CHAPTER 9

A History of Hurricane Forecasting for the Atlantic Basin, 1920–1995

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Introduction

Whether measured in terms of loss of life or property damage, tropical cyclones are among the world's costliest natural hazards (White 1994). Hebert et al. (1993) have shown that the loss of life in the United States from tropical cyclones has dramatically decreased in the last century, even though the number of people at risk and the economic losses have increased. However, they also stress that large loss of life in the United States from tropical cyclones is still possible. The decrease in fatalities is largely due to improvements in hurricane forecasts and warnings. In this paper the history of hurricane forecasting from the time of the establishment of the American Meteorological Society (1920) to the present will be reviewed. Although tropical cyclones are natural hazards in many parts of the world, the focus of this review will be on forecasting of tropical cyclones in the Atlantic basin, which includes the North Atlantic, Caribbean, and Gulf of Mexico.

At the present time, the National Hurricane Center (NHC, renamed the Tropical Prediction Center in 1995) in Miami, Florida, has responsibility for tropical cyclone forecasts and warnings out to 72 hours for the Atlantic and eastern North Pacific basins, and the Central Pacific Hurricane Center (CPHC) in Honolulu, Hawaii, has the responsibility for the North Pacific from 140°W to the date line. Prior to 1988, the Weather Service Forecast Office in San Francisco, produced the forecasts for eastern North Pacific tropical cyclones. The forecast and warning process requires a coordinated effort between several agencies and involves many meteorological and nonmeteorological factors (Sheets 1990). A distinction is made between the estimation of the current and future storm track and intensity (forecasting) and the communication of this information to emergency managers and the public so that appropriate action will be taken

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(warning). In this paper, the emphasis will be on the history of forecasting, although some discussion of the warning process will also be included.

In the Atlantic basin, tropical cyclones with 1-min maximum sustained surface winds >33 m s^{-1} are referred to as hurricanes. Historically, much of the loss of life and property damage has resulted from hurricanes of category 3 or greater (maximum winds >50 m s^{-1}) on the Saffir–Simpson scale (Hebert et al. 1993). Occasionally, however, extensive damage occurs from less intense tropical cyclones, due to inland flooding (e.g., Hurricane Diane in 1955 and Tropical Storm Alberto in 1994). The warning and emergency response procedures vary greatly depending on the storm intensity at landfall. However, the forecasting methods are very similar for hurricanes and weaker tropical cyclones. For simplicity, the forecasts for all tropical cyclones will be referred to as hurricane forecasts.

The methods for hurricane forecasting have undergone substantial changes during the past 75 years. Many of these changes can be attributed to technological advances such as the implementation of the upper-air network in the late 1930s, the establishment of routine aircraft reconnaissance in the 1940s, the advent of numerical weather prediction beginning in the 1950s, and the availability of satellite observations starting in the 1960s. The agencies responsible for producing the forecasts have also undergone considerable evolution since 1920. For organizational purposes, the 75-year history is divided into several smaller time periods as shown in Table 9-1. The boundaries of these periods loosely correspond to times when significant changes in hurricane forecasting procedures occurred.

TABLE 9-1. Organization of the history of hurricane forecasting.

Time period	Description
1920–1934	Hurricane diagnosis and extrapolation
1935–1942	The use of upper-air data and forecast office reorganization
1943–1955	Technological advancements: aircraft reconnaissance and radar
1956–1965	Increased research efforts and the development of objective forecast methods
1966–1973	The use of satellite observations and improved forecast models
1974–1987	Geostationary satellites and three-dimensional forecast models
1988–1994	Increased interaction with the research community and the use of global model output
1995–2005	Present status and future outlook

1920–1934, Hurricane diagnosis and extrapolation

At the beginning of this period (1920) hurricane forecasts and warnings for the United States and surrounding areas were the responsibility of the U.S. Weather Bureau in Washington, D.C. This responsibility had been transferred from Havana, Cuba, in 1902 (Calvert 1935). Considerable effort was required to diagnose the current position and intensity of a storm. Calvert (1920) made an analogy between the work of a forecaster and that of a physician. He stated that,

> The means of detecting the beginning of hurricanes . . . can be compared to a physician who diagnoses a case in which there is menace and death to his patient by symptoms that he recognizes because of his technical skill and experience. . . . The forecaster has less than the physician on which to base his diagnosis, oftentimes a single wireless report of weather conditions from a vessel at sea or a land station a hundred miles or more from the storm center.

Despite this difficulty, Calvert (1920) stated that hurricanes rarely occurred without being detected. The primary tools for diagnosing hurricanes were reports from ships at sea and from surface stations in the tropical and subtropical regions. The tides and sea swells at coastal stations were also closely monitored for signs of approaching storms (Cline 1926). Except for an occasional pilot balloon, there was very little direct information about the upper-air conditions (Bowie 1922). However, based upon the work of Father Benito Viñes in the late nineteenth century, indirect information was obtained from the motion of upper- and lower-level clouds (Mitchell 1924).

Knowledge of tropical cyclone structure was fragmentary during this period. The structure of the low-level circulation, including the approximate scale of the outer wind field and the existence of the hurricane eye, was fairly well known (Bowie 1922). Until the mid-1930s, however, there was some uncertainty concerning the vertical structure of storms (Haurwitz 1935). Hurricanes were often described as "flat" systems, suggesting they were confined to the low levels.

The climatology of the formation regions of Atlantic hurricanes was well documented by Mitchell (1924), but considerable disagreement existed concerning the mechanisms responsible for storm formation (Tannehill 1938a). In a review of recent scientific studies, Bowie (1922) summarized two theories of tropical cyclone formation. One theory, referred to as the "convectional hypothesis," suggested that tropical cyclones form when air becomes warm and moist on a large scale. This air rises, which forces horizontal convergence and rotation due to conservation of angular momentum on the rotating earth. As part of this theory, it was suggested that tropical cyclone formation is a relatively rare event because uplifting usually occurs on smaller scales in the Tropics, leading to more isolated thunderstorms. A second theory, referred to as the "countercurrent hypothesis," suggested that atmospheric vortices form along discontinuities between different air masses. In the case of Atlantic tropical cyclones, the discontinuity was the doldrum trough [also referred to as the intertropical convergence zone (ITCZ)] between the northeast and southeast (or sometimes southwest) trades found off the coast of Africa during the peak of the hurricane season (August and September) and in the western Caribbean early and late in the hurricane season. In the western North Pacific, tropical cyclones typically form in the monsoon trough between the northeast trades and the southwest flow at lower latitudes. In a sense, both of these theories were partially correct. The convectional theory is consistent with the results of Pfeffer and Challa (1981) and Montgomery and Farrell (1993), which suggest that tropical cyclone genesis occurs when low-level circulation features interact with upper-level synoptic features in a way that enhances the vertical motion over a large area. However, much of the vertical motion occurs in smaller-scale convective elements rather than as one large-scale region of overturning as suggested by the convectional hypothesis. The countercurrent hypothesis is correct in the sense that the monsoon trough is the source of the low-level rotation for many west Pacific tropical cyclones. The doldrum trough (ITCZ) and frontal discontinuities are the source of the rotation for some Atlantic storms, although easterly waves are more commonly involved in the formation of Atlantic tropical cyclones (Avila and Clark 1989).

The climatology of the motion of Atlantic storms was also well documented by Mitchell (1924), but factors affecting storm motion were not completely understood, primarily due to the lack of upper-air data. A large emphasis was placed on the movement of anticyclones to the north of Atlantic hurricanes. It was generally recognized that hurricanes tend to move out of the tropical and subtropical regions unless a large anticyclone prevented the storm from moving north. For example, Mitchell (1924) stated that hurricanes "seek to move northward at the first available opportunity." For this reason, the movement of anticyclones in relation to the hurricane track was closely monitored as part of the forecasting process (Bowie 1922). Although it was recognized that the flow around an anticyclone must extend above the surface in order to influence the motion of a storm, the extent to which the upper-level flow affected storm motion was not fully appreciated.

Hurricane forecasts during this time were limited to short-range extrapolations (12–24 hours) of current storm positions and trends in motion, with some modifications to take into account large-scale pressure patterns and limited pilot balloon and upper-level cloud observations. As an example of the level of forecast skill during this period, consider the hurricane that struck Miami, Florida, on the morning of 18 September 1926. According to the best-track data from a poststorm analysis of all available information maintained by NHC (Jarvinen et al. 1988), this storm made landfall in Miami just before 1200 UTC (0600 EST) with maximum sustained winds of ~62 m s^{-1} (120 kt). The landfall of the 1926 storm had many similarities with Hurricane Andrew, which made landfall just south of Miami in the early morning of 24 August 1992 with maximum sustained winds of ~64 m s^{-1} (125 kt). The tracks of the 1926 Hurricane and Hurricane Andrew are shown in Fig. 9-1.

According to Mitchell (1926), the 1926 hurricane was first detected

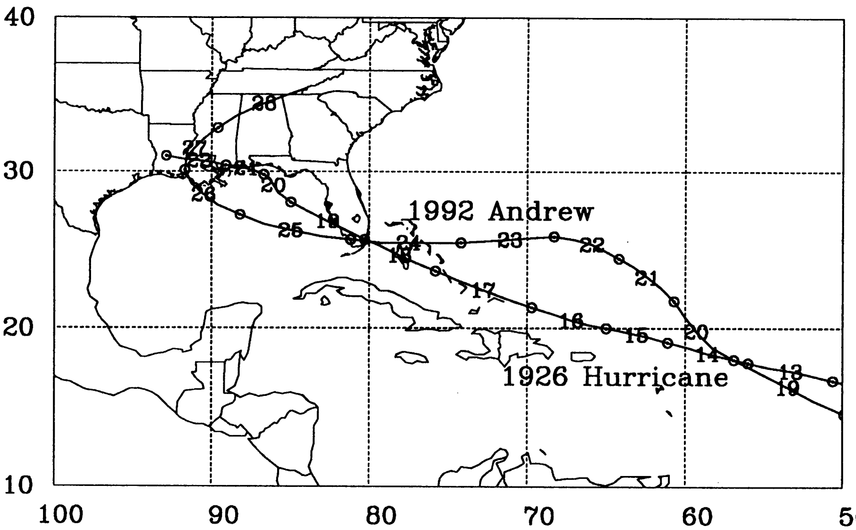

FIG. 9-1. The tracks of the 1926 south Florida Hurricane and Hurricane Andrew (1992). The open circles are the positions at 1200 UTC, and the days of the month (September 1926 or August 1992) are indicated at the 0000 UTC positions.

on 14 September, east-northeast of Puerto Rico. At this time, there was also a hurricane just southwest of Bermuda and a tropical storm moving north over central Cuba. The storm near Bermuda moved to the north in the next few days, but the storm near Cuba moved north over the Bahamas and then turned to the southwest just off the south Florida coast. The latter storm dissipated in the Florida Straits by 17 September (just one day before the 1926 hurricane made landfall). As the 1926 hurricane approached south Florida, the Weather Bureau issued northeast storm warnings (gale warnings) at noon on 17 September (18 hours prior to landfall) from Jupiter Inlet to Key West. The warning message also stated that "this is a very severe storm" and that "precautions should be taken for strong winds Saturday morning" (18 September). However, hurricane warnings were not issued until midnight on 17 September (6 hours prior to landfall).

Historical descriptions by Parks (1986) and Doehring et al. (1994) indicate that the 1926 hurricane took many residents of south Florida by surprise. Contributing factors were that the hurricane warnings were issued after many people had gone to sleep and that many of the residents at that time had not experienced a major storm. The weak tropical system that passed just to the south of Miami the previous day also added to the confusion. The morning edition of the Miami newspaper on 17 September 1926 included a 4-in. story on page one under the heading "Hurricane Reported." However, the editors added that it was not expected to hit Florida. The afternoon paper placed a greater emphasis on the hurricane and included a front-page headline "Miami Warned of Tropical Storm" but did not mention hurricane warnings since none had been issued at the time of publication.

In contrast to the 6-h advance warning for the 1926 storm, a hurricane warning for Andrew was issued at 0800 EDT on 23 August 1992 (21 hours prior to landfall) from Vero Beach to the upper Florida Keys (U.S. Department of Commerce 1993a). A hurricane watch had been issued at 1700 EDT on 22 August (36 hours prior to landfall) from Titusville through the Florida Keys. On the morning of 23 August, the local Miami paper had a front-page headline that read "Bigger, Stronger, Closer." Based upon the author's experience on 23 August, it would have been very difficult to find a person in the south Florida area who was unaware that a hurricane was approaching. However, similar to the 1926 hurricane, a large fraction of the south Florida residents had never experienced a major storm. Thus, despite the effectiveness of the warnings, much of the population was still surprised by the devastating effects of the storm.

In addition to the 1926 hurricane, there were several other strong storms that hit with little advance warning during this period (U.S. Department of Commerce 1993b). A severe hurricane struck Florida in 1928, and about 1800 people drowned when Lake Okeechobee flooded. This storm was the second deadliest in U.S. history (Hebert et al. 1993). Dunn (1971) described another example of a difficult forecast situation. In August 1934 a tropical storm was approaching the upper Texas coast and the Weather Bureau in Washington, D.C., had issued a hurricane warning on a Sunday morning. When the Chamber of Commerce in Galveston wired the Washington office for an update that Sunday afternoon, the forecaster had left his shift (as was the usual procedure) and was scheduled to return in the early evening when more observations were going to be available. The map plotter on duty at the time wired back the comment, "Forecaster on golf course—unable to contact." Although the response was accurate, the Chamber of Commerce in Galveston was somewhat upset. As it turned out, the storm in question did not actually make landfall in Texas.

1935–1942, The use of upper-air data and forecast office reorganization

The growing dissatisfaction with the performance of the Weather Bureau in Washington, D.C., described in the previous section led Congress and the president to decentralize and improve the hurricane warning service (Calvert 1935; Sheets 1990). The forecast service in Washington, D.C., was continued; new centers were established in Jacksonville, Florida, and New Orleans, Louisiana; and a center was reestablished in San Juan, Puerto Rico. A center was also established in Boston, Massachusetts, in 1940. These centers were responsible for issuing warnings every 6 hours, seven days a week, from June to November. The Jacksonville office was the most complete center and had the largest area of responsibility (from Cape Hatteras, North Carolina, to Apalachicola, Florida, and most of the Atlantic). In addition to the new centers, a 24-h hurricane teletype network was set up from Wilmington, North Carolina, to Brownsville, Texas, to improve the distribution of observations and facilitate communications between forecast offices and field locations. In addition, arrangements were made for special ship observations during storm conditions. Because of these improvements, storms were no longer "lost" for up to several days at a time, as had occasionally occurred previously (Dunn 1940a).

Some important conceptual advances were made during this period. Using a theoretical argument based upon hydrostatic considerations, Haurwitz (1935) presented evidence that well-developed tropical cyclones extend through the depth of the troposphere. It was generally accepted that once a hurricane developed, it was maintained by the release of latent heat due to the convection near the storm center (Scofield 1938). McDonald (1942) presented a fairly accurate description of the life cycle of tropical cyclones that included a preliminary phase when a system first becomes organized, a deepening stage when most of the intensification occurs, an expanding stage where the storm increases in size but the maximum winds do not increase, and a declining stage when the storm dissipates. He also suggested that the maximum intensity of hurricanes is limited to a minimum pressure of about 880 mb (26 in.) and that thermodynamic factors are probably responsible for this limitation. To date, the minimum observed sea level pressure for an Atlantic hurricane is 888 mb, which occurred in Hurricane Gilbert (Willoughby et al. 1989a).

Although some aspects of hurricane evolution were understood, there were still some misconceptions about hurricane genesis. By the late 1930s the frontal theory of tropical cyclones had gained general acceptance (Scofield 1938), perhaps on the "coat tails" of the polar front theory of midlatitude cyclones that was making rapid advances during this time (Palmen and Newton 1969). However, this theory came into question as more observations became available. For example, Dunn (1940b) showed that Atlantic hurricane genesis commonly results from the amplification of "isallobaric" (easterly) waves that originate near the African coast.

Another important advancement was the use of upper-air observations. According to Dunn (1940a), the number of pilot balloon observations available in the Caribbean region increased dramatically during the late 1930s, primarily due to efforts by Pan American Airways. In addition, a few radiosonde sites had been established. By the late 1930s, upper-air winds were routinely plotted at 2000-ft intervals up to 14000 ft for hurricane forecasting purposes. It soon became apparent that knowledge of the upper-level flow was extremely useful for determining storm motion, and less emphasis was placed on surface pressure patterns in areas where upper-air data were available (Byers 1935; Dunn 1940a).

Despite the above advances, hurricane forecasting was far from perfect during this period. The upper-air data had a very limited area of coverage, and forecasters still relied heavily on extrapolation of intensity and position estimates based upon surface observations. These extrapolations were often hampered by incomplete information. For example, the hurricane that struck the Florida Keys in September 1935 with a minimum sea level pressure of 892 mb still holds the record for the most intense U.S. landfalling storm (Hebert et al. 1993). However, the only surface observation available to the forecasters just prior to landfall was from the southern Bahamas, which indicated a maximum surface wind of only $\sim$18 m s^{-1} (Burpee 1988). The warning message issued from the Jacksonville office just before landfall indicated that hurricane force winds *probably* existed in a small area near the center (McDonald 1935).

The lack of information near the storm center and the reliance on extrapolation also made it difficult to anticipate rapid changes in the storm speed or direction of motion. An extreme example of this problem is illustrated by the hurricane that struck New England in September 1938. As shown in Fig. 9-2, this storm moved from a location east of Jacksonville, Florida, to the coast of Long Island, New York, in less than 24 hours. According to Tannehill (1938b), this hurricane made landfall on the Long Island coast at about 1900 UTC 21 September and on the Connecticut coast 2 hours later. The Washington, D.C., forecast issued gale warnings at 1500 UTC for the coast from Virginia to New Jersey when the storm was off the Virginia coast but only 4 hours before its landfall on Long Island. The final warning was issued at 1900 UTC for the Long Island coast and Connecticut as the storm was making landfall on Long Island.

To put the forecasts for the 1938 storm in perspective, Fig. 9-2 also shows the track of Hurricane Bob, which made landfall on the Rhode Island coast at about 1800 UTC 19 August 1991 (Pasch and Avila 1992). Hurricane Bob also accelerated rapidly toward the north, although not quite as dramatically as the 1938 storm. At the time of landfall in Rhode Island, Bob was moving at $\sim$14 m s^{-1}, compared with a forward speed of $\sim$24 m s^{-1} when the 1938 hurricane made landfall in New England. These speeds were estimated from the 6-h best-track

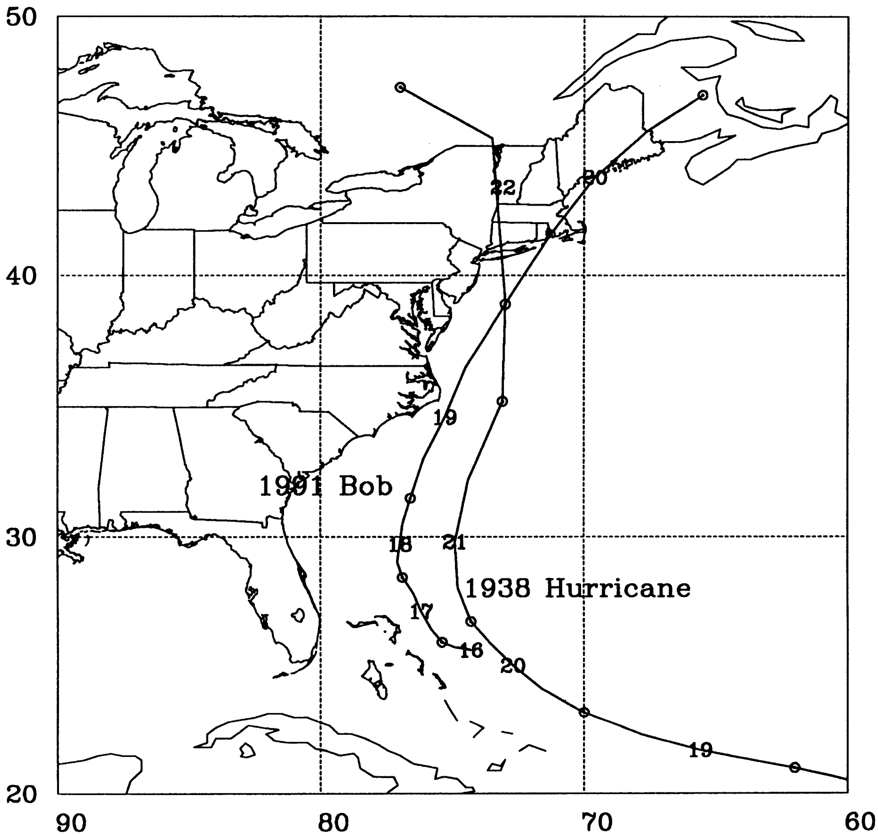

FIG. 9-2. The tracks of the 1938 New England Hurricane and Hurricane Bob (1991). The open circles are the positions at 1200 UTC, and the days of the month (September 1938 or August 1991) are indicated at the 0000 UTC positions.

positions. As described above, warnings for the 1938 hurricane were not issued for New England until just a few hours before landfall. In contrast, The NHC issued hurricane warnings for the region that included Rhode Island 20 hours prior to the landfall of Bob, when the storm was just south of Cape Hatteras, North Carolina (Pasch and Avila 1992).

1943–1955, Technological advancements: Aircraft reconnaissance and radar

At the beginning of this time period, the primary hurricane forecast office in Jacksonville was moved to Miami. The meteorologist in charge (MIC) of this office (which became the NHC in 1955) was Grady

Norton, who was previously in charge of hurricane forecasting at the Jacksonville office. Although Norton died before the Miami office officially became the NHC, he is generally regarded as the first NHC director (Sheets 1990). Norton was recognized for his excellent forecasting and communication skills (Burpee 1988). Considerable insight into the state of hurricane forecasting during this period can be gained from his unpublished soliloquy (Norton 1947). Gordon Dunn became the first official director of the NHC in 1955 (Burpee 1989).

A period of major advancement in hurricane forecasting started when Col. Joseph P. Duckworth completed the first intentional flight into the eye of a hurricane in July of 1943 (Markus et al. 1987). The U.S. Air Force and Navy began regular missions in 1944. Although hurricane forecasting in the Atlantic basin has greatly benefited from aircraft reconnaissance, the initial motivation for these flights came from the massive damage incurred by the U.S. Navy during World War II due to typhoons in the Pacific. The instrumentation and aircraft used for hurricane reconnaissance have varied considerably since 1943 (see Sheets 1990 for a thorough review), but the primary objective of documenting the current location and intensity of a storm has remained the same. As described by Norton (1947), "No forecaster can do much at hurricane forecasting unless he knows where his hurricane is and how intense it is, and there is no quicker way to find out than with aircraft." It is interesting that Norton also stated, "This (aircraft) is an expensive way to obtain reports." The debate over the cost–benefit ratio of aircraft reconnaissance continues today (Gray et al. 1991).

Another objective of the reconnaissance aircraft was to search for tropical disturbances via routine "synoptic track" flights when other observations such as ship reports suggested their existence. However, the advent of weather satellites in the 1960s and 1970s allowed more efficient use of the aircraft and, therefore, reduced the number required to collect needed data. For this reason it became more difficult to justify the cost of reconnaissance, and the U.S. Navy discontinued hurricane missions after 1974. At the present time, aircraft reconnaissance for the Atlantic basin is the responsibility of the U.S. Air Force Reserve at Keesler Air Force Base near Biloxi, Mississippi, and the National Oceanic and Atmospheric Administration's (NOAA) Aircraft Operations Center at MacDill Air Force Base in Tampa, Florida.

The development of meteorological radar also had an impact on hurricane forecasting. Although the radar echoes from precipitation were considered a nuisance in the development of military applications during World War II (Bigler 1981), it soon became apparent that radar could be a valuable meteorological tool. Early radar observations revealed the complicated structure of the inner core of hurricanes and documented the existence of spiral rainbands (Maynard 1945; Wexler 1947). In combination with early aircraft observations, it was discovered that the vertical motion in hurricanes occurs in a narrow band (the eyewall) near the storm center (Wexler 1945; Deppermann 1946). In 1955, a new radar was installed at Hatteras, North Carolina, and all three storms that made landfall in the United States that year passed within its range (Dunn and Miller 1960). Experience during this year demonstrated the usefulness of radar for tracking storms near the U.S. coast. [See chapter 4 by Rogers and Smith, this volume.]

As more accurate storm position and intensity estimates with higher time resolution became available, it was discovered that the intensity and track of the storm can vary more rapidly than was believed previously. For example, prior to 1943, it was generally accepted that once a storm attained hurricane intensity, it remained at hurricane intensity provided that it did not move out of tropical regions (Simpson 1966). In addition, small-amplitude track oscillations were observed by careful examination of aircraft (e.g., Horn 1951) and radar (Dunn and Miller 1960) observations. Modeling studies by Yeh (1950) and later by Kuo (1969) and others indicated that these small-amplitude track variations (often referred to as trochoidal oscillations) are due to internal processes near the storm center and are superimposed on the more smooth path due to large-scale "steering." Forecasting methods have been developed to help separate these trochoidal oscillations from the larger-scale motion of the storm (Sheets 1986).

Another important development during this period was the wartime expansion of the upper-air network through the implementation of radiosonde and rawinsonde equipment (Thompson 1961). Although the coverage in the Tropics was still somewhat meager, numerous synoptic analyses for storms near the U.S. coast and island stations were performed. Riehl and Shafer (1944) used upper-air observations to show that the recurvature of hurricanes is very sensitive to the movement and structure of upper-level troughs in the westerlies. These ideas led to the steering principle for track forecasting, where the winds at the "top" of the hurricane determine the future direction of storm motion (Norton 1947; Gentry 1951). Further studies (Riehl and Burgner 1950; Jordan 1952) deemphasized the use of a single level and advocated mass-weighted layer-mean winds as indicators of future storm motion. The observational study by Jordan (1952) confirmed the theoretical results of Haurwitz (1935), which showed that the hurricane circulation extends through a large fraction of the troposphere.

Synoptic studies also provided new insight into the formation and intensification of hurricanes. Palmen (1948) demonstrated that warm ocean temperatures (>26°C) are required to maintain tropical cyclones, and Riehl and Shafer (1944) indicated that storms do not intensify if the vertical shear of the horizontal wind becomes too large. In an analysis of the genesis of west Pacific storms, Riehl (1948) presented additional observational evidence that the frontal theory of tropical cyclone formation (the countercurrent theory described in the previous section) was not valid and stressed the importance of the interaction between low-level rotation and upper-level troughs.

Hurricane Hazel (1954) provides an example of the improvement of hurricane forecasting techniques during this period. The track of Hazel is shown in Fig. 9-3. As described by Dunn and Miller (1960), aircraft monitoring of Hazel began on 5 October 1954 and continued until the storm made landfall near the North Carolina–South Carolina border at ~1500 UTC 15 October. The aircraft observations documented the intensity and positions of Hazel, including the turn to the north on 10 October and the acceleration toward the north-northwest that began on 13 October. The 500-mb analyses were also used to forecast the turn toward the Carolina coast. Hurricane warnings for the North Carolina outer banks were issued at 1600 UTC on October 14 (23 hours prior to landfall), and gale warnings were issued from Charleston, South Carolina, to Wilmington, North Carolina. The hurricane warnings were extended southward to Charleston at 0700 UTC on 15 October (8 hours prior to landfall). The posting of hurricane warnings near the observed landfall point 23 hours in advance for Hazel is similar to the lead time of the warnings for Hurricane Bob in 1991 and Hurricane Andrew in 1992, described previously, and is a considerable improvement over the very short range warnings issued for the 1938 New England hurricane.

1956–1965, Increased research efforts and the development of objective forecast methods

In addition to Hurricane Hazel, five other significant hurricanes made landfall along the northeast U.S. coast in 1954 and 1955 (Carol

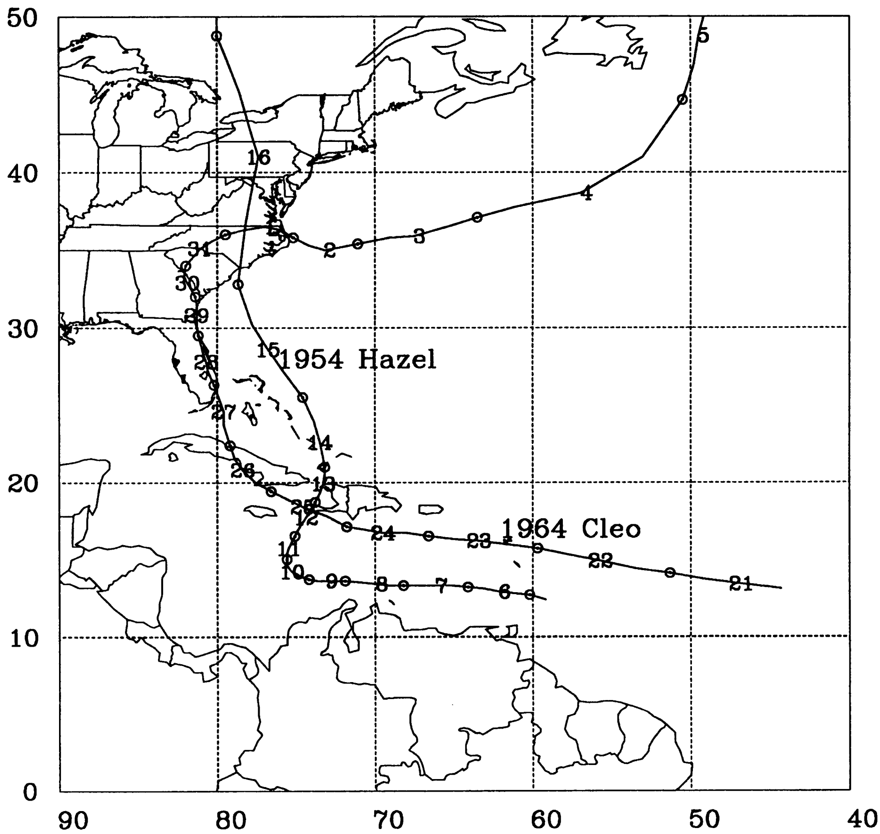

FIG. 9-3. The tracks of Hurricane Hazel (1954) and Hurricane Cleo (1964). The open circles are the positions at 1200 UTC, and the days of the month (October 1958 or August–September 1964) are indicated at the 0000 UTC positions.

and Edna in 1954; Connie, Diane, and Ione in 1955). Although the forecasts were reasonably good (Bigler 1981), the massive damage from these storms (Hebert et al. 1993) heightened the awareness of Congress and led to the formation of the National Hurricane Research Project in 1956 (NHRP Staff 1956; Simpson 1980). The initial goals of this project were to examine the structure of hurricanes and prehurricane disturbances and to determine important parameters for hurricane forecasting using data from instrumented aircraft and conventional sources. After organizational meetings in Washington, D.C., the operations base for NHRP was established in West Palm Beach, Florida. Three aircraft (two WB-50s and one B-47) were furnished by the U.S. Air Force and instrumented by Weather Bureau contractors. In

1959, NHRP was moved to Miami where it was collocated with the NHC. This project has undergone several name changes and reorganizations since 1956 and is currently known as the Hurricane Research Division (HRD) of NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML). Directors of HRD and its predecessor organizations include Robert H. Simpson (1956–1958), R. Cecil Gentry (1959–1974), Noel E. LaSeur (1975–1977), Stanley L. Rosenthal (1977–1992), Robert W. Burpee (1993–1995), and Hugh E. Willoughby (1995–present). The instrumented aircraft have also undergone considerable evolution since 1956 (Gentry 1980). In 1961, the Research Flight Facility (RFF), which maintained and operated the aircraft was separted from NHRP. HRD now uses NOAA's two WP-3D aircraft with sophisticated instrumentation systems including Doppler radar (Griffin et al. 1992). The WP-3D aircraft are operated by NOAA's Aircraft Operations Center. The NHRP and its offspring organizations have made numerous contributions to the hurricane forecasting problem and the general understanding of tropical cyclones. Gentry (1980), Marks (1990), and Burpee et al. (1994) summarize some of these contributions.

Another consequence of the landfalling storms in 1954–1955 was the expansion of the coastal radar network (Wells 1961). Following these storms, Congress appropriated funds for the installation of WSR-57 radars, which provided nearly continuous coverage for the coastal areas from Texas to Maine by the early 1960s (Sheets 1990).

Another important development was the introduction of objective hurricane forecast models. Riehl et al. (1956) described the first of these models, a statistical regression technique relating 24-h storm displacements to 500-mb geostrophic steering currents. By 1965, five other statistical prediction models were being used by NHC for operational track forecasting (Tracy 1966), many of which had been developed in cooperation with NHRP (e.g., Miller and Moore 1960). Statistical model development was also aided by interactions with the Travelers Weather Research Center (Neumann 1979) and the Spaceflight Meteorology Group (SMG), which provided meteorological support for the Apollo launches from Cape Canaveral. The SMG was collocated with NHC from the early 1960s to the early 1970s. Predictors of future storm positions included past motion of the storm (persistence), sea level pressure, 700- and 500-mb heights and tendencies, and 1000–700- and 700–500-mb thicknesses. Forecasts were made for periods up to 72 hours. Dunn et al. (1968) showed that the 24-h forecast track forecast errors were reduced by 10%–12% during the period 1959–1966. Dunn et al. (1968) also indicated that the use of objective forecast methods and the cooperation between researchers and forecasters were the primary reasons for the error reduction.

Parallel with the advancements being made in numerical weather prediction for the synoptic-scale flow (e.g., Schuman 1989), the Joint Numerical Weather Prediction Unit at the National Meteorological Center (renamed the National Centers for Environmental Prediction in 1995) was developing dynamical models for hurricane track forecasting. The first of these models was run operationally from 1956 to 1958 and tracked the streamfunction minimum in a barotropic prediction initialized with a conventional 500-mb height analysis (Hubert 1957). Due to inadequate resolution and the lack of observations in the Tropics, this model was replaced by a model where the storm circulation was removed from the initial condition (Vanderman 1961). In this case, the model was used to obtain the steering flow from which the storm track was determined. This model was later generalized to include the effect of the storm circulation on the steering flow (Vandermann 1962).

There was also a considerable research effort at the University of Chicago supported by the Weather Bureau that focused on numerical prediction of hurricane movement and intensification. Birchfield (1961) presented results from a relatively high resolution barotropic model that demonstrated the feasibility of hurricane prediction without removal of the vortex circulation. These results also indicated that the initialization of the model with vertically averaged fields is preferable to the use of a single level. Jones (1961) presented preliminary results from forecasts with a two-level model, and Kasahara and Platzmann (1963) described an elegant method for partitioning the vortex and large-scale circulation. Kasahara and Platzmann also explained the reason for the failure of earlier models that separated the vortex and larger-scale flows.

Despite the efforts described above, track forecasts from numerical models were generally inferior to those obtained using statistical methods (Tracy 1966; Miller and Chase 1966). For this reason, numerical prediction of hurricane tracks received little attention until the late 1960s (Sanders and Burpee 1968).

The importance of the ocean as an energy source for tropical cyclones became increasingly clear during this period. Fisher (1958) estimated the surface energy fluxes from the ocean and concluded that "the hurricane is a mechanism which massively siphons energy from the sea." Malkus and Riehl (1960) demonstrated the importance of the ocean for increasing the energy of low-level air spiraling into a storm. Miller (1958) introduced the concept that the ocean temperature controls the maximum possible intensity of tropical cyclones. He also showed that hurricanes rarely reach this theoretical upper bound and suggested that interactions with the large-scale environment probably limit the intensity of most storms. It was also becoming clearer that interaction with the large-scale environment, particularly in the upper levels, is important for hurricane genesis (Ramage 1959). Advances were also made in the understanding of the hurricane inner core, including the importance of the eyewall in the maintenance of the entire storm circulation (LeSeur and Hawkins 1963).

A storm that impacted forecasting methods during this period was Hurricane Cleo (1964), whose track is shown in Fig. 9-3. This storm formed from an easterly wave on 20 August 1964 and developed into a small but intense hurricane by 24 August. On 26 August the storm weakened as it crossed Cuba and then headed toward south Florida. Cleo was closely monitored by reconnaissance aircraft prior to reaching Florida and was under constant radar surveillance after it crossed Cuba (Dunn et al. 1965). The last aircraft left Cleo about 3 hours prior to landfall in Miami, having found a central pressure of 984 mb and no hurricane force winds on the western side of the storm. However, during the next 3 hours, the storm intensified rapidly and reached Miami with a pressure of ~967 mb. Sustained surface winds well above hurricane force were observed over land. Some of the forecasts prior to landfall in south Florida suggested that the center of the storm would remain just offshore, although, as described by Dunn et al. (1965), the storm was following a "mildly zigzag course." This "zigzag course" was probably a trochoidal oscillation that caused the storm to move more to the west than was predicted. This relatively small change in course, combined with the rapid intensification, resulted in much stronger effects from the storm than were anticipated. In hurricane warnings after Cleo, less emphasis was placed on the location of the exact center of the storm.

1966–1973, The use of satellite observations and improved forecast models

The potential of meteorological satellites for hurricane surveillance (e.g., Hubert 1961) and tropical analysis (e.g., Frank 1963) was demonstrated shortly after the launch of the first U.S. weather satellite (*TIROS-1*) in April of 1960. The beginning of the era where satellites were heavily relied upon for operational tropical analysis and forecasting followed the launch of *ESSA-1* and *ESSA-2* in February of 1966 (Sheets 1990). [See Chapter 5 by Purdom and Menzel, this volume.]

Another important advance was the continued improvement of statistical track forecast models. Hope and Neumann (1977) categorized these models as analog, simulated analog, statistical–synoptic, and statistical–dynamical. The analog technique, which uses information from previous storms to determine the future storm track, was applied in the HURRAN (hurricane analog) model (Hope and Neumann 1970). HURRAN became operational in 1968 and was run until the early 1990s. In some cases, it is not possible to find an historical analog. For this reason, Neumann (1972) developed the CLIPER (climatology and persistence) model, which uses climatological and persistence predictors to forecast the storm track. Because CLIPER includes information from previous storms but does not find specific analogs, it was categorized as a simulated analog model. CLIPER is still run at NHC and is often considered a benchmark for the evaluation of other models. If a model has smaller average errors than CLIPER, it is considered skillful (Neumann and Pelissier 1981a).

The statistical–synoptic and statistical–dynamical models are similar to the early regression models described in the previous section. Statistical–synoptic models combine current storm information and synoptic predictors. By the end of this period (1974), two models of this type were run operationally for storms in the Atlantic basin: NHC-67 (Miller et al. 1968) and NHC-72 (Neumann et al. 1972). Statistical–dynamical models include variables from numerical forecasts in addition to current storm information and synoptic predictors. The early attempts to use predictors from numerical forecasts were unsuccessful (Veigas 1966). This lack of success was attributed to the poor quality of the barotropic forecasts in low latitudes. The six-layer primitive equation model became operational at NMC in 1966, which led to improved forecasts of the 500-mb flow (Schuman 1989). In 1973, the first successful statistical–dynamical model became operational at NHC (Neumann and Lawrence 1975).

In the late 1960s, there was renewed interest in the development of numerical models for track forecasting. Under support from the National Hurricane Research Laboratory (formerly NHRP), a new barotropic model was developed at the Massachusetts Institute of Technology (Sanders and Burpee 1968). Special emphasis was placed on the analysis in the vicinity of the storm, and the large-scale flow was determined from a vertically averaged wind field. This model was nicknamed SANBAR (Sanders barotropic) and became operational in 1970 (Neumann and Pelissier 1981a). A number of modifications were made to SANBAR in later years (Sanders et al. 1975, 1980), and the model was used operationally until 1989.

During this time period, there was an apparent divergence of interests between the forecasting and research communities. Ooyama (1964) and Charney and Eliassen (1964) presented theoretical results, which suggested that the development of tropical cyclones could be explained by a cooperative interaction between the cumulus convection near the storm center and the larger-scale tropical cyclone circulation. This cooperative interaction is often referred to as conditional instability of the second kind (CISK). Ooyama (1969) and Yamasaki (1968) described numerical simulations that could simulate the life cycle of tropical cyclones including the mature stage. Following the publication of these papers, a considerable research effort was aimed at the numerical prediction of tropical cyclones (e.g., Rosenthal 1970; Anthes 1972; Kurihara 1975). Although these numerical modeling studies provided an increased understanding of tropical cyclones, they did not have direct forecasting applications. These models were either axisymmetric (due to computer limitations) or used idealized three-dimensional initial conditions, and the focus was often on the specific representation of cumulus convection (e.g., Rosenthal 1978; Anthes 1977). For a more detailed description of the early development of numerical hurricane models, see Anthes (1982).

Another problem that provided a research focus was Project STORMFURY, which was conducted from 1962 to 1983 (Willoughby et al. 1985). The purpose of this project was to determine if hurricanes could be modified by seeding the convective clouds in the eyewall or those surrounding the eyewall with silver iodide. This was a joint project by the Department of Commerce and the U.S. Navy and fulfilled one of the original goals of the NHRP (NHRP Staff 1956). As part of this project, four storms were seeded on a total of eight days during the period 1961–1971. Project STORMFURY ended as it became apparent that the microphysical requirements for seeding were usually not satisfied in hurricane convection. In addition, it was discovered that the natural evolution of the inner core of many intense hurricanes is very similar to behavior expected from seeding (Jordan and Schatzle 1961; Willoughby et al. 1982). This similarity made it difficult to distinguish between responses to seeding and the natural evolution of a storm. Despite the fact that STORMFURY did not lead to an operational method for hurricane modification, many worthwhile investigations were performed as part of this experiment, and STORMFURY funds were used to obtain the NOAA WP-3D aircraft (Willoughby et al. 1985). Also, many of the early modeling studies were motivated by the need to improve understanding of seeding responses (e.g., Rosenthal 1971; Jones 1976). However, the attention devoted to this project may have reduced the emphasis on studies that would have had more direct forecast applications.

In 1968, Gordon Dunn retired and Robert H. Simpson became the director of NHC (Sheets 1990). Simpson established a small research and development unit at NHC, where many of the statistical track forecast models described previously in this section were developed. This unit was also briefly involved in numerical model development and attempted one of the first three-dimensional hurricane simulations initialized with real data (Miller 1969). Simpson trained with Dunn in 1967 and created the "hurricane specialist" positions, with the responsibilities of tropical cyclone forecasting during the hurricane season and research and public service in the remainder of the year (G. Clark 1995, personal communication). Arnold Sugg became the first official hurricane specialist in 1968.

1974–1987, Geostationary satellites and three-dimensional forecast models

The first Geostationary Operational Environmental Satellite (GOES) became available at the beginning of GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment in June 1974 (Kuettner and Parker 1976). The importance of these satellites for tropical analysis and forecasting was stressed by Sheets (1990), who stated: "If there was a choice of only one observing tool for meeting the responsibilities of the NHC, the author would clearly choose the geostationary satellite." GOES satellite observations are extremely useful for determining storm positions and for estimating storm intensities using the method first described by Dvorak (1973). In addition, satellite data are used to determine "cloud track" winds, primarily at upper and lower levels. These winds contribute significantly to the operational database in tropical regions where conventional upper-air observations are not available (Dey 1989).

Another technological advance that had an impact on hurricane forecasting was NOAA's acquisition of two WP-3D aircraft for hurricane research and reconnaissance, which were put into operation in 1976 and 1977 (Sheets 1990). Although these aircraft were obtained in connection with Project STORMFURY (Willoughby et al. 1985), they were never actually used in a hurricane-seeding experiment. However, the observations from these aircraft have contributed greatly to knowledge of hurricane structure (e.g., Marks 1990). In 1977, the Aircraft Satellite Data Link (ASDL) was implemented, which allows observations from the NOAA aircraft to be transmitted directly to NHC in real time (Parrish et al. 1984). The ASDL system greatly increased the utility of the research aircraft for operational forecasting. A similar data observation and transmission system (the Improved Weather Reconnaissance System) was developed in the late 1980s for the WC-130 reconnaissance aircraft operated by the air force reserve.

Another important development was the implementation of a three-dimensional hurricane model for operational track forecasting in the Atlantic basin (Hovermale and Livezey 1977). This model was developed at NMC and included 10 vertical levels with a horizontal resolution of 60 km. Due to computer limitations, the model had a fairly small horizontal domain (3000 km × 3000 km), but the domain moved so that it remained approximately centered on the storm. For this reason, the model was referred to as the Moveable Fine Mesh (MFM). The MFM became operational in 1976 and was run until the end of the 1988 hurricane season. Due to computer limitations, the MFM was run only to 48 hours during the period 1976–1983. After 1983, it was run for 72 hours. Due to initialization difficulties, the MFM had relatively large forecast errors at 12–24 hours. However, the longer-range forecasts had considerable skill, especially for higher-latitude storms (DeMaria et al. 1990). As described by Hovermale and Livezey (1977), the

MFM was developed because the feasibility of three-dimensional tropical cyclone simulations had been demonstrated in the research environment. Thus, some of the modeling efforts in the late 1960s and early 1970s began to have forecast applications.

Statistical track forecast models also continued to advance during this period. Neumann (1988) developed a new statistical–dynamical model (NHC83) that used output from NMC's global spectral model. On average, this model outperformed all other guidance models during the period 1983–1987, including the MFM (DeMaria et al. 1990). Because of the success of NHC83, the older statistical models (NHC67, NHC72, and NHC73) were no longer run at NHC after 1988 (Sheets 1990). NHC90 (Neumann and McAdie 1991) is a modified version of NHC83 that is still used at NHC.

When the number of guidance models increases, it becomes more likely that there is disagreement between the track predictions. For example, Fig. 9-4 shows some of the model forecasts that were available for Hurricane Allen (1980). The forecaster must use subjective judgement of the model guidance and other available information to produce the official NHC forecast. Partially because of the proliferation of models, greater emphasis was placed on model verification during this period. Detailed descriptions of the official NHC forecasts for 1970–1979 and the guidance models for the period 1973–1979 were presented by Neumann and Pelissier (1981a,b). DeMaria et al. (1990) provided a verification of the Atlantic track guidance models for the period 1983–1988. Verification of the official and model forecasts for the past several years have also been published in the minutes of the Annual NOAA Interdepartmental Hurricane Conference (e.g., Lawrence and Gross 1994).

Some minor progress was also made in intensity forecasting during this period. Jarvinen and Neumann (1979) developed a Statistical Hurricane Intensity Forcast (SHIFOR) model that uses climatological and persistence predictors in combination with current storm characteristics. This model is analogous to the CLIPER track prediction model. Because SHIFOR does not include any direct synoptic information, it is useful only for predicting average intensity changes. Hebert (1977, 1978) modified a decision ladder approach that was used to forecast whether or not a tropical cyclone would intensify. This approach was based upon the earlier work of Simpson (1971), modified to include some of the factors such as vertical wind shear suggested by Gray

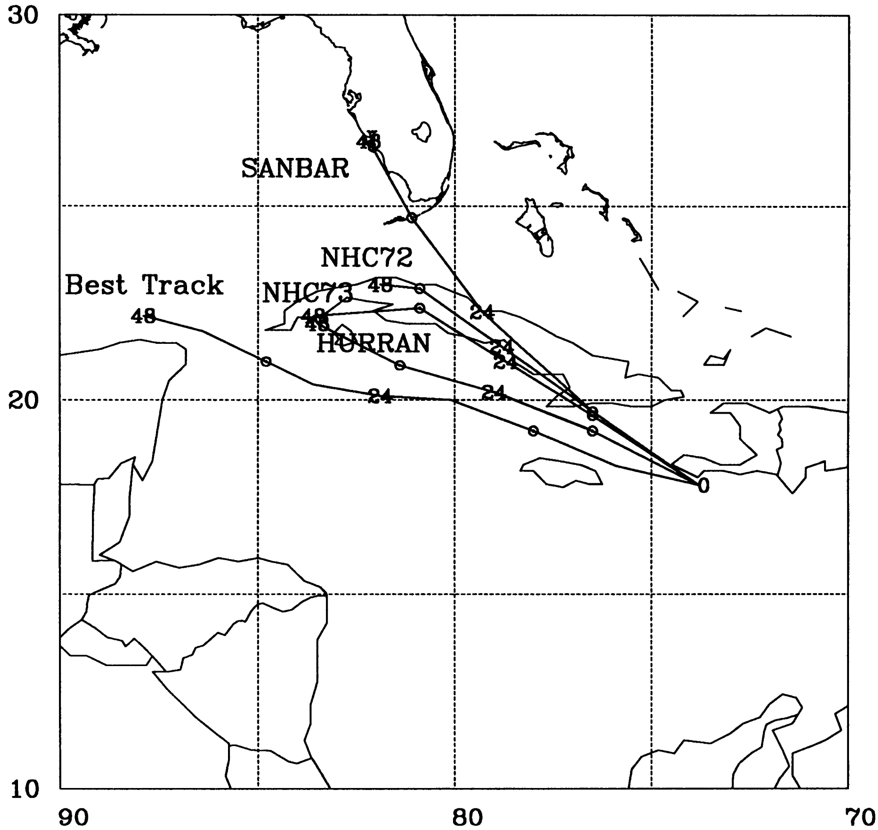

FIG. 9-4. The 48-h best track for Hurricane Allen (1980) beginning at 0000 UTC 6 August 1980. Also shown are the 48-h forecasts from the HURRAN, NHC72, NHC73, and SANBAR track forecast models.

(1968). Although the revised decision ladder approach includes synoptic information, it does not provide a quantitative intensity estimate. Pike (1985) attempted to include geopotential heights as additional predictors in a model similar to SHIFOR. However, this synoptic information resulted in only a marginal improvement relative to SHIFOR.

Another change that affected hurricane forecasting during this period was the appointment of Neil L. Frank as NHC director in 1974 following the retirement of Simpson (Sheets 1990). Frank placed great emphasis on the hurricane warning and preparedness aspect of the hurricane forecasting problem (Frank 1984), and considerable improvements were made in this area during his 13-year tenure. Also, Frank effectively used electronic media as a means to provide information to people in areas threatened by storms.

Another administrative change was that all tropical cyclone forecasts for the Atlantic basin became the responsibility of the NHC in 1980. As described previously, this responsibility had been shared by the Miami, New Orleans, San Juan, Washington, and Boston offices following the reorganization of the hurricane warning service in 1935.

1988–1994, Increased interaction with the research community and the use of global model output

In 1988 Robert C. Sheets became the director of NHC. He was the acting director of NHC in 1987 after the retirement of Frank. Sheets had previously been one of the directors of Project STORMFURY (Gentry 1980).

Considerable progress was made during this time period in the numerical prediction of hurricane tracks. In 1988 the MFM was replaced by the Quasi-Lagrangian Model (QLM). The QLM had higher vertical and horizontal resolution than the MFM and used a larger model domain (Mathur 1991). In 1988, there were a large number of low-latitude storms, and the QLM did not perform well relative to other guidance models (DeMaria et al. 1990). However, these early difficulties were related to the vortex initialization and model modifications corrected this problem (Mathur 1991). The QLM produced skillful forecasts for the period 1989–1993 (Aberson and DeMaria 1994).

In 1992, the research model developed at the Geophysical Fluid Dynamics Laboratory (GFDL) was adapted for real-time forecasting. This model includes moving nested grids and a sophisticated vortex initialization scheme (Bender et al. 1993). The horizontal grid spacing on the inner mesh is ~20 km, which is one-half that of the QLM. Near-real-time forecasts were made during the 1992–1993 hurricane seasons, and in 1994 the model was transferred to NMC. Although the sample size is fairly small, the GFDL model outperformed all other models (in terms of average track error) during the 1992–1993 seasons (Aberson and DeMaria 1994). The GFDL model replaced the QLM for the 1995 season (Kalnay et al. 1994). During 1995 the GFDL model had smaller average position errors than any of the other track models.

In 1989, the SANBAR model was retired after 19 operational seasons. Beginning that year, an experimental barotropic track prediction model (Vic Ooyama barotropic model, VICBAR) was run in near real time (DeMaria et al. 1992). Since that time, VICBAR has been run in an experimental mode in real time. The main advantages of VICBAR relative to SANBAR are that VICBAR obtains lateral boundary conditions from the NMC global forecast model and uses a much more accurate numerical method.

The Beta and Advection Model (BAM) also uses the barotropic steering concept. The track forecast is obtained by following a trajectory in the vertically averaged horizontal wind from the NMC aviation global forecast model, with a correction that accounts for vortex drift (Marks 1992). The BAM model that uses a deep-layer mean horizontal wind has been run since 1989. Starting in 1990, two additional versions of BAM (with medium- and shallow-layer mean winds) have been run. The medium and deep BAMs have considerable track forecast skill (Aberson and DeMaria 1994), and the differences between the three versions of the model provide useful diagnostic information.

The large-scale regional and global prediction models from NMC have long been used as an aid in hurricane forecasting by providing forecasts of the hurricane environment. The skill of the global forecast models has improved considerably during the 1980s and 1990s (Kalnay 1994; Bonner 1989). This improvement can be attributed to improved model physics, increased horizontal and vertical resolution, and improved data assimilation techniques. Bengtsson et al. (1982) first presented examples of warm-core vortices produced by a global forecast model that were similar to tropical cyclones. In the following several years, the feasibility of forecasting tropical cyclones with research global models was demonstrated (e.g., Krishnamurti and Oosterhof 1989). Beginning in 1992, a tropical cyclone bogussing system was implemented in the NMC operational global model (the aviation model) for track forecasting (Lord 1991). Preliminary results from the 1992–1993 Atlantic seasons are encouraging (Aberson and DeMaria 1994), although the results from the 1994 and 1995 Atlantic hurricane seasons suggest that some modifications to the model or initialization procedures might be necessary (N. Surgi 1995, personal communication).

The current suite of models for track forecasting in the Atlantic includes the simple analog model CLIPER, the statistical–dynamical model NHC90, the barotropic model VICBAR, the three versions of the trajectory model BAM, the GFDL regional baroclinic model, and the aviation model. All of the these models except CLIPER use information from the aviation model for calculation of predictors, for trajectories, or as boundary conditions. One other exception is a version of NHC90 (referred to as UK90) that uses output from the U.K. Meteorological Office global forecast model.

Some improvements have also been made in the models for intensity prediction during this period. Research results have emphasized the importance of the influence of the storm environment (especially in the upper levels) on hurricane intensity changes (e.g., Merrill 1988; Molinari and Vollaro 1989). In addition, Emanuel (1988) developed a theory showing that the maximum intensity of tropical cyclones is determined by the sea surface temperature and the temperature near the tropopause, in qualitative agreement with the earlier study of Miller (1958). These ideas were incorporated into a Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic basin (DeMaria and Kaplan 1994). The SHIPS model has been run in an experimental mode, similar to that described above for VICBAR, since 1990. Preliminary results suggest that the average intensity errors for SHIPS are 10%–15% less than those from the simple climatology and persistence intensity model (SHIFOR), although this improvement has not been demonstrated in an operational setting.

In addition to the SHIPS model, intensity prediction has also been attempted in the GFDL model, beginning in 1992 (Kurihara et al. 1993). Although, at the present time, the horizontal resolution (20 km) is marginal for the representation of the inner core of some intense hurricanes, this effort represents the beginning of the era in which three-dimensional models predict intensity as well as track.

The operational application of the GFDL model and the implementation of VICBAR and SHIPS are examples of the increased interaction between the research and forecasting communities that occurred during this period. The development of the BAM model described above was also based upon research results (Holland 1983). The implementation of the ASDL system on the NOAA research aircraft (described previously) also made a number of research applications available for operational use (Burpee et al 1994). During Hurricane Emily (1993), a series of radar reflectivities were transmitted from the aircraft to NHC in real time. In addition, omega dropwindsonde (ODW) observations collected in the storm environment were included in the operational database. Similar ODW experiments have been performed in several storms beginning in 1982, and research results have demonstrated that this information improves the track forecasts in barotropic (Franklin and DeMaria 1992) and baroclinic (Lord 1993) models. In addition, methods for analyzing and displaying the NOAA flight-level data (developed at HRD) have been used for operational forecasting at NHC since the late 1980s (Willoughby et al. 1989b; Sheets 1990). Methods are also being developed at HRD for providing real-time surface wind analyses by combining observations from a number of different platforms (Powell et al. 1996).

1995–2005, Present status and future outlook

Before attempting to project into the future, it is useful to consider what has happened in the recent past and to summarize current hurricane forecasting problems. McAdie and Lawrence (1993) have examined the NHC official track forecast errors for the period 1970–1991, where the errors were corrected to account for interannual variability in the forecast difficulty (Neumann 1981). These results indicate that the 24-, 48-, and 72-h average track forecast errors have decreased by 0.7%, 1.0%, and 1.2% per year during this period. This error reduction is undoubtedly due to the advances in the tools available for track prediction, as described earlier in this chapter. The greater rate of improvement for the longer forecast periods is consistent with the improvements in the NMC global forecast model and the statistical–dynamical and baroclinic track prediction models that provide the most accurate longer-range forecasts.

Although many advancements have been made during the past 75 years, the problem of hurricane forecasting has not been solved. The population at risk from tropical cyclones along the U.S. coastline has increased at a much faster rate than the improvement in track forecast errors. For example, in recent years, the coastal populations of Florida and Texas have increased at about 3% per year (Sheets 1990), while the average 24-h track forecast error (probably the most important for coastal evacuation) has decreased by only about 0.7% per year. In addition, it is currently not possible to provide hurricane warnings long enough in advance, relative to the time it takes to evacuate some of the most hurricane-prone areas (e.g., New Orleans or the Florida Keys) unless the size of the warning area is significantly increased. However, expanding the warning area is very costly and increases the areas that are overwarned (Sheets 1990).

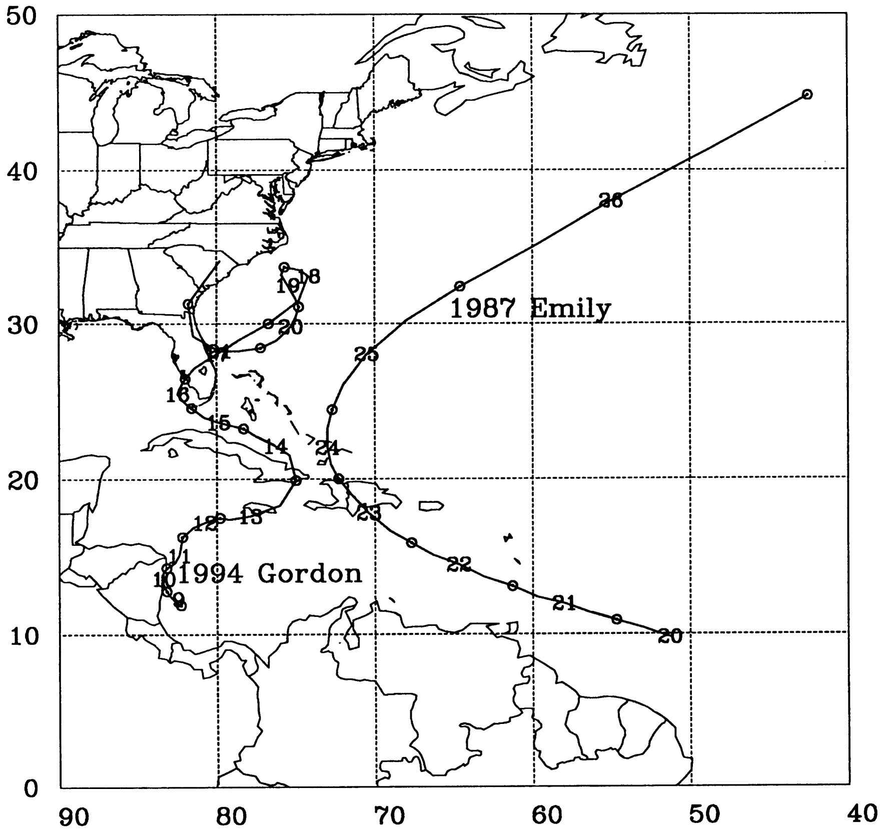

FIG. 9-5. The tracks of Hurricane Emily (1987) and Hurricane Gordon (1994). The open circles are the positions at 1200 UTC, and the days of the month (September 1987 or November 1994) are indicated at the 0000 UTC positions.

Although the possibility of a tropical cyclone striking the U.S. coast without being detected (as occasionally occurred in the first half of this century) is extremely unlikely, some meteorological surprises are still possible. For example, Fig. 9-5 shows the track of Hurricane Gordon, which was the last storm of the 1994 Atlantic season. This storm had a rather erratic track, and the forecast errors from the guidance models were generally larger than average. However, the most difficult forecasts were for later stages of the storm. After crossing over Florida on 16 November, Gordon intensified to hurricane strength and appeared to be accelerating toward the northeast. Nearly all of the guidance models initiated at 1200 and 1800 UTC 17 November predicted a rapid recurvature, and the official NHC forecast was consistent with the models. However, Gordon interacted with an upper-level trough to its west, rapidly decelerated, and turned toward the south by 19 November as it weakend to below hurricane strength. Although Gordon did not make landfall in the Carolinas, the lead time for the forecast in that region would have been quite short had the loop in the track of Gordon on 18–19 November been a little larger.

Another example of a difficult forecast was for Hurricane Emily (1987), whose track is also shown in Fig. 9-5. Emily formed from a disturbance on the ITCZ and intensified rapidly to a category-3 hurricane on 22 September (Case and Gerrish 1988). Emily was a small storm and weakend rapidly as it crossed Hispaniola on 23 September. Emily was expected to regain hurricane intensity after emerging into the Atlantic. However, the maximum winds remained less than ~30 m s^{-1} for the next 24 hours. By 0000 UTC 25 September, the storm began to accelerate toward the northeast and remained weak. In addition, there was a frontal system to the northwest of the system, so Emily was forecast to weaken. However, in the next 12 hours the storm intensified rapidly and reached Bermuda by 1145 UTC 25 September with sustained winds of 39 m s^{-1} and gusts to 52 m s^{-1}. As described by Case and Gerrish (1988), this intensification was not anticipated, and the rapid acceleration was underestimated. Fortunately, no deaths were reported in Bermuda, although there was considerable damage from the storm.

The occurrence of large, unanticipated track changes as described above are not very common. More typically, the track guidance models in combination with satellite observations (especially water vapor imagery) illustrate the range of possible storm tracks. However, rapid intensity changes are much more difficult to forecast, and underestimates for rapidly intensifying storms are fairly common. For example, the intensities of Hurricanes Hugo in 1989 and Andrew in 1992 were both underestimated prior to landfall in South Carolina and in South Florida, respectively (U.S. Department of Commerce 1993a; National Research Council 1994). Despite the advances described in the previous section, there is considerable room for improvement of hurricane intensity forecasts.

The next several years should be another era of rapid change in hurricane forecasting. Robert W. Burpee became the director of NHC in 1995, following the retirement of Sheets, and the forecast office has moved to the Florida International University campus in Miami. In addition, as part of the restructuring of NMC, NHC is now the Tropical Prediction Center/National Hurricane Center in recognition of its past and expanded role of providing general weather guidance in the Tropics, in addition to tropical cyclone forecasts (McPherson 1994).

There are also several technological changes that will have an impact on hurricane forecasting. The WSR-88D Doppler radar network is in its implementation phase. Although these radars will probably not impact longer-range forecasts due to their limited range, they have the potential to improve forecasting as storms approach the coast (McAdie and Sandrik 1994). Perhaps the most improvement from these radars will be for short-term forecasts and site-specific warnings for inland winds associated with hurricanes. The recent landfalls of Hurricanes Hugo (1989) and Andrew (1992) have emphasized that hurricane winds can be a threat to inland locations as well as along the coast. Another technological change is the implementation of the next generation of geostationary satellites (GOES-I). These satellites have improved imaging systems, which will provide much higher spatial resolution than the *GOES-7* systems (Menzel and Purdom 1994). Technology is also being developed for improving estimates of surface winds from aircraft and satellites (e.g., Tanner et al. 1987; Rappaport and Black 1989). More accurate determination of the extent of high winds could lead to refinements in the areas warned for landfalling storms. [See chapter 5 by Purdom and Menzel, this volume.]

In the longer term, a Gulfstream IV jet aircraft, obtained by NOAA, is scheduled to perform hurricane surveillance in July 1996 and research missions by 1998. The main advantage of the jet relative to the aircraft currently used for hurricane reconnaissance (the Air Force Reserve WC-130s and the NOAA WP-3Ds) is that it will be possible to examine the upper levels of tropical cyclones. Theoretical results suggest that interactions with the environment in the upper levels can have significant impacts on intensity changes (e.g., Holland and Merrill 1984; Montgomery and Farrell 1993).

Even with the new jet aircraft, Doppler radar and GOES-I satellites, the lack of observations over the tropical oceans (especially in the mid levels that are important for storm motion) will still be a problem in many forecast cases. This problem could be even worse if the conventional upper-air network continues to degrade (e.g., Bosart 1990). A technological development that has the potential to make a major impact in this area is the unmanned aircraft. There are currently two types of these aircraft under development: a very small "aerosonde" that can provide in situ data (Holland et al. 1992) and a somewhat larger aircraft capable of releasing sondes to obtain vertical soundings (Langford et al. 1993). The feasibility of these types of systems will be evaluated within the next five years. [See Chapter 3 by Serafin, this chapter.]

Perhaps a fitting way to end this review is to speculate about the state of hurricane forecasting at the end of the next period of change. In Table 9-1, the 75-year history was divided into seven sections of roughly 10 years each. In the next 10 years, the general skill of hurricane track forecasts should continue to improve. Although there is probably an upper limit to the forecast accuracy, it is likely that this limit has not yet been reached. For example, Neumann (1987) indicated that the minimum possible average 24-h track error from statistical models is ~120 km. This minimum is 35% smaller than the average 24-h error of the official NHC forecast (185 km) for the period 1983–1992 (Lawrence and Gross 1994). There has been a dramatic increase in research on tropical cyclone motion that began in the mid-1980s, partially in connection with field experiments in the western Pacific sponsored by the Office of Naval Research (TCM-90, TCM-92, and TCM-93; Harr 1994). The impact of this research should continue to help guide hurricane forecast model development. In addition, the NMC global forecast model, upon which nearly all of the track models depend, should continue to improve.

The above discussion suggests that the average track errors will decrease slowly. However, more significant improvements should be attained in a few individual cases where strategically placed dropwindsondes are released from the NOAA Gulfstream jet and WP-3D aircraft. Preliminary estimates by Burpee et al. (1995) suggest that error reductions of 20%–30% are possible for the 24–60-h forecasts. Track forecasts will also be significantly improved if the unmanned aircraft technology comes to fruition.

Ten years from now, the method for making track forecasts will probably include ensemble forecasting techniques. In the last few years, there has been a considerable emphasis at NMC on this technique (Toth and Kalnay 1994). The method is well suited to the track forecasting problem, where the range of possible tracks could be estimated.

There will probably be some improvement in intensity forecasting, although it is not obvious that this will be accomplished by direct numerical simulation with three-dimensional models. The increased understanding from upper-level observations of hurricanes using the Gulfstream jet, in combination with new theoretical tools being developed (e.g., Shapiro and Montgomery 1993), has the potential to improve intensity forecasts. The ability to transmit aircraft radar information to NHC in real time might also have an impact on short-term intensity forecasts (12–36 hours) and the WSR-88D radars will be useful for short-range forecasting of storms near the coast. It may also be necessary to include the effects of the ocean response when predicting intensity changes, especially for intense and slow-moving storms (e.g., Khain and Ginis 1991). Ensemble forecasting techniques might also be feasible for evaluating the ranges of intensity that are possible, especially if a three-dimensional atmospheric model is successfully coupled with an ocean model.

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