ORGANIZATION AND MOTION OF THE SPIRAL
RAINBANDS IN HURRICANES: A REVIEW*

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ABSTRACT

The basic characteristics of hurricane rainbands are reviewed.
These basic characteristics are: width spacing, inward spiralling,
life-time, and movement of the bands. Movement of individual cells
in the bands is also reviewed. The changes of meteorological varia
bles within the bands are examined, as well as the surface changes in
weather elements observed during the passage of the rainbands. The
formation of tornadoes within hurricanes is briefly discussed. Fina
lly, the explanations for band formation are treated in a succinct
fashion: explanations inferred from observations, from laboratory ex
periments, and from the results of analytical and numerical studies.

RESUMEN

Se revisan las características básicas de las bandas de lluvia
de los huracanes. Estas características básicas son: ancho, sepa-
ración, forma espiral hacia adentro, tiempo de vida, y movimiento
de las bandas. Se revisa también el movimiento de las células indi
viduales en las bandas. Los cambios de las variables meteorológi-
cas dentro de las bandas son examinados, así como también los cam
bios en superficie de los elementos del tiempo observados durante
la pasada de las bandas de lluvia. La formación de tornados en hu
racanes es discutida brevemente. Finalmente, las explicaciones pa
ra la formación de las bandas son tratadas en una forma sucinta:
explicaciones deducidas de observaciones, de experimentos de labo-
ratorio, y de los resultados de estudios analíticos y numéricos.

1. Introduction

A tropical cyclone is defined as a warm core cyclonic wind circulation in which the maximum sustained winds are 18 m s^{-1} or greater. Tropical cyclones in which the maximum wind equals or exceeds 32 m s^{-1} are called **hurricanes** when they occur in the Atlantic, and typhoons in the Pacific. In the United States a tropical cyclonic circulation is called a tropical depression if the maximum sustained winds are less than 17 m s^{-1}, tropical storm if the maximum winds are between 17 and 32 m s^{-1}, and hurricane if the maximum winds are greater than 32 m s^{-1}.

The horizontal scale of a hurricane is normally defined by the radius of the longest closed isobaric surface. Characteristic radii vary between 500-1000 km, depending on the hurricane. The average radial extent of hurricane force winds is only about 100 km, but winds greater than 14 m s^{-1} may extend 500 km from the center.

Following Anthes (1974), we can divide the hurricane into four regions in order to visualize the main aspects of its structure. Fig. 1 shows these regions. Region I is a relatively inactive region separating regions II and IV, which are respectively the inflow and outflow layers. In this region the vertical velocities and vertical wind shear are small. Radial flow is negligible compared with the tangential flow and the flow is, in general, in gradient balance. Region II is the frictional (Ekman) boundary layer. In this region surface friction destroys gradient balance and produces strong inflow and moisture convergence. Region III includes the eye and eye wall. The air that is accelerated toward low pressure into the center of the storm cannot penetrate beyond some minimum radius because of the excessive velocities required by the conservation law of angular momentum. The air then rapidly rises to the high troposphere in a ring of strong upward motion. This ring is called the eye wall and is characterized by vigorous
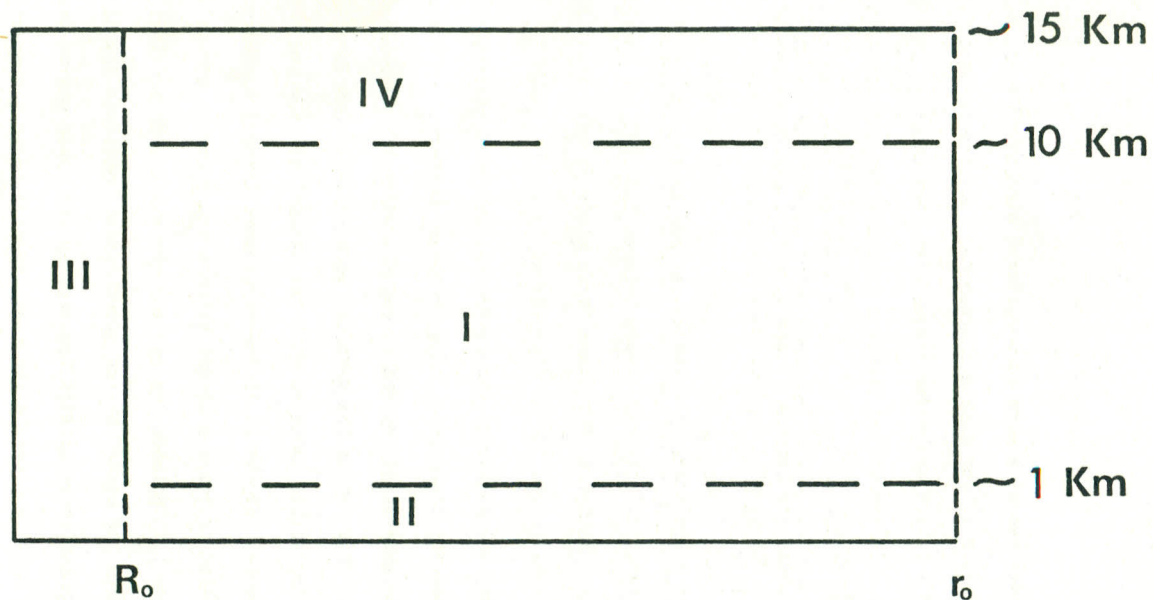
Fig. 1   Partition of hurricane into four regions.   Mass inflow is
significant across dashed boundaries and negligible across
solid boundaries. R_0 is the radius of maximum wind (about
40 km) and r_0 is the radius of hurricane domain (about
1000 km).   (From Anthes, 1974)

cumulonimbus clouds and large amounts of precipitation. Latent heat flux in these convec
tive cells produces the warm core structure that is especially pronounced in the upper
troposphere. This warm core structure is one of the essential characteristics of the tro
pical cyclone. Temperature differences between this region and the surrounding environ-
ment could be greater than 10°C at the 10 km level. The horizontal temperature gradient
beyond 100 km is small (approximately 0.5°C per 100 km). Inside 100 km the temperature
rises sharply and reaches a maximum inside the eye. In the lower troposphere the warm
core exists only in the eye. In the eye the winds are light and variable, in sharp con-
trast to the maximum winds that occur in the eye wall. The eye is typically free of sig
nificant cloud cover. Subsidence of upper tropospheric air of high potential temperature
is necessary to achieve the extremely low surface pressures observed in the eye. A ty-
pical value is 950 mb but a value as low as 887 mb has been registered. In the hurricane
about 50% of the total pressure drop occurs within 90 km, which is about twice the radius
of maximum winds. Observational studies show that the energy required to drive these sys
tems is derived from the latent heat of condensation released in the eye wall. Latent
heat in the warm core maintains the hurricane baroclinic structure and releases available
energy, which is continuously converted to kinetic energy. The eye and eye wall typically
occupy less than 5% of the total storm volume. Region IV is the outflow layer. Above
10 Km to the tropopause, weak radial pressure gradients prevail because of the warm core
structure, and the air flows outwards. The outward motion is clearly observed in satelli-
te photographs by cirrus cloud (Cb anvils) that extend away from the storm to great radii.
The diameter of the hurricane's cirrus shield is typically 600-800 km. The circulation
in this region is anticyclonic relative to the earth. This anticyclonic circulation is a
result of the loss of angular momentum to the sea along the air's low-level inflow trajec-
tory. The outflow layer is quite asymmetric and barotropic processes appear to play an

important role in maintaining the kinetic energy of the eddies.

The strongest horizontal winds in the hurricane circulation are located near the top of the boundary layer. Because of the hurricane's warm-core structure, these winds slowly decrease in speed through the troposphere. The mean vertical motion throughout most of the hurricane circulation is weak. Subsidence occurs over a large area surrounding the storm (at radial distances greater than 300 km), as is seen by the nearly cloud-free atmosphere beyond the radius. Diagnostic studies using observations and theoretical models indicate typical mid-troposheric subsidence values of the order of 1 cm^{-1}. Upward motion occurs inside 300 km. The maximun circular mean updraft is of the order 1 m s^{-1} and occurs in the eye wall.

The clouds in the hurricane occur mainly in the region of mean upward motion. The dominant cloud type is convective; cumulonimbus clouds erupt in the ascending convectively unstable tropical air. The cloud bases coincide approximately with the top of the Ekman boundary layer. The many cumulonimbus clouds generate a dense cirrus canopy in the upper troposphere. The convective elements are organized into spiral bands, as is clearly observed in radar and satellite pictures. These bands appear to originate near the center of the hurricane and spiral anticyclonically outward to great distances from the center. The physical mechanism or mechanisms which are responsible for the organization of convective elements into spiral bands and the outward propagation of some of these bands relative to the eye, as we will see later, are still uncertain.

In this paper the main features of hurricane rainbands, as observed on radar and other observational techniques will be described. The discussion is based on observational data of hurricane rainbands reported in the literature, as well as data obtained by the author from radar films and surface data. The author has examined seven

radar films of tropical cyclones: Hurricane Donna (1960), Cleo (1964), Betsy (1965) and
Caroline (1975), which formed in the Caribbean Tropical Cyclone Tracy (1974), which
struck Darwin, Australia, Typhoon Vera (1959) which struck Japan, and Typhoon Rose (1971),
which struck Hong Kong. A review of the ideas concerning the origin of hurricane rain-
bands will also be made in this paper.

2. Basic Characteristics of Hurricane Rainbands

2.1. The hurricane radar weather model

The radar films of many hurricanes reveal a sequence of hurricane radar weather
which have been described by Senn and Hiser (1959) as follows (see Fig. 2):

"The first echoes as seen by a radar well in advance of the storm center are
sharply defined and form narrow pre-hurricane squall lines. In some storms those
squall lines are far enough away from the center so that the tangential motion of
the storm, as indicated by the echoes within the lines is small compared with the
radial component. In other storms, the hurricane's cyclonic circulation is easily
observed in these squall lines several hundred kilometers ahead of the storm cen-
ter. Pre-hurricane squall lines are generally separated by 80 km or more from the
first echoes of the rain shield, a ragged mass of spiralling weather which extends
from 80 to 160 km ahead of the storm center, or there may also be scattered hard-
core echoes between the pre-hurricane squall lines and the lighter precipitation
of the rain shield. As the hurricane moves closer and the pre-hurricane squall
lines have passed the station, the rain shield, when examined more closely, seems
to be composed of many spiral bands which apparently merged as they have been thrown
outward from the storm, becoming wider and longer and less well defined in the pro-
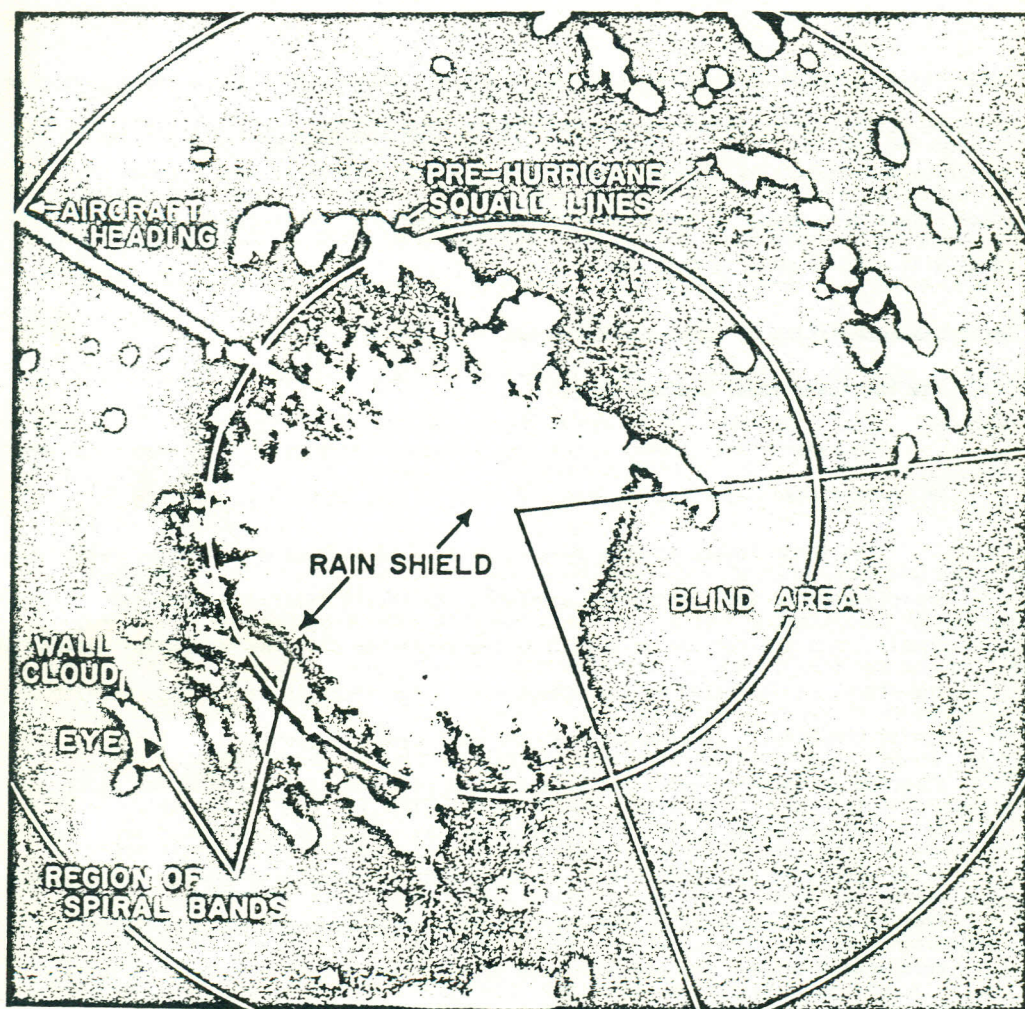cess. The leading edge of this rain shield has often been observed to have the

Fig. 2   Airborne radarscope photograph of Hurricane Daisy,
1946 Z, 27 August 1958, 50 mile range circles.
(From Senn and Hiser, 1959)

shape of a well-defined spiral band. As the center of the storm comes into view, it is usually not directly connected to this mass of spiralling weather but   is separated from it by a space of 16 to 80 km which is occupied by one or several much more discrete spirals. The spiral bands nearest the storm center are most clearly defined and continuous, and it is these which often define the eye   of the hurricane". In the literature, the pre-hurricane squall lines are frequently called outer rainbands, and the bands between the eye wall and the rain shield are called inner rainbands.

In order to illustrate the organization of rainbands in a hurricane, we will describe the horizontal radar composites of Hurricane Dora (1964). The discussion is based on information given by Sheets (1968).

Fig. 3 presents the horizontal composites for September 4, 5, 8 and 9, 1964. On september 4 (Fig. 3a)many spiral bands are observed. A compact eye wall is observed in the northeast quadrant while the other quadrants present only broken echoes. Most of the convective activity is concentrated in the northeast and southeast quadrants. The radar composite shows that the well organized spiral bands are concentrated in a region that extends to a radial distance of approximately 40 n.mi (74 km) north and 60 n.mi (111 km) south ot the storm center. Beyond these limits some broken echoes are observed but are not well organized. According to Sheets, the nose camera film showed considerable layered clouds in the eye, with a small break in the cirrus shield near the center of the circulation. Large middle level overhanging clouds also extended well into the eye. Below these was a broken-to-overcast stratocumulus cloud deck. The cloud film substantiated the radar struc ture, with solid clouds and nearly continuous precipitation observed over most   of
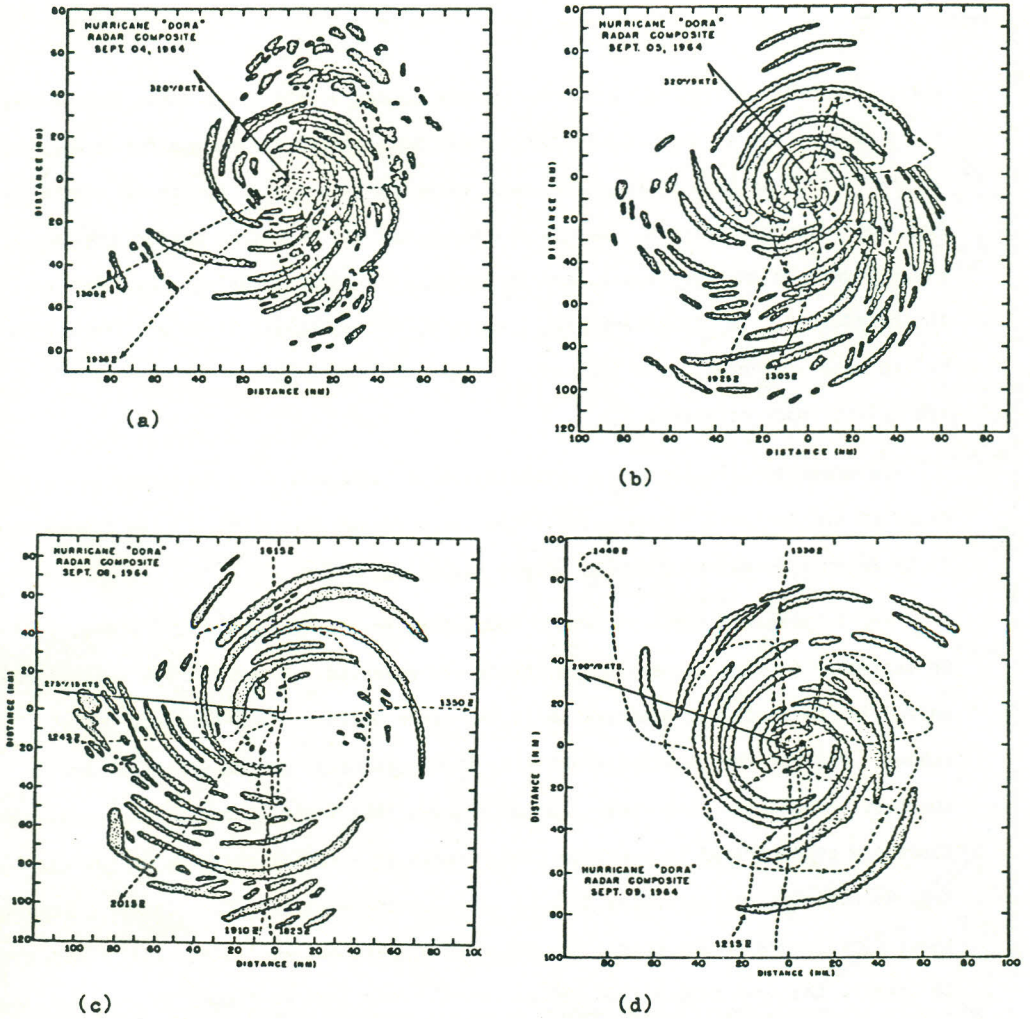
Fig. 3   Horizontal radar composites for Hurricane Dora (1964):

(a)   September 4   (b)   September 5   (c)   September 8

and   (d)   September 9.   (From Sheets, 1968)

the eastern half of the storm in the region where well organized bands were obser-
ved by radar. In the outer regions of the northeast quadrant, where the radar com
posite indicated broken echoes, the cloud film showed generally layered clouds,
with the aircraft being in and out of light-to-moderate precipitation. It also
showed layered clouds, with some breaks between the two major rainbands observed
by radar in the southwest quadrant.

On September 5 (Fig. 3b) the storm appears to be well organized. The spiral
bands extend to a radial distance of 100 n.mi (185 km) from the storm centre. The-
re is a defined eye wall in the northwest quadrant but not in the other quadrants.
Most of the convective activity is in the southern part of the storm, although it
is better distributed then than on the previous day. There could have been activi
ty in the northwest quadrant, but the track flown did not cover this area. A band
free of echoes is observed at a radial distance of approximately 40 to 50 n.mi (74
to 93 km) south of the storm center. This band spirals into the storm center, with
the width decreasing downstream.

On September 8 (Fig. 3c) many spiral bands are observed and most of them are
concentrated in the western part of the storm. However, on this day no eye wall is
defined, and there is a central region free of echoes, which in the west direction
extends to a radial distance of approximately 40 n.mi (74 km).

On September 9 (Fig. 3d an eye wall is observed, except in the northeast qua-
drant. This eye wall had not been seen on the previous day. A band free of echoes
is observed in the west part of the storm at a radial distance of approximately 20
to 25 n.mi (37 to 46 km). On this day, well organized bands extend to radial dis-
tances of 60 to 80 n.mi (111 to 148 km).

In general, looking at the radar composites of Fig. 3 one gets the impression that there is a gradual spreading and some rotation of the convective activity.

Penetrative convection in a hurricane is very restricted in area occurring on ly in the major lines of cumulonimbi. For example, Malkus et al. (1961) found that on the formation day of Hurricane Daisy (1958) about 1% of the rain area(r<370 km) was covered with "hot towers" defined as cumulonimbi with tops above 11 km. This figure had increased to 2.5% on the deepening day, and 4% on the mature day, on which about 200 hot towers were estimated.

2.2. Width of the bands

The width of the bands vary not only from storm to storm, but also in time and space in the same storm. Individual inner bands vary in width from 5 to 13 km, whi le the outer ones are wider, in some cases as much as 32 km. However, in the cases of extreme width, definite evidence of multiple sub-bands is found. The width of these sub-bands is in the 5-13 km range.

Although estimating the width of the bands from radar photographs is rahter subjective, the values given above agree fairly well with those obtained by Gentry (1964) from normal traverse flights in hurricanes.

2.3. Spacing of the bands

As with the width, the spacing between the bands varies from storm to storm and also in the same storm. The distance between the bands varies in general from 3 to 16 km, with greater spacing for the outer bands.

2.4. Inward spiralling of the bands

Radar photographs of hurricanes show that there exists considerable inward

spiralling of the bands. Senn et al. (1957) derived a logarithmic spiral in order to provide a realistic fit to some of the radar rainbands. This logarithmic spiral is of the form.

$$\ln (r-r_o) = A + B\theta$$

where A and B are constants, r is the radial distance from an assumed storm center to a point on the spiral band, r_o is the radius of an inner limiting circle which is the origin of the spiral, and θ is the angle between the radius and an assumed axis of origin.

Jordan (1963) evaluated the accuracy of using the equation of the logarithmic spiral mentioned above to determine the position of the hurricane eye. He found a median error of about 32 to 40 km between the eye positions estimated by spiral overlay and the official storm tracks published in the Monthly Weather Review. However, Jordan concluded that the spiral overlay technique is useful when the eye is not observed directly.

Several studies (Fritz et al., 1966; Watanabe, 1963; Sivaramakrishan and Selvam, 1966) show that the crossing angle between the cloud-band and concentric circles decreases as the storm becomes more intense. During the early stage of storm development, a crossing angle of 25 to 30° is usually noted. As the mature stage is reached, the crossing angle decreases and the bands become tightly coiled The crossing angle of the mature stage is characteristically between 10 and 15°, with bands approaching concentric circles in the most intense tropical cyclones.

2.5. Band life time

The observations of rainbands using radar films show that most of the indivi

dual bands have measurable life times only slightly longer than the larger echoes which form them, usually one or two hours. In some exceptional cases, however, the band life time may be as much as 6 or 7 hours.

2.6. Band movement

Analysis of hurricane radar films have shown that some hurricane rainbands form near the center of the hurricane and move outwards, while growing in lenght. A good example of band movement has been described by Senn and Hiser (1959) who presented the history of a well formed spiral band of hurricane Diane (1955) from its inception to the time it becomes an indistinguishable part of the rain shield. The band moved across the space between the storm center and the rain shield until it finally merged with the rain shield. They found that the band moved outward from the storm center at 5 m s^{-1} along the storm path NNW, and at over 8 m s^{-1} normal to the path on the right side of the storm. The outward propagation of the head end in the left front quadrant was slowest, smaller than 3 m s^{-1}; that of the tail end in the right rear quadrant was greater, near 15.5 m s^{-1}. The center moved at an average speed of 6 m s^{-1} during this period.

Tatehira (1962) made a mesosynoptic and radar analysis of a typhoon rainband. The radar band was initially generated near the eye and was on the radar PPI photographs at subsequent times. Disregarding the movement of the individual cells composing the band, the main part of the band appeared only in the northeast quadrant of the eye, which moved northeastward a speed of 12.5 m s^{-1}. The band moved outward at about 4 m s^{-1} relative to the eye.

3. Movement of Individual Cells in the Bands

Ligda (1955) made a radar study of a Florida hurricane of 23-28 August, 1949. He

used in his study a very fine radar film of such a hurricane. The film consisted
of pictures taken at about 30 second intervals of the PPI of an SCR 615-B (10 cm)
type radar. The tracks of small precipitation areas in various sections of the
storm were observed and collected over half-hour periods of storm time. Ligda
found that in the storm of 23-28 August, 1949, there was little or no actual ro-
tation of the spiral bands as a whole around the eye. There was, however, motion
of small precipitation echoes along the outer spiral bands towards the center.
Protuberances on the bands and small precipitation echoes between the bands near
the eye also moved along or parallel to the bands. Fig. 4 shows six of the thirty
vector patterns made by Ligda in the study of precipitation echo motion during this
storm. The length of each vector represents the movement of a small precipitation
area in one half-hour, so that speed of the echo is directly proportional to the
lenght of the vector. The cross marks the location of the radar relative to the
eye of the storm, which is indicated by the hurricane symbol. Because the speed
of the eye during the time these tracks were observed varied between 3-11 mph
(1.3-5 m s^{-1}), the motion of the storm contributed little to the small precipita-
tion area velocity. Therefore little error exists if these vectors are assumed to
be relative to a stationary center. In the period 0515-0545 EST, 27 August, a small
precipitation area velocity of 98 mph (44 m s^{-1}) was found some 25 miles (40 km)
from the eye. In the period 1430-1500 EST, 27 August, except close to the eye of
the storm, the lenght of the vectors is quite uniform, indicating speeds of about
65 mph (29 m s^{-1}). Ligda compared the speed and direction components of the surfa-
ce winds and the small precipitation area velocity near three stations. There seems
to be a fairly consistent difference between small precipitation area and surface
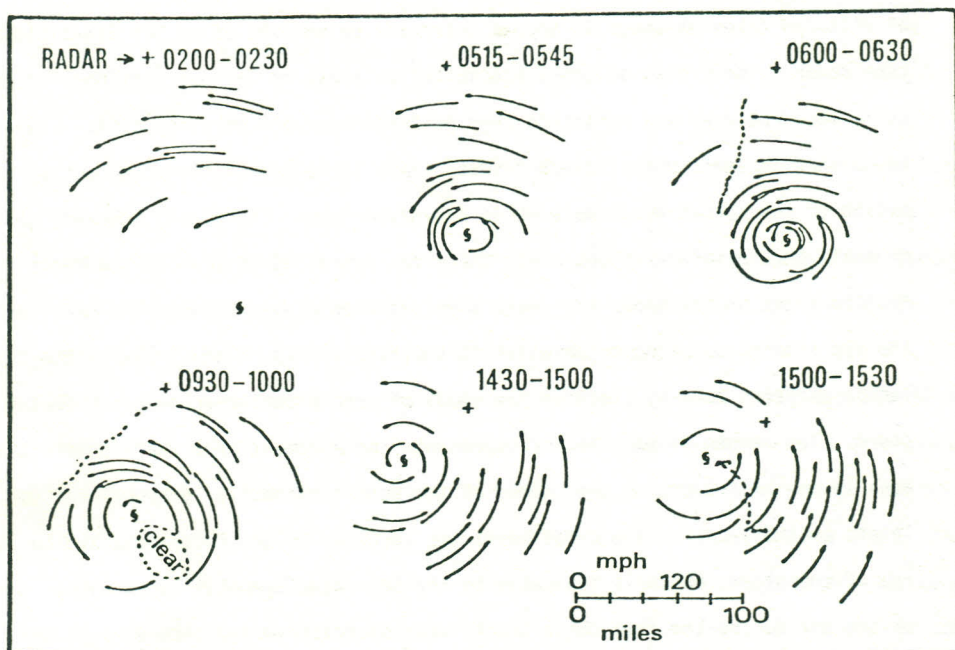
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Fig. 4   Six vector patterns of precipitation echo motion observed
in the hurricane of August 23-28, 1949.   (From Ligda, 1955)

wind velocity. Relative to the relationship between small precipitation area and surface wind direction, there exists a fairly consistent difference of about 45° between the two. Apparently in this storm small precipitation areas moved fairly close to the gradient wind direction.

In the study of Tatehira (1962) identification of the individual cells constituting the band was attempted (see Fig. 5). Only during about one hour was such identification possible, and new cells appeared at the windward (southeast) end of the rainband and the old ones dissipated at the leeward end. The rates of appearance of new cells and disappearance of old ones were about 100 km hr^{-1} (28 m s^{-1}) measured along the length of the band. This phenomenon is closely related to the apparent divergence of the rainband from the eye.

The facts concerning the displacement of the band studied by Tatehira and the facts concerning the trajectory of the individual cells are summarized in a model shown in Fig. 6. Although each cell constituting the rainband rotates nearly concentrically around the eye at a high speed, the rainband seems apparently to propagate radially outwards owing to new generation in the windward part and dissipation in the leeward part of the cells and to a non zero crossing angle of the band with a circle about the eye.

Fig. 7 shows the wind profiles relative to the hurricane's center of the tangential (V_t) and radial (V_r) components at a distance of about 120 km form the storm's center. The figure was constructed with information given by Miller (1958) who combined wind data from a number of hurricanes and obtained a composite picture of the hurricane circulation. If the speed of the convective elements forming a rainband is about 29 m s^{-1} at a distance of 120 km, as Ligda's results show, then
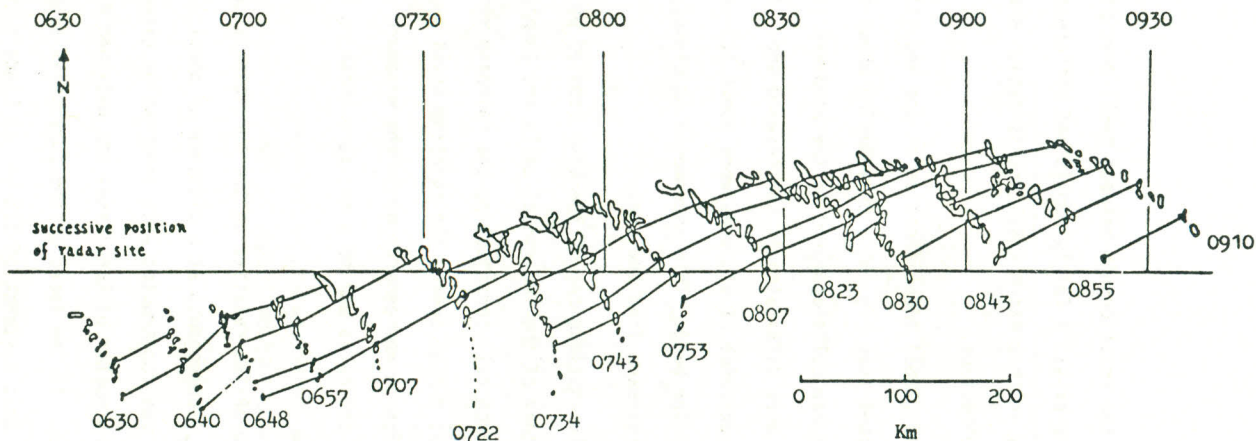
Fig. 5   Identification of individual cells constituting a rainband of
         Typhoon Helen (1958).   The cells connected with thin lines are
         identical.   The position of the radar site is shifted with time
         along an east-west axis.   (From Tatehira, 1962)
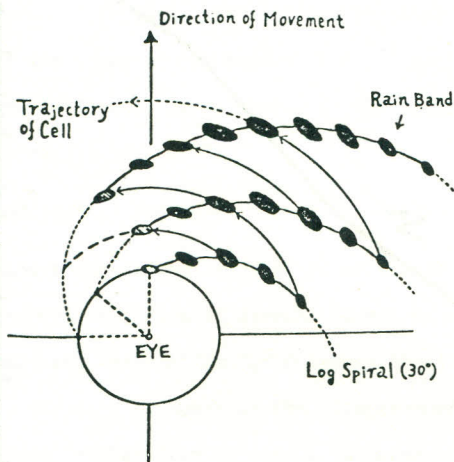
Fig.6.   Model displacement of a rainband relative
           to the eye.   In this figure the crossing
           angle of the rainband is exaggerated.
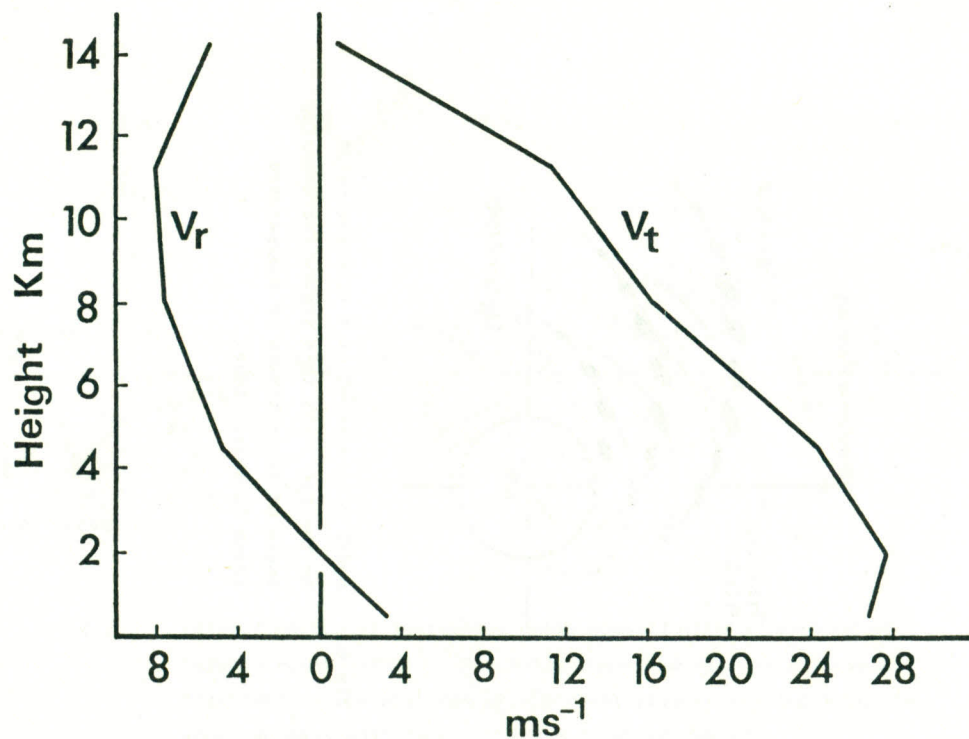   (From Tatehira, 1962)

Fig. 7   Wind profiles relative to the centre of the hurricane. V_r is the radial component and V_t is the tangential component. These profiles are at a distance of about 120 km from the eye.

it can be inferred from the V_t-profile (Fig.7) that there is relative inflow at all levels at the front of the convective elements. On the other hand, the rainband as a whole may be moving outwards relative to the eye with a speed between 3 to 15 m s^{-1}, as was pointed out before. Thus the wind profile relative to the band may show inflow at all levels if the speed of the band is 8 m s^{-1} or larger, or it may show inflow at low levels and outflow at upper levels if the speed of the band is smaller than 8 m s^{-1} (see V_r-profile of Fig. 7).

4. **Measurements of Meteorological Variables Within the Bands**

Gentry (1964) made observational studies of rainbands analysing data collected in longitudinal and normal traverses at several levels on different flights. For a specific rainband, however, information for only one level is given. Figs. 8 and 9 show data collected across a rainband of the intense Hurricane Daisy of 27 August, 1958. Data measured along (rather than across) a rainband in Hurricane Ella (1962) are presented in Fig. 10. Based on the cases presented in Figs. 8, 9 and 10, plus many others not reproduced here (see Gentry, 1964), Gentry suggests the following conclusions:

(1) Rainbands in tropical storms (i.e. less than hurricane intensity) are likely to have a mean temperature colder than that of the ambient atmosphere, but will usually have some much warmer portions. This is especially true for the outer bands.

(2) Rainbands in mature hurricanes are more likely to have higher mean temperatures than those in the ambient atmosphere, especially when the band is located near the eye wall.
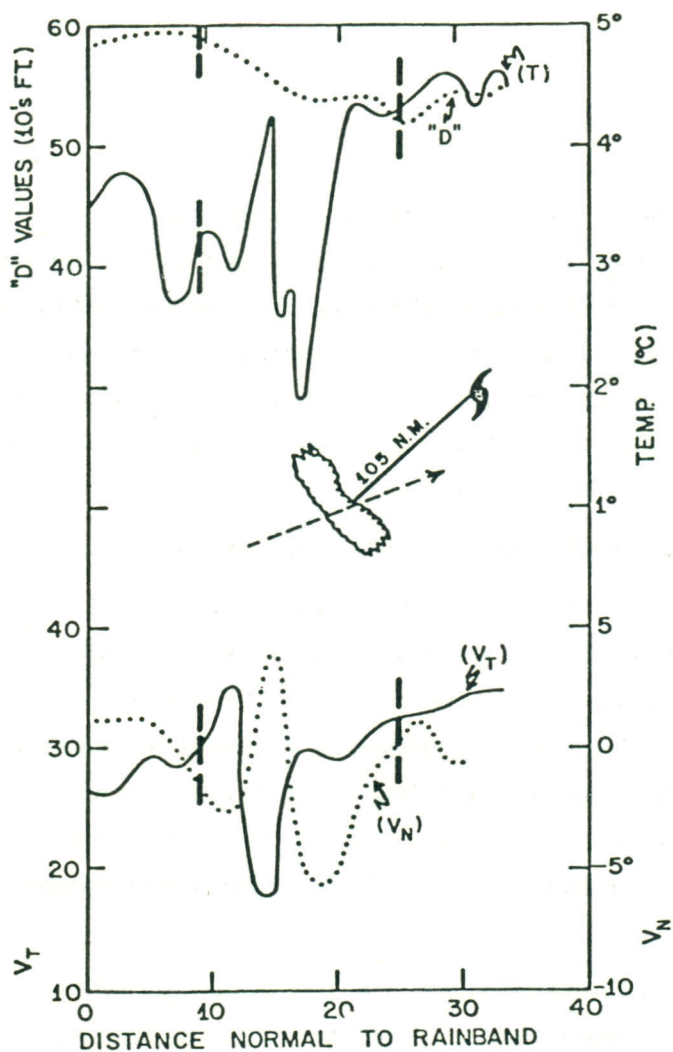
Fig. 8   Temperatures, D-values and wind components
          (in knots) along a track normal to the rain-
          band about 105 n mi southwest of the centre
          of Hurricane Daisy, August 27, 1958.   Broken
          vertical lines on the profiles mark band
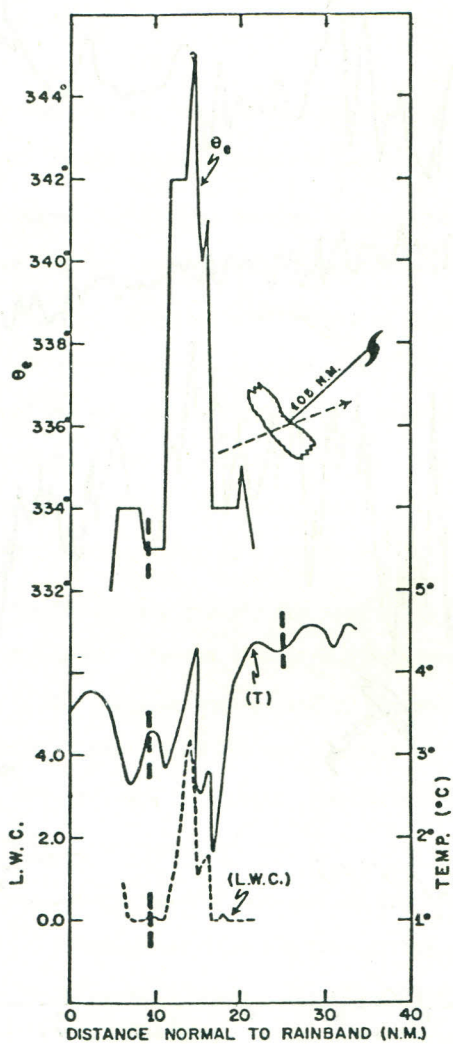   boundaries.   Flight elevation, 13,000 ft.
          (From Gentry, 1964)

Fig. 9   As for Fig. 8, except data are
          equivalent potential temperature,
          liquid water content (g m^{-3}), and
          Temperature.   (From Gentry, 1964)
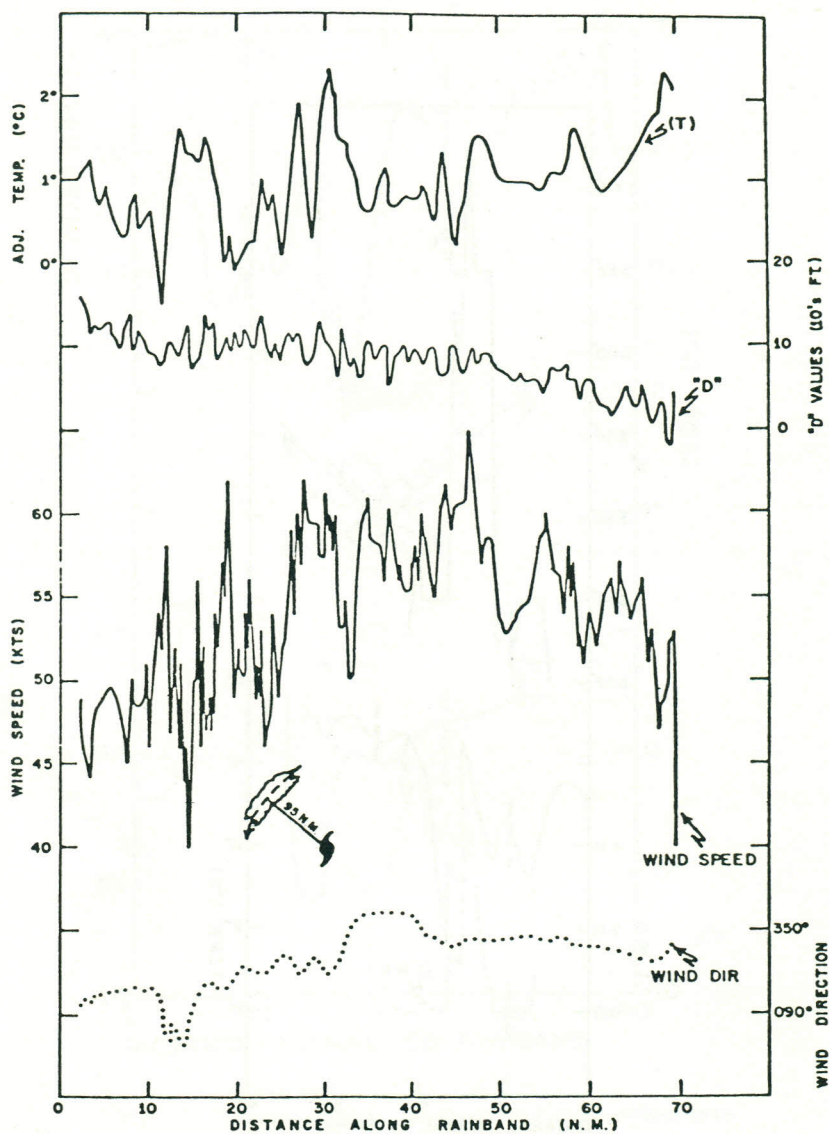
Fig. 10   Temperatures, D-values and winds recorded on
           longitudinal traverse of a rainband about 95 n mi
           northwest of the centre of Hurricane Ella,
           October 17, 1962.   Wind speeds are in knots.
           Flight elevation, 13,800 ft.   (From Gentry, 1964)

(3) Gradients of temperature, wind direction and wind speed are much greater inside
     rainbands than in the areas between the bands.

(4) There is no strong correlation between location of the maximum (minimum) wind
     speed and the high or low pressure sides of bands (except in the eye wall).

(5) Temperature gradients within the bands are as much as 2.5°C per 2 n.mi (2.5°C
     per 3.7 km) and are frequently greater than 1.5°C per 10 n.mi (1.5°C per 18.5 km).
     The anomaly of the mean temperature in the bands varies directly with the inten-
     sity of the storm, directly with altitude (at least to above the 5000 m level),
     and inversely with radius. The later relationship, however, is not noticeable
     except for bands within about 50 n.mi (93 km) radius of the storm's center.

(6) Winds along the bands vary greatly and apparently in association with microscale
     features of the band. Gradients in wind speed frequently exceed 10 kts per 5 n.mi
     (5 m s^{-1} per 9 km) and sometimes exceed 20 kts per 5 n.mi (10 m s^{-1} per 9 km).
     These gradients in wind speed are not as great as those along radii near the cen
     ter of the storm, but are far greater than previously indicated for variations
     along the bands.

(7) Exchange of air between various portions of the same band and between the various
     bands and their inmediate environment takes place very rapidly both in the outer
     bands and in the walls of the eye. This is indicated by the large gradients of
     the component of the wind normal to the bands, both within the bands and in the
     air 1 to 5 n.mi (1.8 to 9.3 km) on either side of the bands.

In some cases, the aircraft explorations do not show appreciable and systematic
changes in meteorological variables, especially winds, at the boundaries of the rain-
bands. This may be due merely to the fact that the bands contain a chain of indivi-

dual cumulonimbus and that changes of wind aloft will depend upon the position
of the aircraft traverse with respect to the individual clouds. Therefore ac-
counts of changes of the surface wind during the passage of such bands may be
more informative than aircraft measurements.

In the next section the surface changes in some meteorological parameters
observed during the passage of hurricane rainbands will be examined.

5. Surface Changes in Weather Elements Associated With The Passage of Tropical
Cyclones

5.1. General sequence

The general sequence of surface changes in meteorological variables
when a tropical cyclone approaches a station will be illustrated with
Hurricane Cleo (1964) when it struck the greater Miami area. This hurri-
cane remained small and concentrated most of the time, and destructive
winds were confined to a small area near the eye.

Figure 11, constructed with hourly data, presents a sequence of the
changes of surface weather elements at Miami International Airport. It
can be seen that when this hurricane approached Miami the wind speed in-
creased, the wind direction shifted gradually, the relative humidity in-
creased, the temperature and pressure decreased, and the rainfall increa-
sed. The maximum wind speed in Fig. 11 is about 32 m s^{-1}. However, it
is necessary to point out that the plotted wind speeds are average values
for a period of about five minutes, and that the recorded winds show
strong gusts with a maximum of about 44 m s^{-1}. In the period 0900 EST on
26 August to 0600 EST on 27 August, the wind backed gradually through
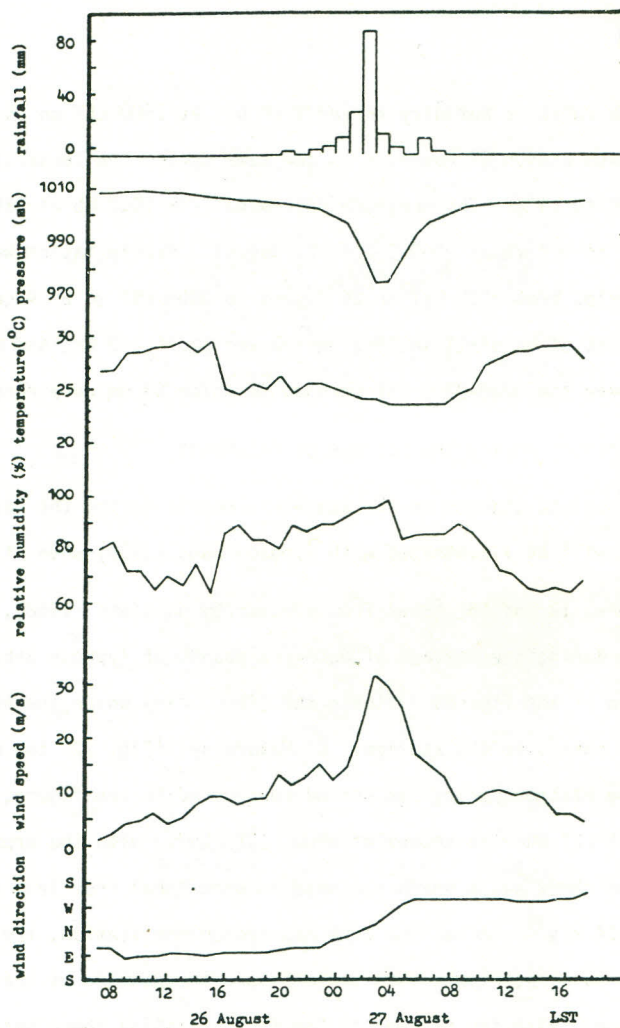
Fig. 11   Sequence of surface changes in weather elements
          at Miami International Airport during the passage
          of Hurricane Cleo (1964).

240°. The relative humidity varied from 65% at 1500 EST on 26 August to 100% at 0400 EST on 27 August. In the same period the temperature fell from 30 °C to 24°C. The pressure decreased from 1012 mb at 1100 EST on 26 August to 977 mb at 0300 EST on 27 August. Precipitation was recorded in the period from 2000 EST on 26 August to 0800 EST on 27 August. The total amount of rainfall in this period was about 162 mm, and most of this fell between the 0200-0300 EST period, in which 93 mm were recorded.

5.2. Surface changes during the passage of rainbands

The surface changes in the weather elements during the passage of rainbands will be illustrated with Typhoon Babs (1956) when it struck Japan.

Figures 12 and 13, taken from a paper by Ushijima (1958), present surface data during the passage of outer rainbands of Typhoon Babs. The arrow in the top of the figures indicate the time during which the bands were observed to pass over the station. At Makurazaki (Fig. 12) two other bands passed the station during the period considered in the figure, the first at about 0645 LST and the second at about 1020 LST. With the approach of the first band there was a sharp increase in wind speed from less than 10 m s^{-1} to about 24 m s^{-1}. After the band had passed the station, the wind speed decreased to values lower than those before the passage of the band over the station. With the passage of the first rainband there was a shift in wind direction, a decrease in temperature, an increase in pressure, and rain fell (the rainfall trace indicates no precipitation before the band had passed the station). The increase in pressure, which is caused by the cooler air in the downdraft, is preceded by a pressure dip of about 1 mb. With the

Fig. 12   Surface changes in weather elements at
            Makurazaki during the passage of Typhoon
            Babs, 1956.   Arrows show the arrival of
            the rainbands.   (From Ushijima, 1958)
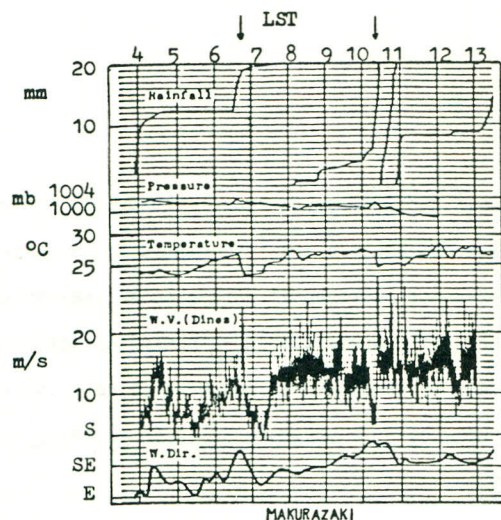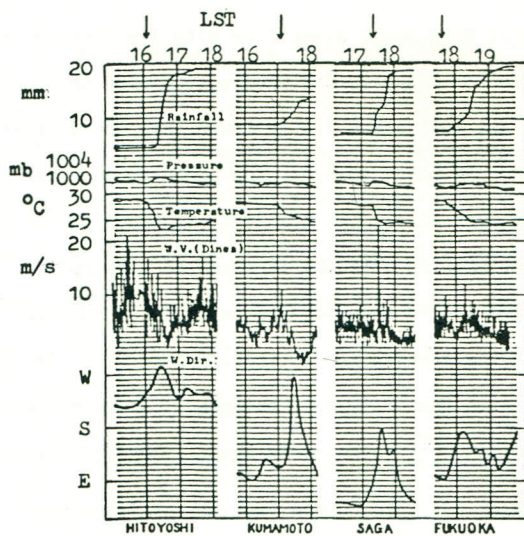

Fig. 13   Surface changes in weather elements at
            several stations during the passage of
            Typhoon Babs, 1956.   Arrows show the
            arrival of the rainbands.
            (From Ushijima, 1958)

passage of the second band (at approximately 1020 LST) the wind speed increased
from very low values of about 5 m s^{-1} to 30 m s^{-1}. In this case, however, the
wind speed decreased to values which were greater than those observed before
the passage of the band. A small change in wind direction was observed, toge
ther with a decrease in temperature and an appreciable increase in pressure,
which was again preceded by a pressure dip. An increase in rainfall intensity
was also observed.

Figure 13 presents surface data concerning changes in weather elements at
several stations during the passage of the outer band which, according to
Ushijima, passed over Makurazaki at about 1020 LST. At all these stations the
wind speed records show gusts associated with the passage of the band. At Hi-
toyoshi, Kumamoto and Fukuoka, the wind speed, once the gusts had taken place,
decreased to values that are a little lower than those observed before the pas-
sage of the band. At Saga, however, the contrary occurred. A shift in wind
direction is observed at all the stations, although in the case of Hitoyoshi it
does not coincide exactly with the increase in wind speed. The temperature de-
creased at all the stations during the passage of the band, and an increase in
pressure preceded by a pressure dip is also observed. At all the stations it
started to rain with the passage of the band. At Hitoyoshi and Fukuoka, the
passage of other bands is observed at about 1530 and 1730 LST respectively.

From the cases discussed above, as well as from others reported in the li-
terature (e.g., Wexler, 1947; Ushijima, 1958; Tatehira, 1962; Sethu Raman, 1977),
the following conclusions can be made in relation to the surface changes obser-
ved during the passage of hurricane rainbands over a site:

1. There is an increase in pressure produced by the downdraft, which is prece-
    ded by a pressure dip of about 1 mb. The nature of this dip is inclear but
    it suggests the existence of mesolows in advance of hurricane rainbands.
    Mesoslows in advance of mid-latitude cumulonimbus cloud systems have   been
    studied by Hoxit et al. (1976).

2. In general, the temperature falls and the relative humidity increases. Howe_
    ver, in one case (Tatehira, 1962) no significant variation of temperature
    and relative humidity was observed. In another case (Ushijima, 1958) the
    temperature increased and the relative humidity decreased during the passage
    of the rainband.

3. During the passage of a rainband the rainfall intensity increases apprecia-
    bly.

4. The wind increases sharply and large gusts are clearly observed in the wind
    strip charts. There is also an abrupt shift in wind direction.

    In summary, the surface changes associated with the passage of hurricane rain-
    bands are very similar to those observed during the passage of tropical squall
    lines (e.g. Fernández, 1982).

6. Tornadoes Associated with Hurricanes

    It is not our intention to examine in detail the formation of tornadoes within
hurricanes, but some aspects will be duscussed.

    Several cases of the occurrence of tornadoes associated with hurricanes have been
reported (e.g., Malkin and Galway, 1953; Sadowski, 1962, 1966; Rudd, 1964; Pearson and
Sadowski, 1965; Smith, 1965; Hill et al., 1966; Orton, 1970; Fujita et al., 1972;   No-

vlan and Gray, 1974). An exceptional case was Hurricane Beulah in 1967, in which 115 tornadoes were observed to occur (Orton, 1970). Most of the tornadoes have been observed to occur close to the time at which the storms cross land (Novlan and Gray, 1974) and most of them have spawned in the right front quadrants of the hurricanes (Smith, 1965; Fujita et al., 1972). The tornadoes are often associated with the strongest convective elements on the outer rainbands (Hill et al., 1966; Fujita et al., 1972). With a few exceptions the tornadoes associated with Hurricane Beulah (1967) occurred outside the area of hurricane force winds (Orton, 1970). Novlan and Gray (1974) have found that the most important difference between hurricanes which produce tornadoes and those which do not, are the values of wind shear between surface and 850 mb. This averages about 20 m s^{-1} for the tornado cases, but is much less in the cases which do not produce tornadoes. They also found that the differences in vertical stability are very small. Thus the dynamical aspects appear to dominate the thermodynamic aspects. Novlan and Gray have speculated that convective downdrafts may help to develop local areas of low-level horizontal wind shear which, from boundary layer frictional arguments, leads to intense small scale convergence, spin, and velocity concentration. This is supported by a detailed mesoanalysis of one typhoon-tornado case in Japan which was made by Fujita et al. (1972). Their study revealed the existence of a mesocyclone and a mesojet in the inmediate vicinity of the spawning ground of the tornado.

7. Explanations for Band Formation

Several possible explanations about the origin of the spiral bands in tropical cyclones have been suggested in the literature. However, the physical mechanism or   mechanisms   which are responsible for the organization of convective elements into spiral bands and the outward propagation of these bands is still uncertain.

In this section a review of such explanations will be made.

7.1. Explanations inferred from observations

Fletcher (1945) suggested that the spiral bands were formed when lines of clouds observed frequently within the ITCZ are "coiled" into the center of growing cyclones. According to Fletcher's theory only those hurricanes forming on the ITCZ will have spiral bands. This, of course, is not the case.

Wexler (1947) took into account the objection mentioned above to Fletcher's theory and extended his explanation. Wexler pointed out that if a circular vortex is introduced into a region of cloud streets originally oriented along the wind, as are frequently observed in tropical regions, then these streets or bands will spiral inward toward the center. Their width and spacing will change, depending on the vertical wind density gradients and the distribution and magnitude of the horizontal convergence associated with the vortex. Then, in this process, the prevailing bands are drawn into the hurricane circulation, which thereupon accentuates those bands of the proper wave-length and dissipates the reamining ones. This "resonance" effect, according to Wexler, causes the clouds comprising the "chosen" bands to grow into the cumulonimbus type.

Riehl (1951) simply suggested that the development of the spiral bands in hurricanes could be the result of internal gravity waves.

Ligda (1955) supported the idea that there is a distinct difference between the outer and inner spiral bands. He considered that the inner spiral bands are essentially a friction gradient level phenomenon and the outer bands a squall-line type of disturbance. He maintained that the spiral bands close to the eye are not caused by lines of thunderstorms or cumulonimbus clouds, but are a result of raindrop

growth as the hydrometeors fall through lower cloud layers. These clouds, accor-
ding to this theory, may be of the stratocumulus roll type. Concerning the cau-
se of the outer spiral bands, Ligda suggests two possible reasons: first, these
bands may be caused by a kind of microfrontal phenomenon, that is, they may oc-
cur at the boundary between low level air masses of different characteristics; se
cond, the bands may be a type of squall-line phenomenon. Ligda favours the la-
tter hypothesis, since it seems to agree better with occasional observations of
tornadoes in the outer bands, and fits better with the general radar and surface
observations. Kessler and Atlas (1956) simply proposed a banded structure of ho
rizontal convergence.

Senn and Hiser (1959) reasoned that "the spiral bands form near the ring   of
maximum convergence close to the eye, as a result of some phenomena such as gra-
vity waves, or the strong upthrust which occurs at the wall cloud, not by a uni-
form circular release of energy there which would create ever-widening circular
bands of weather, but by energy which is probably released as it oscillates
around the wall cloud which forms the eye. Such an oscillation might create one
portion of a spiral band in a given quadrant at a given time and another section
of the spiral at a later time in the next counterclockwise quadrant. The result
of this time differential in the continuous formation of the band would impart
a spiral shape and establish its quadrants with respect to the storm center.
This also accounts for irregularities in the shape of the eye, which is formed
by spiral bands in the generative stages. Both the gravity wave and the hurri-
cane's upper-level circular or outward wind field could then provide the mecha-
nism for the outward propagation of the spirals which usually remain in the same
quadrant or quadrants in which they form".

Atlas et al. (1963) have reasoned, similarly to Ligda (1955), that the struc
ture of the inner bands is the result of size distribution, trajectories,   and
thermodynamic interactions of falling hydrometeors. They built a three-dimensio
nal model of a spiral band, utilizing vertical radar cross-sections of echo in-
tensity in Hurricane Esther (1961). They support the idea that with the excep-
tion of the outermost band(s) of convective elements (the pre-hurricane squall
lines) and the wall cloud itself, the inner spiral bands of a hurricane are lar-
gely stratiform and have convective clouds only at their upwind ends. The authors
suggest that the stratiform spirals are composed of plumes of precipitation re-
leased from convective generators at the head of the band. According to the au-
thors, the generating clouds appear to propagate up-band, thus manintaining a
virtually continuous plume for one or more hours, the typical band lifetimes.
The next effect is echo motion along the band in both directions; the plume ex-
tends downwind while the source cloud propagates upwind. The outward radial
component of propagation of the source clouds gives the band its outward veloci-
ty.

7.2. Explanations inferred from laboratory experiments

Laboratory experiments trying to simulate spiral bands have been attempted
by Faller (1962) and Arakawa and Manabe (1963a, 1963b, 1966). Faller's thesis
is that the spiral structure is a product of instability of a laminar Ekman boun-
dary layer, the initial instability taking the form of spiral convective bands
whose spacing is proportional to the depth of the boundary layer. Then he made
a comparison of the forms of the basic laboratory experiments with that of hurri-
canes; comparison of the characteristics of the instability with the banded struc

ture of hurricanes, e.g. angles, spacings, etc., and analogy between the laminar
flow of experimental models and the turbulent structure of the atmospheric boun-
dary layer. The fact that hurricane bands are observed to move outward is   a
difference for which two possible explanations consistent with his thesis are su
ggested by Faller: (1) that the average band angle is greater than that of the
stationary roll vortices and that they are advected outward by the normal compo-
nent of flow; (2) that the additional energy source from the release of latent
heat may couple with the original source of convective motion in the bands, so
that the band shape is maintained   but so that they tend to propagate outward.

Arakawa and Manabe (1963a, 1963b) found that in order to create a vortex ty
pe cloud it appears that the typhoon center should have a precession motion and
that the kernal (which consists of intense phenomena such as the atmospheric con
densation occurring near the eye wall) should move with it. No physicial expla-
nation for the spiral bands is given.

7.3. **Explanations based on the results of analytical and numerical studies**

Tepper (1958) applied the model of the squall line he previously proposed
(Tepper, 1950) to the hurricane radar band. His model is the model ot the at-
mospheric gravity wave. As he pointed out, to produce an atmospheric gravity
wave, two meteorological features are required: (1) a stratification of the am-
bient atmosphere, such that there exists a stable layer aloft, and (2) accele-
ration of the flow is required. He assumes, based on evidence of many soundings,
that a stable layer exists aloft. Concerning the second condition, he prescri-
bes that initially, at time t = 0 "something" happens to impress an inflow on
the circulation. Solving the **inviscid** shallow water equations with the method
of characteristics, **Tepper** found a pattern of gravity waves propagating outward.

He concluded that the fact that observations of squall lines and hurricane radar bands are similar, lends credence to the asumption that they may be produced by the same mechanism. Individual convective cells carried by the circulating winds will move relative to the radar band in a manner similar to that of individual convective cells relative to a squall line. His results indicate a propagation velocity of about 14 m s^{-1}.

Krishnamurti (1961, 1962) solved the primitive equations of atmospheric motion utilizing the method of characteristics and imposing on such systems of equations the commonly observed geometry of the tangential wind field in hurri canes. He found that the computed vertical motion exhibits a spiral form, very similar to that wich is observed in radar pictures of hurricanes.

Yamamoto (1963) treated "elastoid waves" and "elastoid-gravoid waves" for a horizontal circular vortex or a simple model of tropical cyclones. He found, introducing those types of waves, that dynamical possibilities for a banded struc ture and for a spiral shape of equal phase regions of upward motion exist in a case of a simple circular vortex of an incomprenssible homogeneous atmosphere.

Tang, Brooks and Watson (1964) extended the work of Yamamoto (1963) to a three dimensional baroclinic model. They obtained spiral bands in the vertical motion field for a thermally unstable atmosphere. Tang (1966) found that the thermal stability is the most important parameter affecting the lateral spacing and the crossing angle between the bands and concentric circles. The crossing angle and lateral spacing decrease as the atmosphere becomes more unstable.

Abdullah (1966) has explained the spiral structure of the rainbands as a manifestation of the Doppler shift. Since the inner part of the hurricane has

a high angular velocity compared with the outer part, a wave that is excited by
a disturbance moving with the wind in the eye wall will be distorted into a
spiral. Abdullah's main hypothesis is that the bands are associated with gravita-
tional waves of finite amplitude propagating at the interface of a high-level in-
version. An external source of disturbance is postulated in the form of a fresh
surge of air at the exterior of the hurricane. He found that this mechanism leads
to the formation of bands of the required shape. Then he suggests that the spiral
bands of a hurricane are closely related to the squall lines of temperature latitu
des. Working a numerical example, Abdullah found that a squall line appears first
at the periphery of the eye, and it grows outward as it rotates cyclonically in
the same sense as the basic flow. Once the squall line appears, it grows outward
at a great rate. In his example, it takes less than 20 minutes to advance from the
periphery of the eye to a point at the radius 100 km. This velocity (83 m s^{-1}) is
very large compared with observational evidence.

Hlachova and Vitek (1967) solved the linearised ω-equation. In their solutions
they found spiral bands of upward and downward motion.

MacDonald (1968) has presented some evidence for the existence of Rossby-like
eddies in hurricanes. As pointed out by Willoughby (1977), MacDonald's idea is
that the spiral rainbands may be vorticity waves that resemble Rossby waves but
depend upon the radial gradient of relative vorticity in the hurricane, rather than
on the meridional gradient of planetary vorticity.

Anthes, Rosenthal and Trout (1971), and Anthes, Trout and Rosenthal (1971) de-
veloped an asymmetric model which produced spiral bands of convection. Further,
Anthes (1972) improved this model in order to describe the formation and maintenan-
ce of spiral bands in greater detail. The spiral bands in the model, with rain-

fall rates averaging about 2 cm/day, are approximately 90 km wide at large distances from the center and somewhat wider close to the center (approximately 200 km). These bands, formed near the center, rotate cyclonically and propagate outward at a speed of about 12 m s^{-1}. Although the spiral bands in the model are internal gravity waves modified by latent heat release, the mechanism for their generation is unknown. The asymmetries in the outflow layer are shown to result from dynamic instability, with the source of eddy kinetic energy being the mean azimuthal flow. However, as pointed out by Diercks (1975), the physical relationship, if any, between inertial instability and spiral bands, is obscure and the simultaneous formation may be only coincidence.

Kurihara and Tuleya (1974) constructed a three-dimensional, 11-level, primitive equation model for a simulation of tropical cyclones. Their model produces spiral bands which behave like internal gravity waves, with a well defined pattern of low level convergence and surface pressure tendency. Once the band is formed in an area surrounding the center, it propagates outward apparently without appreciable further supply of energy. The speed of propagation is approximately 100 km/h (28 m s^{-1}), and the widths approximately 100 km. In their study it was found that the surface pressure tnedency is an appropriate quantity for detecting spiral bands in a tropical cyclone at the mature stage. However, these pressure tendency bands strech much longer than the rainbands and many portions of the bands are without precipitation.

Mathur (1975) investigated the development of the propagating and stationary bands in a three-dimensional model of Hurricane Isbel (1964). Stationary and clockwise propagating bands developed in his model. The shape and the structure of these bands were different from those formed in the models by Anthes (1972) and Kurihara

and Tuleya (1974). He concluded that development of the propagating bands in his model is related to the release of latent heat in the upper **troposphere.** Then the propagating bands in the vertical motion fields in the middle and the upper troposphere form in the regions of strong heating in the upper **troposphere** and weak cooling in the middle troposphere. They dissipate when the cooling in the upper troposphere, due to vertical advection, exceeds the condensational heating. He thinks that their structure is similar to the outer bands observed in hurricanes; they move at an average speed of 8 to 12 m s^{-1}.

Diercks (1975) and Diercks and Anthes (1976b) used a linear model to study the formation of bands **form** internal gravity-inertia waves in a barotropic atmosphere. Their primary result is that rotation organizes initial random perturbations into a spiral form in experiments with unstable static stability. With stable static stability, significant growth is not observed, but random perturbations are organized into a spiral pattern by rotation in the mean flow. These linear experiments also demostrated that neither inertial instability nor latent heat release are necessary for the band formation in the linear model, that the Coriolis parameter is relatively unimportant in forming these bands, and that rotation is necessary before spiral bands form. In addition, bands formed without the effect of including surface friction. It was found that the band separation increases but the growth rate decreases in experiments in which adiabatic warming occurs with descent, and warming due to latent heat release occurs with ascending motion.

Diercks (1975) and Diercks and Anthes (1976a) have also used a three dimensional model (Anthes, 1972) to study the energy and angular momentum budgets of model rainbands. In the nonlinear model, spiral bands of upward motion formed

continuously and propagated outward from the center of the simulated hurricane. These bands were probably travelling gravity-inertia waves, consistent with the small differences in mean radial and tangential velocity components, temperature and humidity between the bands and environment. Also, the nearly identical values of relative vorticity in the bands and environment support the conclusion that the model bands are gravity waves, modified slightly by rotation (the relative vorticity of a pure gravity waves is zero).

Kurihara (1976) investigated the linear development of the band structure in a tropical cyclone by solving an eigenvalue problem for perturbations of spiral shape. He showed that the spiral bands in three different modes may be intensified in an inner area of a tropical cyclone. However, only one of these modes (G-mode in Kurihara's terminology) has been observed in nature. Kurihara found that a spiral band which propagates outward can grow in the presence of the horizontal shear of the basic azimuthal flow. Without the basic circular vortex, this band is reduced to a neutral gravity-inertia wave with a particular vertical structure. The unstable spiral in this mode takes a pattern which extends clockwise from the center of a storm in the northern hemisphere. An azimuthal wavenumber 2 and a radial scale (twice the band width) of 200 km, are preferred by this band. Kurihara also found that there exists practically no instability in the outer region of the storm in any kind of spiral band. He speculated that a band which grows in an inner area and propagates outward may become a neutral spiral while moving toward the outer region. Kurihara considered that some of the outer spiral bands observed in real tropical cyclones may be interpreted as this type of internal gravity-inertia wave. Thus the actual outer spiral bands, at least some of them, may be interpreted as the counter clockwise,

outward-propagating, internal gravity-inertia waves which are intensified in an
inner area by the radial shear of the azimuthal flow and possibly also by the
effect of heating.

Jones (1977) improved the model proposed by Anthes, Rosenthal and Trout (1971)
and Anthes (1972) for hurricane simulation, increasing, signifcantly the domain
size and refining the horizontal grid resolution. This has been accomplished by
a system of three nested grids, the inner two of which move with the hurricane
center. The grids are fully interacting with changes on finer grids feeding back
to the coarser grids. In his experiments, there are two distinct band propagation
rates and band widths. At the mid-troposhere level the bands typically propagate
outward at about 60 m s^{-1} and have a wavelength of about 600 km. At the top of
the boundary layer the typical band propages outward at about 12 m s^{-1} and has a
wave-length of about 120 km. Jones found that the occurrence of outward propaga-
ting spiral gravity wave bands is directly connected to barotropic instability
near the eye-wall of the vortex. As pointed out by Jones, the mechanism for the
generation of the spiral bands can be inferred from the relationship between the
rotating azimuthal wave number two in the wind field (middle troposphere) and the
region of origin of the spiral bands. The spiral bands are produced by the mutual
adjustment of mass and momentum in the rotating elliptically-shaped asymmetry.
Hence Jones concludes that the rotating asymmetry generates the spiral bands.

Fung (1977 a,b) has examined Rayleigh instability of the hurricane's bounda-
ry layer as the mechanism responsable for the organization of the observed rain-
band pattern. She found that Rayleigh instability of the boundary layer produces
spiral regions of upward and downward motion. The regions of upward motion pro-

vide a site for cloud formation, forming a spiral pattern which resembles the observed rainbands in a hurricane.

Willoughby (1977) has made an attempt to model spiral rainbands in hurricanes as inertia-buoyancy waves. The model is based on the nonhydrostatic equations describing in cylindrical coordinates linear perturbations on a barotropic vortex embedded in a uniformly stratified atmosphere. The system supports waves whose frequencies are confined to a passband between the local inertia frequency and the buoyancy frequency, and which obtain energy at the expense of the mean flow's kinetic energy. Willoughby found that the very long radial wavelengths are not possible for outward-propagating waves because the magnitude of an inertia-buoyan cy wave's frequency must lie between the buoyancy and local inertia values and also because of the role of the Doppler shift. On the other hand, for the shorter wavelengths in his model, the rate of energy supply is too slow to permit growth of outward propagating waves in the face of geometric spreading. In addition, a lower limit is imposed on the frequency of these waves because the large local inertial frequency in the eye wall must be less than the intrinsic frequen cy there. This means that the apparent frequency must assume higher values than are observed for spiral bands. So Willoughby (1977) concludes that outward propagating inertia buoyancy waves, excited near the storm's centre, do not seem to constitute a plausible model for hurricane rainbands. On the other hand, Willoughby (1978a) has found that inward propagating waves on a barotropic vortex are a plausible model for hurricane rainbands. In this context, inward propagation means that the energy is propagating inward from the storm's periphery. As pointed out by Willoughby, the intrinsic phase propagation is also inward, but because the waves are advected tangentially around the storm in the cyclonic sen

se, the phase lines appear to propagate outward at a fixed radius.

Willoughby (1978b) extended the model of rainbands on a barotropic vortex developed previously by him (Willoughby, 1977, 1978a) to simulate linear waves on a baroclinic mean vortex. Although the energetics is more complicated than in the case of barotropic vortex, the results support the model of rainbands as inward propagating inertia-buoyancy waves. The spiral bands may be excited with small amplitude perturbations at the storm's periphery by such processes as asymmetric frictional forces, flow over coastal topography, or shearing environmental steering currents. The role of the latter process as a mechanism for the excitation of spiral bands, has been examined by Willoughby(1979). He found that inward propagating inertia-buoyancy waves are excited by imbalances between the Coriolis force due to the storm's motion and the pressure gradient force associated with a shearing environmental geostrophic wind. As the results are consistent with observations, Willoughby concludes that the interaction between the symmetric mean vortex and a shearing environmental steering current may be the cause of spiral bands in hurricanes.

8. Conclusion

In this paper the main characteristics of spiral rainbands in hurricanes have been discussed. The outer rainbands or pre-hurricane squall lines appear to be similar in some aspects to tropical squall lines. Several explanations on the origin and organization of hurricane rainbands have been examined. However, a convincing explanation of their origin is not yet available. Wave theory, as discussed by Willoughby, is an interesting possibility, but a comparison of the theory results with more observational data is essential. Although

numerical models of hurricanes have been able to produce rainbands, some characte-
ristics of the modelled bands appear not to agree with observations. For example,
the modelled bands are much wider than the rainbands observed with radar.

An important aspect not considered here is the role of hurricane rainbands
in the production of kinetic energy. The fact that much latent heat of condensa-
tion is released in the rainbands other than the eye wall, suggests that all
the rainbands are important when considering the energy budget of the hurricane.
Gentry (1964) found that the rainbands play an important role in the transforma-
tion of potential into kinetic energy, even though his data were insufficient to
make a complete kinetic energy budget. This topic should constitute an important
aspect in further studies of hurricane rainbands.

Acknowledgements

References

Abdullah, A. J., 1966: The spiral bands of a hurricane: a possible dynamic explanation.
    J. Atmos. Sic., 23, 367-375.

Anthes, R.A., 1972: The development of asymmetries in a three-dimensional numerical mo-
    del of the tropical cyclone. Mon. Wea. Rev., 100, 461-476.

Anthes, R.A., 1974: The dynamics and energetics of mature tropical cyclones. Rev. Geo-
    phys. Space Phys., 12. 495-522.

Anthes, R.A., S.L. Rosenthal and J.W. Trout, 1971: Preliminary results from an asymmetric
    model of the tropical cyclone. Mon. Wea. Rev., 99, 744-758.

Anthes, R.A., J.W. Trout and S. L. Rosenthal, 1971: Comparisons of tropical cyclone simu-
    lations with and without the assumption of circular symmetric. Mon. Wea. Rev., 99
    759-766.

Arakawa, H. and D. Manabe, 1963a.: Investigation of spiral rainbands and frontal struc-
    tures in terms of shallow water waves. Pap. Meteor. Geophys., 14, 127-143.

Arakawa, H. and D. Manabe, 1963b: A model experiment on spiral rainbands- a dish pan ex-
    periment. Proc. of the Symposium on Tropical Meteorology, Rotorua, New Zealand,
    5-13 November. New Zealand Meteorological Service, Wellington, 404-415.

Arakawa, H. and D. Manabe, 1966: Some considerations on spiral cloud patterns in typhoo-
    nic area by means of experiments using travelling disturbing element through a sha-
    llow water tank. Geophys. Mag., 33, 89-98.

Atlas, D., K. R. Hardy, R. Wexler and R. J. Boucher, 1963: On the origin of hurricane
    spiral bands. Geofísica Internacional, 3, 123-132.

Diercks, J.W., 1975: Propagation and maintenance of spiral bands in linear and nonlinear
    models. Ph.D Thesis, Pennsylvania State University, University Park, Pennsylvania.

Diercks, J.W. and R.A. Anthes, 1976a: Diagnostic studies of spiral rainbands in a non-
    linear hurricane model. J. Atmos. Sci., 33, 959-975.

Diercks, J.W. and R.A. Anthes, 1976b: A study of spiral bands in a linear model of a
    cyclonic vortex. J. Atmos. Sci., 33, **1714-1729**.

Faller, A. J., 1962: An experimental analogy to and proposed explanation of hurricane
    spiral bands. National Hurricane Research Project Report No. 50, U.S. Weather
    Bureau, Washington, D.C. 307-313.

Fernández, W. 1982: Environmental conditions and structure of the West African and
    Eastern tropical Atlantic squall lines. Arch. Met. Geoph. Biokl. A31, 71-89.

Fletcher, R. D., 1945: The general circulation of the tropical and equatorial atmosphere. J. Meteor., 8, 167-174.

Fritz, S., L.F. Hubert and A. Timchalk, 1966: Some inferences from satellite pictures of tropical disturbances. Mon. Wea. Rev., 94, 231-236.

Fujita, T.T., K. Watanabe, K. Tsuchiya and M. Shimada, 1972: Typhoon associated tornadoes in Japan and new evidence of suction vortices in a tornado near Tokyo. J. Meteor. Soc. Japan, 50, 431-453.

Fung, I.Y., 1977a: The organization of spiral rainbands in a hurricane. Sc.D. Thesis, Massachussetts Institute of Technology, Cambridge, Mass.

Fung, I.Y., 1977b: The organization of spiral rainbands in a hurricane. Preprints 11 th Tech. Conf. on Hurricanes and Tropical Meteorology, 13-16 Dec., Florida. Amer. Met. Soc., 40-43.

Gentry, R.C., 1964: A study of hurricane rainbands. National Hurricane Research Report No.69, U.S. Weather Bureau, Washington, D.C.

Hill, E.L.,W. Malkin and W.A. Schulz, Jr. 1966: Tornadoes associated with cyclones of tropical origin-practical features. J. Appl. Meteor., 5, 745-763.

Hlachova, P. and V. Vitek, 1967: Simple theoretical interpretation of the spiral structure of cloudiness in a tropical cyclone. Studia Geophysica et Geodaetica, 11, 311-316.

Hoxit, L.R., C.F. Chappell and J.M. Fritsch, 1976: Formation of mesolows or pressure troughts in advance of cumulonimbus clouds. Mon. Wea. Rev., 104, 1419-1428.

Jones, R.W., 1977: A nested grid for a three-dimensional model of a tropical cyclone. J. Atmos. Sci., 34, 1528-1533.

Jordan, C.L., 1963: The accuracy of center positions of hurricanes as determined by the spiral overlay technique. Weather Radar, 10, 202-207.

Kessler, E. and D. Atlas, 1956: Radar-synoptic analysis of Hurricane Edna, 1954. Geophys. Res. Paper No. 50, Air Force Cambridge Research Center, Bedford, Mass.

Krishnamurti, T.N., 1961: On the vertical velocity field in a steady, symmetric hurricane. Tellus, 13, 171-180.

Krishnamurti, T.N., 1962: Some numerical calculations of the vertical velocity field in hurricanes. Tellus, 14, 195-211.

Kurihara, Y., 1976: On the development of spiral bands in a tropical cyclone. J. Atmos. Sci., 33, 940-958.

Kurihara, Y. and R.E. Tuleya, 1974: Structure of a tropical cyclone developed in a three-dimensional numerical simulation model. J. Atmos. Sci., 31, 893-919.

Ligda, M.G.H., 1955: Analysis of motion of small precipitation areas and bands in the
     Hurricane August 23-28, 1949. Technical Note No. 3., Dept. of Meteorology, Massa-
     chusetts Institute of Technology, Cambridge, Mass.

MacDonald, N.J., 1968: The evidence for the existence of Rossby-like waves in the hu-
     rricane vortex. Tellus, $\underline{20}$, 138-150.

Malkus, J.S., C. Ronne and M. **Chaffee** 1961: Cloud patterns in Hurricane Daisy. Tellus,
     $\underline{13}$, 8-30.

Mathur, M.B., 1975: Development of banded structure in a numerically simulated hurri-
     cane. J. Atmos. Sci., $\underline{32}$, 512-522.

Malkin, W. and J. G. Galway, 1953: Tornadoes associated with hurricanes as illustrated
     by Franconia, Va., tornado, September 1, 1952. Mon. Wea. Rev., $\underline{81}$, 299-303.

Miller, B.I., 1958: The three-dimensional wind structure around a tropical cyclone.
     National Hurricane Research Project Report No.15, U.S. Weather Bureau, Washington,
     D.C.

Novlan, D.J. and W.M. Gray, 1974: Hurricane-spawned tornadoes. Mon. Wea. Rev., $\underline{102}$,
     476-488.

Orton, R., 1970: Tornadoes associated with Hurricane Beulah on September 19-23, 1963.
     Mon. Wea. Rev., $\underline{98}$, 541-547.

Pearson, A.D. and A.F. Sadowski, 1965: Hurricane-induced tornadoes and their distri-
     bution. Mon. Wea. Rev., $\underline{93}$, 461-464.

Riehl, H., 1951: Aerology of tropical storms. Compendium of Meteorology, Amer. Met.
     Soc., Boston, Mass., 902-913.

Rudd, M.I., 1964: Tornadoes during Hurricane Carla at Galveston. Mon. Wea. Rev.,
     $\underline{92}$, 251-254.

Sadowski, A., 1962: Tornadoes associated with Hurricane Carla, 1961. Mon. Wea. Rev.,
     $\underline{90}$, 514-516.

Sadowski, A., 1966: Tornadoes with hurricanes. Weatherwise, $\underline{71}$, 71-75.

Senn, H.V. and H.W. Hiser, 1959: On the origin of hurricane spiral rainbands. J.
     Meteor., $\underline{16}$, 419-426.

Senn, H.V., H.W. Hiser and R.C. Bourret, 1957: Studies of hurricane spiral bands as
     observed on radar. National Hurricane Research Project Report No. 12, U.S. Wea-
     ther Bureau, Washington, D.C.

Sethu Raman, S., 1977: Some micro-meteorological observations during the approach and passage of Hurricane Belle (1976). Preprints 11th. Tech. Conf. on Hurricanes and Trop. Meteor., Florida, 13-16 December, Amer. Met. Soc., 554-557.

Sheets, R.C., 1968: The structure of Hurricane Dora (1964). Technical Memorandum No.83, National Hurricane Research Laboratory, Miami, Florida.

Sivaramakrisham, M.V. and M.V. Selvan, 1966: On the use of spiral overlay techniques for estimating the center positions of tropical cyclones from satellite photographs taken over the Indian region. Proc. of the 12th Conference on Radar Meteorology, Norman, Oklahoma, Oct. 1966, American Meteorological Society, Boston, Mass. 440-446.

Smith, J.S., 1965: The hurricane-tornado. Mon Wea. Rev., 93, 453-459.

Tang, W., 1966: Meteorological variables critical to geometry of hurricane spiral bands. GCA Tech. Report No. 66-17-G. Final Report, Contract No. Cwb-11191, GCA Corporation, Bedford, Mass.

Tang, W., E.M. Brooks and B.F. Watson, 1964: Theoretical and observational studies of vortex cloud patterns. GCA Tech. Report No. 64-2-G., Final Report, Contract No. Cwb-10626, GCA Corporation, Bedord, Mass.

Tatehira, R., 1962: A mesosynoptic and radar analysis of typhoon rainband. National Hurricane Research Report No. 50, U.S. Weather Bureau, Washington, D.C. 115-126.

Tepper, M. 1950: A proposed mechanism of squall lines: the pressure jump line. J. Meteor., 7, 21-29.

Tepper, M., 1958: A theoretical model for hurricane radar bands. Proc. of the Seventh Weather Radar Conference, Miami Beach, Florida Nov. 17-20, Amer. Met. Soc., Boston, pp. K56-K65.

Ushijima, T., 1958: Outer rain bands of typhoons. J. Meteor. Soc. Japan, 36, 1-10.

Watanabe, K., 1963: The radar bands and typhoon structure. Proceedings of the Symposium on Tropical Meteorology, Rotorua, New Zealand, 484-491, New Zealand Meteorological Service, Wellington.

Wexler, H., 1947: Structure of hurricanes as determined by radar. Annals of the New York Academy of Sciences, 48(8), 821-844.

Willoughby, H.E. 1977: Inertia-buoyancy waves in hurricanes. J. Atmos. Sci., 34, 1028-1039.

Willoughby, H.E., 1978a: A possible mechanism for the formation of hurricane rainbands. J. Atmos. Sci., 35, 838-848.

Willoughby, H.E., 1978b: The vertical structure of hurricane rainbands and their interac
     tion with the mean vortex. J. Atmos. Sci., 35, 849-858.

Willoughby, H.E., 1979: Excitation of spiral bands in hurricanes by interaction between
     the symmetric mean vortex and a shearing environmental steering current. J. Atmos.
     Sci., 36, 1226-1235.

Yamamoto, R., 1963: A dynamical theory of spiral rainband in tropical cyclones. Tellus,
     15, 155-161.