CHAPTER 2

FORECASTS AND WARNINGS OF TROPICAL CYCLONES, RIVER FLOODS AND STORM SURGES

General

In a national organization for disaster prevention and preparedness there are many components, each one of which is essential to the smooth functioning and efficiency of the organization throughout the approach, duration and aftermath of a tropical cyclone emergency. The responsibilities for providing forecasts and warnings of tropical cyclones and of the associated winds, rainfall, floods and storm surges fall upon the national Services concerned with meteorology, hydrology and hydrography. It is important that those authorities involved in the planning and the operation of the programme for disaster prevention and preparedness should have a good understanding of the work of the Services responsible for meteorology, hydrology and hydrography and should appreciate their capabilities and limitations. There would be everything to gain as well if the general public were also given background information on these technical services.

The Meteorological Service is accustomed to preparing and issuing weather forecasts from day to day and also warnings of adverse weather whenever appropriate. These responsibilities assume the greatest importance with regard to tropical cyclones because of the possibilities of disaster that arise. At such a time the Meteorological Service, by means of a series of forecasts, advisory messages and warnings, must keep all other concerned services, authorities and the general public fully informed as to the evolution of the tropical cyclone, its intensity, speed and direction of movement, wind strength, the rainfall expected and the possibility of storm surges. The forecasters work closely with hydrologists in regard of river flooding and with hydrographers in regard of storm surges.

The Hydrological Service which, in some countries, forms a combined hydrometeorological organization with the Meteorological Service, also has responsibilities which become ever more important whenever the country faces the threat of a tropical cyclone and, if the threat materializes, during the whole of the time the country is affected. During this entire period, encompassing potential and actual emergency, hydrologists receive a constant flow of data and make assessments of the risks of river flooding and indicate the areas likely to suffer.

The hydrographic service is involved, in conjunction with the Meteorological Service, in the assembly of data required for the prediction of storm surges. Essential hydrographic data include tide prediction, frequent and regular readings of tide gauges deployed along important sectors of the coast and in bays, and information about the topography of the off-shore sea bed.

As with meteorological forecasts and warnings, the assessments of flood risks and of storm-surge probabilities are communicated to associated services, to other responsible authorities and, either directly or indirectly, to the general public.

Nature of tropical cyclones

Tropical cyclones are low-pressure systems or depressions around which the air circulates in an anti-clockwise direction in the northern hemisphere but in a clockwise direction in the southern hemisphere. In the context of disaster prevention and preparedness, interest is mainly concentrated on those tropical depressions around which the wind blows with speeds exceeding 17 metres per second (61 km per hour) near the surface. Meteorologists distinguish between tropical cyclones in which the wind strength is in the range 17 to 32 metres per second (61 to 115 km per hour) and those in which the wind speeds are greater than 32 metres per second. In the latter category the wind is said to blow with full hurricane force.

Tropical cyclones have a variety of names according to the regions in which they occur. These descriptive terms are given in Table I below.

TABLE I

Areas of occurrence of intense tropical cyclones and regional descriptions

Region	*Range of maximum wind speeds (metres per second)*	
	17-32	*32-85*
Western North Pacific Ocean	Tropical cyclone	Typhoon
Bay of Bengal and Arabian Sea	Cyclone	Severe cyclone
South Indian Ocean	Tropical depression	Tropical cyclone
South Pacific Ocean	Tropical depression	Cyclone
North Atlantic Ocean and eastern North Pacific Ocean	Tropical storm	Hurricane

It is important to be aware of the regional names given in the above table so that, for example, it will be appreciated that what is described as a severe cyclone in the Bay of Bengal is essentially the same phenomenon as that which is called a hurricane when it occurs in the North Atlantic. In the *Guidelines* it will be convenient to use the name tropical cyclone except when specific reference is made to a region where a different term is used.

Tropical cyclones form over the open sea in an area where the sea has a high temperature, 25° C or higher. Once a tropical cyclone has formed, its development and speed and direction of movement must be monitored as frequently as possible because the track is apt to be erratic and therefore very difficult to forecast. On crossing a coastline to move over a land area, a tropical cyclone steadily becomes less violent although the rainfall may continue for some time.

A tropical cyclone has been defined above as a tropical depression with winds exceeding 17 metres per second (61 km per hour) and all such storms can cause heavy loss of life and severe damage in a country. However, strong or violent winds are not the only important characteristics of a tropical cyclone. Compared with the depressions of temperate latitudes, a tropical cyclone is small in extent, usually having a diameter of only a few hundred kilometres. Its central or minimum pressure is extremely low, well below 1000 mb and in some cases as low as 900 mb. A central area, known as the eye of the storm, has a diameter ranging from about 20 km to 100-200 km and in this area conditions are relatively quiet with light winds and small amounts of cloud. Thus in the annular ring from the perimeter of the eye to the storm's outer boundary, the pressure gradients are exceptionally strong and here are to be found the violent winds and torrential rains which most people think of when mention is made of a tropical cyclone.

Table II gives the monthly frequencies of tropical cyclones in the areas where they occur.

In the regions mentioned in the left hand column of Table II it is possible for a tropical cyclone to occur in any month of the year but, as the table indicates, the period of maximum frequency in northern hemisphere regions is broadly from June to October except in the Bay of Bengal and the Arabian Sea, where the frequency has peaks in May and October/November. From the standpoint of forming a general, overall picture, frequency data as given in

TABLE II

Frequencies of tropical cyclones by areas and months

Area	*Jan.*	*Feb*	*Mar.*	*Apr*	*May*	*June*	*July*	*Aug*	*Sept.*	*Oct.*	*Nov.*	*Dec*
Northern hemisphere												
Western North Pacific	0.5	0.2	0.5	0.7	1.1	1.7	3.9	5.1	4.5	3.8	2.7	1.1
Eastern North Pacific					0.3	1.3	2.1	2.0	2.4	1.4	0.2	
Bay of Bengal and Arabian Sea				0.3	0.7	0.6	0.5	0.4	0.4	1.0	1.1	0.4
North Atlantic Ocean						0.5	0.5	1.8	2.7	1.7	0.4	
Southern hemisphere												
South Pacific Ocean	2.0	2.0	1.9	0.7	0.1	0.1					0.1	0.7
South Indian Ocean	0.5	0.5	1.8	2.7	1.7	0.4						

Table II serve a valuable purpose but the meteorologist would not rule out the possibility of a tropical cyclone occurring in any particular month, however low the statistical probability might be. Since a tropical cyclone warning and all the action that follows must originate in the meteorological conditions, the forecaster would be on the alert for the least likely as well as for the most probable occurrence. In other words, all tropical depressions would be treated on their individual characteristics in order to avoid rejecting out of hand indications which at a different time of year would leave no doubt that a tropical cyclone was developing.

The destructive power of a tropical cyclone can be shown in three principal effects – strong winds, flooding and storm surges. A disaster prevention and preparedness system must include warnings and protective measures against each of these effects. Winds are a fundamental property of tropical cyclones, flooding and storm surges are consequences of tropical cyclones and various other causes.

Winds

The winds of a tropical cyclone are very strong and gusty and may persist for many hours, even for a day or two. It is most important for everyone to understand that when the centre or eye of the storm passes over a place, the strong winds from one direction give way to a fairly short period of quiet conditions which are then followed by a resumption of strong winds from the opposite quarter. Figure 2 illustrates a typical tropical cyclone moving north-westwards in the direction indicated by the arrow. If we imagine a town at the point marked A, it will be seen that it will experience strong or hurricane-force north-easterly winds until the eye passes over the place and then as the storm begins to move away the winds will blow once again very strongly but this time from the south-west. Thus when the eye of a storm, with its light winds, passes over an area it must not be taken as an indication that danger is over.

The damaging effects of the wind in a tropical cyclone are produced by a combination of their strength, their gustiness and their persistence. Any structural defects in a building, however firm and solid it may appear, can eventually be revealed by gusty winds of gale force.

River floods

Tropical cyclones nearly always give very heavy rain as they move inland from the ocean. At any one station the total rainfall during the passage of a tropical cyclone may exceed 250 mm, all of which may fall in a period as short as 12 hours or may be spread over a period of 48 hours. In either case there could be a high risk of river flooding which could lead to loss of life by drowning and to heavy damage. The topography of a country has an important

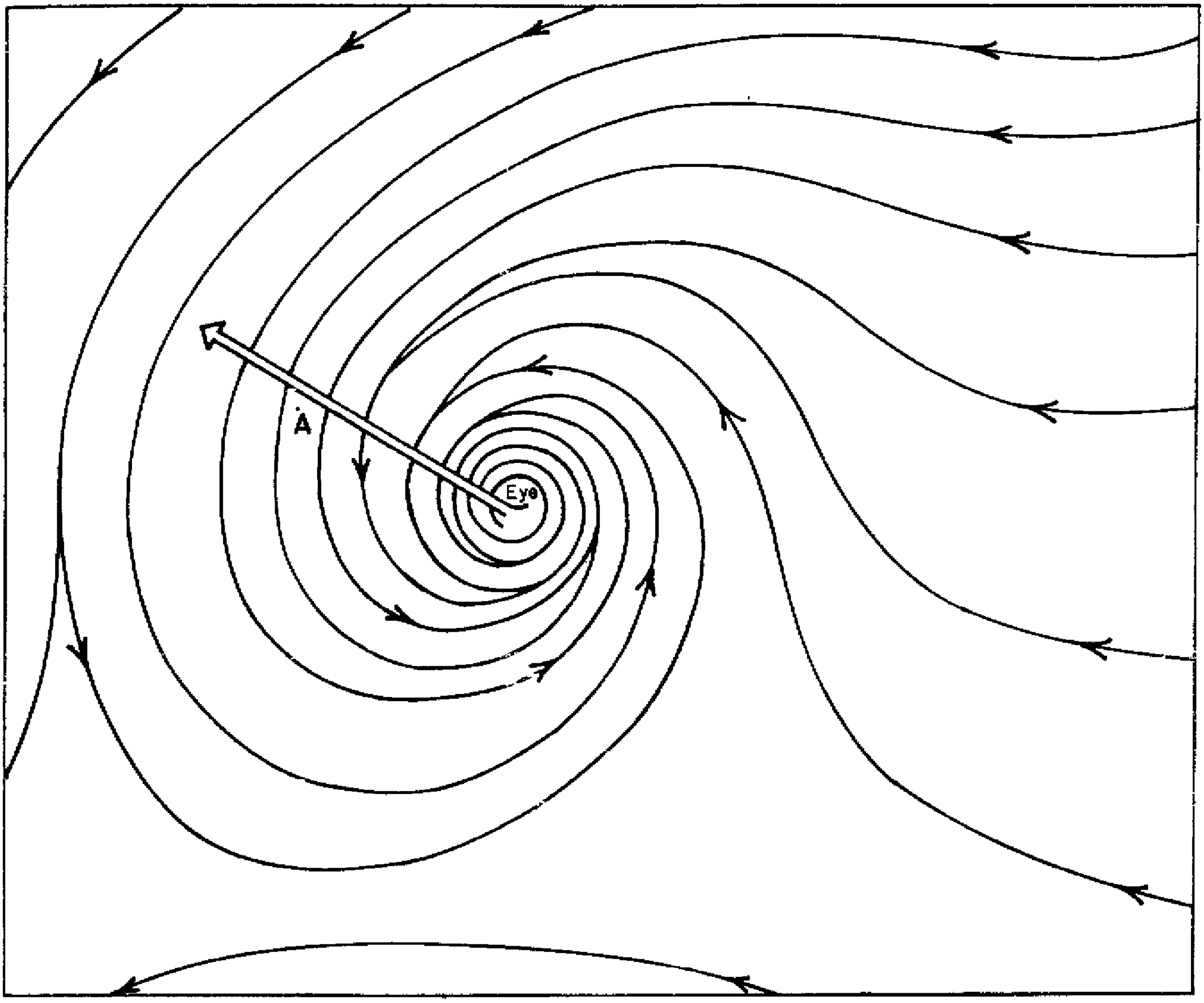

Figure 2 – The eye and wind distribution in a typical tropical cyclone in the northern hemisphere

influence on rainfall and if there are mountains near the coast in the path of a storm, the rainfall may reach extreme values. Flooding due to tropical cyclones frequently constitutes a greater threat than even the winds or the storm surges also caused by the tropical cyclone.

In the forecasting and warning aspects of flood risk there must be the closest co-ordination between the Meteorological and the Hydrological Services, which will be working in concert with the water authorities and local officials. The meteorologist, besides forecasting the intensity, movement and evolution of the tropical cyclone, will also prepare forecasts of rainfall, its time of onset, duration and the amounts expected. Forecasting rainfall amounts is one of the most difficult tasks in meteorology.

The hydrologist is responsible for flood warnings and will have, in addition to the weather forecast, rainfall measurements made at stations maintained by the Meteorological Service, by the water authorities and others, and also extensive reports of river stage and flow, and will assess the implications of the engineering factors. In the collection of such data telecommunications have a vital role. In the preparation of flood forecasts and warnings the Hydrological Service provides data for the responsible authorities and arranges for the general public to be informed as to the peak stages, their times of occurrence, probable duration of flooding and the likely severity. The Service is also prepared to advise on the action that should be taken and on the possible effects if no action is taken.

A most difficult problem is the forecasting and warning of flash floods, especially in hilly terrain. These are caused by intense rainfall with the peak stage occurring a matter of hours after the end of heavy rainfall. In order to give warning of flash floods, special devices are usually installed upstream and these set off an alarm when a selected critical water level is reached.

Some rivers are international waterways and so the threat of flooding from such rivers becomes a matter of international co-ordination and mutual assistance. For example, flood forecasting systems for the Mekong River have been developed jointly by the countries concerned with international support.

Storm surges

A tropical cyclone can cause a rise of several metres in the level of the sea along the coast with the result that large areas inland may be inundated. These effects have accounted for some of the greatest disasters associated with tropical cyclones. The death toll of more than 200000 lives in Bangladesh in November 1970 was caused by a storm surge variously estimated at a level between three and nine metres.

The main meteorological factors governing a storm surge are the wind field in the tropical cyclone and the sea-level pressure at the centre which in the more vigorous tropical cyclones may be 100 mb lower than the pressure in the area surrounding the storm. In general, the most severe storm surges are associated with a large pressure difference inside and outside the storm and with an extensive area of very strong winds which also affect the swell and the height of the waves. Other factors on which hydrographic advice and data are required are the state of the tide all along the coastline, including times of high tide, the nature of the tide and the topography of the sea bed near the shore. Very high storm surges result from a combination of strong winds, high spring tides and a gently sloping ocean floor. Bays and other inlets along the coast are particularly vulnerable to storm surges. Another critical situation may occur at the mouth of a coastal river when the flood crest due to rainfall occurs at the same time as the storm surge and produces even higher water levels.

The storm surge occurs some distance away from the centre of the tropical cyclone, to the right of the centre in the northern hemisphere, to the left in the southern hemisphere. One of the main forecasting problems is therefore to estimate where and when the centre of the storm will make its landfall. This estimate is a preliminary step in predicting the probable height of the storm surge at various places along the coast.

Monitoring and forecasting tropical cyclones

The science and practice of weather forecasting are dependent upon data over a wide area and the telecommunications facilities to allow the data to be collected from the numerous observing stations and to be broadcast for interception by all services requiring the data.

Observational data

In order to forecast for an area of the size of a country or a continent or a greater expanse of the Earth's surface, the forecaster needs data giving conditions at the surface and in the upper atmosphere for a very large area which includes in a central position the area for which forecasts are required. Because atmospheric processes are taking place all the time, the data must be constantly renewed, some reports being required at hourly intervals, others every 3, 6 or 12 hours so that the state of the atmosphere and of the sea surface can be monitored continually. Some observing facilities, e.g. weather radar, permit a continuous surveillance of rain and cloud within the range of the equipment and the information made instantly available in this way is highly valuable.

Since the analysis and prediction of atmospheric conditions require data from other countries as well as one's own, the World Meteorological Organization has laid down general standards for observing networks of surface and upper-air stations and each country undertakes to provide national networks within its own territory, using WMO standards for guidance, and to make the data available for international exchanges.

A country which is liable to be affected by tropical cyclones should install additional observation facilities to supplement the basic meteorological network required for its normal forecasting and climatological requirements for aviation, industry, agriculture, shipping, the general public, etc. The normal or basic network would include observing stations for reporting the values of meteorological elements at the surface and in the upper-air and would also include equipment at main forecasting centres for the interception of satellite cloud pictures which are most valuable for indicating the centres of low pressure systems. The additional facilities required by a country which is vulnerable to tropical cyclones should be developed on the following lines:

(*a*) *Weather radars*

These radars, operating on a 10 cm wavelength, have an effective range of about 400 km for locating tropical cyclones, monitoring their movement and determining the nature and intensity of the associated cloud systems and rainfall. The unique and virtually indispensable advantages of a weather radar are that, within its range, it provides a continuous watch on a tropical cyclone and enables the Meteorological Service to provide accurate, unquestionable information as the storm comes closer and closer to a threatened area. Figure 3 illustrates various important characteristics of a tropical cyclone – the eye, cloud wall, rain shield and feeder rainbands – which would be revealed on a radar screen. Weather radar thus gives a clear picture of characteristics which are of great importance in forecasting the intensity, development and movement of a tropical cyclone.

(*b*) *Auxiliary reporting stations*

These might function on a permanent basis but in any case would come into full operation as soon as a provisional tropical cyclone warning is issued. These stations should be equipped to measure pressure, wind and rainfall. They should be deployed along coastal areas and at important locations inland.

(*c*) *In-flight reports from aircraft*

Reports from commercial or other aircraft are always of great value in providing data from areas remote from the standard observing network, e.g. over the oceans. When it is known that a tropical cyclone exists, requests for the transmission of in-flight weather reports should be made to any aircrew expected to fly in the vicinity of the storm.

(*d*) *Aircraft reconnaissance reports*

Reconnaissance aircraft of the United States penetrate hurricanes in the North Atlantic and typhoons in the Pacific. These flights provide valuable meteorological information including the position of the centre, reports on cloud structure and on the distribution of temperature, wind and pressure. Reconnaissance reports received directly from the central areas of hurricanes and typhoons have been of immense value for warning purposes. It is hoped that the United States will continue to operate these flights and that arrangements can be made to introduce similar facilities in other tropical cyclone areas where they are needed.

Telecommunications facilities

A national Meteorological Service requires an elaborate telecommunications system in order to collect and retransmit data obtained from the national network and also in order to participate in the Global Telecommunication System whereby data from all countries are made available as required to each individual country. The national meteorological telecommunications, which will include landline and radio, should work at appropriate high speeds and should, in addition to exchanges of plain language and numerical coded data, provide for the reception and transmission of weather charts by facsimile equipment and for the interception by the most efficient means of pictures from the meteorological satellites.

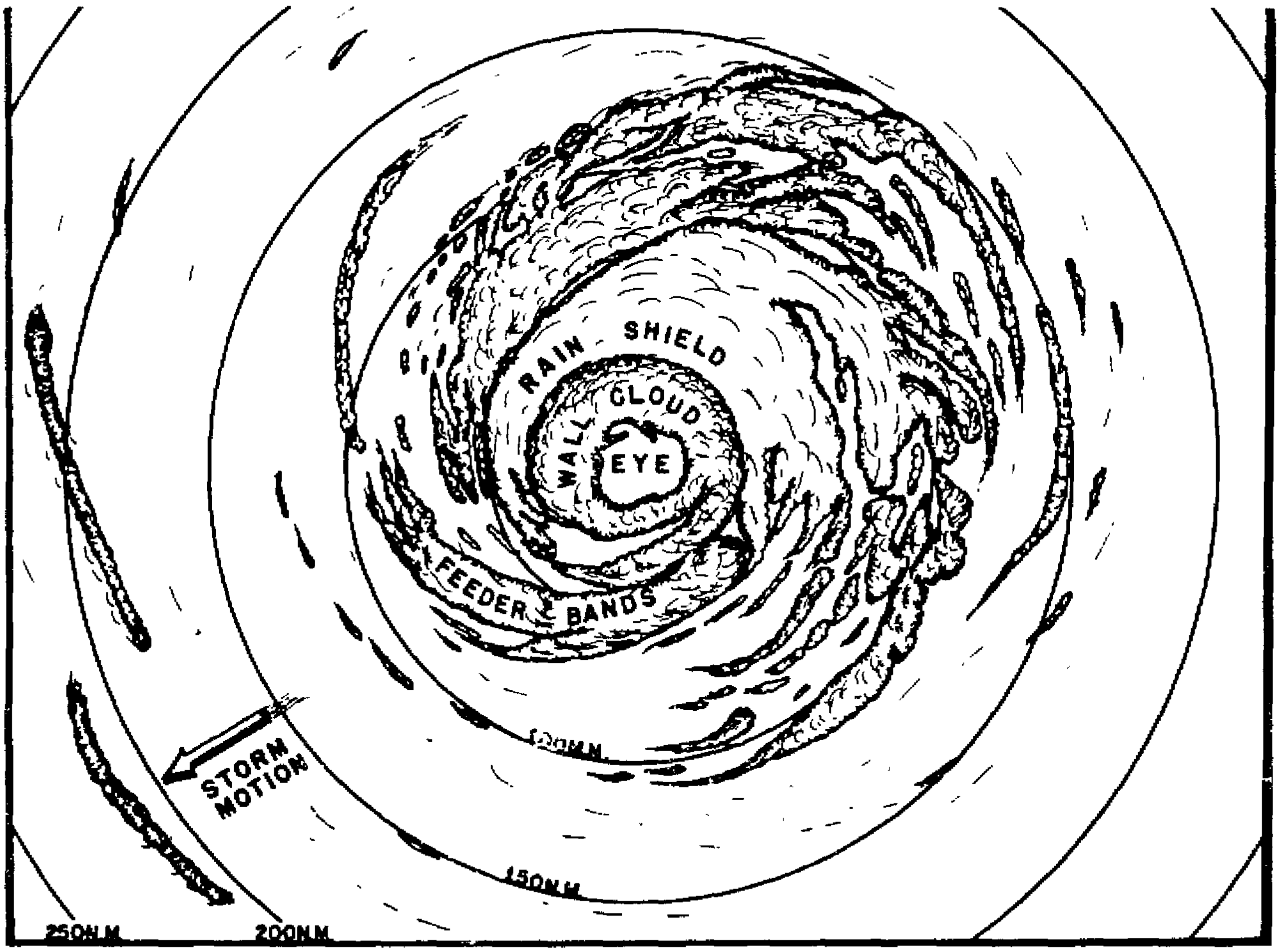

Figure 3 – Schematic diagram showing important features of a tropical cyclone as they would appear on a radar picture

The meteorological telecommunication system within the country functions all 24 hours of the day every day of the year. Its dependability is therefore of paramount importance and clearly it must continue to work on the most vital occasions from the national standpoint such as when there is a threat of a tropical cyclone or when such a storm is actually affecting the country. The system must be robust and have adequate back-up support.

Forecasting methods

During the past two decades the range and flexibility of forecasting methods have greatly expanded as a result of the introduction of powerful computers which permit the application of mathematical techniques in addition to the traditional procedures which have been developed and steadily improved since the early years of the present century.

Computerized techniques have not displaced the older methods and are unlikely to do so. However, it is realistic to appreciate that the computer has provided powerful extensions of the forecaster's equipment. The computer provides a mathematical discipline which is of great value in the continued application of the long-established, largely subjective techniques familiar to all meteorologists. Although the use of computers in meteorology is increasing, it has to be accepted that not all national Meteorological Services possess computers of adequate power for use in day-to-day operational forecasting. Where a computer is not in use, the Service concerned should arrange to intercept the routine facsimile transmission from an appropriate Regional Meteorological Centre or from a World Meteorological

Centre which broadcasts computer-produced forecasts of conditions at the surface and at various levels in the upper air for periods of 24, 48, ... hours ahead. Reception of these transmissions would be of the greatest assistance to forecasters. The information and advice would have an advisory status which would not detract in any way from the responsibilities of the forecaster at the national centre.

The technical routine in a forecasting office consists of the plotting and analysis of synoptic charts and aerological diagrams followed by the construction of prognostic charts depicting the forecast state of the atmosphere 12, 24, 36, ... hours ahead. The efficiency and success of this routine procedure are dependent upon the availability of adequate basic data, as already explained. It should be stressed that many, if not most, of the serious errors in forecasting arise through deficiencies in basic data.

Using the series of actual and prognostic charts, the forecasting service sets out to forecast the development of the tropical cyclone and its direction and speed of movement. The forecasters then prepare forecasts of such important aspects as wind, rainfall and storm surges and formulate advice to assist in the forecasting of floods.

The difficulty of forecasting the track of a tropical cyclone is illustrated in Figure 4, which shows the variety of tracks taken by tropical cyclones in the China Sea and Western Pacific during five days (14 to 18) in the month of August in the 24-year period 1947-1970. A glance at this figure is enough to show the forecaster is confronted with major problems when considering the movement and development of a tropical cyclone. In the northern hemisphere, whilst the movement of a tropical cyclone in its early days has usually, not always, a westerly component, in due course the storm may recurve and move towards the east, occasionally describing a loop.

Tropical cyclone warnings

The Meteorological Service has a crucial rôle in the programme for disaster prevention and preparedness against the effects of tropical cyclones. The alerting of the community and its responsible authorities must begin, at least provisionally, as soon as the existence of a tropical cyclone over the seas bordering the country is known. The earliest notification that the meteorologist can give of the existence and possible approach of a tropical cyclone helps other components of the emergency organization to reach a state of full readiness in good time for all the preparations and tasks that have to be performed. It is clearly appropriate to regard the issue of a tropical cyclone warning as the trigger for starting off all the precautionary and emergency arrangements.

The organization and technical procedures of the forecasting service should be adaptable to the particular situation of a tropical cyclone occurrence since at such a time the available scientific and technical effort should be devoted wholly to giving the nation the best possible service in support of disaster prevention and preparedness. The efficiency of the Meteorological Service is of paramount importance since the recipients of the forecasts and warnings concerning the tropical cyclone will have to take major decisions and must be able to be confident in doing so. For tropical cyclone warning services, the arrangements should be discussed well in advance so that, for each type of customer, a scheme can be drawn up showing what the Meteorological Service will aim to do and what the user will receive in regard to forecasts and warnings when certain prescribed conditions occur or seem likely to occur

An essential element of a warning service is that there should be certainty that the warnings will reach the intended recipients promptly and without any possibility of misdirection. The supporting communications system, including back-up facilities, should therefore be planned and implemented in full detail. Every opportunity should be taken, e.g. during exercises, to test the efficiency and the adequacy of the warning service.

It is also essential that the responsible authorities and individuals who receive tropical cyclone warnings should be clear as to the action that should follow as soon as the warning message has been received. The warning itself might be the signal for prearranged action to be taken. This would, of course, be the first of a series of executive measures that responsible authorities would set in motion. The meteorological warning, besides giving precise information about the tropical cyclone itself and the winds and rainfall to be expected, might serve as a preliminary