CHAPTER 4 SOME CHARACTERISTICS OF TYPHOONS

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4. SOME CHARACTERISTICS OF TYPHOONS

4.1 Introduction

This chapter is concerned with the characteristics of typhoons and severe tropical storms as they occur between the equator and about 35°N. There are differences between typhoons and weaker tropical storms ~~especially when the latter have moved well away from the tropics~~. We will not be concerned here with ~~these complications~~ for there are differences enough between individual typhoons no two of which are exactly alike; many show large departures from the normal in both detail and major characteristics.

It is found that the coarse structure of typhoons, severe tropical storms and the more intense tropical storms is essentially the same; the differences being of degree rather than kind. This typical structure is illustrated in Fig. 1.1. The main visible features common to these storms are the spiral rainbands, a central relatively calm rain-free eye and a canopy of cirrus clouds. ~~In this chapter~~ we will consider all tropical cyclones which possess these three important features rather than to concentrate arbritrarily on typhoons alone. Frank and Jordan (1960), in a climatological study, restricted their attention to those tropical cyclones with a central pressure of 990 mb or less as they found that the eye and spiral bands tended to become well defined at this pressure in Pacific storms but at a somewhat higher pressure in Atlantic storms. Unfortunately, this choice is again arbritrary for the fall of pressure from environment to storm centre has a greater influence on the structure of the storm than has the absolute value of the central pressure itself; furthermore, 21% of published aerial reconnaissance observations in well defined eyes of western Pacific cyclones during the eleven years 1958-68 reported central pressures in excess of 990 mb and 6% gave pressures equal to, or greater than 1000 mb. Accordingly, and notwithstanding the title of this chapter, we will be discussing all tropical cyclones with the characteristics of the genus, that is, with eyes and spiral bands, and this will include all typhoons and severe tropical storms and some well developed tropical storms.

The winds, rainfall and storm surge in tropical cyclones are of prime importance and these will be dealt with in separate chapters.

4.2 Spiral Rainbands and Cirrus Canopy

The most remarkable and distinctive feature of typhoons is the spiral

cloud-bands which converge near the eye around which ~~they~~ is ~~form~~ a "wall" of cloud. These spiral bands or rainbands as they are called are shown schematically in Fig. 1.1. They are composed of convective shower clouds ~~and the proportion of them~~ which ~~grow to cumulonimbus size~~ tend to increase in height and towards the typhoon centre. Because weather radar can "see" rain, a typhoon within radar range appears on the display rather like a spiral nebula or rotating firework (catherine wheel) with rainbands apparently being flung outward from the eye wall. The eye itself seldom contains rain-bearing clouds and therefore usually appears clear. Fig. 4.1 shows ~~a photograph of a~~ radar presentation ~~screen at a time when~~ of T.S. Wendy ~~was centred 200 km southeast of the radar~~. Both the spiral rainbands and the central, clear eye are visible. These remarkable bands are characteristic of hurricanes and typhoons but their existence was entirely unsuspected before 1943 when they were first observed by radar from ships of the U.S. Navy operating in the Pacific (see Sec. 10.6).

Rain, as we know, is formed by rising air in the lower and middle troposphere, the spiral pattern of rainbands therefore indicates the approximate distribution of rising air, at these levels. The rain free areas contain either weak, short-lived, rising currents or clear descending (subsiding) air.

Although normal weather radars detect only those clouds which contain precipitation elements (rain, hail, snow), all clouds can be photographed from high flying satellites. In the photograph in Fig. 4.2 the eye of severe tropical storm Judy can just be ~~seen in~~ discerned. It is surrounded by the high cirrus cloud canopy or shield which, at this stage of development, covers mostly the southwest part of the storm. Spiral cloudbands can be seen outside the cirrus cloud shield; these are the tails of bands which contain ~~the rain "seen"~~ showers and they are detected by radar. Radar and satellite photographs of typhoons Dot 1964 and Shirley 1968 as they were approaching Hong Kong are shown in Fig. 4.3 and 4.4.

The spiral bands seen on radar and the clouds as seen on satellite photographs of typhoons and tropical storms often take the shape of a comma or a double comma (see Fig. 4.2) that is, they have a central circular area with spiral tails swirling out towards the southwest and northeast. This double comma formation is so common that the symbol § is used to represent the centre of tropical cyclones on weather charts. A mature typhoon usually

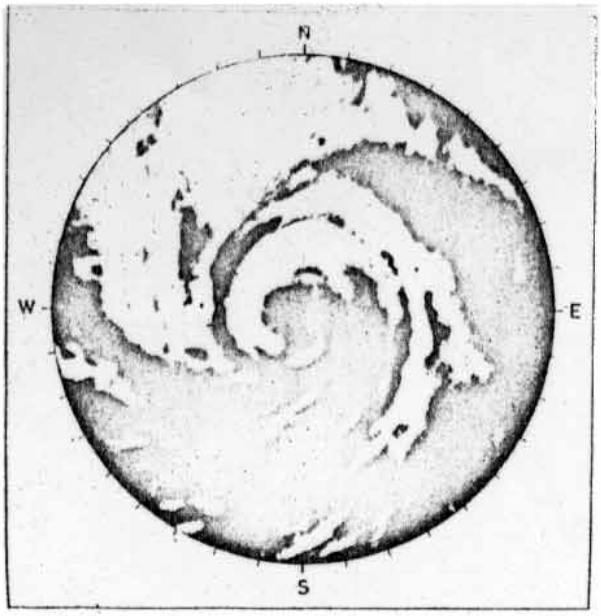


Fig. 4.1

Photograph of a radar display showing spiral rainbands and the rain-free central eye of severe tropical storm Wendy 200 km southeast of Hong Kong at 2115 GMT on 7th September 1968. The eye has a diameter of 25 km and the radius of the picture is 110 km. From aircraft reports the sustained surface winds were around 30 m/s and the central pressure was measured to be 983 mb. The radar - a Plessey Type 43S with 100 mm wavelength - was located at Hong Kong.

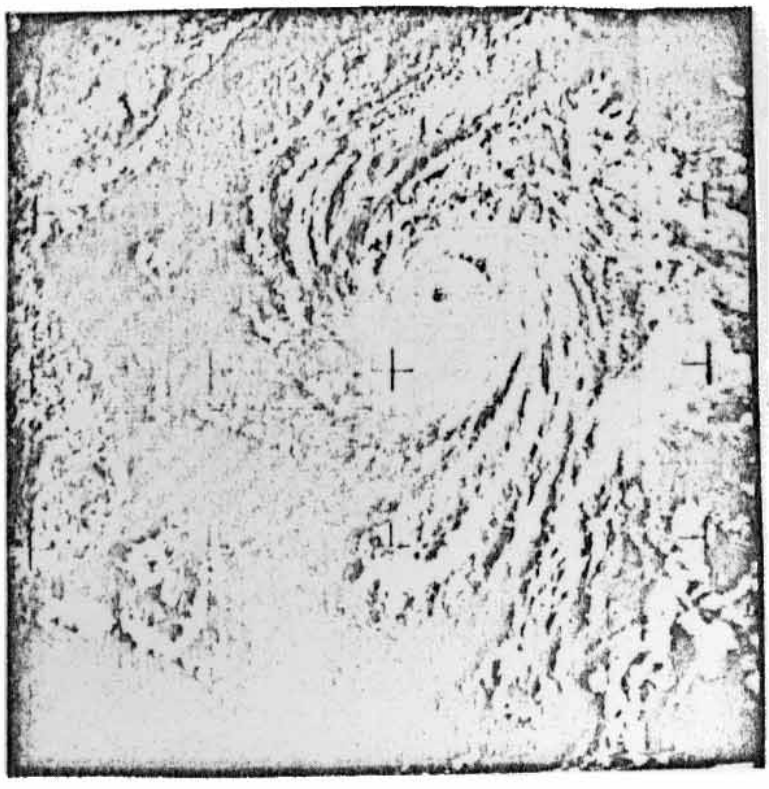


Fig. 4.2

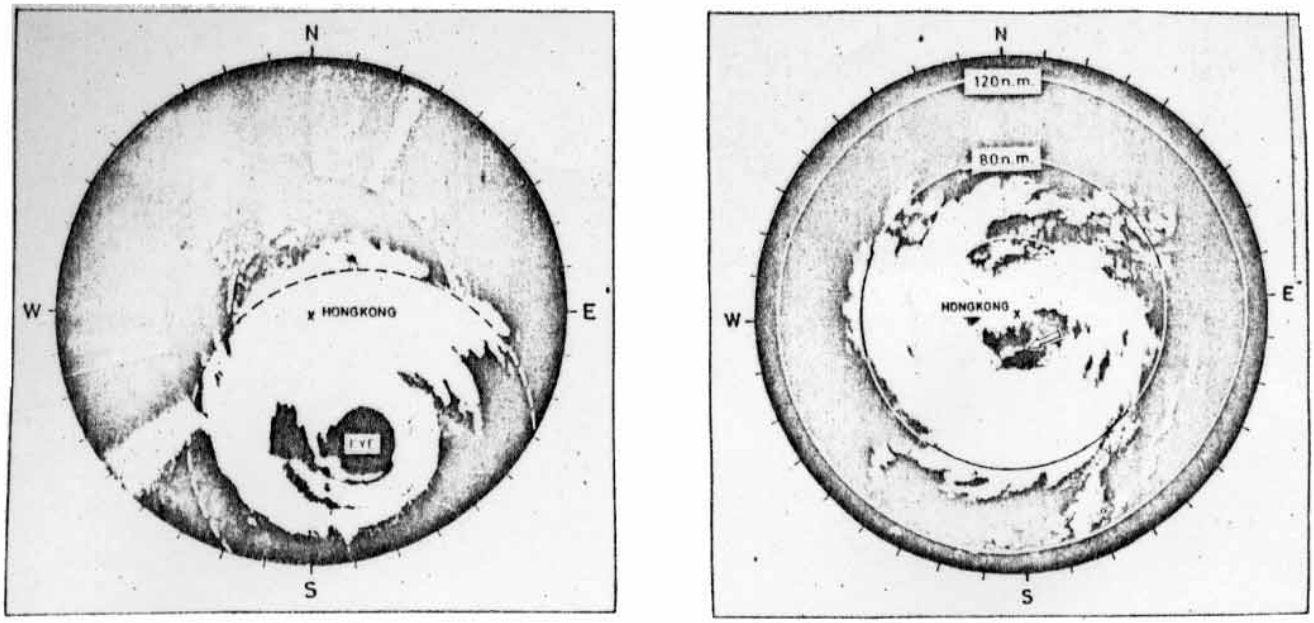
Severe tropical storm Judy as photographed by Nimbus II satellite at 0333 GMT on 28 May 1966 from an altitude of 1,130 km. The photograph was received at Hong Kong direct from the satellite. At this time Judy had an eye about 40 km in diameter, a pressure of 972 mb and sustained winds of approximately 25 m/s. Hainan Island and the east coast of Indo China are visible on the left of the photograph.

has a more circular form (Fig.) the comma shapes being most frequently seen in the formative and dissipative stages of tropical cyclones.

There are several theories to account for the spiral rainbands in the convergent inflow (Gentry 1964) but it is not known which of them - if any - describe the process which is dominant in nature. Wind shear, gravity waves and the systematic seeding of low-level clouds in the inflow by precipitation falling from clouds at higher levels in the outflow, are among the effects considered as possible causes of the spirals. However, similar convective spirals form in laboratory experiments which simulate some of the conditions found in typhoons and they are not unknown in other contexts in the fields of aerodynamic, ~~engineering~~ and hydrodynamics.

When tropical depressions form in the equatorial trough with easterly trades to the north and equatorial westerlies to the south (Fig.), the two airstreams turn cyclonically and converge towards the depression centre. Existing lines of convergence (cloud lines) in the trades and the westerlies intensify and new ones develop as the inflow curves into the northeast and southwest quadrants. Fletcher (1945) first suggested that this mechanism might account for the spiral banding and Wexler (1947) expanded on the theory. The outflow at the top of the depression being anticyclonic is opposed to that in the lower layers and the shear between the levels is found to be greatest in the northeast and southwest sectors (Fig. 8.). This shear spreads out the cumulo-nimbus anvils in the convergent bands and so makes the outer cloud bands broader and more marked than those to the east and west of the centre. This can be seen in the satellite pictures in Figs. 4.2 and 4.4. Over the Pacific, on some occasions, wind speed maxima occur in both the inflowing trades and westerlies and they are probably associated with both the development of the depression and maxima of convergence in the southwest and northeast quadrants.

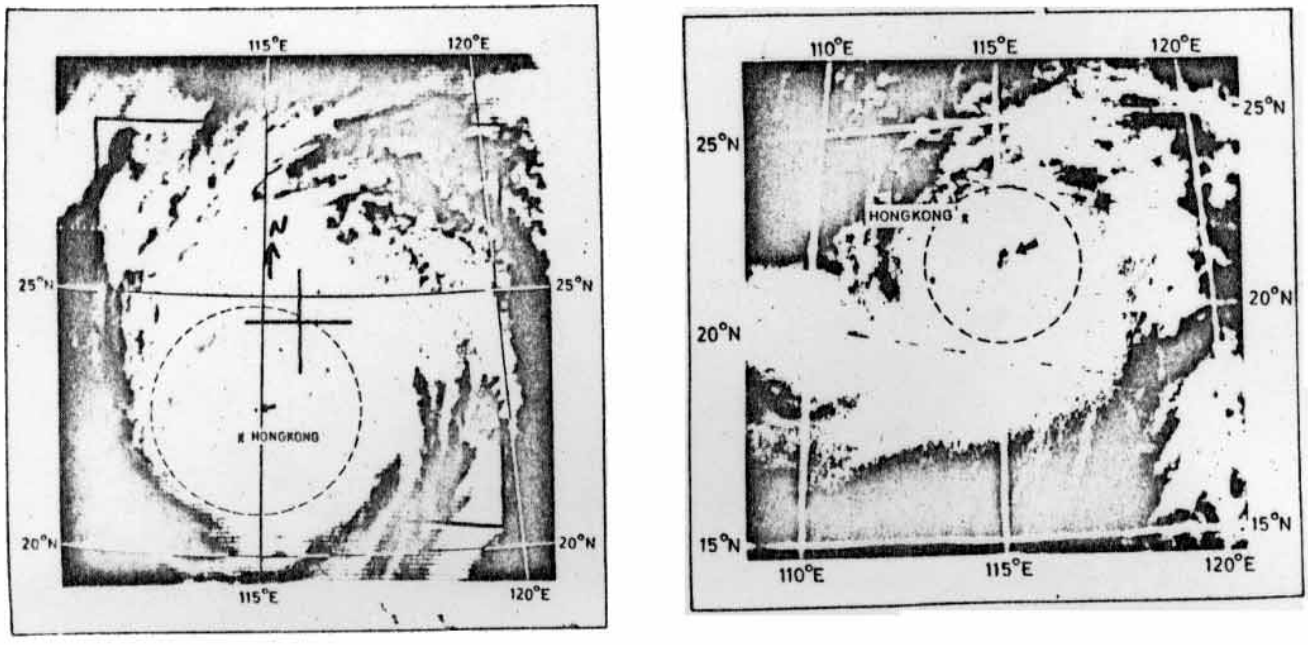
As storms move away from their formative areas and approach typhoon intensity, the upper anticyclonic outflow becomes more developed and the shear between the lower cyclonic inflow and the upper anticyclonic outflow tends to become more symmetrical, the typhoon then appears more circular in shape. The circular symmetry is usually enhanced at this stage because some of the outflowing air subsides and so evaporates its cloud particles to form a sharp edge to the cirrus canopy. This subsiding air also inhibits deep convec-



(a) (b)

Fig. 4.3

Radar photographs showing the rain-free eyes and rain areas in: (a) Typhoon Dot at 0800 GMT on 12th Oct., 1964. The eye, 70 km in diameter was located 185 km south-southeast of Hong Kong and the minimum pressure was about 973 mb. (b) Typhoon Shirley, with pressure 966 mb, centred over Hong Kong at 0945 GMT on 21st Aug., 1968. The diameter of the eye was 90 km and the Lema Islands can be seen (open arrow) about 35 km south of the Royal Observatory radar. The eyes of both typhoons were larger than is usual and in addition, Dot was an exceptionally wet typhoon. The radars used to obtain pictures (a) and (b) had wavelengths of 230 mm and 100 mm respectively.



(a) (b)

Fig. 4.4

The cloud areas in typhoons Dot and Shirley as photographed from satellites TIROS VIII at 0211 GMT on 13th Oct., 1964 and ESSA 6 at 0221 GMT on 21st Aug., 1968 respectively. The dashed circles are centred on the eyes of the typhoons and have a radius of 220 km (120 n miles) in both photographs and in Fig. 4.3 (a).

tion in the outer parts of the spiral bands so giving the typhoon a surrounding "moat" of fine, clear weather. By inhibiting convection in the outer bands the region of vigorous convection is concentrated in the inner regions of the typhoon and the latent heat released there makes a maximum contribution to the warming of the core. The subsiding air in the "moat" is spread over a large area and a limited depth and does not warm air columns in the environment as much as those in the core region.

When a storm meets strong upper westerly winds the cirrus outflow is predominantly in the direction of these winds and broad dense cloud bands extend thousand of kilometres to the northeast (Sec. 11.6); this mechanism ~~also~~ produces an inverted comma configuration.

4.3 Size of typhoons

The size of a typhoon can be expressed in many ways. For some purposes a knowledge of the diameter of the area containing hurricane or gale force winds is useful but this information is often lacking. The cloud mass associated with the storm as seen on satellite photographs, can be used as an index of size and is so used in one method of estimating the maximum surface wind speeds in a tropical cyclone (Sec. 11.4). However, the simplest means of obtaining a measure of size is to use the radii of the outermost closed isobar to surround a tropical cyclone centre on a weather map. A ship or station located within the outer closed isobar will usually be within the circulation, that is, it will be affected by the winds, however light, which are feeding into the storm. The shortest radius to the outermost closed isobar (drawn at 1 mb intervals) is a convenient and easily made measurement and on this basis the distribution of sizes of tropical cyclones with eyes is shown in Table 4.1 together with data on the shortest radius of the closed 1000 mb isobar, if one was present, ~~and it was possible to determine its value.~~ During the eleven years 1958 to 1968 the average length of the shortest radius was 430 km but ranged in individual storms from 60 km to 1100 km. Radii less than 135 km and more than 1050 km were found in most years.

Those who are unfamiliar with typhoons do not usually appreciate how large they can be, in order to illustrate this point I have transposed typhoon Agnes 1968 onto a map of Europe Fig. 4.5. Typhoons of similar size occur in most years. When a tropical cyclone first forms it is often quite small but usually grows to reach maturity and a moderate size over the

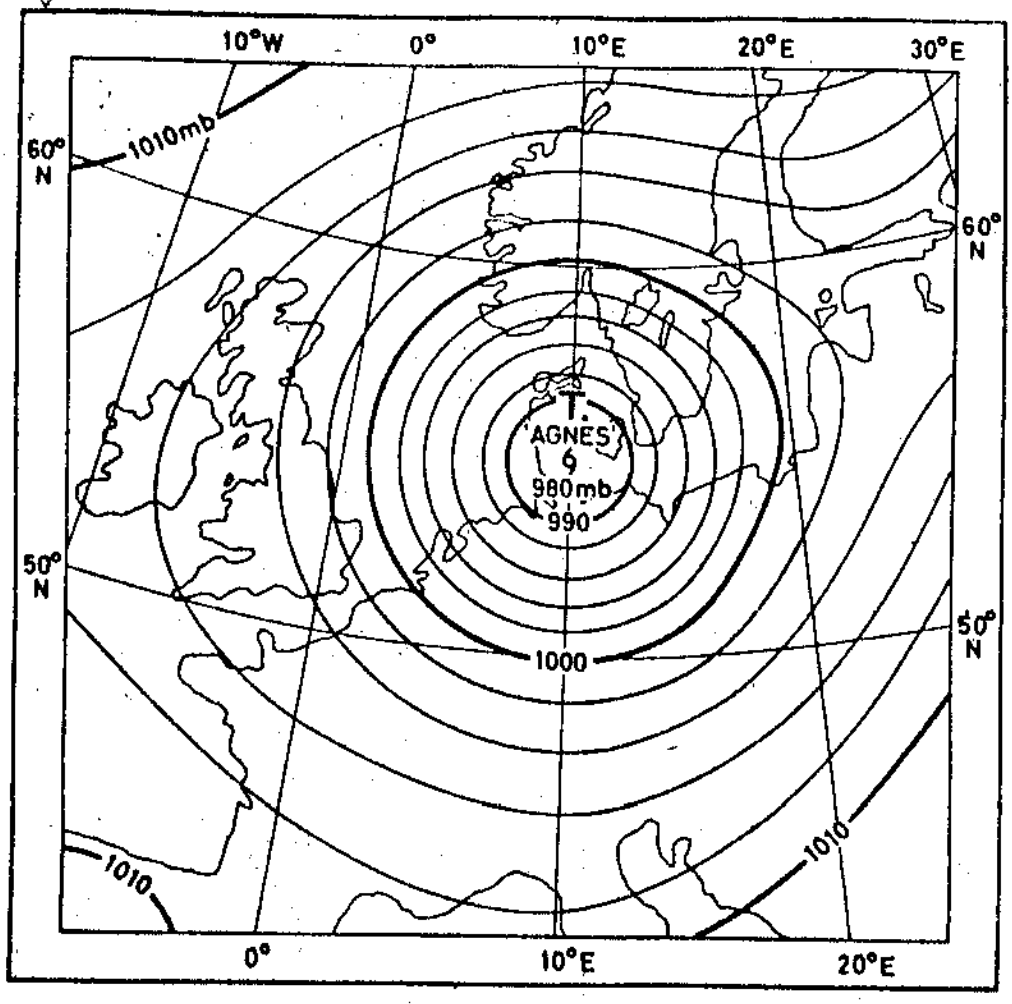


Fig. 4.5

Isobars around the centre of typhoon Agnes - at 1200 GMT on 8th September 1968 - superimposed upon a map of Europe to indicate scale. Agnes was centred near 24.7°N 137.5°E at this time and was weakening to severe tropical storm intensity.

first few days of its life. In those typhoons which grow further to become very large the central pressure usually increases and maximum wind speeds decrease but gales become much more extensive, spreading outwards to affect large areas. Table 4.1 shows that the average radius at the time of minimum pressure is less than that for all observations and much less than the average radius at the time of greatest size.

Table 4.1

Relative Percentage Frequency of Occurrence of the Shortest Radius of the Outermost Isobar (1 mb interval) and of the 1000 mb Isobar in Tropical Cyclones which at some time attained at least Severe Tropical Storm Intensity as determined by Aircraft Reconnaissance.

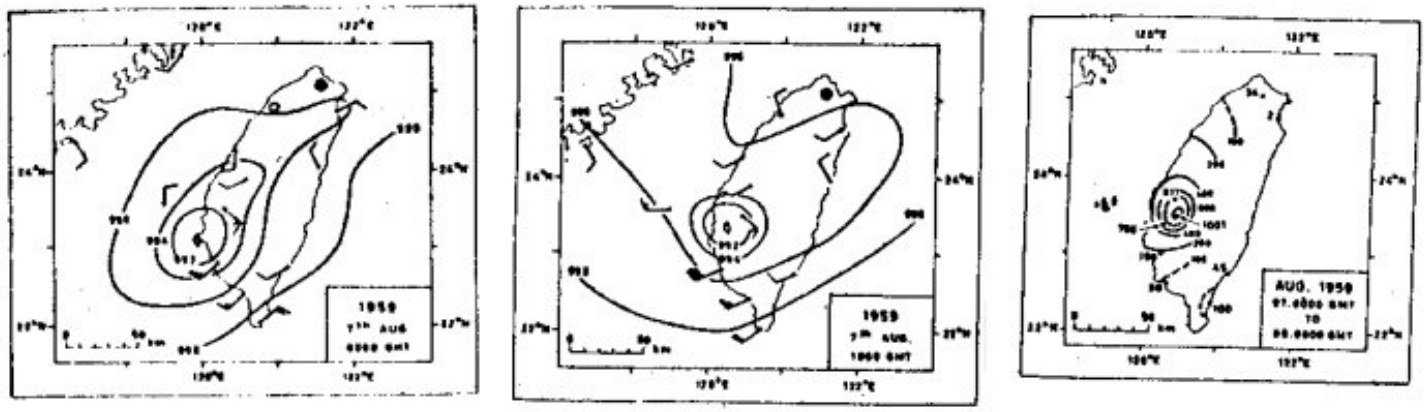
(1958 - 1968)

Range of Radii		All Observations		Largest for each Tropical Cyclone		At the time of Minimum Pressure	
deg. Lat	km	1000 mb isobar %	Outermost isobar %	1000 mb isobar %	Outermost isobar %	1000 mb isobar %	Outermost isobar %
0.0 - 0.9	0 - 100	15.8	1.4	6.7	0.0	21.5	1.3
1.0 - 1.9	110 - 210	35.9	11.0	28.2	3.1	33.9	18.3
2.0 - 2.9	220 - 320	25.0	23.2	25.1	8.4	24.3	22.8
3.0 - 3.9	330 - 430	13.2	23.0	17.9	11.6	12.4	18.3
4.0 - 4.9	440 - 540	6.8	16.9	12.3	19.6	3.4	16.5
5.0 - 5.9	550 - 660	2.6	11.9	7.2	19.1	2.8	13.4
6.0 - 6.9	670 - 770	0.5	7.0	1.5	14.2	1.7	4.0
7.0 - 7.9	780 - 880	0.1	3.5	0.5	10.2	0.0	3.6
8.0 - 8.9	890 - 990	0.1	1.5	0.5	8.0	0.0	0.9
9.0 - 9.9	1000 - 1100	0.0	0.7	0.0	5.8	0.0	0.9
Total No. of Observations		1850	3524	195	225	177	224
Mean (deg. Lat/km)		2.2/240	3.9/430	2.8/300	5.4/460	2.1/230	3.5/390

The areas covered by hurricane force winds and gales are often stated in typhoon warnings and the sizes of typhoons can be compared on this basis. Small typhoons may have only a narrow band of hurricane force winds within about 20 km of the centre whereas in the larger typhoons, such as Ida 1958, hurricane force winds can be found as far as 500 km from the centre. The area of gales is equally variable. For example, in the 1906 Hong Kong typhoon gales were confined within a radius of about 25 km and there have been other typhoons even smaller than this; the Japanese call them "mamie taifu" or "midget typhoons". At the other extreme, once or twice a year, a typhoon grows to have gales as far as 650 km from its centre. On average, in mature typhoons, winds of hurricane and gale force occur within about ~~100~~ 80 km and ~~300~~ 180 km of the centre respectively, as is shown by Figs. and

Fig. 4.6 shows a small severe tropical storm moving onto Taiwan on ~~7th~~ August, 1959. The storm began to form the day before to the north of Pratas Reef and south of Hong Kong ~~Page 4.9.~~ However, its existence was not suspected until ~~62 knots~~ winds of 31 m/s and a pressure of 991 mb were reported from stations in Taiwan. This storm was so small that it escaped observation in an area well frequented by ships and aircraft and surrounded by coastal observing stations. It may have just attained typhoon intensity before landing. The rainfall from so small a storm was remarkable, in twelve hours 1001 mm of rain were recorded at a station to the west of the mountains Fig. 4.7. It may help ~~some readers~~ better to appreciate the magnitude of this downpour if ~~they are reminded~~ it is recalled that the mean annual rainfall for London is ~~only~~ 610 mm! Flooding in southwest Taiwan due to this little tropical cyclone was the worst experienced there for 62 years. The locations and conditions which favour the formation of these small typhoons are discussed in section — .

~~The foregoing is an example of a developing midget typhoon but~~ typhoons of average size sometimes shrink ~~in size~~ during the decaying phase. Fig. 4.1 shows a radar photograph of the relatively small typhoon Wendy 1968 just after weakening to severe tropical storm intensity. The diameter of the cloud cover as seen from a satellite was about 330 km and the diameter of the rain area, as seen by radar, was about 160 km.



(a) (b) (c)

Fig. 4.7

A small severe tropical storm moving onto Taiwan, (a) and (b) show winds and pressures (c) shows daily rainfall. Most of the rain fell in twelve hours. (Adapted from Wang (1960)).

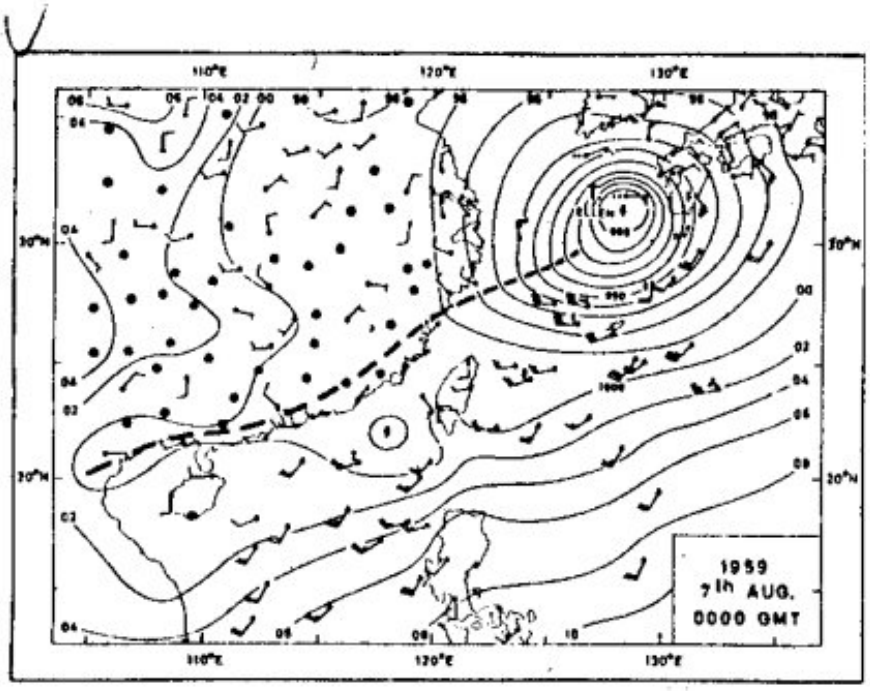


Fig. 4.6

Typhoon Ellen and an unusually small severe tropical storm to the southwest of Taiwan. The storm was not detected until it struck Taiwan (Fig. 4.7)

Improved observations over the Eastern North Pacific have recently revealed that very small tropical cyclones occasionally form there. Tropical storm Katrina 1971, which may have reached hurricane intensity for a time, as indicated by a wind report from one ship, was a very small, tight storm which, in its early stages, had a size approaching that of a tornado (Denney 1972). A similar, very small storm in the same area was reported by Baum (1970). A small hurricane, Rebecca 1968, had maximum winds of 100 knots whilst the diameter of gales was less than 75 km. Denney (1972) ~~concluded~~ found that the diameter of the circle of gale force winds in a tropical storm with an eye and eye wall can be as small as 28 km or so. Figs. 4.6 and 4.7 show that similar typhoon/tropical storms occasionally occur also in the Western Pacific and that, accordingly, the diameter of the circle of gale force wind in this area must be considered to range from about 27 km to a little more than 650 km with an average diameter of about 360 km (Fig.4.) in mature typhoons.

4.4 The height of typhoons

On theoretical grounds both Espy (1841) and Ferrel (1856) considered that typhoons had great depth; the former spoke of them extending to the "surface of the atmosphere" while the latter referred to "some high level" although implying that it was the level of cirrus clouds i.e. 7 - 20 km that he had in mind. However, on crossing extensive mountainous terrain typhoons always weaken and are occasionally destroyed; ~~consideration of~~ this ~~fact~~ led some meteorologists to the mistaken view that tropical cyclones were confined to the lowest layers of the atmosphere.

Heywood (1933) summarised the results of pilot balloon ascents made from Hong Kong on occasions when typhoons were nearby and showed that the cyclonic wind circulation persisted up to at least 9 km. Depperman (1939) agreed with Heywood on the great depth of typhoons and in addition pointed out that on those occasions when they crossed Baguio Observatory - situated more than 1.6 km above mean sea level - a pronounced pressure minimum and a V shaped barograph trace were recorded, indicating that the typhoon must extend far above the mountain top. However, until the mid-nineteen forties, divergent views on the depth of tropical cyclones persisted in the face of these observations and in spite of the fact that theoretical studies as early as 1920 (Sect. 2.1.2) had shown that rising currents and cloud must extend to at least 15 km in order to account for the low surface pressures observed.

In discussing the vertical extent of typhoons one can consider clouds, winds or temperatures; we will here confine our attention to clouds.

Clouds in mature typhoons usually extend up to the tropopause (Fig.) which in the tropical Western Pacific is found near 100 mb at a height of 16.8 km. In the more intense typhoons the rising air penetrates the tropopause and the general cloud top may then be as high as 19.8 km as found in typhoon Ida 1958. Reports from high level reconnaissance flights by U.2 aircraft and some satellite photographs, indicate that cumulo-nimbus tops in the eye-wall sometimes protrude through the general cirrus canopy to form a ring of higher cloud. Similar conditions have been found in Atlantic hurricanes. Gentry (1967) reports that in hurricane Isbell (October 1964, central pressure 968 mb), the pilot of a U.2 reconnaissance aircraft reported

that cirrus tops near the storm centre were at 16.5 km and that some cumulo-nimbus tops protruded through the cirrus up to 18.6 km. The tropopause was at 16.0 km. In hurricane Beulah (September 1967, pressure 950 mb) Waco (1970) reported that cirrus tops rose from 15.2 km (121 mb) at 90 km from the centre to 16.2 km (105 mb) as the eye was approached and then increased abruptly "in wall-like fashion" to 16.5 km (100 mb) at the eye wall. In terms of pressure, U.2 pilots have reported cloud tops ~~up to~~ at 55 mb.

The most frequent observations of cloud-top height in typhoons come from radar observations and although these observations really refer to rain or snow rather than to cloud and although they can be misleading at times, careful analysis has shown that they substantiate other observations that put the top of the clouds between 10 and 20 km according to the intensity of the typhoon. Tops are most frequently found near the tropopause just below the 100 mb level i.e. close to 16 km.

It is of interest to note the disc-like proportions of typhoons and tropical storms for their average diameter of 860 km is approximately fifty times their depth. For comparison we may note that coins usually have a diameter only twenty times their thickness.

A small number of anomalous typhoons occur in which mean wind speeds of about 35 m/s are found at the surface yet cloud tops do not extend above 2.5 km. In July 1967, an aerial reconnaissance of typhoon Billie, (Fett 1968) found surface winds of about 40 m/s whilst cloud tops were no higher than 1.2 km. Fett reported that he had flown into three similar storms and considered that 40 m/s was the upper limit of the surface wind speed in them. Warm subsident air was found over the low level eyes of these typhoons but the exact mechanism by which it was caused is unknown but is probably due to subsidence caused by low level divergence associated with changes in the ring of maximum winds. The temperature of the air at 700 mb above the eye of Billie was 18.5°C and the surface pressure was 982 mb. Aerial and satellite photographs of this typhoon are shown in Figs. 4.8 and 4.9.

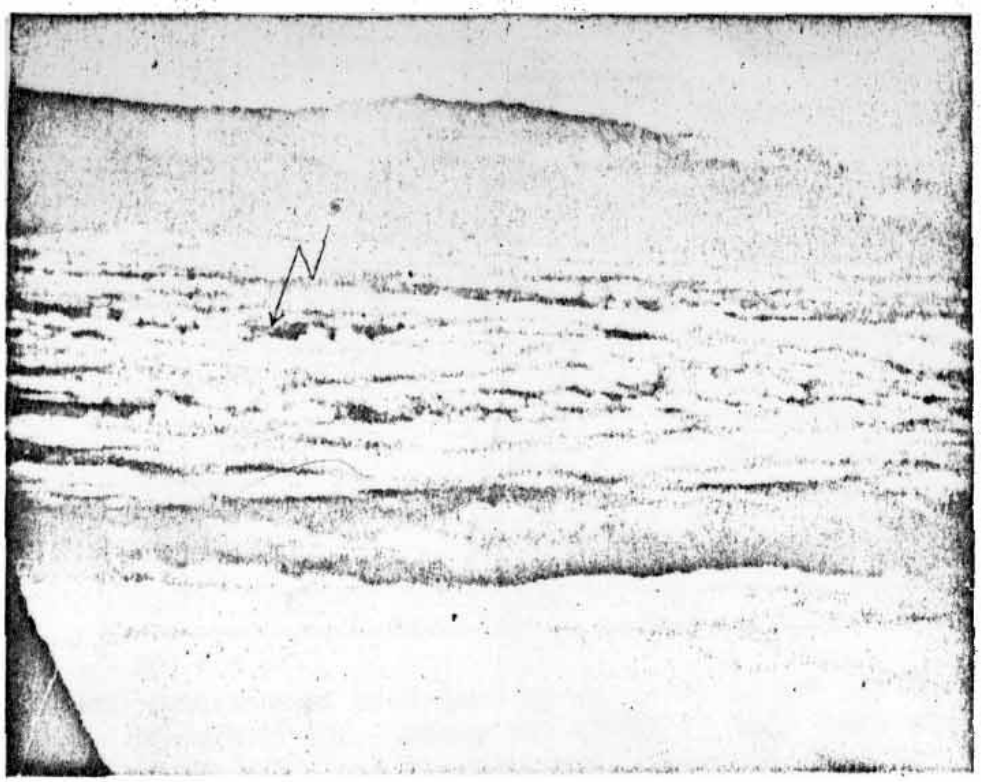


Fig. 4.8 Photograph of the eye of tropical storm Billie taken from a reconnaissance aircraft at an altitude of 3 km at 0330Z on 5th July 1967. The tops of the cumulus and strato-cumulus clouds were about 1.2 km above the surface. Surface wind speeds were 35 to 40 m/s (After Fett 1968)

GMT

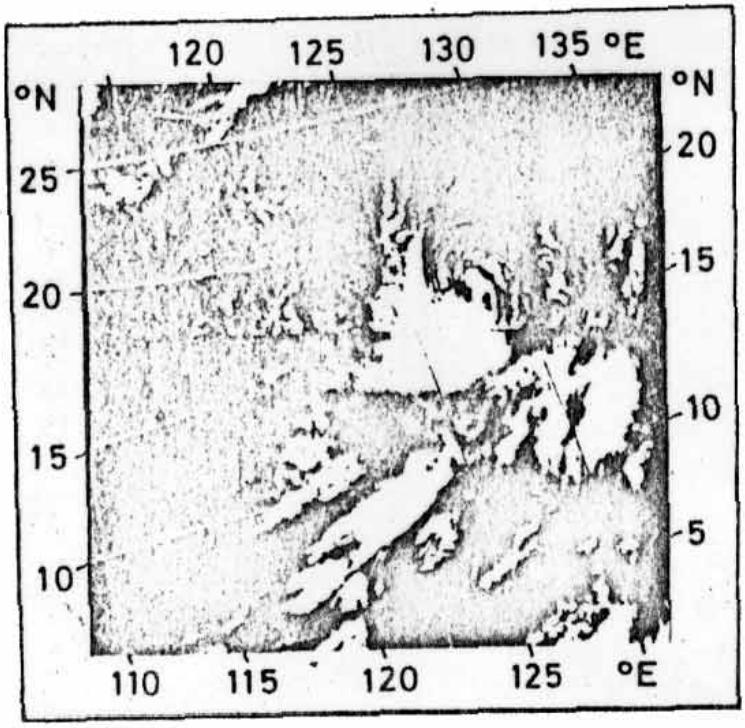


Fig. 4.9 ~~ESSA II~~ Satellite photograph of tropical storm Billie taken at 2320Z on 4th July 1967. The centre of the circulation can be seen near 16.5°N 128°E on the north side of the north side of the mass of overcast cloudiness (After Fett 1968)

Essa 2

GMT

4.5 Pressure

The pressure of the atmosphere at the surface of the earth - the barometric pressure - is very low near the centre of typhoons and it can be said that no lower atmospheric pressures have been recorded anywhere on earth. However, slightly lower pressures may occur in severe tornadoes but, so far such pressures have not been measured.

When a typhoon centre moves across a ship or location at which there is a barograph a "V" trace similar to that in Fig. 4.10 is recorded. The points to note in this figure are the diurnal pressure wave (Sect. 3.3) before and after the passage of the typhoon and the shape of the trace, concave downward, producing an ever steepening curve as the centre of the typhoon moves nearer. The rate at which pressure falls as a tropical cyclone approaches depends on its central pressure, pressure gradients, speed of movement and rate of intensification. Fast-moving typhoons with low central pressures cause the pressure to fall rapidly producing very steep traces on barograms.

The mean-sea-level pressures at each hour before and after the passage of 12 typhoons over or close to the Royal Observatory, Hong Kong have been plotted in Fig. 4.11 they have been corrected for diurnal variation and are centred on the hour of lowest pressure. In general, the typhoons were deeper (that is, they had a lower pressure) than indicated in the figure because, in some cases, the pressure minima occurred between the clock-hour readings and in others, the typhoon centre did not pass directly over the Observatory. The pressures at the different hours have been averaged and used to draw the heavy mean curve. All these typhoons passed sufficiently close to the observatory to cause gales there.

The pressure one day or less ahead of the passage of a typhoon can vary widely. From Fig. 4.11 it can be seen that eighteen hours ahead of the closest passage of these 12 typhoons the pressure has been as high as 1010 mb, in the 1939 typhoon, and as low as 992 mb in typhoon Mary . These two typhoons clearly illustrate that the "pressure depth" - the fall of pressure from the environs to the centre - is more significant than the central pressure minimum itself because, in the 1939 typhoon the eye of which passed over the Royal Observatory, the central pressure was only a little lower than that on the periphery of typhoon Mary . The environment of the 1939 typhoon had a pressure some 18 mb higher than that of Mary.

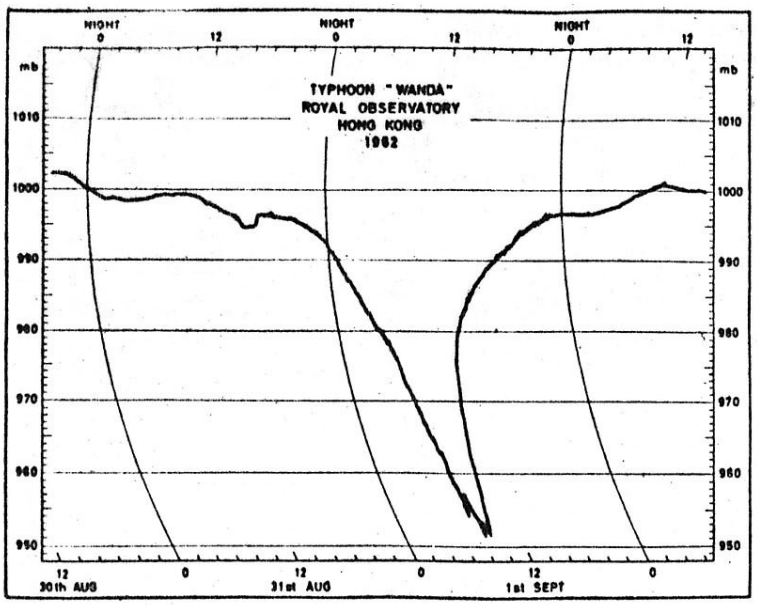


Fig. 4.10 Barogram from the Royal Observatory Hong Kong made during the passage of typhoon Wanda 1962 some 17 km to the south. The barograph reading is uncorrected; the true minimum at the station was 953.2 mb whilst in the eye of the typhoon it was 944.0 mb.

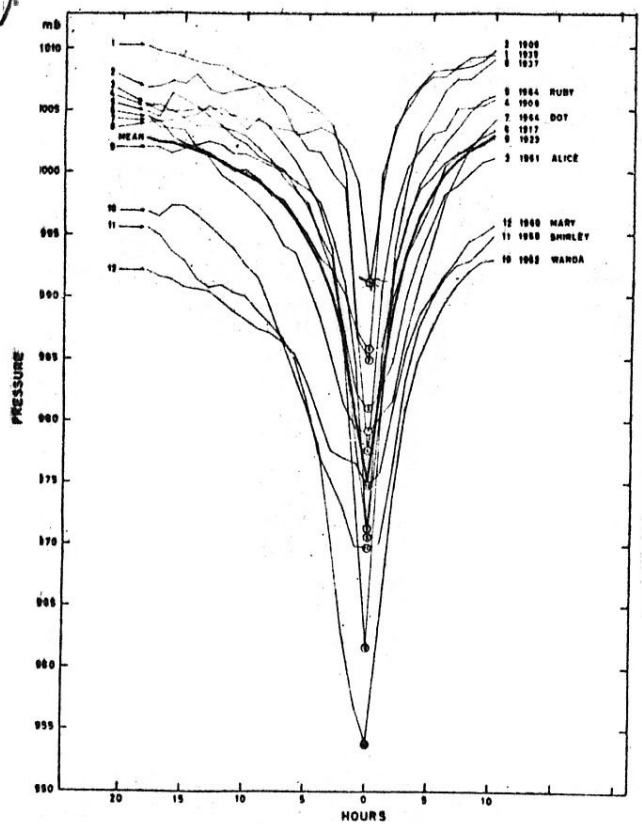


Fig. 4.11 Hourly readings of the barometer at the Royal Observatory Hong Kong before and after the passage of 12 typhoons which caused gales there. The readings have been corrected for the normal diurnal variation of pressure and the curves are centred on the time of the lowest pressure. The heavy curve is the mean of the other twelve.

The very short notice of an approaching typhoon indicated by the barometer on 23rd November 1939 (curve 1 Fig. 4.11) and 18th September 1906 (curve 2) should be noted. The latter storm was the one mentioned in section 2.3. The indication of the barometer most frequently misleads in this manner during the autumn at times when the winter anticyclone intensifies over China and holds the pressure high, or even causes a temporary rise, ahead of an approaching typhoon. Many instances of such developments misleading masters of China clippers in the old days will be found in accounts of their journeys. When the winter anticyclone intensifies it is possible for the pressure to continue to rise at a coastal station as a typhoon approaches although, of course, the typhoon will be usually taking in colder air - the cause of the pressure rise - and weakening. In temperate latitudes a ~~large and~~ rapid fall of station pressure by 60mb or more can occur as an anticyclone is replaced by a fast moving typhoon (see Section. 13.9..1 and Fig. 13.9.3)

The pressure readings of Fig. 4.11 have been plotted against distance from the centre of the typhoon, in Fig. 4.12,to give an indication of the pressure profile for each storm. The figure was prepared with the assumptions that the storms maintained their speed and did not change in intensity during their passage over the station. The curves have a basically similar shape which is shared by the two mean curves based on pressures reported by ships around intense typhoons. In general, the deeper the typhoon the greater the pressure gradient, however, there are some exceptions to this rule and in particular, the very large gradient in the 1906 typhoon - curve 2 - is noteworthy.

Gherzi (1951) states that China typhoons often have a steeper "hourly rise" than "hourly drop" and that "1000 mb seems to be the pressure value preceeding the precipitous "V" fall of the barometer". From Fig. 4.12 we can see that his first statement is correct both in the mean and in individual cases but that his second statement has little value because in some typhoons e.g. curves 1 and 2, pressure is falling fast before 1000 mb and in others e.g. curves 10, 11 and 12, the "V" is not encountered until well below 995 mb. The exact reason why, during the passage of a typhoon, the pressure rise should be faster than the fall, is not known. There are assymetries in the pressure field around a typhoon and in particular the gradient to the right of the direction of movement - usually the side nearest a surface anticyclone - is frequently larger than elsewhere in the storm but this would not explain the rapid rise of pressure behind typhoons crossing Shanghai and Hong Kong. When typhoons cross the coast and move inland

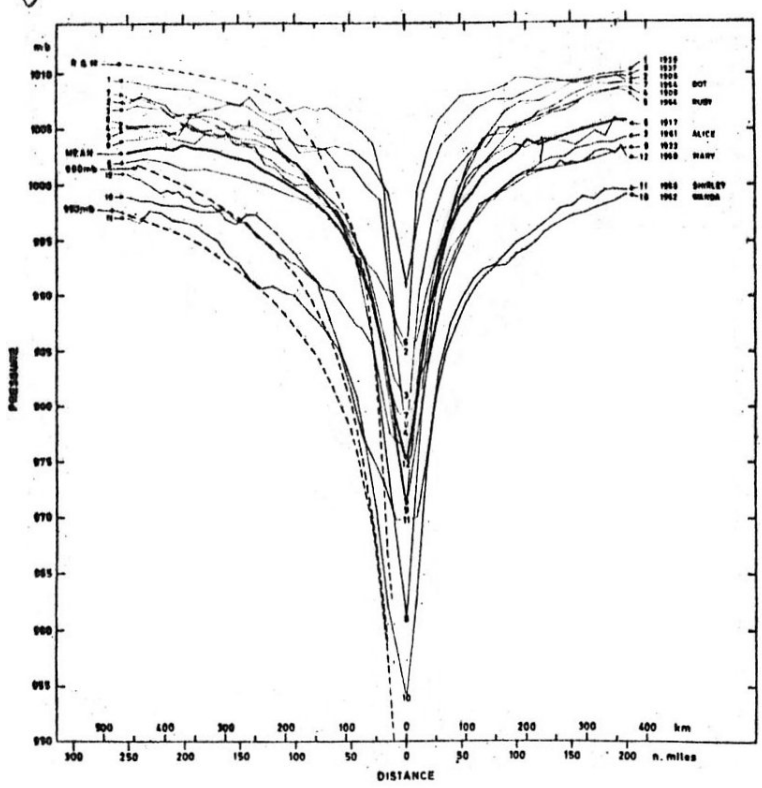


Fig. 4.12 The hourly pressure readings of Fig. 4.11 are here plotted against distance from the typhoon centres. The heavy curve is the mean pressure profile. The curve marked R & M refers to the pressure profile in a 963 mb model hurricane (Malkus and Riehl 1960). The curves marked 960 mb and 950 mb are the mean of pressures reported by ships around 6 and 11 typhoons respectively with central pressure close to the indicated values (Lee 1970).

they are deprived of their source of sensible heat and moisture (the ocean) and immediately begin to fill (Sect. 13.4). The more rapid rise of pressure behind the typhoon can then be attributed to the rising pressure due to the filling of the storm being additional to that due to the movement of the centre away from the coastal observing station. Syōno (1962) shows that the effect occurs in Japan and he also attributes it to the weakening of typhoons as they cross the coast. He illustrated this weakening by showing that the central pressure of the September 1934 Muroto typhoon rose 35 mb during the first two hours after reaching the coast and then rose a further 20 mb during the succeeding two hours. The barograph trace from the 1934 Muroto typhoon is shown by the full line in Fig. 4.13 The traces for the Tacloban and Cantabria typhoons do not show such marked asymmetry suggesting that as these typhoons crossed the Philippines they did not fill as rapidly as those crossing Japan or entering the Asiatic mainland. Barograms recording the passage of typhoons across ships and small islands in the Pacific are usually nearly symmetrical.

The lowest confirmed pressures in typhoons together with those in ~~other~~ tropical cyclones in other areas are listed in Table 4.2 from which it will be seen that the deepest typhoons are found in the region, to the east of Luzon and Taiwan between 12° and 25°N and west of 150°E (see Fig.). Although large and deep tropical cyclones are much more frequent in this area than elsewhere in the world it is nevertheless possible to have equally large and deep cyclones in the North Atlantic, South Pacific, Bay of Bengal and the Indian Ocean but they occur there very infrequently; confirmed pressures below 910 mb have not yet been reported from the last three of these areas nor indeed, from the South China Sea.

During the ___ years 1951 - 197_ reconnaissance aircraft found typhoons with central pressures lower than 900 mb and they are listed in Table 4.3. The circumstances in which the three lowest pressures in this table were measured have been the subject of special investigations. The case of typhoon Ida 1958 (877 mb) was examined by Jordan (1959) whilst Holliday (1975 and 1976) has described the soundings in typhoons Nora 1973 (877 mb) and June 1975 (876 mb). In the case of typhoon June the eye

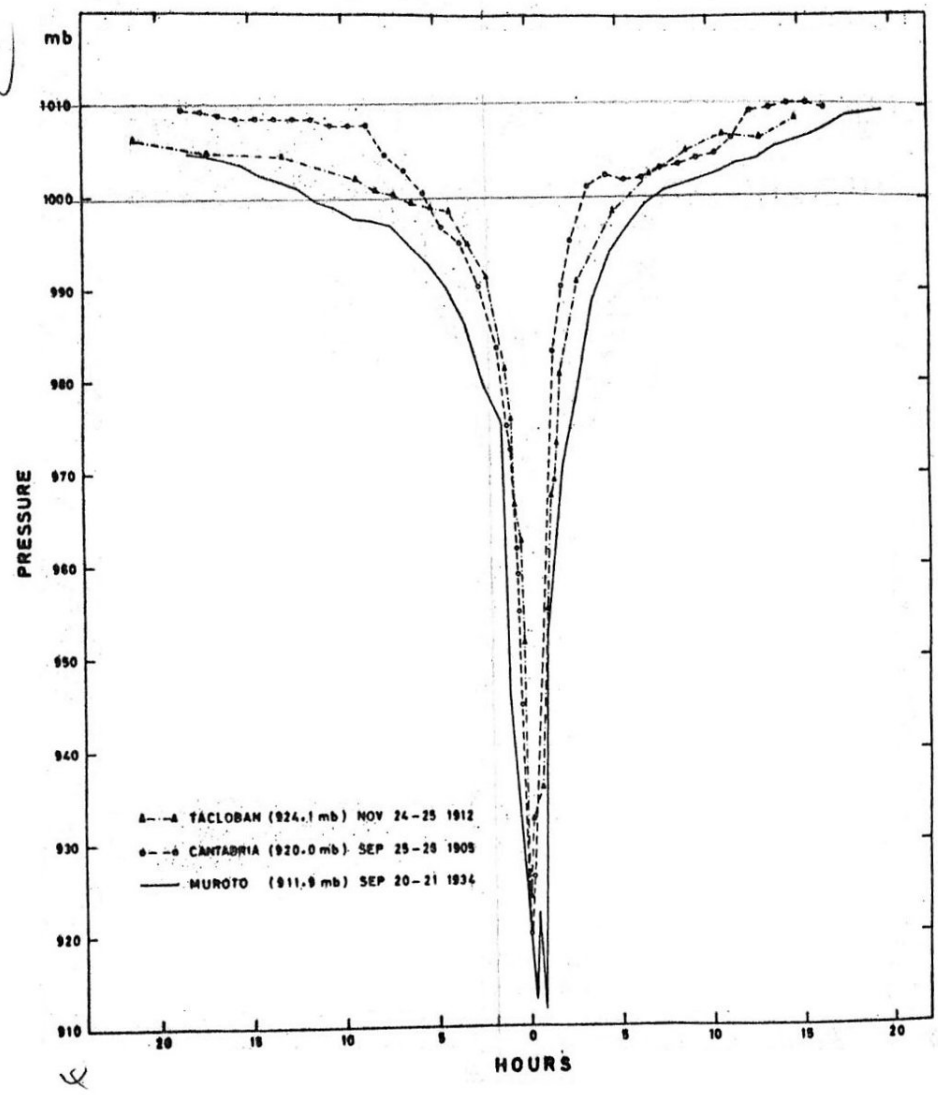


Fig. 4.13 Barograms from the 1912 Tacloban and 1905 Cantabria Philippines typhoons and the 1934 Muroto typhoon, Japan.

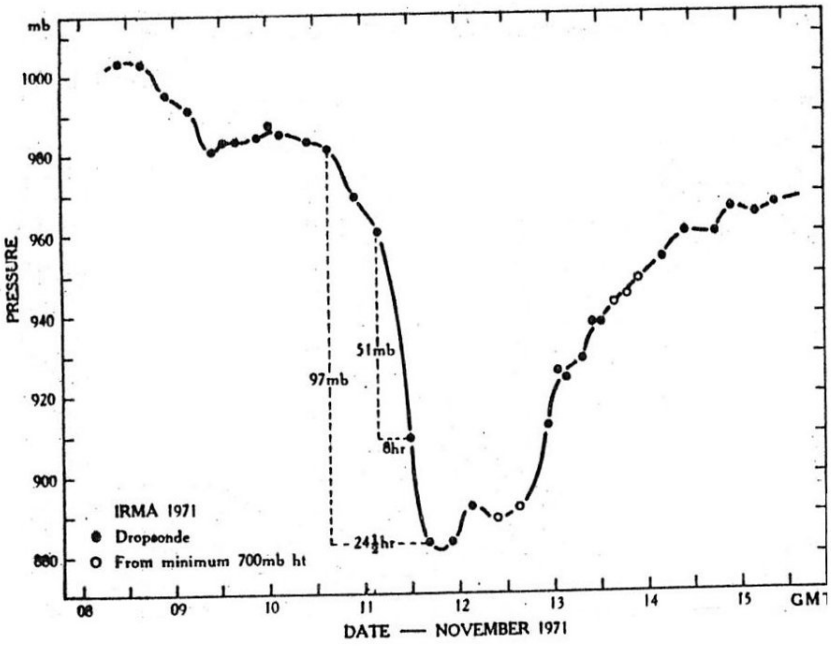


Fig. 4.14 The change of pressure in the eye of Typhoon Irma 1971. The two observations of 884 mb were made near 16°N 132°E. (After Holliday 1973).

diameter was very small (9 km) and the dropsonde entered the eye wall at low levels so missing the region of the lowest pressure. From the 700 mb height of 1984 m - a record low value - it is estimated that the lowest central pressure would have been about 873 mb.

Apart from the "Labour Day Hurricane" of 1935 there are as yet no generally accepted reports of sea level pressures lower than 900 mb from any part of the world other than that just to the east of the Philippines. In passing, it is worth noting that the Matecumbe Key reading of 892.3 mb remains the lowest and only reading of less than 900 mb to be made on land. In hurricane Camille of 14th - 22nd August 1969 - the most intense hurricane since that in 1935 - a pressure of 909.4 mb was recorded on an aneroid barometer at the west end of the Bay St. Louis Bridge (Simpson et al 1970) to the northeast of New Orleans. The lowest pressure reported from a land station during the passage of a typhoon is 908.4 mb recorded at Miyako Jima, Ryukyus in 1959 (Table 4.2).

Both Reid and Piddington presented lists of low pressures recorded on board ships and some of these and others have been discussed by Krebs (1911), Tannehill (1938) and in the Meteorological Magazine (Anon 1933). For completeness we will mention some of the lowest readings from different geographical areas.

Table 4.2
4.5.(1)

LOWEST PRESSURES IN TYPHOONS & HURRICANES

Rank	Place	Latt. & Long.	Method of Observation	Date	Name	Pressure mb	Reference
2	East of Luzon	18.9°N 135.3°E	A/c drop-sonde	24 Sept 1958	Ida	877	Jordan (1959)
3	East of Luzon 400 miles or about	17°N 130°E	S.S."Sapoeroea"	18 Aug 1927	-	886.7	Keijser (1928)
4	East of Ryukyus	25°N 135°E	S.S."No.4 Kaiyo-Maru"	6 Oct 1944	-	898	Arakawa (1954)
5	Miyako Jima (Ryukyus)	24.8°N 125.3°E	Land Station	15 Sept 1959	Sarah	908.4	Ishizaki (1969)
6	Muroto Misaki (Kyushu)	33.3°N 134.2°E	Land Station	21 Sept 1934	-	911.8	Takahashi (1962)
			OTHER AREAS				
1	Matecumbe Key Florida,USA	24.9°N 80.6°W	Land Station	2 Sept 1935	"Labour Day" Hurricane	892.3	Tannehill (1938)
2	False Point India	20.3°N 86.7°E	Land Station	22 Sept 1885	-	918.9	Keijser (1928)
3	Cossack W. Australia	20.7°S 117.1°E	Land Station	7 June 1881	-	914	Tannehill (1938)
1	West of Guam.	12.8°N 141.3°E	A/c drop-Sonde	19 Nov 1975	JUNE	876	Holliday (1976)

The low pressure observed in the Dutch ship SS "Sapoeroea" in 1927 was measured with a mercurial barometer which was subsequently calibrated at Manila. This reading - which was checked by several people on board - was for many years the lowest confirmed sea level pressure in the world until superceded by the 1958 aircraft observation in typhoon Ida . In passing, it is of interest to note that the typhoon through which the "Sapoeroea" passed on the 18th August 1927 subsequently crossed north Luzon and passed about 100 km south of Hong Kong on the 20th having averaged approximately 9 m/s ~~10 knots~~ during the intervening two days. Twenty-seven years before the "Sapoeroea" observation the American steamer "Arethusa" recorded a similar pressure (885.8 mb) at 13.6°N 134.5°E on 16th December 1900. This observation is recorded in the U.S. Pilot Chart for the Pacific for July 1901 and is of interest because, taken with the observations in Tables 4.2 and 4.3, it shows that extreme typhoons (pressure less than 900 mb) have been encountered in the months from June to December inclusive with the sole exception of July.

A low pressure reading made on the 25th September 1905 on board the Coast Guard Cutter "Basilan" is given as a record in some books and papers (e.g. Dunn and Miller 1964). This ship, and the SS "Pathfinder" of the Coast Survey, were sheltering some ~~10 miles~~ 18 km apart in Frank Helm Bay on the island of Samar when the centre of a typhoon, known as the "Cantabria" typhoon (Fig 4.13) passed between them. In the Philippines Weather Bureau's Monthly Bulletin for September 1905, Mata presented an account of the observations made in this typhoon. He records both in the text and tables that the SS "Pathfinder" observed a minimum pressure of 920.1 mb (690.12 mm) and that on board the "Basilan" "the barometer remained ten millimeters below the graduated glass (700 mm)". Both readings therefore indicate a minimum pressure of about 690 mm or 920 mb and both ships entered the eye of the storm. Krebs (1911), quoting Mata's article as the source, gave the "Basilan" minimum as 682.0 mm (909.3 mb) but as the source itself claims a reading no lower than 690.12 mm or 920.1 mb there must be some mistake, accordingly, I have not included this reading in Table 4.2.

The lowest pressure recorded in the South China Sea was on board the "S.S. Empire" in the eye of a typhoon about 175 km southeast of Hong Kong near 21.0°N 115.2°E at 8 a.m. on 17th August 1913. The Royal Observatory Hong Kong recorded the original report as 915.3 mb (27.03") whereas

Table 4.3 ALL TYPHOONS WITH CENTRAL PRESSURE BELOW 900 MB AND OTHER ANNUAL MINIMA AS DETERMINED BY AERIAL RECONNAISSANCE 1951 - 1979

Year	Typhoon	Date	Lat. °N	Long. °E	Pressure (in mb)	Flt.Lvl.Max. Wind (in kn)	Abs.Max Wind (i
1951	Iris	4 May	11.8	129.2	910		
1952	Bess	11 Nov	16.2	131.8	915		
1953	Nina	13 Aug	18.7	136.8	883		
1954	Ida	28 Aug	19.3	124.7	888		
1955	Clara	13 Jul	25.5	125.0	920		
1956	Wanda	31 Jul	23.0	128.0	915		
1957	Virginia	22 Jun	15.0	127.8	895		
1957	Hester	8 Oct	22.3	141.9	898		
1957	Lola	16 Nov	13.7	140.4	897		
1958	Ida	24 Sep	18.9	135.3	877	185	
1959	Joan	28 Aug	21.1	125.2	884		
1959	Vera	23 Sep	19.6	142.9	894		
1960	Trix	6 Aug	23.4	129.8	918	100	120
1961	Nancy	13 Sep	19.9	131.0	882	130	160
1961	Violet	7 Oct	20.2	140.8	882	160	170
1962	Karen	12 Nov	15.6	136.1	897	120	150
1963	Carmen	12 Aug	13.4	124.7	898	115	115
1964	Sally	8 Sep	18.2	124.1	894	90	150
1965	Bess	30 Sep	20.6	143.3	901	130	130
1966	Kit	26 Jun	24.3	132.3	912	100	122
1967	Opal	3 Sep	20.6	157.4	752	150	150
1967	Gilda	14 Nov	15.5	138.2	890	112	130
1968	Agnes	3 Sep	18.5	138.9	904	80	170
1969	Viola	26 Jul	19.7	122.4	891	110	118
1969	Elsie	24 Sep	20.2	137.2	890	112	180
1970	Hope	23 Sep	20.5	147.5	895	110	140
1971	Irma	11 Nov	15.6	132.3	884	80	127
1971	Nadine	24 Jul	19.9	127.1	898	100	145
1972	Betty	15 Aug	21.7	126.8	910	95	110
1973	Nora	6 Oct	14.8	128.2	877	150	150
1973	Patsy	10 Oct	15.8	131.6	893	100	125
1974	Gloria	6 Nov	17.0	125.2	931	120	120
1975	June	19 Nov	12.9	141.3	875	110	115
1976	Louise	3 Oct	15.9	127.8	895	120	165
1976	Therese	15 Jul	22.5	136.6	895	90	110
1977	Babe	8 Sep	21.0	127.0	906	95	123
1978	Rita	25 Oct	12.8	132.1	878	110	141
1979	Tip	12 Oct	16.8	137.7	870	110	125

Gherzi (1951) gives 910.6 mb (683 mm). The lowest pressure reported in the South China Sea (south of 23°N) by aircraft reconnaissance is 915 mb in typhoon Elsie on 13 October 1975. check

In Fig.4.14 the lowest pressure recorded each year in typhoons in the Pacific, in the South China Sea (south of 23°N), at Waglan Island and at the Royal Observatory Hong Kong (R.O.H.K.) have been plotted on Gumbel's extreme probability paper. The pressures over the sea (1951-1975) are from aircraft reconnaissance observations and those at Waglan and at the Royal Observatory Hong Kong (1953-1975) are from barograms. There is a 66% probability that pressures for return periods beyond the last plotted point will lie within the band ~~indicated~~ shown by the arrows. The diagram indicates the lowest pressures appropriate to a return period of 100 years - that is the lowest pressure that will be equalled or ~~passed~~ exceeded once in 100 years, on average - are, reading from top to bottom, 843, 889, 935 and 945 mb respectively.

Two features of Fig.4.14 are of interest. Firstly, the pressures found and expected at Waglan Island are lower than those at the Royal Observatory Hong Kong notwithstanding the fact that the distance between the stations is only 18.7 km. This is attributable to the tendency for typhoons to weaken progressively as they move onto mainland China. ~~approach closer to a coast, and also to the fact that the most frequent track taken by the strongest typhoons in that region is from the east-southeast~~. Secondly, the lowest pressure recorded in the Pacific in 1974 was only 931 mb. This value is plotted at the extreme left of the top curve. The number of tropical storms was 10% more than usual that year but less than half of them developed into typhoons. However, the central pressure in typhoon Gloria was falling fast as it approached the Philippines and it is probable that it fell below 930 mb before landfall but there were no aircraft observations to confirm this.

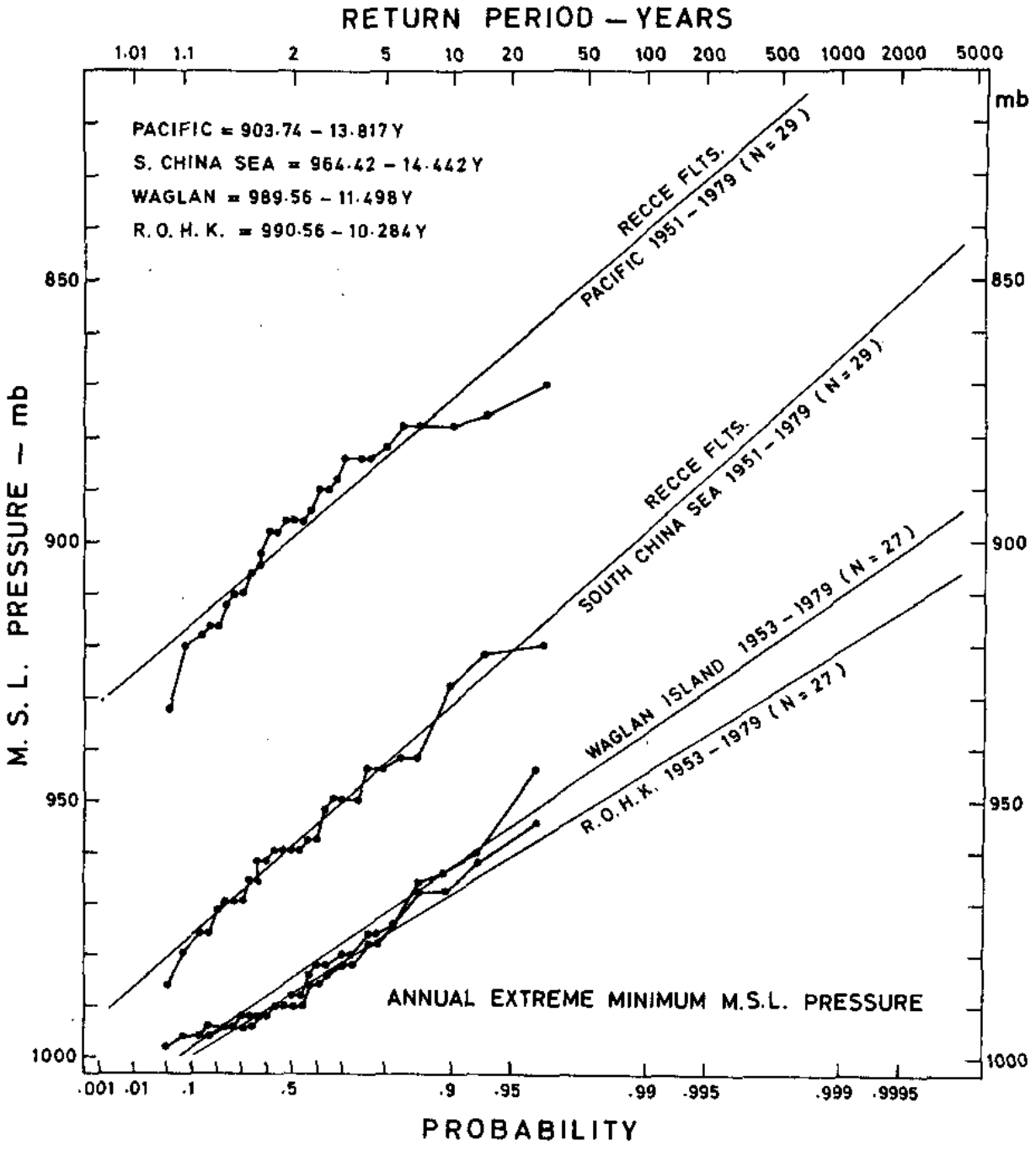


Fig. 4.5(6). Annual minimum pressures recorded by reconnaissance aircraft and at Waglan Island and the Royal Observatory Hong Kong plotted on Gumbel extreme probability paper (see sect 5.7).

4.5.1 PRESSURE GRADIENTS AND FALLS — Small

The pressure gradients found in the region outside the eye wall of mature typhoons in low latitudes are possibly exceeded only by those in tornadoes. Examples from some Philippine typhoons have been given by Depperman (1939) who also listed some repaid falls of pressure which result when typhoons approach a station. In the "Cantabria" typhoon, the difference in pressure between the SS "Pathfinder" in the eye of the storm and Borongan - a station 48 km distant - was 74.7 mb giving a gradient of 1.55 mb/km. Depperman (1939) gave similar gradients for the "Tacloban" typhoon of 24th November 1912. A good measure of a pressure gradient was made on 17th August 1971 when the centre of typhoon Rose passed over a station on Cheung Chau Island some 18.75 km southwest of the Royal Observatory Hong Kong. The central pressure was then 963.2 mb and was 21.4 mb less than the simultaneous reading at the Royal Observatory. This indicates an average pressure gradient of 1.14 mb/km. There is no doubt that gradients in excess or 3mb/km occur in some mature typhoons but good measurements are rarely obtained because stations with accurate barometers are usually too far apart and those few which are close together are seldom crossed by intense typhoons; even when these requirements are met it is difficult to be sure that readings are accurately simultaneous. Approximate gradients can be computed from the rate of fall of pressure at one station if the speed of movement of the typhoon and steady conditions are assumed.

The greatest rate of fall of pressure recorded in a typhoon near land occurred on the SS "Pathfinder" during the "Cantabria" typhoon when the pressure fell 36.3 mb in 27 minutes. At Tacloban, during the November 1912 typhoon a decrease of 36.9 mb in 30 minutes was recorded whilst a fall of 16.53 mb in 5 minutes was measured on a mercurial barometer. The speed of these two typhoons were 16 and 12 knots respectively. Rates of fall of pressure similar to those indicated for the Philippines typhoon in Fig. 4.13 were also recorded in Hurricane Janet on 28th September 1955 when it approached Corozal in British Honduras. A fall of 76 mb in 2h 10 min was recorded on this occasion. Gherzi (1951) cites a fall in pressure at Macau of 33.3 mb in 30 minutes during the approach of the 1906 "Hong Kong" typhoon. I have been unable to confirm these figures because the records are no longer available but they are also quoted by Natario (1957b). The pressure gradient in this typhoon at Hong Kong was also great and can be calculated from curve 2 in Fig. 4.12 to be about 1.43 mb/km. The typhoon was moving across Hong Kong and Macau at about 10.7 knots, or 19.8 km/hr; at this speed the fall in pressure at Macau of 33.3 mb in 30 minutes corresponds to a pressure gradient of 3.36 mb/km. Some very rapid pressure

falls have been reported from moving ships because, of course, when a ship sails towards the centre of an approaching typhoon the time for the pressure at the ship to fall to the central minimum will be much less than for a stationary observer. /6

The greatest falls of pressure over one hour at stations near the centres of approaching typhoons were averaged by Depperman for 25 typhoons of different intensities. His result, converted to S.I. units, are given in Table 4.4 together with his derived gradients in mb/km.

Table 4.4

Minimum Pressure Pc mb	Number of Typhoons	Mean Gradient mb/h	mb/km
920 - 933	4	26.8	1.2
934 - 947	4	14.7	0.6
948 - 960	7	15.2	0.6
961 - 973	8	13.6	0.5

These results indicate that, on average, pressure gradients in typhoons increase as the central pressure falls; a result that is also suggested by the pressure profiles in Fig. 4.11. It is important to realise that this is a generalization; pressure gradients in individual typhoons can vary greatly from the average. The individual observations which were used by Depperman to prepare Table 4.4 show a wide range of variation. For example, the greatest gradients found in typhoons with central pressures around 950 mb varied by a factor of three from 0.25 mb/km to 0.79 mb/km. Or, putting it the other way round, gradients of about 0.81 mb/km were found in typhoons with central pressures as low as 920 mb and as high as 970 mb. The maximum pressure gradient is more closely related to the "pressure depth" i.e. the difference between the pressure of a typhoon's environment and the central minimum than to the central pressure alone but, again, there can be a wide variation between individual typhoons.

There have been many attempts to represent a typhoon's pressure profile (curve showing changes of pressure with distance) by mathematical equations. Some of these equations are discussed in section but, they are all more or less idealised and individual profiles usually show departures from the ideal.

Sometimes, when a typhoon ~~tropical cyclone~~ moves into an area in which environmental conditions are favourable for deepening, the central pressure can fall extremely rapidly. These cases of "explosive deepening" (Sect. 13.2) are usually observed in the same general area as extremely low pressures that is, ~~just~~ to the east of North Luzon and Taiwan and westward to 150°E. Surface pressures in the eye determined from frequent aircraft reconnaissance enable an estimate to be made of the change of central pressure with time or the rate of deepening of a typhoon. The most rapid fall of pressure ever measured in the eye of a tropical cyclone occurred in typhoon Irma during November 10th to 11th 1971 (Holliday 1973). I flew into this storm in the reconnaissance aircraft on the first daylight penetration after a minimum pressure of 884 mb was recorded for the second time; this was at that time the third lowest pressure on record. The change of Irma's central pressure is shown in Fig. 4.15 where it will be seen that falls of 97 mb in 24.5 h and 51 mb in 8 h were recorded. The average rates of deepening were 4.0 mb/h (95 mb/24h) over a 24 h period and 6.2 mb/h (74.4 mb/12h) over a 12 h period; these figures exceed the previous records established in typhoon Ida in Sept. 1958, which were 3.8 mb/h and 4.3 mb/h respectively. The most frequent rate of deepening of typhoons is about 0.6 mb/h.

4.5.2 Frequency of central pressure Minima

Since the advent of aerial reconnaissance in 1945 the centres of most tropical cyclones in the Western Pacific have been penetrated several times each day. On most flights, the mean sea level pressure in the eye is determined or, if no eye has formed, the location and magnitude of the lowest pressure in the storm circulation is reported. From these observations of central pressure minima it is possible to obtain some idea of their relative frequency of occurrence. In the period 1958-68 2 288 observations of the central pressure were made in 224 tropical cyclones which reached typhoon intensity or nearly so. 1) The lowest pressure reached in each of these typhoons has been used to prepare Table 4.5. All these tropical cyclones developed eyes. 2) The third column of the Table shows the number of typhoons to attain minimum pressures within the ten millibar ranges indicated in the first column. Frank and Jordan (1960) show a similar table for the period 1950 - 57 and Jhō (1962) presented one for the period 1950 - 61. Frank and Jordan's results - 1950 - 57 - are shown in Table 4.4 together with those from 1958 - 68. The differences at the higher pressures result from different criteria for storm selection and from the fact that the earlier data includes some estimated pressures read from the tracks of tropical cyclones published by the Japanese Meteorological Agency whereas the later list includes only measured pressures. For pressures lower than 990 mb all three lists show similar distributions.

1) The reconnaissance data in the Guam Annual Reports is intended to refer only to cyclones which attained typhoon intensity as defined by the U.S.A. convention of one minute mean wind speeds.
2) Eye data were not published for 1958 but observations in later years indicate that all severe tropical storms developed eyes.

Table 4.5 . Frequency of Western Pacific typhoons [2] which attained minimum sea level pressures in the listed intervals.

Pressure (mb)	Number		Annual Average		Percent of total	
	1950-1957 [1]	1958-1968 [2]	1950-1957	1958-1968	1950-1957	1958-1968
≥ 1000	12	0	1.5	0	5.8	0
990-999	58	15	7.3	1.4	28.2	6.7
980-989	33	23	4.1	2.1	16.0	10.3
970-979	21	34	2.6	3.1	10.2	15.2
960-969	22	34	2.8	3.1	10.7	15.2
950-959	11	14	1.4	1.3	5.3	6.3
940-949	11	23	1.4	2.1	5.3	10.2
930-939	12	27	1.5	2.5	5.8	12.0
920-929	7	14	0.9	1.3	3.4	6.2
910-919	8	19	1.0	1.7	3.9	8.5
900-909	9	12	1.1	1.1	4.4	5.4
< 900	2	9	0.3	0.8	1.0	4.0
Total	206	224	25.9	20.5	100.0%	100.0%

1) From Frank and Jordan 1960.

2) All typhoons (and some severe tropical storms) penetrated by reconnaissance flights and published in the Annual Reports of the Joint Typhoon Warning Centre, Guam.

It has long been known that typhoons which attain very low pressure are less frequent than those with higher pressure minima but there was no reason to believe that there was other than a gradual and steady decrease of frequency with pressure depth. However, the sets of data presented in Table 4.5 show a marked decrease of frequency at about 960 mb, with only half as many tropical cyclones in the pressure range 950 to 959 mb as are in the range 960 to 969 mb. Furthermore, below 950 mb the data show an increase of frequency, for example, 39 typhoons had minimum pressures in the range 930 to 939 mb whereas there were only 25 in the range 950 - 959 mb. As suggested by Ito (1962) this indicates that there may be some barrier to overcome, or critical condition to be met, before the central pressure of typhoons can fall below 960 mb. When this condition is fulfilled typhoons more frequently continue to deepen to 939 mb or less than to remain at pressures in the range 940 - 959 mb.

The bi-modal distribution is of interest because it indicates that there may be two characteristic types of typhoons; those corresponding to the higher mode having pressures of about 950 mb or more and those corresponding to the lower mode, at about 935 mb, having pressures less than 950 mb. Tropical cyclones with one minute mean winds in excess of 65 m/s ~~(130 kn)~~ are called "super typhoons" by the U.S. Joint Typhoon Warning Center at Guam, but this is an arbitrary choice. The data in Table 4.5 show that a less arbitrary grouping could be made by naming those typhoons having central pressures of 950 mb or less as super typhoons. It can be argued that it is the wind speed which determines the intensity and destructiveness of typhoons and therefore they should be classified by this characteristic. Unfortunately the surface wind speed is estimated and not directly measured by reconnaissance aircraft whereas the central pressure is instrumentally determined. It is true that there is a considerable spread of wind speeds for a given central pressure and for 950 mb there will be a spread around 55 m/s ~~(110 kn)~~ (sect) but nevertheless ~~for all practical purposes complete precaution should be taken against~~ typhoons with central pressures of 950 mb or less will be extremely destruct ~~and inaccurate estimates of maximum wind speeds in storms of this depth add very little useful information.~~ and worthy of some superlative, whatever their precise speed. Of the typhoons placed in the 'super' class by JTWC ~~all~~ in the period 1959 - 1969 all have pressures below 950 mb although there are several with minimum pressure between 945 and 949 mb.

4.5.3 Peripheral pressure

There is a considerable variation in the pressure of the atmosphere surrounding individual typhoons. At Hong Kong, the pressure 12 hours before the commencement of a tropical cyclone gale has been as high as 1011 and as low as 990 mb and the few barograms in figure 4.8 show that a similar variation exists in the pressure on the periphery of typhoons.

In Table 4.6 the mean value of the outer closed isobar (one millibar interval) at the time of 3 517 flights into 224 tropical cyclones has been listed with respect to time of year and location. From this table it will be seen that the monthly mean pressure of this isobar lies between 1007-5 mb and 1008.6 mb from October to April inclusive and is less than 1006 mb in June, July and August. The overall annual average is 1006.8 mb. It is interesting to note that the lowest average pressures were found outside the tropics in the months of July and August. The highest and lowest environmental pressures in individual tropical cyclones in this sample were 1019 mb and 995 mb respectively, the former occuring in the month of November and the latter in July.

The pressure of the outer isobar usually changes little during the life of a tropical cyclone. In the 224 tropical cyclones examined the environmental pressure fell from the first to last observation in 54% of cyclones, rose in 28% and remained the same for the remaining 17%. Similarly the difference between the greatest and least peripheral pressures observed during their lifetimes was usually only a few millibars, with changes of 10 mb or more being found in only 6% of the storms. The greatest observed variation was 13 mb.

The pressure of the outer isobar around a tropical cyclone at any location is usually two to three millibars lower than the normal monthly mean sea level pressure for that particular place; the actual values for the period 1958/68 being 1006.8 mb for the mean environment of tropical cyclones and 1009.0 mb for the normal monthly mean pressure.

Table 4.

The mean pressure of the outermost isobar (1mb interval) of tropical cyclones which at some time achieved at least severe tropical storm intensity. The pressures were read from surface charts nearest in time to individual aircraft reconnaissance flights in the period 1958/68. Monthly mean pressures at selected stations are included for comparison.

Latitude	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Degrees N					Add 1000 mb to figures shown								
≥ 27.5	-	-	-	8.0	7.1	5.8	3.7	4.9	7.2	8.8	6.9	10.7	6.2
22.5 to 27.4	-	-	-	9.8	6.4	5.6	4.1	5.1	6.0	9.0	9.4	6.6	6.2
17.5 to 22.4	-	-	11.3	8.9	5.6	5.1	4.5	5.1	6.2	8.3	9.3	9.0	6.4
12.5 to 17.4	9.2	-	10.4	8.2	6.5	6.0	6.8	6.5	7.4	7.9	8.6	8.2	7.4
7.5 to 12.4	8.8	-	7.5	8.1	7.7	8.7	7.8	7.4	6.8	8.5	8.5	6.7	8.0
≤ 7.4	9.0	-	-	7.9	6.0	8.0	-	-	-	9.0	6.7	4.9	6.6
No.of Observations	34	0	35	175	158	192	478	628	675	597	381	164	3,517
Mean all areas	9.0	-	8.5	8.4	6.6	5.9	5.2	5.4	6.5	8.4	8.6	7.5	6.8
Tokyo 1931/60	15.9	16.0	15.7	14.9	12.5	9.7	9.6	10.7	12.8	17.2	18.7	17.1	14.2
Hong Kong 1931/60	20.4	18.0	16.1	12.9	9.3	6.1	6.3	5.1	8.2	14.3	17.3	20.0	12.8
Manila 1951/60	13.8	13.0	12.9	11.2	10.0	9.3	9.3	8.2	9.2	10.1	10.8	12.7	10.9

4.5.4 Pressure-profile equations

Engineers and meteorologists have made many attempts to find a general mathematical expression for the pressure profile in tropical cyclones. Such a formula is sought by engineers for use in tropical-cyclone models used to compute the effects of waves and storm surge on structures. Meteorologists would use the formula to compute the central pressure and maximum winds in a tropical cyclone from observations of pressure in the outer parts of the storm.

Takahashi (1962) listed five of the numerous empirical formulae which have been used. Theoretical models from which pressure profiles could be deduced have also been postulated. One such model was the modified Rankine vortex (vr = constant) proposed by Depperman (1947). All these formulae may be made to fit quite well the profiles of specific storms at certain times in their life, but they cannot be usefully used for tropical cyclones in general. The main source of difficulty derives from the fact that as a tropical cyclone develops, most of the changes in profile occurs in the inner regions of the storm. Pressures in the outer parts give little indication of conditions further in. This feature is illustrated generally by the profiles in Fig. 4.11 but more specifically by the excellent pressure profiles obtained by aircraft reconnaissance of the developing hurricane Anita (1977) (Fig. 4.5.4(.)). A further difficulty is that a number of tropical cyclones each year fail to develop in the classical manner and show assymmetries such that the winds and pressure profiles vary from one quadrant to another. This condition is most frequent in the autumn when cold air and upper westerly distrubances penetrate to lower latitudes. Sea surface temperature anomalies have also been associated with such asymmetries. Strong asymmetries were found, for example, in the well probed cyclone Kerry (1979) in which aircraft winds up to 70 m/s were observed (Sheets and Holland 1979).

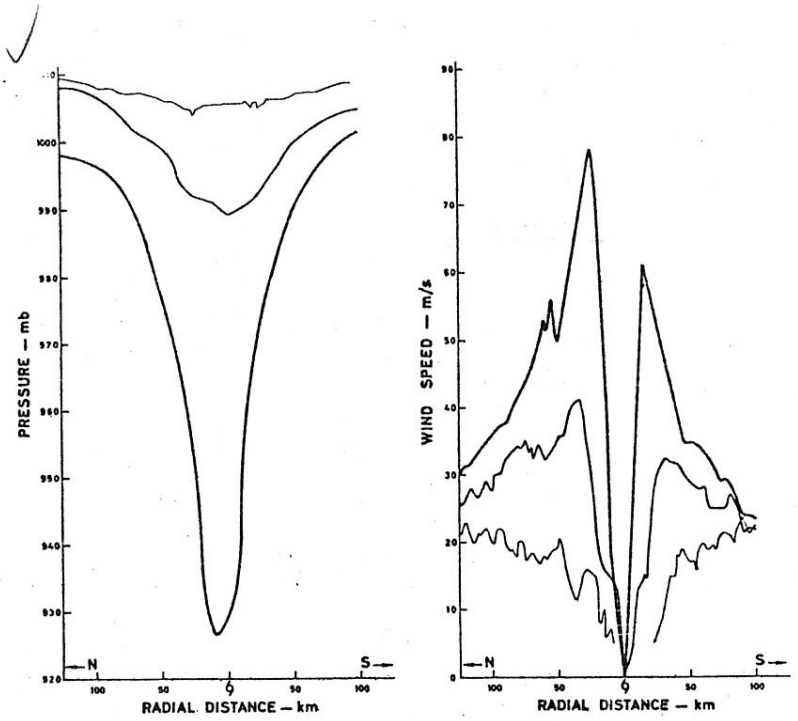


Fig. 4.5.4.(1) Profiles of pressure and wind obtained by aircraft reconnaissance on 30 and 31 August and 2 September 1977 as hurricane Anita formed. The central minimum pressure on these dates was 1004, 989 and 926 mb respectively.

If attention is confined to mature storms of typhoon strength in a relatively steady state then it is found that when their profiles are normalised to reduce the effects of different central pressures p_c and different ambient pressures p_n then they tend to be similar. This was shown by Schloemer (1954) to be the case for nine Atlantic hurricanes and is illustrated in Fig. 4. by plotting $(p_n - p_c)/(p - p_c)$ on a log scale against distance from the centre. P is the pressure at radius r. The curves resemble a family of rectangular hyperbolae of general formula xy = constant. If the radius of maximum winds r_m is taken to be the constant in the general formula then,

$$(p - p_c)/(p_n - p_c) = \exp(-r_m/r) \qquad - (4. \quad)$$

$$\text{or} \quad p = p_c + (p_n - p_c) \exp(-r_m/r) \qquad - (4. \quad)$$

which is the formula most commonly used by engineers. Holland (1980) made the expression more general by the use of scaling factors A and B to give

$$p = p_c + (p_n - p_c) \exp(-A/r^B) \qquad - (4. \quad)$$

The factor B defines the shape of the profile and A determines its location relative to the storm centre. Indeed, by combining equation (4.) and the gradient and cyclostrophic wind equations (sect. 3) he showed that

$$r_m = A^{1/B} \qquad (4. \quad)$$

A lower limit of one for the value of B, is determined from the observation that no tropical cyclone was known in which the radius of maximum pressure gradient was less than half of the radius of maximum winds. An upper limit of three is indicated by the constraint of constant angular momentum (vr = constant) in the inflowing air. In reality there is a loss of cyclonic angular momentum due to friction so that an upper constraint near 2.5 is more realistic. It is probable that B increases as p_c falls so that deep tropical cyclones have values of B around 2.2 while weaker ones have B values of 1.5 or so.

In summary, pressure profiles in mature tropical are best described by equation (4.) if the radius of maximum winds is known and a few inner pressure values are available to define B. If only the radius of maximum winds is known then B can be set equal to 1.5 or to a higher value if satellite images or other sources indicate storm intensity. Setting B at one, gives the original Schloemer (1954) equation (4.).

4.6 The Eye

4.6.1 Introduction

The eye of a typhoon is a unique and awe-inspiring phenomenon which, over the years, has aroused the curiosity of laymen and mariners. As one enters an eye the sudden reduction of the wind speed from hurricane force to 5 m/s or so and the simultaneous cessation of torrential rain is most impressive. On some occasions it is possible to hear the roar of the winds under the eye wall from within the relative calm of the eye. Usually, the sky is covered with a broken layer of low strato-cumulus and cumulus clouds which sometimes heap up near the middle of the eye - see Fig. 1.1 - to form what Robert Simpson (1951) has called the 'hud-cloud'. In most eyes patches of blue sky by day, and starlight by night, are visible from the ground. Aircraft flying in the eye at middle levels by day are in slowly subsiding, warm, cloud-free air surrounded by dazzling, white, eye-wall clouds with broken low cloud below and a deep blue sky above; quite frequently the blue sky is obscured by a thin layer of cirrus cloud at high levels the brilliance of the scence is then greatly reduced and is sometimes quite dull. There exists a popular misconception that there is no cloud in the eye, this error is perpetuated in many books and articles both old and new. There is no cause on record of an eye being completely free of cloud. In a mature typhoon the eye is usually nearly circular but, occasionally in mature typhoons and frequently in weaker storms, the eye will do adopt an elliptical or more distorted shape which may persist for hours or, occasionally, days.

On the 15th August 1951 Robert Simpson flew into the eye of typhoon "Marge" and brought back some magnificent photographs and the following vivid account:-

> " Soon the edge of the rainless eye became visible on the (radar) screen. The plane flew through bursts of torrential rain and several turbulent bumps. Then, suddenly, we were in dazzling sunlight and bright blue sky.
>
> Around us was an awesome display. Marge's eye was a clear space 40 miles in diameter surrounded by a coliseum of clouds whose walls on one side rose vertically and on the other were banked like galleries in a great opera house. The upper rim, about 35,000 feet high, was rounded off smoothly against a background of blue sky. Below us was a floor of low clouds rising to a dome 8,000 feet above

sea level in the centre. There were breaks in it which gave us glimpses of the surface of the ocean. In the vortex around the eye the sea was a scene of unimaginably violent, churning water."

The features of the eye that have been described here are well illustrated in a remarkable photograph of the eye of the intense typhoon "Ida" 1958, this was presented by Fletcher et al (1961) and is reproduced here as Fig. 4.16. The photograph was taken from a U.S.A.F. U.2 reconnaissance aircraft flying over the typhoon at a height of about 21 km (69 000 ft). The near vertical eye wall 19.8 km (65 000 ft) deep with spiral banding can be clearly seen as can the broken low cloud and the sea surface which appears black in the photograph. One hour before this photograph was taken the lowest ~~surface~~ sea-level pressure ever measured on earth - 877 mb - was observed in this eye which was then 17 km ~~(9.4 n.miles)~~ in diameter. The height of the 700 mb surface was 2 005 m ~~(6 580 ft)~~ and the temperature there was 29.8°C or about 19°C more than in the normal tropical atmosphere.

There are many early accounts of conditions in the eye as experienced at sea. The most impressive feature there is the so called "pyramidal sea" caused by the interference of large waves generated by hurricane force winds around the eye. At one moment crests of waves, moving in different directions, combine to form a huge pyramid of water which is quickly replaced by a deep depression in the sea surface as the troughs of the waves re-enforce each other. The appearance of the sea surface has often been described as being like that of boiling water - a greatly magnified version of the choppy conditoons found in busy harbours and waterways. As typhoons cross islands or peninsulas of land, birds, bats, butterflies and other insects are picked up by the inflowing winds and blown into the eye from which they cannot escape. Large numbers of birds have been known to drop exhausted on board any ship that they encounter in the eye.

Observers on land have often reported conditions in the eye as having been "oppressive", "sultry" and "suffocating". It is always hot and usually humid in the eye but the impression of being suffocated is considered as being largely due to psychological reaction following the rapid transition from hurricane winds and torrential rain to relatively calm conditions. Depperman 1939 quotes cases when conditions have been reported as suffocating although no change in temperature or other element was recorded by instruments.

However, extraordinarily high temperatures have been found to prevail at the surface in a few exceptional typhoon eyes due to subsidence (sect).

Before going on to discuss conditions in the eye in more detail we should note that they can be very variable. Pressure, temperature, humidity and the types and heights of clouds vary not only from one eye to another but also change within fifteen minutes or so in individual eyes. The rapid change in eye structures, as revealed by changes in the position and organization of rain-bearing clouds, is readily apparent on the screens of weather radar sets when the eyes are within range. The dramatic changes shown in Figs. 4.16, 4.20 and 4.21 illustrate the rapidly changing conditions in the eye and eye wall. The eye wall is not always a complete ring, breaks in the ring of cloud are quite frequent, even in intense storms but in the latter case the breaks are soon repaired. The apparently unstable state of the typhoon eye gives hope that man may one day be able effectively to modify processes taking place ~~on the periphery of the eye~~ the storm's and so moderate the wind speeds ~~there~~ (chapter).

The formation of an eye is an integral part of tropical cyclone intensification.

back of 4.6.1

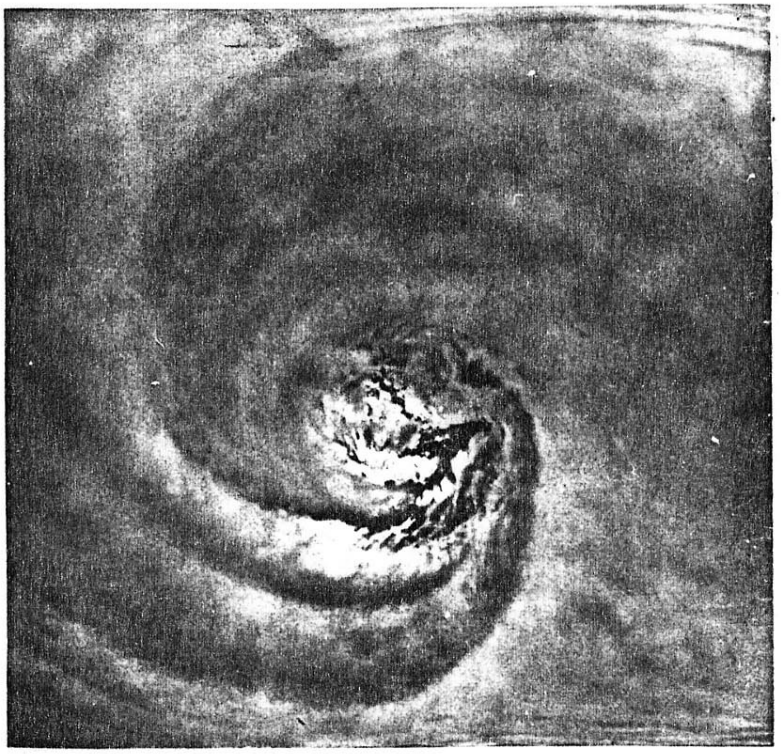


Fig. 4.16 The eye of the intense typhoon "Ida" as seen from a U.2 aircraft flying at a height of about 21 km near 18.9°N, 135.3°E that is approximately 1 000 km northwest of Guam at about 0600 GMT on 24th September 1958. The eye wall extends 19.8km vertically from the sea surface [From Fletcher et al (1961)]

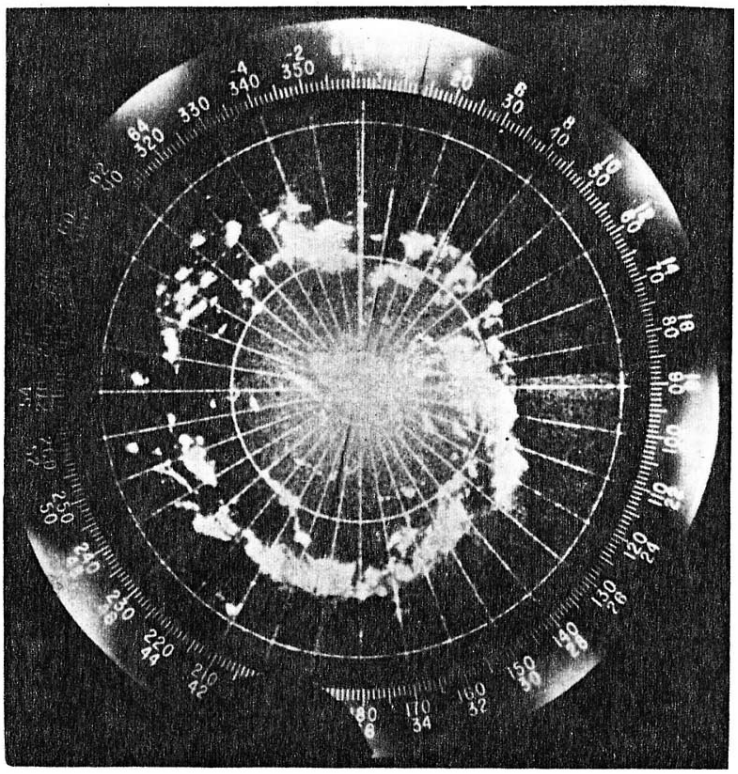


Fig. 4.17 Photograph of a radar screen showing the large, 200 n. mile diameter eye of Typhoon "Carmen" at 2200 GMT on 20th August 1960. The radar was located at Kadena, Okinawa and was a type CPS 9 with a wavelength of 30cm. The range rings are at 100 and 200 n.miles. [from J.T.W.C. Annual Report 1960]

4.6.2 Formation of the eye

There are two features of an eye of a typhoon or tropical storm which need to be explained. Firstly, why is there a central area of relatively light winds at the surface surrounded by a ring of high velocity wind and, secondly, why is there a generalised sinking motion in all but the lowest layers of air in the eye?

It was Ferrel who, in his 1856 paper and his book of 1889, first indicated that inflowing air in the lower levels of a cyclone would accelerate towards low pressure until its speed and the curvature of its path increased to such an extent that the resulting centrifugal force became as strong as the pressure-gradient force driving it inwards (sect). When this position is reached the air cannot make further progress towards the centre and escapes by rising upwards while retaining its strong rotary motion. In the upper part of the storm the pressure gradient decreases (sect) and the ring of cyclonic winds must then expand because the centrifugal force can no longer be balanced by the reduced pressure gradient force. The air continues to move outwards during its ascent because the pressure gradient weakens further with height and even changes direction at the highest levels (sect). As the rotating ring of rising air moves further away from the centre its speed is reduced, and it is deflected to the right by the earth's rotation and so ultimately blows anti-cyclonically around the perimeter of the storm and away from its centre. At the point where the flow changes from cyclonic to anticyclonic rotation the air will be moving radially directly outwards (Fig. 4.18). Ferrel indicated that a fresh supply of air would come down from above into the centre of the typhoon to replace the outward flowing air. It is this subsident motion which warms the air in the eye and keeps it free of heavy cloud and rain.

During the last thirty years Ferrel's theory has been improved and enlarged and put on a firmer mathematical basis. The new theories vary in the number and the kind of assumptions that they use and in their approaches, ~~however, it is usually considered that~~ Durst and Sutcliffe (1938), Byers (1944), Syono (1951), Malkus (1958), Kuo (1959) and Riehl (1963) made significant contributions to the modern, generally accepted theory of eye-formation. Some of these

contributions provided mathematical proofs that an eye is a necessary feature of a typhoon. The earlier of these writers pointed out that as air moved in towards the storm centre the conservation of absolute angular momentum (page) required that the wind speed should increase and become infinite at the centre, however, dynamical analysis was used to show that before the centre was reached cyclostrophic and Coriolis forces (primarily the former) would provide a limit to both the penetration and speed of the inflow and so create a ring of maximum winds. Kuo showed that the total energy gained by the inflowing air is limited by the available pressure fall and that this also puts an upper bound on the maximum speed attainable; in other words, the inflowing air cannot move ever closer to the centre of the storm and so increase in speed indefinitely as would be the case if the conservation of absolute angular momentum were the only consideration. The energy constraint limits the inflow to some minimum radius at which the converging air must turn upward and eventually move outward in the upper part of the typhoon. Kuo also considered the effect of surface friction and showed that this worked so as to permit the converging air to penetrate closer to the storm centre and so form a smaller eye. If the ground below the storm is hilly or mountainous the loss of tangential motion is rapid and the converging air may reach the storm centre, the eye then disappears. The effects of this process can be seen to take place on the radar screen as typhoons move inland (See "Viola" pictures Fig.).

These theories predict that, if certain specified factors do not change, then the eye of a typhoon will be smaller at lower pressures, at lower latitudes and in areas where surface friction is increased; both Kuo and Riehl predict an increase in eye diameter of about ten times as a typhoon moves from 10°N to 30°N Fig. . This seems to be a greater change than is observed in nature, so it is probable that other changes usually take place in a typhoon or its environment to preserve a moderate eye size during its northward movement.

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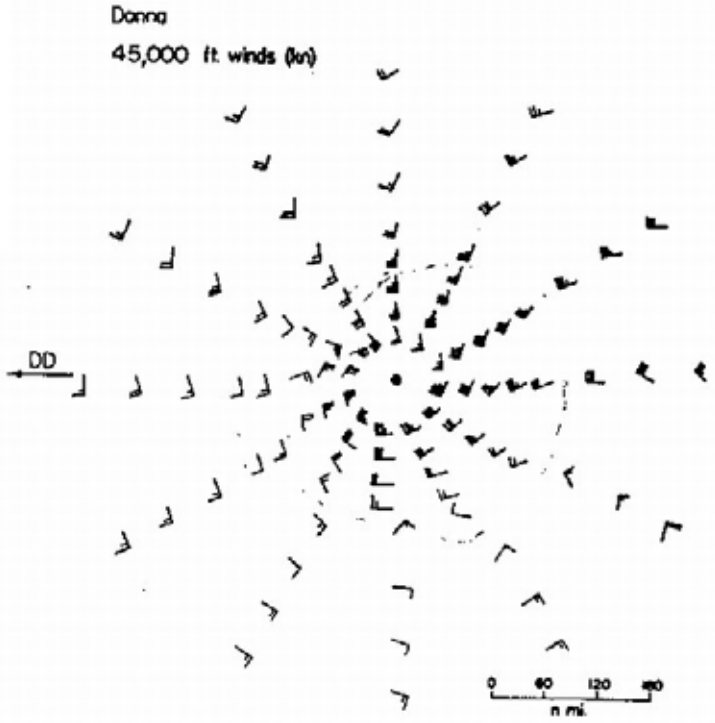

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Fig. 4.[illegible]. Winds in knots at 13.7 km relative to the centre of hurricane Donna as composited from West Indian rawin observations on 6th-9th September 1960. The radius of the inner ring of observations is 111 km ~~(60 n. miles)~~ and of the outer ring 555 km ~~(300 n. miles)~~. The hurricane is moving to the left. The dashed line indicates where the winds are blowing directly away from the centre (After Riehl 1963).

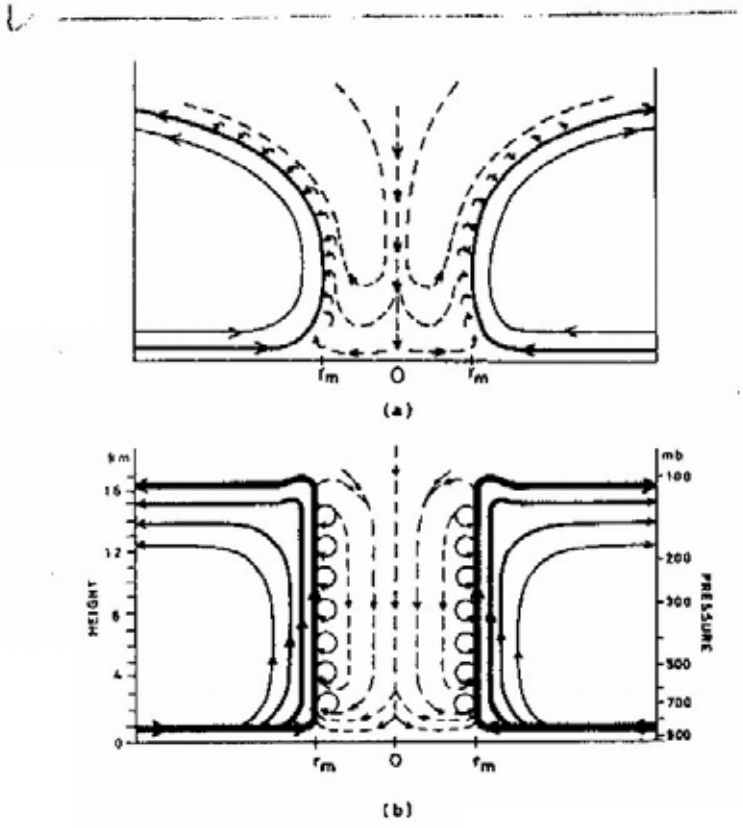


Fig. 4.[illegible]. (a) Schematic diagram of the motion of the air in the eye of a weak typhoon [after Kuo ( )] . (b) Probable air movement in a deeper and more vigorous typhoon with strong convection in eye-wall region.

4.6.3 Air movements in the eye

Durst and Sutcliffe (1938) derived a model of the air motion in and around the eye of a tropical cyclone and they were followed by Malkus (1958) and Kuo (1959) both of whom considered the circulations in the eye in greater detail. Kuo's proposed model is shown in Fig. 4.19 (a).

Durst and Sutcliffe pointed out that the rapidly rotating air just outside the core would impart a rotational velocity to the air in the core and that, being unbalanced by a pressure-gradient force, it would move outward producing subsidence in the core. Malkus noted that the slowly subsiding air receives angular momentum from the eye wall - i.e. is dragged around by the fast moving air in the wall - during the whole of its descent in the core. The cyclonic angular momentum is weak at high levels and increases as the air subsides to levels where the eye wall is rotating faster. When core air arrives in the lowest kilometre or so it has considerable rotational velocity and experiences a centrifugal force which, together with the outward directed coriolis force, causes it to move outwards and rise with the air in the eye wall. This evicted air at low levels is replaced by air from above and a pumping action is established. If there is a small pressure gradient in the eye then the drag must cause the winds to become super-gradient before the pumping action can begin. On the basis of certain plausible assumptions Malkus calculated that in an eye of diameter 60 km the speed of the radial outflow at the eye wall would average about 2 m/s and the subsident flow would average about 0.10 to 0.15 m/s; at this rate, air would take about 24 hours to subside from 200 mb to the lowest 1 km.

Kuo (1954) considered that the great shear between the rapidly rotating eye wall and the relatively calm core air makes the air there unstable for small displacement so that horizontal turbulent eddies are formed at the interface thereby interchanging or mixing eye-wall air with core air and creating drag or friction. He showed, mathematically, that this friction would cause a wind field to be established in the eye such that the wind velocity (mainly tangential) was zero at the centre and increased in proportion to the distance from there. Such a wind profile is frequently observed on reconnaissance flights (see S.

The steady state motion in and around the eye and the low surface pressure there are established by a kind of chain reaction. The diverging low level air in the eye pumps down air which is heated adiabtically as it

descends and so - having a lower density than the replaced air - causes a lower pressure at the surface; this causes a greater and faster low level inflow to the typhoon which, in turn, increases the speed of the air around the eye wall and so increases the pumping action which causes a greater subsidence of air, a greater warming, a lower pressure and so on, until a balance between centrifugal force, pressure - gradient force and frictional force is reached in the air circulating in the core.

If very low pressures are to be produced within the eye the pumping action must be efficient and this, in turn, implies that the eye diameter should be in the optimum range. In a large eye a lot of pumping would be required to cause any significant sinking of the large volume of core air; it is therefore unlikely that sufficient sinking and warming would occur to create very low pressures. On the other hand, in a very small eye a relatively large percentage of the subsiding air would mix with cooler, surrounding eye-wall cloud and be further cooled by evaporation of cloud particles; these processes would hinder the formation of a very warm eye and low surface pressure. Fig. indicates that deep typhoons have eye diameters between km and km and that a diameter of km seems to be optimum.

It is interesting to note that, to maintain a warm core and low surface pressure, it is essential that pumping and subsidence be maintained. If the pumping ceased cooling caused by mixing with eye-wall air and evaporative cooling of cloud particles would soon cause general cooling and a rise in surface pressure. This takes place when a typhoon moves on to land.

The air in the core, whilst maintaining a subsident motion in the average does not sink uniformly or homogeneously as one mass. Currents of more rapidly sinking air are found within the slowly subsiding core mass. The existence of this phenomenon has been determined from the rapid changes in temperature which are frequently encountered in the core by reconnaissance aircraft (e.g. Simpson (195_)) and, more particularly, by the sequence of U.2 photographs of typhoon Ida 1958 which show cloudy and clear air periodically plunging over the rear upper rim of the eye wall rather like a waterfall Figs. 4.20 and 4.21. Such asymetrical sinking and warming can destroy large eyes by providing new localised low pressure centres; similarly, they may well contribute to the instability of eyes of more normal dimensions.

Fig. 4.20. Photograph in the eye of typhoon Ida 1958 from a U 2 aircraft; details are the same as in Fig. 4.11. A cloudy tongue of air can be seen plunging over the rear eye wall - bottom of picture - into the eye. The typhoon is moving towards the north which is at the top of picture. The eye wall is cylindrical with an occasional slight forward tilt. The low-level eye cloud with tops at 2.2 km rotated in a solid, disc-like manner through 281° in 11 minutes i.e. 26°/min or one revolution in 14 minutes. [Fletcher et al ( )].

Fig. 4.21. Close up view of the leading edge of the cascading air column (top right) of Fig. 4.14. The black areas are patches of the sea surface, in shade. The rolled and scalloped edge of this plunging cloud indicates strong shearing and turbulent motion. It is shown at height of about 18 km. When this "ventilation tube" fell to 2.2 km it caused a disturbance of the eye cloud at that level. [Fletcher et al ( )].

4.6.4 Origin of the air in the eye

There has long been uncertainty as to whether some or all of the air in the eye at low levels has come down from the stratosphere. Aircraft observations in the late forties and early fifties showed that the core air was too moist to be of entirely stratospheric origin and Simpson (1952) and Jordan (1952) both pointed out that some lateral mixing of moisture must take place. Malkus (1958) was able to show that the air in the core comes from three places namely, the stratosphere, the tops of cumulo-nimbus clouds in the eye wall and from the eye wall at middle levels. She calculated that approximately 97% of the air in the eye at 700 mb originated from surrounding clouds so that only 3% descended from the stratosphere. Ingenious observations, described in the next paragraph, have confirmed this figure as being of the right magnitude. At 850 mb approximately 25% of the air has come from 400 mb and above and will have originated in cumulo-nimbus anvils which, on growing into the very dry warm core, are rapidly cooled by evaporation and then, being denser than their initial environment, plunge downwards. Kessler 1958 ( ) has shown that on one occasion in-growing cumulo-nimbus anvils produced rain which fell into a hurricane eye. On such occasions the rain could be expected to evaporate rapidly, cooling the ambient air and producing a downdraft current of initially relatively cool air. It is only intitially that the air is colder and falls, it quickly undergoes subsident heating and must then be pumped down against buoyancy.

Ostlund (1967 and 1968) made some very interesting observations of the concentration of tritium in hurricane Hilda 1964 and Betsy 1965. Tritium is an isotope of hydrogen and virtually all of it in the world was produced by the testing of nuclear fusion bombs in 1961/1962. These explosions placed some tritium in the stratosphere from where it has been slowly returning to the troposphere as tritiated water - HTO - in which one atom of hydrogen has been replaced by one of tritium. The concentration of this substance in atmospheric weater vapour is therefore greater than in sea water and this permits trifium to be used as a label or tracer to indicate the origin of a sample of water vapour. Air which spirals into a typhoon picks up water vapour from the sea - low in tritium - whereas water vapour from the stratosphere or upper troposphere should

be rich in tritium. By measuring the concentration of tritium in water vapour in the eye wall and comparing it with the concentration found in the eye, Ostlund was able to show that most of the water vapour in the eye wall had come from the sea surface and of that in the eye at 800 mb, 5% had come from the stratosphere. Furthermore, in the case of Betsy 1965, he was able to show that 86% of the water vapour in the eye wall had come from the sea surface and that the proportion varied with the intensity of the storm. It will, therefore, be seen that calculations and observations currently agree that, at low levels in the eye, a few percent of the total air (plus its water vapour) has come down from the stratosphere.

4.6.5 Size of the eye

The diameter of the eye of a tropical cyclone can be taken as the diameter of the circle defined by the cessation of rain, the diameter of the ring at which the wind speed begins to decrease from the maximum or decreases to some lesser specified value or calm, or the diameter of the cylinder of relatively cloud-free air as seen from an aeroplane, or the diameter of the rain-free area as seen by radar. There is no agreed standard but, to-day, the "radar eye" and the "visual eye" as observed by an aircraft flying in the middle troposphere are the ones that are most commonly used by meteorologists.

Depperman (1937) summarised approximately two hundred cases when a calm or lull in the wind speed was reported as tropical cyclones crossed observing stations in the Philippines. These data are shown in Table 4.7 and it will be seen immediately that the duration of both the calm and the relative calm decrease as the depth of the typhoon increases. The speed of progression of mature tropical cyclones has not been found to depend on their intensity and so the data in Table 4.7 indicate that deeper typhoons tend to have smaller eyes. At an average rate of progression of 6 m/s (12 knots) the eye as defined by the lull would have average diameters ranging from about 10 km for deep typhoons with central pressure below 933 mb to about 60 km for the weaker storms.

Table 4.7. The duration of absolute and relative calms in tropical cyclones over the Philippines compared to their lowest central pressures.

Pressure mb	ABSOLUTE CALM Number of cases	Range minutes	Mean Duration minutes	RELATIVE CALM Number of cases	Range minutes	Mean Duration minutes
below 933	4	10 - 30	18	3	4 - 60	26
933 - 945	7	3 - 40	16	3	12 - 60	29
946 - 959	5	5 - 105	37	10	10 - 120	30
960 - 972	11	2 - 138	32	27	5 - 240	57
973 - 985	15	2 - 210	39	45	3 - 660	110
986 - 999	17	7 - 150	64	44	10 - 480	165
1000 and over	-	-	-	4	8 - 300	107
Total	59	Mean	41	Total 136	Mean	108

Since the introduction of aerial reconnaissance it has been possible to examine the eyes of many more tropical cyclones and to get more information from them. Most reconnaissance flights have been made at a level of 700 mb or approximately 3 km and, in most cases, the eye diameter reported by the air observers is determined from a combination of visual and radar observations at this level. However, when these observations are not conclusive, as is sometimes the case in weak, forming or dissipating storms then the diameters of the rings of strongest winds and steepest pressure gradients are used to assist in defining the eye. In a mature typhoon the difference between the radar eye and the visual eye at the usual flight level (700 mb) is quite small Jordan (1[illegible]) but there can be large differences in weaker storms when the eye wall is not well defined by rain-bearing clouds. The accuracy of the aircraft observations - which were originally made in units of nautical miles - is about one mile for diameters of less than 15 n.mile (27.8 km) but increases to about 5 n.miles (9.3 km) for greater diameters. Observers seldom report the larger diameters as being other than a multiple of five miles.

The relative frequency of occurrence of eyes of different diameter in Western Pacific tropical cyclones as determined from aerial reconnaissance flights during 1958/68 is given in Table 4.8.

Table 4.8

Eye Diameter n.miles	< 5	10	20	30	40	50	60	70	80	> 85	
Eye Diameter km	9	18	37	56	74	93	111	130	148	157	
Number of Observations	13	407	586	479	264	104	65	19	37	36	-2010
Percentage %	1	20	29	24	13	5	3	1	2	2	-100%

Average diameter 50.7 km (27.8 n.miles)
Standard Deviation 34.4 km (18.6 n. miles)

The average eye has a diameter of 50.7 km and this is true for all observations and for the sub-group of those made at the time of lowest pressure in each storm. Although approximately 73% of eyes had diameters between 10 and 60 km individual diameters ranged from 3.7 km (2 n. miles) in typhoons Olive 1965, Irma 1966 and Carla 1967 to 278 km (150 n.miles) in typhoon Sally 1961.

The case of Carmen 1960 is of interest. Air observers several times reported the eye diameter as being 185 km (100 n. miles) as determined from the wind speed maxima and pressure gradients at the 700 mb flight level. However, the diameter of the eye as seen on the radar screen at Kadena, Okinawa, Fig. 4.17, was much greater than this, being approximately 370 k m (200 n.miles). This is the largest eye on record. Sometimes cloud bands become arranged fortuitously and transitorily in a near circular form to produce false eyes, this however was not the case with Carmen for the eye was persistent and the low surface pressure of 979 mb, the 700 mb height of 2,926 m, the 700 mb temperature and dew point of 18°C and 13°C respectively, all indicate a normal weak dynamic eye. At the time of the photograph the maximum surface winds, as reported from the aircraft, were 26 m/s. Typhoon Carmen was relatively weak throughout its life but was quite large with a diameter of over 1 500 km in the later phase of its existence.

4.6.6 Factors affecting the diameter of eyes

Kuo (1959) showed theoretically that the diameter of the eye of a typhoon should decrease if the central pressure is reduced - other factors remaining constant. In practice, of course, other factors do not remain constant, the sea temperature changes, conditions in the environment and in the air feeding into the typhoon change as does the typhoon's latitude, nevertheless, the tendency for low central pressures to be associated with small eye diameters is implicit in Depperman's data and can be illustrated using the observations made from aircraft. Table 4.9 shows the percentage (and numbers) of eyes having diameters and central pressures in various ranges for observations made at the time when each of 179 typhoons attained its lowest pressure. It will be seen that deep typhoons are usually associated with small eyes but that the converse rule does not hold. It is also of interest that the mean diameter in each pressure group increases with pressure until 979 mb and then decreases slightly. The mean diameter of tropical cyclone eyes at pressures less than 920 mb for example, is 34.1 km and increases to 59.4 km for storms with central pressure between 960 and 979 mb and then falls again to 51.6 km for weaker storms. This same tendency, expressed in terms of the duration of relative calm is shown in both Depperman's data (Table 4.8) and in the large sample of over 2 000 observations made by reconnaissance aircraft at times other than that of minimum pressure.

Shimada (124) estimated the diameter of the eyes of 12 typhoons from their speed of movement and the time between the wind speed falling to 5 m/s and increasing to this value again at island stations over which the eye passed. On this basis he concluded that the eye as defined visually - the "cloud eye" - at 700 mb was approximately twice as large as the surface "wind-eye" and that the diameter of the wind maximum at 700 mb was three times as large as the surface "wind-eye". The diameter of the surface "wind-eye" would be under-estimated by Shimada's procedure unless the exact centre of the eye passed over the observing station and, of course, the diameter of the eye as defined by the maximum surface winds would be greater than that defined by winds of 5 m/s. However, his limited results indicate that, in general, the diameter of the ring where the winds are greatest at flight level may be approximately 50% greater than the cloud eye at this level and that at the surface, winds

Table 4.9

The diameter of the eyes of tropical cyclones at the time of minimum pressure - one for each storm - are given here as a frequency distribution by different ranges of M.SL. pressure. The observations are from reconnaissance flights into Western Pacific tropical cyclones which attained at least severe tropical storm intensity during the period 1958 to 1968.

Diameter	Pressure in mb										Total	
	< 920		920 - 939		940 - 959		960 - 979		≥ 980			
n. mile	%	(N)	%	(N)	%	(N)	%	(N)	%	(N)	%	(N)
0 - 20	78.1	(25)	45.7	(16)	48.4	(15)	40.0	(22)	42.3	(11)	49.7	(89)
21 - 40	18.7	(6)	51.4	(18)	45.2	(14)	36.4	(20)	46.2	(12)	39.1	(70)
41 - 60	-	-	2.9	(1)	3.2	(1)	20.0	(11)	3.8	(1)	7.8	(14)
61 - 80	3.1	(1)	-	-	3.2	(1)	1.8	(1)	7.7	(2)	2.8	(5)
> 80	-	-	-	-	-	-	1.8	(1)	-	-	0.6	(1)
Total	17.9	(32)	19.6	(35)	17.3	(31)	30.7	(55)	14.5	(26)	100	(179)

Mean Diameter					
n. mile	18.4	25.2	27.2	32.0	27.8
km	34.1	46.7	50.4	59.4	51.6

greater than 5 m/s will be found for some distance inside the reported eye.

The eye wall of a typhoon as seen by radars which scan in the vertical plane (Fig.) is nearly always vertical over at least the lowest 3 km and the radar eye at 700 mb and near the surface is therefore of approximately the same size. The near vertical nature of the eye wall in typhoon 'Ida' (1958) is seen in Fig. 4.11. Furthermore, Figs. and show typhoons Elsie 1966 and Iris 1970 centred over 370 km ~~(200 n.miles)~~ away from the radar. At this distance, the normal radar horizon for this particular station is over 9 km ~~(30,000 ft)~~ therefore, the radar sees only that part of the top of the typhoon which rises above the horizon i.e. above 9 km. The measured diameter of the radar eye in these typhoons as shown, is 18 and 16 n.miles respectively whereas aircraft at the usual height of 700 mb were reporting 17 and 14 n.miles respectively. Other similar measurements in these and other typhoons show that the high-level radar eye frequently has about the same diameter as that reported at 700 mb, at least, to within the limits of accuracy of the measurements. The surface wind maximum is found under the ~~radar~~ eye-wall ~~and the diameter of the wind maximum at 700 mb will be the same as that at the surface or possibly a little larger, as found by~~ Shimada.

From aerial reconnaissance observations Shimada ( ) showed that on 70% of occasions the eyes of typhoons and severe tropical storms attained their smallest diameter during the 24 hours prior to the lowest pressure being achieved and that, on 10% of occasions, the lowest pressure and smallest eye occurred simultaneously. Similarly, I found that in 200 typhoons and severe tropical storms during the period 1958/68, the mimimum eye diameter occurred before minimum pressure on 80% of occasions, simultaneously on 10% and after the lowest pressure (and maximum winds) on 10% of occasions. However, in this sample, only 25% of the total number of observations of smallest eyes occurred in the 24 hours prior to minimum pressure, most of them having occurred earlier than this. Both of these sets of data are subject to uncertainties imposed by the irregular intervals, usually exceeding six hours, between reconnaissance flights, nevertheless, they do indicate that in about 9 out of 10 typhoons and severe tropical storms the eye attains its smallest size before or near to the time of development of the lowest pressure and maximum winds.

4.9 Characteristics of other cyclones

Since 1949 a bewildering number of new types of cyclone have been discovered, described and named with a certain lack of consistency. Readers will come across such terms as Kona storm, subtropical cyclone, cut-off low, cold low, hybrid cyclone, neutercane, monsoon depression, polar low, heat low, frontal cyclone and extratropical cyclone. Spiegler (1972) has criticised the current practice of naming cyclones according to the location of their formation or most frequent occurrence because, for example, tropical cyclones sometimes form and move outside the tropics, extratropical cyclones have been observed to develop in the tropics in the winter season and subtropical cyclones have developed in both tropical and mid-latitude regions. He proposed that cyclones be classified according to their characteristics and energetics (Table 4.) and be named accordingly. As Spiegler states there are three main categories: baroclinic*, barotropic* and hybrid or intermediate cyclones. His categorisation is helpful but incomplete and his proposed terminology has merit but I will not use it exclusively as some terms are in general, widespread usage and will be better understood by most readers.

Fig. 4.1 is a schematic diagram showing the circulation component of various cyclones and anticylones according to weather, divergence and vertical motion. A similar diagram could be drawn to show how the different kinds of cyclone present a whole spectrum of tropospheric temperature anomalies in their central region ranging from the warm core of the tropical cyclones, to the warm layer over cold layers in the monsoon depression (Fig. 4.8) or the deep cold core found in both subtropical and frontal cyclones.

We will briefly discuss frontal or extratropical cyclones, hybrid cyclones, Indian monsoon depressions, subtropical cyclones and heat lows. For a more complete description of the last three the reader is referred to Ramage (1971).

* See glossary page.

TABLE 4—Cyclone categories, characteristics, and energetics. (From Spreglav 1[illegible])

Cyclone type	Three-Dimensional Characteristics					Configuration of vortex (symmetry with regard to clouds and wind speed)	Slope with height	Primary energetics
	Air mass(es)	Horizontal temperature distribution and advection	Vertical wind shear	Location of maximum winds, from center	Areas of convection			
I BAROCLINIC (frontal)								
A. Wave on polar front	Polar/tropical	Strong temperature gradients & temperature advection in low and/or midtroposphere	Generally increasing winds with elevation to midtroposphere	Widely variable	A. Line in advance of polar front	Asymmetrical noncircular	Slope towards colder air with height	Potential energy (PE) related to temperature gradients. PE converted to kinetic energy
B. Wave on Arctic front	Arctic/polar				B. Ordinarily no significant convection			
II BAROTROPIC								
A. *Warm-core* (tropical)	Tropical	Warm core temperature decrease radially out from center. Little or no advection.	Generally decreasing cyclonic circulation & wind speed with elevation	Near center	Frequently strong organized areas of convection, sometimes in spiral bands comprising area $\geq \frac{1}{2}$ of cyclonic circulation	Nearly circular, symmetrical at mature stage	Nearly vertical	Latent heat of condensation
B. *Cold-core*								
1. Subtropical or tropical	Tropical or tropical and/or modified polar	Nearly homogenous at surface. Temperature *increase* radially outward aloft	Cyclonic circulation *increases* with height	200–500 miles from center if it extends down to surface	Generally some area of organized convection scattered within $\frac{1}{4}$ to $\sim\frac{1}{2}$ of cyclonic circulation	Nearly circular, generally asymmetrical	Nearly vertical	Dynamic instability-latent heat of condensation
2. Polar	Polar and/or arctic	Nearly homogenous at surface. Temperature increase radially outward aloft	Cyclonic circulation increases with height	200–500 miles from center	Little or none	Nearly circular, generally asymmetrical	Nearly vertical	Potential energy converted to kinetic energy in case of occluded, mature polar (or arctic) front cyclone
III INTERMEDIATE (semitropical)	Greatly modified maritime polar and tropical	Weak temperature gradient on poleward edge of cyclonic circulation. Little or no temperature advection. Nearly homogenous within 100–200 mi of center at low levels.	Generally, cyclonic circulation decreases with elevation	Near center	Significant areas of organized convection over an area $= \frac{1}{2}$ of the cyclonic circulation	Asymmetrical, nearly circular	Either slight slope towards cooler temperatures or nearly vertical	Latent heat of condensation and potential energy related to weak temperature gradients

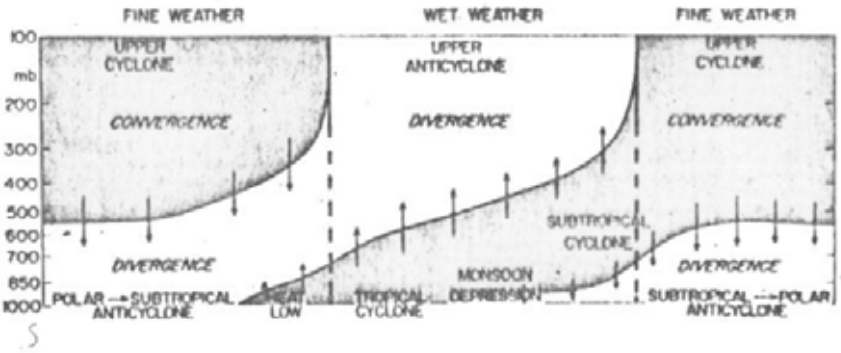


Fig. 4.1 Some weather systems arranged schematically according to weather, divergence and vertical motion. Levels of non-divergence are denoted by heavy lines. (From Ramage 1971).

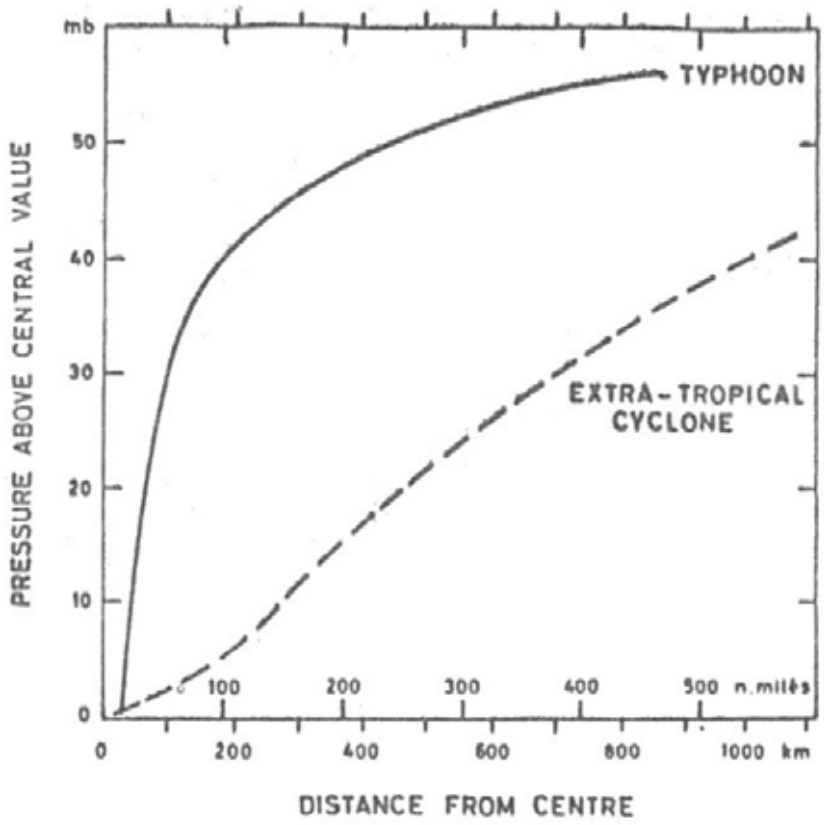


Fig. 4.2 Mean pressure profiles from 14 extratropical depressions and 25 typhoons all having minimum central pressures of approximately 950 mb. The pressures in the individual typhoons and extra-tropical cyclones varied from 937 to 963 mb and 944 to 968 mb respectively.

4.9.1 Frontal or extratropical cyclones

These cyclones form on fronts separating two distinct air masses from which they derive their energy as described in section 3.9.1. Tropical cyclones produce and maintain their own available potential energy whereas frontal depressions derive most of their kinetic energy from the pre-existing potential energy of the baroclinic atmosphere. They can therefore form as readily over land as over sea. On average they tend to be larger than typhoons (Fig. 4.2 and 4.3)and to have higher central pressures. However, their central pressure can fall lower than that in many typhoons. Readings as low as 925.9 mb were recorded in frontal cyclones in Scotland in January 1884 and on H.M.S. "Tarisa" over the North Atlantic in February 1870 (Anon 1933) but these readings do not approach those of many mature typhoons such as are listed in Table 4.3. An essential difference in structure is not in the magnitudes of the central minimum pressure but in the magnitude of the associated pressure gradients. Fig. 4.2 shows the mean pressure profile for 14 mature frontal cyclones and 25 typhoons all of which had central pressures of approximately 950 mb. The rapid change of pressure with distance from the typhoon eye wall is immediately apparent and is in marked contrast to the flatter profile of the extratropical cyclones. The very large gradients in the eye wall of a typhoon accounts, of course, for the extreme winds found there; Fig. 4.3 compares these winds with those found in frontal cyclones of similar depth. The peak in typhoon winds shown in Fig.4.3 is considerably weakened by the averaging process because the radius of maximum winds is found at differnt distances from the centre in different typhoons nevertheless, the magnitude of the peak is sufficient to illustrate the point.

Extratropical depressions have a cold core which slopes with height towards the colder air mass. When the cyclone reaches full maturity and is fully occluded the core will be more nearly vertical - the system will become near barotropic - and wind shear in the vertical will be small. When these conditions are obtained a banded structure in the clouds is often formed and the appearance of the storm from space is similar to that of a large tropical cyclone without an eye. This is illustrated in Fig.4.4 which shows an Atlantic depression which started life as hurricane Lois in the Caribbean. At the time of the photograph the central pressure was 962 mb and the shear (or thermal wind) through the 1000-500 mb layer was unusually weak for such a well defined system. The warm and cold

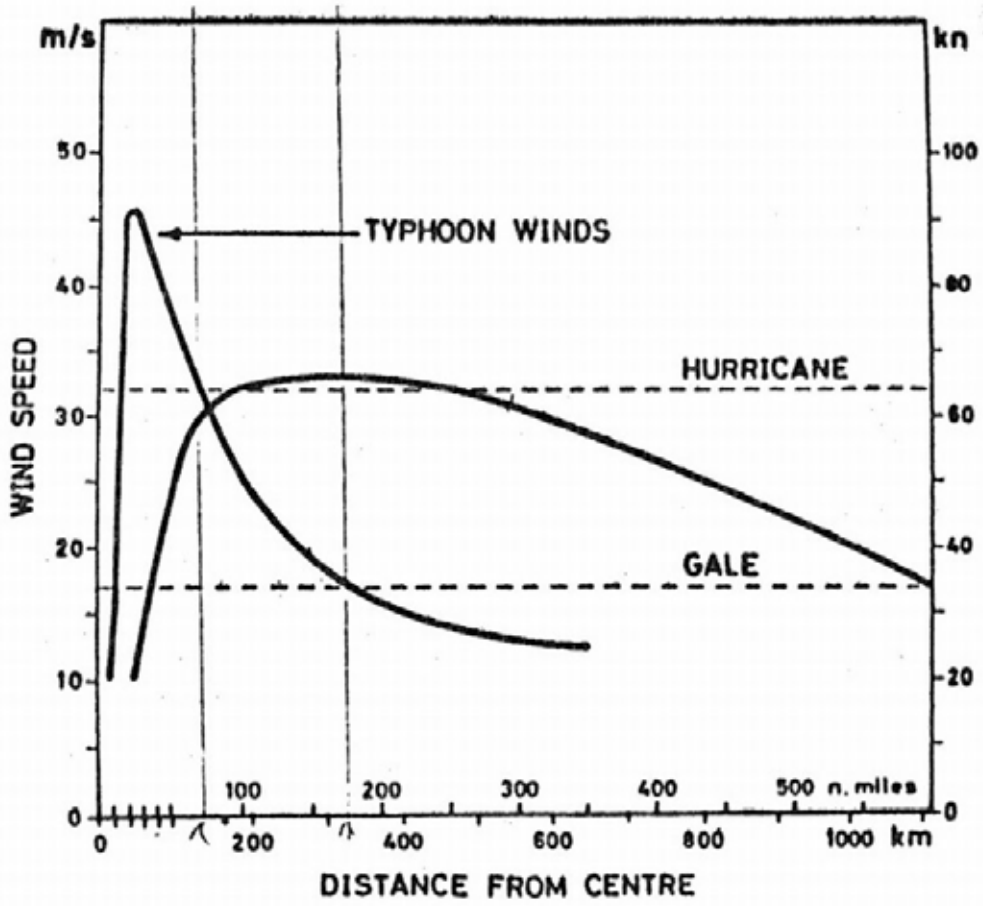


Fig. 4.3 The distribution of average wind speed from 13 intense Pacific extratropical cyclones having centra pressures close to 950 mb and from 13 mature typhoons. The typhoon winds are from Hughes (1952) and refer to a height of about 300 m.

Fig. 4.4 An ESSA II photograph of an Atlantic cyclone at 45°N 20°W at 1018 GMT on 12 November 1966 as received at the Meteorological Office Bracknell. (Crown Copyright)

front zones are well defined (cf. Fig. 3.20). Some of the deepest winter cyclones form when tropical cyclones take on frontal characteristics as they move northeastwards into higher latitudes (Section 13.10).

Some of the differences between typhoons and frontal cyclones are given in Table 4. ; Fig. 4.5 shows how typhoons are much warmer in the troposphere and have a much higher tropopause and a colder stratosphere than have frontal depressions. In the lower and middle troposphere winds increase with elevation in frontal depressions and decrease in typhoons. At one time meteorologists tried in vain to apply frontal theory to tropical cyclones and to put fronts in their circulation - typhoons have no fronts in the sense that different surface air masses are involved. One other significant difference between typhoons and frontal cyclones is that the former move at only a fraction (typically about 10%) of the speed of their maximum winds whereas frontal cyclones travel at speeds comparable to their maximum winds. It follows that if there were fronts in a typhoon they would soon disappear as they become wrapped round and round the centre so mixing the air masses. However, when typhoons reach high latitudes and are carried away at high speeds by the polar westerlies of temperate latitudes they change their nature and acquire fronts (section 13.10).

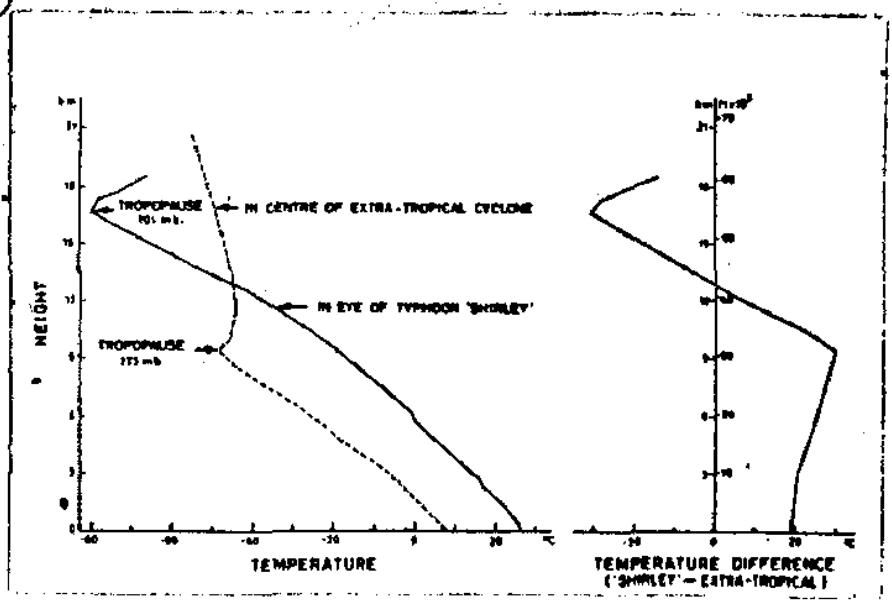


Fig. 4.5 The variation of temperature with height in the eye of typhoon Shirley 1968 (969 mb) at Hong Kong at 1015 GMT on the 21st August and in the centre of an extratropical cyclone (953 mb) at Shemya (52.6°N 174.4°E) at 1200 GMT on the 10th October 1960.

4.9.2 Hybrid or semitropical cyclones

Each year in the Atlantic and North Pacific Oceans several storms occur which are not entirely tropical in character in so far as they derive their energy both from the release of latent heat and from baroclinic processes ~~i.e. available potential energy related to horizontal temperature gradients~~ associated with the proper positioning of warm and cooler air masses. Such hybrid or semitropical storms - in Spiegler's terminology - must develop over warm sea in order to obtain their tropical characteristics and they would be expected more frequently in spring or autumn when surges of polar air are more likely to penetrate far enough southward to develop baroclinic regions over the warm oceans. Simpson and Pelissier(1971) proposed the term 'neutercane' for these storms but Spiegler (1972) is opposed to its use on etymological grounds and since it has not gained general acceptance we will use the terms hybrid or semitropical cyclone.

Moore & Davies (1951) were the first to point out that some pre-season hurricanes comprised a category distinct from the extratropical and the usual tropical cyclones. More recent case studies of hybrid storms have been made by Dunn & Staff (1964), Simpson and Pelissier (1971) and Spiegler 1971. The latter author lists the characteristics of hybrid storms as: 1) containing significant areas of organized convection sometimes with spiral bands containing the more vigorous convection 2) a circular windfield 3) development in a greatly modified maritime polar air mass with, in some cases, mixing with maritime tropical air in the equatorward side of the circulation; temperatures in the lower troposphere are therefore somewhat lower than in the mean tropical atmosphere 4) a weak baroclinic zone is usually evident in the initial stages on the poleward side of the storm but no fronts can be identified near the cyclone centre 5) maximum winds occur near the centre 6) the circulation weakens with elevation 7)there is little or no horizontal temperature advection and 8) the temperature distribution radially outward from the cyclone centre and in the immediate vicinity of the cyclone at low and midtropospheric levels is relatively homogeneous so that there is no significant warm or cold core.

The features which most clearly differentiate semitropical cyclones from tropical storms and typhoons are the absence of a warm core and the presence of temperatures there less than those in the mean tropical atmosphere in the lower and middle troposphere.

Given the necessary environmental conditions - warm sea, little shear in the vertical and no replenishment of the cooler air mass - these hybrid storms can develop well defined eyes and warm cores to become tropical storms or typhoons. To the mariner they will usually be indistinguishable from tropical storms and it is only when conditions are totally unsuitable for transformation that the distinction serves a useful practical purpose.

4.93 Monsoon Depressions

About two monsoon depressions form over the northern part of the Bay of Bengal during each of the months from June to October inclusive. They extend horizontally over some 2000 km (Fig. 4.6) have a height of 10 km and usually move northwestwards although some depressions have been known to move westwards or northwards. Maximum surface wind speeds are found about 400 km from the centre and may reach gale force over the sea but seldom attain 15 m/s over land. These depressions bring copious and vital rainfall to India; daily totals often amount to about 100 mm at first rising to 200 mm or more as the storm moves westward at about 5^{o}/day (about 6 m/s). The region of heaviest rainfall is located slightly to the west of the surface low pressure which seldom exceeds 8 mb below normal and is typically about 992 mb or only two to three millibars less than the planetary scale monsoon trough which usually lies from northwest to southeast across India at this time of year.

Monsoon depressions frequently develop when low-pressure waves move from Burma into the northern part of the Bay of Bengal. The low-pressure wave is ~~sometimes~~ the remnant of a typhoon or tropical storm which ~~entered~~ has crossed Indo-China ~~from the South China Sea~~ or it is associated with the advection of positive vorticity ahead of a westward-moving trough or jet maximum in the upper troposheric easterlies. Of four or five such low-pressure waves which enter the Bay of Bengal in an average monsoon month, two or three intensify into monsoon depressions (Koteswaram and Baskara Rao 1963). Ramage (1971) finds that of 13 tropical cyclones which crossed the Indo-China coast during the period 1929-1937 only 7 redeveloped into monsoon depressions whereas 37 of the latter formed during the same period.

The energetics of monsoon depressions are not yet well understood. In their initial stages the depressions are similar to the tropical depressions that form over the Pacific and it is believed that they owe their origin to similar CISK air-sea interaction processes but, some form of dynamical instability may also be involved (Krishamurti et al 1975). As in the Pacific depressions the clouds are intitially primarily convective but, as the depression moves off the sea, increasing amounts of stratiform cloud form.

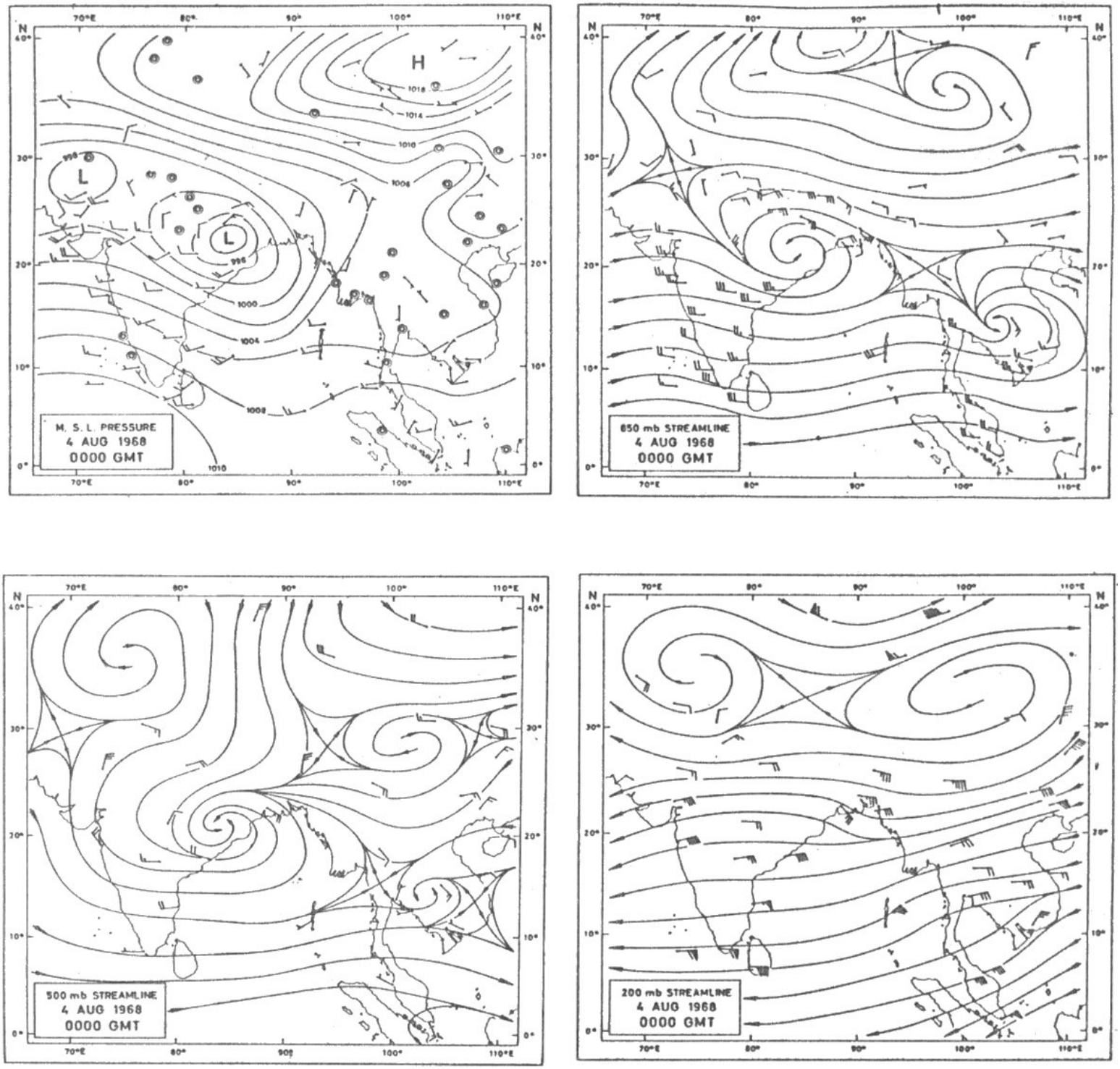
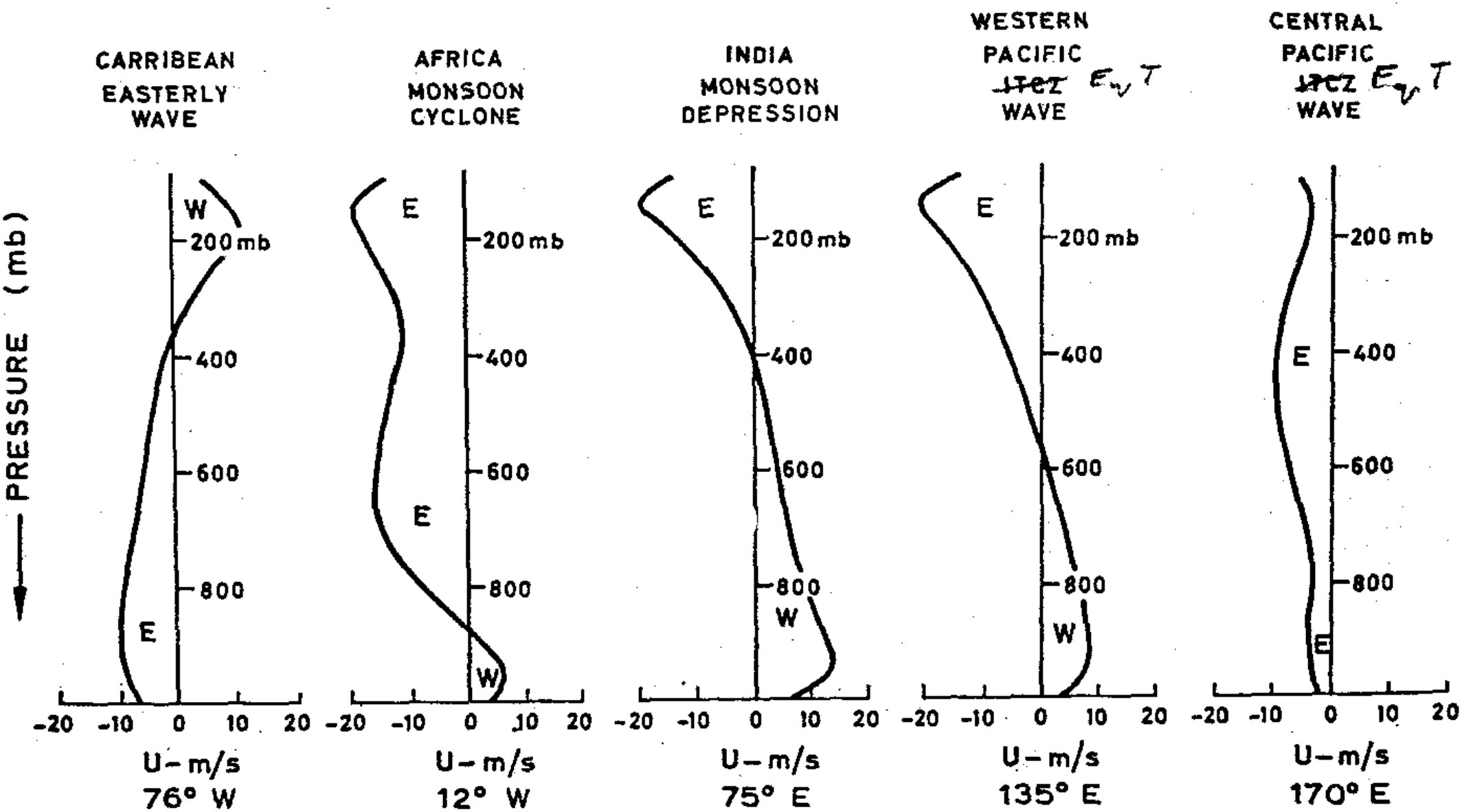


Fig. 4.6 The flow at four levels around and over a typical monsoon depression.

ENVIRONMENTAL ZONAL WIND (U) AS A FUNCTION OF HEIGHT



The question arises as to why monsoon depressions do not deepen into warm-core tropical cyclones as do the Pacific depressions? One important reason is that the monsoon depressions move close to land very soon after formation and thereby loose their primary source of sensible heat and moisture. Secondly, the wind shear over the Bay of Bengal, at this time of year, is strong ($\approx$ 15 m/s between 850 and 200 mb - Fig. 4.7) with low level southwesterlies and strong easterlies at higher levels (Fig. 4.6); conditions which do not favour the establishment of a deep warm core. The shear is much less ($\sim$ 7 m/s) over the Bay of Bengal in November and over the Pacific in summer (Ramage 1971).

Monsoon depressions have a narrow (approx. 1000 km) vertical tube of cyclonic vorticity with a closed circulation extending up to 9 km. The core of the depression is cold in the low levels and warm above 500 mb (Fig. 4.8). The air to the west of the low level cold core is also warm and has its origins over the deserts of northwest India. Above the depression, at 200 mb, strong easterly winds prevail (Fig. 4.6) and these have often been held as the cause of the westward movement of the storms. However, Krishnamurti et al (1975) suggest that simple zonal flow steering concepts cannot account for the motion. They consider that the steering is a baroclinic phenomenon associated with the centre of convergence to the west of the depression centre.

Occasionally, similar depressions form over the South China Sea in the monsoon trough and move into Indo-China.

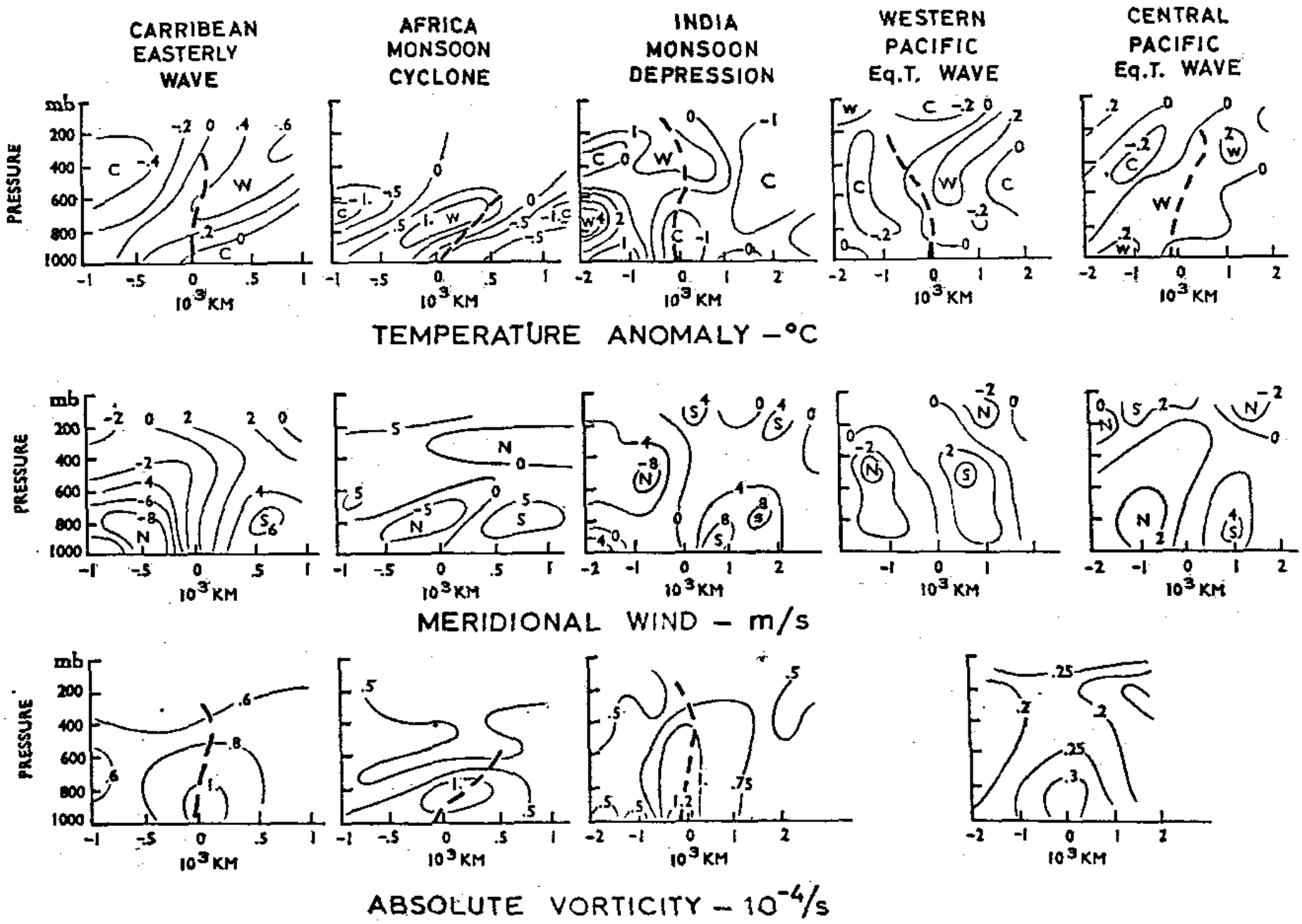


Fig. 4.8 Characteristics of some tropical weather systems (After Krishnamurty et al 1975)

4.9.4 Subtropical cyclones

Sometimes large amplitude waves in the polar westerlies plunge southward and become over extended so that a "cut-off low" is left in what was the trough of the wave whilst the basic westerly current resumes its flow to the north of the cut-off low. This low - which lies in the middle troposphere - is cold relative to its environment so that its cyclonic circulation increases in intensity with height i.e. it is cold cored. Since westerly waves can penetrate as far south as the equator in winter time, cut-off lows have been observed at all latitudes. Palmén (1949), Palmer (1951) and Frank (1970) have studied examples of these tropical, high-level, cold-core storms sometimes called "distal" cyclones. If the vortex is not manifest either at the surface or at 300mbar, as happens frequently near the west coast of India, then the cyclone may be called a "mid-tropospheric cyclone". Rao and Keshavamurthy (1968) have described one of these cyclones and Carr (1977) has discussed their mechanism of their origin and their energetics.

Sometimes, the cyclonic circulation works its way downward and reaches the surface, this happens frequently in the winter over the eastern Pacific to the north of Hawaii where the surface cyclones are known as "Kona" storms and occasionally cause widespread flooding in the islands. Simpson (1952) was the first to describe these surface cyclones which he called "subtropical cyclones" and he showed that they were always preceeded aloft by a cut-off low of the Palmén (1949) type just described. Ramage (1962 and 1971) has subsequently described three cyclones in some detail and shown that the middle troposphere between 400 and 600 mb is the layer of largest pressure gradients, strongest winds and greatest convergence, all increasing from the periphery inwards. As indicated in Fig. 4.1 the convergence leads to rising motion above and subsidence below the 400-600 mb layer - with corresponding divergence.

The subtropical cyclone must be distinguished from a large amplitude trough in the polar westerlies which may also be associated with a surface low and will generally have bad weather concentrated to the east of the trough axis. Although the subtropical cyclone develops from such troughs and may eventually be absorbed by another its fields of motion, clouds, and weather are much more symmetrically disposed. The eye is usually large having a diameter of over 200 km and around it at a distance of 300 to 900 km will be found the maximum winds usually of about 15 m/s over the sea. In the upper troposphere the storm is relatively warm cored like that in a weak tropical cyclone. Subtropical cyclones can persist as very slow moving cyclones for several days.

Occasionally a surface low forms over the south China sea on the eastern edge of a mid-tropospheric cut-off low, moves westward and intensities reaching maximum strength (around gale force) beneath the upper cold-cored vortex. The system can then remain stationary for several days before drifting over Indo China or South China and weakening (Ramage 1959). Rainbird (1968) finds that approximately 25% of the annual rainfall over the Mekong catchment falls from these storms.

The main features which distinguish a subtropical cyclone from a tropical storm or typhoon are firstly the large central eye region having a diameter of 200 km or more, secondly, the large diameter (300-900 km) at which the maximum winds of about 15 m/s are found and thirdly, the mid-tropospheric cold core around which winds increase with height up to about 400 to 600 mb.

Over the sea a subtropical cyclone can change into a tropical cyclone but the process is prolonged and very rare. Because of this feature subtropical cyclones are of significance to mariners who may traverse them in relative safety with little risk of encountering hurricane force winds without adequate warning. These cyclones may be identified in warnings from different centres as subtropical cyclones, cold-cored depressions or as "Kona" storms, but they are often mistaken for tropical depressions.

4.9.5 Heat lows

Heat lows are formed where summer solar radiation warms dry ground day after day through a cloudless sky, absorption by the atmosphere of re-radiation from the ground warms the lower troposphere reducing its density and thereby leading to low pressure - a heat low - at the surface. Although these lows tend to weaken during the night as heat is lost by radiational cooling they can be persistent, though shallow, summer features. Heat lows are predominently a desert phenomenon but they also form occasionally over the Red Basin of Szechwan in the spring where they can persist for three or four days. Surface air converges towards the pressure minimum and rises. Under these circumstances cloud and rain would be expected were it not for the fact that either the humidity is too low or an inversion stops ascent or a combination both (Ramage 1971). Of course, if clouds were to form in a heat low they would then interrupt the solar radiation and so destroy the system. Heat lows are found on the axis of the heat trough and in latitudes frequented by the oceanic sub-tropical highs which maintain the same gentle mid-trospopheric subsidence that also keeps weather fine in these highs (Ramage 1971). Heat lows are of no direct relevance to the study of tropical cyclones but they will sometimes be found over southwest China in the same heat trough that, further east, gives rise to the formation of typhoons. Heat lows cannot move from their source region.

Heat lows are readily differentiated from tropical cyclones because the former are associated with fine weather and are located over land.

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