OPERATIONAL TECHNIQUES FOR FORECASTING TROPICAL CYCLONE INTENSITY AND MOVEMENT
OPERATIONAL TECHNIQUES FOR FORECASTING TROPICAL CYCLONE INTENSITY AND MOVEMENT

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*By Y. Okamura
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FOREWORD

One of the primary objectives of the WMO Tropical Cyclone Project is to strengthen the present capabilities for the detection, tracking and forecasting of tropical cyclones. An important component of this Project is the provision of authoritative guidance material and, to this end, a sub-project has been initiated in order to compile a description of the different techniques at present in use for forecasting tropical cyclone intensity and movement.

This publication is the outcome of this sub-project and its aim is to present an up-to-date review of the existing prediction techniques. The main part of the volume gives detailed information on the methods that may be used for forecasting the tracks of tropical cyclones, their development, and changes in intensity, consideration being given to empirical, statistical and dynamical techniques. Space is also devoted to the verification of tropical cyclone forecasts.

I feel confident that this publication will be of considerable value to those with the heavy responsibility of issuing forecasts and warnings of tropical cyclones.

The preparation of this publication was the responsibility of the sub-project leader, Dr. Joseph M. Pelissier (U.S.A.), and his collaborators, Dr. P. C. Chin (Hong Kong), Mr. V. Balasubramaniam (India), Mr. Y. Okamura (Japan) and Dr. S. N. Sen (Typhoon Committee Secretariat) all of whom contributed significantly, especially in reviewing and editing the material. I would like to record my warm appreciation to the authors of the various chapters and to the sub-project team for the accomplishment of this important work.

D. A. Davies
Secretary-General
PART I

INTRODUCTION AND BACKGROUND INFORMATION
INTRODUCTION
(by S. N. Sen*)

1.1 General

Tropical cyclones, the most destructive of Nature’s phenomena, are known to form over all tropical oceans, with the exception of the south Atlantic and the south Pacific east of about 140°W. Maps showing regions of formation of tropical cyclones and their average tracks are given in many text books and special climatological atlases. These are referred to in Chapter 2 entitled “Tropical cyclone climatology”. Tropical cyclones in matured condition are known as hurricanes in the Atlantic, typhoons in the western North Pacific and cyclones in the Bay of Bengal. While these names are related to the locality of occurrence, all tropical cyclones are essentially similar in origin, structure and behaviour.

In the areas struck by tropical cyclones, the resultant damages are often extensive, especially in developed coastal areas. The principal damaging forces associated with tropical cyclones are the storm surge, floods caused by torrential rains and the high winds. The trends of losses from hurricanes in the United States since the beginning of this century reveal interesting features (Figure 1-1). While the toll in lives inflicted by hurricanes has gradually decreased as a result of improved prediction and warning, property losses continue to rise because of progressive development in vulnerable areas. Hurricane Betsy in 1965 and Hurricane Camille in 1969 caused enormous property damage, each exceeding US $1400 million.

The western Pacific has the world’s highest incidence of tropical cyclones (typhoons). Although the Bay of Bengal area also produces devastating cyclones they occur less frequently. A recent study by the Economic and Social Commission for Asia and the Pacific (ESCAP) has shown that 18 countries of the ESCAP region sustained tropical cyclone and flood damage amounting to US $35,835 million during the period 1961-1975 of which the highest levels of damage occurred in Japan (US $20,963 million), India (US $7,117 million) and in Bangladesh (US $4,312 million). The same study has revealed that the average annual cost of damage (at 1975 price levels) in the period 1961-1965 amounted to US $1,880 million and that it had increased to US $3,132 million for the years 1971-1975, the most recent period for which figures are available.

The Bangladesh tropical cyclone disaster in November 1970 was one of the worst natural disasters in history. According to the official estimates it took a toll of 200,000 human lives, though unofficial estimates put the toll as high as 500,000. An enormous storm surge, with its height variously estimated at three to nine metres accompanied the cyclone and swept over the off-shore islands and low-lying coastal belt. In the same year (1970), a series of typhoons struck the Philippines and caused unprecedented damage. These tragic events evoked worldwide concern and led to a United Nations General Assembly resolution. The resolution called upon WMO to take appropriate action by mobilizing scientists and resources to discover ways of mitigating the harmful effects of these storms and of removing or minimizing their destructive potential.

In response to this resolution, the WMO Tropical Cyclone Project was established. The Typhoon Committee, established in 1968 as an intergovernmental body under the auspices of WMO and ESCAP with the objective of reducing typhoon damage in south-east Asia, forms part of this project and similar regional bodies have since been

*Typhoon Committee Secretariat, Manila
Figure 1-1 – Trends of losses from hurricanes in the United States summarized by five-year periods. Damage statistics have been adjusted to the 1957-59 Department of Commerce Composite Cost Index for Construction (Gentry, 1966)
established in other parts of the world affected by tropical cyclones; they are the WMO/ESCAP Panel on Tropical Cyclones for the Bay of Bengal and the Arabian Sea, the WMO RA I Tropical Cyclone Committee for the South-West Indian Ocean and the WMO RA IV Hurricane Committee for the North Atlantic Ocean, Caribbean Sea, Gulf of Mexico and the eastern Pacific Ocean.

1.2 Nature and structure of tropical cyclones

Tropical cyclones are warm-core low-pressure systems or depressions around which the air circulates in an anti-clockwise direction in the northern hemisphere, and in a clockwise direction in the southern hemisphere. A tropical cyclone consists of a rotating mass of warm humid air, normally between 300 and 1500 kilometres in diameter. The strongest winds, which may approach 200 knots, blow around the eye of a tropical cyclone, a central region of light winds and lightly clouded sky ranging from a few kilometres to over 100 kilometres in diameter. The existence of the eye is most conspicuously revealed by weather radar and satellite imagery. A photograph of Hurricane Anita, 1977, taken by the Geostationary Operational Environmental Satellite (GOES) (Figure 1-2) shows the eye with its spiral inflow pattern very clearly.

A tropical cyclone draws its energy from the convective overturning of the atmosphere. Warm, moist air spirals over the tropical seas towards the storm centre and flows upward in a band of clouds around the almost calm eye. The inflowing air, turning slowly with the rotation of the Earth, gathers speed as it draws towards the storm centre and produces winds of destructive violence. Soundings in the rain areas, which comprise the major part of a tropical cyclone, have confirmed the classical idea that air in the interior of tropical cyclones is less dense or warmer than its surroundings. In other words, tropical cyclones have a warm core.

In an attempt to explain the processes involved in the formation and development of tropical cyclones, many theories have been advanced by meteorologists. Riehl (1948) considered Atlantic cyclone development as a progressive process of intensification of a migrating disturbance or wave embedded in the trade winds which moves under a favourable divergent upper-tropospheric environment. Ramage (1959) advocated an energy-dispersion mechanism from an external source to account for hurricane development. Charney and Eliassen (1964) proposed that a cyclone develops by a kind of secondary instability in which existing cumulus convection is augmented in regions of low-level horizontal convergence. Sadler (1967) has analyses cyclone development resulting from downward intensification of a pre-existing upper-tropospheric trough.

In recent years, a number of studies have been made on numerical simulation of tropical cyclone development using primitive equations and parameterizing cumulus convection and heat fluxes from sea to air. These studies have resulted in gaining better insight into the physical processes involved in the development of tropical cyclones.

Cloud photographs obtained from weather satellites have revealed that a hurricane seedling initially appears as a cluster of rain clouds. The cluster is comprised of a number of thunderstorm-type cells, each of which may develop independently. These cells join together and form the gigantic atmospheric heat pump which is the hurricane system. The pump consists of a spiralling influx of warm, moist air at its intake in the lower boundary layer and an equally large-scale spiralling outflow at the exhaust end or top of the storm system. It is noteworthy that all cloud clusters do not develop into hurricanes. It is estimated that about 100 hurricane seedlings originate in the Atlantic Ocean per year, of which only ten per cent succeed in developing into tropical cyclones.

1.3 Detection and tracking of tropical cyclones

Data from many sources are used to locate and track tropical cyclones. These data include weather satellites, radar, aircraft reconnaissance and ship and land station observations, commercial aircraft observations and radiosonde data.
OPERATIONAL TECHNIQUES FOR FORECASTING TROPICAL CYCLONE INTENSITY AND MOVEMENT
Reconnaissance aircraft penetrate hurricanes and typhoons. These flights provide valuable meteorological information from the central areas of tropical cyclones, including the position of the centre and reports on cloud structure and on the distribution of temperature, wind and pressure.

Ten-centimetre weather radars have an effective range of about 400 km for locating tropical cyclones. The advantage of a weather radar installed in strategic coastal locations is that, within its range, it provides a continuous watch on a tropical cyclone as the storm comes closer and closer to a threatened area. The important characteristics of a tropical cyclone—the eye, cloud wall, areas of associated rainfall, etc.—are clearly revealed by the radar pictures.

In recent years, satellites have provided yet another excellent platform for observations of cyclones. In data-void or data-sparse ocean areas the satellite is sometimes the only tool to detect a tropical cyclone. The polar-orbiting meteorological satellites of the United States and the Soviet Union have photographed, from space, hundreds of tropical cyclones and transmitted information to ground stations. A series of geostationary meteorological satellites, also established under the World Weather Watch Programme, and operated by Japan, the U.S.A., the U.S.S.R. and the European Space Agency, now provides almost continuous surveillance of tropical cyclones over the respective ocean areas.

The principal observing systems, therefore, from which the information needed for detecting, tracking and forecasting tropical cyclones is obtained are:

(a) Regular weather network of surface and upper-air observing stations;  
(b) Mobile and ocean weather ships' stations;  
(c) Commercial aircraft;  
(d) Tropical cyclone reconnaissance aircraft;  
(e) Radar stations;  
(f) Satellites.

1.4 Forecasting of tropical cyclones—Purpose of this publication

The problem of forecasting intensity changes and movement of tropical cyclones, particularly recurvature and landfall, is crucial in many parts of the world. A considerable amount of work on tropical cyclone prediction has been accomplished by the Meteorological Services of a number of nations which share this problem.

Significant progress has been made in developing objective techniques and dynamic techniques for forecasting the tracks of tropical cyclones. Attempts are being made by some countries, notably by the United States and Japan, to develop more sophisticated numerical models of tropical cyclones. In most developing countries, however, computer facilities, data coverage, trained personnel, etc. are not yet adequate to apply the more sophisticated techniques, particularly dynamic techniques, in operational forecasting. Therefore, operational forecasting of tropical cyclones in developing countries is based mostly on subjective consideration of well-known predictors, such as persistence, climatology, steering, etc. However, studies of objective techniques are being progressively undertaken as increasing facilities are coming within reach of Meteorological Services.

The main purpose of this publication is to present information on the techniques available for predicting intensity changes and movement of tropical cyclones, as well as their applicability and effectiveness in operational forecasting. In so far as possible, the scope of this publication is world wide, limited in that respect only by the information available from the various Meteorological Services.
Until now, the various forecasting techniques in use have not been compiled in such a way that their application to other areas may readily be explored and kept under review. It is one of the aims of this publication to assemble descriptions and evaluations of these techniques in a single volume which will be reviewed from time to time and kept up to date. By so doing it is hoped that methods which have been successful in some areas may be adapted to others. It is realized that implementation of some of these tropical cyclone forecasting techniques is dependent on the availability of computer facilities. There are others requiring only meteorological data from a network of conventional surface and upper-air observing stations as basic input. Both types are summarized in this publication. Although the techniques have been described in such detail as would permit junior forecasters with a basic knowledge of synoptic meteorology to understand and apply them where appropriate, the material contained herein may also be used for refresher and more advanced studies. A comprehensive bibliography has been appended to each chapter to facilitate detailed study of any particular topic. The reader will be aware that the procedures described herein represent the state-of-art at the time of publication. However, progress is continuing. Another of the aims of this publication will be accomplished if the exchange of ideas between the tropical cyclone forecasters of various areas will stimulate them to keep abreast of future developments in the world-wide meteorological community.

REFERENCES


CHAPTER 2

TROPICAL CYCLONE CLIMATOLOGY
(by J. R. Hope*)

2.1 Global distribution of tropical cyclones

Tropical cyclones form over all the tropical oceans except the South Atlantic and South Pacific east of about 140°W. Regional differences in tropical cyclone terminology are given in Table 2-1. Tropical cyclones are most commonly observed in the northern hemisphere from May to November, and in the southern hemisphere from December to June. In the North Atlantic, for example, Winston et al. (1959) determined that 97 per cent of all tropical cyclones occur during the period from June through November. On the other hand, a significant number do occur during other months in the western North Pacific, where there is an average frequency of at least 0.2 during any month of the year. Crutcher and Quayle (1974) have divided the globe into six major basins for which they have compiled tropical cyclone frequencies. The boundaries of the basins and the period of record available for each one are outlined in Figure 2-1. These data are available in punch-card form or magnetic tape form from the U.S. Department of Commerce, NOAA, National Climatic Center, Asheville, NC.

The average annual number of tropical cyclones per five-degree latitude/longitude squares in each basin is shown in Figure 2-2. Table 2-2 lists the monthly and annual average number of storms for the six basins. The annual averages range from 5.7 in the north Indian Ocean to 25.3 in the western North Pacific. Approximately 70 per cent (Gray, 1967) of all tropical disturbances which later develop into storms (winds ≥ 34 kt) form in the northern hemisphere.

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*National Hurricane Center, Miami
### Monthly and average number of storms per year for each major basin (from Crutcher and Quayle, 1974)

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<td>*</td>
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</tbody>
</table>

* Less than .05 † Winds > 48 Kts.

Monthly values cannot be combined because single storms overlapping two months were counted once in each month and once in the annual.

It is only in the western North Atlantic and the western North Pacific that a substantial number have their origin poleward of latitude 22½°N.

Tropical cyclones developing deep in the tropics move initially in a generally westward direction along the equatorward peripheries of the large oceanic anticyclones which exist over each ocean. Many turn poleward as they reach the western sides of the anticyclones, and curve towards the east if they reach the high-latitude westerlies. Not all tropical cyclones reach high latitudes intact. Some dissipate over land, while others weaken and die as they move over progressively colder water. Occasionally tropical cyclones may follow highly erratic paths, characterized by loops, sharp turns, or abrupt changes in forward speed. In spite of the variability of storm motion, some preferred tracks can be ascertained (Figure 2-3).
OPERATIONAL TECHNIQUES FOR FORECASTING TROPICAL CYCLONE INTENSITY AND MOVEMENT

Figure 2.2—Average annual number of cyclones per five-degree square, including the main season for their occurrence (from Carley and Goody, 1974).
Figure 2.4 - Average annual speed in knots of storm movement (from Cartter and Quayle, 1974)
INTRODUCTION AND BACKGROUND INFORMATION

As is well known, the forward speed of movement is a variable quantity. There is a tendency for storms to accelerate as they move into higher latitudes. There is considerable variation of average forward speeds of tropical cyclones at low latitudes. Figure 2-4 shows that the speeds equatorward of latitude $20^\circ$ are generally less in the southern hemisphere than in the northern hemisphere.

According to Gray (1967) over 80 per cent of tropical cyclones reaching storm intensity around the globe have their origin equatorward of $20^\circ$ latitude on the poleward side of the equatorial trough as it moves well into the summer hemisphere. Less than 20 per cent of the global total, most of which occur in the western North Atlantic, the eastern North Pacific, or the western North Pacific, develop from disturbances which are deeply embedded in the trade wind flow. In the North Atlantic, however, storms of such origins comprise a substantial percentage of those developing in that area. Frank (1970, 1971, 1972, 1973, 1974, 1975) has shown that, in the period 1969-1974, about 90 per cent of the storms developing from purely tropical systems in the western North Atlantic could be traced to westward-moving disturbances in the trade-wind belt, while the remainder developed from Inter-tropical Convergence Zone (ITCZ) disturbances. An earlier study by Dunn and Miller (1964) indicated that about 15 per cent of North Atlantic tropical cyclones developed in perturbations moving away from the ITCZ. Quite a number also developed from systems that initially were, to some degree, baroclinic, i.e. cold lows, old frontal troughs, etc. Frank’s studies show that about 35 per cent of all North Atlantic tropical cyclones developed from these baroclinic disturbances.

Frank also shows that many of the trade-wind belt waves continue across Central America into the eastern North Pacific where they serve as the initial disturbances from which the majority of the tropical cyclones in that area develop. In the period 1969-1974, 51 per cent of the eastern North Pacific storms developed from waves that could be traced back to Africa, ten per cent from waves that developed in the Atlantic or the Caribbean Sea, and 13 per cent from disturbances on the ITCZ which moved across Central America. The remaining 26 per cent developed in the Pacific and had no known antecedent disturbance in the Atlantic or Caribbean. Similarly, the origin of about 50 per cent of the storms and depressions in the Bay of Bengal can be traced to the south-west Pacific. Also, about 50 per cent of the storms and depressions in the Arabian Sea can be traced to the Bay of Bengal.

Given a storm at some particular location, it might be of interest to examine the paths of other storms that moved through the same area. Figure 2-5 shows examples of computer-generated graphics which display such information. Computer programs can be written to produce a variety of similar charts.

2.2 Tropical cyclone climatology data sources

The U.S. National Hurricane Center has published a number of North Atlantic tropical cyclone climatology papers and technical memoranda based on magnetic-tape-stored data. Among these are the technical memoranda by Hope and Neumann (1969, 1971) and the paper by Hebert and Taylor (1975). Crutcher and Quayle (1974) have also published a large number of charts showing in considerable detail tropical cyclone frequencies and motions in each of the six basins into which they have divided the globe, and tropical cyclone roses over all the oceans based on 12-hour movements. Crutcher and Quinlan (1971) have constructed vector mean charts and have computed storm strike probabilities for 24-hour, 48-hour and 72-hour movement for the North Atlantic. Crutcher and Hoxit (1973) derived similar products for the North Pacific, south-west Pacific and Australian area, the South Indian Ocean, and the North Indian Ocean. Detailed climatological studies of tropical cyclones over the western North Pacific have been undertaken by Chin (1958, 1972). Chin (1977) has also computed 48-hour, 72-hour and 96-hour strike probability values for ten selected locations in south-east Asia. Many other studies on tropical cyclone climatology have been carried out around the world. These include studies by Ballenzenzweig (1957, 1958), Chaussard and LaPlace (1964), Coleman (1971), Colon (1953), Commonwealth Bureau of Meteorology, Australia (1971), Cry (1965), Giovanelli (1952), Giovanelli and Robert (1964), Hutchings (1953), India Meteorological Department (1970) and the Japan Meteorological Agency (1944).
Tracks of all recorded tropical storms and hurricanes which passed within designated 150 nautical miles diameter, circular shaded area, July 16 to September 30, inclusive.

Figure 2-5 – Examples of computer-generated charts showing paths of all storms from 1886 to 1970 which passed through a given area during a given time of year (from Hope and Neumann, 1971)
REFERENCES


1.2-10 OPERATIONAL TECHNIQUES FOR FORECASTING TROPICAL CYCLONE INTENSITY AND MOVEMENT


PART II

TRACK FORECASTING METHODS
3.1 General

This section considers those techniques which can be used without reference to regression equations or requirement of computer capabilities. Some of these techniques have been incorporated into statistical and dynamical models in countries possessing large computer facilities. However, as pointed out by Sen (1974), most developing countries will not be able to use these more sophisticated techniques until data coverage, computer facilities and sufficient trained personnel are available. This should not preclude forecasters in any country having tropical cyclone forecast responsibility from becoming familiar with the statistical and dynamical techniques presented later in this chapter, as many aspects of those techniques can be used subjectively to augment existing regional empirical techniques.

Empirical techniques can be considered as falling into three general categories of which two or more are frequently used in combination to arrive at a forecast for the next 12 to 24 hours. Except in the deep easterlies of the tropics large forecast errors result usually from any attempt to use these techniques beyond 24 hours. These categories are:

(a) Persistence and climatology;
(b) Synoptic;
(c) Satellite.

Descriptions of some of these techniques will include illustrative examples, in most instances, and a discussion of their advantages and disadvantages.

3.2 Persistence forecasts

A persistence forecast assumes that the integrated effect of all forces which have steered the tropical cyclone during some past period will continue to predominate during some future period. In general, persistence is taken as the smoothed past 12- or 24-hour motion of the tropical cyclone. The persistence forecast is then the linear extrapolation of this motion for the next 12 to 24 hours. A higher order persistence forecast can be made by taking into account directional and speed changes during the past 24 hours. However, this is frequently difficult to do under operational conditions because of the uncertainty of both current and past locations. Figure 3-1 gives an example of a first-order persistence forecast (uniform speed and direction). Figure 3-2 illustrates a second-order persistence forecast accounting for speed change, while Figure 3-3 illustrates a second-order persistence forecast accounting for directional change.

In addition to illustrating the persistence forecast, these figures also show the importance of maintaining the continuity of a tropical cyclone track unless there is strong evidence for a departure from previous motion. When a limited number of past centre locations are present, the forecaster must be cautious of straight-line connexions

*National Hurricane Center, Miami
Figure 3-1 – An example of a 24-hour first-order persistence forecast. The cyclone is forecast to continue moving towards the west at ten knots

from fix to fix. Experience at the National Hurricane Center in the United States of America has revealed that the oscillatory motions of a tropical cyclone frequently seen on plots of land-based radar observations, and more recently in movie loops derived from geostationary satellites (Lawrence and Mayfield, 1977), will usually lie within an envelope the size of the eye diameter of the cyclone. These motions are believed to be related to the interaction of the dynamics of the centre with the steering current (Yeh, 1950). Most eye diameters range from 15-100 km (Sheets, 1972). This also happens to be the general range of positioning errors* of tropical cyclones. Therefore, the smoothed track extension should weigh these factors in assessing whether it should be to the left, through, or to the right of the present location. Unless there is strong evidence to the contrary, every effort should be made to fit all position locations so as to minimize directional and speed changes.

The importance of carefully determining persistence is illustrated in Chapter 4 on statistical techniques. Most statistical techniques are strongly dependent on persistence as a predictor for the 12- to 24-hour

*These are the differences between the operational positions used and those obtained in post-analysis of a tropical cyclone. They arise because of the oscillations described above, as well as reconnaissance navigational errors, satellite gridding errors and meteorological interpretation errors.
The main advantage of a persistence forecast is its simplicity. Persistence forecasts tend to be best where and when the climatological frequency of occurrence is high. The advantage of persistence over climatology lies in its usefulness during anomalous movements and at higher latitudes, especially if second-order effects are considered in the latter. However, forecast verifications as given in Part IV, and variance reductions for statistical screening techniques as shown in Chapter 4, point out the rapid decrease in its effectiveness beyond 12 hours.

3.3 Climatological forecasts

A climatological forecast makes use of the temporal and spatial repetitiveness of tropical cyclone tracks produced by the synoptic patterns which steer the cyclones. Chapter 2 gives the global climatology of tropical cyclones. Depending on the sample size, the resultant direction and mean scalar speed of motion can be obtained for latitude squares as small as 2½° and time periods as short as five days. The climatological forecast moves the tropical cyclone in the resultant direction at the mean scalar speed for the given location (latitude and longitude).
and time of year. If the cyclone moves to a position with different mean values during the desired forecast period, the forecast can be modified to take this into account. Figure 3-4 indicates that a cyclone at 26°N, 91°W would be forecast to move north-west at 11 knots during the next 12 hours. When bimodal tracks exist, the appropriate mode should be selected according to current storm motion. Figure 3-5 illustrates the determination of a 24-hour forecast based on climatology for a bimodal track.

The advantages and disadvantages of climatological forecasts are more readily apparent than in most other techniques. They perform best where and when the frequency of occurrence is high. They generally decrease in utility with increasing latitude and/or anomalous synoptic patterns. The recognition of this latter fact is an aid in itself. The tropical cyclone forecaster should always have a thorough knowledge of the regional climatology so that a distinction can readily be made between normal and anomalous situations.

3.4 Persistence-plus-climatology forecasts

This type of forecast was first described by Bell (1962) and has proved to be quite useful in many eastern hemisphere tropical cyclone forecast centres. It can be expressed as \( nP + mC \) where \( P \) and \( C \) stand for persistence
and climatology, and $n$ and $m$ are weighting factors. The most frequently used method is called the $\frac{1}{2} (P+C)$ rule because equal weight is given to both predictors. The persistence vector is obtained as the linear extrapolation of the smoothed past 12-hour motion. The climatology vector is based on the regional climatology for the current location and time of season of the tropical cyclone. The forecast position, usually for 24 hours ahead, is the mid-point connecting the two positions obtained from persistence and climatology when plotted on a Mercator chart. An example is shown in Figure 3-6. An example of the technique with other weightings is shown in Figure 3-7. Amadore (1972) has also modified the technique to give different weightings for obtaining latitude and longitude components separately for tropical cyclones east of the Philippines. However, similar attempts made at the Royal Observatory, Hong Kong, for the South China Sea area did not produce significantly improved results.

The use of higher order persistence and climatology would be analogous to the examples given separately for persistence and climatological forecasts. The main advantage of either a first- or second-order equal weighting of persistence plus climatology is its ready availability. A forecast can be prepared as soon as the current position is available. Other weightings and stratifications require some additional computations. The technique is also independent of the synoptic situation. Among the disadvantages are its decreasing utility at higher latitudes because of recurvature, and insufficient climatology and the presence of bimodal direction in some areas.

3.5 Synoptic techniques

There are two types of forecast which can be considered synoptic. The first is in the conventional sense of the simultaneous observation of pressure, temperature, moisture, wind and other meteorological parameters. The second is equally valid in that it is an extension of a single simultaneous observation of the integrated effect of all

Figure 3-4 — Resultant direction and mean scalar speed by 2½° — latitude squares for all tropical cyclones observed in August during the period 1886-1968 (1 August to 31 August, inclusive, 1886-1968). The climatological forecast moves a cyclone in a given 2½° — square with the resultant direction and mean speed for some future period. See the text for an example.
Figure 3-5 — An example of a 24-hour climatology forecast taking into account a bi-modal frequency and the cyclone's current motion. Each annular ring represents five occurrences and the bars indicate the number of occurrences to eight points of the compass.

The conventional data, i.e. a satellite photograph. The forecast techniques described in this section are those made in the conventional sense. Satellite techniques will be discussed in the next section. Neither type uses regression equations nor requires computer facilities. As with climatology and persistence, however, the concepts utilized have been or will be incorporated into objective techniques.

3.5.1 Surface geostrophic steering

The surface-pressure map together with 24-hour surface-pressure changes (to eliminate large diurnal effects in the tropics) has been used by tropical cyclone forecast centres since the 1950s. It is still used in conjunction with more sophisticated techniques and observing systems to obtain the present motion so vital to the analog, statistical and dynamical techniques, and to assess better the shorter range objective forecasts versus the current synoptic situation.

The surface geostrophic steering technique obtains zonal and meridional components of motion by measuring the pressure gradient (in millibars per degree of latitude) across the storm. The pressure gradient must be measured...
from outside of the tropical cyclone's circulation. This is normally taken as the first anticyclonically curved isobar
and/or the col of the cyclone. The influence of the large gradient of the Coriolis parameter on the geostrophic com-
putation at low latitudes requires that the zonal component be computed as the difference of components measured
north and south from the cyclone centre. Figure 3-8 gives an example of this type of computation. The direction of
motion is also fairly well indicated by laying a straight edge across the tropical cyclone so that it just touches the
same isobar at points of maximum anticyclonic curvature on both sides of the hurricane near or a short distance out-
side of the circulation. This is shown in Figure 3-8 by the thin line touching the 1018-mb isobar.

The computation gives 275°/18 knots for the current motion. The straight edge orientation gives 280°/XX. 
At map time the cyclone was moving 290°/15 kt. The discrepancy is a result of pressures in advance of the cyclone
not being corrected for colder air. If the mean temperature is 2°C colder at P1 and 1°C at P2 and P4 than at the
other points, this would require lowering the pressure at P1 to 1018.5 mb, P2 to 1020 mb, and P4 to 1017.5 mb.
A re-computation of the geostrophic steering will then give 290°/16 kt – very close to the observed motion.
The basic assumption in this technique is that the air mass of the environment steering the tropical cyclone is homogeneous. Even in the tropics this is not a very good assumption. Therefore, a modification to the steering must be based on the estimated mean temperature difference across the cyclone for some thickness of the atmosphere. Where upper-air temperature data are available, it is convenient to determine the temperature difference required to correspond to the surface isobar interval being used in the analysis for the regions of interest. For example, a difference of 2°C in the mean temperature from the surface to 400 mb is equivalent to a surface-pressure difference of three millibars. Referring to Figure 3-8, if the mean temperature difference across the cyclone from point 2 to point 8 were zero, no correction would be required to the east-west computation of motion. If, at the same time, the mean temperature was 2°C warmer at point 4 than at point 6, the pressure difference $P_4 - P_6$ would change from -1 to +2 giving a southward component of motion rather than a northward one.

In the absence of upper-air temperature data, the past and present motion of the cyclone and/or satellite pictures can give some information about the temperature field. When the cyclone steers to the right of the direction indicated for a homogeneous environment, cooler air is in advance, while steering to the left indicates warmer air in advance. Figure 3-9 gives an example of consistent motion to the left of the computed surface steering, indicating warm air in advance of the cyclone. Evidence of troughs and ridges inferred from satellite cloud distributions can be related to the presence of cold and warm air respectively.
Figure 3-8 — Illustration of the computation of the current surface geostrophic steering of a tropical cyclone and estimate of direction of motion. The table below shows how the zonal and meridional components of motion are determined using the pressure values at points 1 to 9 inclusive. The direction of motion is estimated by the thin line touching the 1018-mb isobars. See the text for additional details.

<table>
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<td>25°N</td>
<td>$P_1 = 1021.5$ mb</td>
</tr>
<tr>
<td>20°N</td>
<td>$P_4 = 1018.0$ mb</td>
</tr>
<tr>
<td>15°N</td>
<td>$P_7 = 1016.0$ mb</td>
</tr>
</tbody>
</table>

Computation of north-south component

$$P_1 P_4 P_7 = 1018.5 \text{ mb} \quad P_5 P_8 P_9 = 1019.0 \text{ mb}$$

Gradient equals 0.5 mb/10° latitude at 20°N.

Geostrophic steering at 20°N equals 30 kt for 1 mb/1° latitude

$$0.5 \text{ mb} \times \frac{30 \text{ kt}}{1 \text{ mb/1° lat.}} = 1.5 \text{ kt}$$

N-S component = 1.5 kt northward

Computation of east-west component 20°N-25°N

$$P_2 P_5 P_8 = 1021.8 \text{ mb} \quad P_3 P_6 P_9 = 1018.5 \text{ mb}$$

Gradient equals 3.3 mb/5° latitude at 22.5°N.

Geostrophic steering at 22.5°N equals 27 kt for 1 mb/1° latitude

$$3.3 \text{ mb} \times \frac{27 \text{ kt}}{1 \text{ mb/1° lat.}} = 17.8 \text{ kt}$$

Computation of east-west component 15°N-20°N

$$P_3 P_6 P_9 = 1015.7 \text{ mb} \quad P_4 P_7 P_9 = 1018.5 \text{ mb}$$

Gradient equals 2.8 mb/5° latitude at 17.5°N. Geostrophic steering at 17.5°N equals 32.5 knots for 1 mb/1° latitude

$$2.8 \text{ mb} \times \frac{32.5 \text{ kt}}{1 \text{ mb/1° lat.}} = 18.2 \text{ kt}.$$
Pressure changes in the last 6 to 12 hours, with corrections for diurnal variations, have been utilized by certain Meteorological Services for forecasting intensification and direction of movement of tropical cyclones. In India, for example, five-day normal pressure values for individual stations, computed from climatological data for selected synoptic hours, are used for applying diurnal corrections. The corrected pressure change from 00 to 12 GMT is computed from \((P_{12} - P_{00}) - (N_{12} - N_{00})\), where \(N_{00}\) and \(N_{12}\) represent the normal pressure values at 00 and 12 GMT for the respective stations. Pressure tendency charts based on such corrected pressure changes, particularly at island and coastal stations, sometimes provide a good indication of the direction of movement—including recurvature of an approaching tropical cyclone.

The use of pressure changes can be especially helpful in short-range forecasting at critical times. They can help determine landfall/no landfall forecasts, or assist in evaluating track changes during an approaching landfall. Such forecast decisions will not usually be available from objective techniques with sufficient reliability during the short time periods in which relatively small changes in direction can have profound effects. However, they are equally applicable in less critical situations.

It is also important to recognize the outer limit of the tropical cyclone circulation. Pressure changes inside the circulation indicate the cyclone’s direction during the past few hours. In Figure 3-10 the biggest 24-hour pressure change within the cyclone circulation is five millibars at Corpus Christi near Port Aransas. Hurricane Celia went inland just south of Corpus Christi about nine hours later. Pressure changes outside the cyclone’s circulation often indicate future changes in motion. When there are large pressure changes outside the circulation, their effect is to turn the cyclone at right angles to the line connecting the isallobaric centre and the cyclone centre. In Figure 3-11,
Figure 3-10 – The use of 24-hour surface-pressure changes inside the tropical cyclone circulation as evidence of landfall. The cyclone made landfall near the greatest 24-hour change of five millibars at Corpus Christi, Texas (Port Aransas)

the direction of motion of the hurricane 24 hours after map time is perpendicular to the line connecting these two centres at 0000 GMT 1 October. However, the actual location of the perpendicular cannot be determined in advance.

In the lower latitudes, even a small pressure change south-east or south-west of the centre (north-east or north-west in the southern hemisphere) without a compensating pressure change opposite to it may cause a large directional change in the cyclone. This is reflected in the geostrophic steering concept as a consequence of the
large effect of the Coriolis parameter at low latitudes. The slower the tropical cyclone is moving, the more pronounced will be the change in direction — even for a pressure change as small as one millibar.

The difference in the Coriolis parameter across a circular, stationary tropical cyclone may cause a poleward drift of almost one degree of latitude in 30 hours because of the differential advection of the Earth's vorticity by the cyclone itself (Rossby, 1949). The continuation of this effect alone will create an asymmetry which will eventually result in a westward turn of the cyclone (Jones, 1977). While this effect is normally of little consequence, it could have some significance in nearly stationary cyclones near land areas.
Figure 3-12 – The effect of 24-hour 500-mb height changes on tropical cyclone motion (Hoover, 1957)

A corollary aid to surface-pressure changes, especially at higher latitudes, is the use of 500-mb height change patterns where available. Figure 3-12 shows four types of 24-hour 500-mb height change patterns in the westerlies (outside of the tropical cyclone circulation) which Hoover (1957) points out strongly influence the motion. Types A and B are cases where the changes cause acceleration or deceleration with no directional change. Types C and D will turn the cyclone west or east respectively and most likely be accompanied by speed changes also. Deceleration is likely with type C and acceleration with type D.

The main advantage of the surface geostrophic steering concept is that all forecast offices have a surface-pressure analysis and can use it when no other aids are available. The use of pressure or height changes in conjunction with the computation of present motion gives the forecast an added dimension beyond just persistence. In addition, it can help prevent forecast errors based on misinterpretation of centre fix data which implies radical departures from the previous smoothed track. It also aids in determining critical track changes during landfall situations, an occurrence not normally picked up by analog, statistical or dynamic techniques.

The main disadvantage of using the geostrophic steering techniques is their sensitivity to inaccuracies in the surface and upper-air analyses which must be drawn over data-sparse areas. The sensitivity of the computations to the Coriolis effect at lower latitudes can lead to large forecast errors for small (one-millibar) analysis errors. While pressure and height changes help in determining directional and speed changes, their magnitudes and movement relative to the tropical cyclone make the timing of these changes rather difficult.
Operational Techniques for Forecasting Tropical Cyclone Intensity and Movement

Direction of 500mb Wind at P₅

24 Hour Forecast
12 Oct 1964 0000 GMT
320°/06 KT

0000 GMT
11 Oct 1964

0600 GMT
10 Oct 1964

1800 GMT
12 Oct 1964

5° LAT

0000 GMT
11 Oct 1964

(a) The computation

(b) 500-mb streamline analysis for 0000 GMT, 11 October 1964, Typhoon Dot

Figure 3-13 An example of the fixed control-point method for obtaining a 24-hour forecast (Chin, 1970)

3.5.2 The control-point method

This method for predicting the direction of movement of a tropical cyclone is described by Chin (1970) and has been used by the Hong Kong Forecast Centre for several years. It is based on a high correlation between the direction of movement of tropical cyclones and the wind direction at certain points in the middle troposphere. This direction is combined with the mean speed obtained from the \( \frac{1}{2} (P+C) \) technique to arrive at the 24-hour forecast location. The control point lies on a straight line perpendicular and to the right (left in the southern hemisphere) of the past 24-hour displacement vector passing through the cyclone centre.

In the fixed-point method, the point along the perpendicular from 3° to 8° of latitude at 700 mb or 500 mb which gives the smallest mean angular deviation from the cyclone's subsequent 24-hour motion in the data sample is always used as the control point. Experience at the Royal Observatory, Hong Kong, has shown that a different fixed point is more desirable for typhoons (hurricanes) than for weaker tropical cyclones. An example of a 24-hour forecast using the fixed-point method is given in Figure 3-13. Experience at Hong Kong also indicated that results could be improved by taking into account the size of the cyclone circulation to vary the control point. In this variable control-point method the strength of the cyclone is no longer considered.

As described by Chin (1970), the method is as follows. The normal pressure at the position where the tropical cyclone is located is obtained from the regional climatological atlas. Next, the distance from the tropical cyclone to this pressure on the current synoptic chart is measured along a straight line perpendicular to the displacement vector. This distance is plotted against the optimum distance on the nomogram derived from the data sample. It is then assumed that the extent of the circulation at 700 mb or 500 mb is the same as at the surface, and the wind direction at that point is used with the \( \frac{1}{2} (P+C) \) speed to obtain the 24-hour forecast location.
The advantage of the control-point methods is their simplicity and the fact they include some synoptic data beyond climatology and persistence. They are probably most useful south of the subtropical ridge. The accuracy of the required streamline analysis at middle tropospheric levels may be a definite disadvantage in data-sparse areas. Even satellite cloud motion vectors are sparse at these levels. The techniques become inapplicable when the control points are located in the cols of the wind field. However, this usually occurs during stationary or slow-moving cyclone situations except when binary or tertiary systems are in proximity. The techniques then have little forecast value.
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Figure 3-15 - Characteristic changes in cloud patterns associated with directional changes of motion of tropical cyclones (Fett and Brand, 1975)

3.5.3 The Fujiwhara effect

Fujiwhara (1921) first noted the tendency for vortices in proximity to one another to rotate about a point located on a line joining their centres. If the cyclones are of equal size and intensity, this point will be midway between the two centres. The tracks of Typhoons Kathy and Marie of 1964 illustrate the Fujiwhara effect (Figure 3-14). The two typhoons swung around each other during the period 15 to 19 August 1964 and merged into one typhoon on 20 August. During the merging process the circulation of Typhoon Marie apparently weakened and dissipated while the circulation of Typhoon Kathy was maintained.

3.6 Satellite techniques

Studies have been made which attempt to relate past changes in cloud features associated with tropical cyclones to future changes in the direction of movement. Certain assumptions or use of other techniques are necessary to obtain the speed of movement in order to arrive at a 12-or 24-hour forecast location. Two examples of such techniques are:

(a) A study by Fett and Brand (1975) considers six identifiable cloud patterns and extrapolates the rotation of one or several of these features during the past 24 hours to obtain the directional change of motion during the next 24 hours. An analogy is made with the relationship of the turning of a tropical
(a) Central cloud mass, CCM (diameter 100 to 200 km, changes configuration with time, and from one picture to the next); (b) One or two outer cloud bands (separate from central cloud mass, cumulonimbi more developed at downstream end, pattern remains unchanged for several hours); (c) Precursor band (downstream end occurs along the same outward radius as that of the outer cloud band); (d) One or more cirrostratus streamers; (e) Cumulonimbus-free sectors (Lajoie and Nicholls, 1974) cyclone to the hyperbolic point associated with it, as discussed by Sherman (1953). Figure 3-15, reproduced from the study by Fett and Brand, shows the six cloud patterns used. The change in direction is indicated by the extent of rotation of a specific feature from orientation 1 to orientation 2 as illustrated in the figure.

(b) A similar study by Lajoie and Nicholls (1974) of the Australian Bureau of Meteorology used cloud features of the currently available satellite picture to obtain the succeeding 12-hour directional change. The primary feature used is the first outer cloud band beyond the central cloud mass. Tropical cyclones were found to change frequently to the direction given by the line connecting the centre of the cyclone to the most developed cumulonimbus cluster at or near the downstream end (in a cyclonic sense of the inflow current) of the outer cloud band. Cyclones were also found not to move or continue moving towards a cumulonimbus-free sector. Other cloud features noted by Fett and Brand are also considered as refinements to the two primary ones cited. Figures 3-16 and 3-17, reproduced in part from the study by Lajoie and Nicholls, show schematically the cloud features and interpretation of the forecast rules.
Unlike most of the previous techniques discussed in this section, these two satellite techniques have not been used on a routine basis by major tropical cyclone forecast centres and subjected to operational verification. However, the Lajoie and Nicholls study is used operationally at times by the Australian Weather Bureau. The main advantage of these two techniques is their capability to be used in otherwise data-sparse areas. The studies would also indicate that they are capable of catching sharp directional changes which other techniques may not forecast. However, they suffer from the subjectivity inherent in the interpretation of satellite pictures. They also require rather good quality, high-resolution, and/or enhanced infra-red satellite pictures.

Another aid in helping determine the direction of motion of a tropical cyclone is the extension of cloudiness. This corresponds to the depiction of the warm, moist tongue or thickness steering used in other techniques. It has been observed that cloudiness often extends in advance of the direction of movement of tropical cyclones. Thus, cloud photographs obtained from satellites and observations of cloudiness or precipitation reported by coastal stations ahead of the cyclone sometimes provide a good indication of its direction of movement. Figure 3-18 gives an example of a satellite picture illustrating this feature.
The extension of cloudiness along the direction of tropical cyclone movement has been reported by Ramage (1973). An earlier radar study by Tatehira and Itakura (1966) of a typhoon approaching Japan by means of the powerful radar at Mount Fuji also gave indication of such correlation. Successive locations of the observed spiral cloud band were in good agreement with the impending movement of the recurving typhoon.

Westward-moving cyclones sometimes interact with travelling upper-air troughs in the westerlies and recurve towards the north-east. Chan (1978) noted that the recurving of a tropical cyclone over the western North Pacific is related to the following parameters which can be determined from satellite imagery:

(a) $D/d$, where $D$ is the diameter of the central dense overcast of the tropical cyclone and $d$ the average width of the cloud band associated with the interacting trough;

(b) $\theta$, the angle between the axis of the cloud band and the latitude of the tropical cyclone centre.

When the value of $\theta$ lies between $30^\circ$ and $40^\circ$, it is highly probable that a tropical cyclone will recurve if $D/d$ is less than 1.5.
REFERENCES


CHAPTER 4

STATISTICAL TECHNIQUES
(by C. J. Neumann *)

4.1 Introduction

In this chapter, subject matter relating to statistical prediction of tropical cyclone motion will be discussed. This includes historical background, some basic guidelines on the development of statistical models and a qualitative assessment of the advantages, disadvantages and performance characteristics of the various classes of statistical models. Also included are several appendices listing some applicable computer program segments, some mathematical treatment of probability ellipses and material pertinent to the important but often overlooked question of significance tests. Excluded are quantitative verification statistics on the performance of the various models. This topic is covered in Chapter 10.

Statistical models for predicting tropical cyclone motion can be grouped into two broad categories: those models based on analogs and those based on regression equations. The latter, in order of increasing sophistication, can be further categorized as follows:

(a) Those models which use predictors based on climatology and persistence;
(b) Those models which include, but which are not limited to, predictors derived from observed synoptic data;
(c) Those models which include, but which are not limited to, predictors derived from numerically-forecast data.

The models indicated under (c) are known as statistical/dynamical models, while those under (a) and (b) have been referred to respectively as simulated analog models and classical models. The term statistico-synoptic has also been suggested (Annette, 1976) for the models indicated under (b).

4.2 Analog models

4.2.1 Historical development

The development of the first fully operational model for predicting tropical cyclone motion by analog methods was a by-product of the United States Space Program. At the request of program officials, Hope and Neumann (1968) and Neumann (1969), using techniques suggested by Haggard et al. (1965), developed computerized methods of providing launch directors with the climatological probability of winds from a tropical cyclone eventually affecting the Kennedy Space Center. Shortly thereafter, Hope and Neumann (1969, 1970) adapted the method to the 72-hour forecast requirement of the United States National Hurricane Center, Miami, Florida. The technique, known by the acronym HURRAN (HURRICane ANalog), has been in continuous use at the Center since the beginning of the 1969 hurricane season (Simpson et al., 1970).

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Concurrently and independently, Hodge and McKay (1970) collaborated with the United States Navy and developed an analog prediction model for North Pacific typhoons. Their model, known as TYFOON, was revised and extended by Jarrell and Somerville (1970) and became operational at the U.S. Fleet Weather Central/Joint Typhoon Warning Center, Guam, in August 1970. Like its counterpart in the Atlantic, TYFOON proved to be moderately successful. Part of the popularity of analog models relates to the presentation of forecasts in terms of probability ellipses, the latter providing a considerable amount of diagnostic information (Simpson, 1971).

Following the introduction of HURRAN and TYFOON, the analog concept became quite popular. Through the WMO international exchange programme, the HURRAN system was introduced to the Indian Meteorological Service and adaptations were made for the North Indian Ocean by Gupta and Datta (1971). Another analog-like model for the Indian Seas was developed by Sikka and Suryanarayana (1972). The Gupta and Datta model was then modified by Brand et al. (1974) for operational use by the United States Navy, which then prepared analog models for the remaining tropical cyclone basins. Among the models included were a revised one (TYFOON-72) by Jarrell and Wagoner (1973) for the North Pacific, one by Brand et al. (1974) for the south-west Indian Ocean, one by Jarrell et al. (1975) for the north-eastern Pacific and finally, completing the cycle, one by Brand and Blelloch (1976) for the south-west Pacific and Australian area.

Other Meteorological Services have developed experimental or operational analog models. These include the CYCLOGUE model (Annette, 1976) for the Australian area, a model for the Malagasy Republic (Neumann and Randrianarison, 1976) and an adaptation of the HURRAN model for the People's Republic of China (Chen, Liangshou, 1977).

4.2.2 The analog concept

Temporal and spatial analyses of tropical cyclone tracks show that they tend to be repetitive and to be associated with identifiable and likewise repetitive synoptic patterns. In Figure 4-1, for example, the well-defined storm track extending from the western Caribbean Sea, northwards into the Gulf of Mexico and thence north-eastwards into the Atlantic Ocean, reflects the influence of eastward-moving troughs in the poleward westerlies. On the other hand, the well-defined east-south-east to west-north-west-oriented storm track through the Caribbean Sea set out in Figure 4-2 can be shown to be typically associated with a ridge of high pressure to the north of the storm. Similar examples can be drawn from other tropical cyclone belts.

Analog models capitalize on the ability to identify families of storm tracks. Through a series of computer algorithms, a current storm is associated with its parent track, thus allowing inferences to be made about the future behaviour of the storm. The analog concept is not new; tropical cyclone forecasters have been using subjectively-founded analog principles for a number of decades. Unfortunately, the large amount of manual data processing precluded routine objective use of the method. However, the gradual introduction of computer technology into offices responsible for forecasting tropical cyclones provided, and continues to provide, a means of rapidly archiving, retrieving, screening and processing large numbers of historical storm tracks.

4.2.3 Historical storm tracks

The development and operational usage of an analog model require the availability of archived storm tracks. Except for the north-eastern Pacific, reasonably reliable records of tropical cyclone tracks date back to the previous century. In the above-cited area, adequate data do not exist prior to the introduction of weather satellites in the early 1960s (Sadler, 1964). In considering the reliability of historical tracks (particularly before or without the availability of aircraft reconnaissance and weather satellites) one must consider a number of factors. Included would be the number of synoptic reporting stations, the intersection of tropical cyclone tracks with shipping lanes, the documentation guidelines specific to given Meteorological Services and perhaps, most importantly, the care which went into the formulation of the tracks from the often fragmented information available.
The question naturally arises as to the effect of track positioning inaccuracies on the performance of analog models. Obviously, it is a factor. Experience has shown, however, that over the open oceans the effect is minimal. The compositing nature of the analog process tends to average out random errors. However, the premature termination of storm tracks once they cross coastlines or after they become extra-tropical can produce serious biases to analog-founded forecasts. These biases will be discussed in a later subsection.

Punched computer card decks or magnetic tapes containing tropical cyclone track data for each of the six tropical cyclone basins are available from the United States Department of Commerce, NOAA, National Climatic Center which is located in Asheville, North Carolina, U.S.A. A complete description of these data is given by Crutcher and Quayle (1974). In most cases, meteorological summaries published by the countries located within the various basins were used to prepare these storm-track files. In the Pacific area, for example, the tracks are based principally on the work of Chin (1972), and in the Atlantic on that by Cry (1965).

The data files described in the preceding paragraph typically contain storm positions twice per day and some measure of storm intensity. For many purposes, including the implementation of some of the operational models discussed in subsection 4.2.1, as well as for computer plotting of storm tracks, storm positions are required at intervals more frequent than once every twelve hours. Accordingly, a non-linear interpolation scheme must be used to obtain the intermediate positions. Experience in the Atlantic area has shown that the polynomial interpolation method described by Akima (1970) gives highly satisfactory results. A FORTRAN program listing of Akima’s method is included as Appendix 4.A.
4.2.4 The analog selection process

The analog process identifies historical storms temporally and spatially similar to a current storm. In a typical analog system, analog candidates are selected by considering such factors as time of year, the storm’s initial direction of motion and speed and the position of the analog storm relative to the current storm. Selected analog tracks, translated to a common origin, and combined with persistence, form the basis of the final forecast.

Experimentation in other tropical cyclone basins, notably by the U.S. Navy Environmental Prediction Research Facility (NAVENVPREDRSCHFAC) and the U.S. Naval Postgraduate School located in Monterey, California, has led, and continues to lead, to many refined selection criteria tailored to specific tropical cyclone basins. These refinements include analog weighting schemes, consideration of past as well as current motion, better combinations of climatology and persistence, etc. For details, the reader is referred to specific analog models indicated in subsection 4.2.1.

4.2.5 Probability ellipses

Analog forecasts are typically presented to the user as probability ellipses. The most probable track is given as the centroid of these ellipses. Less likely tracks are suggested by the size, shape and orientation of the elliptical bounds. An example of a tropical cyclone forecast track with superimposed 50 per cent probability ellipses is shown in Figure 4-3. Fifty per cent of the forecasts can be expected to fall within the elliptical bounds. It can be noted from the orientation of the 12- and 24-hour ellipses along, rather than perpendicular to, the track that the forecast problem can be expected to be one of speed rather than direction for the early portion of the forecast period. Probability ellipses represent the projection of a three-dimensional bivariate normal surface on a two-dimensional plane.
A brief mathematical treatment as given by Hope and Neumann (1970) is set out in Appendix 4.B and a FORTRAN listing of a computer program to fit $N$ pairs of $x, y$ data to a bivariate normal distribution is given in Appendix 4.C.

The question arises as to the choice of this particular density function to represent storm motion. Although Crutcher (1971) provides sufficient justification for its use over open oceanic areas, there are indeed many areas where the assumption of bivariate normality does not hold. This would include regions where storm tracks are locally influenced by topography. Also, in some cases, large land masses bring about divergent storm tracks and the statistical evolution of storms downstream from this point is best described by a bimodal rather than a unimodal bivariate normal distribution. The topic is discussed by Crutcher (1977). Failure to recognize the presence of a bimodal distribution will result in the elliptical centroid representing a less likely rather than a most likely storm track.

Further use can be made of the probability ellipse data. By integrating the bivariate normal density function (Equation (1) in Appendix 4.B, Hope and Neumann (1970)) over a circular area ($A$),

$$
\int_A \int P(x, y) \, dx \, dy
$$

one can obtain the probability of a storm being within a given area at a given time. The FORTRAN program listing to perform this numerical integration appears as an appendix to Crutcher (1971). Such an integration provides the capability of giving the probability of a storm being within some given distance of any specified city during the forecast period. A specific example of the utility of this approach over the Indian area is given by Neumann and Mandal (1977).
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4.2.6 Advantages and disadvantages of the analog method

Properly used, the analog method (including superimposed probability ellipses) is a powerful tool. In the hierarchy of diagnostic aids available to the operational forecaster, it is generally the first forecast available and as such represents the first guess in so far as the forecaster's decision ladder (Simpson, 1971) is concerned. Modification of the forecast is warranted only after consideration of past, current and forecast tropospheric flow patterns. In some tropical regions, the lack of reliable synoptic information indeed warrants accepting the analog forecast with little or no modification. Even with the availability of synoptic data, Neumann and Hope (1972) point out the relative superiority of the method when storms remain embedded in the easterlies. One of the main advantages of the analog is its relative simplicity. Along with regression equation models which incorporate analog-like predictors, it is typically the first guidance received by the forecaster. The method provides a maximum amount of information from a minimum amount of computer time. On advanced computer systems the entire process, including the scanning of 100 years of historical storm tracks, takes but a few seconds. On older model computers, however, the input and processing of the storm tracks are a fairly slow process and can take up to 30 minutes of computer clock-time depending on the number of archived storms. This could be a serious problem at forecast centres which lack sufficient computer power.

Analog forecasts should be recognized for what they are. They represent typical or normal tropical cyclone behaviour. Deviations from normal in the deep tropics are small and analog forecasts are often difficult to improve upon. Poleward, into the westerlies, anomalous situations are much more common and analog forecasts, as reflected in the large size of the probability ellipses, are more unreliable. In some cases (about one out of three in the Atlantic area) the forecast situation is too anomalous for an analog method to arrive at a solution. This is one of its main shortcomings and, in general, it can be stated that the analog method by itself is not a good forecast tool when storms are recurving into the westerlies. For a treatment of typical analog error characteristics both for storms in the easterlies and westerlies, the reader is referred to Neumann and Hope (1972).

Another disadvantage of the analog method concerns the introduction of forecast bias under certain situations. Jarrell and Wagoner (1973) illustrate such a bias towards recurving storms in the western Pacific while Neumann and Leftwich (1977) illustrate such a bias towards non-recurving storms over the eastern Pacific. These biases typically occur when, for one of a number of reasons, storms are prematurely dropped from the storm history tape and the forecast is excessively influenced by the remaining storm tracks.

To summarize therefore, although analog models have certain frailties, they should be included in the prediction model inventories of any forecast office having forecast responsibility in the tropics. The models are relatively easy to formulate and require only a minimum of computer power for operational implementation. Properly interpreted, they are a powerful tool and represent a first guess to the final operational forecast.

4.3 Regression equation models

4.3.1 Historical development

Although statistically founded rules of thumb have always been used in tropical cyclone forecasting, the first really objective system for predicting 24-hour tropical cyclone motion is generally attributed to Riehl et al. (1956). The method, known as “Riehl-Haggard”, was based on the steering principle that the tropical cyclone moved in proportion to the speed of the vertically integrated flow surrounding the vortex. The 500-mb level was used to approximate this flow and the height difference across a small grid was found to be significantly correlated with subsequent 24-hour storm motion.

The 500-mb-based Riehl-Haggard method was developed on Atlantic storms. More or less concurrently in the Pacific, Wang (1954, 1956, 1970) developed statistical regression equations relating 24-hour storm motion to pre-
dictors selected from the 700-mb level. Miller and Moore (1960), after examining other levels, also selected 700 mb together with persistence as the basis for the “Miller-Moore” method in the Atlantic. Arakawa (1963a) and Tse (1966) developed similar sets of prediction equations for the Pacific as did Kumar and Prasad (1973) for the north Indian area. The Tse method is somewhat unique in that one of five sets of regression equations was used, depending on the existence of one of five easily identifiable 700-mb patterns. The method is one of six objective methods currently used by the Royal Observatory, Hong Kong (Chin, 1976, 1977) for the preparation of 24-hour forecasts of tropical systems.

Each of the above-cited methods uses a relatively small steering grid or its equivalent to forecast 24-hour tropical cyclone motion. However, because of their sensitivity to the initial analysis, all suffer from the subjectivity of uncertain analysis over the storm area.

In the late 1950s and early 1960s, the Travelers Weather Research Center was quite active in objectivizing Atlantic area hurricane forecasting procedures and many significant papers appeared. Veigas et al. (1959) applied powerful stepwise screening regression methods tailored and programmed for meteorological application by R.G. Miller (1958). Rather than restrict the source of predictive information to the storm vicinity, Veigas used predictors from a large storm-centred grid to relate systematically large-scale weather patterns as well as steering to subsequent 24-hour hurricane motion. This method, known as T-59, was subsequently modified as the T-60 (Veigas, 1961 and 1962) method. Both T-59 and T-60 had the advantage of being less sensitive to the initial analysis near the storm area. Modified Veigas-Miller methods are still used operationally at the Royal Observatory, Hong Kong (Chin, 1976). Arakawa (1963b, 1964) also used the large-grid approach of Veigas-Miller as applied to both the surface and the 700-mb levels.

A major advance in statistical prediction of hurricane motion occurred with the development of the NHC64 method (Miller and Chase, 1966) by the U.S. National Hurricane Research Laboratory in Miami, Florida. The technique used R.G. Miller’s (1958) stepwise screening regression program to select systematically predictors from the surface, 700- and 500-mb levels. The rationale behind NHC64 was to combine the better features of the Travelers, Miller-Moore and Riehl-Haggard methods into a single model. The prediction equations were designed to predict hurricane motion over a period of 48 hours. Subsequently, the system was expanded to produce forecasts through the 72-hour forecast period. The application of these stepwise screening regression models was primarily responsible for a significant increase in forecast skills at the National Hurricane Center in the early 1960s (Dunn et al., 1968).

In the United States prior to the year 1965, the analyses at the surface, 700- and 500-mb levels as required by the various objective techniques were hand produced. Obtaining the necessary gridded parameters was an extremely laborious and subjective procedure. However, in 1965 the NHC64 model was programmed to use the objective 1000-, 700- and 500-mb analyses produced by the U.S. National Meteorological Center. This greatly expedited the delivery of the final forecast product to the forecaster responsible.

Miller et al. (1968) revised the NHC64 model in 1967. The revision, known as NHC67, is still in use at the National Hurricane Center in Miami. The revision incorporated several additional years of dependent data allowing for a finer stratification based on the storm’s initial location and speed of motion.

The late 1960s saw the initial development of operational analog models. As previously pointed out, one of the shortcomings of analog models is their inherent inability to provide a forecast under anomalous weather situations. This is particularly troublesome when an analog forecast is used as input to a higher echelon prediction model. Another difficulty with analog models is the large amount of clock-time required for a small computer system to scan through the storm track file. To offset these difficulties, Neumann (1972) developed a statistical model for the Atlantic area known by the acronym CLIPER (CLImatology and PERsistence). This rather simple regression equation model uses the same predictors in the functional sense as used in the non-functional sense by analog models. Indeed it has been referred to as a simulated analog model. Prediction systems similar to CLIPER have recently been developed for the South Indian Ocean (Neumann and Randrianarison, 1976), for the North Indian Ocean (Neumann and Mandal, 1977) and for the eastern North Pacific (Neumann and Leftwich, 1977).
Operational use of analog and simulated analog models in the early 1970s showed that they were making better use of climatology and persistence than were earlier models whenever storms were embedded in the easterlies. When storms recurved out of the tropics, however, these models proved to be inferior to older models such as NHC67 which were cognizant of environmental flow patterns. Accordingly, Neumann et al. (1972) blended the better features of both approaches into the Atlantic area NHC72 model.

In the early 1970s a large number of Atlantic storms with anomalous motion characteristics highlighted the inherent inability of the purely "classical" models typified by NHC67 and NHC72 to forecast such motion with acceptable accuracy. This gave impetus to the development of the so-called statistical/dynamical (as well as the purely dynamical) models which conceptually should respond better to anomalies. Such models use the output from a numerical model as input into a statistical prediction framework. Veigas (1966) experimented with this approach but achieved relatively little success, due presumably to the questionable value of the late 1950 and early 1960 barotropic prognostic charts over the tropics. A much greater degree of success (principally on the longer-range forecasts) was achieved by Neumann and Lawrence (1975) with the statistical/dynamical NHC73 model. Here, certain predictors are selected from the 24-, 36- and 48-hour 500-mb geopotential field forecasts as produced by the U.S. National Meteorological Center Primitive Equation (PE) model (Shuman and Hovermale, 1968). Another statistical/dynamical model developed by Nomoto et al. (1976) is being tested by the Japan Meteorological Agency on western North Pacific typhoons.

The term statistical/dynamical can also be applied to the HATRACK (hurricane and typhoon tracking) (Renard, 1968) and the MOHATT (modified HATRACK) (Renard et al., 1973) techniques used at the U.S. Joint Typhoon Warning Center (JTWC), Guam. Regression equations are not used. Instead tropical cyclones are geostrophically steered in six-hourly time steps using the U.S. Navy’s smoothed numerical 500- or 700-mb prognoses from which the vortex is initially subtracted. The operational forecasts starting at a time \( T \) are based on a previous forecast cycle starting at time \( T - 12 \) hours, thus allowing for an error measurement of the motion for the first 12 hours of an 84-hour projection. This error, assumed to be a bias, is linearly applied, with certain constraints, to the remaining 72-hour forecast track. Conceptually, the method is quite appealing. A practical difficulty arises, however, in that the error contains both deterministic and random-like components. In an operational environment, these cannot be separated, and the extrapolation of the latter can lead to unpredictable results.

4.3.2 Development of regression equation models

In meteorological literature, one may find a number of examples of statistically-oriented procedures which violate basic principles of classical statistics. Such procedures, often showing great promise on development data, may give disappointingly poor results when used in an operational environment. The problem can generally be traced to one of two factors. Either the prediction equations lack adequate statistical significance, that is to say they contain a large random error component, or the characteristics of the operational data (means, standard deviations, etc.) differ significantly from the data set from which the model was developed. To avoid such unexpected pitfalls, it is highly recommended that the meteorological researcher obtain a working knowledge of statistical principles before attempting to develop a statistical model. The problem is succinctly summed up by the pre-computer-age applied statistician Mills (1955), who states that "Wisdom in the selection of functions, time units, strategic periods, etc. requires some understanding of the ground plan of nature in the particular field of study, as well as competence in the application of statistical techniques. The task of analysis is never purely mechanical."

The ready availability of complex statistical procedures through the scientific subroutine packages available at most large computer installations does, contrary to Mills's axiom, seem to make the process purely mechanical. Indeed, such programs are powerfully sharp tools. However, to quote further from Mills, "Sharp tools may be grievously misused without this deep familiarity with reality in the area of investigation... if such techniques are to be well and wisely employed, they must be adapted, with understanding, to the materials under study." Following Mills’s philosophy the remainder of this subsection will concern itself with some didactic principles relating to the development of statistical models.
4.3.2.1 Use of a test-statistic

Because of the many pitfalls in the development of statistical models, it is customary and desirable to assess the operational performance of a model subsequent to its development in a research environment. This assessment can take one of several forms. The classical F-test, named after R. S. Fisher by Snedecor (1946), is typically used as a test-statistic in many statistical computer packages. Like other test statistics, it is designed to assess the play of chance in the relationship between variables. Use of the test is perfectly valid but assumes rigid adherence to certain basic assumptions inherent in the theoretical F-distribution function. The use of the F-test to assess the significance of meteorological prediction models developed from the stepwise screening regression concept violates several of these assumptions. Two of these violations can be readily identified by considering an expression typically used to determine the value of the F-statistic, $F_s$ (as distinguished from the theoretical $F_t$) from the variance analysis,

$$F_s = \frac{r^2}{m} \left/ \frac{1 - r^2}{N - m - 1} \right.$$

(2)

where $r$ is the multiple correlation coefficient, $m$ is the number of predictors in the regression equation and $N$ is the sample size. The computation of $F_s$ from Equation (2) assumes that individual cases comprising the data set are serially independent. Since storm parameters are usually measured and archived every twelve hours, this is obviously
not the case. Thus $N$, in Equation (2), is greatly inflated and in turn yields a higher value of $F_s$. Since large $F_s$ is associated with greater significance, this can lead to acceptance of a prediction equation when perhaps it should have been rejected.

To avoid this pitfall, $N$ must be effectively reduced in proportion to the amount of correlation between successive observations, typically taken at 12-hour intervals. An approximation to this reduction can be obtained by the application of the classical statistical “run-theory” as described by Siegel (1956) and applied by Enger et al. (1964). Application of this test to the Atlantic tropical cyclone basin shows that $N$ in Equation (2) should be divided by a factor of approximately 3.5 to achieve effective serial independence. Thus, 350 cases of actual data would be equivalent to only 100 cases of effectively independent data in so far as the amount of predictive information is concerned. Since regional differences play a role in the magnitude of this factor, it is recommended that the run-test described by Siegel be applied separately to given tropical cyclone basins. Even within given basins, however, there are considerable temporal and spatial variations to the effective reduction. Further information on the test is given in Appendix 4.D.

In the use of Equation (2) another pitfall relates to the quantity $r$ (multiple correlation coefficient). The synoptic data predictors used by statistical prediction models are typically screened from a large body of predictors given by storm-centred moving grids. Figure 4-4 shows one such grid that has frequently been used for introducing multi-leveled geopotential height data into Atlantic area models. An analysis of the predictors used by these models shows that they are typically selected in pairs. These pairs represent gradients, thicknesses, temporal height changes.

Figure 4-5 - Distribution of multiple correlation coefficients obtained by activating a stepwise screening regression program exactly 100 times on randomly selected predictands (from Neumann et al., 1977)
or combinations thereof. Many of these pairs (for example, those related to geostrophic gradients across a storm) can easily be identified. Other pairings are more subtle. The stepwise screening procedure (Efroymson) looks at one predictor at a time. Accordingly, there is no guarantee that all pairings will be recognized. However, to ascertain that a given predictor and its mate are at least potentially available, it is customary to make a large number of predictors simultaneously available. Modern computers can handle as many as 250.

The inclusion of so many potential predictors has some undesirable side effects. Some of these relate to programming difficulties. The main problem, however, is a marked increase in the chance relationships among variables. Indeed, the problem becomes so acute with large numbers of available predictors that without proper safeguards an entire prediction model can be built around random data. Basing his research on the work of Lund (1970), Neumann et al. (1977) used Monte Carlo methods to investigate the scope of the problem as it relates to the formulation of statistical models. Figure 4-5 shows the distribution of multiple correlation coefficients which one obtains by activating a stepwise screening regression program exactly 100 times on a randomly selected predictor. In this example, the limited sample size \( (N) \) consisted of 127 cases, and 12 out of 120 potential predictors \((k)\) were allowed to be selected. In half of the screening runs, the multiple correlation coefficient \((r)\) exceeded 0.56. By varying the number of available predictors \((k)\) and holding sample size \((N)\) and number of predictors selected \((m)\) constant, the authors obtained the family of distributions shown in Figure 4-6. Here, the inflationary effect of large numbers of available predictors is clearly evident. It follows from Figure 4-6, for example, that the experimentally determined 99 per cent significance level of the multiple correlation coefficient reaches 0.71 when 12 out of 250 possible predictors are selected from a sample size of 127 cases. It can be noted that the computation of \( F_s \) from Equation (2) in no way
accounts for the availability of more predictors than are eventually chosen for retention. The critical value of $F_p$ in this case (degrees of freedom 12 and 113) is associated with a correlation coefficient of only 0.48. Thus, prediction equations with $k$ equal to 40, 120 and 250 would have been judged significant most of the time even though they were developed from randomly selected predictands.

While Figures 4-5 and 4-6 specifically address the problem of excess predictors they do not provide guidance for other than the case of $m = 12$ and $N = 127$. Miller (1958, 1966, 1976) addressed the problem of screening large numbers of predictors for any combination of degrees of freedom and $k$. To test the significance of the $i$ th predictor of an $m$-predictor equation he suggests replacing the regular tabular value of $F_p$ at, say, the 95 per cent level, which can be expressed as:

$$F_{,95} = F(1 - 1/20)$$

(3)

†The term degrees of freedom refers to the real rather than the apparent number of cases.
Figure 4-8 – Observed displacement errors of the CLiPER (Neumann, 1972) statistical forecast model for the Atlantic 1973 hurricane season (left scale) and percentage reduction in these errors (right scale) by using best-track data. Numbers in parenthesis give sample size.

by an adjusted value,

\[ F^{*}_{0.95} = F(1 - 1/20k) \]  

(4)

Since \( F^{*}_{0.95} \) will normally compute to a value for which tables are not available, Miller suggests the use of the inverted Paulson (1942) function for determining its approximate value. The procedure is described in Appendix 4.E. \( F^{*}_{p} \) is then compared to \( F^{*}_{0.95} \) and an additional predictor is assumed significant at the 95 per cent level if \( F^{*}_{p} \geq F^{*}_{0.95} \).

4.3.2.2 Independent data as a test-statistic

Statistical models typically consist of a number of regression equations bound together in some sort of prediction algorithm. A method often used for assessing the statistical significance of the entire package is to test its performance on independent data. Such data, in effect, can be considered as a kind of test-statistic and, in a qualitative way, they establish the reliance of the model. However, in most tropical cyclone basins, the sample size is too short to lay aside a subset for testing purposes. Prudence suggests that all models should be tested on operational data (which may differ from independent data) before a system is finally accepted. However, it is suggested that this operational test be used to confirm a prior statistical hypothesis rather than as a test per se.
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Figure 4-9 – Linear correlation coefficient field between 24-hour zonal tropical cyclone motion and 500-mb geopotential height field. Hatching shows areas of negative correlation

4.3.2.3 The effect of non-homogeneity in data sets

For a number of reasons, most relating to convenience, data sets used to develop statistical prediction models are derived from best-track data. Persistence, in the form of an initial motion vector, is thus known with a greater precision than it is under operational conditions. In so far as the development of statistical models is concerned, predictors derived from these best-track data are given too much weight in the statistical analysis. It is suggested, therefore, that best-track derived data be contaminated somewhat to make them less attractive to the screening program and more commensurate with reality. The easiest way to accomplish this is by defining the error characteristics between a recent common record of both best-track and operational initial motion vectors. These errors, possibly fitted to a statistical distribution, can then be randomly appended to older best-track data. The entire procedure is described in some detail in Neumann (1975).

Another problem arises when operationally available surface and upper-air data exhibit statistical characteristics different from those of the development data set. Such a situation can occur, for example, when older hand-drawn analyses are replaced by an objective analysis procedure. While both modes of analysis are apt to be similar in data-rich areas, significant differences may occur in the data-void areas typified by the tropical cyclone belts. Some analysis methods, for example, may not include the storm circulation. In the case of a model which assumes the presence of a storm vortex, this can lead to unpredictable and undesirable results.

Another problem relates to the low-standard deviations typically associated with geopotential height fields in the tropics. Some of these standard deviations are made fictitiously low due to the climatological component inherent in archived hand-analysis, often used to develop statistical models. In a simple regression equation relating the displacement of a tropical cyclone (predictand) to the geopotential height at some point (predictor) the regression coefficient is given by the product of the correlation coefficient and the standard deviation of the predictand divided by the standard deviation of the predictor. Thus, if the standard deviation of the height values is too low,

†The term best-track refers to the final, archived storm track as distinguished from the more uncertain operational track.
the regression coefficient becomes too high, assuming a reasonable (possibly non-significant) correlation between predictand and predictor. The net effect of this is to make the forecast extremely sensitive to the analysis. This, possibly more than any other single factor, has discouraged the use of synoptic parameters as statistical predictors of tropical cyclone motion over the deep tropics. If the standard deviation of a geopotential height falls below 15 metres, it should probably not be used as a predictor. This value is approaching the errors in the measurements of upper-level height fields and those inherent in the different analysis schemes.

4.3.2.4 Sources of statistical predictive information

The predictors traditionally used to reduce the variance of tropical cyclone motion are selected from one or more of three sources, i.e. climatology, persistence and synoptic data. As emphasized by Neumann and Hope (1973), any optimized statistical model must derive a portion of its predictive skill from each of these three sources. An additional source of possibly independent predictive information is being provided by weather satellites. The full potential of this medium for this purpose has yet to be fully exploited. However, Fett and Brand (1974) as well as Lajoie and Nicholls (1974) demonstrate the feasibility of the concept.

Figure 4-7, adapted from the data used to derive that Atlantic NHC72 model, illustrates the relative variance-reducing potential of each of these three sources of predictive information over the Atlantic tropical cyclone basin. In the overall sense, it can be noted that larger reductions are associated with zonal motion. However, because of the relative nature of the quantity “reduction of variance” (see Equation 5), undue significance should not be associated with this result. For meridional motion, it can be seen that climatology, consisting of present storm motion and time of year, is a practically worthless predictor. That is to say, knowing the latitude and longitude of a storm says little about its future meridional motion. In the case of zonal motion, however, climatological knowledge does offer some predictive information. The curves labelled ‘P’ in Figure 4-7 give the reduction of variance obtained from using the present and past motion of a storm as predictors of future motion. The availability of continuous satellite views of storms does provide a reasonably accurate picture of past storm motion. However, the determination of a conservative present storm motion vector in an operational environment is more difficult since the current motion is imperfectly known. Consequently, the full predictive potential of persistence, as envisaged in Figure 4-6, cannot be realized.
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Figure 4-11 – Partial correlation coefficient field between 24-hour meridional tropical cyclone motion and 500-mb geopotential height field, given that variance reduction from starred predictor has already been accounted for. Hatching shows areas of negative correlation.

Figure 4-12 – Partial correlation coefficient field between 24-hour meridional tropical cyclone motion and 500-mb geopotential height field, given that variance reduction from both starred predictors has already been accounted for. Hatching shows areas of negative correlation.
Neumann (1975) discusses the impact of correct initial motion vectors as it relates to tropical cyclone forecasting. Figure 4-8, taken from this source, demonstrates the improvements which can be effected to one statistical model by the use of a best-track derived initial motion vector rather than an operationally-defined motion vector.

Returning to Figure 4-7, the curve labeled 'S' refers to the reduction of variance typically obtained from synoptic data. In this example, six fields of synoptic data were made available to a stepwise screening regression program on grids identical to the grid shown in Figure 4-4. These included the 1000-700- and 500-mb current and 24-hour-old fields at these same levels. In the shorter range forecast periods, a priori reasoning, as well as the early work of Riehl et al. (1956), Miller and Moore (1960), and others— as recently confirmed by George and Gray (1976, 1977)— shows that the synoptic-scale storm motion (as distinguished from small-scale, trochoidal storm motion) is largely controlled by the surrounding steering forces.

For the longer range forecasts, predictors are typically selected from areas farther removed from the storm centre. These predictors are indicative of future steering forces. Since the analysis uncertainties are greater in and immediately around the storm area, the 'S' curve takes on the shape shown in the figure. As pointed out by George and Gray (1976), given better data definition in and around the storm centre, however this may come about, it is logical to assume that greater variance reductions for the short-range forecasts could be attained from surrounding environmental parameters. However, present storm motion, being a direct measure of the integrated steering forces, would probably continue as a major source of variance reduction.

The shape of the curves shown in Figure 4-7 exhibits large regional variations. The variations are discussed in Neumann and Hope (1973). As storms recurve into the westerlies, for example, the initial variance-reducing potential of persistence is soon compromised by often rapidly changing synoptic patterns. Hence, in these areas, synoptic considerations take on increased significance. Accordingly, it will be difficult to improve on the performance of statistical prediction models in these areas unless:

(a) Analysis in and around the storm area is improved;

(b) Account is taken of changing synoptic patterns by the introduction of the output from numerical models into a statistical prediction framework.

4.3.2.5 Partial correlation coefficients

Further insight into the predictive potential of synoptic data is provided by Figures 4-9 to 4-12. These give the correlation and partial correlation coefficients between 24-hour tropical cyclone motion and 500-mb heights. The sample size consists of 339 tropical cyclone forecasting situations occurring between the years 1946 and 1974. The hand-drawn correlation analyses are based on computations at each of the 8 x 15 movable grid points augmented by a bivariate interpolation method described by Akima (1973). For proper spatial perspective, the storm has been placed at the average position of the 339 individual cases making up the sample.

In making further interpretations of these data, it is necessary to consider the relationship between the multiple correlation coefficient ($R$), reduction of variance ($RV$), the standard error ($SE$) and the standard deviation ($SD$), where the standard error represents the standard deviation about the fitted regression hyperplane rather than about the mean. This relationship is given by:

$$RV = R^2 = 1 - SE^2/SD^2$$

(5)

Thus the reduction of variance is a quantity relative to the attributes of a given sample. This fact must be kept in mind when one attempts to compare the reduction of variance or correlation coefficients obtained from different data sets. Thus, a correlation coefficient of, say, 0.9 from data set $A$ and 0.8 from data set $B$ does not necessarily imply a lower standard error from set $A$. This factor should be kept in mind before attempting to make intercomparisons between, say, Figures 4-8, 4-9 and 4-10.
Given the correlation field shown in Figure 4-9 with all 120 grid points of the 8 x 15 grid available for selection, a stepwise screening regression program would select the grid-point located two positions north of the storm as the most significant predictor of zonal motion out through 24 hours. Following Equation (5) approximately 65 per cent reduction of variance ($R^2$) is provided by the height value at this single grid point. Similarly, in Figure 4-10, the grid point located directly (434 nautical miles) north-west of the storm would be selected as the best single predictor of 24-hour meridional motion. The reduction of variance, 0.21, is much less than that provided in the case of zonal motion.

Following the initial selection of a predictor, subsequent selection of additional predictors is a much more complex process and depends on the inter-relationships among variables. These relationships are given by partial correlation coefficients. A partial correlation coefficient $r_{ij,k}$ is defined:

$$r_{ij,k} = (r_{ij} - r_{ik} r_{jk}) / \sqrt{(1 - r_{ik}^2) (1 - r_{jk}^2)}$$

where the notation $r_{ij,k}$ refers to the linear correlation coefficient between predictand $i$ and predictor $j$, given that predictor $k$ has already entered the regression; $r_{ij}$ is the correlation coefficient between predictand $i$ and predictor $j$; $r_{ik}$ is the correlation coefficient between predictand $i$ and predictor $k$; and $r_{jk}$ is the correlation coefficient between predictors $j$ and $k$. The entire procedure is discussed in considerable detail in Mills (1955), pages 637-643.

The square of the partial correlation coefficient gives the fractional reduction of the unexplained variance remaining from the previous and not the original (zero-order) step. Hence these reductions cannot be added to obtain the total fractional reduction of the original variance. The total reduction of variance between predictand $i$ and predictors $j$ and $k$ is given by:

$$R^2_{i,j,k} = 1 - (1 - r_{ik}^2) (1 - r_{jk}^2)$$

Application of Equation (6) to each of the grid point in Figure 4-10 yields the pattern shown in Figure 4-11. Here a new maxima of correlation, with opposite sign, appears slightly to the north of a point 600 nautical miles east of the storm. The maximum gridpoint value of $r_{ij,k}$ is 0.55. Substitution in Equation (7), using the value of 0.21 for $r_{ik}^2$ gives a total reduction of 0.45. Thus, the incremental reduction from the previous step is 0.24. This is greater than the reduction offered by the original zero-order step. The explanation is related to the fact that, although the two predictors are working as a pair, the screening selection process considers only one predictor at a time. It can be noted in Figure 4-11 that the contribution of the original grid point to the reduction of variance, as would be expected, drops to zero.

The process can be continued with still higher order partial correlation coefficients $r_{ij,km}$:

$$r_{ij,km} = (r_{ij,k} - r_{im,k} r_{jm,k}) / \sqrt{(1 - r_{im,k}^2) (1 - r_{jm,k}^2)}$$

where $r_{ij,km}$ is defined as the partial correlation coefficient between predictand $i$ and predictor $j$, given that predictors $k$ and $m$ have already entered the regression. The remaining lower order partial correlation coefficients in Equation (8) are obtained from lesser order equations of type (6). The application of Equation (8) to each of the grid-points in Figure 4-10 yields the pattern shown in Figure 4-12. Here, a further incremental variance reduction of about nine per cent is provided by inclusion of the 500-mb height value located some 750 nautical miles north-north-east of the storm. The physical explanation here is that a north-south elongated ridge of high pressure located east of the storm is more effective in bringing about continued northerly storm motion than a flat ridge located east of the storm. The stepwise selection process can theoretically be continued until all 120 grid points are accounted for. However, the limit of absurdity is soon reached when the incremental variance reduction falls below some critical value set by application of classical statistical significance tests and physical meteorological reasoning. At this point, the selection of additional predictors should be halted.
The foregoing procedure describing the concept of partial correlation provides the basis of stepwise screening regression. Properly interpreted and displayed, these intermediate correlation fields can be a significant aid in the formation of statistical models for the prediction of tropical cyclone motion.

### 4.3.3 "Simulated" analog models

One of the simplest regression equation models for the prediction of tropical cyclone motion is referred to as a "simulated" analog model. The term was initially used by Neumann and Randrianarison (1976) to describe a regional adaptation of the model to the South Indian Ocean. However, as previously noted, a similar model, known as CLIPER, has been in continuous operational use over the Atlantic area for a number of years. The distinguishing feature of such models is their explicit use of climatology and persistence and the exclusion of all synoptic data in the prediction equations. In this respect, they closely resemble analog models. Indeed, the predictors used by "simulated" analog models are identical to those used in the analog sense by purely analog models. A characteristic feature of analog models is the presentation of forecast tracks in the form of probability ellipses depicting less likely tracks. "Simulated" models also provide this capability.

The variance-reducing potential of "simulated" analog models is derived from seven basic predictors. These include the Julian day number, initial latitude, initial longitude, average meridional speed, meridional speed during the past 12 hours, average zonal speed during the past 12 hours, average meridional speed during the past 24 hours, and average zonal speed during the past 24 hours. If available, the wind speed or central pressure may be included as the eighth basic predictor. Non-linear trends in the data (Efroymson) can be accounted for by the inclusion of the products and cross-products of the basic predictors as still additional predictors. The only restriction here is that the additional number of predictors generated are commensurate with the sample size. The number of predictors generated by this procedure is shown in Table 4-1. Adequate statistical significance levels can be determined by adherence to the procedures described in Appendices 4.D and 4.E. The principle advantage of the method is its simplicity. The regression equations can be readily solved on small computer systems or on desk calculators. Analog models, on the other hand, require a more complex set of calculations.

### Table 4-1

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<thead>
<tr>
<th>Number of first-order variables (m)</th>
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other hand, require the processing of large masses of historical storm tracks each time the program is activated. On large computer systems, this is not a problem. On small systems, however, 15 to 30 minutes clock and CPU time is often required. Another advantage of simulated analog models is their reliability. The model will always produce a forecast. Analog models will fail under anomalous forecast situations. Although the problem can be minimized by recycling through the tracks with more liberal selection criteria, this requires an additional amount of computer time. Since the output of analog or "simulated" analog models is often used as input into more sophisticated models, the failure of the program would have further downstream consequences. The one disadvantage of "simulated" analog models is their inability to identify the actual storms which form the basis of the forecast. Hurricane forecasters favour the ability to interface with the analog process and, indeed, a certain amount of diagnostic information relating to the forecast can be obtained by examination of plotted tracks of the actual storms forming the basis of the analog guidance. However, this is not considered to be a serious shortcoming. In addition to the two regional "simulated" analog models identified in the first paragraph, such models have also been designed for the eastern North Pacific (Neumann and Leftwich, 1977) and for the North Indian Ocean (Neumann and Mandal, 1977).

4.3.4 Regression equation models incorporating observed data — Classical models

The next echelon model in the hierarchy of statistical models incorporates predictors obtained from current or recently observed synoptic data. Several models in this category are in current operational use at the various tropical cyclone forecast centres. These would include Arakawa's (1963b, 1964) and Tse's (1966) Pacific models; Kumar and Prasad's (1973) North Indian Ocean model; the North Atlantic NHC67 (Miller et al., 1968) and NHC72 (Neumann et al., 1972) models; and the Leftwich and Neumann (1977) EPHC77 model for the eastern Pacific. The common denominator of all of these models is the use of observations of predictand and predictor at the current time \( T_0 \) and possibly at \( T+12 \) hours to forecast values of the predictand at \( T+h \) hours with \( h \) extending forward as much as 72 hours. This is the same framework set forth in precomputer-age classical statistics (see, for example, the corn-yield v. temperature problem in Chapter 18 of Mills, 1955); hence, the term "classical" is often used to describe such models. Although the process has been streamlined by the introduction of stepwise screening regression methods (Miller, 1958) the basic concept is nevertheless unaltered.

The reduction of variance of such models typically decreases rapidly with increased forecast projection. Predictors are selected from climatology and persistence as well as from one or more of the current and 24-hour-old 1000-, 700- and 500-mb height fields. Storm-centred movable grids of the type illustrated in Figure 4-4 are generally used to represent the data fields, and predictors are systematically selected using the stepwise screening regression process. Figures 4-9, 4-10, 4-11 and 4-12 have already been introduced in a previous subsection to illustrate this process.

The size of the grid to be used to represent a synoptic data field depends on the length of the forecast period. Models which limit the forecast projection to 24 hours can use a grid extending outward from the storm no more than 600 nautical miles. However, models which attempt to forecast through 72 hours should use a grid at least as large as that illustrated in Figure 4-4. In the larger grid systems, grid spacings of 300 nautical miles are typical. However, models developed from the smaller grids might benefit from a finer grid-spacing of 150 nautical miles. A nested grid system with the coarseness increasing with distance from the storm has never been used in statistical models for the prediction of tropical cyclone motion.

Classical models are not restricted to synoptic data, but may also use predictors selected from climatology and persistence. Indeed, Figure 4-7 shows that persistence provides most of the reduction of variance in the shorter forecast. The operational Atlantic NHC72 model uses the output from the simulated analog model CLIPER (Neumann, 1972) as a single predictor combining all the attributes of climatology and persistence.

If sufficient development data are available, it is desirable to develop separate sets of regression equations (stratification) representing different synoptic patterns. The Tse (1966) model stratifies according to certain easily identifiable 700-mb patterns. The NHC67 model stratifies according to whether the storm is initially located north
or south of 30ºN with an additional substratification dependent on the storm’s speed. A stratification based on the storm’s initial motion is used by the NHC72 model. Stratification conceptually improves on the performance of a model but care must be taken to avoid drastic reductions in sample size. This is a pitfall of stratification to be rigorously avoided. There is evidence (Takeuchi, 1976) that the Atlantic NHC67 and NHC72 models use more predictors than warranted by the sample size. In this connexion, both of these models (as well as the NHC73 model) utilize predictors from the three levels: 1000, 700 and 500-mb. Tests conducted at the National Hurricane Center subsequent to the development of these models suggest that better operational performance could be effected by the elimination of the 700-mb level. Data at this level are highly correlated with the 500-mb level and the inclusion of both sets of predictors does nothing more than complicate the assessment of statistical significance of the results. It may also be profitable to use a pressure-weighted height over a deep-layer as a single predictor field. For example, over the depth 1000 through 100 mb, such a function could take the form:

$$H_d = \frac{(75H_{1000} + 150H_{850} + 175H_{700} + 150H_{500} + 100H_{400} + 75H_{300} + 50H_{250} + 50H_{200} + 50H_{150} + 25H_{100})}{900}, \quad (9)$$

where \(H_d\) is the pressure-weighted height at some point and the remaining heights are at their designated level. Also, as suggested by Simpson (1971), the depth of the layer could be made a function of the central pressure of the storm with the most intense storm being associated with the deepest layer as given by Equation (9).

There are many innovations in statistical modeling which have been used by investigators to deal with various problems. One particularly annoying problem is the production of a “stairstep” or otherwise unrealistic forecast track. Such a track, although statistically sound, conveys a certain degree of scepticism to the forecast. It arises because of the practice of forecasting the storm track in 12-hourly time steps. Each segment is more or less independent of the other segments. To avoid the problem, the same predictors could be used for each time step for each component of motion. Alternately, the forecast for time \(T+h\) hours could have been made a function of the forecasts for \(T+h-12\) and \(T+h+12\) hours.

4.3.5 Statistical-dynamical models

The upper echelon of statistical models for the prediction of tropical cyclone motion is considered to be those models which derive a portion of the variance reduction from predictors taken from the output of a numerical prediction model. Such models can also derive a portion of their forecast skill from other sources such as climatology, persistence or currently observed synoptic data.

It is generally agreed that the use of Model Output Statistics (MOS) is conceptually the most effective means of introducing numerically forecast data into a statistical prediction framework. The MOS concept (with examples drawn from mid-latitude forecasting) is described by Klein and Glahn (1974). Basically, the method involves the direct introduction of the output of a numerical model, in both the developmental and operational modes, into a statistical model. However, there are numerous practical problems involved in using this approach in the data-void areas of the tropics. Foremost among these problems has been the inability to obtain a long enough data sample to ensure adequate statistical significance. In the not too distant future, this problem will be overcome in some of the tropical cyclone basins and MOS models will be developed.

In the interim there are substitute methods of using the statistical-dynamical approach. One of these is referred to as the “perfect-prog” and another as the simulated model output statistics (SMOS) approach. Both of these methods are described in detail by Neumann and Lawrence (1975). Both methods are considered inferior to the direct model output statistics (MOS) approach. Nevertheless, the NHC73 model, in operational use in the Atlantic area for several years and using both the “perfect-prog” and SMOS approach, has shown considerable promise. A schematic of the NHC73 prediction model is shown in Figure 4-13. It can be noted that the model generates three sets of forecast displacements, identified as CLIPER, steering and synoptic. The CLIPER forecast, described in
subsubsection 4.3.3, is based exclusively on predictors or predictor functions representative of climatology and persistence. The steering forecast is based on synoptic predictors defined by relatively fine-mesh grid points located within 600 nautical miles of the storm centre. Finally, the synoptic forecast is based on the large-scale synoptic pattern as specified by the large and relatively coarse-mesh grid system depicted in Figure 4.4. A weighting scheme (with weighting coefficients ideally derived from operational data) is used to combine these three forecasts into a single final forecast. The weighting factors vary both temporally and spatially.

In Japan, a recently introduced statistical-dynamical model is also designed around the perfect-prog concept. The model, described by Nomoto et al. (1976) and recently tested on 1973 and 1974 independent data, has shown considerable skill. It is currently undergoing operational tests by the Japan Meteorological Agency.

Still another method of statistical-dynamical prediction is described by Renard (1968) and Renard et al. (1973). The method focuses on the use of the instantaneous geostrophic steering concept applied in six-hourly time steps to the U.S. Navy’s smoothed numerical prognoses. The technique, in current operational use by the U.S. Navy (see subsection 4.3.1), has proved somewhat inferior to other operational models in use by the Navy. Conceptually, however, the method, with some modifications, appears to have considerable forecast potential.

For a number of reasons, the development, testing and operational implementation of statistical-dynamical models are fraught with difficulty. Accordingly, the development of such a model is not recommended unless the developer is at least familiar with some of the problems involved in the development of lower echelon models. The
question of predictor overweighting when using the perfect-prog approach is particularly troublesome. Some of these problems are discussed by Neumann and Lawrence (1975) wherein the development of the statistical-dynamical NHC73 model for the Atlantic area is described.

Other problems associated with these models relate to the operational availability of the necessary numerically-forecast height and wind fields. Unless immediate computer access to these data is possible, the delays involved in the delivery of the final forecast product will cripple the operational utility of the method.

4.3.6 Future development of statistical models

Research into the statistical (and numerical) prediction of tropical cyclones is continuing in the various worldwide tropical cyclone forecast and research centres. The type of research depends to a large degree on the data and computer resources available to the given Meteorological Service. Those services with complete access to objective analyses, numerical prognoses and adequate computer resources may well benefit by exploring the statistical-dynamical approach. On the other hand, limited computer resources and limited accessibility to fields of objectively analysed data may dictate the analog or “simulated” analog approach. However, it has been found that increased sophistication in statistical modeling has not always been a guarantee of improved operational performance. Much of this apparent contradiction relates to the poor quality of archived data in the tropics and attempts by researchers to extend their sophistication to a point beyond that commensurate with the available data. If proper attention is given to statistical significance concepts, some of which have been discussed earlier in this chapter, it is believed that improved performance can indeed be effected in statistical models.

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Annette, P., 1976: Recent events concerned with importing objective aids to predict tropical cyclone motion. Australia Bureau of Meteorology, Meteorological Note 90.


Chin, P. C., 1976: A diagnostic approach in tropical cyclone movement forecasting by objective techniques. Reprint Number 63, Royal Observatory, Hong Kong.


Note: A chronological listing of all NAVENVPREDRSCHFAC publications, including abstracts, may be obtained by contacting the Commanding Officer, Naval Environmental Prediction Research Facility, Monterey, CA 39950, U.S.A. Enquiries as to pertinent publications of the National Hurricane Center may be directed to the Librarian, NOAA Miami Branch Library, P.O. Box 248285, Coral Gables, FL 33124, U.S.A.
FORTRAN COMPUTER PROGRAM LISTING OF THE AKIMA (1970) POLYNOMIAL INTERPOLATION METHOD

Immediately following the listing is a sample program output obtained from the following calling sequence:

```
DIMENSION ALAT(4), ALON(4)
COMMON/BL50/X(1000),Y(1000),L
ALAT(1)=15.0
ALAT(2)=17.0
ALAT(3)=21.0
ALAT(4)=30.0
ALON(1)=70.0
ALON(2)=72.0
ALON(3)=71.0
ALON(4)=73.0
NSTEP=6
NPTS=4
CALL PPCSCF(ALON, ALAT, NPTS, 0., 1., 0., 1., NSTEP, 0., 0., INDEX)
DO 10 I=1,L
   10 WRITE(6,15) I, Y(I), X(I)
```

```
15 FORMAT(10X,15,2F8.2)
STOP
END
```

Note from the output that the program generates NSTEP – 1 positions between each of the four specified latitudes and longitudes and passes through these “anchor” points. The results are stored in the common block. Note, however, that independent plotting of the points may be accomplished by removal of the “C” from the appropriate calls to ZPLOT. There are two of these calls. The arguments in ZPLOT may have to be altered depending on the conventions of a given installation.
II.4.A-2 OPERATIONAL TECHNIQUES FOR FORECASTING TROPICAL CYCLONE INTENSITY AND MOVEMENT

SUBROUTINE PPSCF(XARRAY,YARRAY,NPTS,XOFF,YOFF,XFCT,YFCT,NSTEP,* DASHL,VOIDL,INDEX)
C
C PLOT A SMOOTH CURVE THRU XARRAY(I),YARRAY(I),I=1,...,NPTS, WHERE
C NPTS IS GREATER THAN 2. SCALE THE OUTPUT AS FOLLOWS...
C X XPAGE = (X-XOFF)/XFCT
C Y PAGE = (Y-YOFF)/YFCT
C WHERE X,Y IS A POINT ALONG THE CURVE AND XPAGE,YPAGE ARE THE
C PLOTTER COORDINATES.
C THERE WILL BE NSTEP-1 INTERMEDIATE POINTS GENERATED BETWEEN
C GIVEN POINTS XARRAY(I),YARRAY(I).
C
C IF THE OUTPUT IS TO BE DASHED, DASHL OR VOIDL MUST BE NONZERO.
C DASHL IS THE LENGTH OF THE SOLID PART AND VOIDL IS THE LENGTH
C OF THE VOID PART, INDEPENDENT OF SCALING.
C INDEX CAN BE USED AS DESIRED
C
DIMENSION XARRAY(5) ,YARRAY(J) , A(4) , B(4)
COMMON/BLS0/XSAVE(1000) ,YSAVE(1000) , L
DATA DSDT1/O.
C CALL ZPLOT((XARRAY(I)-XOFF) /XFCT,(YARRAY(I)-YOFF) /YFCT,3)
C ABOVE STATEMENT SETS THE PLOTTING PEN TO INITIAL POSITION
L = 1
XSAVE(1)=XARRAY(1)
YSAVE(1)=YARRAY(1)
S = 0.
ASSIGN 80 TO KGO1
ASSIGN 100 TO KGO2
IF (DASHL.LE.0 .AND. VOIDL.LE.0.) GO TO 10
DVL = DASHL+VOIDL
ASSIGN 70 TO KGO1
ASSIGN 90 TO KGO2
10 M = NSTEP+1
DELT = 1./FLOAT(NSTEP)
A(1) = 3.*(XARRAY(2)-XARRAY(1))-2.*(XARRAY(3)-XARRAY(2))
B(1) = 3.*(YARRAY(2)-YARRAY(1))-2.*(YARRAY(3)-YARRAY(2))
A(2) = 2.*(XARRAY(2)-XARRAY(1))-(XARRAY(3)-XARRAY(2))
B(2) = 2.*(YARRAY(2)-YARRAY(1))-(YARRAY(3)-YARRAY(2))
A(3) = XARRAY(2)-XARRAY(1)
B(3) = YARRAY(2)-YARRAY(1)
DO 140 I=1,NPTS
IF (I.LT.NPTS-1) GO TO 30
IF (I.LT.NPTS) GO TO 20
A(4) = 3.*(XARRAY(NPTS)-XARRAY(NPTS-1))-2.*(XARRAY(NPTS-1)-
* XARRAY(NPTS-2))
B(4) = 3.*(YARRAY(NPTS)-YARRAY(NPTS-1))-2.*(YARRAY(NPTS-1)-
* YARRAY(NPTS-2))
GO TO 40
20 A(4) = 2.*(XARRAY(NPTS)-XARRAY(NPTS-1))-(XARRAY(NPTS-1)-
* XARRAY(NPTS-2))
B(4) = 2.*(YARRAY(NPTS)-YARRAY(NPTS-1))-(YARRAY(NPTS-1)-
* YARRAY(NPTS-2))
GO TO 40
APPENDIX 4.A

II.4.A-3

30 A(4) = XARRAY(I+2) - XARRAY(I+1)
B(4) = YARRAY(I+2) - YARRAY(I+1)
40 W2 = ABS(A(3)*B(4) - A(4)*B(3))
W3 = ABS(A(1)*B(2) - A(2)*B(1))
A0 = W2*A(2)+W3*A(3)
B0 = W2*B(2)+W3*B(3)
DD = SQRT(A0*A0+B0*B0)
IF (DD.GT.0) GO TO 50
C1 = 0.
S1 = 0.
GO TO 60
50 C1 = A0/DD
S1 = B0/DD
60 IF (I.LE.1) GO TO 120
RR = SQRT(A(2)*A(2)+B(2)*B(2))
P0 = XARRAY(I-1)
Q0 = YARRAY(I-1)
P1 = RR*C0
Q1 = RR*S0
P2 = 3.*A(2)-RR*(C1+2.*C0)
Q2 = 3.*B(2)-RR*(S1+2.*S0)
P3 = -2.*A(2)+RR*(C1+C0)
Q3 = -2.*B(2)+RR*(S1+S0)
DO 110 J=1,M
FJM1=J-1
T = FJM1*DELT
X = (P0+T*(P1+T*(P2+T*P3))-XOFF)/XFCT
Y = (Q0+T*(Q1+T*(Q2+T*Q3))-YOFF)/YFCT
GO TO KG01,(70,80)
70 DSDT1 = 0.5*SQRT((P1+T*(2.*P2+T*3.*P3))/XFCT)**2+(Q1+T*(2.*Q2+T*
* 3.*Q3))/YFCT)**2)
80 IF (J.LE.1) GO TO 110
IPEN = 2
GO TO KG02,(90,100)
90 S = S-DELT*(DSDTO+DSDT1)
IF (AMOD(S,DVL).GT.DASHL) IPEN = 3
100 CONTINUE
C CALL ZPLOT(X,Y,IPEN)
L= L+1
XSAVE(L)=X
YSAVE(L)=Y
110 DSDTO = DSDT1
120 CO = C1
S0 = S1
DO 130 J=1,3
A(J) = A(J+1)
130 B(J) = B(J+1)
140 CONTINUE
RETURN
END
## Sample program output

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MATHEMATICAL BACKGROUND ON THE BIVARIATE NORMAL DISTRIBUTION
( PROBABILITY ELLIPSES)
(extracted from Hope and Neumann (1970), pp 925-926)

The bivariate normal probability density function is expressed as:

\[ f(x, y) = \frac{1}{2\pi \sigma_x \sigma_y \sqrt{1-\rho_{xy}^2}} e^{-\frac{(x-\mu_x)^2}{2\sigma_x^2} - \frac{2\rho_{xy}(x-\mu_x)(y-\mu_y)}{\sigma_x \sigma_y} + \frac{(y-\mu_y)^2}{2\sigma_y^2}} \]  

(1)

where \( G \), the locus of which in the \( x, y \) plane describes an ellipse, is:

\[ G = \frac{1}{1-\rho_{xy}^2} \left[ \frac{(x-\mu_x)^2}{\sigma_x^2} - \frac{2\rho_{xy}(x-\mu_x)(y-\mu_y)}{\sigma_x \sigma_y} + \frac{(y-\mu_y)^2}{\sigma_y^2} \right] \]  

(2)

(Lindgren 1962) where the population parameters are:

- \( \mu_x \) mean of the \( x \) (longitude) co-ordinates;
- \( \mu_y \) mean of the \( y \) (latitude) co-ordinates;
- \( \sigma_x \) standard deviation of the \( x \) co-ordinates;
- \( \sigma_y \) standard deviation of the \( y \) co-ordinates;
- \( \sigma_x^2 \) variance of the \( x \) co-ordinates;
- \( \sigma_y^2 \) variance of the \( y \) co-ordinates;
- \( \rho_{xy} \) correlation coefficient between the \( x \) and \( y \) co-ordinates.

In making computations from sample data, the population parameters are replaced by the respective sample parameters \( \bar{x}, \bar{y}, \sigma_x, \sigma_y, S_x^2, S_y^2, \) and \( r_{xy} \). The probability that a randomly selected point \( (x, y) \) falls into the region \( S \) of the \( x, y \) plane is given by the integral of the probability density function:

\[ P(S) = \int \int f(x,y) \, dx \, dy \]  

(3)

(Burlington and May, 1953).

However, the locus of \( G = c^2 \) is a constant and defines an equi-probability ellipse where, for each value of \( c \), \( f(x, y) \) is a constant. For example, when \( c = 1.1774 \), \( P = 0.50 \). In general, the probability defined by a particular value of \( c \) is given by:

\[ P = 1 - \exp(-c^2/2) \]  

(4)
The semi-lengths of the major and minor axes of the ellipses thus obtained are computed by multiplying the standard deviation along these axes by the value of $c$ for the particular probability desired. For obtaining the standard deviation along the major and minor axes, however, the ellipses must be rotated first through an angle $\psi$ relative to the latitude-longitude grid to eliminate the cross product term in Equation (2). The components along the rotated axes are then uncorrelated. The angle $\psi$ is determined by considering the general equation of an ellipse centred at the origin:

$$Az^2 + Bz + Cy^2 + F = 0$$

and rotating the axes through an angle $\psi$ defined by:

$$\tan 2\psi = \frac{B}{A - C}$$

which in terms of Equation (2) becomes:

$$\tan 2\psi = \frac{2rsrS_a S_y}{S_a^2 - S_y^2}$$

(Groenewoud et al., 1967).

The variances along the rotated axes $K_a^2$ and $K_b^2$ are computed from the determinantal equation (Hald, 1952):

$$\begin{vmatrix} S_a^2 - K^2 & r_{xy} S_a S_y \\ r_{xy} S_a S_y & S_y^2 - K^2 \end{vmatrix} = 0.$$

Solving for $K^2$, one obtains:

$$K_a^2 = \frac{S_a^2 + S_y^2 + \sqrt{(S_a^2 + S_y^2)^2 - 4S_a^2 S_y^2(1 - r_{xy}^2)}}{2}$$

where the larger value $K_a^2$ is the variance along the major axis and the smaller value $K_b^2$ is the variance along the minor axis.

The semi-length of the rotated axes is determined by multiplying the standard deviations $K_a$ and $K_b$ by the appropriate value of $c$ obtained from Equation (4). For example, suppose that, for a particular distribution of analog storms 48 hours after the initial time, the mean latitude was 31.1°N and the mean longitude was 70.2°W. This point is the centroid of the distribution from which the ellipses are to be computed. Suppose further that the standard deviation of the longitude co-ordinates $S_x$ is 1.49° of latitude, the standard deviation of the latitude co-ordinates $S_y$ is 2.08° of latitude, the correlation coefficient between the longitude and latitude co-ordinates is $-0.896$, the angle of rotation $\psi$ by Equation (6) is $-55.3^\circ$, and the standard deviations along the rotated axes $K_a$ and $K_b$ by Equation (8) are 2.50° and 0.55° of latitude, respectively. The appropriate value of $c$ is determined from Equation (4). In this example, if the 0.50 ellipse is computed, the value of $c$ is 1.1774. The semi-length of the major and minor axes is given by $1.1774 \times 2.50 = 2.95$ and $1.1774 \times 0.55 = 0.65$ degrees of latitude. The axes lengths for any probability values desired are computed in a similar fashion.
FORTRAN COMPUTER PROGRAM LISTING FOR FITTING N PAIRS OF \( x, y \) DATA TO BIVARIATE NORMAL DISTRIBUTION

FORTRAN listing of programs to fit N pairs of storm positions given by arrays QLAT and QLON to a bivariate normal distribution. Note that ellipse rotation is measured from the east. Positive angles are towards the north and negative angles are towards the south. Thus, in the example given, the major axis of the ellipse is oriented from west-north-west to east-south-east. This output example was obtained by calling subroutine ELFIT with 13 pairs (N) of QLAT, QLON as arguments.
SUBROUTINE ELFIT(QLAT,QLON,N)
C FIT N PAIRS OF STORM POSITIONS GIVEN BY ARRAYS QLAT AND QLON TO A
C BIVARIATE NORMAL DISTRIBUTION
DIMENSION QLAT(N),QLON(N)
C GET MEAN LATITUDE AND LONGITUDE (ELLIPSE CENTROID)
SUMLAT=0.
SUMLON=0.
FN=N
DO 10 I=1,N
SUMLAT=SUMLAT+QLAT(I)
10 SUMLON=SUMLON+QLON(I)
YCNR=SUMLAT/FN
XCNR=SUMLON/FN
C GET PRODUCTS AND CROSS-PRODUCTS OF DEVIATIONS FROM MEAN.
C EXPRESS LONGITUDINAL DEVIATIONS IN UNITS OF DEGREES OF LATITUDE
C
SUMXY=0.
SUMXSQ=0.
SUMYSQ=0.
DO 20 I=1,N
DY=QLAT(I)-YCNR
C IN SOUTHERN HEMISPHERE, REMOVE C FROM FOLLOWING STATEMENT
C
DX=(XCNR-QLN(I))*COS((.5*YCNR+.5*QLAT(I))*0.01745331)
C FOR LONGITUDE EAST OF GREENWICH, REMOVE C FROM FOLLOWING STATEMENT
C
DX=-DX
20 SUMXY=SUMXY+DX*DY
SIGX=SQRT(SUMXSQ/(FN-1.))
SIGY=SQRT(SUMYSQ/(FN-1.))
COVXY=SUMXY/(FN-1.)
R=COVXY/(SIGX*SIGY)
THETA=0.5*ATAN2(2.0*R*SIGX,SIGX*SIGX-SIGY*SIGY)
THETA=THETA*57.29578
RADICL=SQRT((SIGX*SIGX+SIGY*SIGY)**2.-4.*SIGX*SIGX*SIGY*SIGY*(1.-R*R))
AK1=(SIGX*SIGX+SIGY*SIGY+RADICL)/2.
AK2=(SIGX*SIGX+SIGY*SIGY-RADICL)/2.
SIGXPM=SQRT(AK1)
SIGYPM=SQRT(AK2)
WRITE(6,30)(QLAT(I),QLON(I),I=1,N)
30 FORMAT(45H1 LIST OF LATITUDE AND LONGITUDE PAIRS..../) 
*(5X,2F7.1,2X))
WRITE(6,35)N,SIGX,SIGY,COVXY,R,THETA,SIGXPM,SIGYPM
35 FORMAT(/5X,15H NUMBER OF CASES,16/ 
*5X,4D7.1,2X))
*/5X,4HSTANDARD DEVIATION ALONG UNROTATED X AND Y AXES,F8.2,F7.2/ 
*/5X,13HCOVARIANCE XY,F8.2,5X,23HCORRELATION COEFFICIENT,F7.3/ 
*/5X,44HROTATION (DEGS) OF MAJOR (X') AXIS FROM EAST,2X,F8.1/ 
*/5X,45HSTANDARD DEVIATION ALONG ROTATED X AND Y AXES,2X,F8.2,F7.2)
APPENDIX 4.C

WRITE(6,40)
40 FORMAT(38H PROBABILITY ....SEMI LENGTH..../
  *6X,35H(PERCENT) MAJOR AXIS MINOR AXIS)
DO 45 K=5,100,5
  J=K
  IF(J.EQ.100)J=99
  AMULT=SQRT(2.*ALOG(1./(1.-FLOAT(J)/100.)))
  AAXIS=SIGXPM*AMULT
  BAXIS=SIGYPM*AMULT
45 WRITE(6,50)J,AAXIS,BAXIS
50 FORMAT(9X,I2,8X,F7.2,5X,F7.2)
WRITE(6,55)YCNTR,XCNTR
55 FORMAT(//10X,34HELISE CENTROID (MEAN LAT/LON) IS,2F9.2)
WRITE(6,60)
60 FORMAT(//10X,48HNOTE....ALL DISTANCES ARE IN DEGREES OF LATITUDE)
RETURN
END
# Operational Techniques for Forecasting Tropical Cyclone Intensity and Movement

**List of Latitude and Longitude Pairs**

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<td>17.1</td>
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<tr>
<td>17.1</td>
<td>73.5</td>
<td></td>
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</tbody>
</table>

**Number of Cases** 13

**Standard Deviation Along Unrotated X and Y Axes** 2.86 1.69

**Covariance XY** -1.18 **Correlation Coefficient** -0.243

**Rotation (Degs) of Major (X') Axis from East** -11.9

**Standard Deviation Along Rotated X and Y Axes** 2.90 1.62

**Probability**

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<td>8.81</td>
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</table>

**Ellipse Centroid (Mean Lat/Lon) is** 15.59 76.02

**Note**... All distances are in degrees of latitude.
APPENDIX 4.D

STATISTICAL SIGNIFICANCE: DETERMINATION OF EFFECTIVE INDEPENDENT SAMPLE SIZE

Given a sample $N$ of 36 tropical cyclone displacements from several storms, these displacements (predictands) are arrayed as follows:

$$78, 82, 90, 96, 98, 150, 130, 140, 120, 115, 105, 99, 82, 115, 91, 92, 123, 125, 200, 66, 83, 91, 102, 169, 171, 134, 60, 63, 82, 84, 90, 72, 103, 99, 100, 102$$

These data, most of which are observed at twelve-hourly intervals, are serially correlated. To estimate the number of independent observations in the sample ($N_e$) the procedure is as follows:

1. Determine the mean ($\bar{x}$) of the sample $\bar{x} = 3802/36 = 105.6$
2. Count the number of runs above ($R_a$) and below ($R_b$) the mean. These runs, set out in the array above, total 4 above and 5 below;
3. Count the number of observations below ($N_b$) and above ($N_a$) the mean,
   $$N_b = 24 \quad N_a = 12$$
4. Compute the expected number of runs ($E$)
   $$E = 2N_bN_a/(N_a + N_b) + 1 = 17.0$$
5. Determine $N_e$
   $$N_e = (R_a + R_b)/E = 19.1$$

Thus, the 36 observations of serially correlated observations are equivalent to 19.1 independent observations.

Note: The above procedure is adapted from Siegel (1956).
APPENDIX 4.E

STATISTICAL SIGNIFICANCE: R. G. MILLER'S (1958, 1976) EQUIVALENT F-TEST FOR ASSESSING THE SIGNIFICANCE OF THE \( i \)th PREDICTOR OF AN \( m \) PREDICTOR EQUATION

Given a sample size of 500 serially independent cases \( N \). Given further that the first predictor selected when screening 120 possible predictors \( (P_a) \) yields a correlation coefficient \( r \) of 0.25. Is this value significant at the 95 per cent level?

Step 1 – Compute \( F_s \) from the variance analysis:

\[
F_s = \frac{r^2}{n_1} / \frac{(1 - r^2)}{n_2}.
\]

The degrees of freedom \( n_1 \) and \( n_2 \) are given by 1 and \( N - m - 1 \), respectively, where \( m \) is the number of predictors already selected. Miller's method is designed to assess the individual significance of each additional predictor, hence \( n_1 \) will always equal 1 but \( n_2 \) will be decreased by 1 for each step of the regression. Thus for the first predictor selected:

\[
F_s = \frac{.25^2}{1} / (1 - .25^2) = 33.2
\]

Step 2 – Determine equivalent \( F^*_{.95} \):

\[
F_{.95} = F(1 - \frac{1}{20})
\]

\[
F^*_{.95} = F(1 - \frac{1}{20 P_a}) = F(1 - \frac{1}{20 \times 120}) = F_{.99958}
\]

Note that \( P_a \) should be decreased by 1 for every predictor selected.

Step 3 – Determine \( F_{.99958} \).

The inverted Paulson (1942) function for approximating \( F_p \) for degrees of freedom \( n_1, n_2 \) is given by:

\[
F_p (n_1, n_2) = \left[ \frac{ab + V a^2 b^2 - [a^2 - (1 - a) c^2] [b^2 - (1 - b) c^2]}{[b^2 - (1 - b) c^2]} \right]^{3}
\]

where \( a = 1 - 2/9n_1 = 1 - 2/9 = .77778 \)

\( b = 1 - 2/9n_2 = 1 - 2/(9 \times 498) = .99955 \)

and \( c \) is the number of standard deviations that the accumulated probability \( p (.99958) \) is from the mean in the normal distribution. Tables of this quantity are found in standard statistical references. Alternately, the value of \( c \) can be
approximated from Equation (26.2.23), page 993 of Abramowitz and Stegun (1964). Use of this approximation or Table 26.1, page 972, from this same reference gives the value of $c = 3.344$. Substitution of $a$, $b$ and $c$ into Equation (4) gives:

$$F_{.95}^* = F_{.99958} = 13.17.$$

Step 4 – Compare $F_s$ to $F_{.95}^*$.

Since $F_s$ as determined from the sample variance analysis clearly exceeds $F_{.95}^*$, the predictor is significant at the given level.

Step 5 – Repeat Steps 1 through 4 with additional predictors. Discontinue the addition of predictors when $F_{.95}^*$ exceeds $F_s$. Note that for the first selection, as just described, $r$ is the correlation coefficient between the predi­
tand and the first predictor. For subsequent selections, $r$ is the partial correlation coefficient between the predi­
tand and the new predictor, given that the previous predictors have already entered the regression (See Chapter 4, Equations (6) and (7).)

*Note:* Since the test is designed to assess the significance of individual predictors, it is possible that the significance of predictors acting in pairs will be overlooked. Accordingly, it is recommended that the process be continued for one or possibly two more steps. An increase in the incremental variance reduction over that obtained from a previous step suggests that predictors are working in combination. In this case, the additional predictors should probably be included. However, because of the nature of the forward stepwise screening process, there is no guarantee that all predictor pairings will be recognized.
CHAPTER 5

DYNAMICAL TECHNIQUES
(by J. M. Pelissier*)

5.1 General

Historically, the development of operational dynamic tropical cyclone prediction techniques has failed to keep pace with that of statistical methods. However, recent advances in the accuracy of numerical models would indicate that the gap is rapidly closing. There are several reasons for the historical lag in dynamic forecasting compared to statistical prediction. In principle, it is possible to formulate a numerical model, initialize it with data from observations, and integrate the time-dependent hydrodynamic equations numerically for a suitable time period to obtain the desired forecast. This procedure is, in fact, followed every day at forecast centres around the world. However, when it is applied to the tropical cyclone problem, certain difficulties arise.

First, hurricanes and typhoons occur over the data-sparse regions of the tropical oceans, and accurate specification of the initial state of the atmosphere is particularly difficult. Secondly, the high-wind region of a tropical cyclone is small compared to synoptic-scale systems. A numerical model with a single mesh-length short enough to resolve details of the vortex is impractical. Thirdly, the dynamics of the tropical atmosphere and the interaction of a hurricane with its surroundings are less well understood than circulation regimes of middle latitudes. In recent years, technological advances and ingenious numerical methods have partially solved some of these problems. Geostationary satellites provide wind data to supplement conventional observations. These wind fields are derived from cloud motion vectors obtained by the use of time-lapse movies of satellite pictures. The resulting winds are then incorporated into data fields which are objectively analysed to provide the initial conditions for numerical models. In the near future, geostationary satellites are expected to provide distributions of temperature and humidity as well.

The problem of scale size has been partially solved by the development of even faster computers which are able to handle the vast amounts of data required by a multi-level, large-area, fine-mesh numerical model. However, it is not practical to cover the entire computational domain with a grid fine enough to resolve details of the storm's inner core. Such resolution can be achieved by the use of "nested grids". In such models, a fine grid is centred on the storm and "nests" within a larger grid which is of appropriate size to define the storm environment. The smaller grid is then moved, or relocated, as the storm traverses the larger, stationary grid.

Our understanding of the dynamics of the tropical atmosphere and the interaction of a tropical disturbance with its environment is continually improving. The Global Atlantic Tropical Experiment (GATE) serves to illustrate the attention that has been focused on these problems in recent years.

Attempts at dynamic forecasting of tropical cyclone tracks have proved more successful than those aimed at predicting intensity changes. This results from the fact that a storm's movement is mainly a function of the "steering current" in which the storm is embedded. Thus, models have been developed in which the following devices are used:

(a) The storm circulation is subtracted from the total flow, and the storm is advected as a "point vortex", or
(b) The actual storm circulation is replaced by a predetermined, symmetric, non-interacting vortex.

*National Hurricane Center, Miami
In view of the inherent difficulties in formulating a dynamic tropical cyclone prediction model, one might ask why the effort to develop such schemes has continued, considering the relatively good performance achieved by statistical methods during the past decade. It is the nature of statistical techniques that they are most reliable when used to predict storms possessing characteristics similar to the average of those comprising the dependant data sample from which the method was derived. While the foregoing statement is somewhat of an over-simplification, it is true that statistical schemes are more likely to fail in a situation in which a storm is behaving erratically, such as stalling, looping, oscillating, or otherwise departing from steady movement. Since storms normally move along smooth tracks, past motion correlates highly with future motion and is invariably weighted highly in statistical schemes.

Since a dynamic model does not depend on the statistical relationships between a current storm and historical storms, one might expect the reliability of such a scheme to be more independent of the details of a storm's past behaviour. In other words, variations in the future course of a storm ought to be implicitly predicted through the equations of motion. If such were the case, a dynamic model would be useful in supplementing guidance from statistical models and would perhaps be given more consideration in cases where statistical models prove most frail. This is part of the reason for the simultaneous development of both types of models at tropical cyclone forecasting centres around the world. Some dynamic prediction schemes for tropical cyclones are discussed in the following sections.

5.2 The SANBAR barotropic model

The barotropic model is perhaps the simplest dynamic tropical cyclone track prediction model which contains sufficient detail to generate a fairly accurate forecast of a storm's steering current and, consequently, a storm's future track. Since late 1970, a filtered barotropic prediction model using winds averaged with respect to mass through the troposphere has been in operational use at the United States National Hurricane Center (NHC). This model, known as SANBAR, was originally designed by Sanders and Burpee (1968) and later modified by Pike (1972). Portions of what follows are taken from the above-mentioned articles.

The SANBAR model predicts tropical cyclone motion by the tracking of minimum stream function and maximum vorticity centres. Computations are made on a Mercator projection grid of mesh length 1.5 degrees of longitude and extending from the Equator to latitude 55°N and from longitude 36.5°W to 123.5°W. A similar version has recently been developed for the eastern Pacific. A time step of 30 minutes has been used and the forecasts have generally been made out to 72 hours.

In operational practice, the pressure-depth over which the initial wind observations have been averaged has varied from 1000 - 400 mb to 1000 - 100 mb. Experience has shown that best results are obtained using the 1000 - 100 mb layer, and this depth is now invariant. On account of large oceanic areas with no routine upper-wind soundings, 44 bogus mean winds have been used to supplement actual observations. These winds were originally obtained by a subjective analysis of the mean wind field as defined by the real data. In the current operational version, they are objectively interpolated from the automated NHC 200-mb and low-level analyses. Both real and bogus winds then form the basis for an objective analysis, based on the work of Eddy (1967), which produces a wind field specified at the grid points.

Once the initial winds have been specified, their non-divergent part is obtained by relaxing for the stream function \( \psi \) in the interior of the grid by means of:
\[ p^2 \psi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} + u \frac{\tan}{R_E} \text{ (lat.)} \]  

where \( u \) and \( v \) are respectively the eastward and northward components of motion, \text{lat.} is the latitude, and \( R_E \) is the radius of the Earth. Boundary conditions are such that the wind component parallel to the Boundary is specified. The simple barotropic vorticity equation may then be used to predict \( \psi \):

\[ (p^2 - M) \frac{\partial \psi}{\partial t} = J (f + p^2 \psi, \psi) \]

(see Haltiner, 1971, section 6.1). The horizontal Laplacian operator is denoted by \( p^2 \), \( M \) is the Helmholtz coefficient, \( \frac{\partial}{\partial t} \) is the local time derivative, \( f \) is the (variable) Coriolis parameter, and \( J \) represents the Jacobian. A storm centre may be identified with a local minimum in \( \psi \) or maximum in \( p^2 \psi \); in practice, the average position between the two extremes is used. If a \( \psi \)-minimum cannot be found, the \( p^2 \psi \)-maximum, which is more persistent, is used alone.

Since details of the wind structure of a storm's vortex are unavailable and unresolvable by the model grid, the storm is replaced by an idealized, circularly-symmetric vortex. The speed field of this vortex is given by:

\[ \nu_g = 0.72 \nu_{\text{max}} \left[ \sin \left\{ \pi \left( \frac{r}{r_m} \right) \left( \frac{\ln 0.5}{\ln (r/e/r_m)} \right) \right\} \right]^{1.5} \]

where \( \nu_g \) is the symmetric tangential wind speed. In operational practice the forecaster specifies the storm's current latitude, longitude, maximum wind \( (\nu_{\text{max}}) \), radius of maximum wind \( (r_m) \), and maximum storm influence distance motion.

In the original version of SANBAR, the idealized vortex was subtracted from the observational and bogus wind data within the influence region before the objective analysis was performed, and then added back in. However, a significant problem developed which is common to many dynamic models, i.e. the initial storm motion computed by the model did not agree with the actual storm motion. In statistical models, short-term forecast motion is invariably highly correlated with current motion. Since the forecaster usually has a good estimate of current storm motion at forecast time, it was felt that this information could be incorporated advantageously into the SANBAR model. Pike (1972) accomplished this in the following way. All observational and bogus wind data within the influence region of the storm, \( r < r_m \), are discarded and replaced by a wind set equal to the best estimate of the current storm motion vector. The idealized axisymmetric vortex is then added to the resulting wind field and the Eddy objective analysis is performed as before. This modification resulted in much improved forecasts of direction, especially in the first 24 hours, but the slow bias largely remained. It was later found (Sanders, Pike and Gaertner, 1975) that the speed bias was largely the result of two causes. First, truncation error in the finite difference analogs of the stream function and the prediction equation calculations resulted in underestimated phase speeds, especially for short wave lengths. Secondly, relaxation of the stream function produced a steering flow which was too weak. These deficiencies are corrected in the current operational version of the model. These problems are dealt with here at some length, since they serve to illustrate the type of problems one encounters in developing a dynamic model for operational use. Even if the physics of the model are correct, many often unforeseeable problems may crop up in operational testing. It is frequently the case that data initialization and numerical problems are as difficult to solve as the hydrodynamic ones. (Error statistics for the SANBAR model are included in Chapter 10.)

A number of experimental forecasts were carried out by De las Alas and Guzman (1976) using a similar, but somewhat simpler, model to predict typhoon tracks in the vicinity of the Philippines. Their model employs a relaxation of the non-divergent barotropic vorticity equation to compute the stream function. The track of the
typhoon is computed by following the trajectory of a point representing the initial surface position of the centre as it is advected by the large-scale wind field.

Experiments were conducted using various weighting combinations of the 700-mb, 500-mb and 300-mb wind fields. These wind fields were obtained by manual streamline and isotach analyses. The computational domain consists of a 19 by 13 grid with mesh length equal to one degree of longitude at the Equator. Initial experiments on a small number of cases produced encouraging results.

5.3 A balanced barotropic model*

The Electronic Computation Centre of the Japan Meteorological Agency performs numerical predictions of typhoon movement when a typhoon moves northward of latitude 20°N and threatens Japan. A northern hemispheric balanced barotropic model adapted to 500 mb, with a 51 by 51 grid whose mesh length is 381 km at 60°N, is employed for the forecast. Steep pressure gradients associated with typhoons are artificially modified in the computational procedure of the model. The results of the numerical typhoon track forecasts show some systematic errors, as follows:

(a) Forecast positions for low-latitude storms are occasionally poor due to a westward bias in the predicted tracks;

(b) The predicted typhoon generally moves slower than the actual one;

(c) The predicted trajectory tends to recurve with less curvature than is observed.

In spite of these errors, results of this dynamic method, combined with other forecasting techniques, are widely used in formulating typhoon advisories and warnings.

The operational computation proceeds in the following way. The automated data-processing system, in which meteorological data are collected, checked and objectively analysed by the correction method, derives the initial height value at each grid point. Over oceanic areas, especially around a typhoon, bogus data from manually-analysed weather maps are used to supplement observations. Although there is no definite rule for adding bogus data in such areas, the attempt is made to approximate the steering flow of the typhoon. Since the strong pressure gradient of the typhoon and the relatively large mesh length of the model will produce considerable truncation errors, bogus data are also used to adjust the height profile near the centre of the typhoon. From experience, it has been determined that the maximum vorticity of a typhoon should be limited to:

$$ \psi^2 \ Z = Z - Z_s \leq 100 \, \text{m}. $$

(4)

Only conventional surface observations and AIREPs are utilized in the objective analysis. Satellite data are excluded. Bogus data are treated in the same manner as observational data.

The initial stream function, $\psi$, is obtained from the geopotential by solving the "balance equation":

$$ \nabla \cdot (f \psi) + 2 \left( \frac{\partial^2 \psi}{\partial x^2} - \frac{\partial^2 \psi}{\partial y^2} - \frac{\partial^2 \psi}{\partial x \partial y} \right) = \psi^2 \varphi $$

(5)

where $\varphi$ and $f$ indicate geopotential and the Coriolis parameter respectively.

* By Y. Okamura
In order to satisfy the elliptic condition of the equation an adjustment is adopted by which analysed height fields are slightly deformed only at the beginning stage. Also, to limit the applicability of the balance equation only to the north of certain latitudes a modified form of the Coriolis parameter, expressed by:

\[
f = 2\Omega \sin (\text{lat.}) + \frac{30^\circ - \text{lat.}}{30^\circ - 2\Omega \sin 15^\circ}
\]

is introduced into Equation (5). The finite difference analog, using Arakawa's scheme, conserves kinetic energy and total vorticity. The modified Coriolis parameter, expressed by Equation (6), produces a reduction in the $\beta$ effect which influences the forecast displacement of the disturbance to some degree.

Forty-eight-hour forecasts are usually performed twice a day, based on 0000 GMT and 1200 GMT data. The Forecast Division has the option of extending the forecast period. Results are printed out at 12-hour forecast intervals. By associating the position of the typhoon centre with the corresponding maximum vorticity centre at 500 millibars, the typhoon trajectory is determined by manual tracking of the sequence of forecast results. The nearly circular vorticity pattern of the typhoon at the initial instant, however, generally tends to elongate along the direction of large-scale flow during the calculation process. Such stretching of the vorticity pattern cannot be avoided unless the dynamical model includes the self-exciting mechanism of the tropical disturbance.

![Figure 5-1 - Errors in direction of movement of forecasts with the Balanced Barotropic Model. Arrow indicates actual direction of typhoon path; dots represent predicted centre positions. Unit radius is equal to grid interval](image-url)
For relatively small-scale typhoons, and typhoons whose surface centres do not agree with 500-mb vorticity centres, empirical and manual adjustment or correction of the numerical forecasts is needed.

Verification statistics for all typhoon cases predicted by the model have been compiled. Errors in the direction of typhoon displacement are shown in Figure 5-1, in which the arrow indicates the actual direction of movement and the dots are the relative predicted positions of the typhoon centre. The unit radius of the circle is equal to the grid distance, i.e. 381 km at 60°N. Tables 5-1 (a) and (b) show the frequency distributions of direction errors. In these tables, the first row contains the ranges of absolute differences between observed and predicted directions of displacements, and the extreme left column shows the forecast period. From the above figure and tables, no directional bias of the forecasts is apparent. Figure 5-2 shows predicted positions of typhoon centres relative to the actual positions, which are at the centres of the polar diagrams. The unit radius of the circle is equal to the grid interval. Errors in the predicted speed of movement are summarized in Tables 5-2 and 5-3. Table 5-2 shows the frequency distribution of the errors in the term \( |R - F|/R \), where \( R \) is an actual displacement and \( F \) is a forecast displacement. The extreme left-hand column of the figure shows the forecast period. In Table 5-3 the errors of predicted speed of movement are classified according to location relative to the point of recurvature. The column labeled “over run” indicates the number of typhoons which moved more slowly than predicted. This is seen to occur frequently before recurvature but never afterwards.

**TABLE 5-1**

Frequency distribution of direction errors of forecasts produced by the Balanced Barotropic Model

(a) Angular error distribution for westward-moving typhoons

<table>
<thead>
<tr>
<th>Angular interval (degrees)</th>
<th>0 - 5</th>
<th>6 - 10</th>
<th>11 - 20</th>
<th>21 - 30</th>
<th>31 - 45</th>
<th>45</th>
<th>Total cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecast period</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24-hour</td>
<td>10</td>
<td>12</td>
<td>13</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>54</td>
</tr>
<tr>
<td>48-hour</td>
<td>8</td>
<td>7</td>
<td>9</td>
<td>10</td>
<td>3</td>
<td>7</td>
<td>44</td>
</tr>
</tbody>
</table>

(b) Angular error distribution for eastward-moving typhoons

<table>
<thead>
<tr>
<th>Angular interval (degrees)</th>
<th>0 - 5</th>
<th>6 - 10</th>
<th>11 - 20</th>
<th>21 - 30</th>
<th>31 - 45</th>
<th>45</th>
<th>Total cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecast period</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24-hour</td>
<td>11</td>
<td>14</td>
<td>16</td>
<td>10</td>
<td>5</td>
<td>3</td>
<td>59</td>
</tr>
<tr>
<td>48-hour</td>
<td>15</td>
<td>8</td>
<td>10</td>
<td>4</td>
<td>8</td>
<td>5</td>
<td>50</td>
</tr>
</tbody>
</table>
Figure 5-2 – Predicted positions of typhoon centre using the Balanced Barotropic Model. Actual position is at the centre of the polar diagram. Unit radius is equal to the grid interval.

<table>
<thead>
<tr>
<th>Angular interval (degrees)</th>
<th>0 - 10</th>
<th>11 - 20</th>
<th>21 - 30</th>
<th>30 - 40</th>
<th>40 - 50</th>
<th>50</th>
<th>Total cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecast period</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24-hour</td>
<td>22</td>
<td>13</td>
<td>10</td>
<td>20</td>
<td>17</td>
<td>25</td>
<td>107</td>
</tr>
<tr>
<td>48-hour</td>
<td>11</td>
<td>14</td>
<td>12</td>
<td>12</td>
<td>9</td>
<td>23</td>
<td>81</td>
</tr>
</tbody>
</table>

TABLE 5-2

Frequency distribution of the quantity $|R - F|/R$, where $R$ is an actual typhoon displacement and $F$ is a prediction by the Balanced Barotropic Model.
TABLE 5-3

Errors in predicted speed of movement relative to recurvature point. "Over-run" number indicates number of typhoons which moved slower than forecast.

<table>
<thead>
<tr>
<th>Typhoon position</th>
<th>Forecast hours</th>
<th>24-h forecast</th>
<th>48-h forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total number</td>
<td>Over-run number</td>
<td>( R-F )</td>
</tr>
<tr>
<td>Before recurvature</td>
<td>42</td>
<td>16</td>
<td>0.406</td>
</tr>
<tr>
<td>Near recurvature</td>
<td>45</td>
<td>13</td>
<td>0.334</td>
</tr>
<tr>
<td>After recurvature</td>
<td>20</td>
<td>0</td>
<td>0.340</td>
</tr>
<tr>
<td>Total (mean)</td>
<td>107</td>
<td>29</td>
<td>(0.381)</td>
</tr>
</tbody>
</table>

5.4 A primitive equation model

A primitive equation model is used as operational guidance for tropical cyclone forecasting in the Pacific region by the U.S. Navy. The model is in use at both the Joint Typhoon Warning Center (JTWC) at Guam and the Fleet Numerical Weather Center at Monterey, California. The operational model, known as the coarse mesh grid model (CMG), is a single version of a more sophisticated, triple-nested-grid model which is currently under development. The following description of the model is condensed from a report by Hinsman (1977). The model employs the primitive equations in pressure-coordinates in the following form (using conventional symbols):

\[
\frac{\partial u}{\partial t} = -L(u) + f v - M \frac{\partial \phi}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} \tag{7}
\]

\[
\frac{\partial v}{\partial t} = -L(v) - f u - M \frac{\partial \phi}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} \tag{8}
\]

\[
\frac{\partial \theta}{\partial t} = -L(\theta) \tag{9}
\]

\[
\frac{\partial \psi_{1000}}{\partial t} = -L(\psi_{1000}) \tag{10}
\]

\[
\frac{\partial w}{\partial p} = -M^2 \left[ \frac{\partial}{\partial x} \left( \frac{u}{M} \right) + \frac{\partial}{\partial y} \left( \frac{v}{M} \right) \right] \tag{11}
\]
\[
\frac{\partial \phi}{\partial \rho} = \varphi C_p \frac{\partial}{\partial \rho} \left( \frac{p}{1000} \right) \frac{R}{C_p}
\]

where

\[
L (S) = M^2 \left[ \frac{\partial}{\partial x} \left( \frac{u_s}{M} \right) + \frac{\partial}{\partial y} \left( \frac{v_s}{M} \right) \right] + \frac{\partial}{\partial \rho} (w_s)
\]

The computational domain consists of an east-west channel with free slip conditions on the north and south walls, and cyclic boundary conditions on the east and west ends. There are three layers in the vertical in which dependent variables are calculated at the levels shown in Figure 5-3.

A tropical cyclone forecast is produced in the following way. A relocatable grid is positioned over the storm such that the storm resides in the lower centre of the domain at the initial time. The grid spans 56° of longitude and approximately 48° of latitude, with a mesh length of 2°. The flow fields at 850, 700 and 250 mb, as well as the 850-mb temperature field, are extracted from the routine large-scale analysis, which includes a bogus wind circulation based on the current position and intensity of the storm. These fields are objectively analysed on the grid of the model. The model is then integrated numerically in ten-minute time steps, and from the forecast wind fields the corresponding vorticity distributions are computed. The centre of maximum vorticity is then tracked and its position is printed out at six-hourly intervals to 72 hours. This track of the maximum vorticity centre serves as the prediction of the storm track which is then transmitted to the appropriate forecast office (JTWC or Monterey). The model takes about thirty minutes to run once the initial temperature and wind fields are available for initialization. The model was tested operationally on certain storms during the 1976 hurricane season in the eastern Pacific and during the typhoon season in the western Pacific.

The following table lists average forecast errors for each region individually and for the two regions combined. For an individual forecast, the error represents the distance in kilometres from the forecast position to the corresponding position on the "best track", as determined by post-analysis of all available data.

<table>
<thead>
<tr>
<th>Area</th>
<th>Forecast period (number of cases in parentheses)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24-hour</td>
</tr>
<tr>
<td>Western Pacific</td>
<td>287</td>
</tr>
<tr>
<td>(65)</td>
<td>(57)</td>
</tr>
<tr>
<td>Eastern Pacific</td>
<td>263</td>
</tr>
<tr>
<td>(18)</td>
<td>(15)</td>
</tr>
<tr>
<td>Both</td>
<td>283</td>
</tr>
<tr>
<td>(81)</td>
<td>(72)</td>
</tr>
</tbody>
</table>

5.5 A moving fine-mesh model

During the past few years a multi-level, nested-grid tropical cyclone prediction model has been undergoing development and testing at the National Meteorological Center (NMC) of the U.S. National Weather Service (Hovmoller and Livezey, 1977). The model is known as the moving fine mesh (MFM) model, in reference to its unique feature among operational models—a nested high-resolution grid centred over the storm which moves through a
coarser outer grid during the process of integration. The model is continually evolving, but operational testing during the past two years has produced very good results, and the essential features of the model will probably remain fixed until some future date when the detailed structure of a hurricane's inner core can be incorporated into real-time initialization. The model uses the primitive equations in $\sigma$ co-ordinates and is structured such that there are ten layers in the vertical. The fine-mesh horizontal grid covers approximately a 3000 X 3000 km area with a mesh length of 60 km. The MFM model is initialized with fields generated by the routine NMC hemispheric analyses.

![Figure 5-3 - Vertical distribution of dependent variables and pressure levels in the CMG model (Hinsman, 1977)](image)

Since it is impractical, from both observational and numerical standpoints, to initialize the model with the detailed structure of the actual hurricane vortex, a model storm, derived from an axisymmetric vortex which is qualitatively similar to the hurricane, is used. This two-dimensional analog has been empirically formulated so that, when it is added to the initial steering current, a balanced, stable initial field is produced, which forms the initial conditions for the numerical integration. This problem of initial vortex "spin-up" proved to be one of the most difficult encountered in the development of the model.

A 48-hour forecast requires about two hours of computer time. In operational practice the MFM forecast is available to the forecaster approximately eight hours after the time of observation. Table 5-5 lists average forecast errors for all storm cases for which the model was run during the 1976 and 1977 hurricane seasons. While the sample size in this table is limited, the results indicate that the performance of the MFM model is very...
good. There are not enough cases to compile a meaningful homogeneous sample with other operational techniques, but an idea of the relative accuracy of the MFM model may be obtained by comparing the above table with the verification statistics presented in Chapter 10. The most striking feature of the MFM model's performance has been its ability to produce relatively more accurate forecasts for longer time periods, that is, the accuracy of the MFM forecasts does not, in general, deteriorate as rapidly with time as do other operational models. Also, experience with the model suggests that it tends to predict the path of a hurricane with very good accuracy and that a large percentage of the forecast errors are due to speed errors rather than direction errors. A moving nested-grid model (MNG) is also under development by the Japan Meteorological Agency (Ookochi, 1978). Preliminary results with this model are promising in comparison to the performance obtained by the fixed-grid method.

### Table 5-5

Average forecast errors for 1976 and 1977 for the moving fine-mesh hurricane prediction model. Errors are expressed in kilometres

<table>
<thead>
<tr>
<th>Forecast period (hours)</th>
<th>Mean error (km)</th>
<th>Number of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>104</td>
<td>27</td>
</tr>
<tr>
<td>24</td>
<td>204</td>
<td>24</td>
</tr>
<tr>
<td>36</td>
<td>253</td>
<td>21</td>
</tr>
<tr>
<td>48</td>
<td>328</td>
<td>18</td>
</tr>
</tbody>
</table>

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Ookochi, V., 1978: Preliminary results of forecasting typhoon movement using a moving nested grid. (To be published).


PART III

FORECASTING DEVELOPMENT AND CHANGES IN INTENSITY
EMPIRICAL TECHNIQUES
(by P. J. Hebert*)

6.1 General

Empirical techniques for forecasting development and changes in intensity of tropical cyclones can be categorized analogously to those for forecasting tracks although they are not so clearly defined and not so numerous. It is rather difficult to address the problems of development and changes in intensity separately under the different types of techniques. It is equally unsatisfactory to address both together for each type of technique. The latter has been chosen for the simple reason that it is consistent with other sections of this publication. In the context of this chapter, development will be defined as the formation of a cyclonic circulation, while changes in intensity will refer to existing tropical cyclones.

The same comments made in section 3.1 of Chapter 3 on track-forecasting methods apply here. In addition to the categories discussed in Chapter 3, several tropical cyclone forecast centres have detailed check lists for anticipating initial depression development and/or intensification/weakening. These check lists include many of the indicators or predictors covered in this and the following two chapters, but will not be presented here. However, those not included will be introduced where appropriate in conjunction with the technique being discussed.

6.2 Climatological and persistence forecasts

6.2.1 Development

The obvious starting point in any region of the world is to look at the seasonal variation of the locations of the cyclone tracks in climatological atlases. In addition, some cyclone forecast centres have reduced this type of depiction to a statistical one for 2½°- or 5°-of-latitude squares. Some of this information is included in Chapter 2. The favourable conditions for development of individual cyclones have been summarized by Riehl (1954) and also in a composite or climatological sense by Gray (1968). They will not be listed here, as most of them are presented later under synoptic techniques. The major advantage of a climatological forecast of development is the same as for forecasting other meteorological phenomena. It is a good constraint to know what has never previously occurred in a given region. However, the major disadvantage follows directly from this because the climatological forecast will not catch the rare and usually significant event. Another disadvantage is that the forecaster tends to predict development in climatologically favourable areas and non-development in climatologically unfavourable areas, even though synoptic indicators suggest otherwise. There is little to be said for persistence in the context in which development is used in this chapter.

6.2.2 Intensity changes

Very little has been done on a climatological basis in regard to intensity changes. Riehl (1954) makes some qualitative comments on this, but they are more properly related to synoptic techniques. Fung (1970) carried out a statistical analysis of the intensity of typhoons over the western North Pacific for an 11-year period (1958-1968).

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III.6-2 OPERATIONAL TECHNIQUES FOR FORECASTING TROPICAL CYCLONE INTENSITY AND MOVEMENT

Figure 6-1(a) - Atlantic tropical cyclones (1951-1971) May to November (inclusive). Twenty-four-hour changes (knots) for storms > 44 knots.

Key to histograms:
- Solid bars: 1 knot
- Shaded bars: 5 knots
- Dotted bars: 10 knots
- Cross-hatched bars: 15 knots

Legend:
- Mean deviation
- Number of cases
- Significant figure

Source:
- Mean deviation
- Number of cases
- Significant figure
Figure 6-1 (b) – Atlantic tropical cyclones (1957-1971) May to November (inclusive). Twenty-four-hour changes (knots) for storms $>64$ knots, stratified by direction of movement (Michaels, 1973)
and found that, in general, typhoons had their minimum pressure values to the north-east of the northern Philippines. In addition, most of the very deep typhoons occurred in a fairly limited area east and north-east of the Philippines, suggesting that these typhoons experienced considerable weakening before striking China and Japan, or before reaching latitude 20°N.

In the western North Atlantic, Michaels (1973) has stratified changes in the maximum sustained winds of cyclones over various future time periods by 5°-latitude squares, based on the observed maximum sustained wind speeds in four categories. These changes have also been stratified by direction of movement of the cyclones. Michaels (1971) did a similar study for the western North Pacific. Figures 6-1 (a and b) are reproduced from Michael's study for the Atlantic. The climatological forecast of intensity in this example for a cyclone with winds of 65 knots located at 22.5°N, 87.5°W would be an increase of 15 knots in 24 hours. Figure 6-1 (b) shows that almost all cyclones in this square lie in the same sector for direction of movement. By contrast, a cyclone located at 27.5°N, 77.5°W shows a mean increase of six knots in Figure 6-1 (a) but for movement between 285-345° it is 15 knots while between 345-045° there is a decrease of three knots. This shows the importance of including the direction of motion near the latitude of recurvature.

Riehl (1972) has shown that two-thirds of recurving typhoons in the western North Pacific during the period 1957-1968 reached their maximum intensity within 12 hours of recurvature. Most of the other one-third reached maximum intensity within one day prior to recurvature. The mean latitude varied seasonally, as might be expected, but with a rather wide range for individual typhoons as a result of varying synoptic situations. Riehl also found that an estimate of the percent reduction of maximum wind speed in the 48 hours after recurvature was primarily a function of the latitude effect. This estimate can be obtained from:

\[
\frac{V_{\text{max}}}{V_{\text{o max}}} = \frac{1}{1 + \left(\frac{\beta}{f_0} \cdot y\right)}
\]

where \(V_{\text{max}}\) is the maximum wind speed at a given time, \(V_{\text{o max}}\) the highest maximum wind speed recorded during the life of the typhoon, \(\beta\) is the change of Coriolis parameter \((f)\) with latitude \(\frac{df}{dy}\) and \(y\) is the distance north of \(\phi_0\). For large distances an additional 10 to 15 percent decrease may occur because of unfavourable environmental conditions (e.g. lower sea-surface temperatures). Riehl states that this approach should be applicable to other tropical cyclone regions.

Tsui et al. (1977) examined the change in intensity of 25 typhoons in the western North Pacific using satellite and aircraft data and showed that there is a 0.64 probability that a typhoon will have intensified during the 24 hours prior to the formation of a plume of medium or high cloud streaming from its centre towards the north-east as first seen on a satellite photograph.

Brand (1973) has done a climatological study of rapid intensification and low-latitude weakening of western North Pacific tropical cyclones. In this study he also presents monthly maps similar to Michaels (1973) for average 24-hour intensity changes of all tropical storms and typhoons by 10°-latitude squares. These maps were produced from a much more extensive tabular report by Brand and Gaya (1971) which stratified changes by current intensity, month and amount of change for 12-, 14- and 48-hour periods for each 10°-latitude square. Brand (1972) has also done a study of geographical and monthly variations of very large and very small typhoons in the western North Pacific. This could be of some limited use to forecasters in regard to the size of the overall wind field associated with these cyclones.

The only persistence forecast which does not use synoptic data is the extrapolation of a past central pressure change for a future time period. The conversion of the forecast central pressure to a maximum sustained wind can then be made from regionally-used pressure/wind relationships. This type of forecast is also discussed under synoptic techniques. The advantages and disadvantages of using these aids are the same as those stated for development.
6.3 Synoptic techniques

6.3.1 Development

Riehl (1954) pointed out the need for a pre-existing disturbance in order for a cyclone to develop. The advent of meteorological satellites confirmed the universal validity of this statement. The type of pre-existing disturbance constitutes one of the major regional differences in the initial development of a tropical cyclone. Correspondingly, the synoptic weather patterns which lead to the formation of the pre-existing disturbance also vary from region to region. The evidence from all regions suggests that once the cyclone has formed there is basically little difference in requirements for intensification (Gray, 1968). Several necessary but not sufficient conditions appear to be uniformly required for development, regardless of the synoptic weather pattern which has produced the disturbance. Many of these conditions can now be deduced or computed with the aid of satellite observations, and to a much greater extent than was possible in earlier years. However, they should be considered as synoptic indicators and will be treated as such in this section. Indicators using only satellite information will be treated in the section on satellite techniques.

This section will not deal with general circulation or individual synoptic patterns which lead to the necessary criteria for development. Riehl (1954) and Gray (1968), among many others, give extensive discussions of the theoretical and physical processes leading to the establishment of the necessary conditions, and their subsequent importance in the development process. Much of the discussion in the following portions of this section will be taken from the above sources. Satellite observations have largely solved the problem of detection. It is up to the regional forecaster to determine from his information sources whether or not a particular disturbance will meet these criteria.

The need for sea-surface temperatures greater than 26.5°C (Palmén, 1948) and a deep lower level moist layer (Riehl, 1954) has been well documented by Gray (1968). However, except during the early and late portions of tropical cyclone seasons, and near the poleward borders of preferred regions for development, these two criteria are almost always present when there is a pre-existing disturbance. The establishment of the warm core necessary for a concentrated pressure fall and cyclogenesis is more dependent on dynamic rather than thermodynamic criteria. The single most important inhibitor of warm core development is a strong vertical shear between the horizontal winds of the lower and upper boundary layers. Another important dynamic requirement is the presence of a large area of surface cyclonic vorticity associated with the disturbance (Gray, 1968). Its presence can usually be inferred from surface maps and/or satellite pictures. Cyclonic vorticity is necessary in order to produce the moisture convergence required for net warming of the troposphere and it helps to protect this warm core from being ventilated (dried or cooled) by the vertical wind shear. Finally, a large area of anticyclonic vorticity at upper levels enables the disturbance to establish a suitable outflow mechanism for mass divergence (S. Erickson, 1977).

These criteria and/or the synoptic weather features which accompany or presage them have been incorporated into various decision ladders (Simpson, 1971), check lists (Hebert, 1977; Australian Bureau of Meteorology, 1977) and indices (Gray, 1968, 1975). Since most of them are regionally oriented, it would not be appropriate to include them here. However, each tropical cyclone forecast centre should be familiar with all such procedures in order to ascertain their utility in the centre’s forecast responsibility area. The same holds true for the following section on intensity changes.

6.3.2 Intensity changes

Little success has been demonstrated by any quantitative synoptic approach to forecasting changes in intensity of a tropical cyclone. Persistence, climatology, satellite techniques, or subjective evaluation of current and forecast synoptic patterns are the forecaster’s primary tools. Because of sparsity of data and lack of computing facilities most tropical cyclone forecast centres will have to rely on satellite techniques for many years to come. Work in this area is discussed in section 6.4.
The basic processes necessary for strengthening an existing tropical cyclone are generally agreed on. The vertical mass circulation which has been established in the depression stage must be accelerated. Any synoptic weather pattern or other criteria necessary for initial development which will enhance the inflow/outflow mechanism and increase the central core warming will do. Changes in the four basic criteria listed under development should be reflected in intensity changes of tropical cyclones. At most forecast centres these can only be inferred from standard surface and upper-air charts. However, changes in observed values of other criteria related to these basic criteria can be extrapolated and related to changes in the cyclone's intensity. Some of these are discussed in the following paragraphs.

Forecast centres having computer facilities can make realistic computations of radial velocity (inflow and outflow), vorticity, divergence and other dynamical quantities (Jarvinen and Hebert, 1978). An evaluation of such computations made at the U.S. National Hurricane Center (Hebert and Jarvinen, 1977) showed some diagnostic and prognostic skill in that trends in cyclone intensity are related to radial velocity in the lower and upper boundary layers. However, data limitations precluded obtaining realistic values within a 3° latitude radius of the centre but usable values were obtained in the range of 4-6° of latitude. Other fields such as vorticity, vorticity advection and divergence have not been thoroughly tested. Attempts over the years to compute radial velocities manually at various forecast centres have met with little success.

Figure 6-2 - Central pressure versus time trace for Hurricane Eloise, 13-24 September 1975. The text gives an example of how to use the past 12- or 24-hour central pressure change to obtain a 24-hour maximum wind forecast (Hebert et al., 1977)
Other means of following intensity changes of a cyclone and extrapolating their persistence are obtained from satellite, reconnaissance and radar data. One of the primary uses of reconnaissance data is in determining the central pressure change with time in an individual cyclone. The past 12- or 24-hour central pressure changes can be extrapolated to obtain the expected central pressure 12 and 24 hours in the future. Figure 6-2 shows the central pressure versus time profile for Hurricane Eloise. In Figure 6-2, for example, this would have given a central pressure of 950 mb for landfall on 23 September, 1200 GMT. This is based on the past change of 18 mb during the 12 hours prior to 23 September 0000 GMT. In this case, the extrapolation would have closely approximated the 955-mb landfall pressure of Eloise. Maximum sustained winds can then be estimated from the regional pressure-wind nomograph. Another bit of reconnaissance (and sometimes ship) information which is occasionally useful is the change in the radius of maximum winds. A decrease usually indicates strengthening. Extrapolation of the observed maximum wind change is not a good technique, since this change is frequently non-linear with time.

Land-based radar observations of changes in the eye diameter of an individual cyclone have been found to be indicative of changes in intensity. Shrinking of the eye diameter is usually a sign of strengthening. Formation of a double eye wall usually indicates a severe cyclone (frequently less than 940 mb) (Hoose and Colon, 1970). Radar echo cell movements in advance of the eye are not well correlated with maximum sustained winds. They can give some information about changes in intensity of weaker cyclones, as well as in the intensity of rain bands preceding the centre. Little skill beyond extrapolation has been demonstrated in attempts to forecast rapid intensification. While some synoptic patterns are known to be favourable (Holliday, 1977), delineation of climatologically favourable areas (Brand, 1972) and extrapolation of observed trends are still the forecasters’ best tools.

The advantage of techniques using synoptic data over those using climatology and/or persistence is to indicate favourable or unfavourable departures from the latter. Synoptic indicators in toto usually achieve this goal through subjective interpretation. However, none of the individual aids discussed in this section can presently be used with a high degree of confidence. This stems partly from the disadvantages of synoptic techniques. They include lack of sufficient data, lack of computer facilities to process such data and lack of prognoses with the proper resolution in the tropics of almost all synoptic parameters considered favourable for cyclogenesis/intensity change (Hebert, 1977).

6.4 Satellite techniques

6.4.1 Development

The advent of geostationary satellites enabled certain countries to compute cloud motion vectors or “winds” primarily at the cirrus and cumulus base levels. These “winds” have been used in several studies (C. Erickson, 1974; Rodgers et al., 1977) to compute divergence, vorticity, vertical shear of the horizontal wind and other quantities. Use of this type of satellite information as applied to tropical cyclones was discussed under synoptic techniques.

Studies by S. Erickson (1977) and Arnold (1977) have dealt with observed differences between developing and non-developing tropical disturbances, primarily of the western North Pacific Inter-tropical Convergence Zone (ITCZ) type. Such observations were also compared to measurements composited from rawinsonde data for verifications purposes. The data used were obtained from the very high resolution satellites belonging to the Defense Meteorological Satellite Program (DMSP) of the US Department of Defense. However, pictures from polar-orbiting satellites and geostationary satellite products should give meaningful comparisons. The conclusions in their studies based on satellite observations alone could be of future use to forecasters. Table 6-1 is taken from S. Erickson’s paper (1977) and summarizes the cirrus cloud measurements for developing and non-developing disturbances. The disturbances are classified according to the amount of penetrative convective elements within certain temperature ranges over specified grid sizes used with the satellite data. For example, the percentage of cirrus area coverage in
Cirrus I for penetrative elements of Kelvin temperature less than or equal to 210 degrees in the $1 \times 1$ grid square (corresponding approximately to a radius of $1.4^\circ$ outward from the centre of the disturbance) was 43 for non-developing disturbances (designated 00') and 31 for developing disturbances (designated ESI). The following conclusions from Erickson's study based on the DMSP satellite-observed cloud characteristics between these two classes of systems are worth noting:

(a) The per cent area covered by penetrative convection and total cirrus within the $1 \times 1$ area ($r \sim 1.4^\circ$) and the $3 \times 3$ area ($r \sim 4.2^\circ$) is much the same;

(b) There is significantly more penetrative convection ($\sim 3$ to 1) and total cirrus ($\sim 2$ to 1) in the outer environmental area of the developing disturbances. These systems are more distinguished by their convective differences at outer radii;

(c) Cirrus density (three IR grey shades) differences between disturbance classes indicate cirrus level outflow patterns to be significantly different between systems. In general, flow is anticyclonic in the developing disturbance and uni-directional in the non-developing disturbance;

(d) The average lifetime of even the more conservative non-developing disturbances is short. Disturbances with the potential to maintain themselves for more than two days have a significantly higher intensification potential.

### TABLE 6-1

Summary of cirrus area coverage measurement of penetrative convection for developing and non-developing disturbances for specified disturbance radii (coverage expressed in per cent and based on Data Set 3)

<table>
<thead>
<tr>
<th>Disturbance classe</th>
<th>Grid stratification</th>
</tr>
</thead>
</table>
|                    | $1 \times 1$  
$r \sim 1.4^\circ$ | $3 \times 3$  
$r \sim 4.2^\circ$ | $5 \times 5$  
$r \sim 7.1^\circ$ | Outer 8  
$r \sim 1.4-4.2^\circ$ | Outer 16  
$r \sim 4.2-7.1^\circ$ |
| Cirrus I ($T \leq 210$ K) | | | | | |
| Non-developing (00') | 43 | 20 | 9 | 17 | 5 |
| Developing (ESI) | 31 | 16 | 9 | 14 | 4 |
| Cirrus II ($210 \leq T < 216$ K) | | | | | |
| Non-developing (00') | 23 | 15 | 8 | 14 | 4 |
| Developing (ESI) | 29 | 20 | 13 | 19 | 9 |
| Cirrus III ($216 \leq T < 222$ K) | | | | | |
| Non-developing (00') | 10 | 11 | 7 | 11 | 5 |
| Developing (ESI) | 15 | 14 | 12 | 14 | 11 |
| Total cirrus ($T \leq 222$ K) | | | | | |
| Non-developing (00') | 76 | 46 | 24 | 42 | 14 |
| Developing (ESI) | 75 | 50 | 34 | 47 | 24 |

Arnold (1977) also found relative minima in convection both adjacent to and within cloud clusters. He hypothesized that these areas are produced by forced subsidence resulting from cirrus level convergence. The latter results either from a favourable positioning of groups of convective cells within the cluster or from interaction of one of these groups with a synoptic-scale feature such as an upper-level trough. It is this relatively cloud-free area which eventually becomes the depression centre. However, non-developing clusters also have such areas, and the differences given by S. Erickson also need to be considered.
6.4.2 Intensity changes

The Dvorak (1975) technique is probably the most widely used aid at tropical cyclone forecast centres around the world. It is fully discussed in the WMO sub-project publication on geostationary satellites. A technique by Hebert and Potenet (1975) for estimating the intensity of subtropical cyclones is also discussed in that publication. It is primarily of interest to countries in subtropical or middle latitudes. Neither of these studies will be discussed here, as both are included in WMO Technical Note No. 153 (1977) on The use of satellite imagery in tropical cyclone analysis.

In Arnold's (1977) study, he examined numerous cyclones of all sizes and strengths. He concluded that the single most important result from the analysis of satellite pictures was the extreme variability of cloudiness on a diurnal, day-to-day and cyclone-to-cyclone basis. This variability was present in the amounts of deep convection, cirrus coverage and banding features of tropical cyclones. This leads to the problems encountered in using satellite cloud models such as Dvorak's. Arnold's study considered nine different stratifications of the satellite data versus various cyclone parameters. These included pre-depression versus typhoon stage, slow versus fast-moving systems, directional differences, rapid deepening versus steady typhoons, past and present cloudiness versus intensity, and equatorial versus trade-wind disturbances. His conclusion was that there is little hope in trying to relate the amount of cloudiness of an individual cyclone to any of the nine parameters considered. For the present, however, the Dvorak technique remains one of the most useful satellite techniques employed at tropical cyclone forecast centres.

Recently Dvorak (1977) devised a classification technique based on infra-red imagery which is designed to supplant the technique which uses visible imagery.

REFERENCES


Australian Bureau of Meteorology, 1977: The Australian tropical cyclone forecast manual. (Rough draft.)


7.1 General

These techniques consist of either the compositing of various parameters associated with the formation and intensification of tropical cyclones (the analog approach), or regression equation models.

7.2 Analog models

7.2.1 Development

Figure 7-1 - Average isotach (m s⁻¹) and streamline analysis for developing disturbances (designated ESI) above and non-developing disturbances (designated 00') below: (a) at 950 mb and (b) at 200 mb (S. Erickson, 1977)

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Namias (1955) pointed out that tropical cyclogenesis is probably related to general circulation features. Ballen­zweig (1957, 1959) related monthly anomalies in the 700-mb height patterns to regional and annual differences in cyclogenesis over the North Atlantic. In addition to the synoptic and climatological indicators presented earlier, it is helpful for the forecaster to know which general circulation patterns are conducive to development or non-development. This type of study would probably be useful in other tropical regions.

A different type of comparison can be made by relating fields of individual cyclogenesis parameters to those obtained by compositing many cases. Gray (1968, 1975) has made such composites for most tropical oceans. While the values of criteria close to the disturbance are important both individually and as a group, the distribution of these parameters in the environment surrounding the disturbance is also important. Figures 7-1 (a) and (b) are reproduced from S. Erickson (1977) to illustrate the importance of this consideration. Many criteria derived from these composites would be the same for both development and non-development, but the difference in the individual patterns means development in one instance and non-development in another.

7.2.2 Intensity changes

In general, the comments on development in section 7.2.1 are also applicable for intensity changes. Hebert and Miller (1969) did a study similar to Ballen­zweig’s, but for composites of daily anomalies and mean 700-mb height fields for the three-day sequence leading to hurricane formation. These anomaly composites reflected the interaction of a trough in the westerlies with the intensifying tropical cyclone for several different geographical areas, as suggested by Riehl (1954). While not equivalent, the 24-hour height changes at 700 mb or 500 mb would give some indication of the presence of an interacting trough, as would the anomalies of the surface-pressure field.

7.3 Regression equation models

7.3.1 Development

No techniques of this type are known by the authors to be operationally useful at the present time.

7.3.2 Intensity changes

Arakawa (1961) was the first to derive a statistical forecast scheme for intensity changes using operational data. He used the surface-pressure field surrounding the cyclone as well as cyclone parameters to predict the 24-hour central pressure change. Most of the variance in the forecast was explained, however, by combinations of present and/or past changes of the cyclone itself. Elsberry et al. (1974) did a similar study for the western North Pacific using only cyclone parameters and extended the forecasts out to 48 and 72 hours. Synoptic data at 700 mb were also introduced as initially suggested by Arakawa. However, this refinement provided only minimal predictive value at 48 and 72 hours for cyclones north of 20° latitude. Both techniques showed improvement over persistence, but had large standard deviations and are primarily useful for “normal” cases. Neumann and Jarvinen (1978) have done a similar study for the North Atlantic using only the cyclone’s date, location and intensity as predictors.

While regression techniques have shown an advantage over climatology and persistence, they do not perform well in abnormal situations. In view of the partial success obtained with this type of technique in forecasting intensity changes, and its larger success in predicting cyclone tracks, it is probably worth while to pursue the development of similar techniques if additional significant predictors can be established.
REFERENCES


PART IV

VERIFICATION OF TROPICAL CYCLONE FORECASTS
CHAPTER 8

DYNAMICAL TECHNIQUES
(by P. J. Hebert*)

There are currently no operational forecast techniques which can realistically predict either development or changes in intensity of tropical cyclones. A form of dynamical technique invented by Shapiro (1977) for predicting the evolution of North Atlantic tropical waves into tropical depressions which continue to develop into tropical storms has shown some success in its first year of application at the National Hurricane Center. The criterion for development versus non-development of a depression is a dynamical one based on wave-number criteria of the tropical wave train moving across the Atlantic in the lower boundary layer mean flow. A map of the development index is derived daily from the NHC lower boundary layer chart. This technique involves non-linear interactions and requires computer facilities. It does not deal with other types of disturbances which develop into tropical storms. Since the North Atlantic is the only ocean which has this type of disturbance, studies elsewhere would have to seek a different approach to using wave numbers. However, the usefulness of this approach is not precluded by the initial regional application. The sole dynamic approach at present (Shapiro, 1977) is limited in scope both regionally and for a particular type of disturbance.

REFERENCE


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CHAPTER 9

TRACK FORECAST ERROR CHARACTERISTICS
(by C.J. Neumann*)

9.1 Introduction

Chapters 9 and 10 are concerned with various aspects of tropical cyclone forecast verification. No attempt will be made to present verification statistics on all the prediction models one finds around the world. Such a verification would have little meaning because of the non-homogeneity of the fragmented verification samples. Rather, the verification (as given in Chapter 10) will be limited to different classes of models. Since a homogeneous sample of all classes of models is available only from the North Atlantic, comparative error statistics will be presented for that basin only. Verification of tropical cyclone forecasts is related to errors in the initial positioning (positioning "error") of tropical cyclones. For this reason, this chapter includes information relative to this topic.

The operational utility and accuracy of a tropical cyclone prediction model must ultimately be based on its performance in an operational environment. Typically, the average displacement error, defined as the vector difference between forecast and observed position in the various forecast projections, had been used as a verification standard. However, there are other, less objective criteria upon which performance should be based. These additional criteria would include such factors as the timeliness of a forecast, economic considerations, performance on the more "difficult" or "critical" forecasts and, finally, the manner in which the forecast is presented to the user. Although a really successful model may not necessarily excel in all of the above factors, it may represent a "trade-off" in some areas. Forecasts based on climatology and persistence, for example, are economical and timely; however, their accuracy out of the tropics is limited. On the other hand, complex statistical and numerical models may offer some improvement in accuracy but at added expense and loss of forecast lead time. The resources, needs and area of forecast responsibility of a given Meteorological Service will typically determine the type of model or models best suited for that service.

9.2 Displacement error

The displacement error ($E$) is defined as the distance between the forecast ($X_f, Y_f$) position and the observed ($X_o, Y_o$) position of a storm -- $X$ and $Y$ being longitude and latitude, respectively. On the Earth’s surface, this (great-circle) distance is given by:

$$E = 60 \arccos \left[ \sin Y_o \sin Y_f + \cos Y_o \cos Y_f \cos (X_o - X_f) \right]. \quad (1)$$

A good approximation to (1) is given by:

$$E' = (E_z^2 + E_m^2)^{1/2} \quad (2)$$

where

$$E_z = (X_f - X_o) \cos \left( (Y_f + Y_o) / 2 \right) \quad (3)$$

and

$$E_m = (Y_f - Y_o) \quad (4)$$

$E_z$ and $E_m$ being, respectively, the zonal and meridional errors. The algebraic signs of (3) and (4) will require adjustment depending on whether the errors are being computed for areas east or west of Greenwich and north or south of the Equator. As an example of the magnitude of the error in using (2) rather than (1), consider a storm observed

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at 15°N, 50°W but forecast to be at 30°N, 70°W. The great circle distance from (1) computes to 2636.5 km (1423.6 n.m.) while the approximation from (2) is 2644.6 km (1428 n.m.), a difference of only 8.1 km (4.4 n.m.).

9.3 Positioning error

9.3.1 Definition of positioning error

Verification of tropical cyclone forecasts may involve the determination of positioning “error”. This quantity is defined as the distance, measured by (1) or (2), between the operationally determined initial storm position and the possible corrected initial storm position as later determined from a post-analysis. This post-analysis track is the track that is eventually archived and is generally referred to as “best-track”.

9.3.2 Components of positioning error

Figure 9-1 – Portion of Hurricane Carla (1961) track over the Gulf of Mexico showing four unsmoothed trochoidal oscillations of storm centre. Track is based on “fixes” from three coastal radars. Heavy track, offset to north-east, shows portion of smoothed “best-track”. Range markers are at 20 n.m. intervals 37 km. (figure adapted from Weatherwise, October 1961.)
The precise path of the centre of circulation of a tropical cyclone typically shows small-scale (less than 40 km) trochoidal oscillations about some reasonably conservative mean track representative of the synoptic-scale steering forces. The best-track is an estimate of this latter scale of motion. Although some semi-objective methods of constructing best-tracks have been devised, the process remains essentially subjective. An example of best-track scale of motion compared to the actual path of a storm centre as estimated by three coastal radars is shown in Figure 9-1. In this rather striking example, the small-scale oscillations were quite extreme and rather heavy smoothing was required. A more typical example of a small-scale trochoidal motion of the storm centre as documented by weather satellite is shown in Figure 9-2. Eventual best-track smoothing removed much of this smaller scale of motion.

Figure 9.2 – Composite, infra-red satellite photograph of Hurricane Belle, 7 to 8 August 1976, showing small-scale trochoidal motions of "eye". The outlines of the Florida and Carolina coasts appear in lower and upper left, respectively (from Lawrence and Mayfield, 1977)
In view of the smoothing inherent in the construction of best-tracks of tropical cyclones, the component of positioning error cited in the preceding paragraph is really a "pseudo-error" relative to the smoothed track. However, positioning errors also reflect actual errors in locating the centre of a tropical cyclone by one or more of the standard observational platforms. These observational errors (Sheets and Grieman, 1975) are typically less than 22 km (12 n.m.) on the more intense storms which are usually associated with well-defined circulation features but may exceed 50 km (27 n.m.) on the weaker systems with poorly organized circulation patterns. Finally, another component of positioning error relates to errors introduced by extrapolating (forecasting) the latest available "fix" to the required time of the initial position of the tropical cyclone. The magnitude of this error is a function of the frequency of satellite imagery available to the forecaster. To summarize, therefore, positioning errors contain three components. These include:

(a) A "pseudo-error" introduced by the removal of real small-scale oscillations;

(b) Actual errors in locating the centre of circulation;

(c) Extrapolation errors.

9.3.3 Characteristics of positioning error

Figure 9-3 - Distribution of positioning "errors" over the North Atlantic tropical cyclone basin 1967-1976. Origin represents location of best-track estimate of storm location while plus sign (+) represents relative location of operational estimate. Nine cases are located beyond the bounds of the x and/or y axes.
Figures 9-3 and 9-4 show some of the statistical characteristics of initial positioning error. The data upon which these figures are based are the operational positioning errors which have been observed at the U.S. National Hurricane Center between 1967 and 1976. Figure 9-3 simply shows the distribution of these errors relative to the best-track storm position. The plot shows that the errors are approximately circularly distributed. However, standard statistical tests show that the distribution is not circular normal or bivariate normal, there being too many cases near the centroid of the distribution. It can also be noted from Figure 9-3 that there is very little bias in the distribution.

A histogram showing the magnitude of these positioning errors as computed by an equation of form (2) is given in Figure 9-4. Approximately 70 per cent of the errors are seen to be under 25 n.m., i.e. 46 km. Errors exceeding this amount typically occur on weak storms with a poorly defined cloud and wind circulation centre. Many of the large errors shown in Figure 9-4 were observed prior to the availability of continuous satellite coverage over the North Atlantic basin. In these instances, "fixes" on distant storms were available only once per day and the extrapolation component of the positioning error becomes the major source of error. With continuous satellite coverage, positioning errors exceeding 100 km (54 n.m.) are rare. The gradual improvement in the ability to position tropical cyclones in an operational environment is shown in Figure 9-5. The irregular downward trend in this error reflects the increasing availability of satellite coverage and improved technology in the ability to position a tropical cyclone from satellite imagery and aircraft reconnaissance observations. Similar trends have been noted in other tropical cyclone basins. Average positioning error, as currently defined, has a practical lower limit estimated to be near 20 km (11 n.m.). This limit is set by the fact that the quantity is defined relative to a smoothed best-track. Also, positioning of a tropical cyclone in an operational environment requires a certain amount of skill over and above that involved in the construction of a final best-track where the future, as well as the present position, of a storm is known.
In developing a prediction model, it is tacitly assumed that a storm is located at a given latitude/longitude intersection and the prediction algorithm is structured accordingly. However, when activating the model in an operational mode, it usually turns out that the initial position supplied to the model is in error. Figure 9-3 illustrates these errors. Re-running the model on the correct position as later determined from the best-track typically gives a better forecast. The question arises as to the manner of treating these initial positioning errors in forecast verification. In some Meteorological Services, it is customary to displace the entire forecast track so that the initial position of the forecast track corresponds to the initial position from the best-track. Other Meteorological Services make no allowance for initial positioning error. Ample justification exists for using either of these two approaches. As shown in Table 9-1, the effect on displacement error is minimal. The table compares verification statistics over a six-year period with positioning errors both retained and removed.
TABLE 9-1

Average displacement errors 1971-1976 in the official forecasts issued by the U.S. National Hurricane Center on North Atlantic Tropical cyclones. Errors are tabulated both with positioning error included and removed. Errors are in kilometres.

<table>
<thead>
<tr>
<th>Forecast period (hours)</th>
<th>Position error included</th>
<th>Position error removed</th>
<th>Number of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>107</td>
<td>96</td>
<td>854</td>
</tr>
<tr>
<td>24</td>
<td>217</td>
<td>206</td>
<td>737</td>
</tr>
<tr>
<td>48</td>
<td>480</td>
<td>470</td>
<td>518</td>
</tr>
<tr>
<td>72</td>
<td>765</td>
<td>759</td>
<td>366</td>
</tr>
</tbody>
</table>

It can be noted that the percentage differences in the error range from near eleven per cent to less than one per cent for the 12-hour and 72-hour forecast periods, respectively. If positioning error is to be removed, then the terms $Y_o$ and $Y_f$ in Equations (1) and (2) should be replaced by $Y_o - \Delta Y_o$ and $Y_f - \Delta Y_o$, where $\Delta Y_o$ is the difference between best-track and operational latitude. Similar corrections must be made to longitudinal ($X_o$ and $X_f$) components. Care should be taken that the algebraic signs of $\Delta Y_o$ and $\Delta X_o$ are correctly assigned.

REFERENCES


CHAPTER 10

COMPARISON OF TROPICAL CYCLONE TRACK FORECAST TECHNIQUES
(by C. J. Neumann*)

10.1 Factors relating to forecast "difficulty"

The character of tropical cyclone motion is known to vary from one portion of a tropical cyclone basin to another. Although there are notable exceptions, storms at low latitudes are typically steered by deep easterlies and exhibit relatively slow, steady motion when compared to storms which have recurved out of the tropics, the motion of which is likely to be faster and more erratic. These differences in motion characteristics are reflected in displacement errors which typically increase with latitude. This factor and others must obviously be considered when comparing error statistics over different basins or over different portions of the same basin.

10.1.1 Differences among basins

Figure 10-1 shows the geographical bounds of the major portions of six tropical cyclone basins. Because of differences in geography and sea-surface temperature regimes, the latitudinal centroids of these basins are seen to show considerable variation, ranging from about 16°N for the eastern North Pacific basin to about 26°N for the North Atlantic basin. Average displacement errors observed in tropical cyclone forecasts over these two basins reflect this difference and are considerably higher over the North Atlantic. In Figure 10-2, for example, the small displacement errors attained by two prediction models on Hurricane Iva over the eastern North Pacific could virtually never be attained on a storm over the North Atlantic basin. The average latitude of a basin is therefore a measure of forecast "difficulty".

Another measure of comparative forecast "difficulty" is the standard deviation of tropical cyclone motion. This quantity is shown for four of the six basins in Figure 10-3. The largest standard deviations of North Atlantic storms result from these storms being tracked from the deep easterlies northwards into the deep westerlies where translational speeds, often exceeding 30 knots, can lead to large displacement errors even on reasonably "good" forecasts. The small standard deviations observed on eastern North Pacific and north Indian Ocean storms reflect the relative infrequency of easterly-moving storms over these basins.

An example of the effects of different inter-basin motion characteristics on the performance of a given statistical prediction model is shown in Figure 10-4. This figure shows the displacement errors obtained from the independent data test of a "simulated" analog model (see section 4.3.2) which has been developed for each of the specified basins. At 72 hours, the difference between the model as it performs over the North Atlantic basin (Neumann, 1972) and the North Indian basin (Neumann and Mandal, 1978) amounts to 254 km (137 n.m.). This is nearly twice the range one obtains from different models over the same basin as shown, for example, in Table 10-1. Thus comparing different models over different basins is utterly meaningless and mainly reflects different characteristics of the basins rather than differences in the models themselves.

10.1.2 Differences within given basins

Forecast "difficulty" also varies within given basins. In Figure 10-5 (b), for example, isolines of equal 48-hour forecast errors over the western North Pacific are seen to increase from less than 400 km (216 n.m.) south

*National Hurricane Center, Miami
of the central Philippine Islands to over 550 km (297 n.m.) north-north-eastward over central Japan. The 24-hour errors show a similar but more irregular gradient. Over the North Atlantic basin, Figure 10-6 shows that the 36-hour forecast errors for the specified prediction model average less than 200 km (108 n.m.) for a storm moving 285/10 knots (a motion typical of a storm at low latitudes) to over 550 km (297 n.m.) for a storm moving towards the north-east at 20 knots (a motion typical of a storm after recurvature). Because of these differences, displacement errors compiled by one Meteorological Service on storms affecting a limited area of forecast responsibility cannot be compared with those of another Service located in the same basin but having a different area of forecast responsibility.

10.13 Temporal differences

Within the same tropical cyclone basin, differences in tropical cyclone motion characteristics are known to occur from one year to the next, from one decade to the next or over longer periods. In the year 1969, for example, the “official” 24-hour forecast error at the U.S. National Hurricane Center was 246 km (133 n.m.) while in the following year, 1970, it was only 141 km (76 n.m.). The difference does not necessarily reflect an increase in forecast skill, 1970 over 1969, but rather that none of the 1970 storms and almost all of the 1969 storms recurved into the westerlies. The different characteristics of the two seasons is also reflected in the latitude of the storms which averaged 31°N for 1969 and 22°N for 1970.
10.1.4 Need for normalization of tropical cyclone forecasts

Because of the temporal and spatial differences in the character of tropical cyclone motion as discussed in the previous three subsections, some type of normalization of forecast errors for the purpose of "benchmark" comparison is desirable. Although research on this subject continues, a satisfactory method of effecting such a comparison has yet to be developed. The problem is further discussed by Jarrell et al., 1978, and Neumann, 1977.

10.2 Performance of various classes of prediction models

Because of heterogeneities discussed in subsections 10.1.1 to 10.1.4 inclusive, a comparative performance of the various models one finds around the world — if this performance is based on displacement error — would be meaningless. However, virtually all the available verification statistics from the various forecast centres are, indeed, based on this quantity. Furthermore, these are fragmented samples collected under different operational constraints. However, a temporally, spatially and operationally homogeneous sample of displacement errors of all classes of prediction models (except baroclinic models) is available for the North Atlantic basin for the period 1973 to 1976 inclusive. These data are summarized in Tables 10-1, 10-2 and 10-3 and represent the operational errors for the specified prediction model as well as for the "official forecasts" issued by the U.S. National Hurricane Center.
Table 10-1 gives displacement errors for four classes of prediction models: "simulated" analog (CLIPER), statistical-synoptic (NHC67 and NHC72), statistical-dynamical (NHC73) and barotropic (SANBAR). Although NHC67 and NHC72 are similar models, the latter is somewhat more refined in that it combines the better features of the CLIPER and the NHC67 models into a single model. It may be noted that the Atlantic analog model HURRAN is not included in Table 10-1. This omission is due to the fact that the analog model fails under anomalous forecast situations and its inclusion would have reduced the sample size by approximately one third. However, the HURRAN model is compared with the CLIPER model in Table 10-2. The data contained in the latter table are for a longer period of record and include four forecasts per day whereas the data in Table 10-1 represent two forecasts per day based on observations at 0000 GMT and 1200 GMT.

Table 10-1 discloses that there is a maximum difference of 14, 10, 23 and 20 per cent in the displacement errors registered by the various models at the 12-, 24-, 48- and 72-hour forecast projections respectively. Poorest performance (including Table 10-2) has been shown by the analog HURRAN model in all forecast periods, whereas the statistical-dynamical NHC73 model has observed minimum displacement error. The barotropic SANBAR model has also shown up well at the 48- and 72-hour forecast periods. Likewise, and somewhat surprising, the CLIPER
VERIFICATION OF TROPICAL CYCLONE FORECASTS

Figure 10-4 – Average displacement errors observed by identical prediction model developed for three tropical cyclone basins. Errors based on independent data tests using best-track initial motion vectors (from Neumann and Mandal, 1978).

TABLE 10-1

Average displacement error (km) observed by specified prediction methods on a homogeneous sample of operational tropical cyclone forecasts 1973-1976 over the North Atlantic basin. Column labeled “reference” gives location in text where a given class of model is discussed.

<table>
<thead>
<tr>
<th>Official forecast, model and number of cases</th>
<th>Reference</th>
<th>12-hour</th>
<th>24-hour</th>
<th>48-hour</th>
<th>72-hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Official forecast</td>
<td>–</td>
<td>98</td>
<td>207</td>
<td>480</td>
<td>730</td>
</tr>
<tr>
<td>CLIPER</td>
<td>4.3.2</td>
<td>102</td>
<td>228</td>
<td>496</td>
<td>683</td>
</tr>
<tr>
<td>NHO57</td>
<td>4.3.4</td>
<td>102</td>
<td>217</td>
<td>532</td>
<td>802</td>
</tr>
<tr>
<td>NHC72</td>
<td>4.3.4</td>
<td>98</td>
<td>217</td>
<td>493</td>
<td>715</td>
</tr>
<tr>
<td>NHC73</td>
<td>4.3.5</td>
<td>94</td>
<td>209</td>
<td>433</td>
<td>667</td>
</tr>
<tr>
<td>SANBAR</td>
<td>5.2</td>
<td>107</td>
<td>217</td>
<td>463</td>
<td>696</td>
</tr>
<tr>
<td>Number of cases</td>
<td>–</td>
<td>206</td>
<td>183</td>
<td>135</td>
<td>94</td>
</tr>
</tbody>
</table>
IV.10-6 OPERATIONAL TECHNIQUES FOR FORECASTING TROPICAL CYCLONE INTENSITY AND MOVEMENT

Figure 10-5 – Geographic distribution of mean 24-hour (a) and 48-hour (b) Joint Typhoon Warning Center (JTWC) forecast errors for western Pacific tropical cyclones. Errors are based on 1966-1975 data and relate to mean forecasts from initial positions. Values are given in km (in parentheses) and n.m. (from Jarrell et al., 1978)

TABLE 10-2
Average displacement error (km) observed by specified prediction methods on a homogeneous sample of operational tropical cyclone forecasts 1971-1976 over the North Atlantic basin. Column labelled “Reference” gives location in text where a given class of model is discussed

<table>
<thead>
<tr>
<th>Official forecast, model and number of cases</th>
<th>Reference</th>
<th>Forecast projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Official forecast</td>
<td>–</td>
<td>98</td>
</tr>
<tr>
<td>HURRAN</td>
<td>4.2.6</td>
<td>202</td>
</tr>
<tr>
<td>CLIPER</td>
<td>4.3.2</td>
<td>107</td>
</tr>
<tr>
<td>Number of cases</td>
<td>–</td>
<td>335</td>
</tr>
</tbody>
</table>

model – a regression equation model based on climatology and persistence – shows up reasonably well at the extended periods. For reasons discussed in section 10.1.1, the displacement errors observed over the Atlantic basin (and the western Pacific) will be larger than over the other basins.
Figure 10-6 - Thirty-six-hour North Atlantic analog model displacement errors (solid lines labelled in n.m.) as a cubic polynomial function of initial speed (concentric dashed circles labelled at three-knot intervals) and direction (radials in degrees) towards which the tropical cyclone is initially moving according to best-track. Elliptical envelope includes 99 per cent of sample size N. Multiple correlation coefficient between error and storm motion ($R_{EUV}$), sample size N, standard error of estimate S.E.E. and mean error are given in the lower right-hand corner (from Neumann and Hope, 1972)

<table>
<thead>
<tr>
<th>Model and number of cases</th>
<th>Forecast projection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12-hour</td>
</tr>
<tr>
<td>NHC72 north of latitude 24.5°N</td>
<td>104</td>
</tr>
<tr>
<td>CLIPER north of latitude 24.5°N</td>
<td>115</td>
</tr>
<tr>
<td>Number of cases</td>
<td>213</td>
</tr>
<tr>
<td>NHC72 south of latitude 24.5°N</td>
<td>104</td>
</tr>
<tr>
<td>CLIPER south of latitude 24.5°N</td>
<td>102</td>
</tr>
<tr>
<td>Number of cases</td>
<td>344</td>
</tr>
</tbody>
</table>
Other factors to be considered when interpreting Table 10-1 relate to the timeliness of the forecast and the required computer resources needed to produce the forecast. The CLIPER and HURRAN models, since they do not require fields of current synoptic data, can be activated immediately after the current position of the storm has been determined. The CLIPER model has the additional advantage of requiring only the most basic computer facility, whereas the analog HURRAN model requires greater computer sophistication in order to provide for rapid processing of many years of historical storm tracks. Also, as pointed out previously, the analog model fails to provide a forecast under anomalous forecast situations.

Activation of the statistical-synoptic NHC67 and NHC72 models requires access to analysed geopotential height fields. At the National Hurricane Center the required data are obtained through a computer linkage to the U.S. National Meteorological Center analyses files. A preliminary analysis at the required levels is available about two hours after initial observation time and the final prediction package from these two models is available to the forecaster about 15 minutes later. Thus, forecaster access to this class of model depends on the availability of the required data fields which could vary significantly from one Meteorological Service to another.

Activation of the SANBAR model must await the availability of a complete tropospheric wind analysis over the domain of the grid system. At the National Hurricane Center, such an analysis is available at about four hours after observation time and the prediction package is made available to the forecaster shortly thereafter. Finally, the statistical-dynamical NHC73 model, requiring the output of the National Meteorological Center Primitive Equation (PE) baroclinic model (Shuman and Hovermale, 1968) over a period of 48 hours, is received by the forecaster about five-and-a-half hours after observation time.

In addition to the five classes of models presented in Tables 10-1 and 10-2, a baroclinic model known as the movable fine-mesh (MFM) model (see section 5.5) is activated on North Atlantic and eastern Pacific tropical cyclones which threaten the United States. Although a sample of forecasts from this model is too small to be included in Table 10-1, present indications are that the model is performing on a par with or even better than the NHC73 and the SANBAR models over the area for which it has been tested. Under current operational and computer resources, the results from the model are not available to the forecaster until about seven hours after observation time. Thus, it appears that in areas with adequate initial analysis, increased sophistication does, indeed, provide better forecasts but at a sacrifice in forecast lead time.

10.3 The problem of “over-sophistication”

In many of the observational void areas typified by the tropical cyclone belts, there are many uncertainties in the initial analysis fields. In these areas, there is always the danger that the degree of sophistication will transcend the quality of the data. As shown in Table 10-3, this can lead to degradation in performance. This table separately compares the performance of the Atlantic NHC72 and CLIPER models over latitudes both north and south of 24.5°N. Most storms south of this latitude continue to show a westerly component of motion throughout the 72-hour forecast period. The NHC72 prediction algorithm is such that two sets of forecasts, one using the CLIPER model and the other based on predictors selected from 1000-, 700- and 500-mb geopotential height analyses, are statistically combined. It can be noted from Table 10-3 that, south of 24.5°N, the inclusion of the synoptic data has actually degraded the forecasts, whereas, north of this latitude, the inclusion of the synoptic data improves the forecast. The explanation is related to the fact that the dependent data used to develop the NHC72 model were inadequate over the data-void regions south of 24.5°N. Accordingly, the statistical predictors located in this region lack adequate statistical significance levels, as discussed in section 4.3.2.3.

The data from Table 10-3 further suggest that no single prediction model will satisfy the needs of any Meteorological Service where forecasting responsibility extends from the deep easterlies polewards into the deep westerlies. In these areas, several different models with the degree of sophistication tuned to the quality of both
dependent and operational data will be required. It is considered likely that satellite technology, improved aircraft reconnaissance instrumentation and communication – as well as improved objective analysis procedures and improved computer resources – will gradually enhance the quality of the data. This will require periodic updating of prediction models to ensure an optimum trade-off between the various factors which dictate the choice of prediction model.

REFERENCES


Neumann, C. J. and G. S. Mandal, 1978: Statistical prediction of tropical cyclone motion over the Bay of Bengal and Arabian Sea. (Submitted for publication, Indian J. Met., Hyd. and Geophysics).