The evidence for the existence of Rossby-like waves in the hurricane vortex

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(Manuscript received September 1, 1966)

ABSTRACT

The qualitative and quantitative evidence for the existence of Rossby-like eddies in hurricanes is examined. It is found that the spiral rain bands exhibit many characteristics similar to those found in the troughs in the "Rossby Waves" of the general circulation. In addition to many qualitative analogies, the spiral bands are regions where a substantial amount of potential energy is converted to kinetic. Although there are no direct measurements to show that the spiral rain bands mark the presence of a Rossby-like wave structure, observations of the momentum budget suggest that there is an eddy flux of momentum into hurricanes in the same sense as that observed in the general circulation.

1. Introduction

One observed property of rotating fluids is the frequent appearance of undulating, wave-like motions in a horizontal or spherical surface normal to the axis of rotation. The wave motions indicate the presence of an organized eddy structure in the fluid. Where observations are available, the eddy structure, in certain cases referred to as "Rossby Waves", frequently effects a counter gradient transport of physical quantities along the horizontal surface. From the rotating tank experiments of Hide (1953) and Fultz *et al.*, (1959) it has been surmised that the appearance of the Rossby waves depends both on the rate of rotation and the thermal gradient impressed radially along the horizontal plane. The Rossby waves that are found in the fluid motions that comprise the general circulation of the terrestrial atmosphere are also thought to be dependent on the earth's rotation and the solar-induced latitudinal temperature profile. Some recent rotating tank experiments described by Lambert & Snyder (1966) have shown that horizontal velocity shear can also affect the critical Rossby number at which the fluid motion changes from the symmetrical (simple convection) to the Rossby wave regime. Observational studies of the proper motion of sunspots have led Ward (1964), (1965), to conclude that Rossby waves exist in the photospheric "wind" field of the solar atmosphere. Whether a latitudinal thermal profile exists along the solar surface or not is still debatable. Finally, Webster reports (1961), (1965) that the eddy structure found in the Gulf Stream produces a surface flux of momentum toward higher mean velocities. Furthermore, associated with the momentum flux is a surface transfer of kinetic energy from the eddies to the mean flow. It thus appears that Rossby-like waves (or eddies) are a frequent, if not common, property of rotating fluids in general.

In all cases where measurements have been possible in a fluid containing Rossby waves, it has been found that the organized eddy structure effects a countergradient flux of momentum to maintain a velocity maximum in the mean flow against frictional and possibly other kinds of dissipation. In the tank experiments, in the general circulation and the Gulf Stream, it is known that the momentum transports (and kinetic energy transformations) by the eddies act to maintain a horizontal velocity profile having a maximum not only of linear but also of angular velocity relative to the rotating solid. In the solar atmosphere it should be noted that the Rossby waves transport mo-

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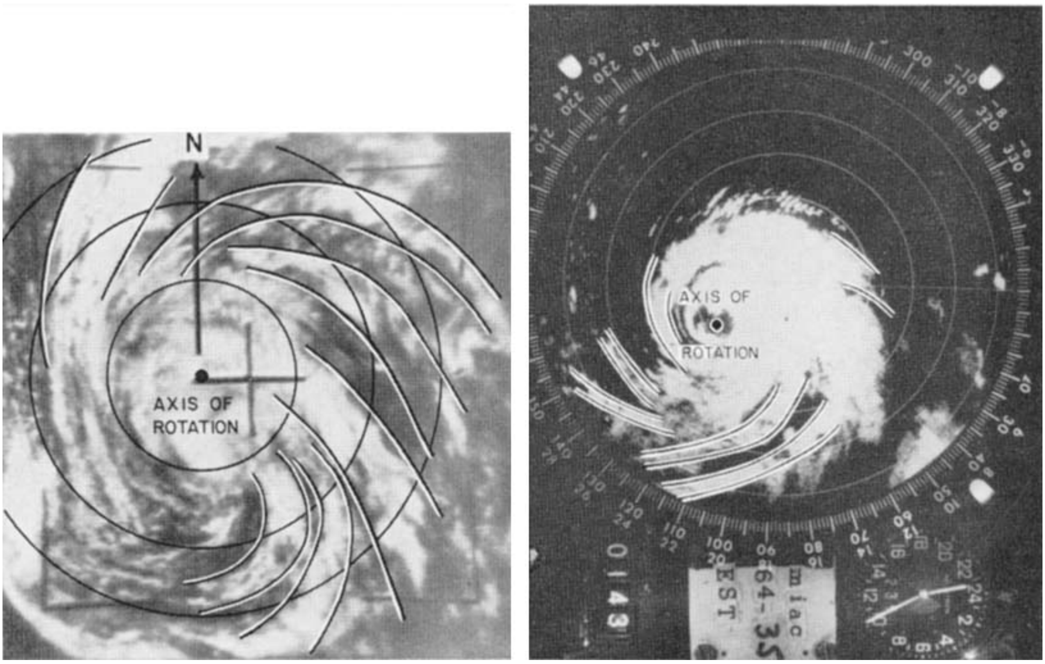

a *b*

Fig. 1. The spiral cloud patterns as photographed by a satellite (*a*) and through the radar scope of a high-flying aircraft (*b*). The lines enclosing the reflected radiation denote the outer limits of the major spiral bands.

mentum up the gradient of absolute angular velocity so as to maintain the equatorial acceleration against dissipation.

The fully developed, mature hurricane can be considered as a fluid in rotation with a horizontal (and vertical) shear of the fluid motion that perists throughout much of the lifetime of the hurricane. It is the purpose of this paper to examine the evidence for the existence of Rossby-like waves in the hurricane vortex. Certain qualitative arguments will be advanced to show that the spiral rain (or cloud) bands indicate the presence of such an eddy structure. The quantitative evidence is summarized and it is shown that there frequently is an inward transport of cyclonic angular momentum by the horizontal eddy exchange process in those hurricanes where sufficient wind measurements were available. The transport by the eddies is, on occasion, within a factor of three of the surface frictional drain of momentum.

2. Qualitative considerations

One of the outstanding features observed in a hurricane is the spiral cloud structure shown in satellite photographs and identifiable on radar scopes as shown in Fig. 1. Numerous studies have shown that the bands are regions of heavy rainfall and large convective-type clouds. The regions between the bands, while not cloud free, are areas where precipitation is, at the most, modest and the vertical development of clouds is at a minimum. The nonuniform distribution of clouds and precipitation implies that, in addition to the mean large-scale convection process, there must be some important horizontal asymmetries in the vertical motion field of the hurricane.

The spiral bands tilt outward from the axis of rotation of the hurricane in the same sense as the "throughs" in the wave structure of the general circulation. The clouds associated with the typical northeast-southwest troughs (N. H.) should appear, from an extraterrestrial viewpoint, to spiral outward from the axis of rotation of the earth as depicted in Fig. 2. The spiral clouds in hurricanes appear to be analogous to those in tropopsheric through in many other ways. Tatehira (1962) has shown that convergence in the surface wind field leads

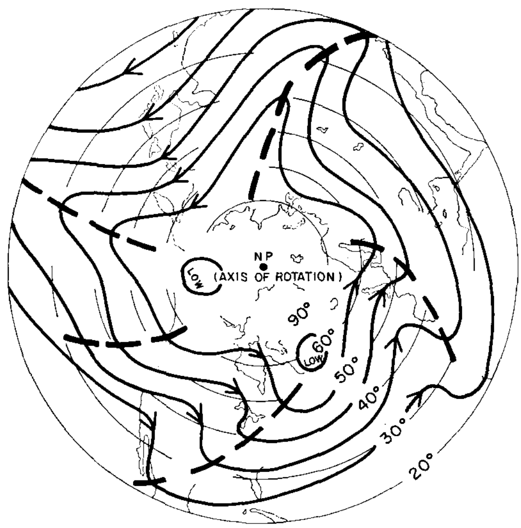

Fig. 2. An artist's conception of how clouds associated with tilted troughs in the troposphere might appear from an extra terrestrial viewpoint.

the bands and divergence follows. The heavy rain consistently observed under and in the bands implies that the upward motion of the air is most pronounced in these regions. It is a generally accepted fact that the upward vertical motion of air in the planetary scale circulation is common in the troughs.

As studies by Senn & Hiser (1959), and Wexler (1963) have shown, the spiral cloud bands are composed mostly of numerous, large convective, cellular clouds. The individual cells form on the upwind side of the band and move inward toward the axis of rotation as their horizontal and vertical dimensions increase. The decay and eventual dissipation of the cells takes place some 10 to 20 miles downwind, at or near the edge of the band. Thus, the bands are marked in the optical and radar portion of the spectrum by the reflections from the dense concentrations of water droplets in the convective cells. From a study of the azimuthal motion of a large number of bands, Senn & Hiser (1959) have concluded that the aximuthal motion is substantially less than the mean tangential component of the wind field in which they are found, i.e., the air moves *through* the bands. It is a well-known fact that the large-scale waves in the general circulation move longitudinally at a speed less than that of the mean zonal wind field in which they are embedded. Within the confines of the troughs in the general circulation, the individual cloud and precipitation-filled cyclones form, grow and move poleward toward the axis of rotation of the earth. In many ways, then, the troughs in the general circulation and the spiral bands in hurricanes appear to be superficially analogous, albeit on a different time and space scale.

3. Quantitative aspects

One analogy between these two phenomena has some quantitative support. It is observed that much of the kinetic energy of the gross motions near the earth's surface is found in the migratory cyclones that are generally found under the upper-level troughs. The author has found that the surface winds were stronger under the spiral rain bands associated with two New England hurricanes than the winds outside the bands. Hurricanes Edna (1954) and Esther (1962) passed over southeastern New England and were well monitored by radar as reported by Kessler (1957) and Atlas (1963) for a period of 10 and 20 hours respectively. The surface winds recorded at hourly intervals by the Weather Bureau observers at locations within the range of the radar were used to compute the average wind speed under and outside of the spiral rain bands. In the first column of Table 1, the difference between the mean tangential (V_t) and radial (V_r) wind components under and outside of the bands was determined using all of the 220 wind observations made during the passage of Edna and 400 observations during Esther's passage. The second column shows the difference between the magnitude of the wind components with each observing point entering the mean with equal weight. The weighting procedure consisted of a computation of the average wind under and out of the band at each location over the period of observation. Each average so computed (22 locations in the case of Edna and 20 during the passage of Esther) was used to compute the mean shown in column 2 of Table 1. This latter method was used to minimize the effects of any bias produced by orographic effects on the wind speed or the exposure of the anemometer. In this table, and throughout the paper, the tangential wind is considered positive in the cyclonic sense. An inward component of the radial wind is treated as positive. It can be seen from Table 1 that

Table 1. *The difference, Δ( ), between the magnitudes of the time averaged tangential and radial components of the surface wind, $\bar{V}_t$, and $\bar{V}_r$ respectively, under and outside of the spiral rainbands associated with two New England hurricanes*

The positive values of $\Delta(\bar{V}_t)$ and $\Delta(\bar{V}_r)$ signify that the average wind is stronger under the band. Units are knots.

		Column	
		I (Unweighted)	II (Weighted by location)
$\Delta(\bar{V}_t)$	Esther	0.3	0.3
	Edna	1.9	1.5
$\Delta(\bar{V}_r)$	Esther	3.2	1.5
	Edna	2.9	4.0

both components of the surface winds were consistently stronger under the bands than outside.

If the bands are Rossby-like waves or eddies in the general circulation of the hurricane, then one should expect that energy transformations within the eddies should be important. Saltzman & Fleisher (1961) have shown that the conversion of available zonal potential energy to kinetic takes place in the eddies in the tropospheric general circulation with a wavelength comparable to the dimensions of typical cyclones. Most of the kinetic energy is found in cyclones so that it seems likely that the potential energy conversion takes place through the correlation of the vertical motion and temperatue field associated with cyclones. Simultaneous measurements of the vertical motion and temperature field have been made by aircraft flying in a number of rainbands in hurricanes as reported by Gentry (1964). According to him these observations show that the fluctuations of the vertical motion and temperature, associated with the convective cells in the bands, are correlated so that available potential energy is converted to kinetic. Gentry estimates that as much kinetic energy is produced in the bands as previous studies had indicated to be generated from all other sources in the average hurricane.

If Rossby-like waves are present in the hurricane one should also expect that angular momentum should be transported into the vortex by the eddy structure. Observational studies by Starr, *et al.* (1954) of the momentum budget of the general circulation have shown that, over most latitudes, the flux of relative angular momentum toward the axis of the earth's rotation occurs through the horizontal eddy exchange process. With the possible exception of the tropics, the poleward transport of momentum by the meridionally oriented mean vertical eddies[1] is either negligible or negative. On the other hand, it is generally believed that a substantial flux of cyclonic momentum into hurricanes takes place through the mean vertical circulation produced by free or forced convection. It is crucial to the hypothesis that spiral bands reflect the presence of Rossby-like waves, to determine the relative importance of the horizontal eddy flux in the momentum budget of hurricanes. Some efforts in that direction have been reported in the literature notably by Pfeffer (1958*a*, 1958*b*) and Riehl (1961) using composite or mean climatological data to make the estimates. In his paper, Pfeffer concluded that cyclonic angular momentum is transported into the outer periphery (within 120 nautical miles) of the vortex by the surrounding horizontal eddy structure. But until recently, wind observations closer to the center of the hurricane vortex have been sparse and not in sufficient quantity for a decomposition of the mean and eddy wind components around the center. In the past decade data have been collected by aircraft instrumented for research purposes within several hurricanes. From the wind observations obtained by these flights it has been possible to measure the momentum flux at a number of levels by the horizontal eddy exchange process closer to the center.

4. The momentum flux in hurricanes

It is convenient to measure the transport of angular momentum into a cyclonic vortex in the manner first suggested by Starr (1953) and later applied specifically to hurricanes by Pfeffer (1958*a*). The instantaneous momentum transport is measured across a series of vertical walls surrounding the atmospheric volume of a stationary hurricane with each wall chosen to

[1] *The Hadley cells produced by free or forced* convection.

enclose a fixed cylindrical volume about the axis of rotation of the hurricane. Assuming that the diameter of the base of the atmospheric volume is small and the hurricane is located away from the equator, then the beta effect can be neglected (see Pfeffer 1958*b*). The vertically integrated flux of angular momentum from the top of the atmosphere to the surface relative to the axis of rotation, across the fixed boundary at one instant in time is given by:

$$\frac{1}{g}\int_0^{P_0}\oint_L M V_r \, ds \, dp =$$

$$= \frac{2\pi R P_0}{g}\{\overline{[M]}\,\overline{[v_r]} + \overline{[M]^*[v_r]^*} + \overline{[M'v_r']}\} \quad (1)$$

where:

M = absolute angular momentum per unit mass relative to the specified axis,
V_r = radial wind component (normal to the wall) and considered positive when directed inward,
L = $2\pi R$,
R = distance of the wall from the axis of rotation,
g = acceleration of gravity,
P_0 = surface pressure.

The brackets refer to the azimuthal means and the bar the mean with respect to pressure. The primes and asterisks refer to the departure from these means, respectively. It is tacitly assumed in this formalization that the hydrostatic assumption is valid and that a pressure surface is nearly enough at a constant height at the distance, R, around the vortex.

The first term on the right of (1) describes the momentum flux produced by the net transport of mass into or out of the volume. As Pfeffer (1958) has noted, in hurricanes it seems unlikely that this term, by itself, is important in maintaining a steady state hurricane. These systems usually weaken when the pressure rises. The remaining terms comprise the flux by the vertical and horizontal eddy exchange process. The importance of the vertical eddy can be measured by the vertical correlation of the azimuthal means of M and V_r at one instant in time. A net inward transport by the vertical eddy takes place when there are cyclonic winds in the low-level inflow area and anticyclonic (or weaker cyclonic) motions in the region of upperlevel outflow. The horizontal eddy component depends on an azimuthal correlation between M and V_r at individual levels in the vertical wall. If the term is consistently positive, the angular momentum should be greatest where the inflow is strongest and vice versa allowing a net inward flux by the horizontal eddies.

It should be noted that the pressure (and frictional torques) and the vertical transports of momentum are not contained in (1). For purposes of this paper, no effort is made to examine the redistribution of momentum in the atmospheric volume by vertical motions but the intent is to examine the flux normal to the whole vertical wall only. In the absence of fixed topographical barriers (such as mountains) the pressure torque vanishes identically. The net effect of molecular and small-scale eddy viscosity along the boundaries of the atmospheric volume is probably very small compared to the torque exerted by the underlying surface (i.e., skin friction). The surface torque is presumably draining the cyclonic momentum from the steady-state hurricane at a rate comparable to the flux described by (1).

The angular momentum per unit mass, M, described in (1) is composed of that due to the earth's rotation and that associated with the motion relative to the earth's surface around the axis of rotation of the hurricane, so that:

$$M = \Omega R^2 + V_t R \quad (2)$$

where Ω is the earth's rotation rate about the axis of the cylinder, and V_t is the cyclonic tangential wind component. Assuming that $[\overline{V}_r] = 0$ at the wall, then the momentum due to the earth's rotation is constant about the chosen axis of the cylinder. Under these conditions, the variability of M depends only on the tangential wind component at the distance R of the wall from the axis of rotation. Without a net inflow of mass, the angular momentum due to the earth's rotation cannot be transported inward to increase the total within the whole volume.

5. Estimates of the momentum flux

Ideally, the measurements of the winds necessary to decompose the eddy fluxes should be made by aircraft making simultaneous observations azimuthally around a fixed radial distance from the center and at altitudes ranging from the low-level cyclonic inflow and including the anticyclonic outflow layer. The purpose of such flights would be to sample the vertically integrated flux across the wall into the atmospheric volume. Practically, such coordinated flights have been difficult to make for a variety of reasons, among them the scarcity of well-instrumented aircraft.

In the past there have been some samples of the flux made at one or two levels by research aircraft flown by the NHRL[1] and the Air Force Cambridge Research Laboratories. Using the data collected on those flights, estimates of the horizontal eddy flux in several hurricanes have been made. The flux by the horizontal eddy exchange process at one level is measured by the covariance of V_t and V_r. When the correlation[2] of V_t and V_r is significantly different from zero, the momentum flux by the horizontal eddies is not negligible. The spatial correlations of the V_t and V_r wind components have been computed at several levels and certain distances from the center of hurricanes Carla (1961), Gladys (1964) and Betsy (1965). A complete summary of the aircraft type, flight dates, time, altitude and the distribution of the points where the observations were made with respect to the cyclone centers is contained in the appendix.

The correlations were computed only from those cases where observations were made circumferentially through at least 180 azimuthal degrees with respect to the storm center. Vertical walls were selected of a finite horizontal width of 20 miles to allow a sufficient number of observations for significant correlations. Each wall was restricted to this radial extent to minimize the effect of the radial variations of $[V_t]$ and $[V_r]$ that are both believed to be increasing inward. In addition, all data collected on radial flight patterns were excluded. The computations were further stratified by using only observations made over 2000 ft intervals in the vertical to minimize the chance of spurious correlations introduced by the presence of the vertical variations. It is assumed that time variations of V_t and V_r over the 1- to 3-hour period of each flight were negligible. The distribution of the mean tangential and radial components; also the covariances and correlations are shown in Table 2. The correlations are further summarized in Tables 3 and 4.

The 17 sets of correlations in Table 2 are summarized in Table 3 and stratified by radial distance from the hurricane center and by sign. Table 4 displays the same set of correlations distributed by height and sign. The number of positive correlations exceeds those that are negative by about a factor of 2 to 1. The number of correlations significant at or above the 99% confidence level[3] denoted in parentheses, is well in excess of that expected by chance. Two-thirds of the significant correlations are positive, and one half of these occur in the very low levels in the region of maximum cyclonic wind. The negative correlations imply that the eddy structure tilts away from the axis of rotation in the opposite sense to the average spiral band. Such orientation of the bands is occasionally observed. It is of interest to note that two significant negative correlations were found in hurricane Betsy during the time the direction of motion was reversing and the hurricane wall cloud was collapsing.

The correlations were computed, separately, in each quadrant and there was no obvious bias in the distribution of correlations by quadrants. It can be seen from Table 3 that there is no obvious bias in the importance of the eddy flux with distance from the cyclone's center. Table 4 clearly indicates that the sampling, to date, has been strongly biased to the lower levels of hurricanes.

A direct comparison of the relative importance of the contribution of the horizontal and vertical eddies to the momentum flux is not possible from the data collected to date. It is therefore of interest to determine whether the inward component of the horizontal eddy flux is, on any occasion, significantly close to the rate at which momentum is lost to the earth's surface by friction in the typical hurricane. The average covariance of V_t and V_r was obtained from the 3 cases where the correlations were significantly positive at a distance of 60 nautical

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[2] $r(V_t, V_r) = ([V_t' V_r'] / \sigma V_t \sigma V_r)$.

[3] The confidence level assumes that the pairs entering the correlations are independent. However, serial correlation is present and the degrees of freedom are somewhat lower than N shown in the tables.

Table 2. *The mean tangential and radial wind components* $[V_t]$, $[V_r]$ *respectively, the spatial covariance* $[V_t', V_r']$, *and the correlation* $r(V_t, V_r)$ *of* V_t *and* V_r *computed from wind data collected during 14 flights in three different hurricanes*

N refers to the number of data points entering into the computation of the means and the number of pairs entering the correlation. R refers to the average distance from the storm center and H to the average height. The asterisk denotes the correlations significant at or above the 99 % confidence levels respectively.

Hurricane name and date	N	$[V_t]$ (m/sec)	$[V_r]$ (m/sec)	$[V_t', V_r']$ (m^2/sec^2)	$r(V_t, V_r)$	R (n. mi.)	$H(\times 10^3$ ft)
Carla							
9.8.61	94	30.1	0.6	2.85	.26*	80	10
9.9.61	65	30.2	0.8	3.16	.32*	80	20
9.9.61	110	33.6	0.5	2.12	.10	80	5
Gladys							
9.17.64	69	28.6	0.7	−2.88	−.15	60	10
9.17.64	27	11.5	−0.7	−1.55	−.11	80	42
9.17.64	57	33.4	0.1	−0.20	−.01	40	5
9.17.64	34	34.7	−1.2	4.87	.18	40	10
9.17.64	35	29.9	1.3	1.31	.07	40	15
9.17.64	61	36.0	−0.5	14.30	.80*	40	2
Betsy							
9.3.65	89	27.5	0.8	−5.82	−.30*	60	12
9.3.65	98	27.9	9.2	11.49	.75*	60	2
9.3.65	61	26.3	−2.4	0.21	.01	60	18
9.3.65	89	31.6	0.5	1.97	.19	60	7
9.5.65	50	29.7	5.1	4.09	.36*	60	2
9.5.65	96	27.7	2.0	−8.76	−.62*	60	7
9.5.65	103	10.9	−2.6	2.05	.32*	60	25
9.5.65	72	31.7	−0.9	−4.32	−.44*	60	12

miles from the hurricane center. The measured fluxes ranged in height from 2000 ft to 25,000 ft and averaged 5.9×10^4 cm^2/sec^2. Assuming that the net flux above the 30,000 ft level ($\sim$300 mb) by the horizontal eddies is negligible, then from (1) the average eddy flux of cyclonic momentum across the vertical wall centered 60 miles from the center is 1.6×10^{22} gm cm^2/sec^2. The rate of the frictional drain of momentum over the surface area contained at the base of the at-

Table 3. *The 17 sets of correlations shown in Table 2 summarized with respect to distances from the storm center*

Parentheses denote number of these correlations significantly different from zero at or above the 99 % confidence level.

Distance from hurricane center (nautical miles)	$r(V_t, V_r) > 0$ (inward eddy flux of momentum)	$r(V_t, V_r) < 0$ (outward eddy flux of momentum)	Total
71–90	3 (2)	1	4 (2)
51–70	5 (3)	4 (3)	9 (6)
31–50	3 (1)	1	4 (1)
Total	11 (6)	6 (3)	17 (9)

Table 4. *The 17 sets of correlations shown in Table 2 summarized with respect to height above msl*

Parentheses denote those correlations significantly different from zero at or above the 99 % confidence level.

Height above msl ($\times 10^3$ ft)	$r(V_t, V_r) > 0$ (inward eddy flux of momentum)	$r(V_t, V_r) < 0$ (outward eddy flux of momentum)	Total
1 to 9.9	5 (3)	2 (1)	7 (4)
10 to 19.9	4 (1)	3 (2)	7 (3)
> 19.9	2 (2)	1 (0)	3 (2)
Total	11 (6)	6 (3)	17 (9)

mospheric volume within 60 N miles of the center is estimated by:

$$\int_0^{2\pi}\int_0^R \tau r^2\, dr\, d\theta \tag{3}$$

where τ is the surface stress, approximated by

$$\tau = \partial_0 V_t |V_t| C_d \tag{4}$$

In this approximation, we let $V_t = [V_t]$ be a function of r alone where $[V_t]$ is the azimuthal mean tangential wind component averaged at 12-mile intervals along r; C_d is the drag coefficient, and ∂_0 is the surface density. The radial profile of $[V_t]$ from the 60 to 30 miles was obtained from the "average" hurricane wind profile data published by Hughes (1952). The profile farther inward to the center was determined by a linear interpolation between the value at 30 miles and zero at the center. A drag coefficient, C_d, of 3×10^{-3} was estimated from an extrapolation of the data published by Deacon *et al.* (1956). From these data and the use of (3) and (4) the rate of frictional drain was computed to be 4.5×10^{22} gm cm^2/sec^2. The cyclonic angular momentum pumped into the hurricanes by the horizontal eddies, in the cases where the correlations were significantly positive is, therefore, within a factor of 3 of this rate. In view of the difficulties inherent in the wind measurements and the uncertainties in the estimates of the frictional drag, this agreement is about as reasonable as can be expected.

Discussion

The consistent observations of the variability of clouds and precipitation outward from the hurricane wall clouds can be interpreted, qualitatively, as evidence for asymmetries in the upward vertical motion field. From the correlations that have been presented in this paper, it appears that azimuthal asymmetries (or eddies) are often found in the horizontal wind field over most elevations inside the hurricane vortex. The eddies are frequently organized in such a fashion that cyclonic angular momentum is transported inward toward the tangential wind maximum found close to the axis of rotation of the hurricane. The measurements showing an inward eddy transport of momentum disagree with some earlier estimates reported by Riehl (1961) from data assembled over a period of several days. Unless the asymmetries remain azimuthally fixed with respect to the hurricane center and their time variations over several days are negligible, the compositing of data will mask the eddies. Observations by Senn & Hiser (1959), Tatehira (1962) and Wexler (1963) have shown that the spiral bands do not remain in a fixed position within the hurricane, but rather move, appear and disappear over periods of a few hours. If the bands are associated with the asymmetries, then the form of compositing done previously amounts to a smoothing which damps out the variance of the spatial wind field and hence masks the contribution of the eddies to the momentum flux. In most of the results described in this paper, the measurements taken during the flights were made over a period of time close to that of the average lifetime of the spiral bands and more closely approximate the instantaneous wind field.

Other asymmetries in fluids subject to rotation that appear qualitatively similar to the spiral bands have been found to be waves of the Rossby type. This is specifically the case in the general circulation of the terrestrial atmosphere where the waves are transporting relative angular momentum up the gradient of relative angular velocity. Although the same process appears to be at least partially responsible for the momentum transport in hurricanes, the observations described in this paper do not show that the spiral bands are, themselves, a portion of Rossby-like waves in the general circulation of the hurricane vortex. That question can best be answered by resolving the cyclonic and radial wind field in and around the bands or by decomposing the eddy wind component into wave components and examining the momentum flux contributed by each wave number. Future research plans include an observational program designed to examine the wind field around the spiral bands and to resolve the instantaneous vertical and horizontal eddy fluxes. However, the results to date suggest that there are horizontal asymmetries, similar to Rossby waves, in the cyclonic wind field of hurricanes, that play a role in the angular momentum budget of hurricanes. It seems likely that spiral rain bands mark the location of these asymmetries within the hurricane vortex.

Acknowledgemcnts

My appreciation is extended to Mr. C. N. Touart and Dr. F. Ward of the Air Force Cambridge Research Laboratories for the many helpful suggestions and criticisms during the paration of this manuscript. To Professor V. P. Starr of the Massachusetts Institute of Techology, my special thanks are due for reviewing the final manuscript. The staff of the NHRL (ESSA) and their director, Dr. R. Cecil Gentry, have been extremely cooperative in the coordination of the research flights. Finally, to Dr. R. Cunningham and Mr. D. M. McLeod of AFCRL my thanks for the time and effort spent in the logistics involved with the flights of the Air Force aircraft.

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ПРОЯВЛЕНИЕ СУЩЕСТВОВАНИЯ ВОЛН ТИПА ВОЛН РОССБИ В ВИХРЕ УРАГАНА

Изучается качественное и количественное проявление факта существования вихрей типа волн Россби в ураганах. Найдено, что спиральные системы дождевых облаков обладают многими характеристиками, аналогичными тем, которые найдены для гребней «волн Россби» в общей циркуляции. В дополнение ко многим качественным аналогиям, спиральные структуры являются областями, где значительное количество потенциальной энергии превращается в кинетическую энергию. Хотя не существует прямых измерений, показывающих, что спиральные структуры дождевых облаков выявляют присутствие структуры типа волн Россби, наблюдения над балансом импульса дают основания предполагать, что имеется вихревой поток импульса в ураганы в том же смысле, как и тот поток, что наблюдается в общей циркуляции.

APPENDIX

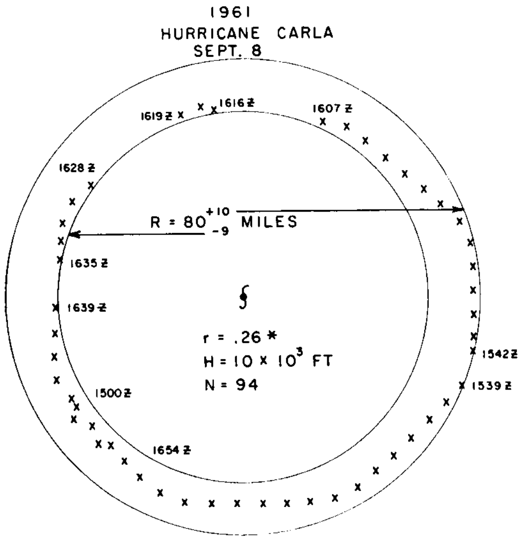


Fig. 3

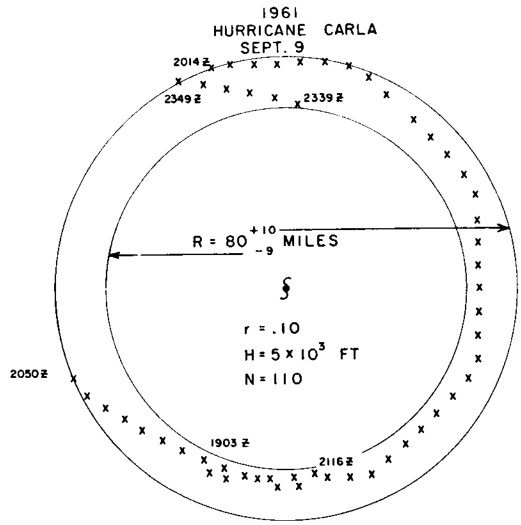
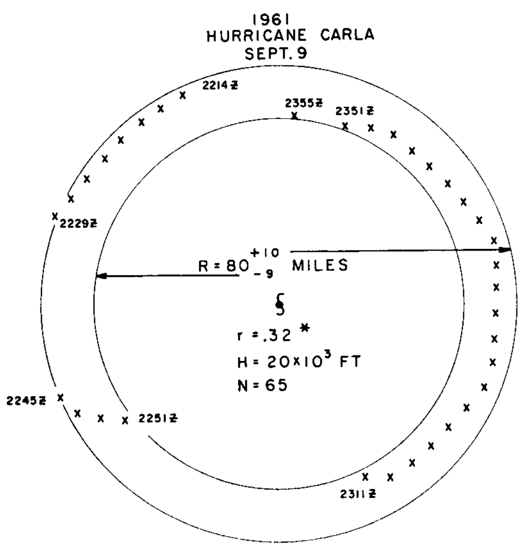


Fig. 5



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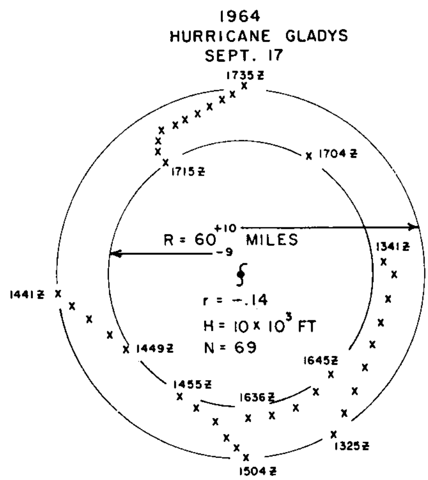

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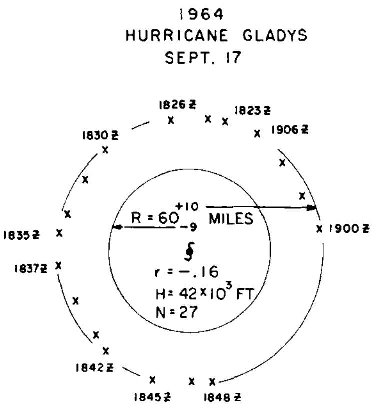
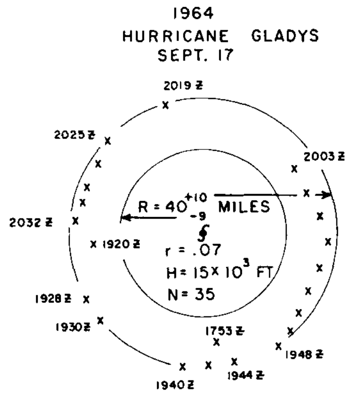


Fig. 7



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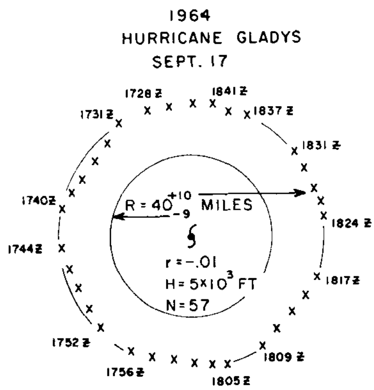

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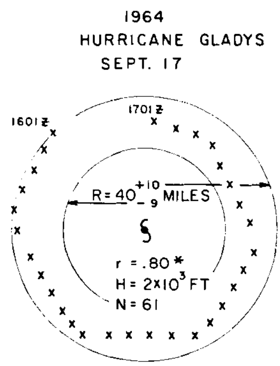
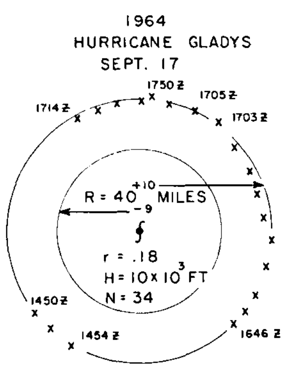


Fig. 11



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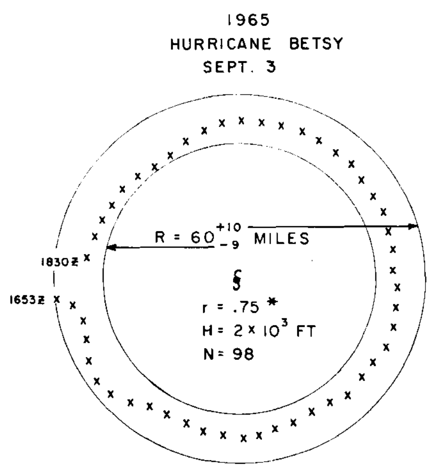

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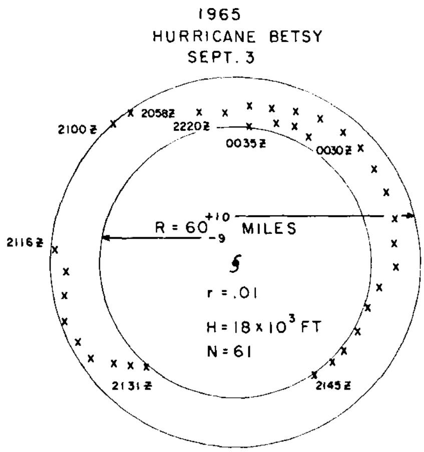

Fig. 13

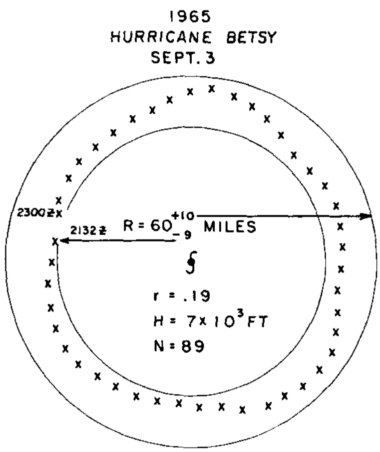

Fig. 14

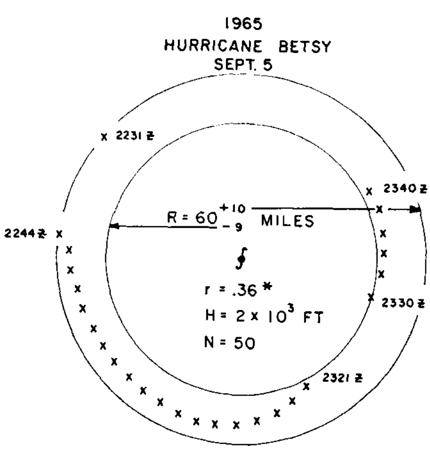

Fig. 15

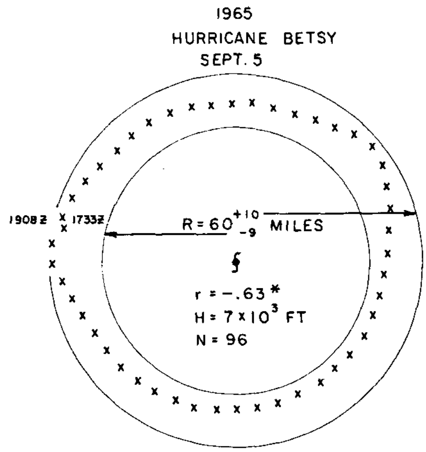

Fig. 16

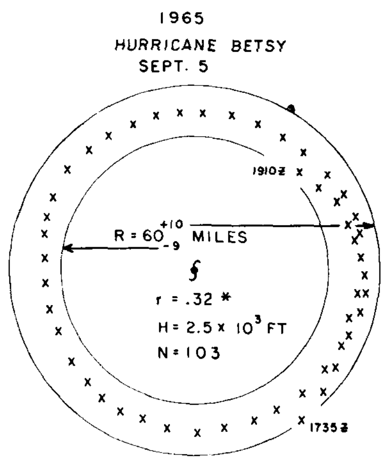

Fig. 17

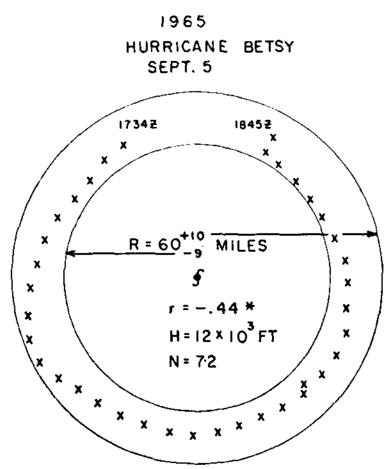

Fig. 18

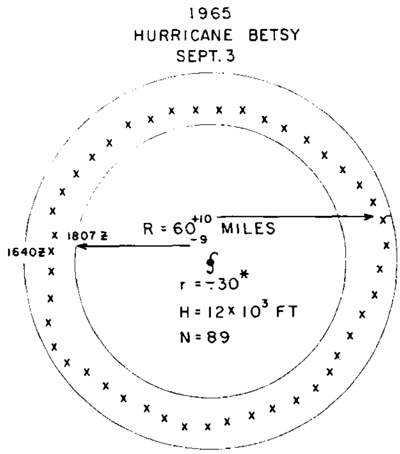

Fig. 19

A summary of the hurricane flights from which the data contained in Tables 2 through 4 were obtained. The dates, time range of flight level, aircraft type, and $r(V_t, V_r)$ are shown in Figs. 3 through 10 for the 14 flights from which the 17 sets of correlations were obtained. The spatial distribution of the data points of the one-minute averaged winds that were used to compute $r(V_t, V_r)$ plotted at 2-minute intervals in each 20-mile wide "wall" are also shown.