Effects of oceanographic media on Equatorial Atlantic hurricanes

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ABSTRACT

This study was performed in an attempt to determine the relationship between tropical storms which reach hurricane intensity and the mean corresponding oceanographic environmental conditions.

An historical analysis of vertical temperature gradients in the Equatorial Atlantic (July–September) from the sea surface to the 200-foot level reveals favorable and unfavorable potentials in the oceanographic media for intensification of tropical storms to hurricanes.

A chart depicting the number and location of tropical storms which reached hurricane intensity during 1901–1965 is presented. Approximately 90 per cent of these storms reached hurricane intensity when the vertical temperature difference between the ocean surface and the 200-foot level was 7°F or less. Only 4 per cent of all tropical storms reached hurricane intensity when vertical temperature differences within the first 200 feet of the ocean surface exceeded 15°F.

Data from satellite and aircraft reconnaissance flights depicting intensity of tropical storms in the Equatorial Atlantic for the period 1960–1965 show similar relationships with the oceanographic media.

Introduction

Tropical storm development in the Equatorial Atlantic is most frequent in August, September, and October. Satellite and aircraft observational platforms indicate that some tropical storms attain hurricane intensity, while others never exceed the depression or storm status. The exact nature of the mechanics of generation and/or development of the tropical storm is still not completely understood. However, during the past decade, the knowledge gained through the use of various observational platforms has decreased the mystery surrounding storm development. There exist many conditions in the atmosphere and the oceanographic environment that contribute to and/or inhibit the tropical storm formation and intensity.

This study was prepared in an attempt to relate solely the effects of the oceanographic environment upon the intensity of tropical storms. Only tropical storms which reached hurricane intensity in the Equatorial Atlantic (Equator to 20° N and 0° W to 60° W) from 1901 to 1965 are presented. Although it is realized that the atmospheric influence upon tropical storm intensity plays an integral role, it will be neglected in this study.

The fairly recent sea-air interaction studies on hurricane development, motion, structure, and intensity have revealed many interesting concepts. Fisher (1957) indicates a direct relationship between warm surface waters and some physical properties of the atmosphere. He also attempts to relate formation and direction of motion of tropical storms to areas of relatively warm water. Perlroth (1962) further pursued this concept by relating the sea surface temperature influence on short term fluctuations in the structure and intensity of tropical storms. There appears to be little supporting evidence that the paths of tropical storms follow the warmest water as indicated by Fisher (1957) and Tisdale & Clapp (1963).

In describing different modeling techniques for the atmosphere, the meteorologist has utilized climatology and various analog methods. With the advent of satellites and *in situ* systems, synoptic platforms for obtaining meteorological information for the data-sparse ocean areas have been improved gradually. However, at present the oceanographer, unlike the meteorologist, lacks even a crude synoptic platform for describing oceanographic environmental conditions, and it will probably be several years before satellite systems and various *in* *situ* platforms can be expected for the realization of a true oceanographic synoptic network. In the past, synoptic oceanographic analyses have been carried out only in limited ocean areas holding an abundance of data.

Data sources

The data banks utilized for the analyses of the physical oceanographic environmental parameters (currents, sea surface temperatures, and vertical temperature gradients) were obtained from the files of the National Oceanographic Data Center, Washington, D.C., and the National Weather Records Center, Asheville, North Carolina.

The following historical data banks were used: Surface current observations from the Dutch marine deck, 1854 to 1938; bathythermograph data, 1944 to 1965; and sea surface temperature data, 1854 to 1958.

The sea surface temperature data were obtained from the following decks: Deutsche Seewarte Marine, 1859 to 1939; Dutch marine observations, 1856 to 1953; Navy Hydrographic Office marine IBM deck, 1904 to 1945; and supplemental decks to 1958.

Mean wind velocity data for hurricanes in this study area were obtained from the *Annual Tropical Storm Reports*, 1960 to 1965, compiled by the Fleet Weather Facility, Jacksonville, Florida.

The data banks utilized were reduced to a common 1-degree square grid network. The resultant surface currents were composited from historical data files for July, August, and September. Bathythermograph data were also composited from historical data for the same 3 months. The monthly mean sea surface temperatures by 1-degree square quadrangles were summarized by the Naval Oceanographic Office.

Equatorial Atlantic Surface Currents

The historical data for mean surface current circulation in the Equatorial Atlantic for July, August, and September are presented in Fig. 1. Here, three distinct types of surface current circulations are evident: The North Equatorial Current, the Equatorial Countercurrent, and the South Equatorial Current. The North Equatorial Current is positioned north of 10° N; the South Equatorial Current generally lies south of 5° N; the Equatorial Countercurrent lies between the two.

During the summer season, the Equatorial Atlantic Countercurrent is fully developed and plays an integral part in the structure of the water mass profile. The intensity of the South Equatorial Current is also pronounced during this season. It is apparent that the magnitude of the surface current circulation in the Equatorial Atlantic varies in response to the intensity and/or changes in the major prevailing wind systems.

A cyclonic current shift axis is noteworthy along the zone between the North Equatorial Current and the Equatorial Countercurrent. This shift axis reaches its most northern limit during the late summer and in early fall. The mean position of the Inter-Tropical Convergence (ITC) zone approximately at or north of 10° N latitude coincides with the cyclonic current shift axis. Wyrtki (1966) found a similar relationship in the eastern Equatorial Pacific Ocean between the surface Pacific Countercurrent and the North Pacific Equatorial Current. The southern limit of the Atlantic Countercurrent is characterized by an anticyclonic surface current shift axis which separates it from the South Equatorial Current.

The analyses of mean surface current are essential for understanding the mechanics of the water mass profile in the Equatorial Atlantic essential for understanding the mechanics of the water mass profile in the Equatorial Atlantic. Unique relationships exist between the surface current profile, the sea surface temperatures, and the vertical temperature gradients. These relationships will be discussed in the sections dealing with sea surface temperature analyses and thermal structure.

Sea surface temperature analyses

The mean montly sea surface temperature analyses for July, August, and September are shown in Figs. 2, 3, and 4. The surface current circulation shown in Fig. 1 is utilized as a model for analyses of the sea surface temperature data. The zones of cyclonic and anticyclonic surface current shift indicate the areas of pronounced surface thermal gradients.

The warmer surface waters in the Equatorial Atlantic coincide with the position of the Equatorial Countercurrent. A mean location of the

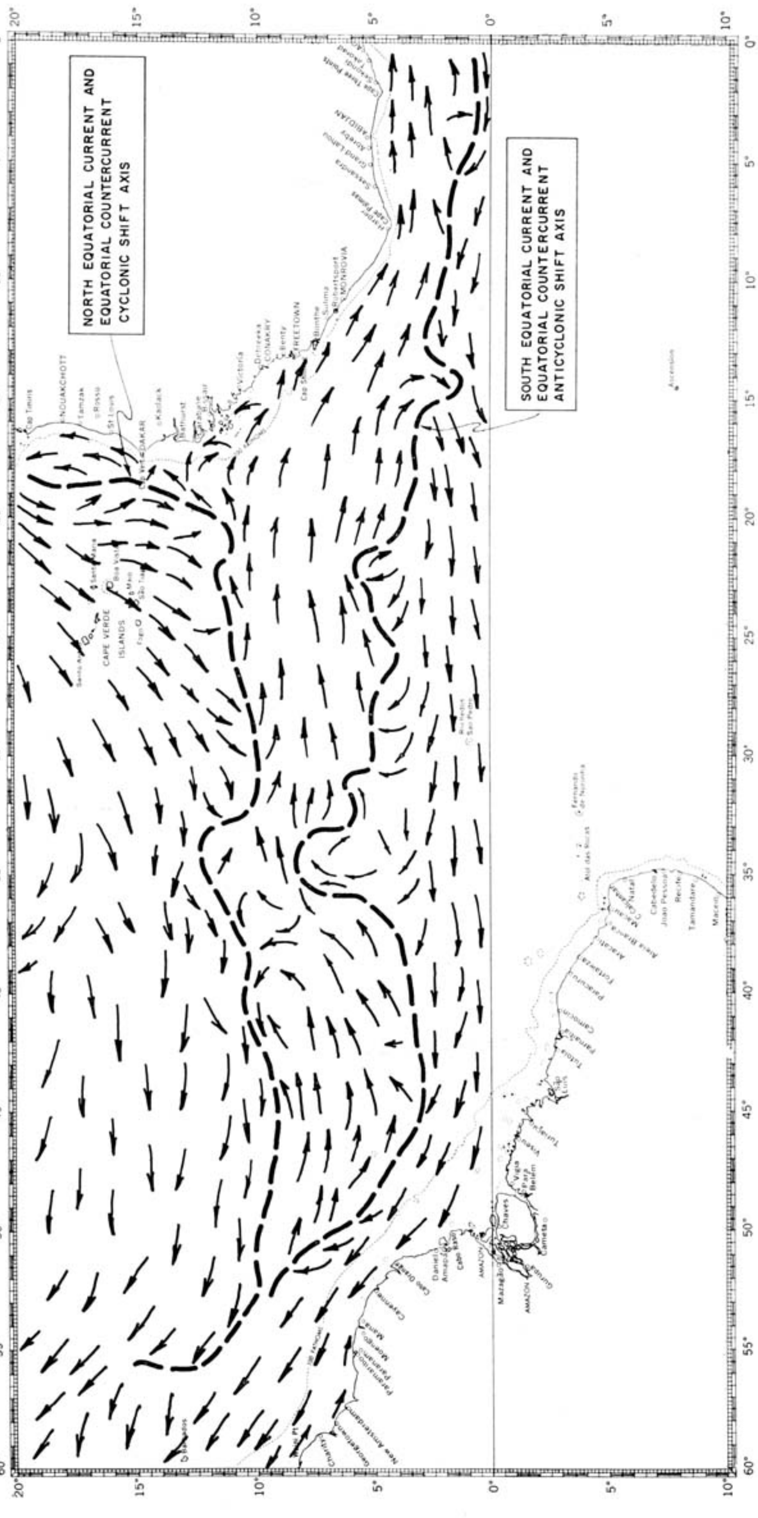

Fig. 1. Historical ocean surface currents in the Equatorial Atlantic for July, August and September.

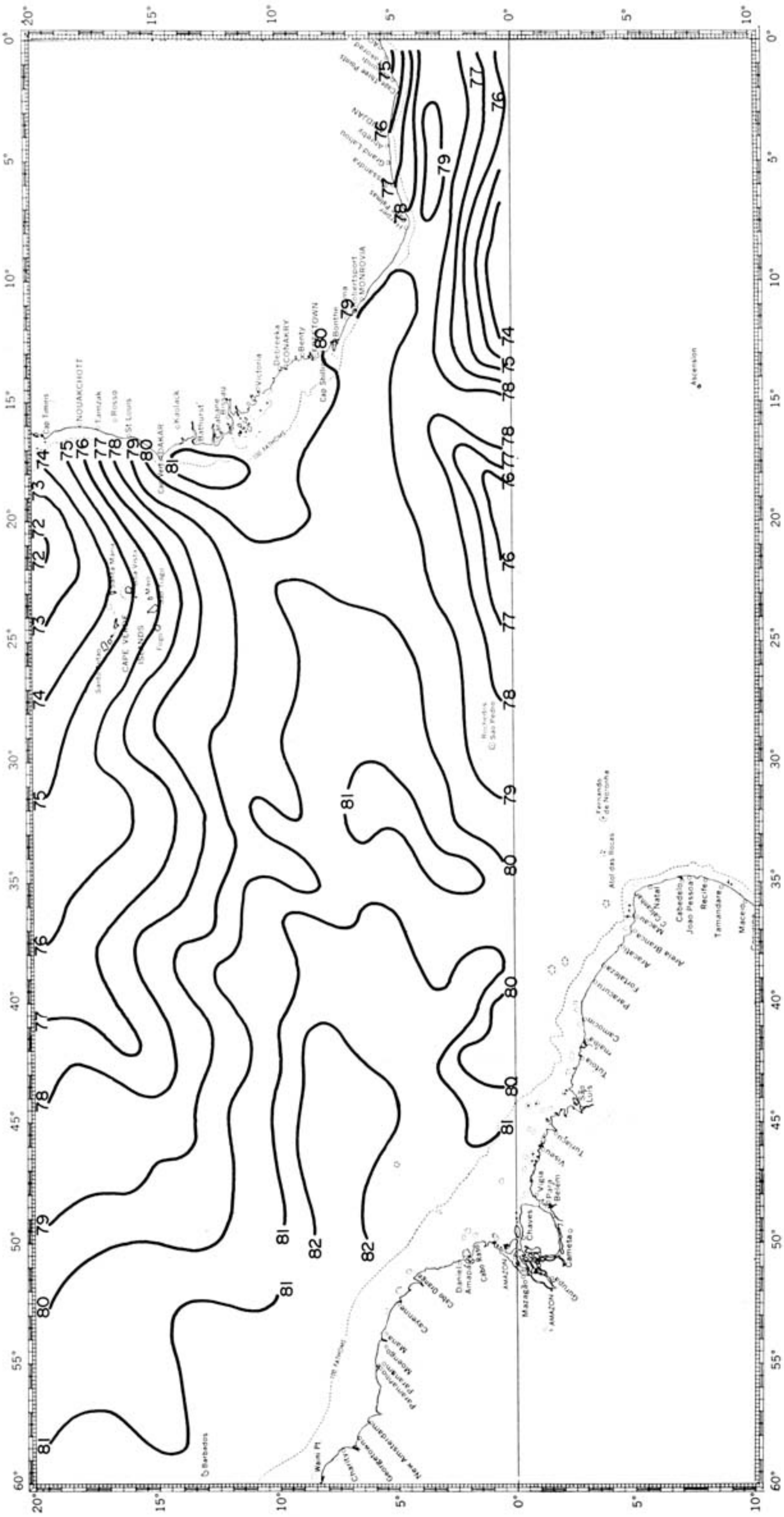

Fig. 2. Historical July sea surface temperature chart.

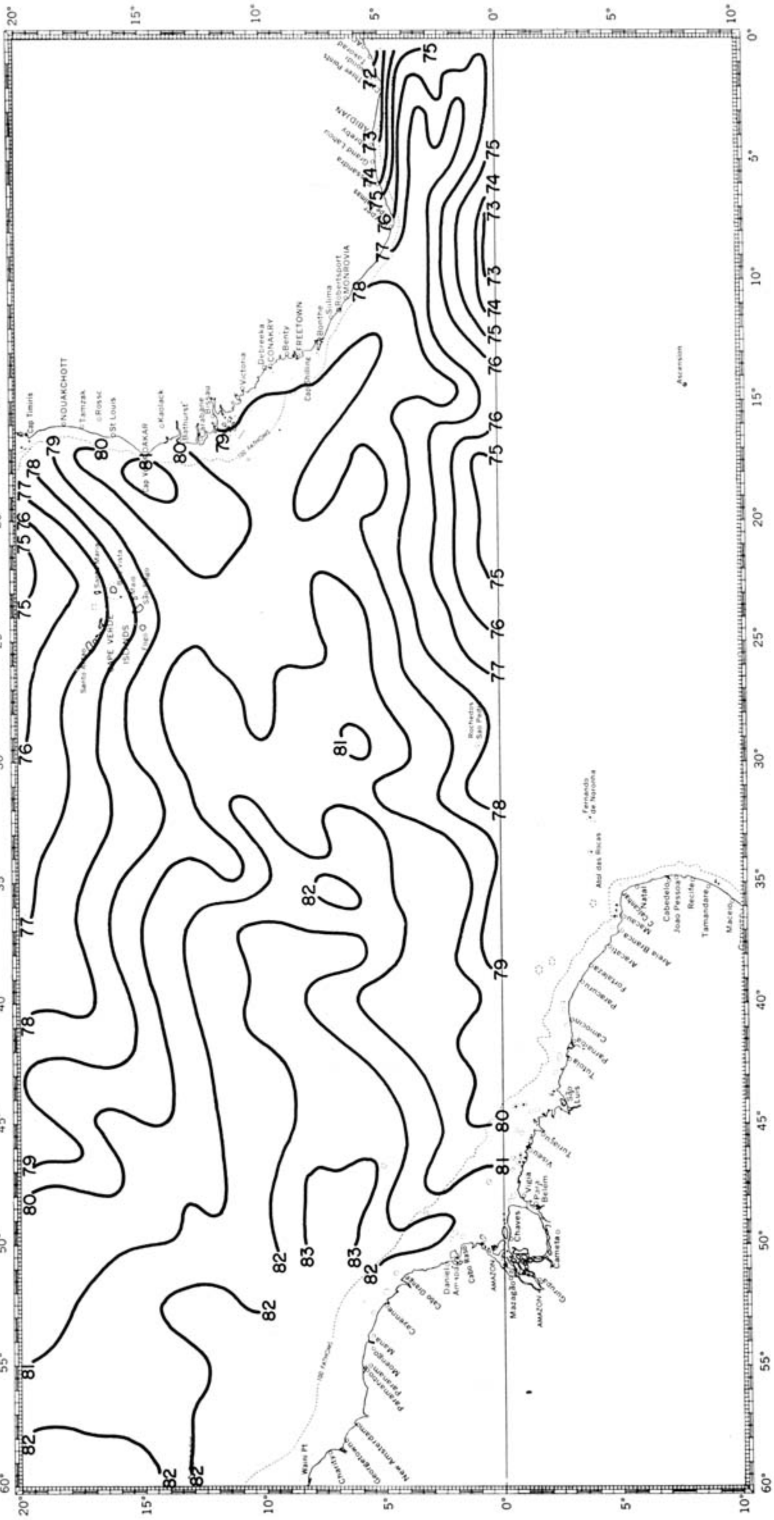

Fig. 3. Historical August sea surface temperature chart.

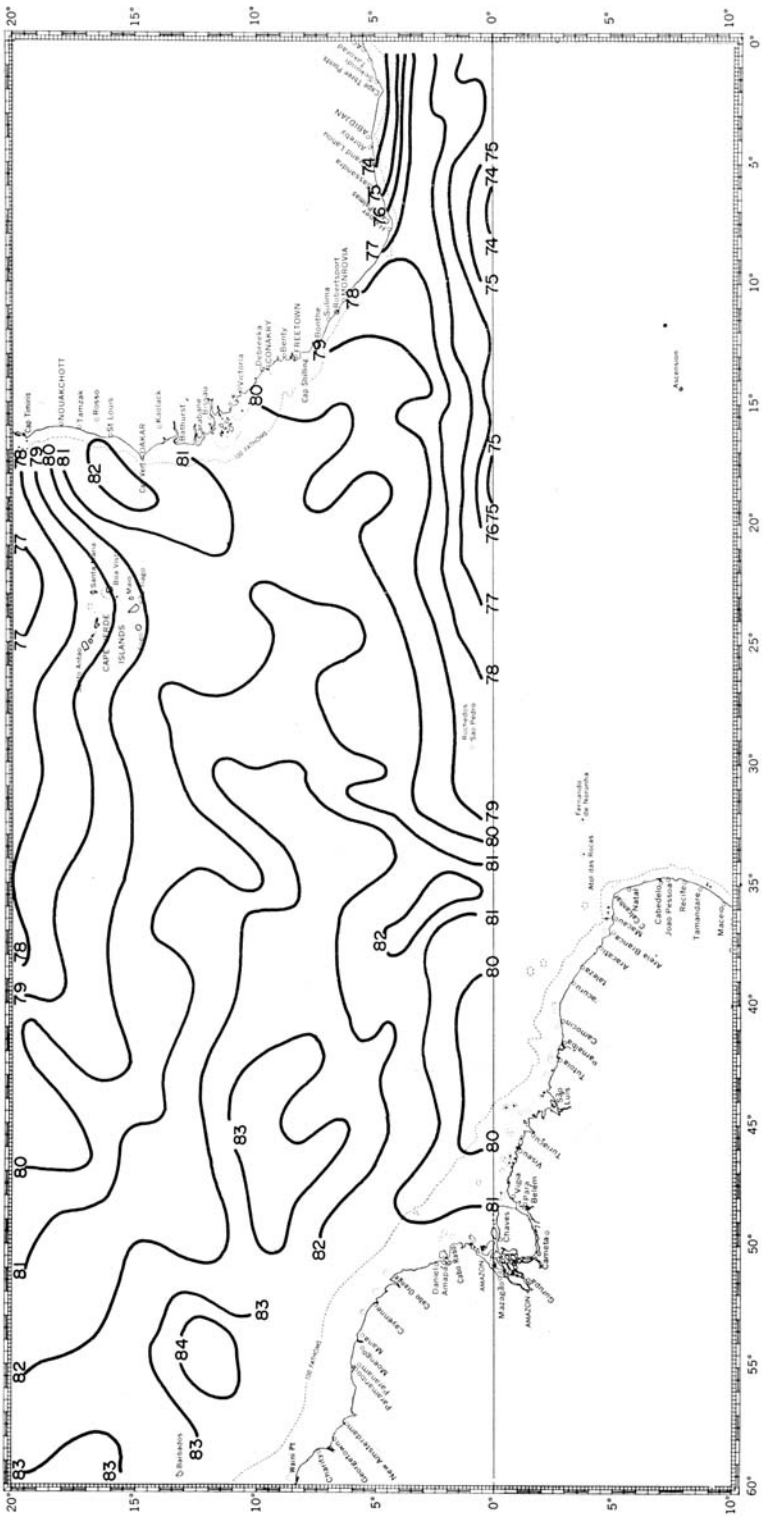

Fig. 4. Historical September sea surface temperature chart.

Atlantic Countercurrent is represented on the 3-month current analysis. The July monthly sea surface temperature analyses (Figure 2) show the mean position of the warmer water displaced to the south of 10° N latitude, somewhat further south than shown on the surface current depiction in Fig. 1. The southward displacement of the warm water noticeable in the July versus the September sea surface temperature analyses is accounted for by the early summer seasonal effect. With the progression of the summer season, the extent and northward shifting of the warm countercurrent water are noteworthy.

In general, the warmest surface waters lie in the western portion of the Equatorial Atlantic (west of 35° W), as can be seen in the analyses shown in Figs. 2, 3, and 4. The surface thermal limits along the boundaries of the countercurrent are well defined in the north and south directions.

As indicated earlier, the mean position of the cyclonic shift axis between the Equatorial Countercurrent and the North Equatorial Current defines the mean position of the ITC zone. The area of maximum cloudiness and convective shower activity (doldrum belt) also coincides with the warm surface countercurrent waters. The northward shifting of this doldrum belt coincides with the northward displacement of the warm surface waters.

A secondary area of relatively high sea surface temperatures occurs off the coast of Dakar during the same three months. These warmer surface waters in the eastern Equatorial Atlantic appear to be caused by at least two factors: First, by a northward transport of surface waters from the region of the Equatorial Countercurrent; and second, by the warming effect of the southerly summer monsoon. These warmer waters, Figs. 2, 3, and 4, show a gradual northward displacement. The maximum northward flow occurs during September.

The effect of the North Equatorial Current can be seen in the sea surface temperature field. The North Equatorial waters at the surface are relatively cooler (by several degrees F) than the waters of the Equatorial Countercurrent. The strongest surface thermal gradient occurs in July when the temperature contrast between the North Equatorial water and the Countercurrent is greatest. This can be seen by the progressive decrease of surface temperature with latitude north of 10° N (Fig. 2). The effect of surface heating during the summer months reduces the gradient zone appreciably by September (Fig. 4). The cooler waters associated with the North Equatorial Current are caused by the convergent flow of the prevailing northeasterly winds and the high surface evaporation resulting from this flow. The coolest water is still evident in the eastern part of the Equatorial Atlantic in the North Equatorial Current.

The southern boundary of the Atlantic Surface Countercurrent is also characterized by a relatively cool water flow. This cooler water, associated with the South Equatorial Current, is caused by the displacement of waters from the South Atlantic. During the summer months, a southeasterly flow of rather high constancy prevails. The cool waters associated with the South Equatorial Current (5° N southward) are characterized by a minimum of cloudiness and a relatively high evaporation rate. Figs. 2, 3, and 4 relate the northward extent of the cool South Atlantic water with the most pronounced surface thermal gradients in the central and eastern equatorial regions.

The mean sea surface temperature profiles, as will be seen later, have an integral effect in relating areas in the Equatorial Atlantic where tropical storms reach hurricane intensity. However, the absolute values of sea surface temperatures depicting warm and cool water masses must be related to the vertical extent of these water masses. The thermal structure in the Equatorial Atlantic to a large extent inhibits and/or enhances the potential development of tropical storms to hurricane intensity.

Thermal structure

Perlroth (1967) indicates that in given oceanographic areas a unique relationship prevails between sea surface temperature patterns and the corresponding vertical temperature gradient profiles. The analysis of surface currents and the related surface temperatures delineates the distribution of thermal structures for the Equatorial Atlantic.

Along the zone of cyclonic current shift (between the North Equatorial and Equatorial Countercurrents) is a shallow layer of surface convergence. This downwelling of surface water is restricted to the first 20 to 40 feet of water. Beneath the shallow layer of convergence seems to be an area of subsurface divergence which accounts for pronounced vertical temperature gradients with depth in the eastern part of the Equatorial Atlantic. Fig. 5 depicts this strong vertical temperature gradient zone between the surface and the 200-foot depth. These differences of vertical temperature gradients were obtained from historical bathythermographs for the summer season summarized by a 1-degree square grid.

The surface water mass profile along the cyclonic current shift zone and in the northern two-thirds of the Equatorial Countercurrent is characterized by an extremely shallow mixed surface layer (20 to 40 feet). Just beneath the mixed layer, the temperature decreases rapidly with depth. Temperature decreases in the magnitude of 20 to 25°F are noteworthy within the first 200 feet. The area of maximum vertical temperature decrease (Fig. 5) lies on either side of the surface cyclonic current shift and is most pronounced to the south. Wyrtki (1966) found a similar relationship in the vertical temperature gradient structure in the eastern Equatorial Pacific between the North Pacific Equatorial Current and the Pacific Countercurrent.

A marked change in the thermal structure of the water mass in the Equatorial Atlantic is evident north of 15° N, as noted by the temperature gradient distribution in Fig. 5. The effect of the change in thermal structure causes the transition from countercurrent water into the North Equatorial water. The high constancy of the northeasterly trade winds during the summer months effects a piling up of the surface waters (net convergence) as indicated by Neumann (1965). The thermal structure profile relates mixed surface waters of 150 to 250 feet. As will be shown later in the section on environmental effects on hurricanes, the North Equatorial water mass appears to have the necessary heat potential to develop tropical storms to hurricane intensity. The western part of the area appears most suitable for hurricane development.

In the southern sector of the Equatorial Countercurrent adjacent to the South Equatorial Current, a surface divergent flow is evident in the near surface waters. However, a net convergent flow exists in the subsurface waters, establishing a relatively deep mixed layer profile. The cool waters associated with this South Equatorial Current attain isothermal structure from the surface to 200–300 feet.

Equatorial Atlantic hurricanes and their relationships with the oceanographic environment

Studies on the effect of the ocean-atmosphere interface have only recently been carried out on a synoptic scale. Previous studies on the climatology of the oceanographic environment have been so generalized that the application to meteorological models was very limited. Leipper (1967) indicates in his study of oceanographic conditions immediately after the passage of hurricane Hilda (1964) that a synoptic oceanographic platform was used to make observations of the waters in the Gulf of Mexico.

Historical averages of sea surface temperatures in this study area have related a rather uniform horizontal temperature field during the summer months. The refinement of a detailed grid (1° square) has enabled a greater degree of resolution in the analyses of sea surface temperature data. The model approach presented in this study may be applicable to any ocean area describing pronounced or established current profiles. The analyses of the surface current profile are extremely important in understanding the influence of the surface structures on the vertical water mass profile.

Fig. 6, prepared by Dunn and Miller (1960), depicts locations where tropical storms attained hurricane intensity. The storms studied represent all historical August and September hurricanes from 1901 to 1965. Superimposed upon hurricane intensity locations in Fig. 6 are isopleths of selected vertical temperature gradients (Fig. 5). From inspection, one can relate the correlation between small vertical temperature decreases and the high frequency of hurricane occurrence (Fig. 7). The average ΔT gradient by 1° square for the summer season is compared to the estimated locations of hurricane intensity. As indicated by Dunn and Miller (1960), some of the locations of tropical storms reaching hurricane intensity are questionable; however, Fig. 6 can be used as a good reference to describe various influences and effects in the oceanographic environment. As indicated earlier, the influence of atmospheric

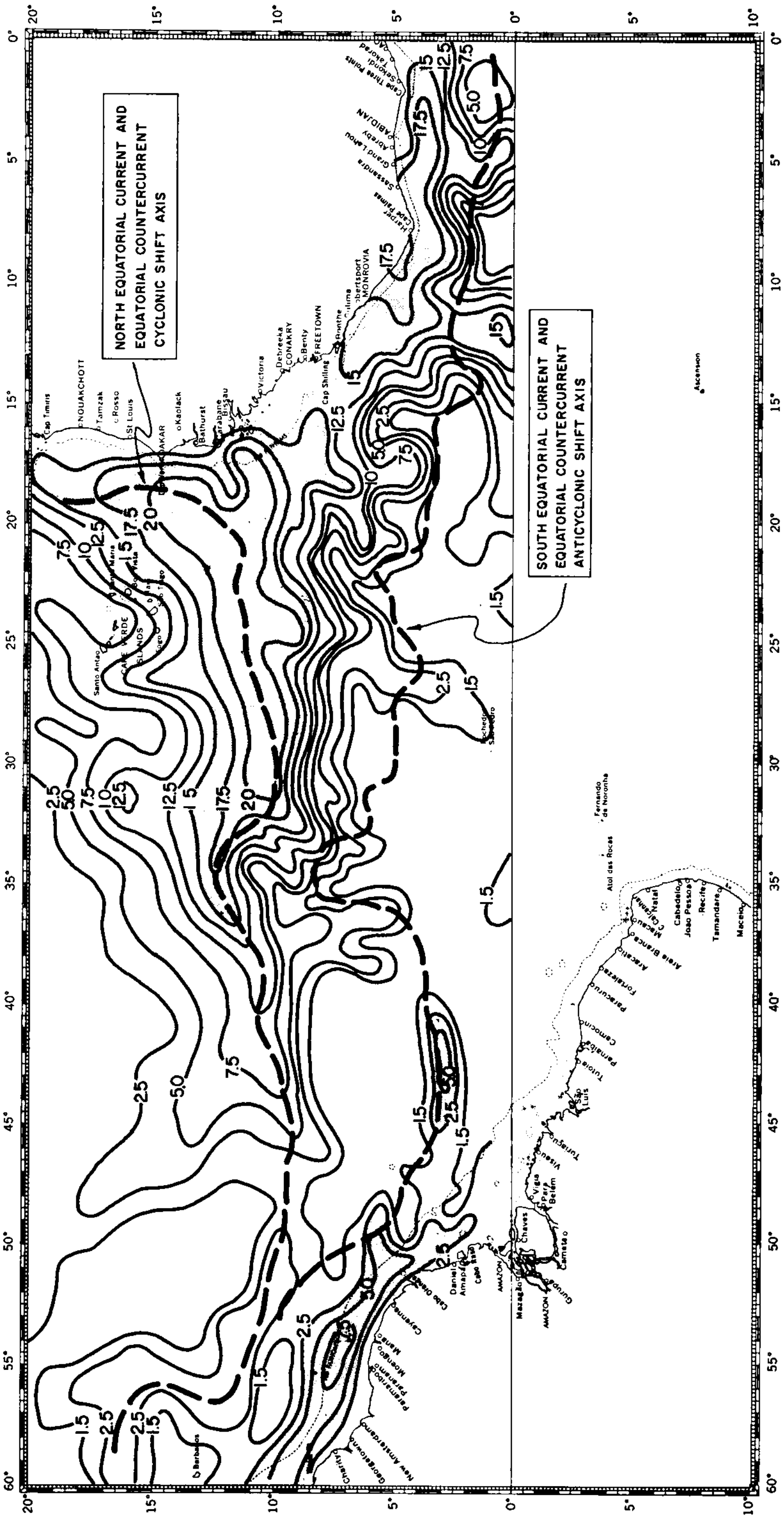

Fig. 5. Historical vertical temperature difference chart (surface – 200 feet) for July, August and September (temp. °F).

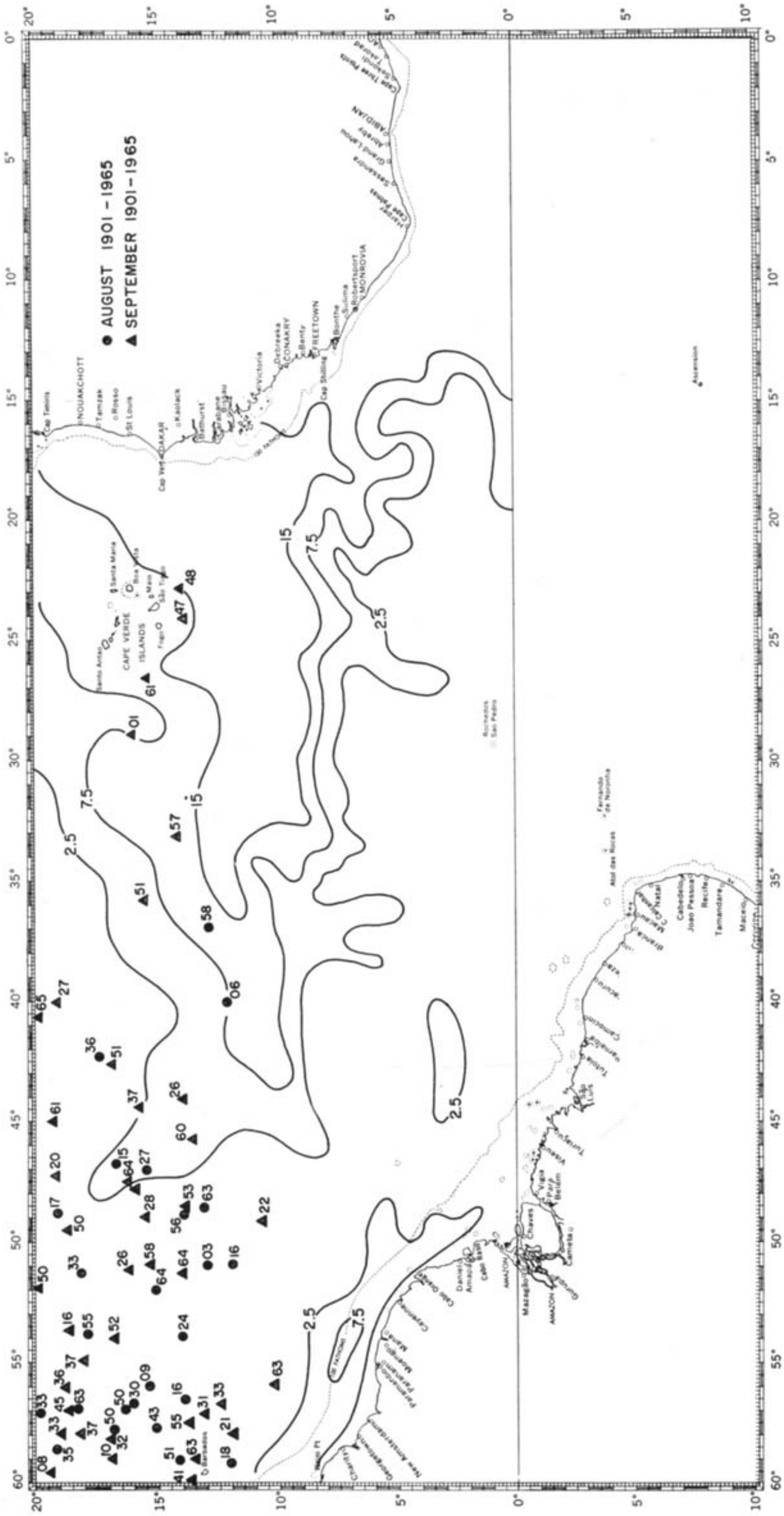

Fig. 6. Locations of August and September tropical storms reaching hurricane intensity.

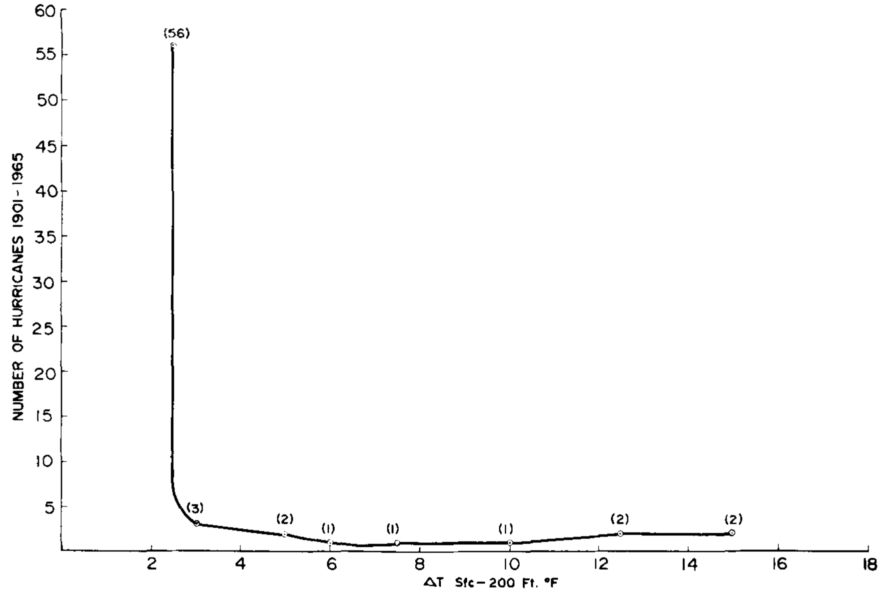

Fig 7. Effect of ΔT on hurricane frequency.

processes in hurricane formation has been neglected in this study, although it is apparent that in the initial development of tropical storms and/or depressions into hurricanes these processes cannot be divorced. However, this study is only intended to emphasize the effects of the near surface oceanographic environment to hurricane generation.

From 1901 to 1965, 68 hurricane cases were compared to the average thermal structure profiles in this study area. Approximately 87 per cent of tropical storms reaching hurricane intensity did so when the average ΔT vertical temperature gradient was 3°F or less. Over 92 per cent of all historical tropical storms in this study area reached hurricane intensity when vertical temperature differences (surface to 200 feet) were 7°F or less. Conversely, when ΔT gradients of 15°F or greater were evident from the surface to 200 feet, only 3 per cent of the tropical storms reached minimum hurricane intensity. As indicated by Perlroth (1967), there appears to be a relationship between the hurricane intensity and the thermal structure of the water masses over which the hurricane passes.

Upon inspection of the data and the analyses presented in this study, the western half of the Equatorial Atlantic has a much greater frequency of hurricane occurrence than does the eastern half. At the height of the hurricane season in the Equatorial Atlantic (September) the mean sea surface temperatures in the eastern and western sectors of this study area do not differ markedly. The mean sea surface temperature structure may suggest areas of maximum hurricane occurrence; however, the vertical thermal structure of the area relates a much greater significance. This is evident when one considers the water mass structure of the eastern part of the Equatorial Atlantic. The September position of the cyclonic current shift, ITC zone, and warm surface waters is just to the west of Dakar, West Africa. Although surface water temperatures reach 82°F in September, just beneath this warm layer (20 to 40 feet) is a very cool body of water.

History has shown that many tropical depressions and/or storms develop in this region; however, very few attain hurricane intensity. When tropical storm development occurs in the warm surface waters over this strong vertical temperature gradient zone, the oceanographic influence relates its effect. The mechanical mixing of the surface waters caused by wind action results in marked cooling of the surface waters. The amount of latent heat released in a storm is a function of the water vapor and

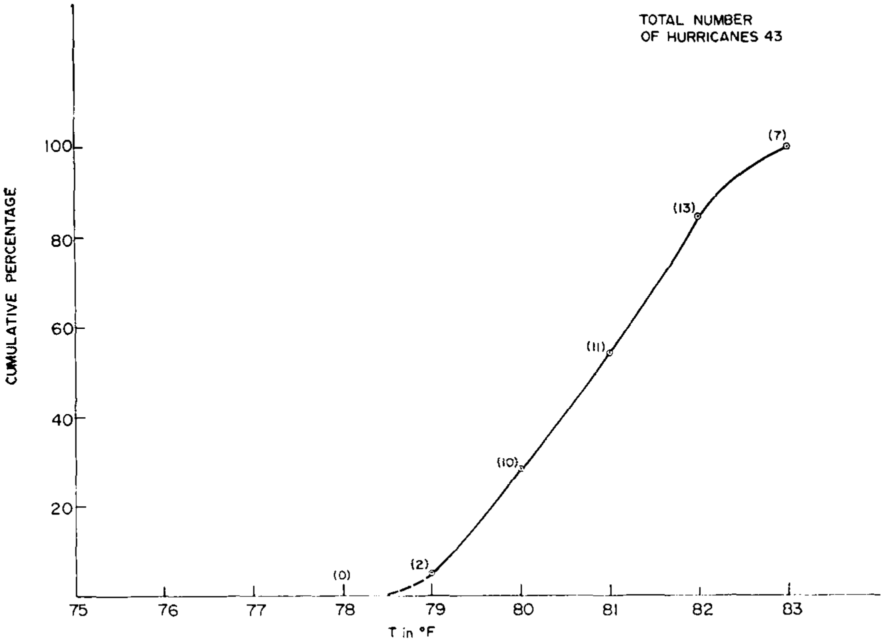

Fig. 8. Temperature at which August tropical storms reach hurricane intensity.

sensible heat available in the lower layers of the atmosphere. The role of sensible heat transfer in the formative and developing stages of tropical disturbances is a critical one. Consequently, a tropical storm that forms off the west African coast and moves westward rarely increases in intenstiy until the storm, if maintained, reaches an area of thermal structure more favorable (north of 15° N and west of 35° W) for development. This is evident from Fig. 6 which shows a low occurrence of hurricanes in the eastern Equatorial Atlantic.

It has been frequently stated that hurricanes form over warm tropical waters, when the water temperatures exceed 79°F. It is interesting to relate the average historical sea surface temperatures for the 68 cases of hurricane occurrence in this study area. Figure 8 shows the sea surface temperature at which August tropical storms reached hurricane intensity. One tropical storm out of the 25 which occurred in August reached hurricane intensity when the sea surface temperature was 79°F. There were no cases of tropical storms reaching hurricane intensity when the sea surface temperature was less than 79°F. Fig. 8 shows that 96 per cent of the August tropical storms reached hurricane intensity when the sea surface temperature exceeded 79°F. A similar relationship is shown in Fig. 9 for the historical September cases. No hurricane formation occurred in September when the sea surface temperature was less than 79°F, while 95 per cent of the storms reached hurricane intensity when the sea surface temperature exceeded 79°F. The sea surface temperatures at the estimated hurricane locations for the August and September months are mean temperatures in an undisturbed state. It is apparent that actual sea surface temperatures within the area of hurricane force winds may be several degrees lower than the critical temperature mentioned above. This is implied from the results of Leipper's (1967) study of the Gulf of Mexico. The amount of cooling of the surface waters immediately after hurricane passage is a function of storm intensity, forward progress, and the potential thermal structure of the oceanographic environement.

The oceanographic effects on hurricane intensity are related in Figs. 10 and 11. The average wind speeds plotted for these figures were obtained from the annual tropical storm reports. In most cases presented (1960–1965), when the vertical temperature differences be-

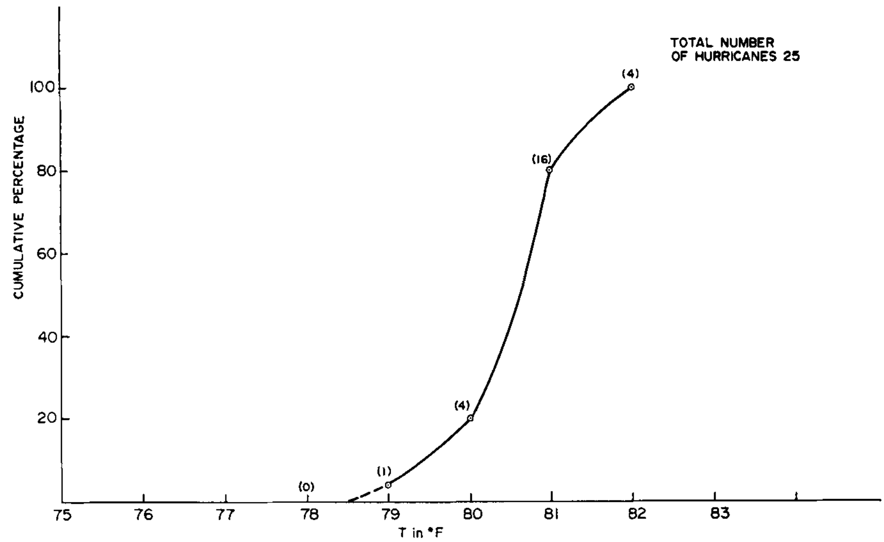

Fig. 9. Temperature at which September tropical storms reach hurricane intensity.

tween the surface and the 200-foot depth decreased, the wind speed (intensity) increased.

Tropical storm Debbie (1961) developed in the eastern Equatorial Atlantic, in an area where the mean sea surface temperature averaged 80°F. The ΔT approximated 12.5°F. Maximum intensity was reached when the ΔT (surface to 200 feet) was 7°F. Reconnaissance

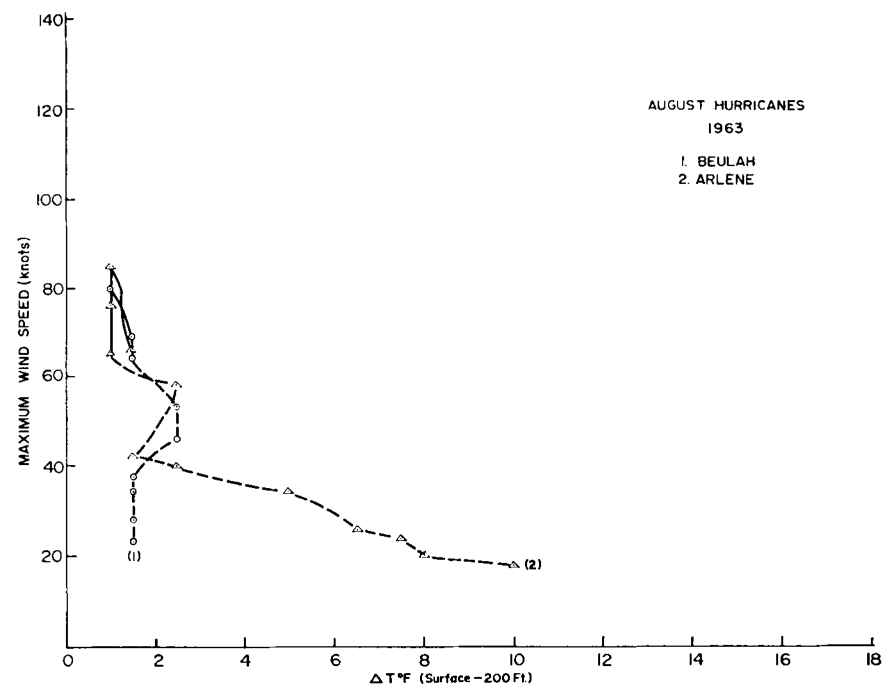

Fig. 10. Effect of ΔT on wind speed of August hurricanes (1960–1965).

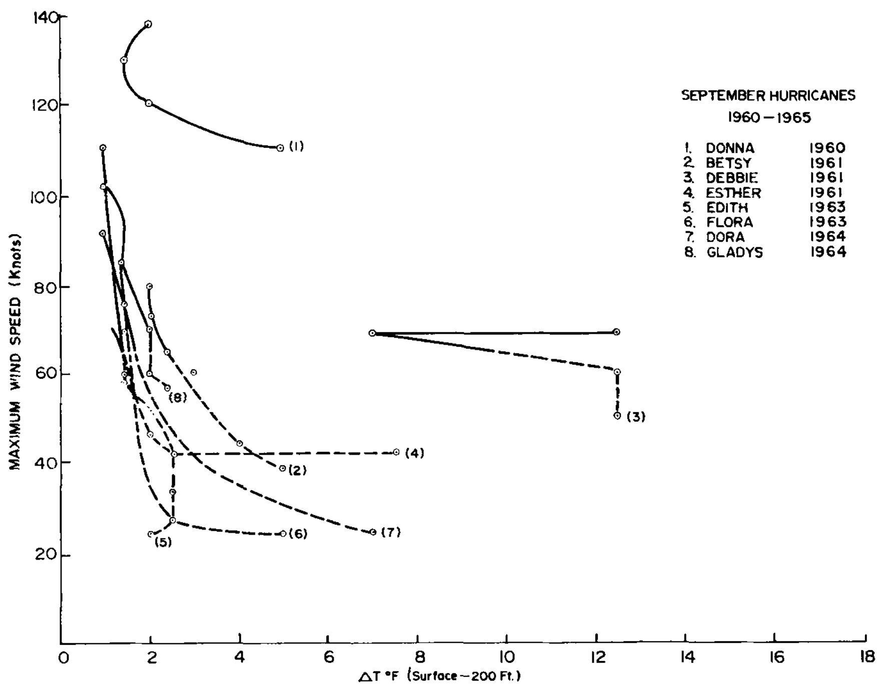

Fig. 11. Effect of ΔT on wind speed of September hurricanes (1960–1965).

flights were not attempted in this storm owing to the great distance from landbased aircraft. Consequently, wind determinations for this storm were made by satellite photography. Deepening of the hurricane ceased as the storm veered north and northeastward over a water mass profile not potentially suitable for intensification. In the 10 cases presented from 1960 to 1964, the heat source of the oceanographic environment contributed to a significant increase in storm intensity.

Conclusions

An attempt has been made to relate various averaged oceanographic parameters to areas where tropical storms reach hurricane intensity. Although this is a historical and climatological study, the results presented here may serve as potential models for future synoptic air-sea interaction programs. As already emphasized, there appears to be substantial evidence of the oceanographic influence on hurricane development and/or intensity.

This study also identifies the need for a related synoptic meteorological-oceanographic network, which could greatly assist the meteorologist in better understanding some of the complexities inherent to tropical storm formation and/or development. The knowledge of the thermal structure and water mass characteristics can serve as an important tool in understanding the life cycle of the hurricane.

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ЭФФЕКТ ОКЕАНОГРАФИЧЕСКИХ УСЛОВИЙ НА УРАГАНЫ В ЭКВАТОРИАЛЬНОЙ АТЛАНТИКЕ

В данном исследовании делается попытка определить взаимосвязь между тропическими штормами, которые достигают ураганной интенсивности, и средними условиями, соответствующими окружающей океанографической обстановке. Исторический анализ вертикального температурного градиента в Экваториальной Атлантике (июль–сентябрь) в слое высотою в 200 футов от поверхности моря указывает на благоприятные и неблагоприятные возможности в океанографической среде для интенсификации тропических штормов в ураганы. Представлены карты, описывающие местонахождение и число тропических штормов, которые достигали ураганной интенсивности в течении 1901–1965 гг. Приблизительно 4% всех тропических штормов достигает ураганной интенсивности, когда разница температур по вертикали между поверхностью моря и уровнем высотою в 200 футов составляла 7°F или меньше. Только 4% всех тропических штормов достигает ураганной интенсивности, когда разница температур по вертикали в нижнем слое высотою в 200 футов от поверхности океана превышает 15°F. Спутниковые данные и данные самолетных исследовательских полетов о тропических штормах в Экваториальной Атлантике за период 1960–1965 гг. показывают аналогичную связь с океанографической средой.