CHAPTER 15 OTHER RELATED PHENOMENA

15.1 The Tropical-cyclone Tornado

Tornadoes occur relatively frequently in the southern U.S.A on inner and outer rainbands in the northeast sector of hurricanes. Within this sector tornadoes are usually confined to the area experiencing winds of gale force or less. The average hurricane which spawns tornadoes yields about 10 but, when hurricane Beulah entered Texas in September 1967, at least 115 tornadoes were formed only two of which were located within the ring of hurricane force winds (Orton 1970).

Tropical-cyclone tornadoes are much less frequent in other parts of the world and they have been reported only from areas where they also occur independently of tropical cyclones (sect. 3.13)

In Japan tornadoes and waterspouts are known collectively as "tatsumaki" (tatsu, dragon and maki, whirl) and Shimada (1967) found that each year approximately ten of them are reported mostly in the period from early winter to early spring, but, on average, only 3 will be associated with tropical cyclones. From the limited number of cases available for study Shimada found that tornadoes occur most frequently in the N.W. quadrant of typhoons and tropical storms before they recurve, and in the N.E. quadrant after recurvature, and that they mostly occur on the outer rainbands between the isobars of 990 and 1010 mb.

Fujita et al (1972) studied some 68 Japanese tornadoes which were associated with tropical cyclones during the 22 years 1950 - 1971. They find that they occurred mostly on the plains bordering the Pacific Ocean and particularly on the Kanto plain to the northeast of Tokyo where the more intense tornadoes were most frequent. Although tornadoes occur throughout the typhoon season in Japan - July to October inclusive - they are most frequent in August. Figure 15.1 (1) shows the locations of tornadoes in tropical cyclones in the U.S.A. and

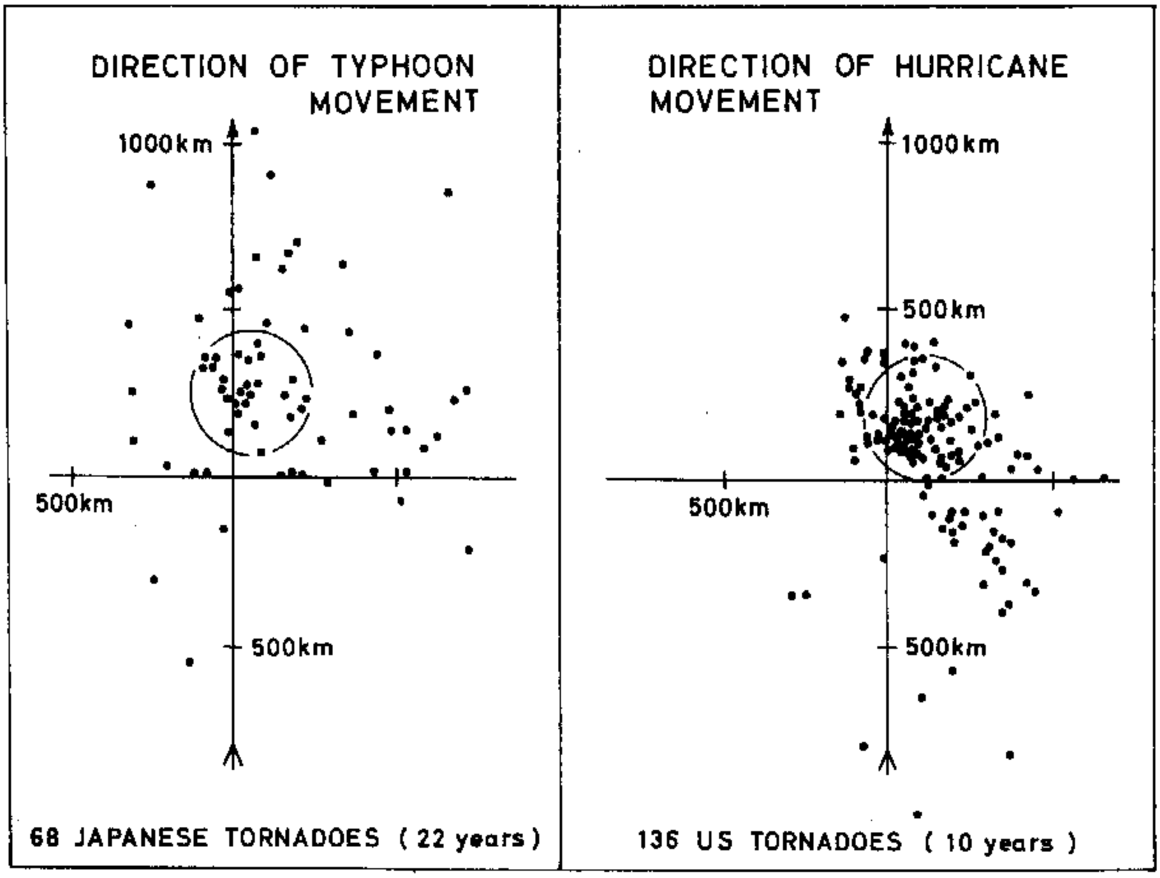


Fig. 15.1(1). The location of tornadoes in Japan and the U.S.A. shown relative to the centre of their parent tropical cyclone and its movement. The circles contain 5 out of 6 tornadoes with wind speeds in the range 70-93 m/s. (Japanese tornadoes from Fujita et al 1972 and U.S. tornadoes from Hill et al 1966).

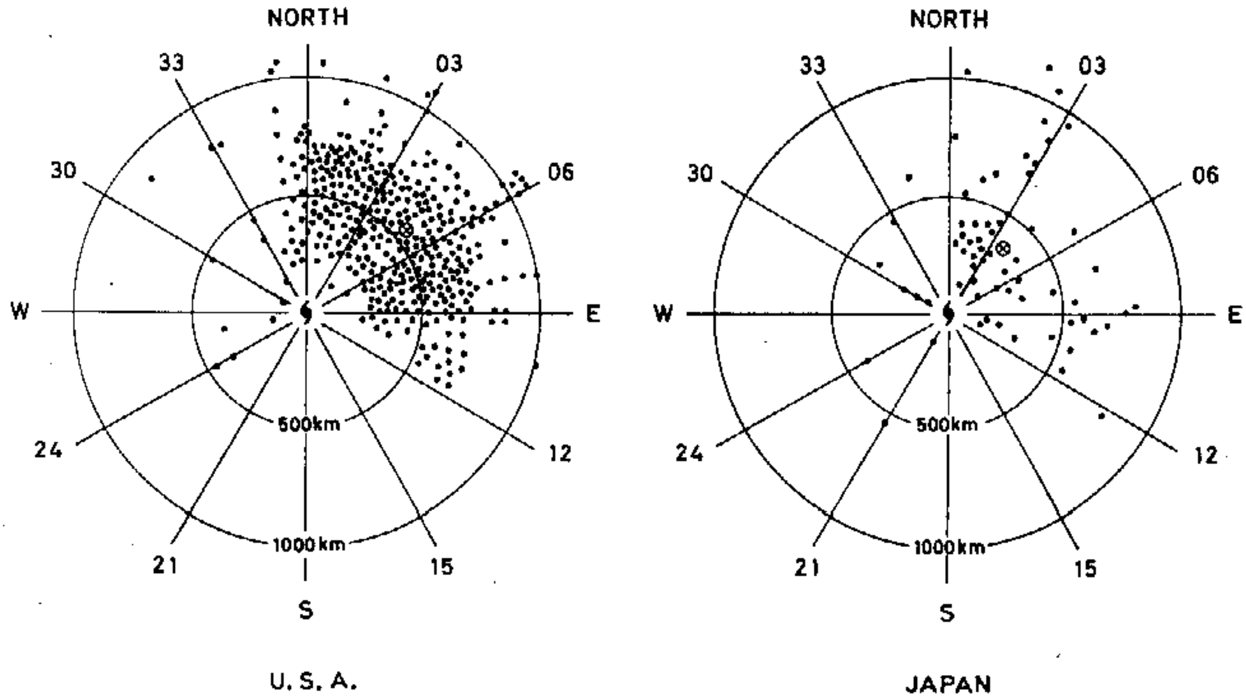


Fig. 15.1(2). The location of 373 U.S. hurricane tornadoes (1948-1972) and 68 Japanese typhoon tornadoes (1950-1971) with respect to the hurricane centre (§) and true north. The symbol ⊗ refers to the centroid of all cases. (After Novlan and Gray 1970).

in Japan relative to direction of movement of the tropical cyclone. Intense damaging tornadoes with winds speeds in the range 70 to 92 m/s are much more frequent in the U.S.A. than in Japan. However, Japanese tornadoes originating as waterspouts over the sea can also become intense and, on average, appeared to be stronger than their counterparts off the Gulf Coast states in the U.S.A.

Tornadoes also occur in Bangladesh and Northeast India and there are a few reports of them occuring in these areas in association with tropical cyclones. In India, on the east coast near 16^{o}N, a tornado in the November 1969 cyclone caused the loss of some 300 families. In Bangladesh two tornadoes occurred at Cox's Bazar during the passage of the December 1965 cyclone.

To understand why intense tropical cyclone tornadoes are so much more frequent in the southern U.S.A. than elsewhere, we need to know why they occur in tropical cyclones at all - and our knowledge here is imcomplete. Tornadoes are known to form under cumulo-nimbus clouds and rainbands when the vorticity at low levels is cyclonic and large and when there is great convective instability. The latter is not normally found in tropical cyclones. However, there is evidence (Hill et al 1966) that the necessary convective instability may occasionally develop in hurricanes from the advection of cool, dry air at intermediate levels into the cyclone environment above the warm moist air flowing from the south in the northeast sector. Tropical cyclones form in a warm moist homogeneous maritime air mass so that tornado formation within them would be expected only in those parts of the world where the intrusion of cool, dry air at intermediate levels could be achieved - this limits their occurrence to areas where tropical cyclones encounter upper westerly winds. This latter situation is found most frequently over Japan and the southern U.S.A. and, in spring and autumn, over the northern part of the Bay of Bengal. Both in Japan and the U.S.A. tropical cyclones are most frequently under the influence of westerly winds and moving in a northeasterly direction when tornadoes occur. However, Novlan and Gray (1974) have convincingly shown that it is not instability which is the dominant factor but the strong low-level vertical wind shear which arises when a storm enters land and fills rapidly so forming a cold core in the boundary layer. Winds at a height of 1.5 km or so are then typically stronger - by 20 m/s or more - than the 5 - 10 m/s surface winds. Cumulus downdrafts at such times bring fast moving air to the surface causing high values of cyclonic shear, and frictionally forced convergence which, when coupled with the updrafts into large convective clouds, can lead to intense, concentrated, small-scale vorticity centres and high velocity winds i.e. a tornado. As low level air moves in towards the centre of such a vortex without ascent, angular momentum considerations dictate that it spins more rapidly, as does bath water as it approaches the outlet.

The mean direction of travel of tornado hurricanes is 030° while for those without tornadoes it is 300°. The mean motion of Japanese typhoons with tornadoes is also towards the northeast (020°). However, there are many storms which move in these direction which do not spawn tornadoes. Figure 15.1(2) shows the locations of tornadoes relative to the centre of hurricanes and typhoons and their mean positions, or centroids, at 050°, 278 km and 040°, 370 km respectively. The greatest frequency of tornadoes occurs when the storm centre is about 50 miles inland. Intense storms, and those which are intensifying as they cross the coast, favour the formation of tornadoes because these are the storms which will have strong low-level shear in the vertical during filling. The central pressure of hurricanes and Japanese typhoons which spawned tornadoes rose, on average, at a rate of 30 mb/12 h but the average for hurricanes which did not have tornadoes was only one-third of this rate.

Hurricane tornadoes are not as intense as the more usual inland - or Great Plains - tornadoes, this is probably because of the limited instability which can be realised in a hurricane circulation. Nevertheless, it is said that they contribute up to 10% of the overall fatalities and up to a half percent of the overall damage of the hurricanes which spawn them.

During the process of becoming frontal, U.S. hurricanes sometimes spawn tornadoes in their southwest quadrants (Hill, et al 1966). This is the sector which contains the trough in which the cold front has formed or is forming. Japanese typhoons also undergo a similar metamorphis and Fig.15.1(2) shows that a few tornadoes are observed in the southwest quadrant of the storms in both areas.

Typhoon tornadoes in China, Taiwan and the Philippines are rare, probably because the mountainous topography of these regions causes deep turbulence and so reduces low-level wind shear, also, typhoons in these areas, and those which enter the flatter terrain of north China, are not usually moving under the influence of upper westerly winds. Typhoon Doris 1975 (Fig. 13.)was moving under the influence of the upper westerlies as it recurved over the relatively flat Pearl River delta. Several tornadoes were reported near Canton in this typhoon. Tornadoes are also very rare at Hawaii but, in 1971, one was filmed as it came in off the sea and damaged a reenforced concrete building. The event was associated with a Kona-type cyclone.

It is clear that given sufficient low level cyclonic vorticity and deep instability then tornadoes could form in tropical cyclones in any part of the world. However, in mountainous areas and regions well south of the polar westerlies their occurrance will be a rare event.

15.2 Microseisms

In 1894, Father Algué drew attention to the fact that typhoon winds impinging on the Philippine mountains generated small earth tremors or microseisms. Ten years later he (Algué 1904) showed that microseisms could be used as "an indirect precursory sign of a cyclone". With the introduction of moderately sensitive seismographs in the nineteen-twenties these small regular earth tremors, of amplitude up to 10 μm, were seen to consist of a pattern of beats in which the amplitude of the microseisms regularly increased and decreased Fig. 15.2(1). The periods of the waves involved were in the range 3 to 10 seconds. In the course of the last 50 years the origin of these waves has been the source of considerable controversy. Father Gherzi (1930), at Shanghai, suggested that they were caused by fast changes in air pressure (pumping) near the typhoon centre. This explanation was not accepted because air pressure changes amount to only a small fraction of one atmosphere whereas pressure changes produced by storm waves in the ocean are of the order of magnitude of one atmosphere. Indeed, Banerji (1935) believed that the motion of gravity waves in water was large enough to reach the ocean bottom and cause microseisms. He was led to this conclusion because the strongest microseisms in the Bay of Bengal were recorded several hours before storms reached the coast. This could be explained if the microseisms were generated in deep water and transmitted along the sea bed.

After the war Båth (1949) showed that the microseisms with periods of 4 to 10 seconds recorded at Uppsala, Sweden belonged to at least two types; one caused by surf driven against the steep Norwegian coast and the other caused by cyclones in the North Atlantic. It was considered that the latter transmitted a small fraction of their energy into the water and then to the ocean bottom. A difficulty with this and Banerji's hypothesis is that an ordinary train of waves in deep water cannot transfer energy to the sea bed because the pressure fluctuations below a train of progressive waves decrease exponentially with depth, becoming negligible at depths greater than a few wavelengths. However, Miche (1944) was able to show that in standing waves there are second order pressure variations of twice the wave frequency which do not disappear at great depths; they are caused by the changing vertical momentum of the water and so produce fluctuations in pressure on the sea bed. Longuet-Higgins (1950) next attributed the cause of microseisms

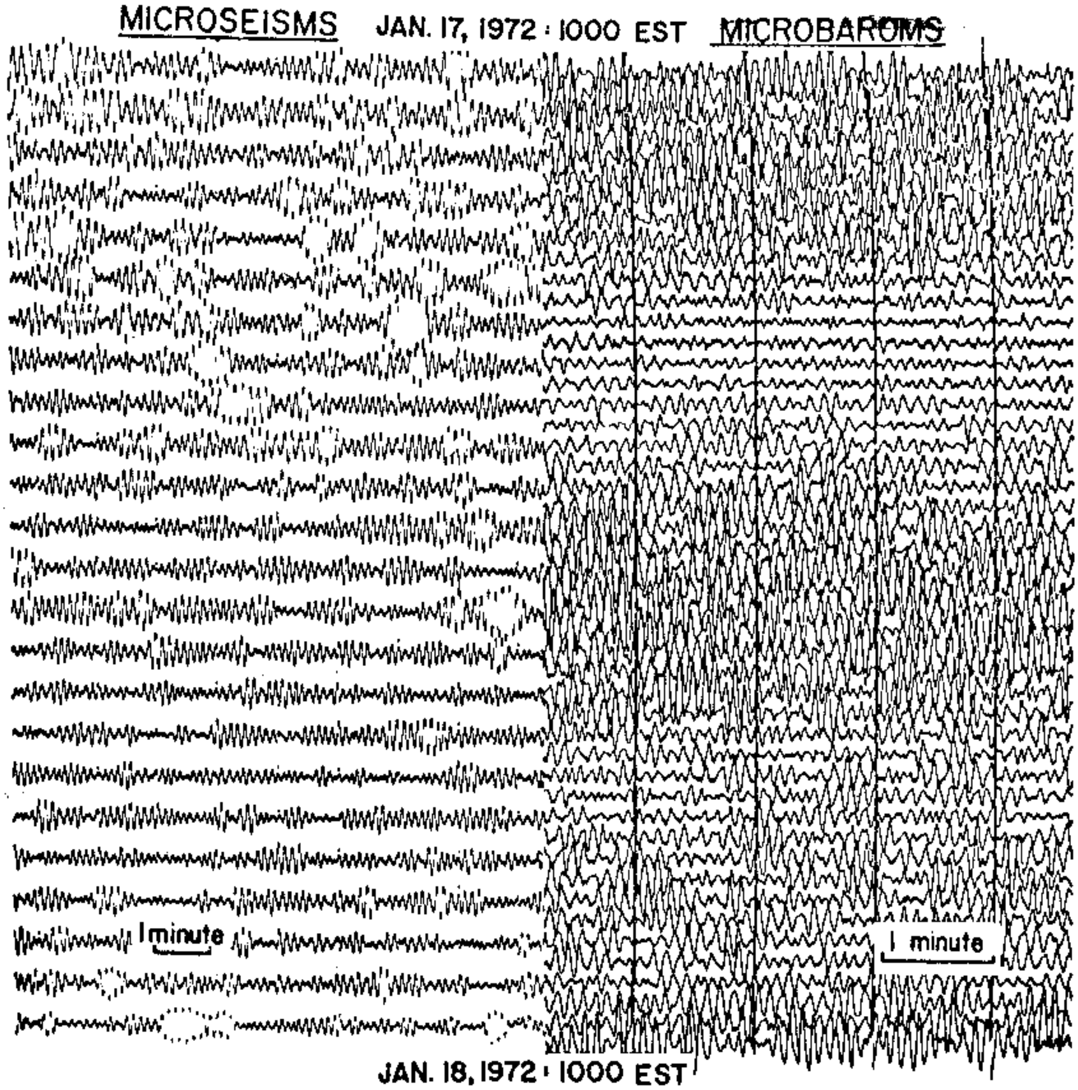


Fig. 15.2(1) Records of microseisms and microbaroms. The microbaroms show semidiurnal amplitude variations. The time scale of the seismogram is one half that of the microbarogram. (From Donn and Naini 1972.)

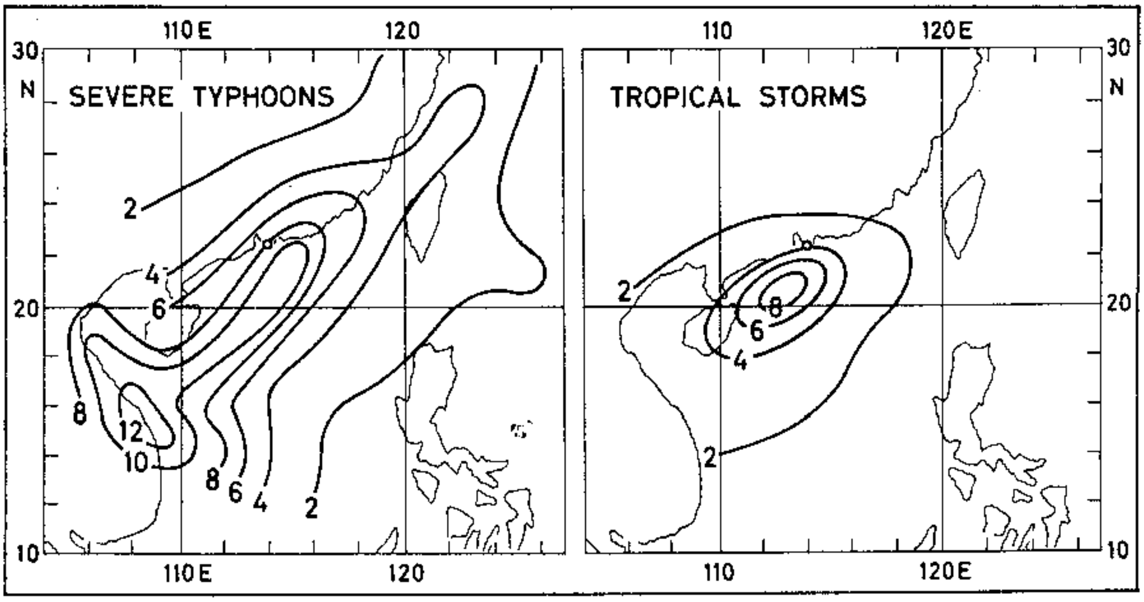


Fig. 15.2(2) The double amplitude in mm of E-W microseisms as recorded on the Hong Kong seismographs and caused by typhoons (left) and tropical storms (right) centred in different locations over the South China Sea. (Adapted from Heywood 1954.)

to these sea bottom pressure fluctuations below standing waves and considered that the latter owed their origin to the interference of two wave trains of the same period and travelling in opposite directions. The distinguishing feature of this mechanisms is that the period of the microseisms will be half the period of the parent waves.

Waves formed on either side of a tropical cyclone propagate in opposite directions and could be expected to interfere somewhere near the storm centre and generate microseisms there in accordance with the Longuet-Higgins theory. This concept immediately raised the possibility of locating tropical cyclones by observing their associated microseisms and experiments were begun with this end in view. The primary requirement was to determine the direction of arrival of the microseisms and so get a bearing on their source. Two or more such bearings should then locate the source and the causative tropical cyclone. Bearings on the direction of propagation of an identifiable wave front can be obtained by noting its time of arrival at three stations situated at the corners of a triangle. Such stations, known as tripartite stations, were established by the U.S. Navy in areas of the Atlantic and North Pacific prone to tropical cyclones. Because microseisms have wavelengths of about 25 km and travel at the high speed of 4 500 m/s it was necessary to space the three stations a few kilometres from each other so that the time differences could be accurately measured. The results of these experiments were described by Gilmore (1946) and Gilmore and Hubert (1948). Unfortunately, the method was found to suffer from many difficulties. Firstly, due to the structure of the sea bed some rays were refracted or curved secondly, the microseisms seemed not to traverse certain areas containing deep faults or having some special geological structure and thirdly it became clear that microseisms were being formed along the shore as well as out at sea.

Heywood (1954) found that even if some microseisms were generated under the centre of typhoons it was obvious that there must also be other mechanisms. Moreover, as shown in Fig. 15.2(2), typhoon and tropical storms continue to produce microseisms after their central regions have moved inland.
He noted also that kona storms (sect.) generated small microseisms although they do not possess the central high winds of tropical cyclones. It was not possible to produce systematic diagrams, such as Fig. 15.2(2) for these storms.

In the early nineteen sixties evidence began to accumulate that some microseisms were caused by a mechanism which produced a one-to-one relationship between the periods of microseisms and the waves which generated them. For microseisms to be generated by sea waves we now know that two conditions must be met. Firstly, the wave pressure must be perceptible at the sea bottom and secondly it must take the form of a progressive wave along the sea bed with a phase speed equal to that of the natural seismic (Rayleigh) waves so that resonance can take place. Hasselman (1963) showed that the primary microseisms, i.e. those having the same frequency as the waves, could be explained by the direct coupling of wave energy into the sea bed during shoaling action in shallow water. As a wave train moves into the shoaling zone its amplitude increases until breaking occurs and then decreases towards the shore. Such modulation of wave trains results in wave energy in the shoaling zone being spread over a number of frequencies some of which will interfere to produce fast moving pressure waves which will propagate and resonate with Rayleigh waves. In the case of secondary microseisms i.e. those having double the frequency of the generating gravity waves, Hasselman showed that when the frequencies of two wave trains moving in different directions are not quite equal a fast moving pressure wave travels along the sea bed and, if the frequency difference is just right, the speed will equal that of the ground wave and resonance will occur. This will happen whether or not the gravity wave amplitudes are equal and it can occur in deep or shallow water.

Darbyshire and Okeke (1969) further investigated these mechanisms for the generation of primary and secondary microseisms and determined the ratio of wave to microseism intensity which could be expected. They found that the ratio for primary waves should increase with the fifth power of the wave period, the steepness of the coast and inversely with the width of the breaker zone. The microseisms would therefore be expected to have a long period - usually observed to be 10 seconds or more - and to be favoured by a steep coast and short breaker zone.

Donn and Posmentier (1967) described low-frequency acoustic (infrasonic i.e. below the limit of audible frequencies) waves in the atmosphere with periods of about 5 seconds and which came from storms over the sea. These waves are called "microbaroms" and have amplitudes from 1 to 5 mbar. Donn and Naini (1973) have shown that microseisms and microbaroms have nearly identical frequencies and a common direction of approach. They concluded that interfering ocean waves couple both to the sea bed and to the atmosphere so that the resulting microseisms and microbaroms are caused by the same wave trains. However, the two disturbances travel independently and at different speeds. Fig. 15.2(3)

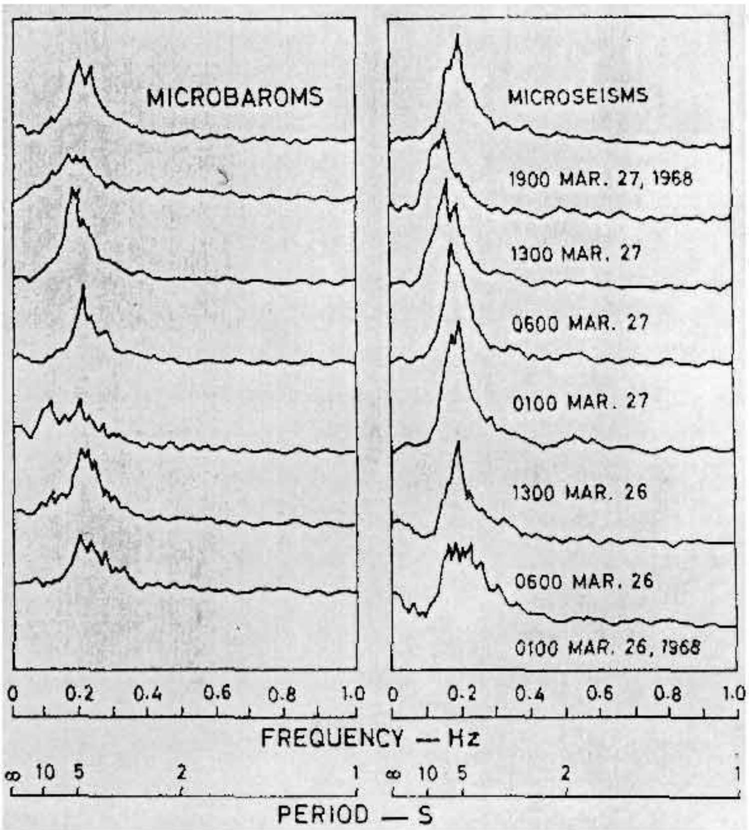


Fig. 12.2(3)Simultaneous amplitude spectra of microseisms and microbaroms. Each spectrum was taken over a continuous interval of 20 minutes. (From Donn and Naini 1973).

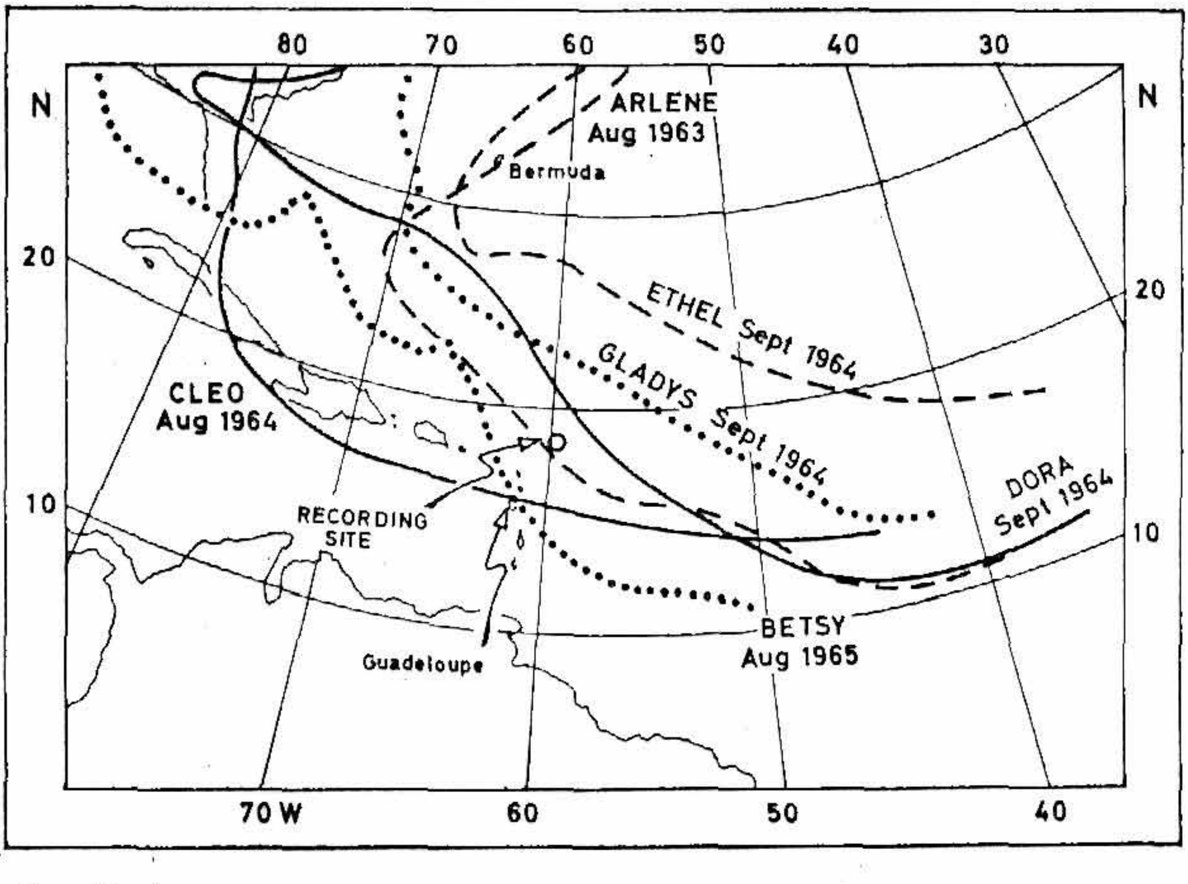


Fig. 15.2(4) . Six hurricanes which passed near the ocean bed hydrophone sited 260 km northeast of Antigua.

shows simultaneous amplitude spectra of both the atmospheric and the earth waves as recorded at Palisades, New York on a tripartite array of microphones and seismographs. The source of these particular waves was a strong extratropical cyclone northeast of Labrador and south of Greenland in which the wave heights attained 10 metres.

In an attempt to get a better understanding of the causes and propagation of microseisms, seismometers have been carried under water in free floating neutral buoyancy containers (Bradner at al 1970) and they have been mounted on the sea bed to record vibrations as tropical storms pass overhead. A hydrophone was located approximately 260 km northeast of Antigua in the British West Indies, at a depth of 5.7 km to measure the amplitude and frequency of water pressure waves having periods between 1 and 10 seconds. This has provided excellent records during the passage of the six hurricanes shown in Fig. 15.2(4). These observations and those of Latham and Nowroozi (1968) have greatly clarified our understanding of storm microseisms.

They have confirmed that microseisms are primarily Rayleigh waves and propagate in the fundamental mode, that deep sea ocean waves do indeed generate microseisms such that the period ratio of waves to microseisms, and to microbaroms, is in the ratio 2:1. Although microseisms originate from interfering storm waves, the interaction does not take place near the centre of the storm. This is yet another reason for the failure of the microseismic storm location method. Latham et al (1967) found that the maximum microseisms on the sea bed occurred many hours after the peak hurricane winds had passed the point of closest approach to the hydrophone. It is believed, therefore, that the microseisms are generated in the regional wave action following in the wake of the tropical cyclone as described by Longuet-Higgins (1952). Under this hypothesis the interval between the time of closest approach of a hurricane to the hydrophone and the time of peak activity would be the time required for storm waves to establish an effective interference pattern. This may be established directly within the wake of the storm or between waves incident on, and reflected from, the nearest island of the West Indies. Evidence to support this hypothesis is given in Fig. 15.2(5) where the amplitudes of the waves from hurricane Arlene at Antigua and Guadeloupe (Fig. 15.2 (4)) are compared with the microseisms recorded on the sea bed. A spectrum of the microseisms recorded underwater is shown in Fig. 15.2(6). From our knowledge of the two mechanisms which produce microseisms, Latham et al (1967) suggested that (1) the microseismic peak near 2.8 seconds is produced by wind wave interaction because the sea waves near Antigua varied in period between 4 and 6 seconds during Arlene (2) the microseismic peak near 5 seconds is produced by swell wave interaction because the period of the swell varied between 10 and 14 seconds but was usually near 10 seconds (see sect. 14.), and finally (3) the microseismic peak near 10 seconds is produced by direct wave action (swell) in shallow water. No microseismic component is associated with direct wind wave action because these waves on the shore are small in amplitude compared with swell. Hasselman's (1963) theory shows that the efficiency of microseismic generation by the direct shoaling action of waves increases rapidly with increasing wave period.

The short-period (2.8s) microseisms, predominant in Fig. 15. 6 were absent on records from more distant hurricanes. Also, microseisms with the longest periods were related to the most distant storms. This suggests that the shorter-period microseisms are produced by wind waves as these, from distant storms, would be very small or non-existent near Antigua; the longer period microseisms would be produced by swell the predominant period of which would increase with storm distance.

The difficulties attending the operation of tripartite microseismic stations together with the introduction of meteorological satellites have led to the general abandonment of techniques based on microseisms as operational tools for tracking tropical cyclones. However, they can still be of great use for giving an immediate indication of the probable intensity of a storm in a known position and they provide valuable information in cases when intensification of a slow moving storm takes place suddenly. This is facilitated at a given station if diagrams similar to those in Fig. 15.2 (2) for Hong Kong are available. They indicate the amplitude of the E-W microseisms to be expected at Hong Kong when the location of the centre of a severe typhoon or a tropical storm over the South China Sea is known.
The peculiar shape of the lines of equal microseismic amplitude point to some of the difficulties in the way of using tripartite stations for tracking storms. The maximum near the coast of Indo China suggests that the arrival at the South China Coast of long typhoon swells, generated by the southerlies of long fetch, are probably the dominant cause of microseisms at such times. For a tropical storm the swell will be less and the storm centre has to be quite close - but to the west - to generate microseisms which even then have only 66% of the amplitude of the typhoon microseisms. It is probable that the location of the continental shelf

and its geologic structure make some contribution to the shape of the isolines. Indeed, Heywood's figures show that an increase in amplitude can be expected when a storm reaches the continental shelf.

If microseisms can be observed continually in the weather forecast office - as is the case in Hong Kong - then use can be made of them. There are no large microseisms in the absence of heavy swell and there is no heavy swell without it having been generated by an appropriate wind. The intelligent interpretation of microseism intensities in conjunction with other meteorological data can yield much immediate and useful information. Because microseisms travel many times faster than swell they could be used in tropical cyclone areas to give early warning of the approach of swell. Such warnings would be of great value for offshore drilling rigs and other marine engineering operations.

15.3 Earthquakes and Tropical Cyclones

Reid (1838) found the residents of the West Indies pre-disposed to believe that earthquakes accompany hurricanes. Although he conceded that earthquakes may occur with hurricanes he was not convinced that they were necessarily related. Piddington (1864) mentions a number of instances when earthquakes were reported in association with tropical cyclones including the following:-

" On the night between the 11th and 12th October, 1737, there happened a furious hurricane at the mouth of the Ganges, which reached sixty leagues up the river. There was at the same time a violent earthquake which threw down a great many houses along the river-side in Colgota (i.e. Calcutta) alone, a port belonging to the English. Two hundred houses were thrown down, and the high and magnificent steeple of the English church sunk into the ground without breaking. It is computed that 20,000 ships, barks, sloops, boats, canoes, &c. have been cast away: of nine English ships then in the Ganges, eight were lost, and most of the crews drowned. Barks of sixty tons were blown two leagues up into land over the tops of high trees; of four Dutch ships in the river, three were lost with their men and cargoes; 300,000 souls are said to have perished. The wate rose forty feet higher than usual in the Ganges."

One of the great earthquakes of modern times was that in Tokyo on the 1st September 1923. This earthquake occurred at meal time during the passage of a typhoon. Lighted cooking stoves were upset by the earthquake motion and so set fire to many homes. The flames were fanned by the typhoon winds which, at 11 p.m., reached 45 knots at Tokyo. There was no rain. The changing direction of the wind, as the storm passed, caused changes in the path of the fire so trapping people who were trying to escape. The fire took 99 331 lives and 43 500 people were missing. It is estimated that half a million buildings were destroyed.

There is no doubt that in many cases the damage caused by tropical cyclone winds or storm surge has been incorrectly attributed to earthquakes. I have myself been impressed by the number of times that the seismometers at Hong Kong have recorded large tremors during the passage of tropical cyclones but, when one realises that on average significant tremors from two earthquakes are recorded there each day, then, it becomes clear that the probability of one being recorded on a tropical-cyclone day is quite high without the two events being in any way dependent. It has not been demonstrated that earthquakes are more numerous or more severe when tropical cyclones are nearby than at other times. Nevertheless, there are several reasons why the probability of an earthquake at some sensitive localities could increase when tropical cyclones are at hand. Firstly, the huge mass of water brought to the coast and possibly inland by the storm surge will cause changed loading and strains in the earth's surface layers. Flooding to a depth of 3 m adds three million tonnes to each square kilometre but this could be lessened by about 25% because of the reduced barometric pressure - a 70 mb drop decreases the air load on each square kilometre by about 0.7 million tonnes. Secondly, flooding by rain and/or storm surge usually causes water to penetrate below ground where it may "lubricate" faults permitting sliding to occur earlier than would otherwise be the case. In addition, the heavy microseismic activity which accompanies tropical cyclones could be the "last straw" to trigger a local earthquake. //The first two factors are now known to be important in increasing the local seismic activity following the impounding of water in some large reservoirs. That is to say, earthquakes with foci in the immediate vicinity of some reservoirs have a greater frequency and intensity than normal for the region. However, in other cases, including some reservoirs with large storage volumes exceeding 20 cubic kilometres, no increased activity has been observed. A small number of these earthquakes, some with magnitudes close to 6 on the Richter Scale, have been strong enough to cause not only wide-spread concern but also damage to structures, including in at least one case damage to the dam itself.

The Hsinfengkian dam in Kwantung Province, south China was completed in 1959. It covers 390 km^2 and can impound up to 11 500 x $10^6 m^3$ of water. As the water level rose in the dam so did the frequency of local earthquakes which originated predominantly at a depth of 4-5 km.

Most of the shocks had a surface wave magnitude of 2 to 3 but in March 1962 a magnitude 6 event occurred. It was at a depth of 5 km and the intensity at the epicentre was VIII. Up to 1972 over a quarter of a million local shocks of magnitude greater than 0.2 had been recorded at this site.

Present indications are that earthquakes are induced by about one reservoir in 14 among those with maximum depth greater than 100 m and water volume greater than 1 km^3. It is considered that the increase in pore pressure resulting from water penetration is a more important factor than the incremental loud stress. Nevertheless, in most cases the filling of reservoirs has not been accompanied by a significant increase in local or regional seismicity. It is believed, therefore, that special geotechnic or hydrogeological conditions are required in order that storm surges or the impounding of water should be able to trigger earthquakes of significant intensity.

15.4 Ionosphere

There is a region of the atmosphere above about 60 km which contains ions and free electrons in concentrations sufficient to reflect radio waves in the high frequency band between 1.6 and 30 MHz. Watson-Watt in his Symons Lecture to the Royal Meteorological Society in 1929 gave the name "ionosphere" to this region of the atmosphere. The concentration of electrons and ions there tends to be stratified as a result of differences in the physical properties of the atmosphere at different heights, and because various kinds of radiation are involved in the ionisation processes. The levels at which the electron density attains maximum values are known as layers. The three principal daytime layers are called E, F_1 and F_2. The heights of the E and F_1 layers are relatively constant at about 110 and 220 km respectively. The F_2 layer ranges over heights between 250 and 350 km.

In the early 1930s it was noted that the strength of radio transmissions received via the E layer varied with the occurrence of cyclones and anticyclones below the propagation path (e.g. Colwell 1932). It was then shown that the ionisation density of the E layer was directly related to the underlying surface pressure patterns (Ranzi 1932, Martyn 1934). Many other relationships between meteorological and ionospheric phenomena have been established in different parts of the world since World War II. These relationships come about through vertical motions in the ionosphere being induced by underlying large scale weather systems or from gravity waves which originate from the surface or upper troposphere. Thunderstorms (Prasad et al 1975), tornadoes (Hung et al 1979), tsunamis (Peltier & Hines 1976) and earthquakes (Weaver et al 1970) have all been observed to cause atmospheric gravity waves which affect the ionosphere. The amplitude of atmospheric gravity waves of certain frequencies increases exponentially with height because of the decreasing density. The growth factor is given by the square root of the ratio of the atmospheric density at source and at the height of interest. A displacement at the earth's surface of a few centimetres can originate an atmospheric gravity wave which will grow in amplitude to several kilometres at ionospheric levels. Growth factors of 10^4 to 10^5 are typical. The layers of constant electron density move up and down with oscillatory motions similar to the acoustic pressure wave itself. This phenomenon has been proposed as a method for detecting tsunamis (Peltier and Hines 1976). Normal ocean waves do not generate acoustic waves which grow exponentially with height because their periods are well below the Brunt-Vaisala period of the atmosphere (about 300s) and their speeds are much less than the speed of sound (330 m/s); a combination which gives rise to atmospheric waves which quickly fade with height.

From the foregoing discussions it might reasonably be expected that typhoons would also affect conditions in the ionosphere through both the atmospheric gravity waves from their strong convective towers (sect.) and the associated synoptic-scale motions in the stratosphere and ionosphere. Only gravity waves have been found. Tsutsui and Ogawa (1974) used a high frequency Doppler sounder to determine vertical motions in the ionosphere as typhoon Helen crossed Honshu (Japan) on 16-17 September 1972. They observed gravity waves at their sounding frequencies of 5 and 8 MHz. The virtual height of the reflecting layers (the virtual height is greater than the true height because the sounding transmissions are retarded in ionised regions) and the double amplitude of the Doppler frequency shifts observed are shown in Fig. 15.4(1). ←(A)

Gherzi (1946) was the first to suggest that ionospheric soundings could be used as an aid for weather forecasting and for predicting the movement of typhoons. His papers are frequently quoted and for this reason they will be considered here. Much of this work was based on misconceptions and some of his claims on this subject have not stood up to scrutiny. The 1946 article stated that low power pulses ($\lesssim$ 20W to avoid returns from

When hurricane Eloise was crossing the Caribbean on 23 September 1975 it generated gravity waves in the ionosphere which were detected by Hung and Kuo (1978). The peak of the spectrum of wave periods was at 23 min and the horizontal phase speed of the waves was measured at 160 m/s at one time and 195 m/s some hours later. The wave periods agree with those measured from photographs of hurricane cloud tops which were taken from Skylab (Black 1977). The cause of the waves was attributed to the rise and fall of convection cloud tops as they overshot the tropopause in the eye-wall area of the hurricane. Hung and Kuo (1978) used a continuous wave-spectrum high frequency radio wave (4 to 6 MHz) Doppler sounder array at 3 sites. They used a group-ray-tracing technique to locate the sources of the waves. (A)

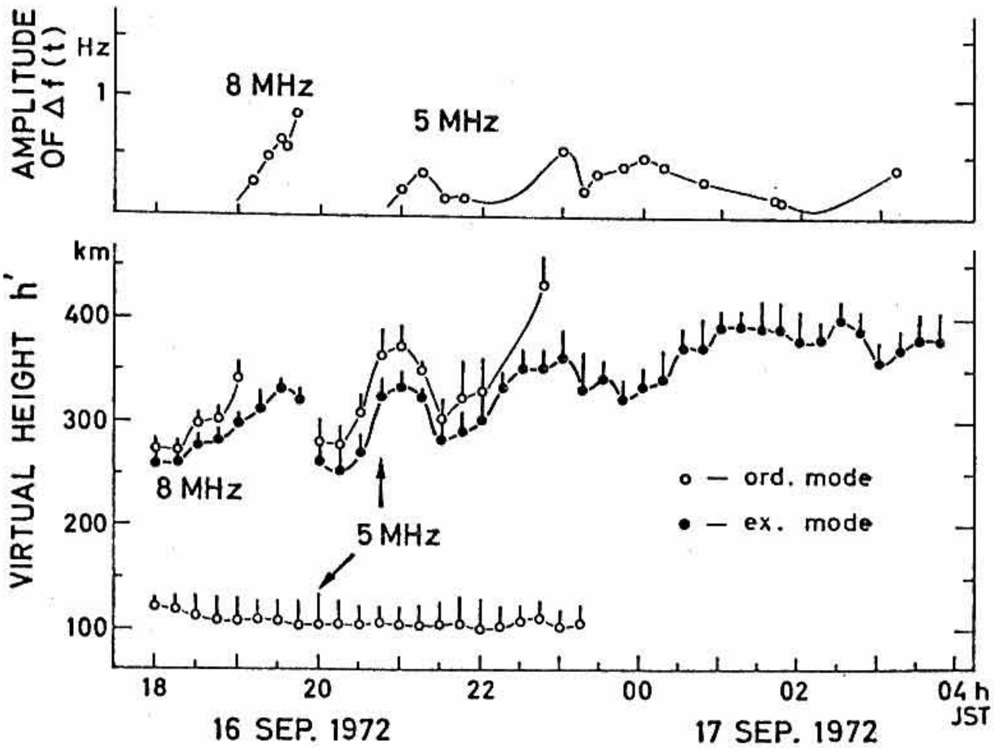


Fig. 15.4(1) The double amplitude of Doppler frequency shifts (upper) due to vertical motions of ionospheric layers and changes in height of these layers (lower) during the passage over Japan of typhoon Helen in September 1972. Soundings were made at frequencies of 5 and 8 MHz and returns of the ordinary (O) and extraordinary rays (●) are shown. (Adapted from Tsutsui and Ogawa 1973.)

weakly ionised layers) were transmitted from Shanghai at 6 MHz - a frequency which would not normally be reflected at the E layer - and were returned by the E, F_1 or F_2 layers depending on whether Pacific (tropical maritime), Siberian or Tropical (equatorial) air masses were affecting the station. I repeated the experiments at Hong Kong with Gherzi's co-operation but found no such simple correlation. The strong synchronous seasonal change in the frequency of occurrence of air masses (or of high and low pressure) and of the echoes suggests a relationship. For example, in winter echoes from the F_1 layer prevail as does high pressure and Siberian air. Whereas in June and July one expects and finds, neither F_1 echoes nor Siberian air. It is the transition months which test the theory and it is then that the one to one relationship fails. In both May and September, for example, the returns (on 6 MHz) on days with Pacific (tropical maritime) air prevailing were distributed:E 15%, F_1 30% and F_2 55%.

Gherzi (1946) also claimed that the sounding method could be used for forecasting the approach of typhoons. He mistakenly considered that typhoons were no higher than "2 to 4 or rarely 6 km" and thought that the driving (steering) Pacific air mass would cause "an abundant accumulation of rain" at the 3 km-level ahead of the storm. Sounding pulses would be reflected from this assumed layer (not ionospheric) if the typhoon was approaching. He claimed that all forecasts made by this "method" were correct! (see Bell 1974).

After his work was criticised Gherzi (1950) changed his stated method of forecasting the movement of typhoons:- "When a typhoon had been located on a weather map, at about 200 miles distance, an E-echo would show that the maritime air mass would bring the cyclone dangerouly close to us. An F echo would show that no danger was threatening the Shanghai area, since the typhoon would recurve". Gherzi (1952) repeats these claims for Macau - the Portugese enclave near Hong Kong - and gives examples of their successful application. However, most of his examples do not accord with the facts.

It is probable that there are characteristic changes in features of the ionosphere around a tropical cyclone but, apart from gravity waves, none has been adequately established. Subsidence in the eye (sect 4.   ) of a typhoon and the main outflow in the cirrus layer near the tropopause, singly or jointly, could conceivably generate compensating downward flow in the stratosphere and lower ionosphere and so affect the height and intensity of the E layer. Similarly, if ionospheric changes related to vertical motions in environmental troughs and ridges, could be reliably identified then, they might have use in predicting tropical cyclone behaviour in some cases. However such phenomena are not yet sufficiently well understood as to compete in any way with more conventional techniques for predicting tropical cyclone movement.

15.5 The Foehn Effect in Typhoons

On the 20 October 1882 a typhoon eye passed directly over Manila. Father Algué (1904) described how the temperature in the eye at ground level rose from 25°C to 31.5°C while the relative humidity fell to 43% a value rarely observed there in summer. Fig. 15. 5(1) shows an even greater rise in temperature in a Taiwan typhoon. A controversy arose over the cause of the warm air, some considering that it was caused by warming by solar radiation penetrating to ground through breaks and thin cloud in the eye, others contending that it was caused by air subsiding to ground level in the eye. The warming at Taitung (Fig. 15.5(1)) took place at 9 p.m. so that, on this occasion, it could not be attributed to solar radiation. Indeed, it is now known that the effect is quite often observed in mountainous regions, that it is not confined to the eye and that it is due to the warming of air as it sinks to the lee of mountains, a phenomenon known as the "foehn effect".

When a cyclone is located so that some part of its circulation blows across a mountain range, air flows down the lee slopes from levels above the top of the range. During descent this air is heated adiabatically and becomes hot and dry. Such winds blow off the European Alps and the mountains of the western U.S.A. where they are known as the "foehn" and "chinook" respectively. Similarly, when a typhoon is centred near the southern tip of Taiwan warm dry winds stream through mountain passes and down the west side of the Taiwan mountain range. A typhoon near the northern tip of the island causes flow down the east side of the mountain range. In both cases hot and dry Foehn-type winds result .

A good example of this effect occurred when typhoon Wendy moved to the west of the southern tip of Taiwan on 6 September 1968. At that time, several stations on the west coast reported high temperatures and low humidities. At Taichung (24.1°E; 120.7°N) a temperature of 39°C was recorded. This temperature would be attained if air, originally at 25°C, rose the 3 km from the east coast to the top of the mountain pass, at the appropriate saturated adiabatic lapse rate of 5.3°C/km, and then descended at the dry adiabatic lapse rate of 10°C/km. Although the effect is most frequent on the west coast of Taiwan it also occurs on the east coast as

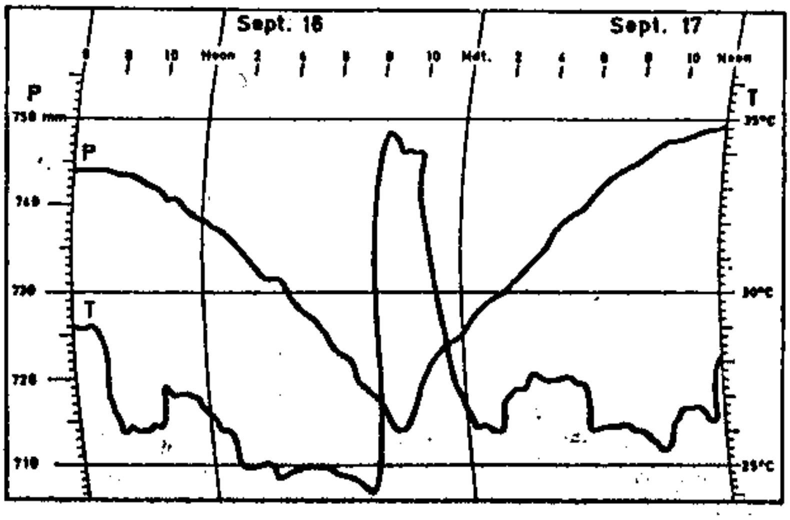


Fig. 15.5(1) Traces from a barograph (P) and thermograph (T) at Taitung (22.7°N, 121.1°E) on the southeast coast of Taiwan 16-17 September 1912 (from Chu 1918).

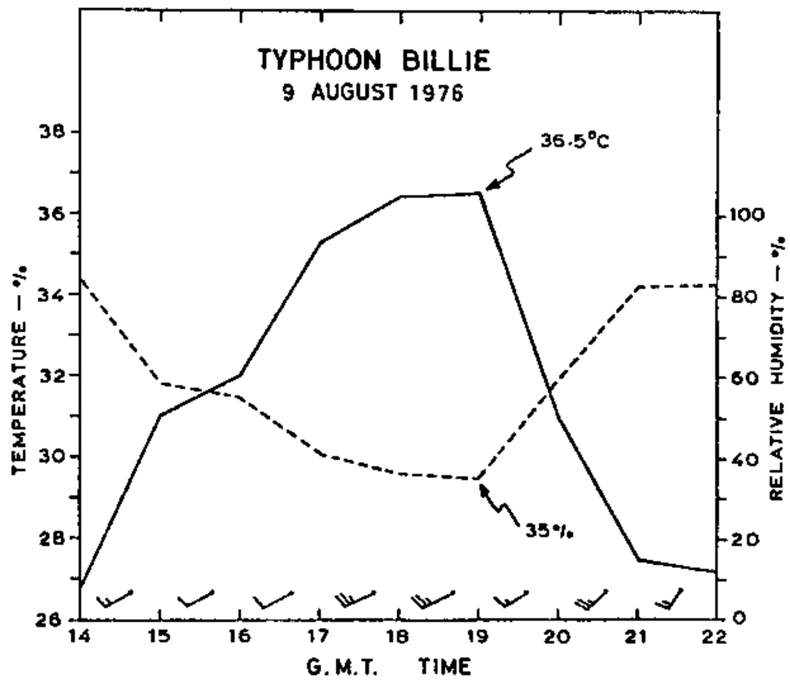


Fig. 15.5(2) Hourly readings of wind, temperature and relative humidity at Sinkong (23.1°N, 121.4°E) on the east coast of Taiwan during the passage of typhoon Billie to the north.

shown by the recordings from Taitung in Fig. 15.5 (1). A more recent case of an east coast foehn wind occurred in August 1976 as typhoon Billie moved to the west of the northern tip of the island. Fig. 15.5(2) shows that the temperature at Sinkong rose to 36.5°C and the relative humidity fell to 25%.

15.6 Electrical Effects

15.6.1 Lightning and thunder

The incidence of lightning in tropical cyclones varies greatly both from storm to storm and with time in any one storm. The most frequent sequence of events is that the embryonic disturbance from which a typhoon grows contains many thunderstorms among the big comulonimbus clouds of which it is largely comprised. When the embryonic disturbance becomes organized into a tropical cyclone and deepends the lightning discharges become very much less frequent and may sometimes cease altogether. During the weakening phase lightning returns and is a common feature of the decaying stage, especially if the storm enters land. The frequency of this association has led some tropical meteorologists and mariners to consider lightning to be an indication of weakening. Unfortunately, this sign can often be misleading because there are frequent departures from this typical cycle of electrical activity. After the initial formation of a tropical cyclone lightning may be widespread, scattered or absent at any subsequent phase of its life cycle.

Reconnaissance crews often report lightning in the eye wall of mature typhoons and hurricanes and it has been detected there many times by special sensors on board DMSP satellites and in images made in reduced light from the same satellite (Fig. 15.6.1 (1)). Sometimes lightning is nearly continuous in the eye wall. Observers on night penetrations into the eye have described such displays as being most vivid and impressive. A near continuous sequence of lightning flashes occurred in the eye of the intense and mature typhoon Irma 1971 when its minimum sea level pressure was a near record 884 mb. Reconnaissance flight crews found the nighttime illumination to be so like daylight as to permit them to observe the sea state. The eye diameter was only 9 km and it was just as small when I accompanied flight crews there next morning (I had a good and memorable lunch while circling in the eye) but by then the lightning had ceased and the central pressure had risen to 893 mb. Dunn & Miller (1960) cite the case of reconnaissance aircraft being struck by lightning three times in three days while flying near the eye wall of a hurricane in 1955. Aircraft have been struck by lightning when flying as far as 80 km from the nearest thunderstorm. Furthermore, a pilot of a U-2 aircraft flying at about 20 km over a typhoon, saw a lightning from the top of a convective turret flash upwards into the stratosphere (Vonnegut 1980). The

Fig. 15.6.1(1). Typhoon June centred about 390 km west of Guam as seen by moonlight at 1002GMT on 19 November 1975. The central minimum pressure was 875 mb and the maximum surface winds about 80 m/s. A lightning discharge can be seen as a white line across the eye of June. (DMSP imagery.)

pilot - Ronald Williams - was flying over typhoon Anita in the Gulf of Tonkin at the time and the cloud top, which had not developed an anvil was at an altitude of about 19 km. The flash was yellowish in colour and persisted longer than usual. Lightning flashes upwards from cloud tops have been seen from the ground before but, this was the first flash seen from above cloud.

On the ground it is difficult to hear any thunder at the height of a typhoon because of the noise of wind and destruction but lightning is sometimes reported as being nearly continuous and, of course, the thunder is more discernable when winds abate as when the storm weakens or the eye passes over head. In an account of his experiences in cyclone Tracy 1974 a victim wrote "Then came the very worst. Tracy was obviously having her last fling and it was beyond description. The thunder and lightning were continuous. The thunder was a distant rumble, blanketed by wind noise which was a cross between a screech and a roar" (Cole 1977). The association of thunder with the eye and outer regions of tropical cyclones; as given in many accounts may be in part attributable to the fact that the decreased wind force in these areas reduces the general noise level and permits thunder to be heard.

The precursor rainband on the forward periphery of a tropical cyclone (sect 10.   ) has the nature of a squall line and usually contains thunderstorms. The lightning in these rainbands can be seen by night from places as far as 150 km or more ahead because of the fine weather which usually precedes tropical cyclones. Lightning is particularly frequent in the outer parts of a typhoon approaching the South China coast from the east in the evening. The northerly winds in the forward outer circulation bring southward continental air which is hot at that time of day. Over the South China Sea it picks up moisture and may become unstable to great heights. Peterson (1976) found that temperatures in excess of 35°C can occur at Hong Kong when typhoons and tropical storms are centred in the Luzon Straits and northward to Taiwan.

15.6.2 The causes of lightning

The electrical activity of clouds depends upon characteristics of the condensation and precipitation processes taking place within them. These processes, and their interaction with the earth's electric field (+120 V/m in fine weather) cause a separation of charges in strong convection. The average thunderstorm has a positive charge ($\sim$+ 24 C) in its upper regions above the -30 ^{o}C isothern and a volume with negative charge ($\sim$-20 C) is centred a few kilometres lower near the -5 ^{o}C isotherm. A smaller volume with a lesser positive charge ($\sim$+4 C) is found at the melting level or just below. These are average values about which there can be a wide variation.

Lightning occurs when the separated charges cause a potential gradient which exceeds that which the atmosphere can sustain. Dielectric breakdown occurs for potential gradients of about 3 MV/m in dry air and about one third of this when water drops 2 mm or so in diameter are present. Lightning may occur within one cloud, from cloud to cloud or from cloud to ground. A lightning discharge to ground consists of a negatively charged "stepped leader" which moves towards earth in discrete steps. As it approaches ground it induces positive charge there and a "travelling spark" moves up to meet the leader. A large number of electrons then flow to ground and the lightning stroke propagates up the path of the stepped leader to the cloud. This is the lightning stroke proper and is called the "return stroke". It carries a current typically between 1 and 100 kA and completes its journey in about 100 µs. Approximately 20 GJ of heat are released in the flash which rapidly raises the temperature of the lightning path to 30 000 ^{o}C or so, causing pressure rises there of 10 to 100 times. The rapid increase in atmospheric pressure generates a supersonic shock wave. As it propagates this wave changes to the sound waves responsible for most of the sound of thunder. In addition, some sound is generated by the sudden contraction of the cloud as droplets are discharged and cease to repel one another (Colgate and McKee 1969). Apart from sound waves, electromagnetic waves of many frequencies also radiate from all lightning strokes.

There are a number of known mechanisms by which vigorous convection could lead to the separation of electric charges in clouds under certain circumstances (see Mason 1971). However, the relative importance of the various cloud-physics processes in real clouds is in dispute (Mason; Moore 1976). The relevant theories fall into two categories. The first consists of theories in which the principal mechanism for separating electric charges is the vertical separation of larger hydrometeors from smaller ones by virtue of their differing terminal velocities. Individual theories in this category differ mainly in the way the hydrometeors acquire their charge. Theories in the other category consider cloud particles to be the principal charge carriers and that they are separated by differential convective motions within the cloud. In these theories lightning can occur before precipitation is formed. Furthermore, there is dispute about the relative importance of electrification processes which involve ice. Observations of lightning from clouds everywhere above 0°C have been reported but are not accepted as totally reliable by all cloud physicists. More observations are needed to resolve this point. In 87 penetrations into comulonimbus clouds over the Malay Peninsula, Frost (1954) found no case of lightning in clouds with tops lower than 10.7 km. The transition from cumulus to cumulonimbus occurred at a height of 9 to 10 km where the temperatures are -30 °C to -35 °C. The chance of lightning was one in two or three if the tops exceeded 10.7 km.

All cumulus clouds are electrified to some degree. In the humid tropics relatively small cumulus clouds are associated with quite large electric fields. Indeed, standard lightning counters, which count sudden changes in the electrostatic field, can be triggered at Hong Kong by even fine weather cumulus. However, lightning from warm clouds has not so far been observed there. Similarly, Takahashi (1978) finds that warm clouds at Hawaii are electrified and yield high rainfall rates but that lightning is not associated with them. In particular, in the warm-cloud rains there on 20 February 1979 rainfall amounts of 78 mm in one hour were observed without the occurrence of lightning (Cram and Tatum 1979). The rawinsonde ascent showed a freezing level at 4084 m and visual observations from Mauna Loa Observatory (3398 m) confirmed that cloud tops were below 4000 m during the period of heaviest rain. Short-duration rainfall rates of 268 mm/h have been observed to fall from warm-rain in Hawaii without lightning. Takahashi (1978b) observed that rainfall rates and electrical effects in warm clouds at Ponape (7^{o}N, 158^{o}E) in Micronesia were similar to those in Hawaii although the clouds were higher.

When a tropical cumulus cloud grows through the level of the 0^{o}C isotherm, (typically near 5 km) and upwards to become a cumulonimbus cloud it will then contain both liquid and frozen hydrometeors. As they fall in a downwardly - directed electric field they may be considered as conducting spheres that become polarised with their upper halves negatively charged and their lower halves positively charged. Cloud particles colliding with, and rebounding from, the lower parts, will carry away positive charge and leave a net negative charge on the hydrometeors provided that the time of contact is as long as that necessary for conduction of the charge. In particular, ice crystals rebound from soft hail pellets (graupel) which thereby acquire a negative charge and, by gravitational separation, intensify the electric field. Although there are a number of other charge generation processes Mason (1971) considers that "the fragmentation of freezing droplets on, and the rebound of ice crystals or cloud drops from, the surfaces of soft hail pellets are possible and, so far, the most likely, major mechanisms of charge generation and separation in thunderstorms".

Takahashi (1978a) considers that the main charge in thunderstorms develops when supercooled drops collide with ice crystals to form graupel. Ice splinters carry off charge of opposite polarity. His laboratory experiments indicated that the charge separated in the formation of graupel depends on both the temperature and cloud water content as shown in Fig. 15.6.2(1). Small water content is associated with small numbers of ice cystals and little opportunity for high electrification. Graupel is highly electrified when the water content is 1-2g/m^3 with the charge being positive at temperatures warmer than -10^{o}C and negative at lower temperatures. Higher water content inhibits the electrification of graupel as indicated in the figure. Tokahashi (1978b) believes that this is the reason for the relative rarity and weakness of thunderstorms in the humid tropics. He established that the electrification was relatively weak in four Ponape thunderstorms by releasing special sondes into them and also by noting that only a few flashes occurred in each cloud. He found the charge distribution to be similar to that in mid-latitude thunderstorms.

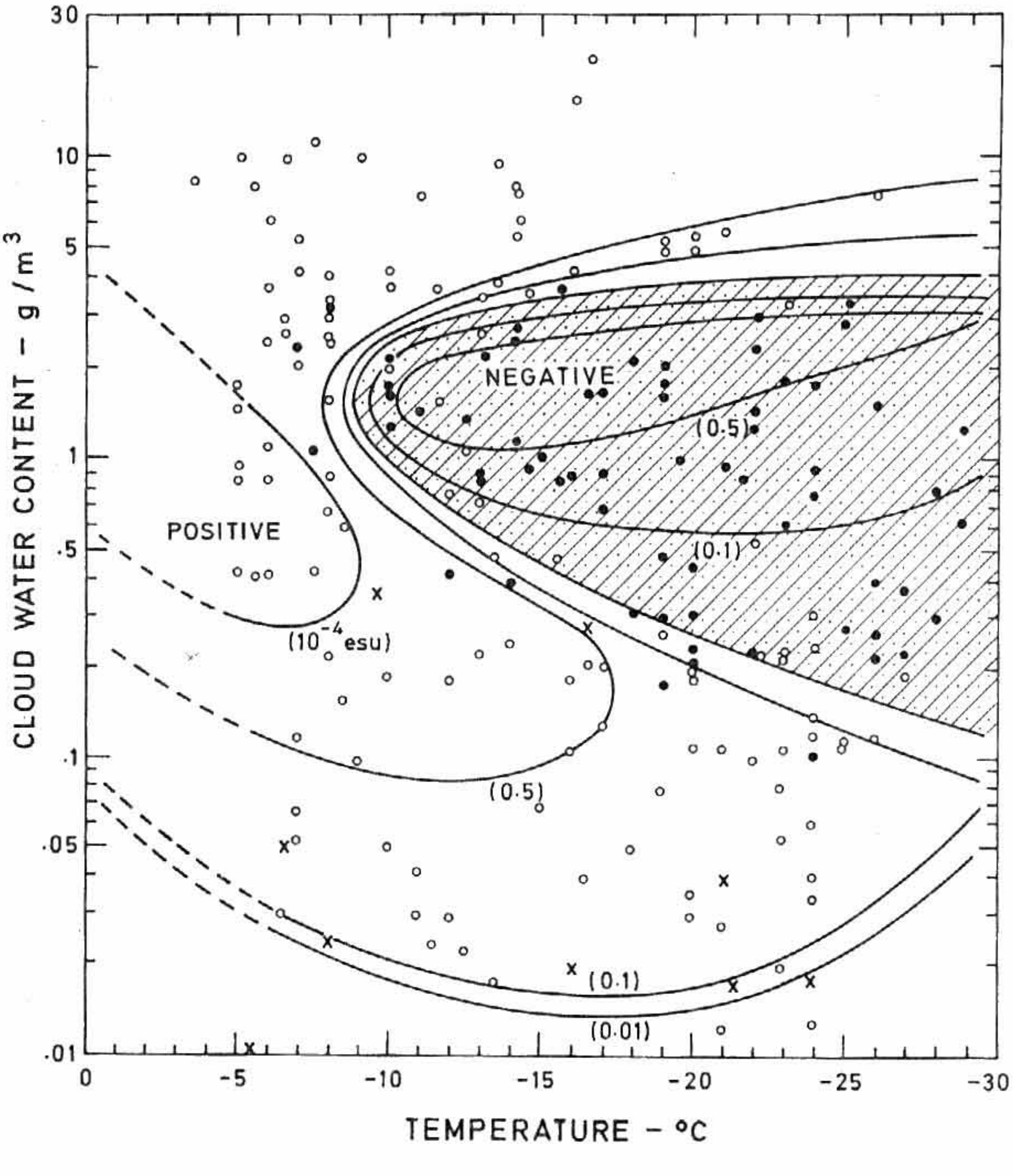


Fig. 15.6.2(1). The electrification of graupel as a function of temperature and cloud water content. The region in which the electrification on graupel is negative is shown shaded. The magnitude of the electric charge separated per ice crystal collision is shown in units of 10^{-4} esu. Open circles are cases of positive charge, solid circles negative charge and crosses represent cases of no charge. (After Takahashi 1978a.)

Although the isolated tropical comulonimbus may often be less strongly charged that a similar sized storm in higher latitudes, tropical thunderstorms may on occasion be a truly awe inspiring phenomenon. In certain tropical weather systems, for example, in the east-west surface SW monsoon trough (Bell 1969), or in the outer rain-bands of weakening tropical storms (sect 6.4.3) the lightning can be intense and near continuous. If there is heavy rain at such times there will usually be thunderstorms. The tropical cyclone, by contrast, shows a great variation in this respect but, the reasons why some generate many lightning flashes and others almost none, remain unknown. The problem constitutes a challenge for cloud physicists. It is hoped that observations from the multi-level hurricane reconnaissance flights by highly instrumented aircraft may soon obtain the data necessary for enlightenment.

15.6.3. Sferics

Gherzi (1925) was the first to point out that thunderstorms were relatively infrequent in typhoons over the sea. He had noticed that when communicating by radio with ships in tropical cyclones the number of atmospherics - the crackles and bangs heard on radio due to lightning - were much less than usual. This point was not generally realized by meteorologists until the post World War II years when it was found that "sferics" equipment could not be used to reliably locate and track tropical cyclones. Sferics is the word used by meteorologists for atmospherics and equipment and techniques used to detect them. Watson-Watt (1926) pioneered triangulation techniques to locate the source of low frequency (L.F.) radio waves emanating from lightning discharges. He arranged that these radiowaves were received on two orthogonal loop aerials so that the induced voltages were related to the bearing of the source. A third vertical aerial was necessary to resolve the 180^{o} ambiguity. The bearing was displayed on a cathode ray tube. Synchronising signals enabled observers at different stations to take readings on the same discharge and so to determine its source. The method was used operationally in Great Britain during World War II and proved invaluable for locating cold fronts over the Atlantic and the continent from where conventional observations were then not generally available.

Attempts by the U.S. Air Force to adopt the technique for locating tropical cyclones in the Pacific in the early 1950s were not successful. Similar unsuccessful results were obtained in Australia. It was found that embryonic disturbances could be located but, as Gherzi had earlier indicated, atmospherics usually became less frequent as the storms developed. Furthermore, even when sferics were received it was not possible to determine from which part of the tropical cyclone they had originated. For these reasons the method is no longer used for tropical cyclone tracking although it retains its value in temperate latitudes. In 1980 the British network was still operational but studies were under way to determine whether it could be replaced by a single station technique. In this method, the bearing of the source of the radiation is determined by the usual vertical and loop aerials and cathode ray tube but the distance to the source is obtained by analysing the received wave form.

Sferics are received at the Royal Observatory Hong Kong on a special 10-100 kHz receiver adjusted to record only signals from lightning flashes within a radius of 200 km or so - a range confirmed by using radar, satellite and conventional observations. The number of sferics counted during the passage of tropical cyclones and the timing of their occurrence is found to be widely variable. A selection of sferics recordings made near the time of closest approach of some typhoons and tropical storms is shown in Fig. 15.6.3 (1). Typhoon Iris 1976 moved westward as it passed south of Hong Kong; sferics were least frequent during the few hours around the time of closest approach. Fast-moving typhoon Hope 1979 (see track in Fig.) passed directly over the station and shows a similar pattern to Iris. Severe tropical storm Gordon 1978 passed on a parallel track to Hope some 60 km further inland. Gordon contained great electrical activity just after entering land but this decayed shortly afterwards. Severe tropical storm Agnes 1978 formed to the south of Hong Kong moved north and then west. A considerable number of sferics were counted during the formative stage but they died away as the eye became organized (Fig. 10.32b). There was no lightning as the storm passed close to Hong Kong. The records shown in Fig. 15.6.3(1) should be contrasted with the continuous and intense sferics shown in Fig. 15.7(4) and recorded during the passage of a hailstorm. This small sample of sferics recordings confirms the observation of Gherzi (1925) that lightning flashes are frequently inhibited in the inner areas of a tropical cyclone.

The waveform of atmospherics consists of an oscillating "head" with a quasi-sinusoidal "slow tail". The former comprises the very low frequency (3 - 30 kHz) components which arrive first followed by the extremely low frequency components of less than 3 kHz which contribute to the slow tail. The slow tails of positive polarity are mostly generated by the return stroke of cloud to ground lightning discharges. Slow tails with negative polarity are most frequently caused by intra-cloud flashes transfering positive charge from the top to the base of the cloud (Tepley 1961). The polarity is taken to be positive when the electric vector of the initial portion of the waveform is directed upward at the receiving aerial and vice versa. This relationship fails in about 5% and 20% of the cloud to ground and intracloud flashes respectively.

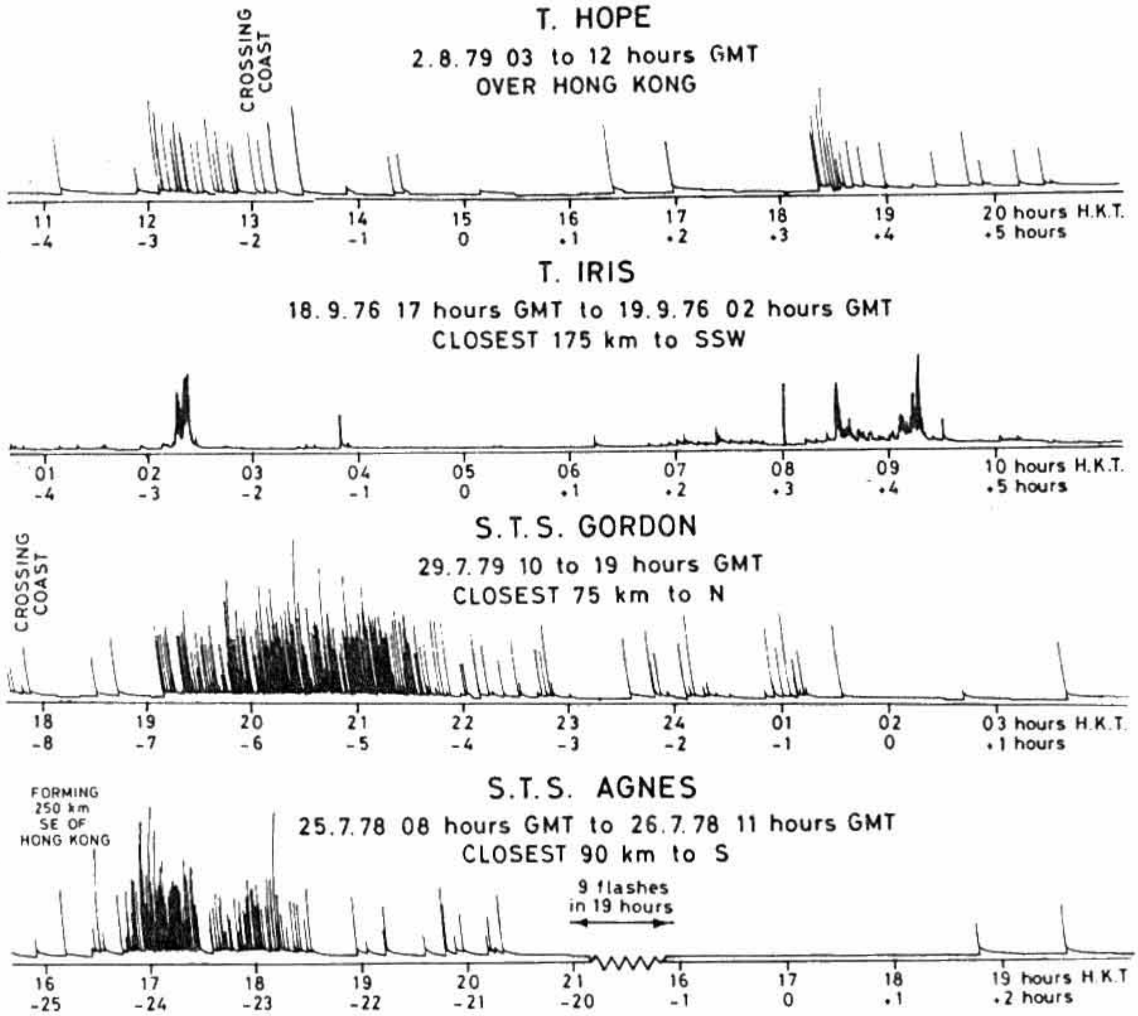


Fig. 15.6.3 (1). Counts of lightning flashes within about 200 km of the Royal Observatory Hong Kong during the close passage of two typhoons and two severe tropical storms. The amplitude scale is arbritrary.

Extremely low-frequency (ELF) atmospherics from typhoon Rita 1966 and hurricane Blanca 1966 were observed by Hughes (1967) at Hawaii between the two storms and some 5000 km from each one. The direction of the atmospherics was determined in the usual way and the distance was estimated from the waveform and known propagation conditions in the ionosphere. The waveforms indicated that most lightning strokes were intracloud these being 10 times more frequent than cloud to ground strokes. This ratio is several times greater than that usually found in frontal type thunderstorms (Tepley 1961) and may be associated with the relative height of development of the clouds in the two varieties of storm (Hughes 1967). The received slow tail waveforms are shown in Fig. 15.6.3(2). The wave shape at (d) is of a type characteristic of atmospherics which propagate westwards at night.

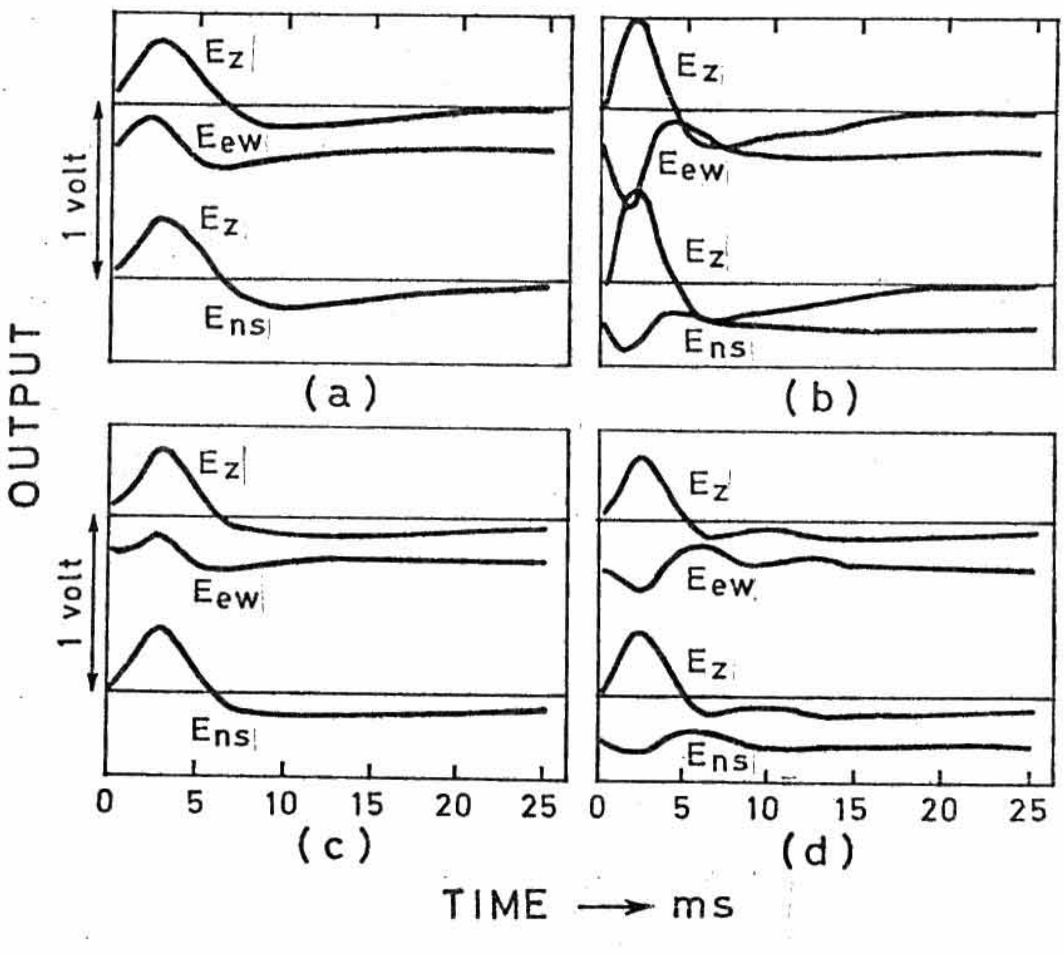


Fig. 15.6.3(2). Intracloud slow tail atmospherics received from typhoon Rita 1966 (daytime a, nighttime c) and hurricane Blanca (daytime b, nighttime d). E_z, E_{ns} and E_{ew} refer to signals from the vertical, N-S and E-W probes respectively. (Adopted from Hughes 1967).

15.6.4 Other electromagnetic radiation

In sect 3.12.1 reference was made to the pulses or bursts of rádio waves which emanate from a tornadoes' parent cumulonimbus cloud. These pulses are emitted over a wide waveband and become more frequent with increasing storm intensity. All cumulonimbus clouds which emit such bursts do not spawn tornadoes, neither do all cumulonimbus clouds - with or without tornadoes - emit this radiation. Similar pulses have been detected from tropical cyclones. Ward (1978) pointed his narrow-beam movable aerial (sect 10.) along the great circle bearing of distant typhoons and South Pacific cyclones and received pulses via the ionosphere on the listening frequency of 20 MHz. On moving the aerial azimuth away from the storms the pulses ceased. Ward noted variations of pulse (burst) rate on two time scales. Firstly, there is a quasi-cyclical build up and decay of activity over 30 to 60 minutes which he associated with a build-up and discharge of electrostatic energy. Secondly, there is a longer term - several days - variation in which activity grows and decreases with the life cycle of the tropical cyclone. For tropical cyclones in the Australian region he found that a burst rate of 30 $\pm$ 5 bursts per second could be recorded.

These bursts are quite distinct from sferics which have a much greater amplitude and occur with separate identities. The cause of the high frequency radio bursts is unknown but is believed to be due to coronal discharges within cumulonimbus clouds. Such discharges are not necessarily visible. The build up in intensity of the radiation bursts as a tropical cyclone matures may not be unconnected with the tendency for lightning to be less frequent at this stage of a storm's life cycle.

15.6.5 Electrostatic and magnetic effects

Dunn and Miller (1964) record that as a hurricane crosses a coast a myriad of minute electrostatic discharges are sometimes seen, rather like millions of tiny fireflies. They are believed to be caused by frictionally generated static electricity as millions of sand particles are picked up from the beaches and driven along by the turbulent hurricane winds. A spectacular display of this kind was seen in the Florida Keys hurricane in 1935.

It is also probable that over the sea the foam and spray generated by the high winds in a tropical cyclone will lead to the formation of a charged aerosol. The mechanism of charge formation is similar to that which sometimes occurs in large oil tankers during cleansing with water sprays. Heron and Ward (1979) considered the whirling charged aerosol plasma in a tropical cyclone to be a ring current, which would, have an associated electro-magnetic field signature. They found anomalies in the earth's magnetic field of 50 γ (nano Tesla) in cyclone Keith 1977 and expect to find perturbations of 5 γ (nT) or so at distances up to 500 km from a tropical cyclone.

15.7 Hail

Hail is defined by the WMO as precipitation of small balls or pieces of ice (hailstones) with diameters of 5 mm or more. They may fall separately or agglomerated into irregular lumps. The largest lumps recorded have 'diameters' in excess of 100 mm. Precipitation in the form of smaller pieces of ice - not snow crystals - are called ice pellets. Hail occurs most frequently near high ground inland in middle latitudes. In higher latitudes the weaker convection and the reduced supply of moisture decrease the likelihood of hailstones. Although these factors are necessary for hail formation they are not sufficient - otherwise most cumulonimbus clouds in the tropics would produce hail whereas, hail is rare there particularly over the warm ocean and in tropical cyclones. Circumstances which are known to lead to the formation of hail will be examined before factors inhibiting the formation of hail in the tropics are discussed.

15.7.1 Hailstorms

English (1973) finds that large hailstones form from millimeter sized embryos in cumulonimbus clouds with a high updraft speed, high liquid water content, and high storm top with a sloping but not far from vertical ($\approx 12^{\circ}$) updraft. These conditions require that the atmosphere holds abundant water vapour at low levels and is unstable to great heights so that a large positive area is indicated on environmental soundings. A high updraft speed is crucial if growing embryos are to be held above the 0°C level for the extra minutes required for them to grow to the size of hailstones. For example, the terminal velocity of 15 mm-diameter hailstones is in excess of 15m/s while it is greater than 30 m/s for hailstones larger than 30 mm. Updrafts of a comparable magnitude are therefore necessary to suspend growing hailstones for periods of 10 minutes or so in areas where the water content will be in excess of 3 g/m^3. Using Doppler radars Nelson (1980) found updrafts exceeding 50 m/s at the 7km level - with downdrafts as great as 25 m/s.

The cores of large hailstones nearly always contain embryos which can be of graupel (soft hail), frozen rain or even water drops. The small embryos (100 - 800 μm) grow in one set of conditions and are then transported to a region with a high content of supercooled water in which they grow to hailstones. There are several categories of hailstorms in which these requirements can be met (Chisholm 1973). They are squall-line storms, multi-cell storms in which there is a sequence of updraft-downdraft life cycles, strongly sheared storms and the most effective of all, Browning's (1962) "supercell" in which a quasi-steady state is maintained for several hours. Most hailstorms are of the multi-cell variety but the archetypal supercell - illustrated in Fig. 15.7(1) - has been well studied and can be used to illustrate a hail-growth mechanism.

The updraft shown enters the storm on its forward side (south or right side of of Fig. 15.7(1)) releasing an abundant supply of cloud water. Where the updraft is strongest the cloud particles have insufficient time to grow to the size of precipitation elements and so show either no radar return or a weak one so creating a "weak-echo vault" within the storm. The updraft is weaker on its flanks and supercooled raindrops or snow pellets can form there to become hail embryos. The inflow imparts a marked cyclonic rotation to the updraft which results in embryos being carried around the right flank (east in Fig.15.7(1)) and forward sides of the updraft to form an overhang or "embryo curtain" there. The embryos, now numerous and large , have reflectivities as high as 50 dBz. At mid-levels the embryo curtain appears on radar as the foreboding "hook echo" (Fig. 15.7(2)) which is the signature of a severe storm usually associated with hail and tornadoes. (A) Embryos of a size no longer supportable at the periphery of the updrafts fall into the stronger central part and are recycled. On this pass they are carried on a trajectory (short arrows in the Fig. 15.7(1)) close to the lower boundary of the weak echo vault and fall out on its northern side. Some trajectories are shown in Fig. 15.7(2) where it will be seen that outflow to the anvil goes to the east (into the paper) carrying with it much of the updraft water which evaporates. Hail following the trajectories marked with threes remains below $-40^{\circ}C$ (where many drops are supercooled) and continues to grow while crossing over the vault, whereas hailstones on the path marked xxx spend more time above $-40^{\circ}C$ and do not grow as large.

There will always be some embryos near the edge of the vault that compete unfairly with others by virtue of their being the first to encounter the undepleted cloud water in the vault. The vault therefore restricts competition between embryos and so permits the chosen ones to better collect the available water and grow large.

(A) In a later study of a supercell over Oklahoma (Nelson 1980) it was found that embryos could originate from many places and that the embryo curtain was the region of most rapid growth of hailstones and could probably be better called a "hail curtain".

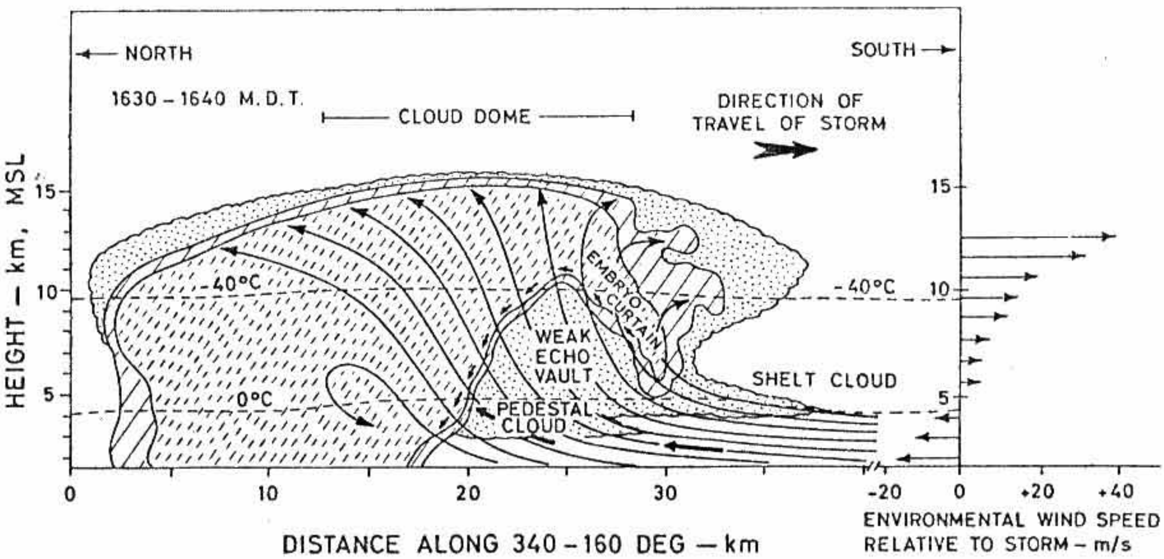


Fig. 15.7.(1). Vertical section of a supercell hailstorm at Fleming, Colorado 21 June 1972. Features of the visible cloud are superimposed onto two levels of radar reflectivity represented by different densities of hatched shading. Areas of cloud devoid of detectable echoes are shown stippled. The thin lines are streamlines of airflow relative to the storm. The short arrows around the weak echo vault represent a hailstorm trajectory. (Adapted from Browning and Foote 1976.)

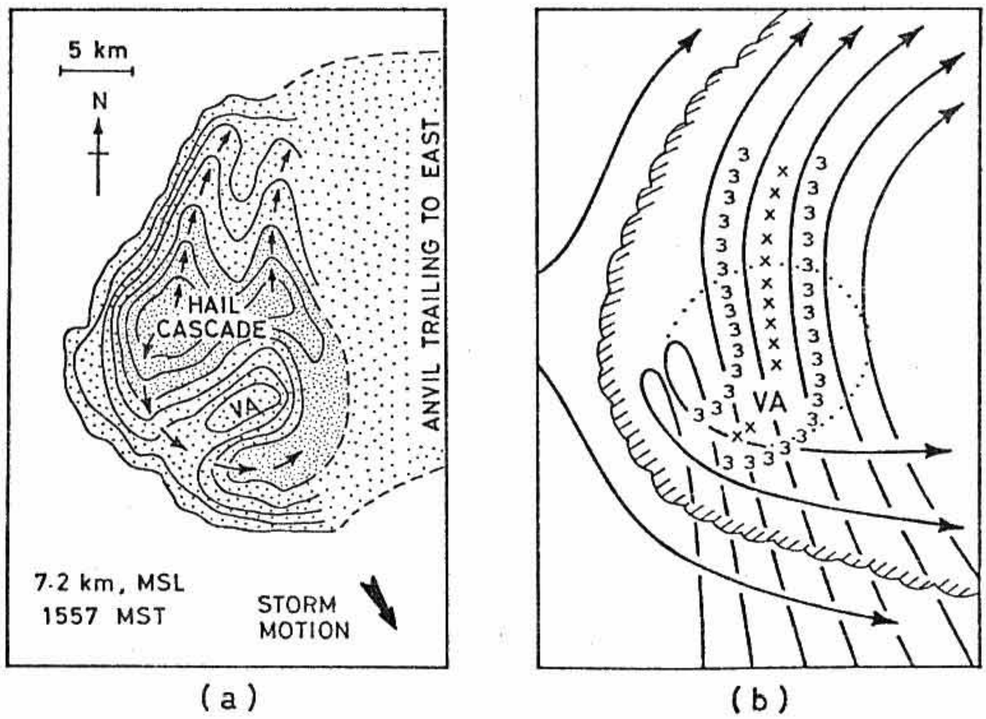


Fig. 15.7.(2) (a) shows a quasi-horizontal section through the Fleming storm with reflectivity contours at 5 dB intervals above 30 dBz. Arrows represent the motion of identifiable parts of the echo motion. VA marks the vault. (b) shows schematic streamlines relative to the storm and hail trajectories below the -40°C level (333) and a trajectory which spends some time above the -40°C level (xxx). (Adapted from Browning and Foote 1976.)

15.7.2 Tropical hailstorms

It was at first thought that hailstones formed in tropical cumulonimbus clouds but melted during their fall to ground. This theory was apparently supported by the greater frequency of hail at some tropical hill stations. However, we now know from both calculations and experiments (see Mason 1971) that hailstones larger than about 15 mm at the $0^{\circ}C$ level can fall through the 5 km or so to the gound without completely melting and that large hailstones suffer an insignificant loss of mass during their fall. The outer temperature of a wet hailstone approaches that of the wet bulb which, in typical tropical maritime conditions, reaches $0^{\circ}C$ about 1 km below the $0^{\circ}C$ level in the environment.

An additional point against the melting theory is that aircraft encounters with hail in the western Pacific area are very infrequent. Frost (1954) made 87 penetrations into Malaysian cumulonimbus clouds in search of hail and found it on only 7 flights. Of these encounters three were with moderate hail and four with light hail. The only report of hail damage to any of the many aircraft flying to Hong Kong over the last 30 years was from the pilot of a Boeing 747 which suffered a cracked wind screen on 27 April 1972 when flying in hail at a height of 4 km 90 km east of Bangkok in an area from which ground reports of hail are known (Frisby and Sansom 1967).

Although the reasons for the infrequency of hailstones in the tropics are not yet fully understood there are at least four factors which work so as to inhibit hail formation there. Firstly, and most importantly, great instability in the middle troposphere seldom occurs in the tropics and strong updrafts are infrequent. Frost (1954) found only one occasion of an updraft in excess of 7 m/s over the Malay Peninsula region. The exception, an updraft of 16 m/s, occurred in a storm with moderate hail. Secondly, as suggested by Frost (1954), the warm-rain process removes liquid water from rising air prior to the transformation of a cumulus cloud into a cumulonimbus cloud and thereby depletes the water content at high levels in the cumulonimbus. Thirdly, the efficiency of the warm rain process produces many raindrops below the $0^{\circ}C$ level which, at higher levels, compete on near equal terms for the already depleted supply of cloud water.

Finally, the high water content of tropical cumulonimbus clouds produces a relatively large downward force (equal to the weight of the drops) which, in the absence of a mechanism to evacuate the drops from the updraft restricts its acceleration and eventually creates the downdrafts which dissipate the cloud.

Hail occurs over most of the tropical western Pacific with a frequency of about one storm in 20 years or less (Frisby and Sansom 1967). As in temperate latitudes hail is more likely in areas near high ground. Apart from reports in the hills of Luzon and New Guinea, hail has been observed near sea level at Kuching, Sarawak only 1.5^{o} north of the equator. Remarkably, hail in Singapore and the Malay Peninsula seems to be very rare indeed even in the hills. Frost (1954) could find no occasion of hail having been reported there.

Hail has occurred at Hawaii and Polynesian stations just within the tropics. Some stations in these latitudes eg. Burma, Thailand and Hong Kong report hail a little more often with a frequency of about once per decade. These storms occur in the spring when deep troughs bring cold air equatorwards in the middle troposphere so creating great instability. Strong shear in the vertical is frequently a feature of these storms. The storm shown on the radar screen in Fig. 15.7(3) dropped hailstones of the size of golf balls onto Hong Kong on the 5 March 1980 and a similar storm occurred the next day (Lam 1980). The first of these storms moved nearly 300 km in 4½ hours averaging 18 m/s. A streamer of precipitation elements was blown off towards the NE. The surface flow was from the east at 6.2 m/s and the strongest upper winds of 58.6 m/s from 235^{o} were found at 11.7 km, giving a shear of 64.8 m/s in 11.7 km or 5.5 m/s per km (5.5×10^{-3}/s). The freezing level was at 4.0 km (627 mb).

Of the eight well documented hailstorms at Hong Kong seven occurred in springtime and one in summer. They were all associated with warmer than usual temperatures at 850 mb and 200 mb and all but one occurred with greater than normal 850/200 mb shear. The 500 mb temperatures were significantly colder than normal in five spring storms but were near normal in the summer storm. On 20 March 1980 two hailstorms occurred at H.K.: the second struck at 10pm (HKT) and dropped hailstones with diameters of about 35mm.

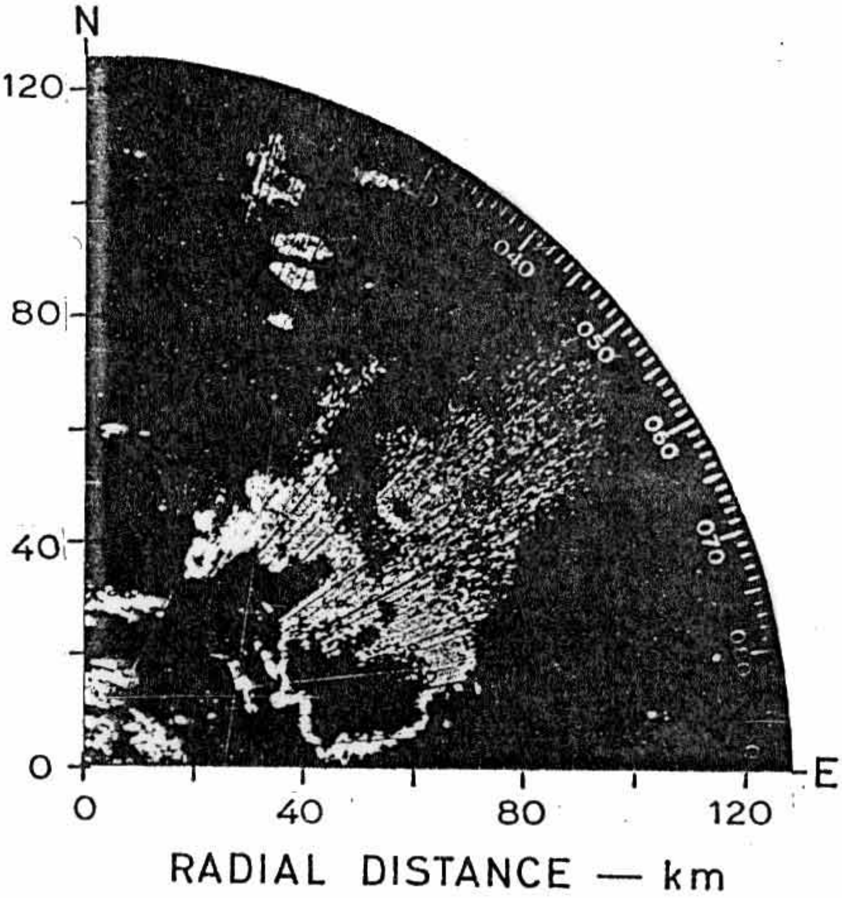


Fig. 15.7(3). A rare tropical supercell hailstorm at 0522 GMT on 5 March 1980 centred about 50 km east of the Hong Kong's 100 mm radar. The outlined black area corresponds to a radar reflectivity greater than 54 dBz. Precipitation in the anvil streaming to the NE has a reflectivity of 22 dBz. This anvil echo grew in width during the prior three hours. The radar image is from a replay of a video tape recording.

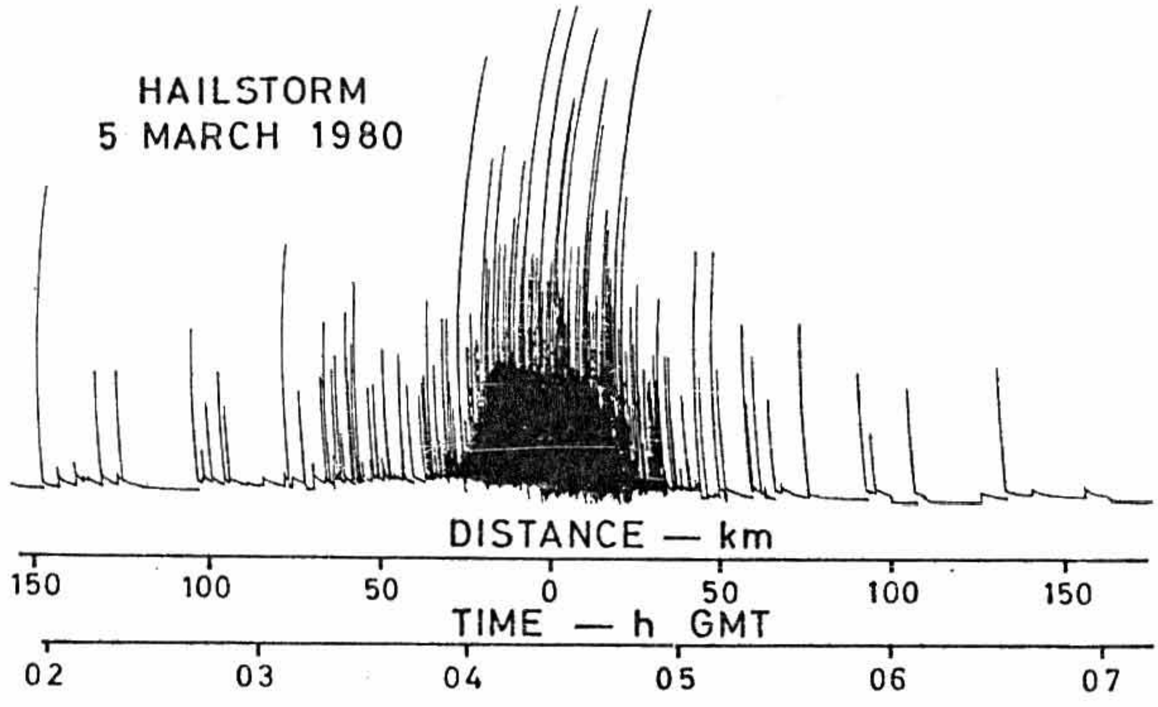


Fig.16.7(4). Sferics recorded at the Royal Observatory Hong Kong as the hailstorm shown in Fig. 15.7(3) passed by.

15.7.3 Hail in tropical cyclones

Hail has occasionally been reported in tropical cyclones by the crews of reconnaissance planes flying at 700 mb. However I can find no evidence of these aircraft suffering damage so that the hail encountered could not have been large. Similarly, there are no reports of hail near sea level in the inner regions of tropical cyclones although heavy hail did fall on the northern periphery of tropical storm Ruth 1977. The event occurred at 0100 GMT on 15 June 1977 at Pratas Reef 300 km southeast of Hong Kong. The only unusual features in the Pratas sounding that day was that the 700 mb temperature (7.8^{o}C) was 2.5^{o}C cooler than normal and there was considerable shear between the winds at 700 mb (135^{o} 18.5 m/s) and 500 mb (060^{o} 6 m/s). The pressure at the surface was 1006 mb, the temperature and dew-point were both 24^{o}C.

Although there is usually neither great vertical shear nor great instability in any region of a tropical cyclone (sects 5. and 4.) updrafts greater than 15 m/s have been recorded in the eye wall. In addition, the precursor rainband often has the nature of a squall line and might be expected to provide both the enhanced convection and vertical shear often associated with hail formation. Certainly thunderstorms are frequent in the precursor band. The reasons for the infrequency of hail in tropical cyclones will be similar to the reasons for the infrequency of hail in the tropics generally. With our current incomplete knowledge of hail formation mechanisms the considerations in the previous section should be taken provisionally as being applicable also to the tropical cyclone case.

15.8 Birds in Tropical Cyclones

In the relatively calm centre of typhoons over the sea, birds sometimes drop exhausted onto the deck of ships which they are doubtless relieved to encounter there Fig. . How they get there is not really known. However, it is reasonable to assume that they join the storm while it is weakened during its passage across land and are either fortunate enough to take to the air in the eye on the approach of stronger winds or are carried into the eye by the converging wind flow. Of course, once the cyclone regenerates on moving over the sea again the birds will be trapped and must journey with the storm. In his book, Piddington (1864) says that there are many instances of ships being surrounded or having their decks covered during their passage of the calm centres of cyclones in the neighbourhood of land, with land and aquatic birds, butterflies, horse flies etc. He offered this as additional evidence for the wind "incurving" or spiralling towards the centre. Once trapped in the eye birds are sometimes carried to areas where they are otherwise rarely seen. In Hong Kong, birds have been reported in the eyes of typhoons that have entered land there but, it is not possible to say whether they came with the storm or whether they survived the hurricane force winds on its approach. Usually long before hurricane force winds reach land it is impossible for birds to retain a hold in trees, they must therefore take to the air and be blown long distances by the storm's peripheral winds.

There is more information on the effects of hurricanes on bird life than of typhoons. When hurricanes reach the maritime provinces of the U.S.A., after moving up the east coast, a variety of unusual birds are usually sighted. Laughing Gulls and Black Skimmers, species which rarely occur in the maritime provinces become especially common (Tufts, 1962). Radar observations of flocks of birds in hurricanes were first made on 14 September 1971 in the remnants of hurricane "Heidi" which moved north over the Gulf of Maine and then inland over Maine (Richardson 1972). These flocks were at heights between the surface and 1.8 km and although their ground speeds were unusually high, they were actually flying very slowly. For example, the ground speeds at noon averaged 22 m/s while the tailwinds averaged 19 m/s, the birds were therefore flying at airspeeds of only 3 m/s or so. Birds watchers in the Far East have a good opportunity to make contributions to knowledge in this field.

Captain W.K. Hole master of m.v. Glenlyon reported an encounter with birds in the eye of the famous Rameswaram cyclone of December 1964 (Hole,1965). This cyclone formed over the Indian Ocean at the low latitude of 5^{o}N and crossed Sri Lanka on the 23rd December. On the 20th December the m.v. Glenlyon entered the eye at 6^{o}N 90.5^{o}E. The sea was short and choppy and flocks of small, brown coloured seagulls, with black heads and small webbed feet tried, with difficulty, to land on the ship. They looked as if they had been fighting the storm for a long time.

A mature tropical cyclone moving onto a coast populated by birds must kill many of them. When trees begin to break or fall birds still sheltering in them will be caught up by the increasing winds and most probably dashed to their death. Cole (1977) wrote that immediately after the 1974 Darwin cyclone "The saturated bodies of hundreds of birds lay on the open spaces of ground in many areas including our College grounds". Birds caught up in the relatively calm eye may fare no better as many of them will be unable to survive long ocean passages.

15.9 Effects on Vegetation

15.9.1 Introduction

Typhoons can devastate large areas of vegetation by direct wind action, by flooding with sea water brought inland by storm surge and wave action, and by the flooding from rainfall which also causes, erosion and the deposition of mud and gravel.

On islands and open coasts the wind damage to vegetation can be total leaving nothing more than tree stumps from the original tree population. Atolls and small islands in the Pacific are particularly vulnerable to damage of this kind to which is added the scouring due to storm surge and large waves. The devastation can be so complete as to make the islands uninhabitable for a decade or more. A case which has been well studied (Blumenstock 1958) occurred when typhoon Ophelia struck Jaluit atoll (5.5°N 169.5°E) in the eastern Marshall Islands on the 7 January 1958. The lagoon measures about 27 by 56 km and rises to about 4.5 m above the sea level. At the height of the typhoon waves were sweeping across most of the islets into the lagoon. Even the biggest trees were lost to wind and water action - some trees had people tied to them - and large coral boulders swept across the islands. One of the islets Mejetto was completely changed by the typhoon, coral debris was spread across more than half the islet to a depth of about one metre and over 90 per cent of the densely packed trees had either been carried away or broken off leaving only two or three metres of tree trunk standing. Whole sections were scoured clean of top soil. A program of rehabilitation followed but it was estimated that at least ten typhoon-free years would be required to restore the islet to its former tropical luxuriance.

15.9.2 Trees

When trees are blown down either they pull their roots out of the water-sodden ground or they snap off some way up the trunk. In some species (e.g. pines) the break is not clean but extends over a length of trunk where the wood, strongly worked to and fro in the wind, breaks down to a stringy consistency before final rupture. Other trees (e.g. banyans) lose their foliage and lesser branches but the trunk and major branches resist wind forces well so that the roots tend to be pulled out before further breakage. There is a great variation between tree species in their resistance to sustaind winds of 50 m/s or more.

The damage to trees in urban areas can be greatly reduced if the crowns are drastically pruned as soon as a tropical cyclone warning is issued. Such cutting back is done routinely by the authorities in some cities (e.g. Hong Kong) which are frequently affected by typhoons. This action is especially effective and worthwhile if there has been a run of a few years without severe winds.

Trees can sometimes provide a clue to the local climatology of wind. For example, Ramage (19) has pointed out that hurricane force winds must be very rare in western North Luzon, because the very old jacaranda trees growing in exposed positions at Clarke Field airbase would not have survived hurricane force winds.

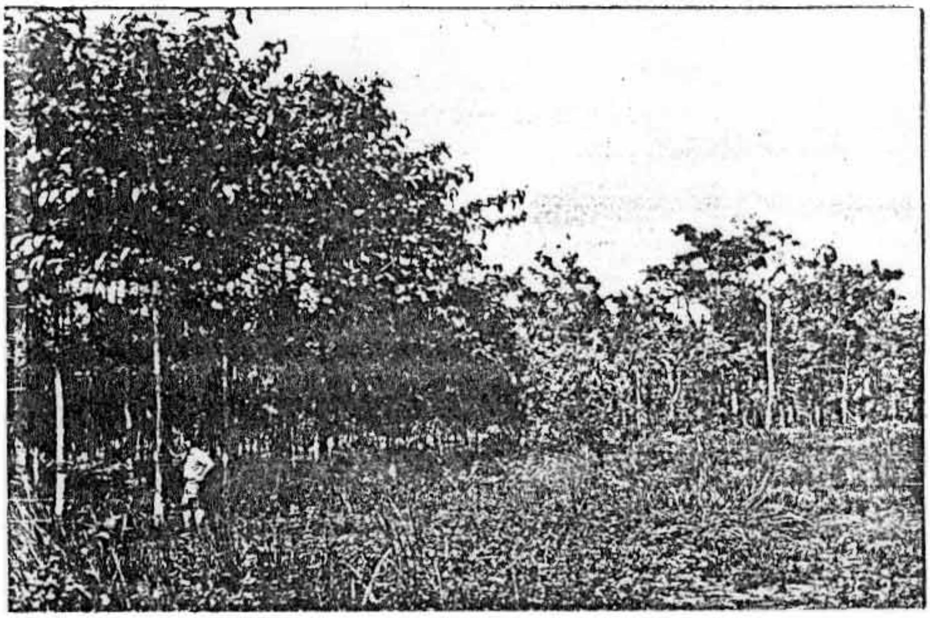
Although there is usually extensive defoliation of trees and bushes during the passage of a mature typhoon it is noticeable that many of the leaves which survive soon turn brown. The effect is variously attributed to "windburn" or to salt water spray carried in from the sea. However, a similar effect has been observed in tornadoes in north-east India and in the U.S.A. far away from salt water. I have observed that the leaves which go brown do so because the stem has been damaged but not completely severred by the agitation due to the wind. Such leaves hang limply on the branch. Similar damage occurs to branches which later hang with their cluster of dead leaves. At the height of a typhoon and just afterwards there is a strong, pungent smell in the air attributable to the wet, mangled vegetation which litters the ground.

The passage of cyclone Tracy across Darwin on 25 December 1974 caused extensive and varied damage to the tree population. Stocker (1976) carried out an extensive survey of the tree damage there and identified five kinds. Uprooting and crown damage were by far the most common while broken or leaning boles were most frequent in monsoon forest areas and plantations. His fifth category of damage - trees standing but dead - was largely confined to the mangroves. The eucalypts and Alstonia were examples of trees which were able to shed twigs and leaves before the wind force was sufficient to cause uprooting or main branch failure. Uprooting was greater on low lying moist ground than on better drained areas. The rainfall during the November and December prior to Tracy had been relatively low so that only low-lying soils would have been near or fully saturated when the storm arrived. Many mangroves were completely uprooted and pushed onto land where some became re-established. Others lost the sand from around their roots by water action before being blown down.

Stocker (1976) noted that "far from being a potential hazard during cyclones trees seem capable of providing a protective screen far more efficiently than surrounding buildings" and Cole (1977) wrote "Trees that withstood the cyclone usually provided excellent debris buffers and protected a number of houses and groups of houses". It was observed that as a general rule, deep rooted trees provided best shelter. Among the many kinds of tree that were noteworthy for their stability in cyclone Tracy and that are also found in south China and other tropical cyclone prone areas were: Cassis spp (Cassia), Ficus virens (Banyan), Carica papya (Paw Paw) and Bambusa spp (Bamboo). Unstable trees included; Ficus elastica (Rubber plant), Melaleuca spp(Paper Bark) and Peltophorum pterocarpum (Golden Flame Tree).

A stand of trees defoliated by cyclone Tracy can be seen in Fig. 5.1(3). The photographs in Fig. 15.9.2 (1) show the experimental plot at Leanyar just before cyclone Tracy and seven weeks afterwards while damage to large trees is shown in Fig. 15.9.2 (2). In all these photographs many trees can be seen to have grown new leaves in the seven weeks since the cyclone.

The tender rain-forest type of trees which suffered extensive defoliation in Tracy did not grow their leaves again until November 1977 - the third wet season after the storm. Even then the trees looked much thinner than previously because the normal complement of branches takes several more years to become re-established. Those poinceana (Delonix Regia or flame tree) which were not uprooted soon returned to normal as did the eucalypts. Green ants, which make their nests in trees, were blown away by Tracy and after three years they had not returned in significant numbers. In December 1979, five years after Tracy, I took the photograph in Fig. 15.9.2 (3) to show that scars still remain.



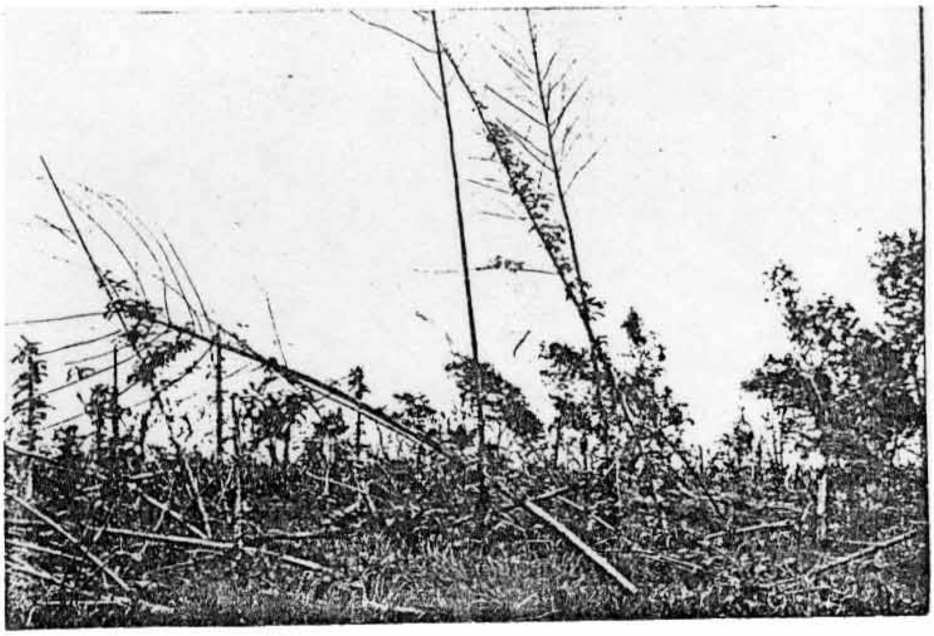


Fig. 15.9.2 (1). The experimental plots at Leanyar in November 1974 before cyclone Tracy (above) and the remnants seven weeks later (below). The Anthocephalus cadamba is seen to be badly damaged while the Eucalyptus camaldulensis on the right is recovering well. (From Stocker 1976).

Fig. 15.9.2 (2). Large broken Acacia aulacocarpa seven weeks after cyclone Tracy crossed Darwin (From Stocker 1976).

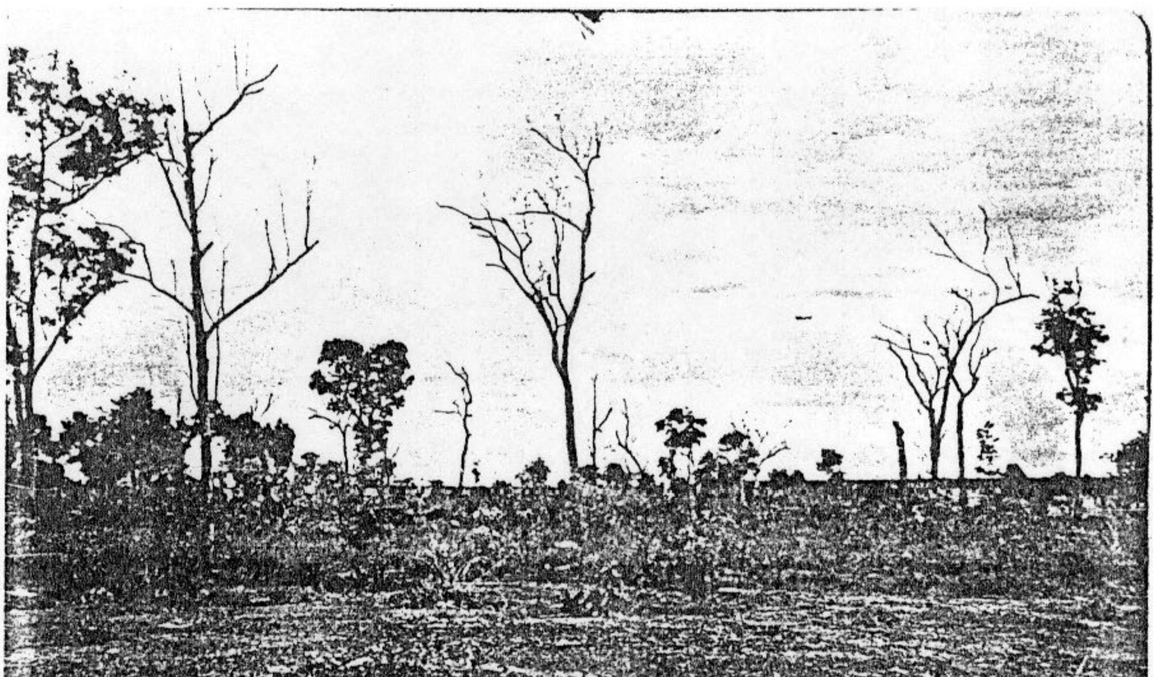


Fig. 15.9.2 (3). Trees in Darwin photographed in December 1979 five years after the passage of cyclone Tracy.

15.9.3 Crops

Wind damage to crops varies greatly with the kind of plant and its state of growth at the time of passage of the tropical cyclone. The subject will not be pursued here; suffice it to say that towards the end of the growing period harvesting can be advanced on the receipt of typhoon warnings to avoid loss and damage. Bananas, rice and many other crops can be saved in this way. Significant advances in this direction have been made in China in recent years. Selected members of communes, trained in making meteorological observations, maintain communication with forecast centres. Tropical cyclone warnings can then be passed to commune committees and appropriate action taken to protect crops.

It should be noted that wind damage can occur in the very lowest layers of the atmosphere so that short crops can also suffer damage. Cole (1977) noticed that during cyclone Tracy 1974 "Even the grass of our area in the northern suburbs (of Darwin) was torn and shredded".

15.9.4 Effects of sea water

When sea water is carried inland it not only ruins standing crops but also impairs the productivity of the soil for a period ranging from months to years. The damage done to crops obviously depends on the type of plant and its growing stage. Damage to the soil depends on how effectively and how quickly the salt water can be drained away and the remaining salt leached out of the soil by heavy rain or fresh water flooding. In large deltas, such as that at the mouth of the Ganges, it may be necessary to await the monsoon rains to leach the soil to the point where it will sustain growth. In smaller areas with hilly interiors and good drainage the subsequent typhoon rains themselves may be sufficient to sweeten the soil sufficiently to sustain new crops - this is usually the position, for example, in Hong Kong.

Gonsalves (1978) studied conditions after the disastrous Andra Pradesh cyclone of November 1977 in which some 24 000 ha (240 km^2) were flooded from the sea. He found that a shallow layer of sea water remained over the paddy fields for a few weeks because of the clayey nature of the soil. Sodium in the sodium chloride in the sea water, defloculated clay particles so reducing permeability and hindering the further downward flow of water into the sub soil. Subsequent evaporation left salt both on the surface and for some distance below in the rooting zone of plants. The situation was exacerbated by the relatively high water table of about 1 m. At this height a small but tolerable background of salinity is maintained which is additional to that due to sea water flooding. A water table level no higher than 1.5 m would be recommended for the area.

Salinity in the soil reduces the availability of water to the plants. This seriously affects germination and the growth of seedlings. Growing plants that survive are stunted. Rice is similarly affected, even when there is a plentiful supply of water around the roots, and yeilds may be reduced by 25%. Stunted rice plants take on a bluish-green colour which is apparent to the trained eye. Flooded crops like rice do not show the more toxic effects such as leaf burn and leaf fall which are found in other plants. However, rice is as susceptible to salt as other non-flooded plants when in the seedling and flowering stages. Crop response to salinity is shown in Table 19.9.4 (1) where the salinity is given in terms of the electrical conductivity of the soil expressed in units of millimhos/cm at 25°C.

Table 15.9.4 (1)

Crop Response to Salinity of the Soil

Salinity (Conductivity at 25°C) millimhos/cm	Crop Responses
0 to 2	Mostly negligible
2 to 4	Yields of very sensitive crops may be restricted
4 to 8	Yields of many crops restricted
8 to 16	Only tolerant crops yield satisfactorily
Above 16	Only a few very tolerant crops yield satisfactorily

Adverse effects from flooding are much reduced in sandy soils and in well drained areas where sea water cannot stand for long and the water table is low. Good drainage is therefore essential for the protection of soils against the longer lasting effects of sea-water flooding. It is also often recommended that sturdy perennial trees be planted in low-lying areas to act as wind breaks and so reduce the penetration of waves and storm surge.

15.9.5 Potable water

The spoiling of potable water stocks can lead to both death and disease in man and livestock if the provision of fresh supplies is delayed by distance or poor communications such as exist in the Ganges delta. In such areas it is of the greatest importance to store some water above the level of possible inundation.

15.10 Bush Fires

In view of the copious rainfall usually associated with tropical cyclones one might at first think that the only effect that they would have on fires would be to extinguish them. While this may be the ultimate result in most cases the peripheral winds of tropical cyclones can cause the rapid spread of fires long before the rainfall arrives. The tragic loss of life and property in the 1923 Tokyo fire is mentioned in sect 15.3 but bush fires are the ones most frequently fanned and spread by tropical cyclones.

Areas subject to both bush fires and tropical cyclones include the southwest coast of the U.S.A. and the northwest coast of Australia. Early hurricanes and cyclones moving offshore along these coasts after the dry season intensify existing bush fires and cause them to spread rapidly.

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