

TROPICAL FORECASTING

Forecasting in the Tropics is a difficult problem. It necessitates a good meteorological and physics background, vast amounts of climatological knowledge, a keen mind's eye that can observe the most minute deviation in a mass of nearly homogeneous data, and last, but not least, diligence and dedication in the approach to the forecast.

The types of forecasts in the Tropics are the same as anywhere, in that you encounter flight, route, terminal, operational, general, fleet, local area, and destructive weather forecasts, as well as pertinent warnings and advisories.

Your concern in this chapter is with preparing local area forecasts, including destructive weather warnings and forecasts, and forecasting the movement of the Inter Tropical Convergence Zone (ITCZ) and tropical waves. The treatment of destructive weather warnings and forecasts is limited to tropical storms and cyclones since tornadoes are largely non-existent in the Tropics. Note also, that thunderstorms are covered in chapter 5 of this manual.

The Composite Warfare Oceanographic Support Modules (CWOSM), Part 1, TM 0492, contains further reading on severe weather features. Information may also be found in the *AG2 TRAMAN*, volume 1, NAVEDTRA 10370.

LOCAL AREA FORECASTS

LEARNING OBJECTIVES: Analyze upper air features and refer to local area climatology for preparation of surface analyses and forecasts.

The importance of local and general area climatology can have a profound impact on operations in the tropics. It is in the preparation of the local area forecast that this knowledge will be most beneficial.

During the analysis of the various charts, most forecasters form a mental image of the forecast charts and develop certain fundamental ideas as to the weather in the area of responsibility (AOR) for the next 24 or 48 hours. Climatology serves as a guide for analysis and

forecasting within the AOR. The next step in the procedure is to expand and refine these ideas.

The ideal approach to a local area forecast is to prog the upper air features first as it is from the upper air charts that the surface chart is eventually prepared. The prognostic surface chart is then used as a basis for the local area forecast. Of course other data must also be considered in preparing the forecast, such as streamline analysis, weather distribution charts, time sections, and climatology.

TROPICAL CYCLONE FORECASTING

LEARNING OBJECTIVES: Recognize synoptic features conducive to tropical cyclone development. Identify situations affecting movement and intensification of tropical cyclones. Interpret tropical cyclone warnings.

There is at present no one formal procedure for forecasting the development and movement of tropical *cyclones*. This can be understood when one considers the enormous complexity of the problem, the sparsity of data in the oceanic tropical regions compared to that available in the highly populated continents, and the lack of ship reports from areas of tropical cyclone activity. There are also regional influences to consider. A very obvious consequence of regional influences can be demonstrated when you compare the North Atlantic area with the North Pacific area. The North Pacific has almost twice the tropical water area and also better than double the average number of tropical cyclones per year.

THE PROBLEM

Forecasting tropical cyclones evolves into the following problems: formation, detection, location, intensification, movement, recurvature, and decay.

The factors that enter into forecast preparation are mainly dynamic (relating to the energy or physical forces in motion), but there are also important thermodynamic influences. For instance, tropical storms will not develop in air that is drier and slightly

cooler in the surface layers than the air normally present over the tropical oceans in summer. This also holds true in air with a trade inversion and upper dry layer present. Surface ship temperature and dew point reports, along with upper air data, are extremely valuable in determining whether the surface layers are truly tropical or whether they contain old polar air not yet completely transformed.

THE DYNAMICS OF TROPICAL CYCLONES

Dynamically, storms (existing and potential) are subject to influences from the surrounding areas. In the Tropics, we usually encounter two layers in the troposphere, and these levels have very different characteristics. Most of the time, a steady trade wind blows in the lower levels (surface to 500 hPa), while a succession of large cyclonic and anticyclonic vortices are present in the upper troposphere in the 400- to 150-hPa strata. In some regions, such as the area between the Mariana Islands and the South China Sea during midsummer, intense eddy activity also takes place near the surface. It is not possible to deduce from charts drawn in the lower layers what is taking place above 500 hPa. Therefore, it is necessary to keep track of events in both layers.

Aside from the surface chart, the 700-hPa level chart is very helpful in determining low-level flow patterns. The 200-hPa level is representative of the upper layer, whereas the 500-hPa level, often located in the transition zone, is of much less use in tropical than in extratropical forecasting.

However, forecast considerations should not be limited to the two layers in the Tropics. Middle latitude weather also influences and shares in the control of weather changes in low latitudes. The position and movement of troughs and ridges in the westerlies affect both the formation and motion of tropical storms. Therefore, middle latitude analysis is important. Since forecasts generally run from 1 to 3 days, there should also be a hemispheric analysis.

The climatological approach to the forecast problem should also be taken into consideration. It is obvious that a forecaster must be familiar with regional and seasonal changes; for instance, areas of frequent tropical cyclone formation, mean storm tracks, the scattering of individual tracks about the mean, and the month to month variations of all of the above. Mean tracks and other data on Pacific storms are available in several publications. These maps and charts reveal that

the "climatological" approach gives some useful information, but it cannot be relied on in anyone specific area, or in the case of any particular storm to the exclusion of synoptic indications for the forecast. These probability considerations are used mainly for long-range planning and when data are unavailable. Therefore, we reach the conclusion that climatological information should be treated as a weighing factor to be included after evaluating synoptic data.

FORMATION

A full-blown typhoon/hurricane cannot be forecast as such when there are no indications of any type of irregularity on the charts or aids used in the tropical analysis. Only when the incipient stage first appears among the data can we begin to think in terms of an actual typhoon/hurricane, and often not even then. For the most part, the forecast evolution from "area of disturbed weather" to typhoon/hurricane is a matter of step-by-step progression. Assume the term *formation* means formation of a "potential" typhoon/hurricane.

Empirical rules or checks have evolved through the years that enjoy a measure of reliability to warrant their use, and of course, the more signs that point to formation, the more likely formation will occur.

Synoptic Conditions Favorable for Development

The following list contains conditions favorable for development of tropical cyclones. In this list, no attempt is made to separate the surface from the upper air indications, as the two are most often occurring simultaneously and are interrelated.

- Marked cyclonic turning in the wind field.
- A shift in the low-level wind direction when easterlies are normally present. Wind-speeds generally 10 knots or more.
- Greater than normal cloudiness, rainfall, and pressure falls. Cloudiness that increases in vertical as well as horizontal extent.
- Moderate to strong outflow aloft.
- Sea level pressures lower than normal. The value is dependent upon the region analyzed; however, a deviation of greater than 3 hPa is the normal criterion.
- Easterly wind speeds 25 percent or more above normal in a limited area, especially when the flow is Cyclonic.

- Temperatures above normal at sea level, generally 26°C (79°F) or more in the lower layers.
- Moisture above normal at all levels.
- Westerlies greater than average, north of the latitude of the seasonal maximum.
- Easterlies weaker than average in a wide zone.
- Easterlies decreasing with height.
- The latitude of the subtropical ridge is higher than normal above the 500-hPa level.
- Evidence of a fracture in a trough aloft (at 200 hPa).
- Long waves that are slowly progressive.
- A zone of heavy convection is present, indicating the absence of the trade inversion.
- An increasing surface pressure gradient north and west of the suspect area.
- The disturbance has relative motion toward the upper ridge at or above 400 hPa.

Other Indications of Development

Other indications of development are sea swell and tide observations. Swells associated with a tropical storm will have a frequency less than average and an amplitude greater than average. The normal swell frequency is 8 per minute in the Atlantic and 14 per minute in the Gulf of Mexico. Hurricane winds set up swells with a frequency that can decrease to four per minute. The period of the swell will also be much longer than usual. Swells will approach the observer approximately from the direction in which the storm is located. The swell height is an indication of the storm's intensity, especially when the swells have not encountered shallow water before reaching shore.

Abnormally high tides along broad coastlines and along shores of partially enclosed water bodies are also a good indication of storm development. The highest tides will normally be found to the right of the storm path, looking downstream.

DETECTION

Meteorological satellites have greatly aided in the detection of tropical disturbances, especially during the early life cycle. It is important for meteorologists, analysts, and forecasters to be able to effectively

interpret these pictures to extract their maximum benefit. Through proper interpretation of satellite data, determination of size, movement, extent of coverage, and an approximation of surface wind speed and direction can be made. Satellites have become the most important method of detection of disturbances.

Aircraft reconnaissance also plays an important role in tropical cyclone detection throughout the North Atlantic, Caribbean Sea, and the Gulf of Mexico. This has become even more important when used in conjunction with the data from satellites. Areas of suspicious cloud structure can be investigated by aircraft whose crews include trained meteorologists. These reconnaissance flights can provide on-station data, either high- or low-level, that would not be available otherwise.

Another method of detecting tropical disturbances is through the use of radar. Present radar ranges extend about 300 miles and can scan an area approximately 300,000 square miles.

The Navy and NOAA also maintain several different types of moored METOC buoys that report various meteorological and oceanographic elements. These stations send out measured data automatically or upon query.

LOCATION

The problems of formation, detection, and location are in reality a single three-in-one problem. One is dependent on the other.

In the case of satellite pictures, reconnaissance, and radar detection, the location is fairly certain, barring navigational errors. If detection is made through the analysis, the exact location is more difficult to ascertain in the incipient stage of the storm, especially when the analysis is diffuse. The exact location should be decided upon only after the most intensive study of the data. The analyst should be prepared to revise his or her decision in the face of developments which are more conclusive.

INTENSIFICATION

Only when easterlies extend vertically to 25,000 feet or more at the latitude of the vortex is intensification possible. This most frequently occurs when the subtropical ridge lies poleward of its normal position for the season. The following characteristics are indications of intensification:

- Movement is less than 13 knots.

- The disturbance is decelerating or moving at a constant speed.
- The system has a northward component of motion.
- A migratory anticyclone passes to the north of the storm center.
- A strong net outflow (divergence) is manifested by anticyclonic flow in the upper levels (200 hPa).
- Long waves are slowly progressive. (Applicable to genesis also.)
- The trade inversion is absent; convection deep.

Other considerations to bear in mind:

- Intensification occurs when the cyclone passes under an upper-level trough or cyclone, provided there is relative motion between the two. There is some indication that intensification does not take place when the two remain superimposed.
- Poleward movement of the cyclone is favorable for intensification; equatorward motion is not favorable.
- Intensification occurs only in areas where the sea surface temperature is 79°F or greater, with a high moisture content at all levels.
- Other factors being equal, deepening will occur more rapidly in higher than in lower latitudes. (Coriolis force is stronger.)
- When a storm moves overland, the intensity will immediately diminish. The expected amount of decrease in wind speeds can be 30 to 50 percent for storms with winds of 65 knots or more; and 15 to 30 percent for storms with less than 65 knots. If the terrain is rough, there is more decrease in each case than if the terrain is flat.

Once an intense tropical cyclone has formed, there will be further changes in its intensity and in the course of its motion within the Tropics and during recurvature. The forecaster should consider these changes in connection with the predicted path of movement.

MOVEMENT

Tropical cyclones usually move with a direction and speed that closely approximates the tropospheric current that surrounds them. Logically, therefore, charts of the mean flow of the troposphere should be used as a basis for predicting the movement of tropical cyclones, but lack of observations generally precludes this approach.

Generally there is a tendency for tropical cyclones to follow a curved path away from the Equator; however, departures from this type of track are frequent and of great variety,

Tropical cyclones move toward the greatest surface pressure falls and toward the area where the surface pressure falls increase fastest with time. Calculation is necessary for this rule to be used.

Numerous theories have been advanced to explain the cyclone tracks of the past and to predict those of the future. Observational data have never been sufficient to prove or disprove most of them.

Tropical storms move under the influence of both external and internal forces. The external forces are a result of air currents that surround a storm and carry it along. The internal forces appear to produce a tendency for a northward displacement of the storm (which probably is proportional to the intensity of the storm), a westward displacement that decreases as latitude increases, and aperiodic oscillation about a mean track.

Initial Movement of Intense Cyclones

The movement of cyclones that are undergoing or have just completed initial intensification (about 24 hours) will be as follows:

- Storms developing in westward moving wave troughs in the easterlies move toward the west and also with a pole ward component given by an angle of approximately 20° to the right of the axis of the trough looking downstream. (See fig. 11-1.)
- The motion of storms developing from preexisting vortices can be extrapolated from the track of these vortices.

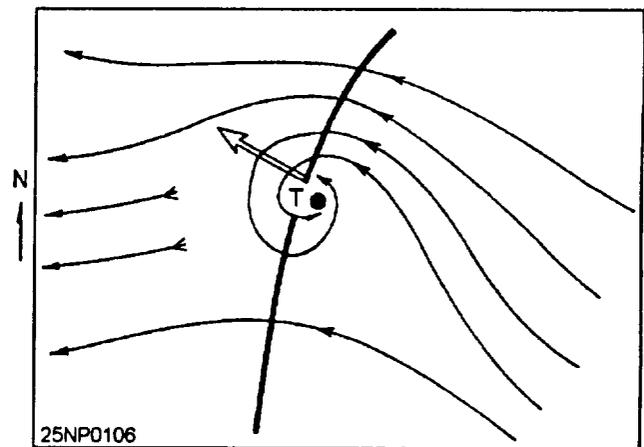


Figure 11-1.-Illustration of initial movement of tropical cyclones forming in a wave trough in the easterlies.

- Storms developing on the eastern edge of polar troughs initially move up the trough.

- Pacific storms forming on equatorial shearlines usually are most active in the southern and southwestern portions at the start and they move slowly northeast. After 1 to 2 days, the influence of the trades becomes dominant and the storms turn back toward a direction ranging from west to north. (This appears to be true mainly for cyclones deepening near or west of 130°E.)

- If a storm is discovered without information as to its past movement and the upper air current, it is best to start it along the climatological mean track and then secure the data necessary to determine the steering current.

Extrapolation

At present, the most practical prognostic technique used by the tropical meteorologist consists of extrapolating the past movement of the synoptic features on his or her chart into the future. The past track of a cyclone represents the integrated effects of the steering forces acting upon it. Accelerations and changes in course are the results of the changes in these steering forces. The effect of these forces can be examined and extrapolated directly from the past position of the cyclone.

Before applying the extrapolation technique, the forecaster must attempt to smooth out the minor irregularities in the past track. The first step in the use of extrapolation is to determine the mean direction and speed of the cyclonic center between each two known positions. The next step is to determine the rate of change in direction and speed between successive pairs of fixes. The forecast position thus determined from extrapolation of movement should be smoothed out for minor irregularities and compared to the applicable climatological tracks of cyclones in the area. If large differences exist, the forecast should be completely reexamined. The climatological tracks should receive less weight for short-term forecasts of 6 to 12 hours and more weight for forecasts in excess of 24 hours.

For short-term forecasts (6 to 12 hours), extrapolation is as reliable as any known method for movement.

Steering

The movement of a tropical cyclone is determined to a large extent by the direction and speed of the basic current in which it is embedded. This concept appears

to work well as long as the cyclone remains small and remains in a deep broad current. By the time a tropical cyclone has reached hurricane intensity, these conditions seldom exist. It then becomes necessary to integrate the winds at all levels through which the cyclone extends and in all quadrants of the storm to determine the effective steering current. Although the principle is not fully understood and has not yet received universal acceptance as a valid rule, it does have practical applications. For example, changes in winds at one or more levels in the area surrounding the cyclone can sometimes be anticipated, and in such cases, a qualitative estimate of the resulting change in the movement of the cyclone can be made. Conversely, when it appears likely that none of the winds in the vicinity of the cyclone will change appreciably during the forecast period, no change in the direction and speed of movement should be anticipated.

Further, this rule applies to situations of nonrecurvature and only some cases of recurvature. It is difficult to determine the steering current, since the observed winds represent the combined effects of the basic current and disturbances. As most storms extend into the high troposphere, it is better to calculate a "steering layer" than a steering level, since presumably the wind throughout most of the troposphere influences the storm movement. One writer recommends an integration of the mean flow between the surface and 300 hPa, over a band 8° in latitude centered over the storm. Another writer indicates that for moderate and intense storms the best hurricane steering winds would be found in the layer between 500 and 200 hPa and averaged over a ring extending from 2° to 6° latitude from the storm center.

STREAMLINE ANALYSIS AND VECTOR AVERAGES.— Other practical applications of the steering concept to short-range tropical cyclone motion use differing approaches in attempting to measure the basic current. One is by streamline analysis of successive levels to find a height at which the vertical circulation diminishes to a point such that the winds are supposedly representative of the undisturbed flow. Another method is to take vector averages of reconnaissance winds near the zone of strongest winds in the storm.

USE OF OBSERVED WINDS ALOFT.— When sufficient data are available, it has been found that the use of streamline analysis of successive levels usually gives valuable indications of tropical storm movement for as much as 24 hours in advance. However, since wind observations are usually scarce in the vicinity of a

hurricane, their analysis is necessarily rather subjective. Some forecasters claim dependable results in using this concept when data were available to high levels near the storm. The technique is not based on the assumption that wind at any single level is responsible for steering the storm, since the forces controlling movement are active through a deep layer of the atmosphere. However, as successive levels are analyzed, a level is found at which the closed cyclonic circulation of the storm virtually disappears. This *steering* level coincides with the top of the warm vortex and varies in height with different stages and intensities of the storm. It may be located as low as 20,000 feet or, in the case of a large mature storm, as high as 50,000 feet. It has been found in analysis that most weight should be given to the winds in advance of the storm within a radius of 200 to 300 miles in preference to those in the rear quadrants. The hurricane generally moves with a speed of 60 to 80 percent of the current at the steering level.

THE DIRECTION OF MOVEMENT.— The direction of movement is not always exactly parallel to the steering current, but has a component toward high pressure that varies inversely with the speed of the current, ranging from almost 0° with rapid movement to as much as 20° with speeds under 20 knots. In westward moving storms, a component of motion toward high pressure could result from the poleward acceleration arising from the variation of the Coriolis parameter across the width of the storm. This would indicate that, to the extent that this effect accounts for the component of motion toward high pressure, northward moving storms would fit the direction of the steering current more closely than westward moving ones. The tendency for poleward drift would be added to the speed of forward motion in the case of a northward moving storm so that it would approach more closely the speed of the steering current. Empirical evidence supports this hypothesis.

Corrections for both direction and rate of movement should be made when this is indicated by the windflow downstream in the region into which the storm will be moving. For prediction beyond several hours, changes in the flow pattern for a considerable distance from the storm must be anticipated. It should also be remembered that intensification or decay of a storm may call for use of a higher or lower level, respectively, to estimate the future steering current.

THERMAL STEERING.— A number of efforts have been made to correlate hurricane movement with thermal patterns. For example, one writer suggests that

a storm will move along tongues of warm air in the layer from 700 to 500 hPa that often extends out to 1,000 miles ahead of the storm. The orientation of the axis of the tongue then may be regarded as a reliable indicator of storm movement for the next 24 hours. A considerable difficulty in applying this technique is created by the fact that the warm tongue sometimes has more than one branch and it is questionable as to which is the major axis.

RECURVATURE

One of the fundamental problems of forecasting the movement of tropical cyclones is that of recurvature. Will the cyclone move along a relatively straight line until it dissipates, or will it follow a track that curves poleward and eastward? When recurvature is expected, the forecaster must next decide where and when it will take place. Then, he or she is faced with the problem of forecasting the radius of the curved track. Even after the cyclone has begun to recurve, there are a great variety of paths that it may take. At any point, it may change course sharply.

The most common recurvature situation arises when an extratropical trough approaches a storm from the west or when the storm moves west to northwest toward a stationary or slowly moving trough.

Indicators of Possible Recurvature

Some of the indicators of possible recurvature are as follows:

- If the base of the polar westerlies lowers to 15,000 to 20,000 feet west of the storm's latitude, and remains in this position, recurvature may then be expected to occur.

- However, if there is the building of a dynamic high or an eastward movement of this high to the rear of the advancing trough, and the westerlies dissipate in the low latitudes, the storm will move past the trough to its south and continue its westward path.

- The above rule also holds true in cases where the polar trough moves from the west against a blocking high. The higher latitude portion of the trough continues to move eastward while the southern segment of the trough is retarded and is no longer connected with the upper portion of the trough.

- Recurvature may be expected when an anchor trough is about 500 miles west of the storm and when the forward edge of the westerlies is from 500 to 700

miles to the west. Correlated with this parameter, R. J. Shafer found that a spot value of the thickness between 850 to 500 hPa 7.5 degrees of latitude to the northwest of the storm was one of the most valuable of all parameters on recurvature or as an indication of future movement of Atlantic hurricanes. This thickness reflects the relative strength of cold troughs to the west essential for recurvature. Low values of thickness, 14,000 feet (approximately 4,270 meters) or less, almost always indicate recurvature; and high values, 14,200 feet (4,330 meters) or more, generally indicate continued westward motion.

- The major trough west of the storm (in the westerlies) is slowly progressive.
- Long waves are stationary or slowly progressive.
- There is a rapid succession of minor troughs aloft.
- The climatological mean track indicates recurvature (use with caution).
- When the neutral point at the southern extremity of the trough in the westerlies at the 500-hPa level lies at or equatorward of the latitude of the cyclone, recurvature into the trough will usually occur. In this situation, the cyclone would normally be under the influence of southerly winds from the upper limits to a level well below the 500-hPa level while approaching the trough.
- When the subtropical ridge at the 500-hPa level is broad and consists of large anticyclones, recurvature usually occurs. This case represents a low index situation in which the cyclone remains under the influence of a single, large, slow-moving anticyclone for a relatively long time.

- Weak troughs exist between two separate subtropical high cells. Sometimes tropical storms move northward through these very weak breaks in subtropical highs.

Nonrecurvature

The following flow patterns are associated with nonrecurvature:

- Strong subtropical anticyclone or ridge to the north of the storm with the mean trough in the westerlies located far to the west of the longitude of the storm. If this pattern develops strongly over the western oceans or continents, a storm will generally be driven inland

and dissipate before it recurves into the western end of the ridge.

- Flat (small-amplitude waves) in the westerlies at latitudes near or north of the normal position. A narrow subtropical ridge separates the westerlies from the tropical trough. In many cases the mean trough in the westerlies may be located at the same longitude of the storm.

Motion During Recurvature

The following rules apply during recurvature only:

- When the radius of recurvature of a storm is greater than 300 miles, it will not decelerate and may even accelerate. The storm will slowdown if the radius of recurvature is less than 300 miles. In general, when the radius of recurvature is large, it is usually very uniform. A small radius will occur along a brief portion of the track. (See fig. 11-2.)
- A large radius of recurvature is to be expected if the high northeast of the tropical cyclone has a vertical axis (fig. 11-3 (A)). This will occur when long waves are stationary.
- When the high slopes south to southeast with height (fig. 11-3 (B)), the cyclone is transferred rapidly from the influence of upper easterlies to that of the upper westerlies and the track has a short bend. This occurs when long waves are progressive.

The following rules refer to short-term (24 hours or less) forecasting:

- Tropical cyclones move toward the area of greatest surface pressure falls (12- to 24-hour pressure change).

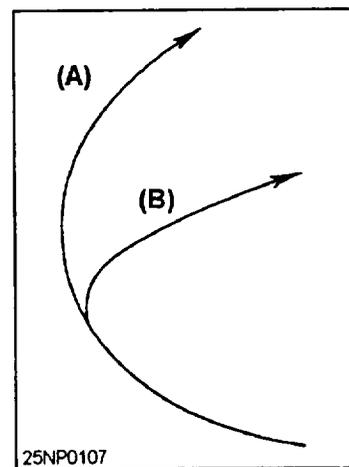


Figure 11-2.- (A) Recurvature at a constant speed; (B) First decelerating and then accelerating.

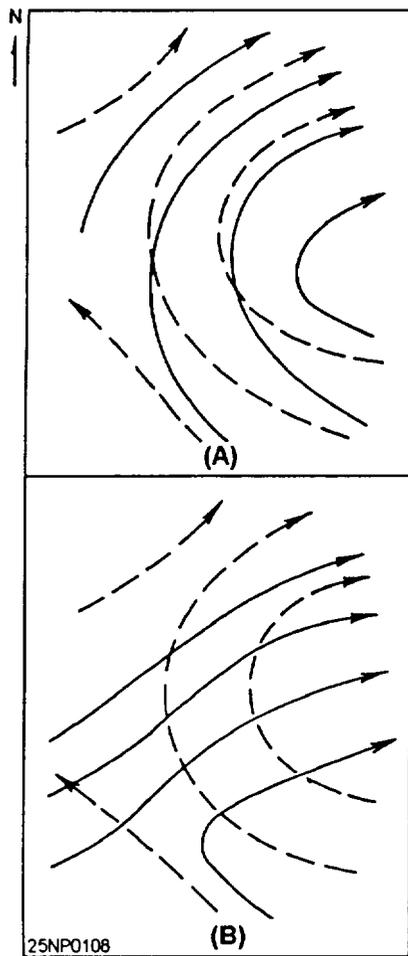


Figure 11-3.-Surface flow pattern (dashed line) and 300- to 200-hPa flow pattern (solid lines). (A) Corresponds to track (A) in figure 11-2; (B) Corresponds to track (B) in figure 11-2.

- Tropical cyclones move toward the area where the surface pressure falls increase most rapidly with time. For calculation, 3-hourly reports are necessary. Take, for example, the 24-hour pressure change at 1800 and subtract it from the 24-hour pressure change at 1500. This gives the acceleration of the pressure fall. If this quantity is computed for a network of stations and isolines are drawn for a suitable interval, the negative center helps to pinpoint the expected cyclone position. This rule is used at intervals of 12 hours or less, and is especially helpful in determining the precise place of landfall for a storm that is just offshore.

CHANGES IN INTENSITY DURING MOVEMENT OUT OF THE TROPICS

During movement out of the Tropics the storm comes under influences different from those in its origin and tropical path. The following rules and observations

can be helpful in forecasting the storm's changes in intensity:

- A storm drifting slowly northward with a slight east or west component will preserve its tropical characteristics.
- Storms moving northward into a frontal area or area of strong temperature gradients usually become extratropical storms. In this case the concentrated center dies out rapidly while the area of gale winds and precipitation expands. The closed circulation aloft gives way to a wave pattern and the storm accelerates to the northeast.
- If the tropical cyclone recurves into a trough containing a deep, slowly moving surface low, it normally will overtake this low and combine with it. Temporary intensification may result.
- If the tropical cyclone recurves into a trough containing an upper cold core low, it appears to move into the upper low in most cases.

SHORT-RANGE PREDICTION BY OBJECTIVE TECHNIQUES

As in all so-called objective techniques, no one method will serve to produce an accurate forecast for all tropical storms or extratropical systems. In the following section several techniques that have been developed in recent years are discussed. It should be mentioned that objective techniques should not be considered as the ultimate forecast tool and that all other rules, empirical relationships, and synoptic indications should be integrated into the final forecast. Wholly inaccurate forecasts may result if objective methods are the only ones considered in preparing a forecast.

Statistical Methods

One of the most prominent and widely used of these methods was devised by Veigas-Miller to predict the 24-hour displacement of hurricanes based primarily on the latest sea-level pressure distribution. Sea-level pressures were used rather than upper air data due primarily to the longer available record of sea-level data, and also because of the advantage of denser areas and time coverage, and the more rapid availability of the data after observation time. In addition to the sea-level pressure field, this method also incorporates the past 24-hour motion and climatological aspects of the storm.

Pressure values are read from predetermined points located at intersections of latitude and longitude lines

with values divisible by 5. Two different sets of equations are used: one set for a northerly zone, between latitudes 27.6° and 40.0°N, and the other set from longitudes from 65.0° to 100.0°W. The southerly zone encompasses the same longitudes as the northerly zone, but the latitudes are for 17.5° and 27.5°N.

The method described in the preceding two paragraphs was tested by Veigas and Miller on 125 independent cases, about equally distributed between the two zones, during the years 1924-27 and 1954-56. The average vector errors in 24-hour forecast position were about 150 nautical miles for the northerly zone and 95 nautical miles for the southerly zone.

30-Hour Movement of Certain Atlantic Hurricanes

R. J. Shafer has developed an objective method for determining the 30-hour movement of hurricanes by use of sea-level data over the ocean areas and upper air data over the land areas. Motion is described in two components: zonal and meridional. Westerly motion is determined by consideration of the component of the sea-level pressure gradient surrounding the hurricane and is opposed graphically by the mean temperature field between 850 and 500 hPa. The correlation of these parameters is modified by extrapolation and the geographic locations. Meridional motion is similarly predicted by sea-level and thickness parameters modified by extrapolation. The meridional and zonal computations are then combined into the final 30-hour forecast.

In a test of dependent and independent data it was found that some 85 percent of the storms predicted in the 31 sample cases fell within 2° of the predicted position.

MOVEMENT OF TROPICAL CYCLONES

Griffith Wang of the Civil Air Transport Service, Taiwan, developed a method for objectively predicting the movement of typhoons in the western Pacific. The method is titled *A Method in Regression Equations for Forecasting the Movement of Typhoons*. The equation utilizes 700-hPa data and is based on the following criteria:

- The 700-hPa contour height and its tendency 10° latitude north of the typhoon center.
- The 700-hPa contour height and tendency 10° latitude from the typhoon center and 90° to the right of its path of motion.

- The 700-hPa contour height and its tendency 10° latitude from the typhoon center and 90° to the left of its path of motion.

- The intensity and the orientation of the major axis of the subtropical anticyclone which steers the movement of the typhoon.

Percentage of frequency of direction of movement and speed tables are provided for a rough first approximation of the movement of the typhoon.

This method, as well as all other methods based on a single chart, is dependent upon a good network of reports and a good analysis. A full test of the value of this method has not been made, but in limited dependent and independent data cases tested it appears to have a good verification and provides another useful tool in the integrated forecast.

Full details on the procedure and application of this method can be found in the *Bulletin of the American Meteorological Society*, Vol. 41, No. 3, March 1960.

Use of the Geostrophic Wind for Steering

The expansion of aircraft reconnaissance reports have made it practical to carry out more detailed analyses of constant pressure surface over the tropical storm belt and to make use of a forecast based on geostrophic components at that level. This technique, developed by Riehl, Haggard, and Sanborn, and issued as an NA publication *Objective Prediction of 24-Hour Tropical Cyclone Movement* uses this steering concept. The technique makes use of 500-hPa height averages alongside of a rectangular grid approximately centered on the storm. The grid is 15° longitude, centered at the initial longitude of the storm and between 10° and 15° latitude with the southern end fixed at a distance of 5° latitude south of the latitude of the storm center. A more northward extension of the grid is used for storms found to be moving more rapidly northward. The relatively small size of the grid indicates that tropical cyclone motion for 24 hours is determined to a great extent by circulation features closely bordering the storm, and that the average features outside this area will not greatly affect its movement within the time interval. The 500-mb chart is the basic chart for computations.

Comparison of Steering Levels

Another method that uses the steering concept is *A Comparison of Hurricane Steering Levels* by B. I. Miller and P. L. Moore of the National Hurricane

Center. In their study it was found that the standard rule for steering tropical cyclones (the movement of the storm from about 10° to 20° to the right of the current flowing over the top of the core) was only reliable prior to recurvature and that storms after recurvature frequently move to the left of the steering current. Operating on the premise that the motion of the tropical storm is not governed by forces acting at any one level, their study encompasses three levels, the 700-, 500-, and 300- hPa levels. They found that the 700- and 500-mb charts were about equal in forecasting hurricane motion. In the final analysis, the 700-hPa level was selected and combined with the previous 12-hour motion of the storm. From their study, a slightly better verification of predicted tracks of hurricanes resulted rather than from use of sea level data (statistical method) or the 500-mb chart alone.

The Basic Grid in Steering Tropical Systems

The basic grid is essentially the same as that used in the 500-hPa method except that gradients were computed at intervals of 2.5° latitude instead of 5°. The previous 12-hour motion was also incorporated into the forecast. This method was tested on 23 forecasts during the 1958 hurricane season. The average error was 95 nautical miles for the 24-hour forecast and ranged from 15 nautical miles to 170 nautical miles.

A further explanation of this method and its procedure for application may be found in the *Bulletin of the American Meteorological Society*, Vol. 41, No. 2, February 1960.

TROPICAL CYCLONE WARNINGS

Tropical cyclone warnings are issued to protect not only Department of Defense assets but also those of allied nations.

Tropical Cyclone Warnings of the Atlantic

Tropical cyclone warnings are issued to operating forces of the Atlantic Ocean, the Gulf of Mexico, and the Caribbean region by NAVLANTMETOCCEN Norfolk, Va. Warnings for the southern hemisphere are provided as required. NAVLANTMETOCCEN primarily uses the National Hurricane Center's interagency and public advisories as guidance.

Hurricane, tropical storm, and tropical depression warnings are issued four times daily at 0300 UTC, 0900 UTC, 1500 UTC, and 2100 UTC. They are listed under

the MAANOP heading *WHNT_ KNGU*. The blank space is for the numerical sequence of the warning.

Special advisories and warnings are issued in the event of significant changes in intensity or movement.

Daily tropical weather summaries are issued at 1800 UTC from 01 June through 30 November for the subtropical Atlantic (south of 30°N), the Caribbean, and the Gulf of Mexico. Daily tropical weather summaries are listed under the MANOP heading *ABCA KNGU*.

Tropical cyclone warning messages are transmitted via AUTODIN and the Fleet Multichannel Broadcast every 6 hours for storms in the Northern Hemisphere.

Tropical Cyclone Warnings of the Pacific

Tropical cyclone warnings are issued to operating forces of the Pacific Ocean (west of 180° longitude), Philippine Sea, South China Sea, Bay of Bengal, and Indian Ocean in both the Northern and Southern Hemispheres by the Joint Typhoon Warning Center (JTWC), Guam.

Tropical cyclone warnings are issued to operating forces of the Pacific Ocean east of 180° longitude by NAVPACMETOCCEN Pearl Harbor, Hawaii. Warnings for the Southern Hemisphere are provided as required. NAVPACMETOCCEN primarily uses the National Hurricane Center's interagency and public advisories as guidance.

Typhoon, tropical storm, tropical depression, and tropical cyclone warnings are issued four times daily at 0300 UTC, 0900 UTC, 1500 UTC, and 2100 UTC. The warnings from the JTWC are listed under the MANOP heading *WTPN PGTW* and the warnings from NAVPACMETOCCEN Pearl Harbor are listed under the MANOP heading *WTPZ PHNL*. The blank space is for the numerical sequence of the warning.

Special advisories and warnings are issued in the event of significant changes in intensity or movement.

Tropical cyclone warning messages are transmitted via AUTODIN and the Fleet Multichannel Broadcast every 6 hours for storms in the Northern Hemisphere.

NAVMETOCCOM centers monitor Southern Hemisphere tropical cyclones in their individual AORs. Because of the limited data and weather satellite coverage of the Southern Hemisphere, warnings are issued by AUTODIN and Fleet Multichannel Broadcast only at 12- and 24-hour intervals and may contain less specific information than Northern Hemisphere warnings.

SUMMARY

In this chapter we have discussed various topics related to tropical forecasting. Our discussion first dealt with local area forecasts in general. Following local area forecasting we then discussed tropical cyclone forecasting. First discussed was the problem involved with forecasting tropical cyclones, followed by the dynamics associated with these systems. Tropical

cyclone formation and detection was then presented. In addition, tropical cyclone movement and factors affecting movement were then discussed. Next, we covered intensity changes and factors affecting those changes, along with a discussion of various objective forecasting techniques for tropical cyclones. Finally, we looked at tropical cyclone warnings, forecast issuing authorities, and forecast issue times.

