A PROPOSED MECHANISM FOR THE DEVELOPMENT OF THE EYE OF A HURRICANE

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ABSTRACT

An attempt is made to explain the process of the development and growth of the eye of a hurricane from the small immature stage to the large mature stage. The assumption is made that a hurricane starts as a simple vortex in the hydrodynamical sense. It is then shown that this, if it persists, leads to the development of the immature hurricane which is characterized by a narrow, warm and clear eye, and by strong winds and intense pressure gradient bordering the eye. It is then shown that the immature stage is not hydrodynamically stable. It develops hydraulic jumps at its most intense region, which jumps are sufficient to destroy its energy and transform it to the mature stage. This last stage is characterized by a wide eye, which may not be warm or clear, and by weaker winds and less intense pressure gradient. A numerical example is considered, to illustrate the importance of the role of the jumps.

1. Introduction

It has been pointed out by various writers (see, for example, Dunn, 1951) that a tropical cyclone undergoes constant metamorphosis, from birth through maturity to decay. The general characteristics of a tropical cyclone vary considerably as the storm progresses from one phase of development to another. McDonald (1942) has suggested that the life history of a tropical cyclone may be divided into four stages:

1. The genesis or incipient stage, which depends largely on the initiation mechanism; this mechanism may conceivably be thought of as the release of instability in the air masses involved, associated with a persistent factor which is capable of removing the air from the center of disturbance (Riehl, 1951); this stage ends when the storm forms a closed circulation and reaches hurricane intensity;
2. The stage of immaturity or deepening, during which the cyclone continues to deepen until the lowest central pressure and maximum intensity are reached; the storm is small and symmetrical during this period, and the winds attain their maximum strength at the borders of the inner region, called the eye; the winds then fall off in strength with increasing distance from the eye;
3. The stage of maturity, during which the storm is gradually spreading out, but its intensity is gradually decreasing; Deppermann (1947) has suggested that the storm in this stage is of the type of a Rankine vortex in which the wind follows the law $q = r \times$ constant in its innermost core, called the eye, and the law $qr =$ constant in its outer region;
4. The decay or the declining stage, in which the storm dissipates or is transformed to an extratropical disturbance when it moves over land or when it recurves.

To the writer's knowledge, no unified hypothesis has been advanced to explain these transformations by hydrodynamical reasoning. The present paper is an attempt in this direction. The main line of thought of the present paper is that the metamorphosis of a tropical cyclone is a manifestation of the development and growth of its eye. This development will be discussed presently.

2. The genesis or incipient phase

No attempt will be made here to discuss, or speculate upon, the nature of the initiation mechanism. It is necessary and sufficient, for the purpose of the hypothesis to be expounded, that this mechanism may be capable of producing a sink in some limited and concentrated region of the lower layers of the atmosphere, and that this mechanism be allowed to persist for a period of time that is long enough to provide for the further development of the cyclone. The mechanism that is responsible for the production of this sink may conceivably be thought of as the release of thermodynamical instability which is normally present in the trade winds or the monsoon air-masses. This viewpoint, which is known as the "convection theory," provides for rising air in the lower layers, which is dynamically equivalent to a sink in a two-dimensional flow. In order that such a mechanism may be capable of producing a cyclone, it must be associated with divergence at an upper level, which is necessary to remove the air from the disturbed region.

The existence of this sink will cause the air to converge from the outside regions into the disturbed area. This, if it persists, on a rotating globe is enough to establish a vortex circulation. It has been shown by Brunt (1941) that, if fluid be removed from the center of a disc of incompressible fluid originally having uniform angular velocity, the consequent convergence towards the center has the effect of superposing, upon the basic rotation, a simple vortex of the form

$$q = kr^{-1}, \tag{1}$$

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where q is the wind velocity, k a constant of proportionality, and r is the radial distance from the center.

It will here be assumed that the genesis phase in the development of a hurricane comprises the first stage of the establishment of the initiation mechanism and the second stage of the establishment of the simple vortex. The time required for the second stage to be established, and hence for the genesis phase to end, depends upon the strength of the sink. Thus, if the sink were strong enough to produce an average radial velocity of the order of 1 m/sec over an area of a radius of 500 km, this process would require a period of the order of one week.

3. The immature phase

The immature stage of a tropical cyclone will here be identified with the final shape which the storm acquires as a result of the genesis phase. In other words, the immature phase is the steady form which is approached by the storm because of the persistence of the simple-vortex circulation.

It has been shown by the writer (1953) that the steady case which is approached by a simple-vortex circulation in a stratified atmosphere is such that the field of motion in the lower layer is divided into three main regimes: (1) a "subcritical" region, in which the tangential wind velocity is less than a certain quantity called the "sonic" velocity, which is the velocity of progress of infinitesimal gravitational disturbances created at the upper surface of the lower atmospheric layer; the subcritical region extends from a certain distance from the center, called the "critical" radius, to infinity, and therefore comprises the whole air in the exterior region of the hurricane; (2) a "supercritical" region, in which the wind velocity is greater than the "sonic" velocity; this region is bounded by the "critical" circle and the borders of the "eye"; it is characterized by strong winds, which may be of hurricane intensity; (3) the "eye" of the immature hurricane, which is the innermost region of the storm and which encompasses the center. The eye is a "prohibited" region, into which the air of the lower layers cannot penetrate, and therefore it must be filled with

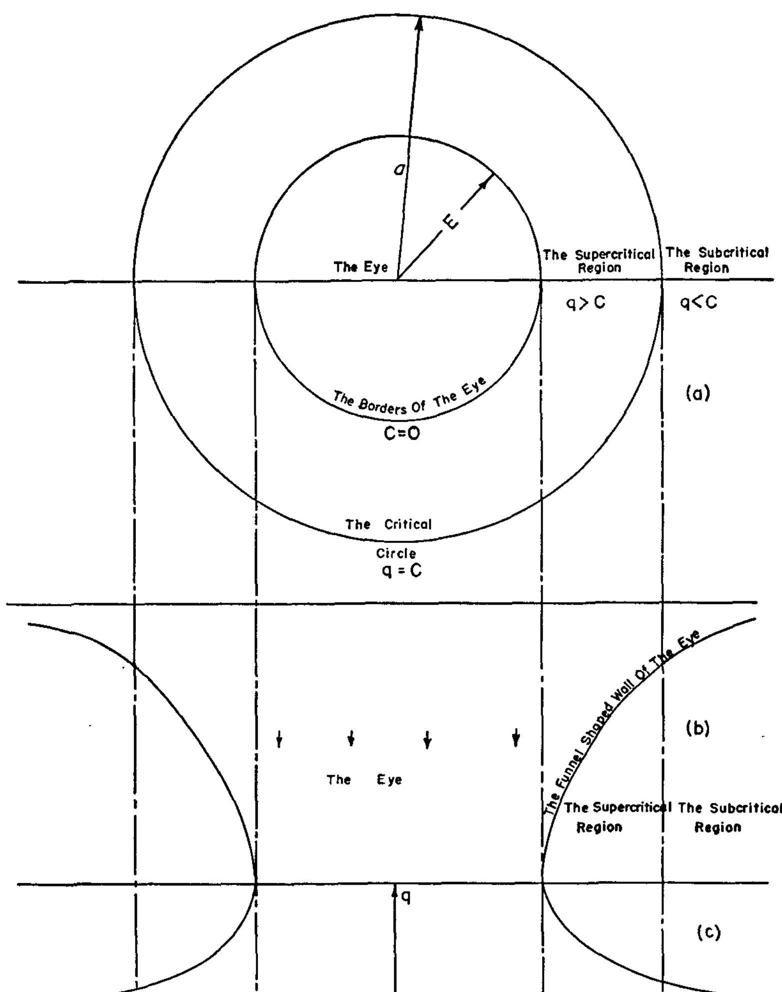

FIG. 1. Schematic representation of immature stage. (a): horizontal cross-section at sea level; (b): vertical cross-section passing through geometrical center; (c): wind distribution. q is wind velocity; r is distance from center.

descending air from the upper layers which do not partake in the vortex circulation.

For a full description of these three regimes, and the mathematical basis for their establishment, the reader is referred to the earlier paper (Abdullah, 1953). It suffices here to refer to fig. 1, which describes these regimes. In this figure, part (a) is a horizontal cross-section of the circulation, (b) is a vertical cross-section taken through the center, and (c) is the wind distribution around the eye. In computation of these figures, the atmosphere was assumed to consist of two main layers: a lower layer, and an upper layer which is assumed to be at a higher potential temperature. The hurricane is assumed to be stationary.

4. Destruction of the immature phase and formation of the mature phase

The supercritical region which is established in the immature phase soon develops the embryo of its own destruction. It is known that gravitational waves of finite amplitude that may form at the upper surface of a supercritical current are unstable (see Milne-Thomson, 1950). Such waves soon develop into discontinuities in the fields of motion and pressure, of the nature of the hydraulic jumps that are normally observed at the surface of a brook. In the revolving fluid which comprises the supercritical region of a hurricane, a jump takes a spiral shape (see fig. 2), as will be shown later. It is stationary relative to the obstacle that causes its formation. The air passes through a jump from its rear face to its forward face. During this passage, the air loses a considerable amount of its mechanical energy. The rate of loss of energy through a jump will be estimated below. The energy that is lost in this manner manifests itself in turbulent and unorganized motion, which is normally observed in a hurricane.

The energy which is lost through the jumps represents a loss of mechanical energy for the whole motion in the supercritical region. Hence the kinetic energy of the flow, and therefore the wind velocity in that region, is expected to decrease. This decrease in wind velocity upsets the balance of the pre-existing pressure gradient, and the air of the lower layer will therefore be able to rush into the "empty" eye from the surroundings. A new state of equilibrium will then be sought by the system.

It appears, therefore, that the jumps act as a "braking" mechanism which tries to slow the system down. It will be shown later that the action of these jumps in dissipating the energy is strongest at the borders of the eye, decreasing gradually with increasing distance. This would tend to make the new state of equilibrium such that the inner particles move more slowly than the outer particles.

A word may be added about the "obstacles" that create these jumps. It appears from fig. 1 that the upper surface of the supercritical region is in touch with the underlying earth's surface, which is usually the ocean surface, but may also be solid ground. Hence the obstacles that create the jumps may be either oceanic waves that are generated by the hurricane winds, or the orographical undulations of the ground. In the case of the oceanic waves, more support is found for the idea that the hurricane creates its own means of destruction.

It is the opinion of the writer that the jumps are the main factor responsible for the dissipation of the energy in the critical region, and for transforming the hurricane to the "mature" phase. These jumps, as may be gathered from the discussion given above, are always present in the supercritical region, and they are very effective in dissipating the energy.

In addition to the jumps, frictional forces are acting. It is clear that the effect of friction is stronger near the borders of the eye, where the depth of the fluid, and hence the mass affected, is smallest. Frictional forces, therefore, act in the same direction as the jumps.

However, frictional forces are not limited to the supercritical region. They are effective in all the regions, and they tend to dissipate the energy of the storm as a whole.

Because the rate of dissipation of energy is greater near the borders of the eye, and because of the inflow of air to the previously empty eye, it seems plausible to surmise that the new state of equilibrium which is sought by the storm is that approaching solid rotation in the inner core. In this new state of equilibrium, which is here identified with the mature phase, the hurricane will consist of two main regions: (1) the outer region, which is not appreciably different from that of the immature stage, and (2) the inner region,

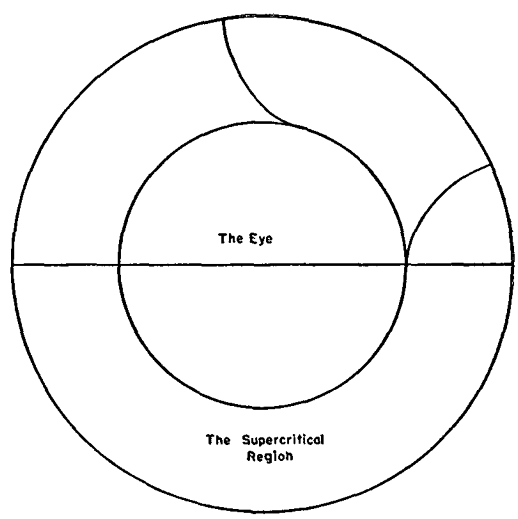

FIG. 2. Schematic representation of jump lines.

which is the "eye" of the mature hurricane, and which has undergone most of the metamorphosis process. The lower layers of the mature eye are now full with the lower fluid, so that the upper air does not reach the earth's surface. The horizontal area covered by the new eye is now much larger than in the immature stage. It is at least three times larger (Abdullah, 1953), since it now comprises the original immature eye plus the supercritical region. The weather in the new eye may show marked change. Thin clouds are now possible, because of the existence of the two layers, and the temperature at the center may not differ appreciably from that of the outer region, since they both consist, at the surface, of the same air masses. The wind distribution in the mature eye is different, as already stated, and the hydrodynamical instability which was existing in the supercritical region is absent in the mature eye, since that region itself is absent. Fig. 3 shows the characteristics of the mature eye.

5. The decay phase

The jumps disappear as soon as the supercritical region is annihilated. The jumps which are under consideration cannot be formed by obstacles in a subcritical flow (see Milne-Thomson, 1950). The only dissipating mechanism that remains to destroy the hurricane is frictional forces. No further discussion will be given here of this mechanism, since it has been treated by various authors. See, for instance, McDonald (1942), or Byers (1944).

6. Some mathematical considerations

Before presentation of the mathematical treatment pertinent to the shape of a jump and the rate of dissipation of energy, it is advisable to summarize the findings of a previous investigation (Abdullah, 1953), relevant to the problem under consideration.

In that paper the assumption was made that an immature tropical cyclone is caused by a stationary simple vortex in the lower layer of an atmosphere consisting of two distinct layers, the upper layer being at higher potential temperature. The initial state of this atmosphere is that of rest. The vortex is assumed to persist for a sufficiently long period of time such that a steady state of equilibrium is established. The two atmospheric layers were substituted for by two incompressible equivalent layers. Under these assumptions, the following results were derived:

1. The depth of the lower layer, Z, is given by the relation

$$Z = Z_\infty - k^2/(2g'r^2), \tag{2}$$

where Z_∞ is the undisturbed depth at infinity, r the distance from the center, k a constant which has the same significance as in (1), and g' is the "reduced" acceleration of gravity, given by the relation

$$g' = g(\rho - \rho')/\rho, \tag{3}$$

where ρ and ρ' are the densities of the lower and upper layers, respectively, and g is the acceleration of gravity;

2. The velocity of progress of an infinitesimal gravitational disturbance at the upper surface of the lower layer is given by the relation

$$c = \frac{k}{2^{1/2}}\left(\frac{1}{E^2} - \frac{1}{r^2}\right)^{1/2}, \tag{4}$$

where E is the radius of the "immature" eye, and c will be called, for brevity, the "sonic" velocity; the name is borrowed from aerodynamics, and is used because of the exact correspondence between the two kinds of disturbances;

3. The radius of the immature eye, and that of the supercritical region, at the sea surface, are given by the relations

$$E = 2^{-1/2}k/c_\infty, \tag{5}$$

and

$$a = 3^{1/2}E, \tag{6}$$

where $c_\infty = g'Z_\infty$ is the "sonic" velocity at infinity, and a is the critical radius, which is the outer radius of the supercritical region; it may be seen from these last two relations that the area, at the surface, of the supercritical region is double the area of the eye; this result was anticipated in the discussion presented in section 4, above.

In the mature storm, which was assumed to be of the nature of a Rankine vortex, the following results were found:

1. The wind distribution was assumed to be

$$\begin{aligned} q &= (k/a^2)r \quad \text{for} \quad 0 \le r \le a, \\ q &= k/r \quad \text{for} \quad a \le r \le \infty, \end{aligned} \tag{7}$$

where now a is the radius of the mature eye, assumed to be identical with the radius of the supercritical region;

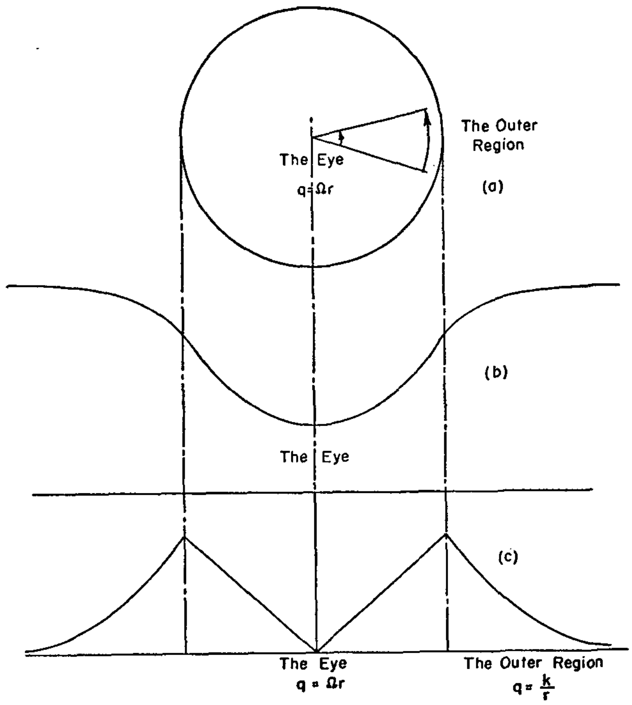

FIG. 3. Schematic representation of mature storm. (a): horizontal cross-section at sea level; (b): vertical cross-section through center; (c): wind distribution. q is wind velocity; r is distance from center. k and Ω are constants.

2. The depth of the lower fluid above the eye is given by the relation

$$Z' = \tfrac{2}{3}Z_\infty - \frac{k^2}{2g'}\left(\frac{1}{a^2} - \frac{r^2}{a^4}\right) \quad \text{for} \quad 0 \leq r \leq a. \tag{8}$$

Now, to compute the shape of a jump in the supercritical region, it is enough to use the relation (see Milne-Thomson, 1950)

$$\sin^2\mu = c^2/q^2 = 1/M^2, \quad q > c, \tag{9}$$

where μ is the "Mach" angle, which is the angle between the direction of the jump line and the streamline at the point at which this angle is measured, M is the "Mach number," and the condition of supercritical flow is expressed by the inequality. It may be added here that the jumps form along the characteristic lines of the flow, since they are the only lines along which discontinuities propagate (see Courant and Friedrichs, 1948).

From (9), (1) and (4), the following relation is derived:

$$|\sin\mu| = (\tfrac{1}{2})^{\frac{1}{2}}[(r^2/E^2) - 1]^{\frac{1}{2}}, \quad a \leqslant r \leqslant E. \tag{10}$$

If it is assumed that the streamlines in the supercritical region are circular, which assumption is very approximately true in a stationary vortex, the shape of a jump line may easily be traced as in fig. 2. It can be seen from (10), that right at the border of the eye, when $r = E$, $\sin\mu = \mu = 0$, and hence a jump line is tangential to the eye. At the critical circle, which is the outer border of the supercritical region, $r = a = 3^{\frac{1}{2}}E$, and therefore $\sin\mu = 1$, and hence $\mu = \frac{1}{2}\pi$. A jump line is therefore tangential to the radius vector at that circle.[2]

[2] It is possible to deduce the geometrical equation of the curve representing the jump line. Fig. 4 illustrates the method. In this figure point O is the geometrical center of the hurricane, and the line J is the jump line. Ox is any fixed axis of reference.

From this figure it follows that

$$\sin^2\mu = \frac{(dr)^2}{(r\,d\theta)^2 + (dr)^2}.$$

But $\sin^2\mu = c^2/q^2$, and from (1) and (8) we have

$$\frac{c^2}{q^2} = \tfrac{1}{2}r^2\left(\frac{1}{E^2} - \frac{1}{r^2}\right).$$

Upon substitution of this in the first relation, and after some manipulation, the differential equation of the curve J is found to be

$$d\theta = \left(\frac{3E^2 - r^2}{r^2 - E^2}\right)^{\frac{1}{2}}\frac{dr}{r}.$$

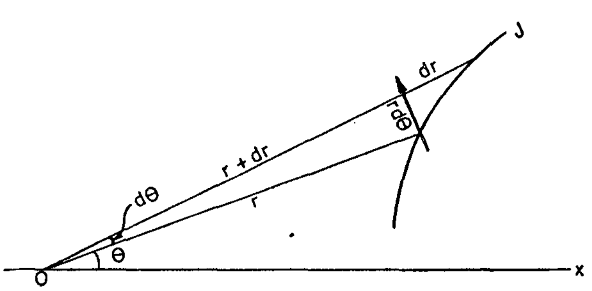

FIG. 4. Derivation of equation of a jump line.

The rate of dissipation of mechanical energy at a jump was computed by Stoker (1948), whose result may be used here with some obvious modifications. He has found that the rate of dissipation of energy, per unit length of a jump, is given by the relation

$$\frac{d\epsilon}{dt} = \frac{mg'}{\rho}\,\frac{(\bar\rho_0 - \bar\rho_1)^3}{4\bar\rho_0\bar\rho_1}, \tag{11}$$

where $\bar\rho_0 = \rho Z_0$, and $\bar\rho_1 = \rho Z_1$ (see fig. 5). The quantity m is the momentum in unit width of the fluid relative to the jump. It is given by the relation

$$m = \bar\rho u,$$

where u is the velocity of the air relative to the jump. If the jump is stationary, u becomes identical with the wind velocity, q.

Stoker (1948) has shown that $d\epsilon/dt$ must always be negative, signifying that energy is always lost by the fluid when it crosses the jump.

Equation (11) may be put in the form

$$d\epsilon/dt = mg'(\Delta Z)^3/Z_1Z_0,$$

where $\Delta Z = Z_0 - Z_1$. If ΔZ is taken as a constant along the jump, it follows that the rate of loss of energy increases rapidly with decreasing depth. Hence, the energy lost is greatest near the boundaries of the eye, and it decreases as the distance from the eye increases. This result was anticipated in section 4, above.

7. Mechanical energy lost by the eye in its transformation

To compute the mechanical energy lost by the eye in the process of transformation from the immature phase to the mature phase, we proceed as follows.

In the steady state of the immature phase, the kinetic energy of the supercritical region is given by

$$(\text{K.E.})_1 = \int_E^a \tfrac{1}{2}q^2\,dM, \tag{12}$$

where M is the mass. The kinetic energy of the eye itself may be neglected, since it has been assumed that

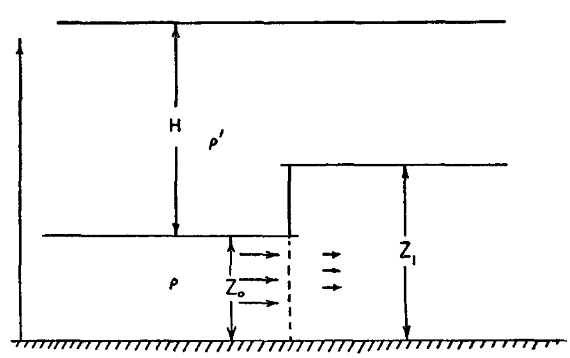

FIG. 5. Schematic representation of jump. H is depth of upper fluid, Z that of lower fluid.

the air in the eye at this stage, which descends slowly from the upper layer, does not take part in the circulation. From (11), (2) and (6), and after some obvious manipulation, the following is obtained:

$$(\text{K.E.})_1 = \pi\rho k^2[1.1\, Z_\infty - k^2/(2g'a^2)]. \qquad (13)$$

The potential energy of the air in the eye and the supercritical region is, in the immature stage,

$$(\text{P.E.})_1 = \int_E^a [\pi\rho g Z^2 + 2\pi\rho' g H(Z + \tfrac{1}{2}H)] r\, dr + \tfrac{1}{2} g\pi E^2 \rho' K^2, \qquad (14)$$

where H is the depth of the upper layer, and $K = H + Z$ is the height of the upper surface of the upper layer. In computation of this energy, the potential energy of the upper layer was taken into account.

From (14), (2) and (6), the following result is obtained:

$$(\text{P.E.})_1 = g'\pi\rho\left(\tfrac{1}{3}Z_\infty{}^2a^2 - \frac{1.1}{2}\frac{k^2}{g'}Z_\infty + \frac{k^4}{4g'a^2}\right) + \tfrac{1}{2}g\pi\rho' K^2a^2. \qquad (15)$$

The kinetic and potential energies of the air in the eye of the mature storm may be computed in a similar way. The results are

$$(\text{K.E.})_2 = (1/6)\pi\rho k^2[Z_\infty - k^2/(4g'a^2)], \qquad (16)$$

and

$$(\text{P.E.})_2 = \tfrac{1}{3}g'\pi\rho\left(\tfrac{2}{3}Z^2a^2 - \tfrac{1}{2}Z_\infty\frac{k^2}{g'} + \frac{1}{8}\frac{k^4}{g'a^2}\right) + \tfrac{1}{2}g\pi\rho' K^2a^2. \qquad (17)$$

The energy lost in the process is therefore

$$\Delta(\text{K.E.}) = (\text{K.E.})_1 - (\text{K.E.})_2 = \pi\rho k^2\left(0.933\, Z_\infty - \frac{11}{24}\frac{k^2}{g'a^2}\right), \qquad (18)$$

and

$$\Delta(\text{P.E.}) = (\text{P.E.})_1 - (\text{P.E.})_2 = g'\pi\rho\left(\frac{1}{9}Z_\infty{}^2a^2 - 0.38\frac{k^2}{g'}Z_\infty + \frac{5}{24}\frac{k^4}{g'a^2}\right). \qquad (19)$$

In addition to this energy, account must be taken of the energy that is carried by the inflowing air during the process. To estimate this energy, the volume, and hence the mass, of the inflowing air will be estimated first.

Thus, it may easily be shown that the initial volume of the lower air in the supercritical region of the immature stage is

$$V_1 = \pi[2/3\, Z_\infty a^2 - k^2/(2g')]. \qquad (20)$$

The volume of the lower layer in the eye of the mature stage is

$$V_2 = \pi[2/3\, Z_\infty a^2 - k^2/(4g')]. \qquad (21)$$

Hence, the volume of the inflowing air is

$$\Delta V = V_2 - V_1 = \pi k^2/4g'. \qquad (22)$$

Since the air in the outer region is assumed to remain undisturbed during the process, this additional volume must have descended from the upper surface of the undisturbed fluid at infinity. The energy which it carries to the eye is therefore

$$(\text{P.E.})_3 = \rho g'\, \Delta V\, Z_\infty = \pi\rho k^2 Z_\infty/4. \qquad (23)$$

This increment of energy is also dissipated during the process. The total energy lost in the process is therefore

$$\Delta\epsilon = \Delta(\text{K.E.}) + \Delta(\text{P.E.}) + (\text{P.E.})_3. \qquad (24)$$

This energy may be computed from (18), (19) and (23).

8. Numerical example

The figures used in the numerical example which is to be computed now are taken from the previous paper (Abdullah, 1953). On the basis of actual observations, these figures are quite conservative and represent a storm of moderate strength.

Let the height of the undisturbed equivalent lower layer be 5.64 km, the density of the lower fluid be 1.03 $\times 10^{-3}$ g/cm³, and that of the upper fluid 0.922 g/cm³. Let the constant k have the value 10^{10} cm²/sec. It can then be shown that the radius of the eye of the immature storm is 15.6 km, that of the critical circle is 27 km, and the reduced gravity is 36.3 cm/sec². Let the difference in pressure between the two sides of a jump be 5 mb. This value is conservative and represents a jump of moderate head.

It is required to evaluate the energy lost during the process of transformation of the storm to maturity, and the rate of loss of energy by one jump. From these, it is required to estimate the period of transition.

In the notation of the present paper, the data are the following: $Z_\infty = 5.64 \times 10^5$ cm, $\rho = 1.03$ g/cm³, $\rho' = 0.922$ g/cm³, $E = 15.6 \times 10^5$ cm, $a = 27 \times 10^5$ cm, $k = 10^{10}$ cm²/sec, $g' = 36.3$ cm/sec².

Upon use of these values in (18), (19), (23) and (24), it is found that the mechanical energy lost in the process of transformation is

$$\Delta\epsilon = 0.90 \times 10^{24} \text{ ergs}.$$

The average depth of the supercritical region is taken to be 3 km. From (11), after an obvious use of the hydrostatic equation, it is found that the rate of loss of energy at a jump is

$$d\epsilon/dt = 28.7 \times 10^{10} \text{ ergs sec}^{-1}\text{cm}^{-1}.$$

But the radial projection of the length of a jump line is equal to the width of the supercritical region, which is 11.4 km. Hence, the rate of loss of energy through one jump is 3.27×10^{17} ergs/sec.

If the number of jumps that are acting simultaneously in one storm is n, the period required for the dissipation of the lost energy is

$$\tau = \Delta\epsilon/(n\, d\epsilon/dt) \text{ sec},$$

which, in the present case, gives

$$\tau = (2.75 \times 10^6)/n \text{ sec} = 31.8/n \text{ days}.$$

As a first guess for the number of jumps, let it be six. This makes the time necessary for the dissipation of the lost energy 5.3 days, on the assumption that the jumps are the only dissipating mechanism. This period seems to be of the right order of magnitude.

9. Discussion and further remarks

A word may be said about the quasi-circular white bands that are sometimes observed on the radar scope, and that surround the central part of a hurricane (see Wexler, 1947), and one may speculate on their significance in the light of the hypothesis presented here.

In another publication, the writer (Abdullah, 1953, part 2) has attempted to explain the band-like structure of a hurricane by assuming that it is a manifestation of some organized vibration undergone by the air masses constituting the hurricane. In that paper it was shown that, if the wind field follows the hyperbolic law as expressed in (1), no quasi-circular bands are possible. The only vibrations possible in such a wind field are such that the air particles which lie on the same radius vector vibrate together in the same phase. The only bands possible are, therefore, the radial bands which give rise to the converging cirrus clouds that are usually observed and recognized as the forerunners of the storm (see Byers, 1944). It was, however, shown in the same paper that circular bands are possible in a wind field which rotates like a solid disc, as explained in the first of equation (7), and which was identified with the "eye" of the hurricane.

It seems, therefore, that the quasi-circular bands may be taken as an indication of the fact that the hurricane in which they are observed is in its mature stage. For, as was surmised in the present paper, the solid rotation is the equilibrium state sought by the mature eye. The quasi-circular bands must, therefore, be observed in the region of the mature eye. These bands are not to be confused with the spiral jumps discussed here. The two phenomena are distinct, and they do not resemble each other in shape.

Moreover, since any mechanical system vibrates most strongly when it is displaced from its equilibrium position and when it is endeavoring to attain a new state of equilibrium, it may be speculated that the vibration of a hurricane is at its strongest when the immature stage has been disturbed, and when it is trying to adjust itself to the mature stage. This would lead to the conclusion that the quasi-circular bands of a hurricane are best developed right at that period, namely at the beginning of the mature phase.

These speculations are in need of further observational verifications. If they are proved to be right, it may be said that the appearance of the bands is an indication that the hurricane is decreasing in intensity, and that its eye is expanding in accordance with the process sketched above.

The writer wishes to make it clear that no claim is made that the hypothesis proposed here explains all the facts known about a hurricane. All that is claimed is that the hypothesis provides for a unified process of metamorphosis which is dynamically possible and which seems to be in agreement with the idealized picture of a hurricane model. In this paper only the hydrodynamical factors have been considered, and various factors have been neglected which are known to be of importance in the development of a hurricane. Probably the most important of these is the thermal source of energy.

It is hoped that the present paper has shown the importance of the hydraulic jumps in the development of the eye of the mature hurricane, and that it has suggested a hypothesis which may be tested by careful observations.

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