does not always directly relate to the attributes of waves reaching the coast. In the final extratropical analysis, I considered the storms associated with waves in a wave height category for longer than 30 hours. Figure 6a shows the cyclone frequencies for storms producing waves in the 5-8 feet category for more than 30 hours. The obvious feature is the pronounced eastward displacement relative to the coast. With the mean track being shifted offshore large waves would be produced at the coast because of the increased fetch. As the storms move far out into the Atlantic ocean they

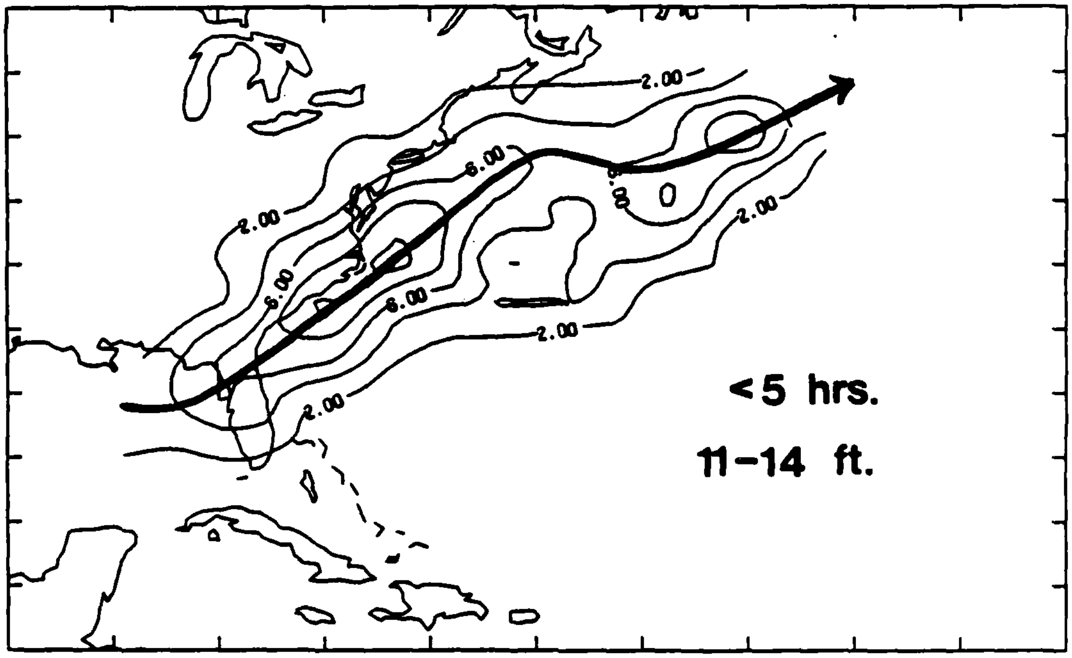

Figure 5c: Same as 5a; 11-14 feet.

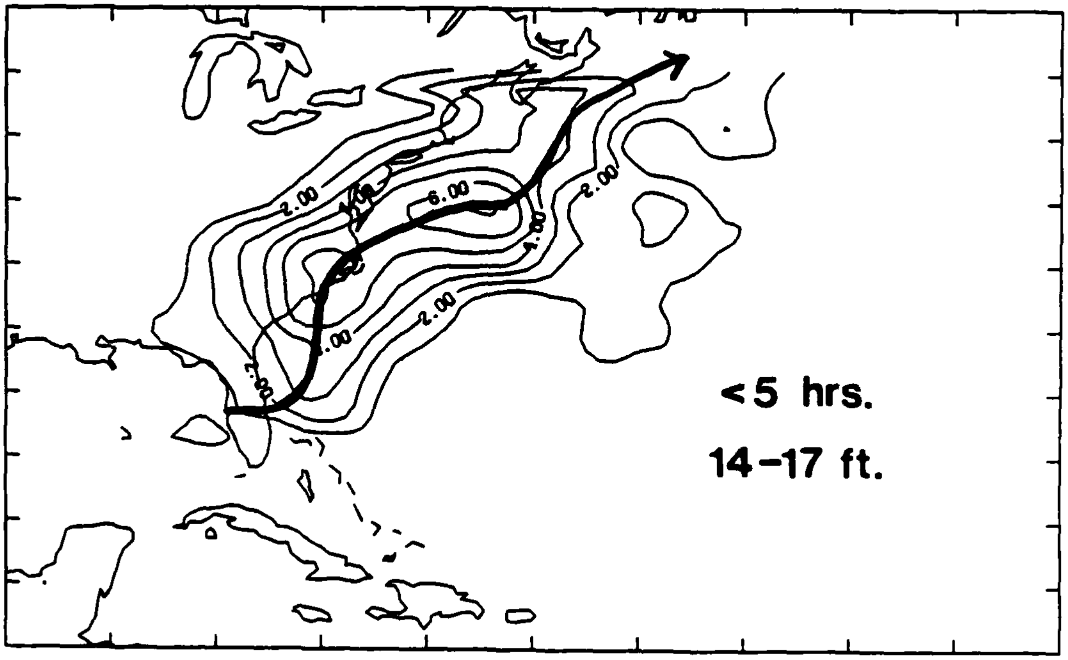

Figure 5d: Same as 5a; 14-17 feet.

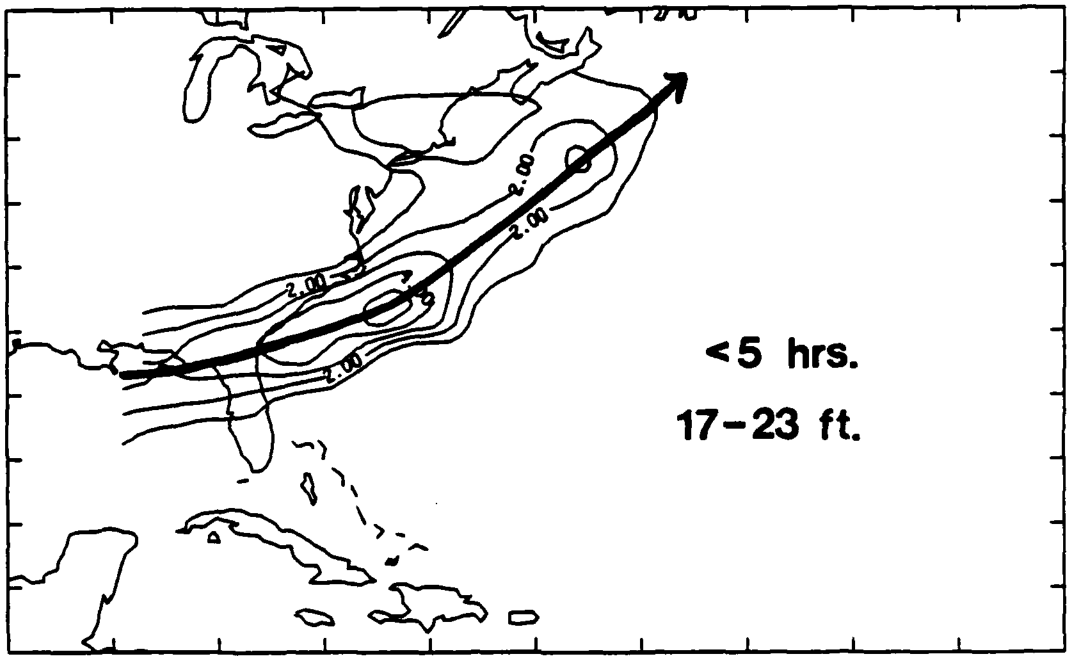

Figure 5e: Same as 5a; 17-23 feet.

cannot obtain the sensible heat associated with the Gulf Stream and do not intensify but weaken. Therefore, storms tracking out into the northern Atlantic and east of the Gulf Stream have no source of warm moist air to strengthen them so they weaken and do not produce large waves.

Figure 6b shows the mean track and associated frequencies for the storms producing waves in the 8-11 feet category for more than 30 hours. While it is closer to the coastline than the previous track, it still remains substantially east of the mainland. As a result of the small number of storms in the higher wave height categories, I combined the next two categories and omitted the last two. The mean track for the storms producing waves in the 11-17 feet category and lasting longer than 30 hours within that category are shown in figure 6c. It is actually closer to the coastline than the previous two tracks. While the proximity to the coast tends to decrease the fetch, the easterly turn in the mean track north of Cape Hatteras allows for significant fetch to produce the larger waves. As in earlier categories, the relatively few number of storms in the higher categories makes determining the mean track somewhat difficult.

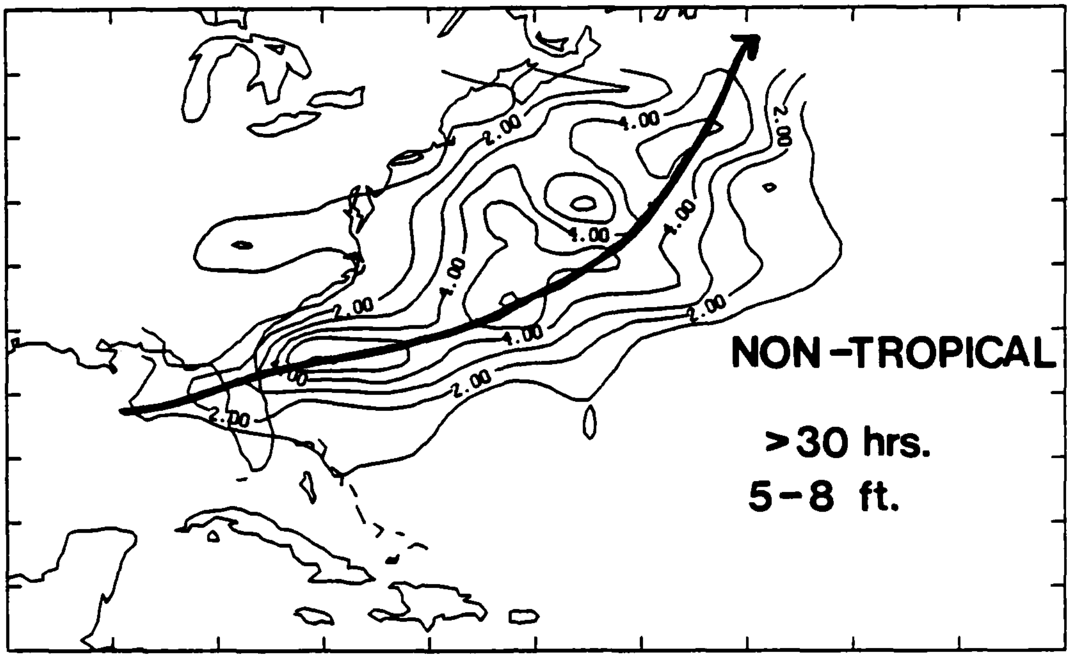

Figure 6a: Mean cyclone track for extratropical storms producing waves with a duration of greater than 30 hours and heights of 5-8 feet.

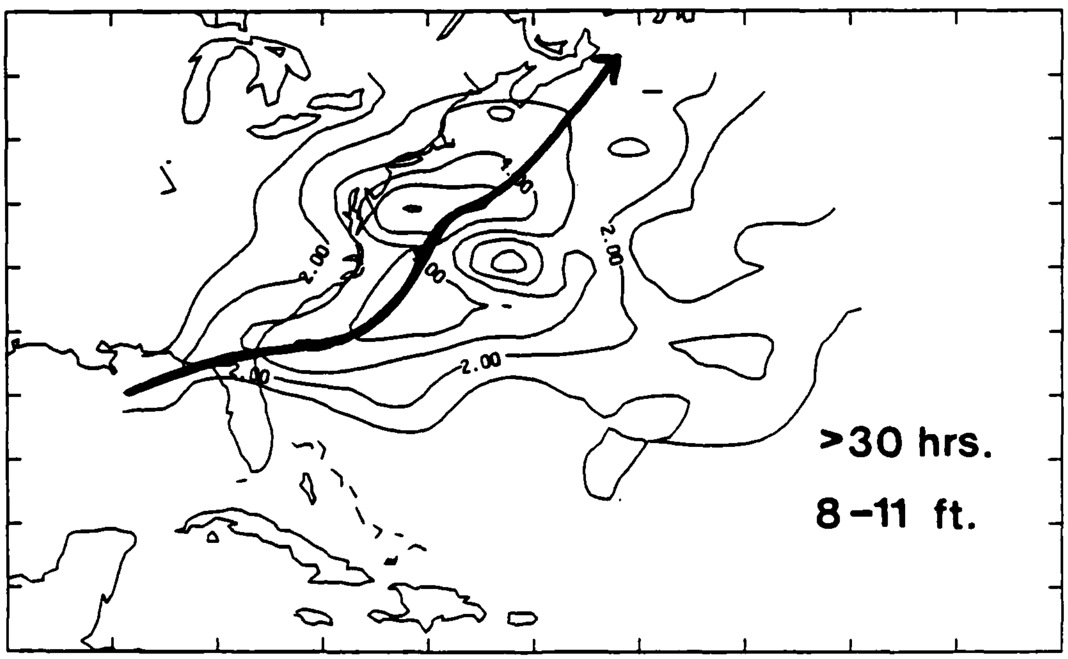

Figure 6b: Same as 6a; 8-11 feet.

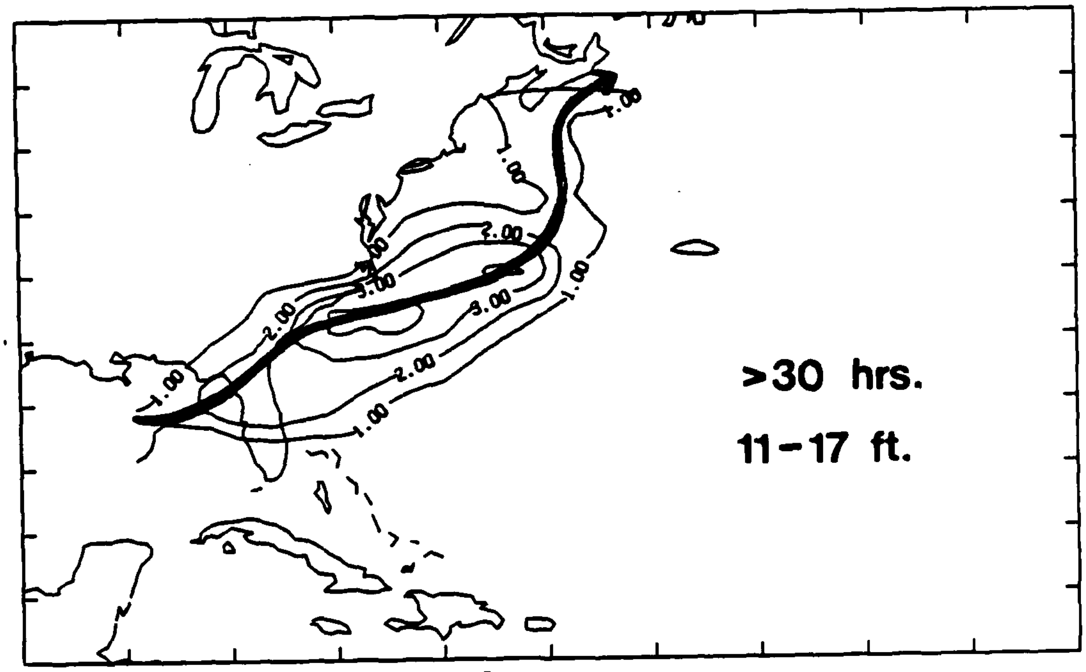

Figure 6c: Same as 6a; 11-17 feet.

TROPICAL CYCLONES

Magnitude

The number of tropical cyclones that track along the mid-Atlantic coast is very small in comparison with the extratropical storms. Figure 7a shows the tropical cyclone frequencies and mean storm track associated with waves in all wave height categories. The track originates in the eastern Atlantic moving northwest through the Carribean, changing direction and paralleling the coastline before sliding offshore in a northeasterly direction. This general recurvature of tropical storms in a path often resembling a parabola has been associated with the shape of the isobars around the western edge of the subtropical anticyclones (Namias, 1955).

Figure 7b shows the mean track of tropical cyclones producing waves in the 5-8 feet category at Cape Hatteras. This pattern is very similar to the track in figure 7a except for the separation of the track just north of Hatteras. As in the extratropical storms, the divergence of the mean track is related to the duration of the waves and will be discussed in detail later. Once the storms approach the coast near Florida they behave similar to extratropical cyclones in their preference for direction.

The cyclone frequencies associated with waves in the

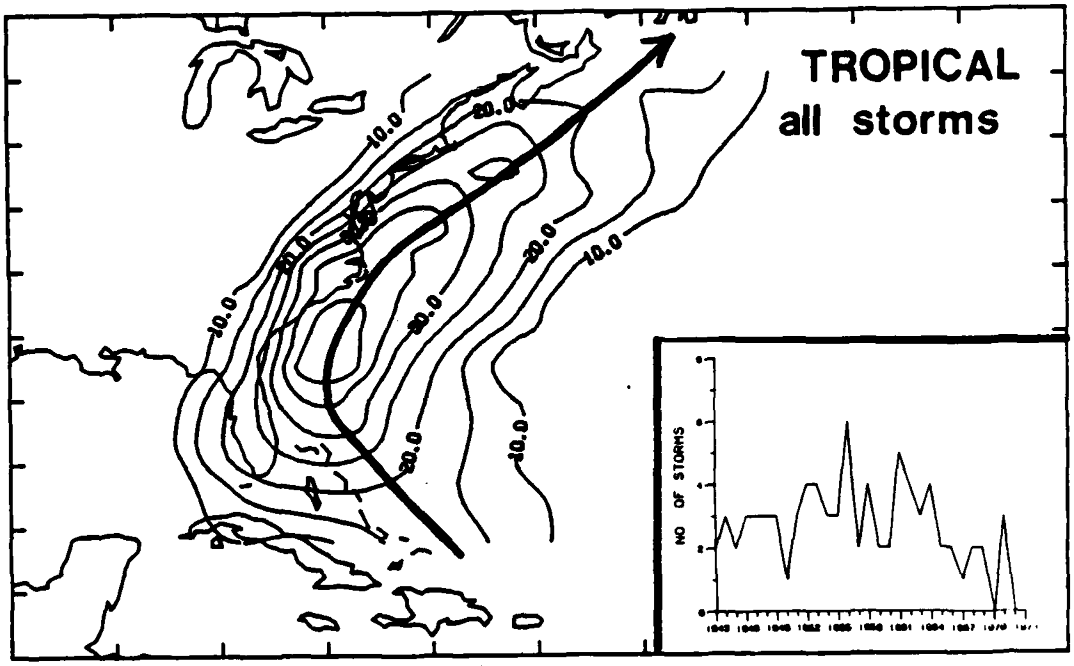

Figure 7a: Mean cyclone track and time series for all tropical storms producing waves at Cape Hatteras, North Carolina.

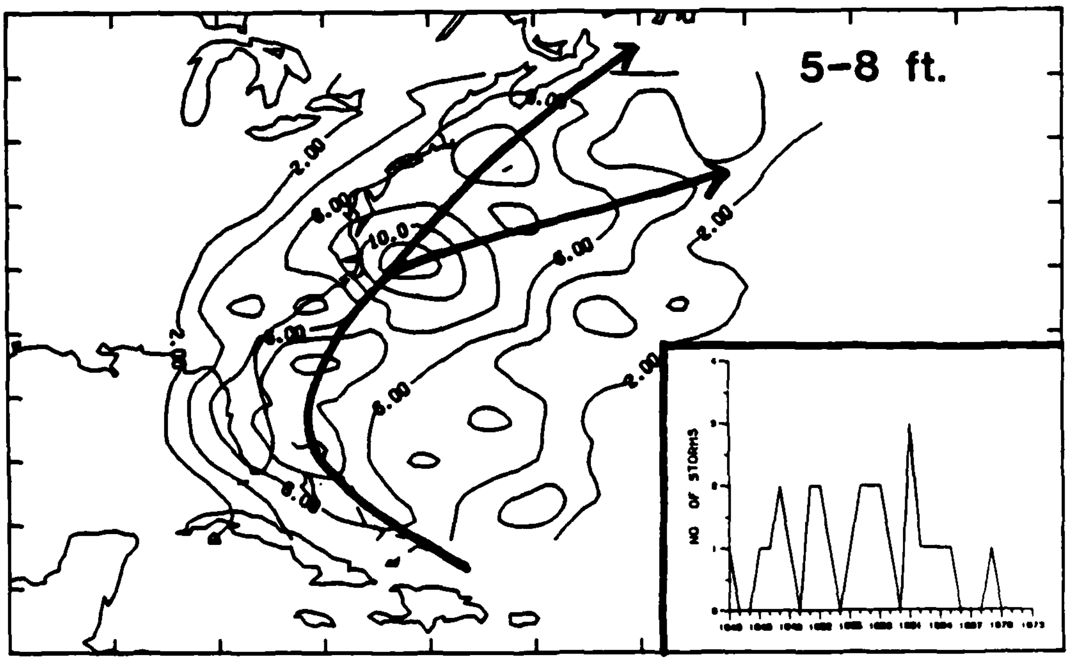

Figure 7b: Mean cyclone track and time series for tropical storms associated with wave heights of 5-8 feet.

8-11 feet category show a track somewhat different from the other tropical cyclone categories (Fig. 7c). Originating below Cuba, the mean track passes across south Florida before moving offshore and following the Atlantic coastline north. The maximum frequency is located south of Hatteras and coincides with a eastward movement in the position of the track. The mean track for tropical storms producing waves in the 11-14 feet category is given in figure 7d. It is very similar to the track in 7a passing over the mainland south of Hatteras with the frequency maxima associated with the landfall of the mean track.

Tropical storms associated with waves in the 14-17 feet category track very close to the Carolina coast before recurving out to sea (Fig. 7e). The location of the maximum frequency north of Hatteras indicates that the majority of storms producing waves in this particular category track along this area, unlike previous tracks where the maximum is to the south. The frequencies for the 17-20 feet category show a return to the southern maxima with the traditional recurvature in the mean track also present (Fig. 7f). The lack of tropical storm activity in these higher wave height categories is evident here as the maximum frequency is only 5.

The interpretation of the remaining two wave height categories is subjective because of the limited number of storms in each category. With only two storms producing

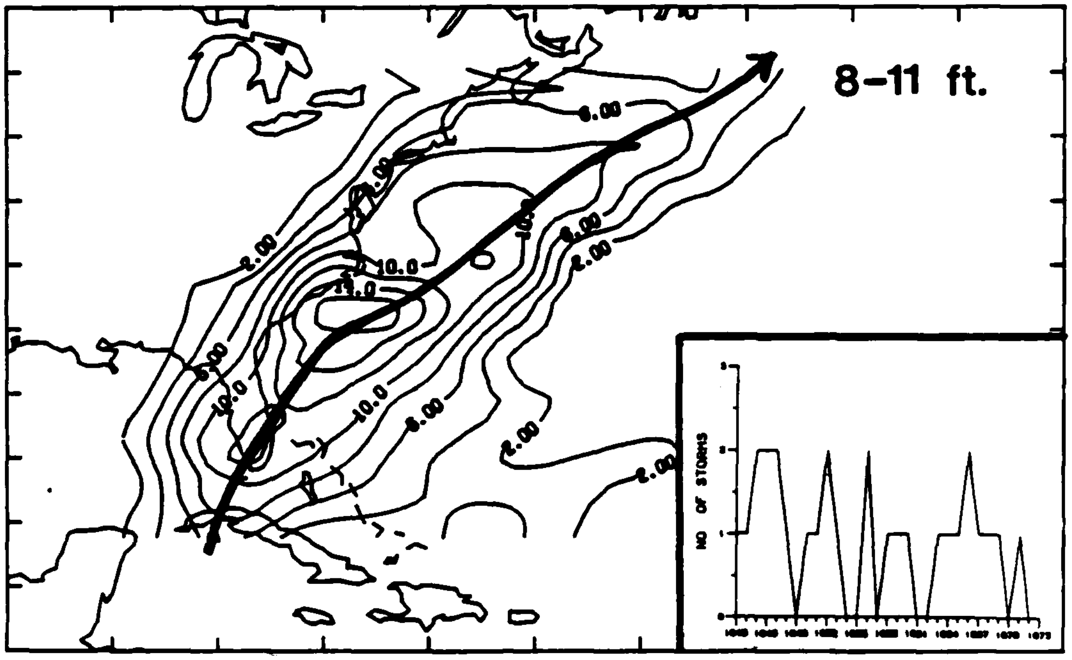

Figure 7c: Same as 7b; 8-11 feet.

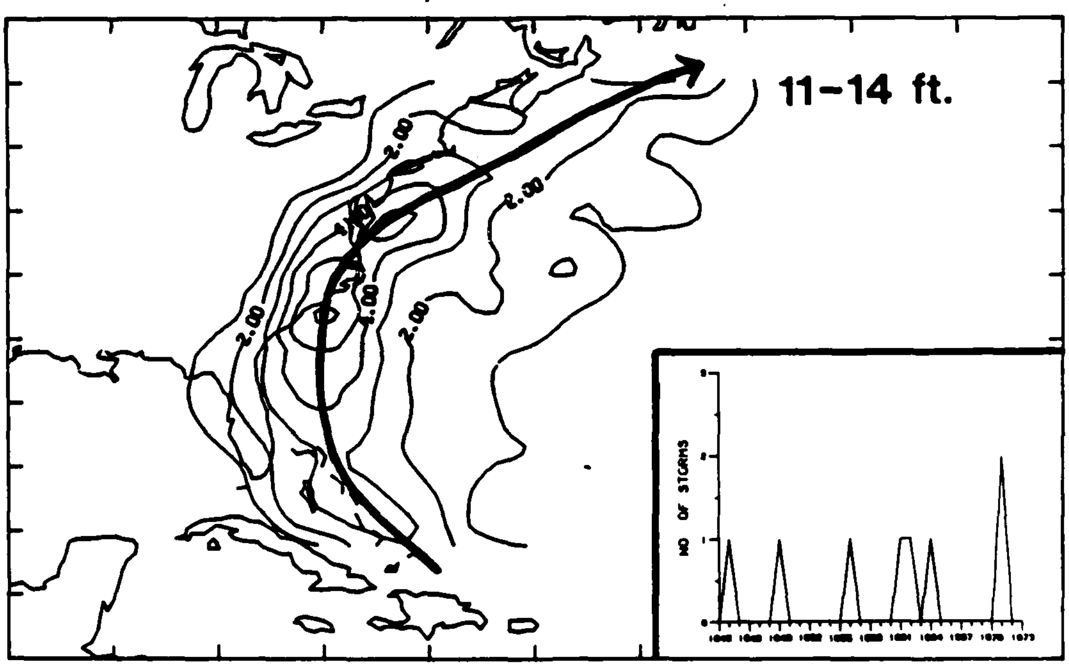

Figure 7d: Same as 7b; 11-14 feet.

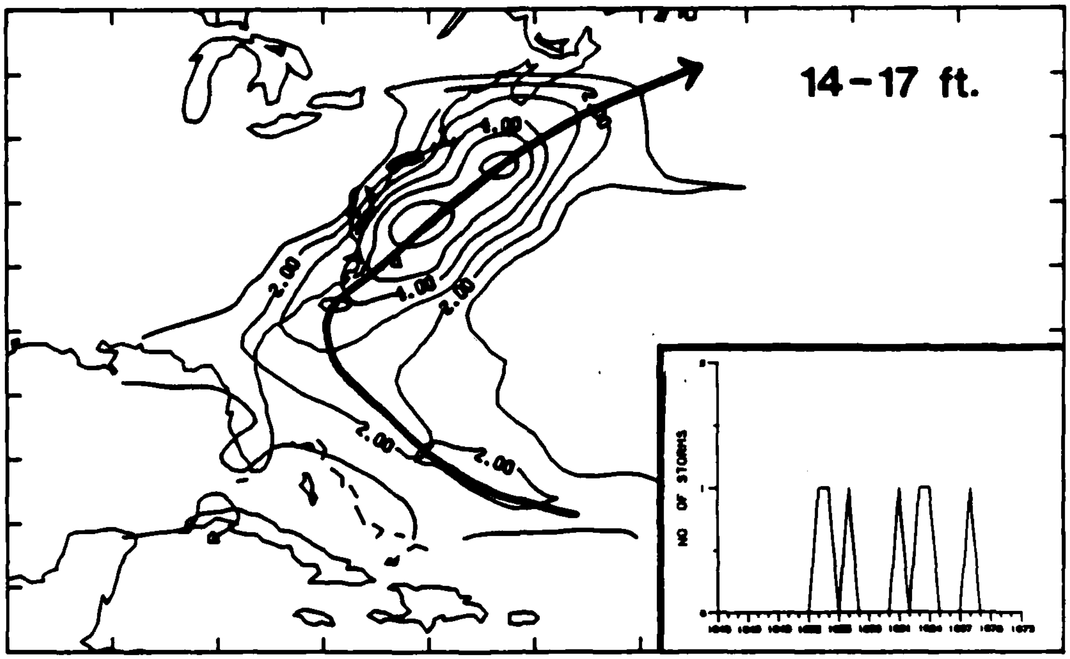

Figure 7e: Same as 7b; 14-17 feet.

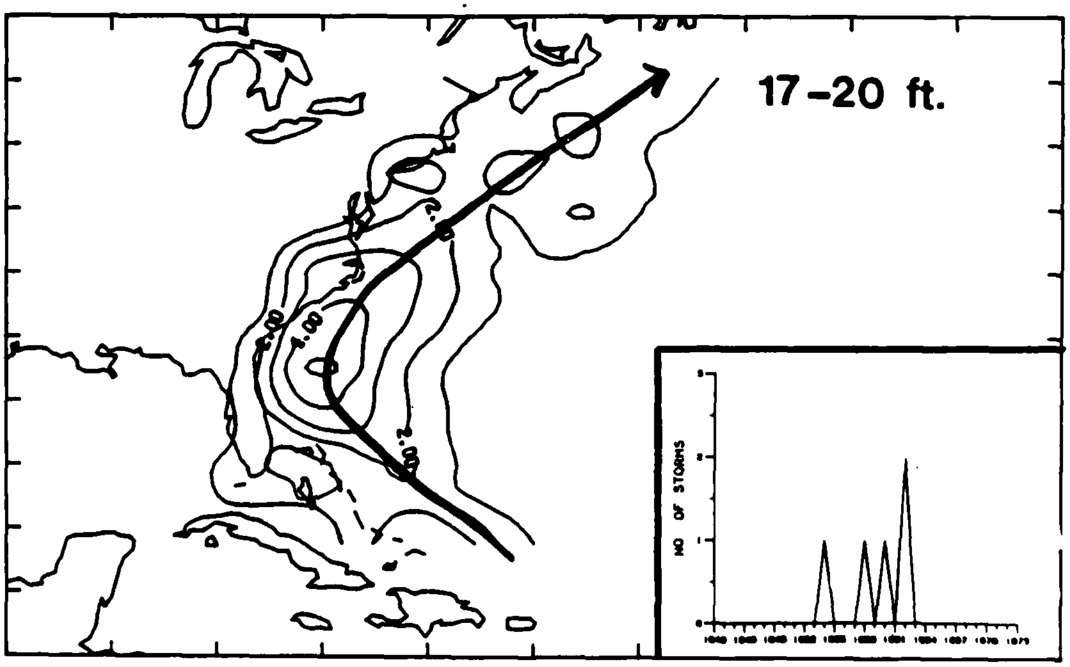

Figure 7f: Same as 7b; 17-20 feet.

waves in the 20-23 feet category, a mean track is statistically unreliable. The track given in figure 7g is actually the combination of the two tracks for the individual storms. Figure 7h shows the mean track for tropical cyclones associated with wave heights greater than 23 feet. Although there are more storms than in the previous figure, the number is still very small. The interesting aspect of figure 7h is the landward track that the storms follow. The most severe tropical storms affecting Cape Hatteras such as Hazel in 1954 actually track over the mainland rather than far offshore as in the extratropical storms.

I calculated the time series associated with the tropical cyclones in the same way as for the extratropical cyclones. For tropical storms producing waves in all wave height categories there is a maximum in the mid 1950's and early 60's followed by a period of little activity in the late 1960's and early 70's (Fig. 7a). This corresponds well to Shapiro's (1982a) study indicating a high frequency of tropical storms along the east coast during the 1950's. The cyclones producing waves in the 5-8 feet category reflect a similar pattern (Fig. 7b) with tropical storm activity being relatively high during the 1950's and early 60's and dropping off during the late 60's and 70's.

The time series for the 8-11 feet category (Fig. 7c) is also similar to the previous ones with three maximum

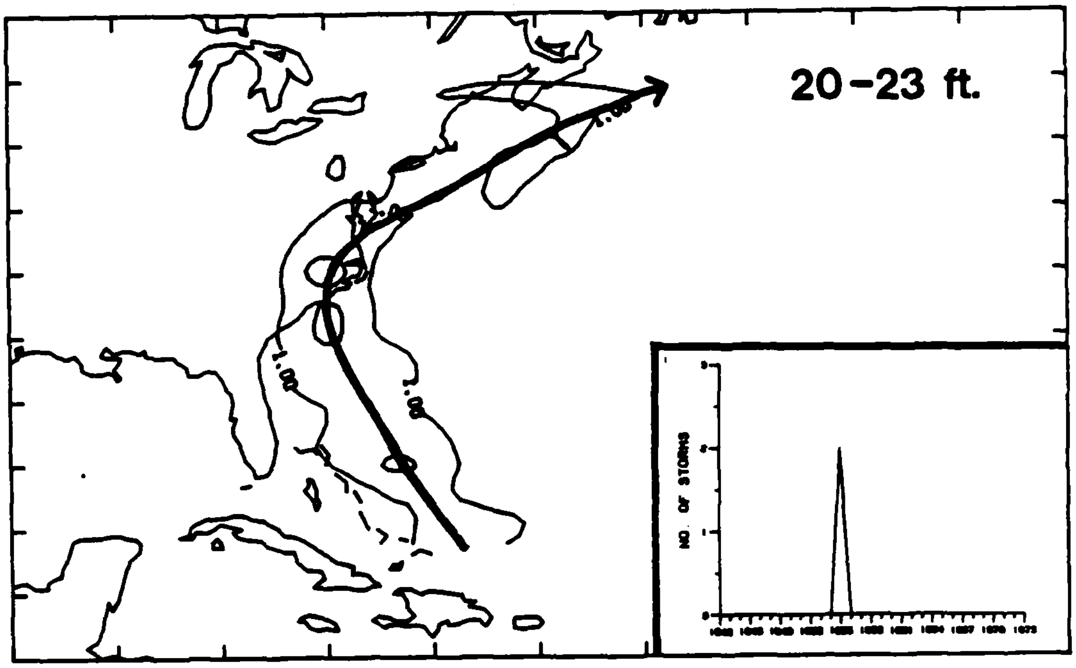

Figure 7g: Same as 7b; 20-23 feet.

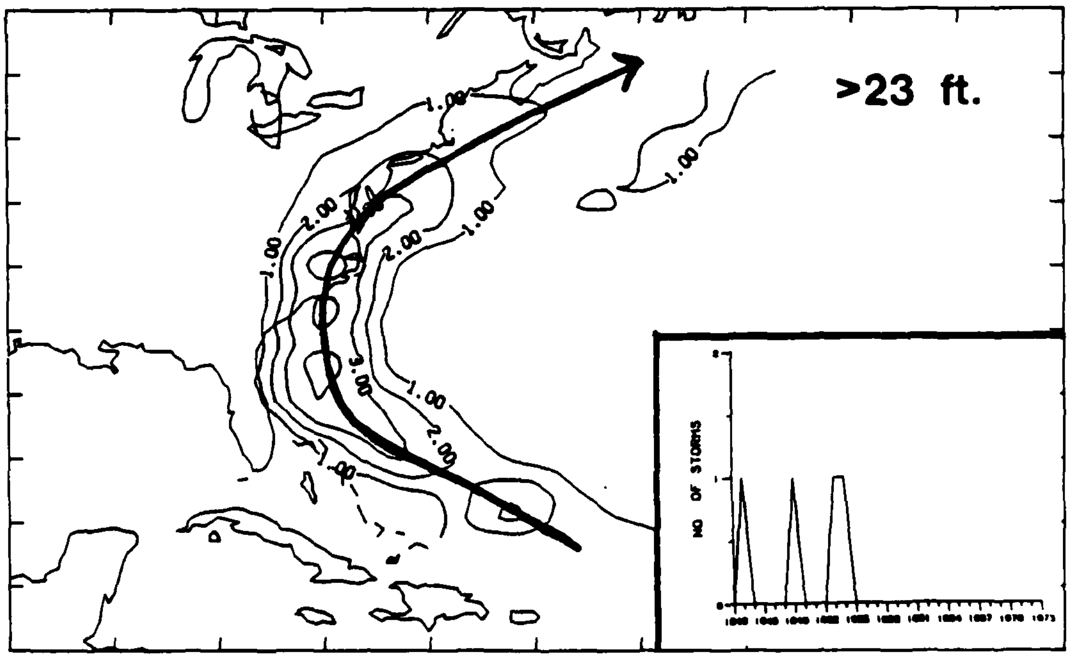

Figure 7h: Same as 7b; Greater than 23 feet.

periods in the late 1940's, late 1950's and mid 1960's. Because of the length of the data record it is difficult to determine if any significant pattern exist. The storms associated with waves in the 11-14 feet category show the 1950's to be relatively quiet compared to the 40's and 60's (Fig. 7d).

The relatively small number of storms in the higher wave categories produce only occasional spikes in the time series. The 14-17 feet category shows the early 1950's and 1960's to be active periods (Fig. 7e). Again, in this case an active year is the occurrance of one tropical storm resulting in high waves at Cape Hatteras. The 17-20 foot category indicates that the 1950's are the most active years in this particular wave height category (Fig. 7f). Tropical storms associated with wave heights between 20 and 23 feet occured only in 1955 and are represented by the lone peak in the time series.

While the 1950's and early 1960's account for the most tropical storm activity along the Outer Banks, the 1940's and early 1950's contain the four biggest storms to affect Cape Hatteras since 1942 (Fig. 7h). In 1944, 1949, 1953 and 1954 tropical storms producing waves in excess of 23 feet occured. A storm of that magnitude has not occured along the mid-Atlantic coast since then. Shapiro's (1982a) results coincide with this well indicating that a stormy year in the Atlantic usually results in high storm activity at Cape Hatteras. The general decline in tropical storm activity along the east coast is well known (Shapiro, 1982a; Neumann, etal. 1981). Even though the late 1970's and 1980's are not included in this study, it is known that no major tropical storms have affected the Cape Hatteras area in that time.

Duration

While extratropical storms vary in duration from a few hours to several days as did the March 1962 storm, tropical storms almost always stall off the coast for several days resulting in long durations. This is evident in the duration stratification results. Tropical cyclones producing waves in any wave height with a duration of less than 5 hours are rare as is evident in figure 8a. With only three storms in the category it is difficult to determine a mean track. In the 5-10 hour category a more definite pattern is evident (Fig. 8b). Although only a few storms occur in this category, they follow similar paths. The mean track is much closer to the mainland before it recurves north parallel to the coast.

The tropical storms associated with wave activity lasting between 10-15 hours (Fig. 8c) follow a pattern similar to the one in figure 7c. Originating south of Cuba this track crosses southern Florida and moves

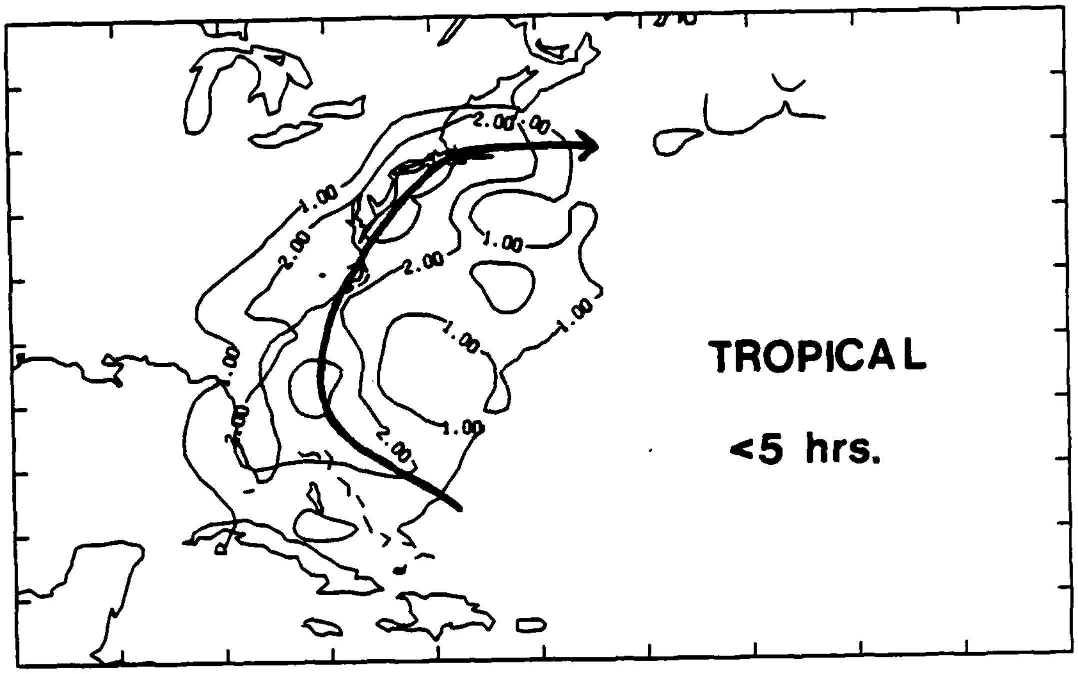

Figure 8a: Mean cyclone track for tropical storms producing waves with a duration of less than 5 hours.

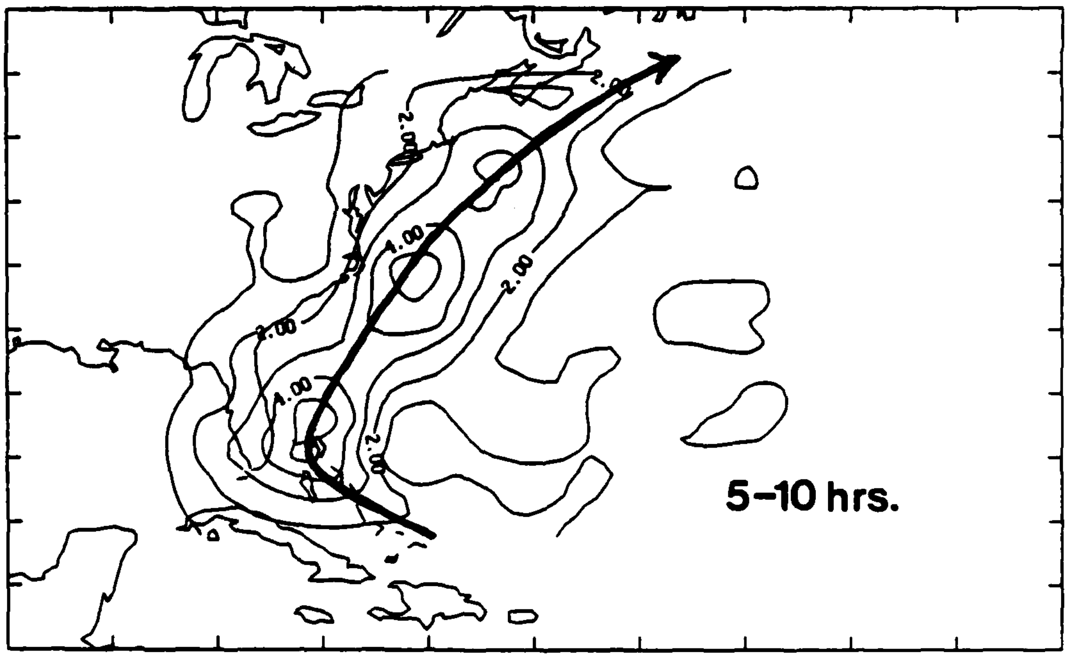

Figure 8b: Same as 8a; 5-10 hours.

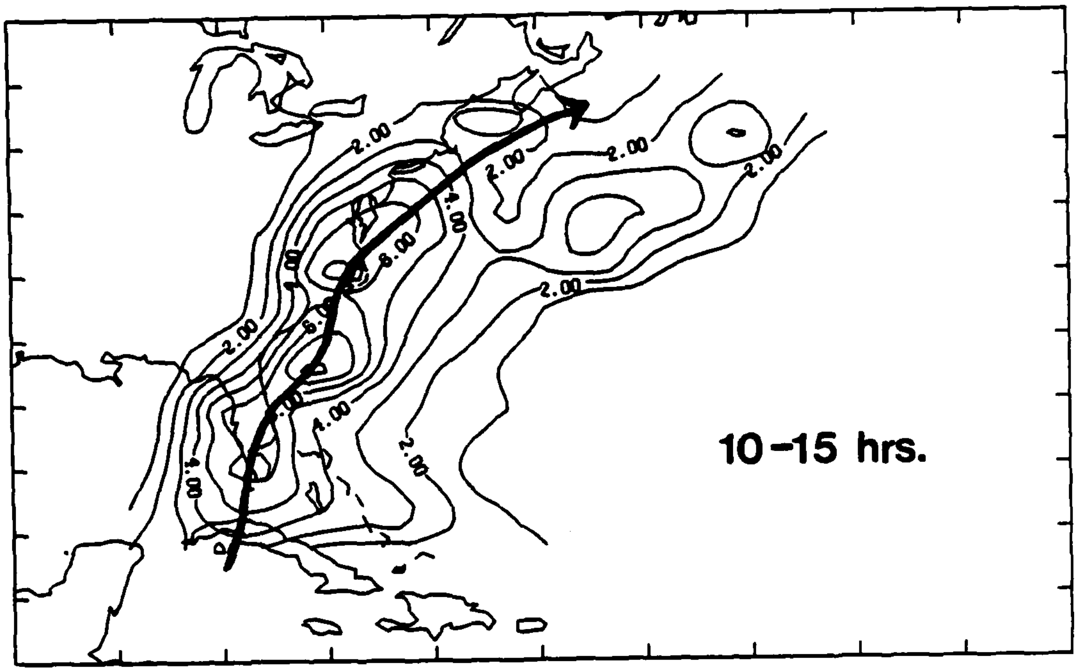

Figure 8c: Same as 8a; 10-15 hours.

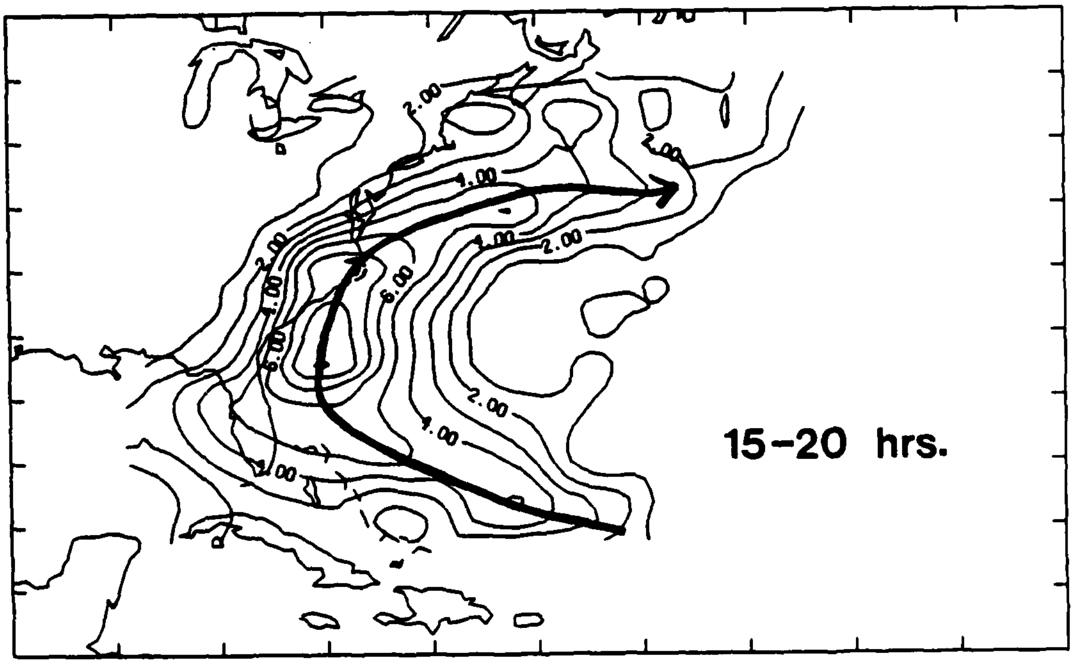

Figure 8d: Same as 8a; 15-20 hours.

northeast along the Atlantic coast actually heading mainland south of Hatteras before turning offshore again. The classic recurvature of the tropical storm track returns in figure 8d. This mean track associated with storms producing waves with a duration of 15-20 hours moves west in the lower latitudes, changes to a northerly direction and finally recurves offshore.

In the 20-25 hour category, the mean track takes a northeast path and does not recurve (Fig. 8e). It actually passes over the Gulf of Mexico before crossing central Florida, turning east and then moving northeast along the coastline. The storms associated with wave activity lasting 25-30 hours follow the more traditional tropical storm track (Fig. 8f). The mean track begins in the lower latitudes, recurves north over Hatteras and then moves offshore. While previous tracks move directly offshore north of Cape Hatteras, this track remains close to the coast.

The majority of tropical storms affecting Cape Hatteras are associated with long duration waves and therefore comprise most of the final duration category. The mean track associated with the greater than 30 hours category follows the basic path described in the earlier categories (Fig. 8g). Unlike the previous patterns which show the mean track over or inland of Hatteras, this track extends well out into the Atlantic.

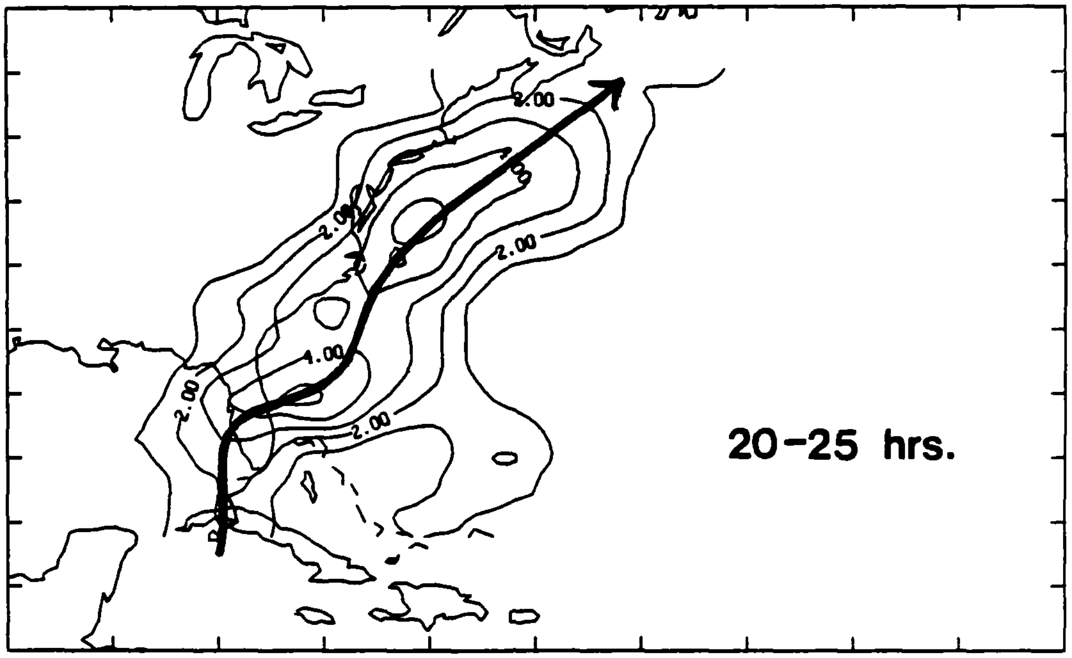

Figure 8e: Same as 8a; 20-25 hours.

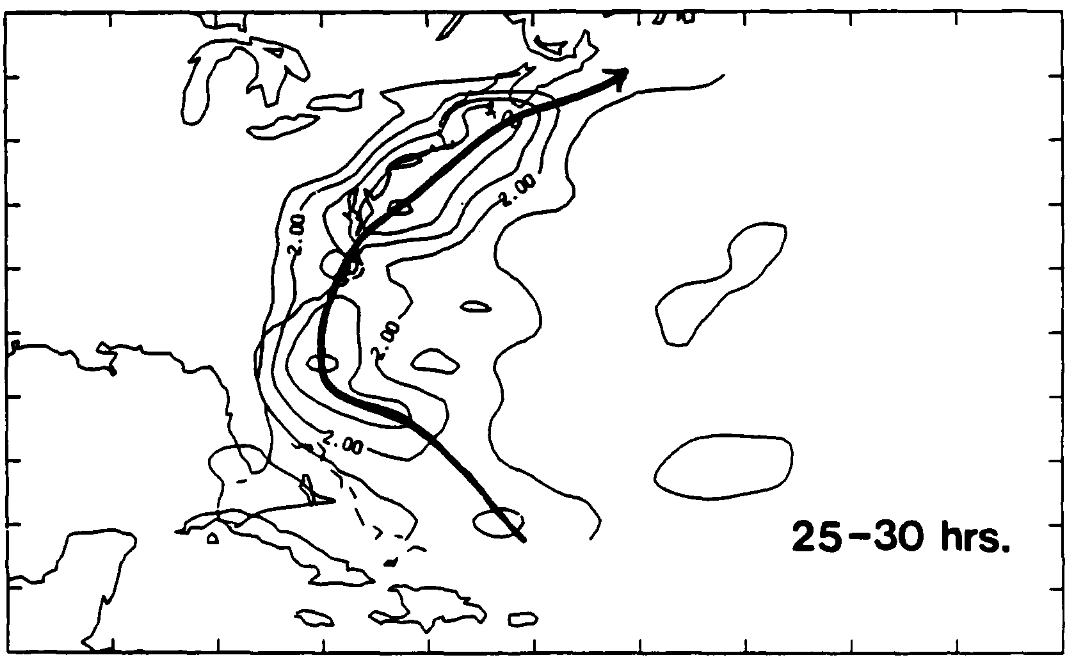

Figure 8f: Same as 8a; 25-30 hours.

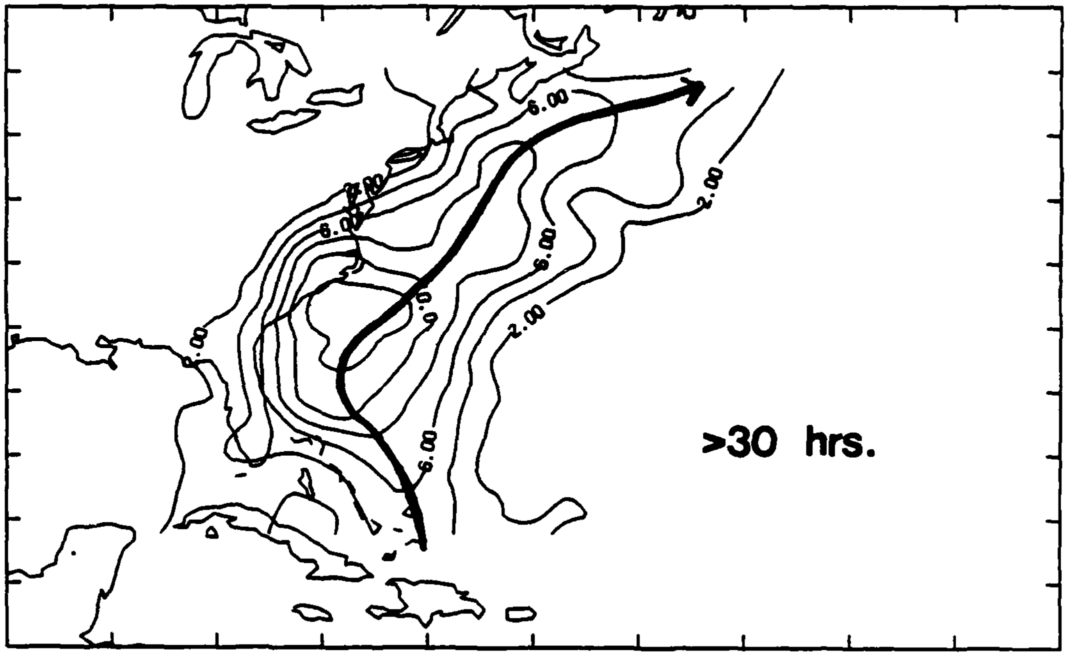

Figure 8g: Same as 8a; Greater than 30 hours.

Magnitude and Duration

Because of the relatively small number of tropical storms, I combined and eliminated certain categories in the magnitude and duration stratifications. Although the majority of tropical storms produce waves lasting longer than 30 hours, they do not do so in each wave height category. Therefore, I eliminated the magnitude and duration categories of greater than 30 hours and combined the less than 5 hour magnitude categories.

The tropical cyclone frequencies associated with waves in the 5-8 feet category with a duration of less than 5 hours are given in figure 9a. The mean track is identical to the pattern in figure 8a. The reason for this is the same for the extratropical cyclones. The 8-11 feet category with a duration less than 5 hours shows a pattern resembling an extratropical cyclone track (Fig. 9b). The low frequency of storms in this category makes the track very subjective and is only included here to emphasize the variability in mean tracks.

The final category combines the 11-14, 14-17, 17-20, and 20-23 feet categories into one 11-23 feet category. The resulting mean track follows the traditional pattern crossing the mainland near Hatteras before moving along the north Atlantic coast. The proximity of the mean track

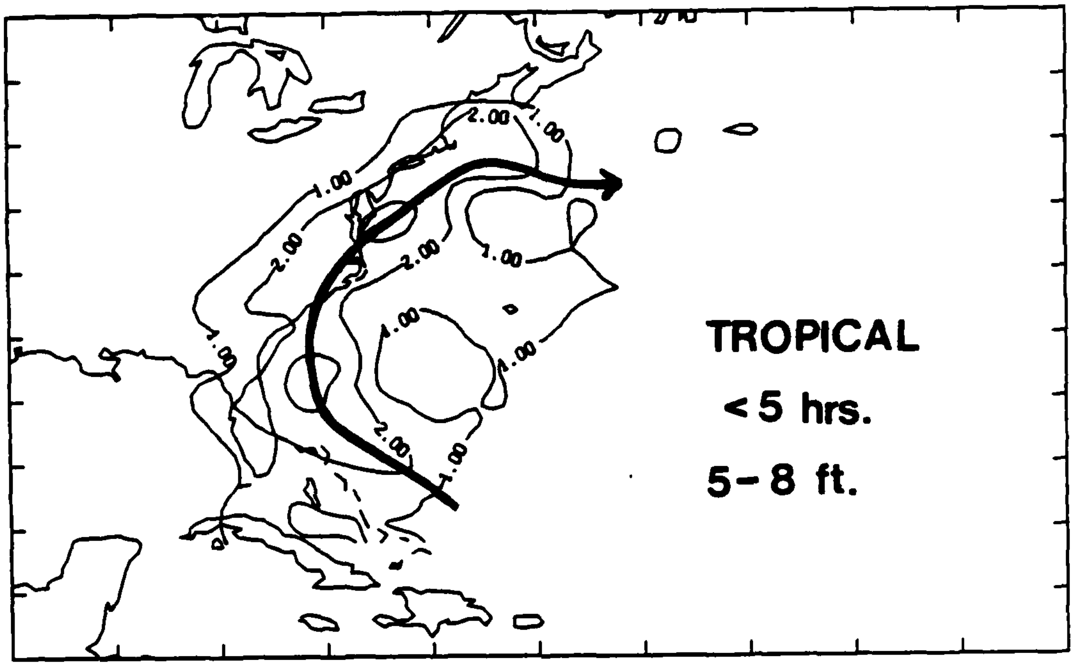

Figure 9a: Mean cyclone track for tropical storms producing waves with a duration of less than 5 hours and heights of 5-8 feet.

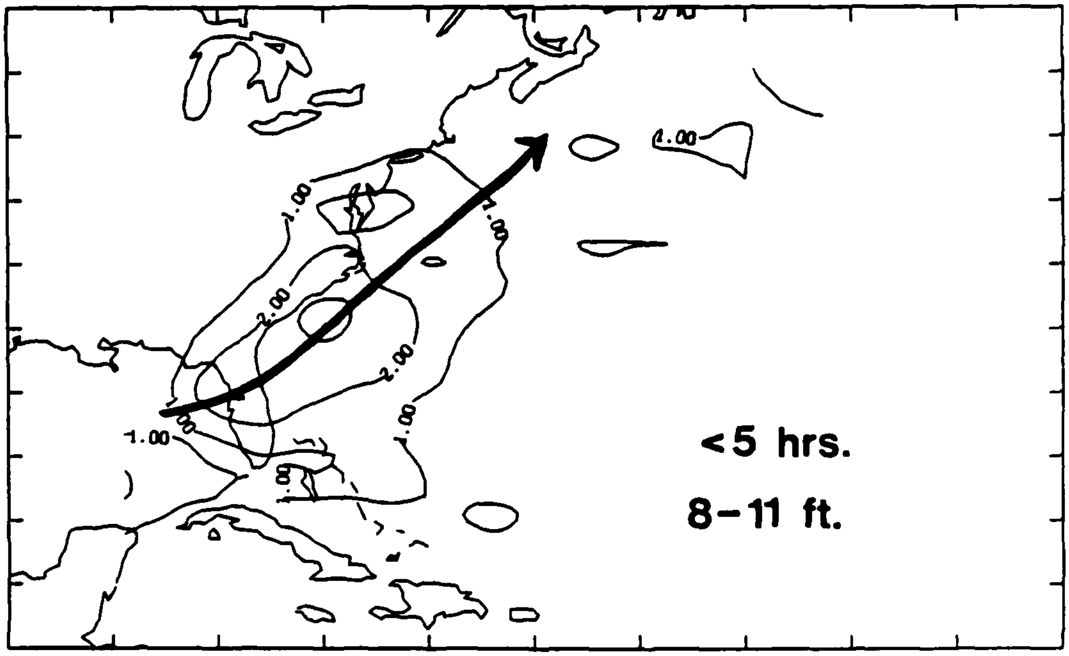

Figure 9b: Same as 9a; 8-11 feet.

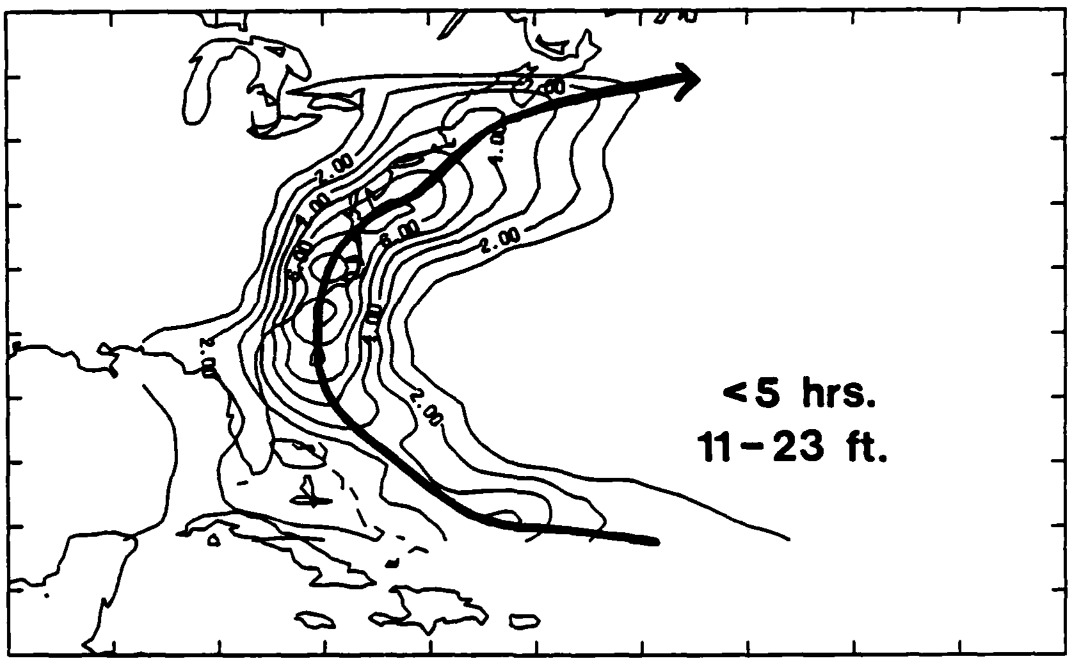

Figure 9c: Same as 9a; 11-23 feet.

to the coastline is most likely a result of the short duration.

DISCUSSION

Based on the 30 and 42 years of storm data analyzed in this study, there are distinct dominant cyclone paths which result in particular significant deep water waves at Cape Hatteras, North Carolina. The cyclone frequencies and associated mean storm tracks given in figures 3 through 9 depict various cyclone means and departures related to wave climates at Cape Hatteras, North Carolina. The dominance of an east coast cyclone track in the extratropical storms is a result of several factors. Bosserman and Dolan (1968) documented the long standing fact that the frequency of storms generating high waves along the mid-Atlantic coast is greatest during the winter months. This maximum frequency coincides with the southward extension of the polar jet which is generally responsible for the movement of the cyclones. Once a cyclone forms, its direction and speed of motion are determined by the orientation and intensity of the upper level jet (Anthes et al., 1981).

The land-sea temperature contrast during the winter also serves as an important factor in the movement of surface cyclones along the coast. The temperature contrast during the winter months causes the coastline to serve as a natural frontal boundary known as a coastal front (Bosart, 1972). The formation and intensification of surface cyclones is enhanced along these fronts because of diabatic heating from the warm ocean. While the general presence of an east coast cyclone track is explained by the upperlevel winds, the various shifts in the tracks associated with specific wave climates is more complex.

Based on the mean extratropical cyclone tracks in figures 3 through 5, the dominant Atlantic coast cyclone track varies significantly with storm intensity and duration. The average track for all storms affecting Cape Hatteras for a year is 57° east of north with an average duration of 15.5 hours. An average track of 45° east of north is where the maximum duration of approximately 30 hours occurs. The reason for this is that most of the energy delivered to the coast arrives within a very narrow window (30°- 60° east of north). Unless a storm track is oriented such that it falls within this window, the energy delivered to the coast will be minimal.

A general eastward displacement of the mean track occurs with increasing wave height (Fig. 3a-h). In the 5-8 feet category a more northern track remaining close to the coastline is evident while the larger wave height categories show a more northeasterly offshore track. This is the result of two factors. The change in direction of the mean track is a function of the speed of the storm. Storms with a south to north track are associated with rapid changes in the wave direction and duration at the coast while storms moving west to east have small and slower changes in wave direction and increased duration.

The heights and periods of waves generated at the coast are determined by the wind velocity, duration, and fetch or distance over which the wind blows (Komar, 1983). As cyclones move offshore from the Atlantic coast they obtain a larger fetch and usually intensify. The intensification of cyclones over the warm ocean during the winter is in part a result of sensible heating. Colucci (1976) shows that greatest cyclone deepening occurs along the north wall of the Gulf Stream and along the immediate Atlantic coast. This area of cyclone intensification coincides with the location of the mean cyclone tracks in the various wave height categories. As storms move offshore they intensify as a result of the warm ocean with respect to the land. Those storms that move further offshore intensify even more because of the same process but associated with the Gulf Stream. The effect of latent heating on cyclone intensification is described by Bosart (1981) and Gyakum (1983a). They relate deepening of extratropical cyclones to deep cumulus convection in and around the storm center. Gyakum (1983a) also reveals that Atlantic cyclones may be "steered" by the low-level warm advection associated with intense sea-surface temperature contrasts such as along the Gulf Stream. Therefore, the most intense cyclones affecting Hatteras are those that shift eastward along the Gulf stream.

The mean tracks of the extratropical cyclones in the duration categories show a similar pattern in the eastward displacement of the track (Figs. 4a-h). In short duration storms a more south-north track occurs running close to the coastline while the longer duration categories are characterized by a more west-east track much farther offshore. Storms maintaining close contact with the coastline do not intensify as much as those moving offshore because of friction effects from the surface and lack of an additional warm water source. As the storms move offshore they intensify and produce waves for a longer period of time because of this intensification. A strong cyclone tracking far offshore can produce significant deep water waves at Cape Hatteras for a much greater length of time than can a weaker storm in the same location. Therefore, for the same reason increased wave heights are associated with the eastward shift in the mean track increased duration also occurs.

The increase in magnitude and duration of deep water waves with an eastward displacement of the mean extratropical cyclone track results from a combination of factors. In figures 5a-e the duration is short while the wave height varies. While an increase in duration is often accompanied by an increase in wave height it is clear from these examples that duration is the more dominant of the two factors in controlling the location of the mean track. With each wave height category having a duration of less than 5 hours the mean track is near the coastline, even with wave heights greater than 17 feet. This implies that storms relatively close to the shoreline move quickly and produce the larger waves only for short periods at a time. Although the speed of cyclone movement is not directly considered in this study it can be inferred from the production of high waves for such a short period of time.

The importance of duration in the location of the mean track is even better defined in figures 6a-c. Storms producing waves in the 5-8 feet category track way offshore in the longer duration category. Although the mean track actually shifts west with increasing magnitude, the east-west orientation of the track compensates for this shift by allowing the storms to focus their energy towards the coast for a lengthy period of time. In general, the duration and magnitude of the waves produced at the coast is a function of the eastward displacement of the extratropical cyclone tracks. While some of the deviations may be a result of seasonal shifts, they still coincide with particular wave climates regardless of the season.

While the relationship between extratropical storm tracks and wave magnitude and duration is relatively simple, the relationship between tropical storm tracks is more complex. The general recurvature of the tropical cyclone track is basically a function of survival. When tropical storms cross over the land they die out abruptly. Tropical storms only form in ocean areas having a high surface temperature, with 26^{0} to 27^{0}C being the lowest such temperature observed at the time and place of formation (Byers, 1974). In order to survive, tropical storms must in part derive their energy from latent heat of condensation. Since this can only occur in the presence of warm moist air the storms must remain near the warmest ocean currents to maintain their strength. The warmest ocean current associated with the Atlantic coast is the Gulf stream which the mean tropical storm tracks follow closely after leaving the lower latitudes. On the average, tropical storms reach their greatest intensity shortly before or just at the recurvature point (Simpson and Rhiel, 1981). Once they acquire a reverse eastward component, their strength diminishes. Therefore, the strongest winds and highest waves are associated with this point.

The specific tracks associated with the magnitude categories (Figs. 7a-h), show a slight westward shift with increasing wave heights. The angle at which tropical storms arrive at Hatteras in the main reason for this shift. Since the strongest winds and largest waves are associated with the point of recurvature, the closer this point is to the coastline, the larger the waves produced at the coast. The unique track associated with the wave height category of 8-11 feet includes all of the storms tracking into the Gulf and then back along the Atlantic coast. This indicates that the majority of tropical storms tracking towards the Gulf of Mexico will continue in that direction and only a small number will head north and cause significant wave activity at Cape Hatteras.

The tropical storms in figures 8a-g do not indicate any particular pattern as did the extratropical storms. The unique track previously mentioned is again evident in figures 8c and 8e implying that this track is not simply a function of magnitude but also of duration. It appears that tropical storms producing waves in the 8-11 feet category have a duration of between 10 and 20 hours. The mean tracks associated with the other categories shifts in various directions offering no specific pattern. This is best explained by looking at figure 8h. The cyclone frequencies in this category are higher than in any other tropical cyclone category, including magnitude. This implies that the majority of tropical storms resulting in significant deep water waves at Cape Hatteras are of long duration and produce waves lasting longer than 30 hours. Since most storms comprise this category it is clear why no specific pattern can be identified in the lower duration categories.

Even though the majority of tropical storms affecting Hatteras result in wave activity of greater than 30 hours the number of individual wave categories with 30 or more hours duration is almost nonexistant. This indicates that the storms move through each wave height category at a rather moderate pace resulting in waves with durations of less than 30 but more than 5 hours in most categories. The tropical storms producing waves of short duration all track over the mainland south of Hatteras except the 8-11 feet category (Figs. 9a-c). By moving landward south of Hatteras the tropical cyclones quickly dissipate and die allowing only a short time and narrow area for the energy associated with the storm to reach the coast.

CONCLUSION

The track of an individual tropical or extratropical cyclone is an important determinant of the magnitude and duration of the waves that will be produced along the mid-Atlantic coast. In general, the position of the tracks of extratropical cyclones play a joint role in the magnitude and duration of the waves. While the movement of the track appears to control the duration of the waves, it is also an important factor in increasing the magnitude. Acting together, these two factors determine that as storms move offshore they intensify and thereby increase the duration of their wave producing components. This relationship results in higher waves at the shoreline. The closer the storms track towards the coastline, the less they intensify. The storms moved quickly up the coast by the upper level winds do not remain along the coast long enough to produce the large waves and thus produce only moderate to small wave activity.

The temporal variations in extratropical cyclone activity indicates that severe storms generally occur during relatively stormy years and not during years of little activity. Although no specific pattern is evident in the time series, it does appear that with the increase in storm activity during the 1980's the occurance of major coastal cyclones is nearing a return to prominance after several years of quiet.

The tropical storm tracks are almost entirely related to the magnitude of the waves; the duration is always so great that it has little affect on the position of the track. The magnitude of tropical storms are such as to allow for large waves to occur over a short period of time while changes in the track are so gradual as to cause little change in the duration. Since the maximum intensity of a tropical cyclone tends to occur at its point of recurvature, the closer the storms are to the shore the greater the amount of wave activity that will result.

The decline in tropical storm activity during the last 5 years is only an addition to the declining trend started in the 1970's. While no pattern can be determined from the time series it is apparent that, like the extratropical storms, the most severe tropical storms occur during years of high overall storm activity.

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The tracks of individual tropical and extratropical cyclones are an important determinant of the magnitude and duration of the waves that will be produced along the mid-Atlantic coast. Based on a data set covering the years 1942 to 1984, an eastward displacement in the mean track of extra-tropical cyclones associated with increasing wave magnitude and duration is evident. Tropical cyclones show a westward shift in the mean track with increasing wave magnitude, but little change with duration. No temporal

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pattern could be identified in the frequency of extratropical storms while the number of tropical cyclones has declined over the past fifteen years. The relationship between sea-surface temperatures, the Gulf Stream, and upper latitude blocking and cyclone movement is briefly discussed as possible reasons for the changes in the mean storm tracks

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