ON THE STRUCTURE AND MAINTENANCE OF THE MATURE HURRICANE EYE

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ABSTRACT

An attempt is made to derive the significant features of a mature hurricane eye in terms of a simplified model of the physical processes undergone by the air composing it. In particular, a quantitative relation is prescribed among the fields of motion, temperature, and humidity on the basis of assumptions concerning the exchange of mass and momentum between the eye and its surrounding cloud bands.

The basic assumptions are that eye air mixes with the cloud wall on its descent; the latter is maintained by lower level outflow caused by unbalanced centrifugal and Coriolis forces, resulting from the incorporation into the eye of high cloud-wall momentum. Joint entrainment and angular momentum calculations for two hypothetical cases of stationary hurricanes of differing intensity show qualitative agreement in major features with existing incomplete observations and delineate a computational framework for real cases when available. Modifications of eye structure in moving storms are finally considered.

1. Introduction

The important role played by the eye in a tropical storm has recently been emphasized by Riehl (1956). He has demonstrated that the phenomenally low pressures (950 to 890 mb) in hurricane centers are not achievable by any possible lifting of the lowest air in the convective systems of the rain areas. He has further pointed out that since most tropical storms are associated with little or no disturbance above 100 mb the low central pressures must come from a very warm eye which slopes outward aloft over the rain area. The eye soundings available to date indicate that adequately high temperatures are indeed found in eyes, the warming being particularly pronounced in the middle and upper troposphere.

It is, therefore, of considerable importance to study the structure and maintenance of the eye and to attempt to discover the manner in which the warming is produced. It has been suggested that descending motion occurs in hurricane centers, but neither the amount of the descent nor the origin of the descending air has been established. In addition to its great warmth and low pressure, the eye has several other mysterious features, the most striking being the weak winds within it, despite the raging cyclonic gales in the convective wall only a few kilometers away.

The purpose of this work is to construct a model in which the eye air comes largely from the convective wall at high levels, descends with some exchange of properties through the mid-troposphere, and undergoes strong divergence and outflow in the lowest kilometer or so. It is first shown that a typical eye temperature and humidity sounding is obtainable by such descent, mixing and evaporation of liquid water. Then an angular momentum budget is made. In the model, eye air begins descent from high levels where cyclonic angular momentum is weak; it acquires angular momentum from the adjacent cloud wall as it descends and arrives at 800 to 900 mb with supergradient cyclonic speeds. Outflow near the surface results from excessive centrifugal and Coriolis accelerations, which give rise to low-level divergence of the order of 10^{-4} sec^{-1}. It is hypothesized that this low-level divergence, produced by the importation of cyclonic angular momentum into the sinking eye air, is responsible for the continued maintenance of the forced descent which is then calculable. If it is assumed that the outflow from eye to surrounding rain band occurs mainly in the lowest kilometer, the descent rate averages about 10 to 15 cm per sec at about 1 km above the surface, which decreases upward in a manner estimable from the calculated mass fluxes. The spreading of the air outward in the lowest kilometer, plus some destruction of angular momentum by surface friction, results in very low average wind velocities in the eye and a sharp gradient in wind at the eye wall. In the final section, modifications in eye structure in a storm moving in a tropical current with vertical shear are considered.

The model evolved here shows qualitatively the significant eye-like features in temperature, humidity, and momentum structure. It relates these fields quantitatively in a self-consistent and physically plausible manner. Beyond this, observations available to test the results are still incomplete. Those used here were primarily an eye radiosonde made at Tampa, Florida

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(Riehl, 1948), a summary of eye dropsondes (Jordan, 1957), aircraft and drop soundings from an exceptionally deep Pacific typhoon (Simpson, 1952), and some recent unpublished data gathered by the National Hurricane Research Project. The work here suggests several critical observational tests which should be made and outlines a method of utilizing future measurements to determine the origin of eye air.

2. Temperature and humidity structure

We shall now determine whether a characteristic eye sounding may be produced by descent, entrainment from the eye-wall cloud band, and evaporation of liquid water. The sounding for the convective wall is taken as curve B in fig. 1. This sounding is arrived at by moist adiabatic lifting of subcloud air which has been isothermally (at 26.0C) expanded to 960 mb and had moisture added up to 19 g per kg. This should be a good approximation to the air structure in the active cloud band around the eye wall of a 960 to 970 mb hurricane (Riehl, 1956; Palmén and Riehl, 1957). Curves T and H, fig. 1, give the mean West Indies sounding for September (after Jordan, 1957a) and the mean hurricane-rain-area sounding (after Schacht, 1947), respectively.

The assessment of the eye-air origin is done in the manner of a standard entrainment calculation, as modified by Malkus (1955) for a downdraft. As the air descends in the eye we calculate what fraction of environment air must be mixed with descending air in each height interval to give eye properties, close to those observed at the next lower level. Evaporation of liquid water is hypothesized below the freezing level or about 450 mb. Evaporation gives rise to cooling at a rate of about 2.5C per g per kg evaporated. This will be found important in slowing down the warming rates above and beyond the slowing by mixing. Accumulating radar evidence confirms the occurrence of this process which will be discussed later in relation to the water budget of the storm.

The calculation is carried out as follows: at 100 mb, a downward flux of mean tropical (curve T, fig. 1) substratospheric air is started, arbitrarily called M g per sec (to be evaluated later). At 150 mb we calculate the amount of mixing (with curve B) required to give eye properties after dry adiabatic descent. It is found that one part convective wall air to two parts descending air is about right, or that $\Delta M/M = 0.5$. This process is continued down to 350 mb, where it becomes more plausible for the entrained cloud band air to be 2/3 undilute B and 1/3 mean hurricane rain area H. This is in agreement with work on large convective clouds (Malkus and Ronne, 1954; Riehl and Malkus, 1958) which suggests that undilute cloud cores are surrounded by more dilute cloud matter of increasing width at lower levels.

Curve E in fig. 1 shows the resulting eye sounding and table 1 summarizes the entrainment calculation. Actual eye soundings are shown in table 2 for comparison. One of the few extending to great heights is reproduced in table 2A and was discussed by Riehl (1948). Noteworthy features duplicated by the calculated results are (1) pronounced warmth confined mainly above 700 mb, and (2) high stability up to 400 mb, above which height the lapse rate becomes steep. The humidities reported by the radiosonde were high and Riehl discarded them as excessive. We see by comparison with table 1 that such humidities are extremely plausible if the eye air comes largely from the convective wall, as in the model. Furthermore, the recent eye dropsondes from 500 mb (Jordan, 1957) show average humidities closely similar to these for hurricanes of moderate strength. Jordan's mean eye

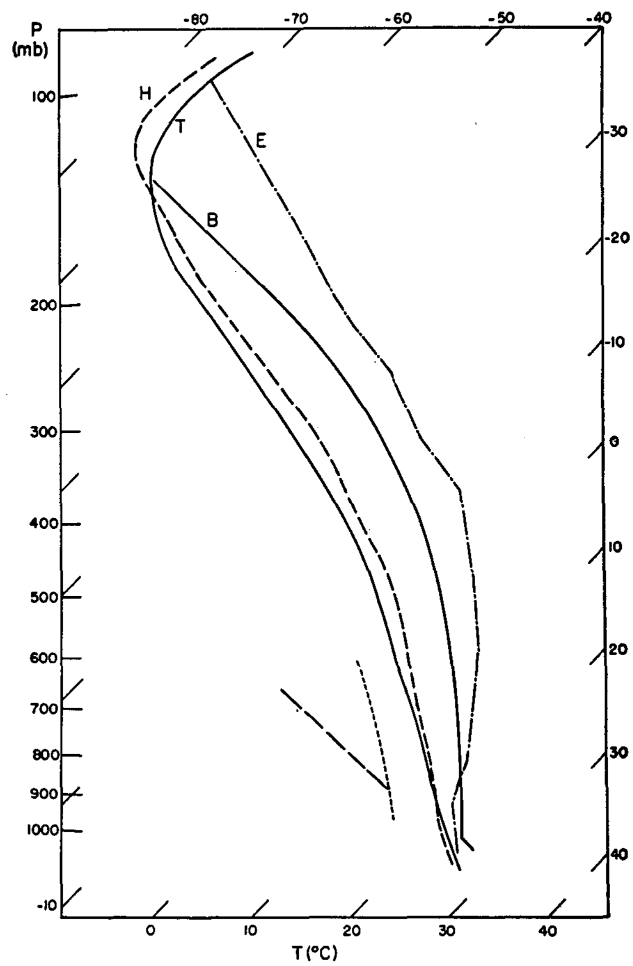

FIG. 1. Tephigram showing T: mean September sounding for the West Indies area, after Jordan (1957a); H: mean hurricane rain sounding, after Schacht (1947); B: sounding obtained by moist adiabatic ascent of subcloud air after isothermal (26.0C) expansion to 960 mb with addition of moisture to 19 g per kg and dry adiabatic ascent to saturation. Used as convective wall sounding for eye calculation for moderate hurricane; E: calculated sounding for moderate hurricane eye (see table 1). The short dashed line gives the slope of dry adiabats. The short dotted line indicates moist adiabat.

sounding for the moderate strength hurricane appears in table 2B.

The calculated eye sounding closely resembles the Tampa eye at upper levels and falls somewhere between the Tampa eye and Jordan's mean moderate eye below 600 mb. In it the eye environment is chosen as more H and less B on descent, becoming totally H at and below 800 mb. Beginning at 450 mb, evaporation is introduced in the amounts indicated while it is assumed to be negligible or small above the freezing level. The entrained cloud-band air can easily supply the water evaporated if the B cloud matter has close to adiabatic liquid or solid water content and the H cloudy air has a water content about half of that. However, we find that 2/3 of the water introduced into the eye model comes in above 500 mb, while nearly all evaporation takes place lower down. The plausibility of this distribution is examined from the standpoint of cloud physics in Section VI on mechanisms.

The downward mass flux in the model (table 1) is the largest at 850 mb (≈1200 m elevation) because we hypothesize divergence and outflow from the eye below that. The entrainment calculation says that 98 per cent of the eye air descending at 850 mb has come from the cloud bands around the eye, about 50 per cent of it from above 500 mb. The 50-mb increments of mass ΔM (units relative to 100 mb) are large between 200 and 500 mb and below 700 mb and rather smaller in between. It should be noted that we could have obtained an equally plausible eye sounding by using less evaporation and more mixing in mid-levels, but this combination will later be precluded for any realistic hurricane model by angular momentum requirements. The qualitative reality of the height distribution of entrainment in table 1 is therefore suggested. In the real hurricane eye, we suppose the high rate of introduction of cloud matter aloft to be due to the spreading of anvils and cloud tops and the low-level secondary maximum to result from intense turbulent mixing and intermittent cloud penetrations due to relative motion between eye and cloud bands which will be considered later.

The rigid test of the entrainment hypothesis for the origin of eye air lies, however, in whether it can lead to a reasonable angular momentum structure.

TABLE 1. Eye sounding calculated by entrainment method.

P (mb)	T (°C)	rh (%)	q (g/kg)	Environment composition	Vertical mass flux (gm/sec relative to 100 mb)	ΔM	Entrainment rate $\frac{1}{M}\frac{dM}{dz}\cdot 10^5(\text{cm}^{-1})$	Evaporation gm/kg
100	−73.9	20	.002	100%B	1	0.5	0.2	
150	−55.0	20	0.03	100%B	1.5	1.05	0.4	
200	−41.0	20	0.1	100%B	2.55	1.25	0.3	
250	−28.0	20	0.3	100%B	3.8	2.3	0.5	
300	−19.5	25	0.7	100%B	6.1	1.8	0.3	
350	−10.0	24	1.2	2/3B, 1/3H	7.9	4.8	0.6	
400	− 4.6	31	2.1	2/3B, 1/3H	12.7	9.4	0.8	
450	0	40	3.4	2/3B, 1/3H	22.1	6.2	0.4	1.1
500	3.7	53	5.3	2/3B, 1/3H	28.3	1.8	0.1	1.6
550	7.2	62	7.1	2/3B, 1/3H	30.1	2.1	0.1	2.1
600	9.9	73	9.5	2/3B, 1/3H	32.2	1.5	0.1	1.7
650	12.3	82	11.4	2/3B, 1/3H	33.7	1.2	0.1	1.6
700	14.4	87	13.0	2/3B, 1/3H	34.9	4.2	0.2	1.0
750	16.8	88	14.2	2/3B, 1/3H	39.1	4.7	0.2	1.5
800	18.1	96	15.8	100%H	43.8	4.4	0.2	1.0
850	19.5	97	16.5	100%H	48.2	3.9	0.2	0.7
900	22.0	91	17.1		31.6*		0	1.1
970 (sfc)	25.3	87	18.3					

* Reduced due to lateral divergence. See text.

TABLE 2. Observed hurricane-eye soundings.

A. Tampa case (1 radiosonde) P (mb)	T (°C)	rh (%)	q (g/kg)	B. Jordan average moderate (20 dropsondes) P (mb)	T (°C)	rh (%)	q (g/kg)
100	−73.9						
200	−41.0						
300	−19.5	23	0.6				
400	− 4.6	30	2.1				
500	3.7	53	5.3	500	− 0.4	70	5.1
600	10.2	73	9.7	600	8.7	72	8.6
700	15.1	86	13.4	700	14.4	83	12.5
800	17.8	93	15.3	800	19.0	89	15.4
900	20.0	93	15.4	900	22.9	91	17.7
966 (sfc)	23.2	97	18.3	~975 (sfc)	25.7	90	18.9

3. Angular momentum budget of the eye

One of the most amazing features of hurricane eyes is their weak surface winds. Any proper theory of eye dynamics must attempt to explain this phenomenon, and any theory of eye air origin must be consistent with it. An apparent obstacle to the acceptance of the entrainment idea has been the high cyclonic angular momenta which must be introduced into the eye if cloud-band air enters it in significant quantity. The present model suggests that high-level origin of much of the air (where the cyclonic circulation is weaker) coupled with destruction by friction and spreading laterally at low levels can produce a near-calm surface eye.

This contention is now backed by a quantitative angular momentum budget. We begin by considering the laws governing the angular momentum of a hypothetical steady-state, symmetrical hurricane. The absolute angular momentum of any ring of air a distance r from the hurricane axis may be altered in only two ways: one, by exchange with surrounding rings (mixing); and two, by destruction due to surface friction. Relative angular momentum is altered by change of distance from the axis.

We shall now inquire how the tangential linear velocity v_θ in its eye is distributed, altered by mixing, friction, and change of radius. The basic idea is that the air aloft which starts to descend in the eye has little or no relative angular momentum at first and acquires cyclonic angular momentum by mixing; these cyclonic velocities can be balanced by small and plausible pressure gradients down to about 1 km where they become supergradient and the air is flung outward again into the convective wall. In dealing with a symmetrical case, we are forced to ignore the marked observed streakiness in the real tangential velocity field of a hurricane and to treat our v_θ as an average around the storm. We also lose any contribution to momentum produced by pressure torques, which probably would prove disastrous in consideration of the dynamics of the rain area, which is the energy-providing region of the storm. It seems, however, that the basic dynamics of the eye are not obscured by the averaging process, as further exposition of this model will show.

First, we shall consider air just within the eye wall, say at a radius from the center of $r = 30$ km. We shall assume it descends with little change in radius down to 1.2 km (850 mb) above the sea, where it spreads out rapidly. The reasons for this will be enlarged upon later. The air just within the eye at $r = 30$ km is mixing with air in the convective band at roughly $r \approx 30$ km also in the amounts calculated in table 1. Since the radius is assumed to change little down to 1.2 km, we may consider only relative momentum per unit mass for the moment. Table 3 shows angular momentum calculation in terms of v_θ, the tangential velocity component ($v_\theta r$ = relative angular momentum per unit mass). The v_θ velocities in the new air incorporated into the eye are given in the column marked "Environment v_θ." This is taken as zero at 100 mb for the twofold reason that many hurricane circulations have nearly or entirely vanished by that level and also we began our descent there with air of undisturbed tropical properties. No complete series of upper level eye wall velocity data exists, much less an average tabulation over many hurricanes; therefore, the remaining values in the "Environment v_θ" column were chosen somewhat arbitrarily. They are at least consistent with the three observed levels (1500, 15,000, and 35,000 ft) of a single moderate storm, namely Carrie, 1957. Down to 500 mb the momentum calculation is straightforward, momentum being introduced to the eye in each interval in proportion to the introduced mass flux. From 500 mb down we call upon the destruction of momentum by friction, in the amounts listed in the fifth column from the left. It may be noted that our frictional destruction equals or exceeds the introduction by entrainment in the low levels of the eye, and we may well enquire whether such a stress distribution is at all realistic. The descent rate in the eye is estimated in the next section and for convenience is entered in column 3. From the time required to descend from one level to the next lower, we estimate the frictional force per unit mass required to produce the Δv_θ and from that the corresponding $\partial \tau_{\theta z}/\partial z$ or rate of upward decay of tangential shearing stress, entered in column 4. There is no way of checking these figures observationally except by noting that the highest values found here are about seven times those measured in the undisturbed trade (Charnock, Francis, and Sheppard, 1956; Bunker 1955) and about 1/3 those calculated (Palmén and Riehl, 1957) for the inner hurricane rain area. Finally we introduced in the lowest 1200 m the amount of radial spreading estimated in the next section (actually all these calculations had to be carried out simultaneously) and arrive at the low-level v_θ values for the eye of 10 m per sec (cyclonic positive) at 900 mb and about 2.7 m per sec at the surface. For the latter calculations it was necessary to consider absolute angular momentum, namely

$$v_{\theta u} r_u + \frac{f}{2} r_u^2 - \text{momentum destroyed by friction} = v_{\theta L} r + \frac{f}{2} r_L^2,$$

where the subscripts u and L denote the upper and lower level, respectively, and f is the Coriolis parameter.

Plausible ranges in friction, mixing, and spreading would give considerable range in eye rim v_θ without even considering the streakiness in v_θ in the convective ring. Thus, the values in the last column in table 3 and their height distribution should not be taken literally but may be expected to vary widely in the average from one storm to the next and in both time and space for a single storm. The point of the calculation described here is rather to make plausible a mechanism for the maintenance of the angular momentum budget of the eye and to set up a framework to be used on actual storm data when available. If the basic features of this model are sound, we would expect a downward increase on cyclonic rotation in the eye to the level where friction and spreading become important; this might well be higher than in the case considered here and observations of middle and low cloud drifts in real situations could be used together with v_θ profiles in the wall to determine the upper limit of frictional and divergence effects.

4. Divergence, vertical motion, and eye maintenance

The radial equation of motion for a steady-state, cylindrically symmetrical hurricane is

$$v_r \frac{\partial v_r}{\partial r} = f v_\theta + \frac{v_\theta^2}{r} - \frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{1}{\rho}\frac{\partial \tau_{rz}}{\partial z}, \qquad (1)$$

where r and v_r are positive outward, $r = 0$ at the center, v_θ is positive for cyclonic wind, and the remaining symbols have their standard meanings.

If we can estimate $v_r\,\partial v_r/\partial r$, we can estimate the divergence and descent rates. The forthcoming calculations are based on the following approximate modelling of the eye: down to 850 mb where outflow is assumed to begin $v_r\,\partial v_r/\partial r \approx 0$ and we may calculate the pressure gradients required to keep our previously calculated v_θ's in balance (if we can say something about radial stress distribution). Below 850 mb we hypothesize that the cyclonic speeds are too large to be balanced by the pressure gradients so that excessive centrifugal and Coriolis forces (primarily the former) cause the descending air to be flung outward again into the rain area, maintaining the forced descent.

We begin by estimating $v_r\,\partial v_r/\partial r$ at the surface, assuming that $\partial p/\partial r$ vanishes there. We take $\partial \tau_{rz}/\partial z$ in roughly the same ratio to $\partial \tau_{\theta z}/\partial z$ ($\sim$40%) as found by Riehl and Palmén (1957) and calculate from equation (1) as follows:

$$v_r \frac{\partial v_r}{\partial r} = 0.5 \times 10^{-4} \times 2.7 \times 10^2 + \frac{(2.7)^2 \times 10^4}{3.10^6} - 10^3 \times 0.31 \times 10^{-4} = 0.7 \times 10^{-2}.$$

In the extreme case considered where $\partial p/\partial r$ at the surface vanishes, any wind is supergradient and will undergo outward acceleration (this is even true of an anticyclonic wind due to the predominance of the centrifugal over the Coriolis term). However, friction will reduce (but cannot reverse) the outward acceleration and if it were much larger than the value used would render it vanishingly small.

Since the height distribution of shearing stress inside a real hurricane eye is not known, we shall not attempt to refine this calculation further but will merely compute the divergence and descent consequent if $v_r\,\partial v_r/\partial r \approx 0.7 \times 10^{-2}$ throughout the lowest 1.2 km.

Since $v_r = 0$ at $r = 0$ we find that

$$v_r \text{ (m/sec)} = (0.13r)^{\frac{1}{2}}, \qquad (2)$$

where r is in kilometers. We obtain maximum outflow rate of about 2 m per sec at the outer edge of a 30 km eye. This is less than 20 per cent of the mean radial inflow from outside into the rain area side of the convective wall and is therefore not implausible. It is envisaged that in nature this outflow is not steady but occurs in fits and starts, as does the average eye v_θ which may oscillate from +2–4 m per sec to −1 or 2 m per sec. Temporary and local intrusions of much higher velocities accompanying cloud penetrations (discussed later) can be common. The oscillations in average v_θ and v_r (which are both of the same order of magnitude) can give the light and very variable wind conditions characteristic of hurricane eyes. It thus would be very difficult by spot observations to assess the small average flow within an eye and its average stress distribution.

The divergence within the theoretical eye comes out of the order of 10^{-4} sec^{-1} and we may estimate the descent rate at 1.2 km (where it is a maximum) using an integrated form of the continuity equation. Equating the downflux at 1.2 km to the efflux through the cylindrical walls we obtain

$$\rho \pi r^2 \bar{w} = \rho (2\pi) r h v_r \qquad (3)$$

and $\bar{w}$ at 850 mb comes out −16 cm/sec. The remaining upper w's in table 3 were calculated from this by ratios of descending mass flux and that at 900 mb was calculated by first subtracting the efflux between 850 and 900 mb. While a descent rate of 16 cm per sec may seem large, it is actually little more than the values found observationally in the subsidence ring around a small heated island and insignificantly small compared to the convective downdrafts associated with an ordinary cumulonimbus. It is not envisaged as being uniform across a real eye, but to be concentrated primarily between cloud regions which may, in fact, show weak ascent (Jordan, 1952). The maximum downward flux across the entire eye (and we have chosen a large eye) is only about 1 to 10 per cent of the upward flux in the eye wall (the range depending

TABLE 3. Angular-momentum calculation for the eye rim.

P mb	Environment v_θ m/sec	w cm/sec	Friction $\partial\tau_{\theta z}/\partial z \cdot 10^4$ dyne/cm³	Effect of friction Δv_θ m/sec	Effect of entrainment Δv_θ m/sec	Effect of spreading Δr km	Effect of spreading Δv_θ m/sec	Final eye rim v_θ m/sec
100	0	0.3		0	1.7			0
150	5	0.5		0	3.4			1.7
200	10	0.9		0	2.6			5.1
250	12.5	1.3		0	2.8			7.5
300	15.0	2.0		0	1.7			10.3
350	17.5	3.0		0	2.0			12.0
400	20.0	4.0		0	3.5			14.0
450	22.5	7.0		0	1.5			17.5
500	25.0	9.0	0.11	−1.3	0.5			19.0
550	27.5	10.0	0.22	−2.3	0.9			18.2
600	30.0	10.0	0.28	−2.2	0.8			16.8
650	32.5	11.0	0.35	−2.2	0.7			15.4
700	35.0	11.0	0.55	−3.2	2.9			13.9
750	37.5	13.0	0.65	−3.2	3.2			13.6
800	40.0	14.0	0.70	−2.7	3.0			13.6
850	42.5	16.0	0.70	−2.8	2.8	4	−1.9	13.8
900	52.0	10.0	0.70	−4.8	0	5	−0.8	10.0
970	52.0	0						~2.7

on the width and strength of the convective updrafts in the wall) and *at most* less than 1 per cent of the upflux in the whole rain area choosing conservative values of convergence and size of rain area.

Since $v_r \Delta t \sim \Delta r$, the amount of radial spreading, and $\bar{w}\Delta t \sim h$, equation (3) enables us to estimate that the total radial spreading from 850 mb to outflow is roughly one-half of the initial radius of the air at 850 mb. This was used in calculating the loss of relative momentum due to spreading appearing in table 3.

The average vertical velocities calculated tell us that the eye air will require different lengths of time to traverse the eye downward, depending on the level where it entered. For example, about 25 per cent of the air descending at 850 mb has entered the eye at 400 mb or above and requires about a day, on the average, to descend from there and flow out. Thus radiational heat losses may be important in the thermal budget of the eye and these have so far been ignored. If the eye lost heat by radiation at 2C per day, it would require 20 per cent less than the calculated evaporation to keep the temperature of the descending air the same as those of table 1. Such refinements are hardly worthwhile until many more observations are available.

5. Pressure-temperature relations and an eye-core calculation

Table 4 shows the radial pressure gradients at the eye rim necessary to make a self-consistent model. They were calculated from equation (1) and the v_θ's of table 3 assuming $v_r \partial v_r/\partial r \sim 0$ above 850 mb and 0.7×10^{-2} below and were adjusted in the low levels to give a plausible upward decay of $\partial\tau_{rz}/\partial z$ from 0.31×10^{-4} dynes per cm³ at the surface to zero at 650 mb. The fourth column expresses them in terms of D (altimeter correction) variations in 10 mi for comparison with the results of the National Research Project. Observations at the one level that penetrated the eye of Carrie 1957 shows at least the same order magnitude. Further checks will require eye penetration at several levels.

We may now investigate conditions in the more central portions of an eye and inquire how the thermal, water, and momentum budgets are to be maintained there. Let us consider, for example, $r = 15$ km. We first calculate the radial pressure gradients there assuming $1/\rho\, \partial p/\partial r$ goes to zero at $r = 0$ (symmetrical eye). Thus at 15 km, gradients are roughly half those at 30 km and these values are tabulated in column 2 of table 5. We next compute v_θ in the eye core assuming no acceleration down to 850 mb and $v_r \partial v_r/\partial r = 0.7 \times 10^{-2}$ below. We take both components of eye-core friction to be roughly one-half of those at the rim, since diminution of stress in the quieter center seems in-

TABLE 4. Pressure gradients at eye rim.

(No radial accelerations down to 850 mb; $v_r \frac{\partial v_r}{\partial r} \sim 0.7 \times 10^{-2}$ below)

P mb	v_θ m/sec	$\frac{1}{\rho}\frac{\partial p}{\partial r} \cdot 10^2$ cm/sec²	ΔD/10 miles ft	$\partial\tau_{rz}/\partial z \cdot 10^4$ dynes/cm³
100	0	0	0	0
150	1.7	2	1	0
200	5.1	11	6	0
250	7.5	25	13	0
300	10.3	41	22	0
350	12.0	54	29	0
400	14.0	72	39	0
450	17.5	111	60	0
500	19.0	130	70	0
550	18.2	119	64	0
600	16.8	102	55	0
650	15.4	87	47	0
700	13.9	70	38	0.10
750	13.6	67	36	0.10
800	13.5	66	36	0.20
850	13.7	66	36	0.20
900	10.0	35	19	0.23
970	~2.7	0	0	0.31

TABLE 5. Eye-core calculation.

P mb	$\frac{1}{\rho}\frac{\partial p}{\partial r}\cdot 10^2$ cm/sec²	v_θ m/sec	T °C	Environment (of core)	ΔM/M	q g/kg	rh %	Evaporation g/kg	Friction Δv_θ m/sec	r_0 km
100	0	0	−73.9			.002	20			
150	1	0.9	−54.9	100%B	.47	0.03	20			27.5
200	6	2.6	−40.9	100%B	.64	0.1	20			22.5
250	12	3.7	−27.8	100%B	.40	0.3	20			20.0
300	20	5.1	−19.2	100%B	.60	0.6	20			18.0
350	27	6.0	− 9.8	100%B	.40	1.0	20			18.0
400	36	7.0	− 4.2	100%B	.84	2.1	30			17.0
450	55	8.7	1.4	1/2B, 1/2E	.55	3.3	35	0.2		17.5
500	65	9.5	3.7	100%E	.29	4.5	45	1.2		17.5
550	60	9.1	6.6	100%E	.29	6.7	60	1.3	−0.7	17.0
600	51	8.4	9.3	100%E	.22	8.0	65	1.3	−1.1	17.0
650	43	7.7	11.7	100%E	.20	10.1	76	1.0	−1.1	18.0
700	35	7.0	13.9	100%E	.17	11.7	80	1.2	−1.1	18.0
750	33	6.8	16.9	100%E	.35	12.9	81	0.7	−1.6	20.0
800	33	6.8	18.2	100%E	.60	15.3	93	1.0	−1.6	20.0
850	33	6.9	19.5	100%E	.30	16.1	95	0.9	−1.6	19.0
900	17	5.1	21.0	100%E	.30	17.0	97	0.5	−1.6	21.0
970	0	2.2	24.3	100%E	.30	18.2	94	0.9	−2.4	24.0

evitable. The resulting v_θ distribution appears in column 3 of table 5.

We may next inquire whether reasonable temperature gradients across the eye could exist to support these pressure gradients and arrive at an eye-core temperature sounding. If we assume vanishing disturbance at 100 mb and no eye radial pressure gradient at the ground, it follows from hydrostatic considerations that the eye core must be warmer than the rim aloft and slightly cooler in the low levels. A detailed calculation of the resulting eye-core temperatures gives the results in column 4. We see that nowhere need the eye-core temperature depart from that at the rim by more than 1.4C to maintain the necessary pressure gradients. Thus it should matter little in what part of an eye a temperature sounding is taken.

A more important question to ask is how can an eye core acquire this thermal and momentum structure? With what air, if any, does it mix on descent? We first tried an entrainment calculation for the eye core similar to that of table 1, but this time assuming the environment tabulated in table 5. It was possible to obtain the eye core sounding with the humidities given in table 5 with roughly the same entrainment rates used for the rim and 25 per cent reduced evaporation. We chose the environment of undilute cloud matter B above 400 mb because we envisage anvil penetrations well across the eye at upper levels (see Section VI). If this cloudy air has adiabatic water content and if some liquid water remains in the eye-rim air E (curve E, fig. 1) introduced into the core, the water budget in the core will balance nicely. Note that both core and rim soundings show near saturation humidities from 800 to 900 mb so that variable weak convergence fields (due perhaps to uneven roughness or heating from below) could easily account for the fluctuating low-level cloudiness so common in many eyes (Simpson, 1952).

The remaining question concerns the eye-core-momentum budget and whether the entrainment and momentum requirements are mutually consistent. It is not possible to make a precise angular-momentum calculation for the eye core, but we can determine what mean radius the incorporated air must have come from to give us the tabulated distribution of the eye core v_θ. These values of r_0, the mean radius of origin of the air entrained into the eye core, are presented in the last column of table 5. This computation was done similarly to that of table 3 except that v_θ was given and r_0 was the unknown. The resulting r_0's are consistent with the postulates of the model, since the air can have come in a long way aloft, while a "mixing length" of only 2 to 3 km (cumulus scale) is permitted in mid-levels. At low levels a rather long exchange length is again permitted due to the high rate of momentum destruction by friction (given in the next to last column assuming $\partial\tau_{\theta z}/\partial z$ is about one half that at the eye rim).

6. Mechanisms and water budget

Nothing has been said yet about the possible slope outward of real eye walls with height, which many workers believe is important in producing low pressures in the inner rain area. We note from the model calculation summarized in table 3, in fact, that no air from a radial distance greater than the minimum (ground) eye radial extent, in our case 30 km, descended throughout the eye, but rather the descending ring was assumed to maintain a more or less constant radius of this size all the way down from 100 to 850 mb. This seems to be required by angular momentum considerations. If any air much outward of 30 km flowed regularly inward, the excessive cyclonic rotation acquired would be so great that it would be rapidly flung out again. No pressure gradients appear available in real cases to balance such forces at great heights nor are any mechanisms at hand to destroy the cyclonic momentum. We are thus forced to conclude that air sinking along sloping eye walls at great heights and distances from the storm center only descends short intervals before being again ejected and incorporated into the cloud band.

To understand the slope of eye walls, we must look to the dynamics of the cloud band itself. The writer believes it important to regard this band as a convective phenomenon with fluctuations and repeating life cycle which only on an average that is long compared to the life of its elements resembles the textbook vortex. It is suggested here that the average outward slope arises for the same reason that trade cumuli, on the average, slant backwards—*i.e.*, negative shear in the radial flow component. The asymmetry in eye-wall slope introduced by a shearing basic current (discussed in Section VIII) supports this view.

When individual cumulonimbi shoot up, they at first grow nearly vertically and only acquire the pronounced backslant as the updraft gradually decays. When a cumulonimbus tower hits the tropopause or an upper tropospheric stable layer, anvils of tens of kilometers extent in all directions appear, caused by the forced outward spreading of the rising air as it strikes a "lid." Time-lapse pictures (see Malkus and Ronne, 1954) show that, although the spreading is greatest in the direction of the shear, they also spread considerably in the opposite direction, often opposing a strong wind. Langmuir[2] has proposed this lateral spreading of cloud matter as an important moisture transfer mechanism in the undisturbed trade, and here we suggest its relevance to tropical storms. When the cumulonimbi composing the eye wall reach up to great heights (limit ~150 mb where curve B, fig. 1, runs out of buoyancy) they do so roughly vertically at first, and by anvil-spreading inject moist air in bursts into the upper eye. The average pronounced outward slope of the eye wall occurs because the growth stage of any cumuliform cloud is negligibly short compared to the dissipation stage, so that most tropical cumulus appear with a strong slant in the direction of the wind shear. This sequence of cloud events showed up very clearly in a beautiful series of aircraft time-lapse films taken by the National Hurricane Research Project in the eye of Hurricane Greta, 1956.

We may now consider the evaporation process and water budget in more detail. We hypothesize that when anvils and cumulonimbus streamers are injected into the eye at great heights (up to about 40,000 ft depending on where the undilute wall air runs out of buoyancy) the cloudy air mixes with the air already there in roughly the calculated proportions and begins descent, aided by local negative buoyancy and well fortified with ice particles which evaporate on the way down. Workers in cloud physics (see, for example, Ludlam and Saunders, 1956) tell us that the large ice particles characteristic of cirrus anvils evaporate only very slowly and thus we have neglected evaporation as small above the freezing level and only introduced it in significant amounts below the melting height, or about 450 to 500 mb. Although the average descent rates calculated here for eye air imply that some of the air entering at great heights would require more than a day to reach low levels, the ice particles would presumably descend much faster after leaving their supporting updraft. If the ice particles are only 100 μ in radius they would descend from 400 to 850 mb in about 3 hr, permitting most of the water entering the eye aloft to reach middle and lower levels before entirely evaporating, as the model requires. We note further that pressure increment for pressure increment, the needed rates per unit mass in the eye of table 1 are comparable to condensation rates in wet adiabatic ascent. Therefore we may conclude that the water consumption in an eye stands roughly in the ratio to the production in the rain area as do the respective vertical mass fluxes. We mentioned earlier that the total eye descent came out about 1 to 10 per cent of the upflux in the eye-wall cloud band and conservatively lower than 1 per cent of estimated upflux in the whole rain area. Thus the water budget of the model eye is quite reasonable.

Confirmation in real cases of this high-level injection and evaporation process has occurred since the original evolution of this model. A series of beautiful radar eye photographs by Atlas (Kessler, 1957) made in Edna, 1954, show the anvil penetration and subsequent sinking and evaporation. Furthermore, Kessler's analysis using eye soundings together with the radar evidence demonstrates rather conclusively that the evaporation was vital in achieving the observed eye humidities which are inexplicable by any other mechanism. The writer has also seen the same process at work in the aircraft radar pictures made at 35,000 ft crossing the eye of Carrie, 1957.

Concerning the water entering the eye below 500 mb (masswise about 1/3 of the total in table 1), we envisage a mechanism more similar to normal convective entrainment, since at low levels large cumulonimbi become wider and are accompanied by outrider clouds which may penetrate into the eye. In a current with strong vertical shear, this effect may be greatly enhanced as we shall describe in Section VIII. Reduced entrainment and water introduction in mid-levels could be a result of two causes: (1) the restricted

[2] During a Woods Hole lecture series, 1956.

"mixing length" at those levels due to angular momentum constraints (see table 5); and (2) the fact that air motion through normal cumuli is minimum at mid-levels, with stronger mixing near cloud base and efflux near the tops (see Malkus, 1954).

Since we have hypothesized evaporation as a brake on hurricane-eye warmth, we may well ask what would happen were upper cloud injection inhibited and the brake weakened. Could this be a contributory link producing an unusually deep warm eye? This possibility is considered in the next section.

7. Very warm eyes; Typhoon Marge, 1951

The hurricane eye penetrated by the Tampa radiosonde (table 2A) had a central pressure of 966 mb; it is well known that the deepest hurricanes on record have central pressures as low as 890 mb and thus must have much warmer eyes. By differentials from the hydrostatic equation we find for tropical storm conditions that

$$dp_c \approx 7d\bar{T}_v,$$

where p_c is the central surface pressure and $\bar{T}_v$ is the mean virtual temperature of the central column from the surface to 100 mb, no disturbance being assumed above that level. Therefore, an extreme hurricane eye must average nearly 11C warmer than the moderate eyes discussed.

There are two ways that an eye may be much warmer and still mix with the wall at about the same rate to satisfy angular momentum requirements. The first is to evaporate less water and the second is to have a warmer convective band. Trial calculations like that of table 1 were undertaken using each mechanism separately. First we altered evaporation alone, reducing it by about 40 per cent. The surface pressure is reduced only to about 913 mb, although the resulting sounding has a warmer, more marked "eye" character than that of fig. 1. The warmer convective band possibility was next considered alone. If subcloud air is expanded isothermally to 890 mb (at 26C) and picks up moisture to saturation (24.5 g per kg), which seems extreme, the resulting moist adiabatic ascent may be used as a wall sounding. Taking the same rates of mixing and evaporation used in table 1, we obtain a central pressure of about 912 mb, which is still not extreme.

It would appear that some combination of the above effects is required to obtain a record low. We successfully produce one in table 6 by using an environment wall B′ (isothermal expansion at 26C to 920 mb; moisture content 21.8 g per kg, ascent shown in curve B′, fig. 2). Evaporation is reduced by 1/3 from table 1 and while the overall entrainment from the wall is closely comparable, we reduce it by about 1/2 above 450 mb, supposing reduced cloud injections. The resulting theoretical eye sounding of table 6 appears as curve E′ of fig. 2. A pressure-height calculation assuming an undisturbed atmosphere above 100 mb gives a central surface pressure of 889 mb. Note the extreme stabilities throughout the low troposphere, the strong lapse rate aloft, and the much lower relative humidities than those of the moderate eyes. Fortunately, sounding and pressure data are available for one real extreme hurricane, namely Typhoon Marge, 1951 (Simpson, 1952), whose temperature and (dropsonde) humidities are repeated in the last two columns of table 6. These are almost identical with those of the theoretical eye except for high humidities in the lowest levels. These probably arose from spume and increased sea surface evaporation which was not considered in the calculation. In this penetration of Marge's eye the central pressure was about 895 mb, so that her upper structure must have resembled that calculated fairly closely.

It is interesting to speculate about the causes of the extremely warm eye. It is possible that a warmer convective rain band is not a cause but partly a

TABLE 6. Hypothetical eye sounding for extreme hurricane and comparison with typhoon Marge, 1951.

P mb	T °C	q g/kg	rh %	Environment	ΔM/M	Evaporation g/kg	Marge T °C	Marge rh (dropsonde) %
100	−73.9	negligible		100%B′	0.25			
150	−51.1	negligible		100%B′	0.35			
200	−34.0	0.1	10	100%B′	0.25			
250	−20.3	0.4	13	100%B′	0.30			
300	− 9.5	1.0	17	100%B′	0.15			
350	− 0.4	1.5	14	2/3B′, 1/3H	0.30			
400	6.0	2.2	15	2/3B′, 1/3H	0.35			
450	10.2	3.6	20	2/3B′, 1/3H	0.15			
500	16.4	4.2	18	2/3B′, 1/3H	.065	0.8	16.6	M
550	20.0	5.3	20	2/3B′, 1/3H	.071	1.0	20.2	28
600	23.1	6.7	22	2/3B′, 1/3H	.048	1.0	23.5	28
650	26.1	7.9	23	2/3B′, 1/3H	.17	1.4	26.0	35
700	26.0	10.0	32	2/3B′, 1/3H	.20	0.8	27.0	40
750	27.0	11.4	38	2/3B′, 1/3H	.25	1.3	27.0	60
800	26.0	13.3	50	100%H	.20	1.4	24.0	79
850	25.2	14.5	60		0	1.2	23.0	96
890 (sfc)	26.4	15.7	65				27.0	92

consequence of the low central pressure, following Palmén and Riehl's (1957) reasoning concerning pick-up heat from the sea under strong winds. Thus it may be that reduced evaporation is critical and if so we must enquire what could inhibit the water supply to the eye by about 30 to 40 per cent, or the major fraction of that entering the moderate eye at upper levels. The evidence points to reduced cloud injections, especially since we had to reduce upper-level entrainment in table 6 to produce a record eye. Reduced anvil penetrations could occur if outflow aloft in the rain area were much stronger than normal, particularly in the early life of the storm. This fits in with Riehl's (1948a) ideas about hurricane formation, which he contends is most explosively intense when a high-level disturbance is superposed on the developing storm and throws air out of it aloft. This upper outflow accelerates the pressure drop (thus indirectly the warming in the convective band) and, according to this reasoning, might also inhibit the cloud-band moisture supply to the storm, thus giving a warmer eye. This can be a self-accelerative growth process.

Some qualitative confirming evidence arises from recent aircraft studies: these soundings (Jordan, 1957) indicate that the low-humidity eyes are associated with the deeper storms. Inspection of eye photographs suggests also that the deeper eyes are visually better-defined and more cloud-free than the weaker ones, this being particularly true of Marge, whose eye was absolutely clear above 9000 ft and whose convective wall sharply terminated at 35,000 ft. Eye cloudiness in weaker storms is the rule and not the exception (Simpson, 1954, 1956).

In this connection, it is tempting to speculate about man-made interference with tropical storms. If inhibition of high-level water supply is an important factor in producing extremely warm eyes, one is led to inquire whether artificial introduction of water might not be able to cool the core and thus inhibit the storm. The amount of water needed to saturate an eye is, to be sure, greatly in excess of what could be carried in by aircraft, but does not vastly exceed the amount of sea water raised by an underwater explosion of an atomic bomb. The Bikini lagoon test raised about a thousand billion grams; evaporation of one hundred times this much water could saturate the eye of a typhoon like Marge (table 6). Unfortunately, cooling of this air to its wet-bulb temperature would only raise the central pressure in the eye from 890 mb to about 930 mb, which is still in the intense-storm range. Saturating the eye of a more moderate hurricane like that of table 1 (which has higher original humidity) could raise the central pressure by 10–12 mb at most. Thus introduction of water into the eye does not appear to be a promising possibility for hurricane modification.

8. Eyes of storms moving in a tropical current with shear

In utilizing observations to model moving hurricanes, we must distinguish between the motion of the low-pressure center, the motion of the eye as visible on radar (*i.e.*, the motion of precipitating cloud bands), and the motion of the air in the eye. It is possible that all of these may be different.

We note that on examining figs. 1 and 2 that the pronounced warmth of the eye occurs mainly above 700 mb, and thus the contribution to low surface pressures must come mainly from the eye column between 700 and 100 mb. A pressure-height calculation readily confirms this, showing the eye D value decreases by less than 10 per cent below 700 mb. We further note from table 1 that 23 per cent of the air in the eye of the model moderate hurricane at 700 mb

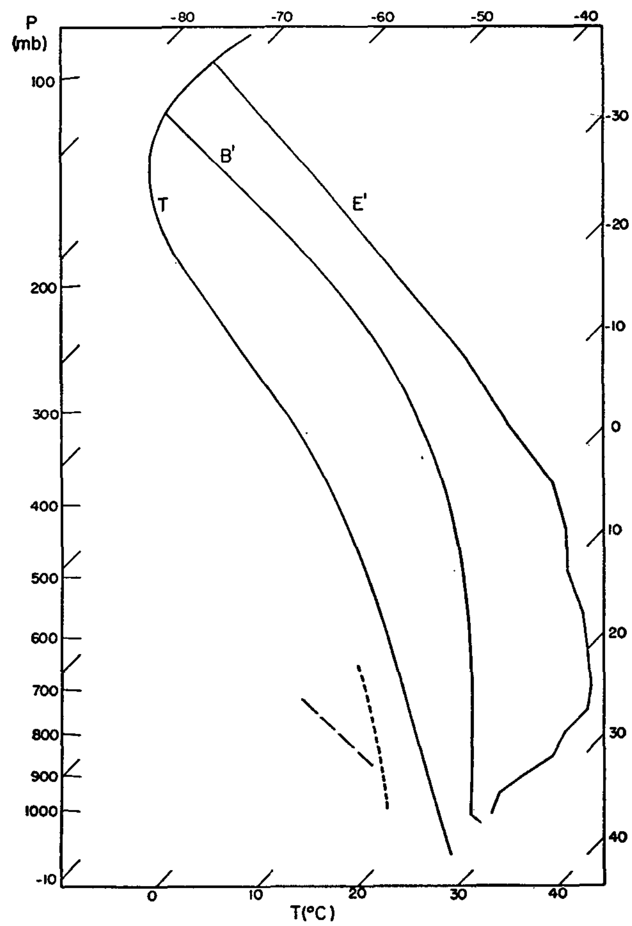

FIG. 2. Tephigram showing T: mean September sounding for the West Indies area, after Jordan (1957a); B′: sounding obtained by moist adiabatic ascent of subcloud air after isothermal (26.0C) expansion to 920 mb, with addition of moisture to 21.8 g per kg and dry adiabatic ascent to saturation. Used as convective wall sounding for eye calculation for extreme hurricane (Section VII); E′: calculated eye sounding for extreme hurricane (889 mb) tabulated in table 6. Very similar to observed sounding in typhoon Marge, 1951 (Simpson, 1952). The short dashed line gives slope of dry adiabats. The short dotted line indicates moist adiabats.

has come from 350 mb or above. Although considerable variation from storm to storm is possible, it seems that in real cases a significant fraction of the air reaching 700 mb must come from great heights to balance the thermal and momentum budgets jointly. This enables us to derive an upper limit for the relative horizontal motion between eye air and low-pressure center. Using the descent rates of table 1, we find it takes approximately one day for air originally in the eye at 350 mb to descend to 700 mb. If air enters the eye at one rim at 350 mb, it may translate through the eye (maintaining constant distance from the center) and just leave at 700 mb from the opposite rim if its translation speed differs by 1 m per sec from that of the low center. The only way that the eye (low-pressure center) could be translating at a vastly different speed from the air within it is to form on one side and die on the other, but this is precluded unless the descent rates are 5 to 10 times greater than those we have calculated. If the descent was multiplied by five, for example, air entering at 350 mb could have a linear speed differing by 5 m per sec from the speed of the low center and still remain in the eye down to 700 mb. Descent-rates this large seem implausible from the viewpoint of the overall budgets of the storm. The outflow of eye air into the rainband would approach 5 to 10 m per sec and the water consumption by the eye would become a significant fraction of that produced in the rain area. We thus predict that the average eye wind above 700 mb differs little (1 to 2 m per sec) from the translation speed of the low center, and that if a mass of neutral density balloons were introduced into the eye at 350 mb a fraction of them at least would remain in the eye for a major part of a day, leaving at 700 mb or below. This prediction is limited in application to steady-state mature storms still in tropical regions.

Below about 700 mb, since the computed descent-rates are much greater, it is possible for the air in the eye to move at a different speed from the eye itself (again defined as the low-pressure center). For this to take place, the lower eye must grow on one side and die on the other or, better said, new cloud bands must form on one side and old ones die on the other so that the center propagates at a different speed from the air within it. According to the calculations in Section IV, the air from 700 to 900 mb in the eye descends at a rate of the order of 10 cm per sec so that its descent time from 700 mb to outflow is roughly five hours. In this time it could move at 3 to 5 m per sec relative to the eye and just cross from one wall to the other following an approximately elliptical path and maintaining the distance from the axis required by angular momentum considerations.

We have suggested that 97 per cent of the air in the eye at 700 mb comes originally from the cloud bands. The translation speed of the low center, which we predict differs little from that of the eye air above 700 mb, should therefore be governed by the linear momentum introduced into the eye from the cloud bands. Thus if there is a mechanism for "steering" the storm, it occurs by the introduction of momentum

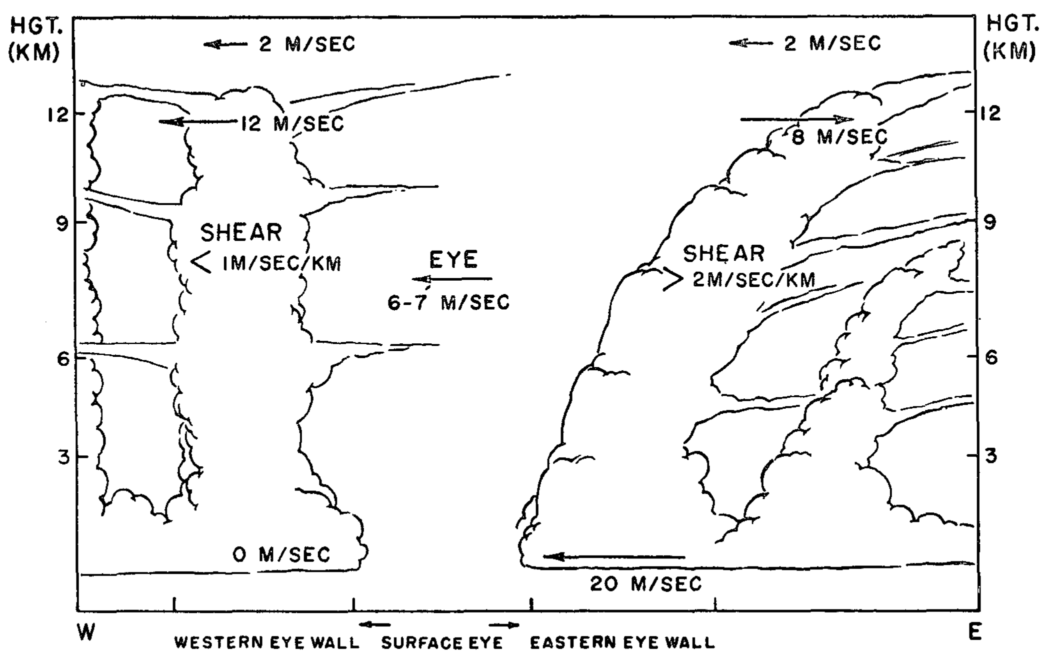

FIG. 3. Schematic illustration of asymmetry in eye structure when tropical easterly current has pronounced negative shear. The velocities given by the arrows illustrate a hypothetical set of winds (coordinates fixed to ground) resulting when a storm circulation with inflow at low levels and outflow aloft is superposed on a trade current of 10 m per sec at the ground decreasing to 2 m per sec in the stratosphere.

into the eye from the cloud bands. How the storm is steered should depend, if this model holds up, upon two factors: first, what the linear momentum in the cloud band is; and second, what portions of the cloud bands are drawn on by the eye.

We shall illustrate by one crude example in which the "steering level" fortuitously comes out to be about 500 mb. Suppose that we have an undisturbed easterly current with strong negative shear, its speed decreasing from 10 m per sec at the surface to 2 m per sec at 100 mb. This is not atypical of the trades in the wet season and would give an easterly speed of 6 to 7 m per sec at 500 mb. Now superimpose this flow upon a storm with radial inflow at low levels and outflow at high levels such that, in coordinates fixed to the ground, the east-west profile of the storm resembles the sketch in fig. 3. From previous work on tropical cumuli (Malkus, 1952, 1954; Malkus and Ronne, 1954) we would expect to find the eastern eye wall showing a much more pronounced backslant than the western wall. Furthermore, since cumuli grow on the upshear side and dissipate on the downshear side, we would expect most of the inflow from cloud band to eye to occur from the western wall. If the upper eye is getting about 75 per cent of its air from the western cloud band and only 25 per cent from the eastern, it will translate about 6 to 7 m per sec toward the west. This should be closely the rate of propagation of the warm core and thus of the surface low pressure center. It fortuitously turns out to be close to the speed of the undisturbed 500 mb easterlies. Although this work suggests that the "steering level" depends on a number of complex factors and may vary widely from storm to storm (or even within the life of a single storm), at least it points to a mechanism governing it and a way to compute it once more about the cloud bands and their interaction with the surroundings is known.

In order to carry on to low levels of the same storm, we recall that entrainment into the eye was calculated to be small between 500 and 700 mb but below 700 mb the eye received again nearly 2/3 the mass that it already had. If it received this entirely from the western cloud bands, it would suffer a braking effect and the air descending in the eye would translate westward at only 3 to 4 m per sec. The outflow from the eye then takes place primarily on the eastern side and probably would begin somewhat higher than in the symmetrical storm.

The motion of the cloud-free space called the "radar eye" would now only *average* 6 to 7 m per sec at low levels and presumably would do so by formation of new cloud matter at the western edge of the eastern band and dissipation at the eastern edge of the western band. We may expect the *propagation speed* of the cloud bands (as distinct from the motions of individual radar clouds) to be controlled by the motion of the warm core. This determines, by controlling the pressure field, the boundary between the rain-area inflow and the eye outflow and thus the line of convergence between these; this is the place where new clouds would be forming at all times. Individual cloud bands may move at much different speeds, however, and instantaneously the radar clouds may have a horizontal velocity quite different from the motion of the low-pressure center and *should not* be used in determining the motion of the storm. Clouds may intrude into the eye, which at low levels may seem to disappear and reform or even jump as old cloud bands die and new ones form.

Thus, this work suggests the following:

1. Under conditions of strong shear in the basic current, the average low-level winds in the hurricane eye may differ significantly from the motion of the low-pressure center, although they should rarely differ by more than 3 to 4 m per sec.
2. The propagation speed of the cloud bands should be the same as the speed of the low-pressure center although the motion of individual clouds and cloud groups may be quite different and should not be used to infer storm motion.
3. At upper levels the average translation speed of the eye air should be closely (within 1 to 2 m per sec) that of the motion of the low-pressure center.
4. The horizontal motion of the low-pressure center has considerable inertia against sudden changes since only about 20 per cent of its air is being replaced every six hours, while the radar eye is much more ephemeral and may change its apparent velocity every hour or so (the lifetime of an individual cumulonimbus) by meters per second and may twist and turn, and even disappear and reappear elsewhere.

All of these predictions may be tested observationally.

9. Concluding remarks

This work suggests the importance of the convective structure of tropical storms in their maintenance and motions, and outlines a calculation framework for utilizing future observations to test the physical ideas. The actual values of the parameters may vary widely from storm to storm and the criterion lies, therefore, in whether they obey the predicted relation to each other in selected cases, although the number of physical constraints should not permit orders-of-magnitude differences from the values used herein. If the broad outlines of the model prove justifiable, it may be extended in the future to discuss eye formation and the role of the convective rainbands in initiation and maintenance of the storm.

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