Conceptual Evolution of the Theory and Modeling of the Tropical Cyclone

By Katsuyuki V. Ooyama

National Hurricane Research Laboratory, NOAA
Coral Gables, Fla. 33146, U.S.A.
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Abstract

Dynamically, the tropical cyclone is a mesoscale power plant with a synoptic-scale supportive system. By the early 1960's, the general structure and energetics of the system and basic components of the supportive mechanism were fairly well documented by the instrumented aircraft observation of hurricanes and through the diagnostic interpretation of the data. The prognostic theory which would have unified these basic findings in a dynamically coherent framework had a more difficult time emerging. When a viable theory finally emerged, a change in the theoretical perception of the problem was necessary. The parameterization of cumulus convection was an important technical factor in the reduction of a multiscale interaction problem to a mathematically tractable form. Nevertheless, it was the change in our perception of the basic problem and the re-arrangement of priorities that made the parameterization a tolerable substitute for real clouds. Even then, the validity and limitation of the new theory, known as CISK, were fully appreciated only through careful experiments with nonlinear numerical models. In the meantime, the mathematical simplicity of certain parameterization schemes enticed many to apply the schemes to other tropical disturbances, including the easterly wave, in the traditional idiom of linear stability analysis. More confusion than enlightenment often ensued as mathematics overran ill-defined physics. With further advances in numerical modeling, the interest in tropical cyclone research shifted from conceptual understanding of an idealized system to quantitative simulation of the detail of real cyclones, and it became clear that the intuitive parameterization of whole clouds would have to be discarded. Now that some models have returned to explicit calculation of the cloud scale, one may wonder if all the exercises with parameterized convection were an unfortunate detour in the history of tropical cyclone modeling. The answer depends on one's philosophical view of "progress."

1. Introduction

The tropical cyclone is a complex system of interacting physical processes and multiscale motions. A complete description would have to cover nearly all the subjects in meteorology, from cloud physics within turbulent convection to general circulations of the tropics, and from interactions with the ocean to radiative heat transfer into outer space. One of the most difficult aspects to theorize upon is the organized moist convection. Although mesoscale organization of convective clouds is also present in many other weather systems, its role in the tropical cyclone has certain unique characteristics. The significance of understanding these characteristics can be clearly seen when one reviews the advances made in tropical cyclone research during the past two decades.

The progress has been neither smooth nor straightforward. At times, communication among investigators has seemed to have presented as difficult a problem as the tropical cyclone itself. Some views of the theoretical progress, such as those presented by Gray (1980), do not promote reasoned dialogs. Those investigators who are more theoretically inclined have also contributed to the difficulty; the confusion about the popular acronym CISK is so wide-spread that it has become a useless term in any sensible communication. Another difficulty is the wide latitude in the usage of words "formation" and "genesis". These words are probably as old as the literature of the tropical cyclone, but their precise meanings remain undefined. This paper is an attempt to reestablish a common basis of communication by summarizing tropical cyclone research and, thus, indicating where we stand in our theoretical view of the problem. For this purpose, mathematical equations are avoided intentionally and references to individual contributions are kept to an essential minimum. An extensive bibliography is available in Anthes (1981).

2. The steady state

In the fully developed stage, the tropical cyclone is a nearly circular, warm-cored vortex, occupying the entire height of the troposphere and extending radially many hundreds of kilometers. Continually active clouds surround the center of the storm and are organized as the eyewall and rain bands. Although small-scale details may change continuously and, sometimes, rapidly, the tropical cyclone, as a whole, is a stable system that may persist for many days over the warm tropical ocean as a recognizable unit. In comparison with severe weather systems elsewhere, the longevity of the tropical cyclone is one of its important characteristics.

In very simple terms, therefore, a mature tropical cyclone may be thought of as an axisymmetric, free-spinning vortex in a steady state. Such was the basis of both observational and theoretical analyses in early times and is still the basic premise in operational forecasts of the storm track. Physically, the simplification is recognition that the necessary rearrangements of the mass and angular momentum fields have already been achieved in the large volume of the vortex, and also that the kinetic and potential energies have been stored in a stable configuration to establish a large dynamic inertia. The low central pressure at sea level is in hydrostatic balance with the warm inner core aloft, and the resulting radial pressure gradient force is opposed by the inertial forces of the rotating wind.

The free-spinning vortex, however, does not account for other important characteristics of the mature tropical cyclone, such as the persistent updraft and precipitation in the eyewall clouds, the inward spiraling airflow in a relatively thin layer above the ocean surface, and the radial outflow in an upper layer of the vortex. The radial and vertical flows, called "the secondary circulation" in fluid dynamics, are as important as the primary (i.e., azimuthal) circulation to the real tropical cyclone. The classical model of the secondary circulation, which consists of three legs of the in-up-out trajectory (Riehl, 1954), is a distillation of those observed facts. It is this secondary circulation that allows a mathematical model of the primary vortex to make first contact with the physical world. To put it another way, the consideration of physics in the secondary circulation, or the absence of it, makes the distinction between a meteorological model of the tropical cyclone and a fluid dynamic model of a "hurricane-like" vortex.

If the vortex together with the secondary circulation were to remain in a steady state, as the real storm does in good approximation, certain conditions would have to be satisfied along the trajectory of the secondary flow. It is obvious that the interior updraft must be in moist adiabatic ascent to maintain the warm core. However, to keep its temperature warm enough for the low surface pressure of a typical storm, the inflowing air must enrich its heat content by picking up sensible and latent heat from the ocean as the air moves toward the low pressure center. For the air to be able to move along the inward trajectory in the inertially stable, steady-state vortex, the angular momentum of the moving air must be partially diminished by friction against the ocean. The outflow leg of the secondary circulation may be physically inactive if the upper region of the primary circulation conforms to the angular momentum transported by the secondary circulation from below.

The above is the essence of the steady-state theory, presented by Malkus and Riehl (1960) and Riehl (1963). Actually, their purpose was not to prove that a steady state is strictly possible, but, rather, to show that the exchange of both angular momentum and thermodynamic energy between the low-level inflow and the ocean is necessary, and empirically sufficient, to explain the coexistent primary and secondary circulations of a mature tropical cyclone in the inner area of a few hundred kilometers. Although numerical estimates of the boundary fluxes may vary with the intensity of the storm or with different data sets (Frank, 1977), the conclusion about the importance of the physically active secondary circulation does not become suddenly invalid if the storm is not yet fully developed, or if the idealized trajectory is modified.

The steady-state theory does not include any dynamic interaction between the secondary circulation and the primary circulation, although the former will not exist without the latter. In particular, the radial pressure gradient that drives the low-level inflow cannot be maintained without the deep layer of the primary circulation. To understand the dynamic relationship between the two circulations, we must consider the time-dependent problem of the combined system in which, as we shall discuss later, energetics and dynamics are also interactive. For the present, we may comment on a few notable episodes off the line of progress. The role of, or even the existence of, the secondary circulation in the tropical cyclone was once cast in doubt by Kuo (1965) in his quest for a steady state. Carrier et al. (1971) attempted to explain the tropical cyclone by decree while sharply criticizing the meteorologists' humble effort to unite energetics and dynamics.

We must emphasize that the steady state is a fair approximation for describing only the inner area of a mature tropical cyclone, and that it should not be used as an idealization for the purpose of theoretically deducing the spatial distribution at larger radii of various properties of the tropical cyclone, especially angular momentum. At 1000 km, for example, a steady state, if it were possible at all, would not be reached during the life of a tropical cyclone. The recognition of the fact that the mature stage should not be blindly equated with the strict steady state is more than a reflection of empirical facts; it is important to the theoretical understanding of the tropical cyclone.

3. Genesis

The question at the other end of tropical cyclone problem, opposite the steady state, is that of tropical cyclogenesis. Speculations and suggestions abound, but we lack a clear understanding. Since it is still the most intriguing tropical cyclone question, we analyze the nature of the problem here.

When the characteristic rotational wind of an incipient tropical cyclone is detected, it appears to have developed in the area of a pre-existent disturbance with organized convective activity. However, although such disturbances frequently occur over the tropical oceans, most of them do not become tropical cyclones. There have been a number of studies on climatological and synoptic conditions (Gray, 1978), but there are no hard data that might reveal the individual circumstances of tropical cyclone formation, or non-formation, in sufficient detail. Even if we were to carry out a field experiment to obtain such data, a diagnostic analysis of formative events would prove very difficult.

It is unrealistic to assume that the formation of an incipient vortex is triggered by a special mechanism or mechanisms, or that genesis is a discontinuous change in the normal course of atmospheric processes. For the reason that is discussed below, it is far more natural to assume that genesis is a series of events, arising by chance from quantitative fluctuations of the normal disturbances, with the probability of further evolution gradually increasing as it proceeds. According to this view, the climatological and synoptic conditions do not directly determine the process of genesis, but may certainly affect the probability of its happening. With a better understanding of the mesoscale dynamics of organized convection, the range of statistical uncertainty can be narrowed down. Nevertheless, the probabilistic nature of tropical cyclogenesis is not simply due to lack of adequate data, but is rooted in the scale-dependent dynamics of the atmosphere.

The schematic diagram in Fig. 1 summarizes the scale dependence. The abscissa represents a spectral decomposition of the motion in terms of horizontal scale l. All the scales of motion on the abscissa may be present at any point in the geometrical space. The ordinate indicates Rossby's radius of deformation λ, which is a measure of the rotational constraint on the motion. In the general state of the atmosphere, in which dis-

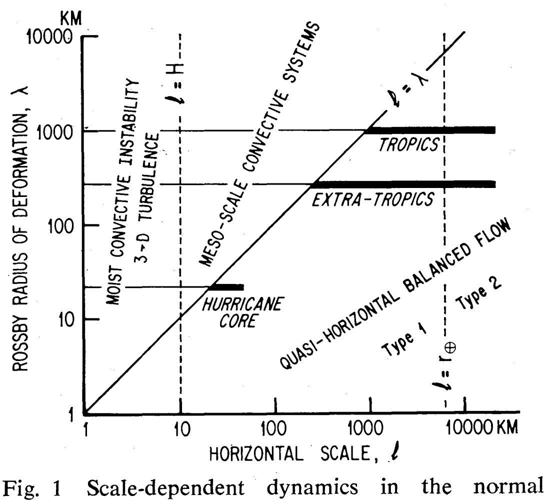

Fig. 1 Scale-dependent dynamics in the normal states of the atmosphere.

turbances are relatively weak, the rotational constraint arises mainly from the earth's rotation. Thus, the spectrum of motion at a given latitude may be represented on an appropriate horizontal line in the diagram. A typical line for the tropics ($\lambda = 1000$ km) and one for the extratropics ($\lambda = 300$ km) are shown. The third horizontal line is discussed later. Static stability of the atmosphere, except for the moist process, is assumed to be constant.

For a given λ, the large-scale components of motion with l greater than λ are quasi-horizontal and nearly in geostrophic balance with the pressure field, being strongly constrained by the earth's rotation. Vertical motion does occur, but only to the extent that is required by the adjustment of one balanced state of horizontal motion to another. Phillips (1963) divides geostrophic motion into two types, but we shall refrain from discussing the detail. According to the theory of geostrophic turbulence (e.g., Rhines, 1979; see also a very illuminating review paper by Tennekes, 1978), the spectral evolution of a two-dimensional flow is characterized by a slow rate of enstrophy cascade; for the atmosphere, the time scale is about a day. The kinetic energy cascade into smaller scales is essentially prohibited. Translated into more practical terms, the theory implies that the quasi-balanced synoptic-scale flow, shown by heavy-line segments in Fig. 1, is deterministically predictable for a period of, at least, a few days. It may be noted that the synoptic scale, here, is dynamically defined relative to λ, rather than by a fixed geometrical scale.

On the small-scale end of the spectrum is a different regime of motion, characterized as three-dimensional turbulence. Since the atmosphere is statically stable, very little energy should exist in this part of the spectrum, unless the air is heated from below, as in the boundary layer, or internally by latent heat of condensation, as in convective clouds. Over the warm tropical ocean, both conditions are regularly met; a well-mixed boundary layer of moist air and numerous convective clouds are ubiquitous phenomena. Horizontal scales of the energy-producing primary eddies (individual clouds) are limited by the vertical scale of a moist-adiabatically unstable layer. Thus, the area to the left of $l=H$ in Fig. 1 represents the regime of free convection, where H is either the scale height or, at most, the depth of the troposphere. According to the theory of three-dimensional turbulence, energy rapidly cascades into smaller and smaller scales, and no deterministic prediction in this regime is possible. Numerical simulation of a typical cloud cell may be achieved with statistical assumptions on in-cloud turbulence. In a more general prediction of the convective regime, clouds themselves must be considered to be statistical entities.

Since the atmosphere is not horizontally uniform, the small-scale free convection does not occur uniformly everywhere, but is modulated in patches of greater horizontal scales. Under certain conditions, the energy of the modulating scale also grows with the constituent free convection, and the modulation may eventually become a self-regulating mechanism. The result is the mesoscale system of organized convection. Unlike the synoptic-scale flow that can persist by itself, the mesoscale system cannot exist without active convection within. Thus, although it may last much longer than individual clouds, the time evolution of a mesoscale system is essentially probabilistic, unless it is strongly controlled by a more deterministic synoptic-scale environment.

Typical scales of the mesoscale convective systems observed during the GARP Atlantic Tropical Experiment (GATE) were several hours long and a few hundred kilometers, at most. These scales were considerably smaller than those of the easterly wave, the prominent synoptic feature in that part of the tropics. Although the occurrence of mesoscale systems was statistically related to the wave phase, the association in terms of individual systems was highly variable. The composite average structure of the easterly wave by Thompson et al. (1979) completely smoothes out the mesoscale variability. This and other analyses of the GATE data, due mainly to a mixed quality of upperair observations, have not revealed what we hoped to see, that is, physical and dynamical links between the mesoscale convective activity and the weakly constraining environment. In the extratropics, on the other hand, the scale separation between the mesoscale and the synoptic scale is small, suggesting a closer control of the former by the latter. In fact, a reasonable warning of severe weather can be issued from a synoptic forecast in mid-latitudes, even though individual tornadoes are not predictable.

Returning to the main topic, we now perceive the question of tropical cyclogenesis to be that of placing probabilistic mesoscale convective systems under the control of a deterministic environment. In the tropics, the mesoscale organization cannot grow to the normal limit of the synoptic scales. (The reason is discussed, later, in conjunction with Fig. 3.) However, if the relative rotation and vorticity are increased in an area, the environment of mesoscale systems in that area is stiffened by the increased inertial stability. In other words, λ is locally decreased and, thus, the lower scale limit of the quasi-balanced flow regime is brought down closer to the mesoscale. If, by any chance, this trend were continued, the deterministic dynamics of the balanced flow would begin to take over the control of the mesoscale convection. The final stage of this process, in which the control is complete, is indicated by the third horizontal line in Fig. 1. A full view of the scale diagram for a mature cyclone is shown in Fig. 2, in which λ is dependent on local inertial stability and, thus, a function of radius, r. (Conversely, r is a function of λ.)

The mature cyclone, adopted here for the illustration purpose, assumes a maximum tangential wind speed of $60\,\mathrm{m\,s^{-1}}$ at $r=30$ km, with the wind decreasing outwards according to the inverse half power of radius. Thus, the local inertial stability, defined as the geometric mean of absolute vorticity and absolute angular speed, will decrease (or, λ will increase) with the $-3/2$ power of radius, until Coriolis parameter due to the earth's rotation becomes dominant at large radii. The line, labeled "hurricane core", in Fig. 1 represents λ at $r=50$ km of this typical cyclone, demonstrating a sharp increase in the local inertial stability, by almost two orders of magnitudes, from the normal state in the tropics.

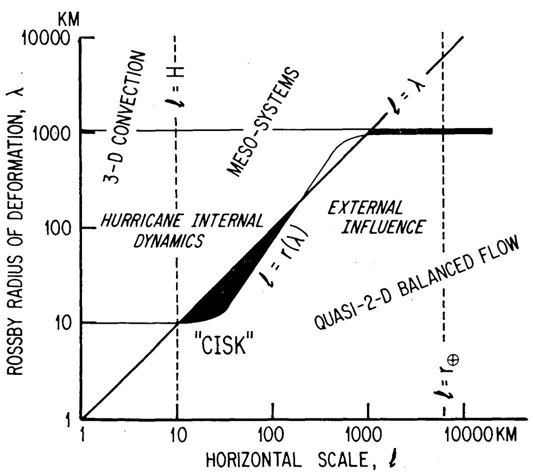

Fig. 2 Scale-dependent dynamics in a mature tropical cyclone.

Clouds are still in the regime of three-dimensional turbulence, but the cloud-organizing mesoscale extends into the quasi-balanced flow regime, as indicated by the heavy line segment. The line terminates at $l=50$ km, because those spectral scales that are greater than the radius under consideration are not wholly affected by high inertial stability of the local area. Therefore, taking all radii together, we may consider $l=r(\lambda)$ in Fig. 2 to be the dividing line between the spectral scales that participate in the internal dynamics of the cyclone under the influence of prevailing local inertial stability and those scales that merely reflect the presence of external influences. The diagrams, above, do not show how much spectral power, or energy, is actually associated with each scale. It is a question for the dynamic theory or numerical model to answer. However, the darkened area in Fig. 2, between $l=\lambda$ and $l=r(\lambda)$, implies the existence of cloud-organinzing mesoscales within the deterministic regime of the balanced flow. This fact, as we further discuss in the following section, is the basis of a closure hypothesis which the popular but badly misused acronym CISK was originally meant to be.

At the beginning of the genesis process, the moist convection is modulated and sustained by the three-dimensional dynamics of mesoscale systems, in which the vertical shear, the rain-induced downdraft, and the propagation of the system relative to the conditionally unstable mixed layer, are known to be important factors. The so-called Ekman pumping, which is a valid approximation for the frictional boundary layer of a deep balanced vortex, has no place in the self-regulating mechanism of the usual variety of mesoscale systems. True to the nature of energy cascading dynamics, understanding of a mesoscale system requires a full consideration of circulations within its scale, especially the vertical circulation. However, the question of tropical cyclogenesis goes beyond the understanding of separate mesoscale systems. It must be concerned with the aggregate behavior of mesoscale systems during the transition from the probabilistic stage to the deterministic stage in controlling moist convection. At present, we do not have sufficient understanding of the control, except for some statistical evidence and conjectures. If the genesis were ever to be understood as a kind of instability in certain synoptic conditions, it would be in terms of the growth of probability for the transitional process, rather than the growth of a disturbance in the traditional idiom of stability theories.

In the conclusion of this section, we may express a word of caution with respect to recent studies aimed at the genesis question. There is no doubt that there exist large-scale influences on the genesis process. However, the composite studies of observational data that have been summarized in Gray (1978) do not necessarily reveal causal effects of large-scale conditions. Their findings in prehurricane and pretyphoon cases may be merely confirmation that the genesis process is already on its way. Numerical simulation studies, such as Kurihara et al. (1981), are necessary and important means of exploring the multiscale three-dimensional problem of tropical cyclogenesis. In numerical models, however, the physics and the resolution of the dynamics are truncated. We must be very careful not to play the game with loaded dice.

4. Intensification and maintenance

Until the early 1960s, attempts were made to theorize and numerically simulate the formation of a tropical cyclone, starting directly from moist convective instability (conditional instability). The intention was correct, in principle, but the execution was naive for lack of understanding that such a theory or model would have to go through many levels of nonlinear, multiscale, interactions before a tropical cyclone could emerge from individual convective clouds. Contrary to the premise of those earlier attempts, modern progress in theory and modeling of the tropical cyclone has descended from the steady-state theory and worked its way backwards, so to speak, to the question of genesis. (The physical time in a theory or model, of course, runs forward.) In the course of this progress, we have gained an invaluable insight into the complex dynamics of the tropical cyclone by being able to explain and simulate all the important aspects of the tropical cyclone in a dynamically coherent framework.

The basis of recent progress is an understanding of the intensification and maintenance mechanisms as a cooperative process between the organized moist convection and the cyclone-scale vortex, or, in the terminology of section 2, a cooperative process between the primary and secondary circulations. In the steady-state theory, the question is the compatibility of the two circulations. In the cooperative intensification theory, it is the dynamic interaction between the two. The importance of physical processes acting on the secondary circulation is unchanged, except that the geometry of the trajectory should not be fixed and the updraft cannot be strictly in moist neutral ascent. It is the presence of the primary circulation that was taken for granted earlier and that now must be explained.

The intensity of a tropical cyclone usually is measured in terms of either the minimum sea-level pressure at the center or the maximum speed of rotational wind that occurs in the zone of eyewall convection, usually within 50 km of the center. As we have mentioned, a low sea-level pressure requires a warm column of air aloft, which, in turn, requires the rotation of air around it to stay in place. If there were no rotation in a deep layer of the cyclone, it would be a matter of minutes, not hours, for the warm inner core to be completely dispersed in all directions. Therefore, regardless of the measure of intensity, the intensification of a tropical cyclone is possible if, and only if, the strength of the primary circulation increases. The frictionally induced inflow in the thin boundary layer cannot be a direct cause of intensification of the primary circulation in the main body of the cyclone, because the radial pressure gradient that drives the frictional inflow can increase only when the primary circulation in a deep layer increases. (For this reason, the sectionalized vortex in the theory by Carrier (1971) would collapse if the artificial walls in his model were removed.) A simple and effective way to increase the rotation in the main body is to induce a radial inflow in the deep layer while conserving the absolute angular momentum. A layer of outflow at the top is needed to keep the inflowing air from accumulating in the interior.

The deep-layer inflow is, in essence, all that is needed for intensification of the cyclonic rotation. Its effect is cumulative and not influenced by surface friction. It may simply cease when the cyclone reaches a mature stage. There is one problem with this scenario, however. Energy is required for it to happen, especially an input of thermodynamic energy to lift the air at the end of its inflow leg to the higher level of the outflow. The kinetic energy necessary for increasing rotational winds is only a fraction of the required thermodynamic energy. As the supplier of the required thermodynamic energy, the secondary circulation in the frictional boundary layer, and in the moist updraft, becomes an indispensable partner of the cyclonic intensification.

The moist updraft must be convectively unstable; that is, the latent heat released by condensation of water vapor in the updraft must be greater than the amount of heat energy required by the moist air to rise from the boundary layer to the outflow level, so that the air from the middle layer can be entrained into the updraft and also lifted to the outflow level. In brief, the excess amount of latent heat released in the unstable convection does not directly raise the temperature of the inner core, but allows the mass flux of the updraft to increase with height by entrainment. This process further permits contraction of the air in the main body of the cyclone. The warming of the inner core is largely due to adiabatic adjustments of the mass field in response to the increasing rotation in the deep layer of the vortex. If the cyclonic intensification continues, however, the inner core becomes so warm that the updraft is no longer unstable. Then, there is no more excess energy for entrainment, and the intensification comes to an end, although a slow change may continue in the outer area where the convection is still unstable. In this quasi-steady state, the frictionally induced inflow does not stop, and the heat input to the boundary layer from the ocean must continue in order to maintain the neutral moist ascent in the warm inner core. Thus, the intensity of a mature cyclone may rapidly respond to a change in the ocean surface temperature, and more drastically to a substantial reduction of latent heat transfer in the case of landfall.

The above is a very abbreviated description of the cooperative intensification theory. To formulate the theory, and numerical models, in a specific and quantitative form, one more point of great technical importance should be considered. Moist convective instability in numerous clouds is an undeniable fact of the tropical cyclone, and we have just shown that it is, indeed, necessary for intensification. As we have shown, convective clouds are in the energy-cascading regime of dynamics. Our problem, here, is how to handle the moist convection without letting the theory, itself, cascade into intractable turbulence. Obviously, we have to institute a closure assumption at some point in the spectrum of cascading scales. The closure, or the so-called parameterization, is an art of approximation by which implicit effects of the truncated smaller scales are put into an explicit consideration of the remaining larger scales. Actually, more than just geometrical scales are involved; that is, the dynamic characters of motion change with the scale. Therefore, we may attempt to bring a closure on organized convective systems, on individual clouds, or on in-cloud turbulence. The rationale for such a closure, as well as the complexity of the consequences, will vary accordingly.

Since the closure is not an exact science, there have been, and will be, different proposals and debates on specifics. Numerical techniques necessary in model simulation are not trivial problems, either. Nevertheless, it is important to recognize the achievements, as well as the limitations, of various model studies in general terms. For this purpose, the main direction of progress in tropical cyclone modeling may be divided into three phases as discussed below.

The models of the first phase, the so-called balanced models, capitalize on the extraordinary strength of local rotational constraint, which characterizes a mature tropical cyclone. As shown in Fig. 2, the motion in a mature cyclone is in a quasi-balanced state (gradient wind balance) on nearly all scales, except for that of individual clouds. Therefore, any organization of clouds in the inner core should be strongly controlled by the balanced flow of the vortex. In other words, the organized convection in the eyewall and in inner rain bands, although geometrically of the mesoscale, is not controlled by the ordinary mesoscale dynamics, but by the deterministic dynamics of the balanced flow. This is the fundamental rationale of the balanced model, with the closure assumption that puts the dynamics and thermodynamics of moist convection completely on the implicit side, and the primary and secondary circulations of the balanced vortex on the explicit side, of the scale division. This closure is invalid in the early stage of the tropical cyclone in which the scale gap between the convective clouds and the balanced flow is too wide, and never was intended for inquiry into the question of tropical cyclogenesis. On the other hand, the validity of the closure improves asymptotically as the cyclone intensifies. Therefore, although a model simulation may be started from as weak a vortex as desired, the results are not interpretable physically until the model cyclone develops into a fully nonlinear stage. For the later stage of intensification and also in the mature stage, however, the model results are not only realistic, but provide us with a clear insight into causal relationships among observed characteristics of the tropical cyclone. The most representative paper of the first phase of modeling is Ooyama (1969).

The second phase of tropical cyclone modeling is marked by the use of primitive equations. Although the balanced vortex is conceptually helpful, it is overly restrictive and even inaccurate in areas of weak inertial stability and in the frictional boundary layer. However, the removal of the balance requirement from the explicit side of the closure brings a drastic change to the dynamic characteristics of the new closure. Even though the thermodynamic aspects of moist convection, which is mainly in the vertical, are still parameterized, the use of primitive equations of motion dictates that the cloud-scale dynamics, especially in terms of horizontal accelerations, be shifted from the implicit side to the explicit side of the closure. Thus, dynamically, the closure of the primitive equation model is on the vertically parameterized individual clouds. This is a welcome change, because the model is now, to a degree, able to generate the mesoscale organization of clouds, such as the eyewall and rain bands, explicitly. On the other hand, the computational burden is substantially increased to cope with cloud-scale instability, even though clouds are vertically parameterized. After considerable efforts to put numerical problems under control, many investigators have succeeded in simulating the tropical cyclone in the intensifying and mature stages. In fact, as documented by Kurihara (1975), those results are a splendid confirmation of the earlier results by the balanced model, as well as the present conceptual understanding of the intensification and maintenance processes.

With the use of primitive equations, there should be no restriction on model experiments starting from a very weak disturbance. Several experiments, including so-called sensitivity studies of initial growth rates, have been reported. The results, thus far, defy a definitive interpretation. There are wide variations among different models and a high dependence on various technical specifications within a model. One of many possible causes of uncertainty is the parameterization of convective clouds. Under a weak or nonexistent rotational constraint, the cloud-scale vertical circulation is a crucial factor in organizing mesoscale convective systems. The vertically parameterized cloud, mainly on the basis of thermodynamical considerations, does not produce the necessary effects, such as rain-driven downdraft. Thus, Yamasaki (1977) and Rosenthal (1978) have opened the third phase of tropical cyclone modeling, by explicitly calculating cloud-scale circulations. The parameterizaiton of clouds is completely removed and the closure is moved down in scale to in-cloud turbulence and cloud physics. The model results demonstrate the formation of squall lines in the early stage of a model run, and the cooperative mode of cyclone intensification in the later stage.

It is too early to say how these numerical models, with or without cloud parameterization, will contribute to our understanding of tropical cyclogenesis. The trend toward bigger and less restrictive models will continue, by allowing a larger domain to represent synoptic-scale conditions, and by improving geometrical and physical resolutions to replicate small-scale processes more faithfully. However, even if we could build a physically perfect model, the probabilistic nature of the genesis question would not change, as we have discussed in section 3. Besides the problem of logistics in running such a model, we must consider the problem of drawing conclusions from a few predictions of an event that has a very low probability of happening. Sensitivity studies with a model are easier to plan and execute, but conclusions may or may not be related to the real question.

5. CISK

Although we have intentionally avoided use of the acronym CISK, it deserves a few comments. Historically, the closure for the balanced model was introduced by Ooyama (1963) and, in a somewhat different form, by Charney and Eliassen (1964), as part of their respective linear theories of tropical cyclone intensification. The newly discovered instability was called conditional instability of the second kind (CISK) by Charney and Eliassen. Linear mathematics necessitated that the theoretical demonstration be confined to the growth of small-amplitude disturbances on the basic state of no-motion. This is technically inconsistent with the physical reasoning of the closure, and the linear theory in either version was not intended to explain tropical cyclogenesis. The linear theory, by definition, also failed to take into account the nonlinear processes which were obviously needed to explain the mature stage. For example, the reduction of moist convective instability due to warming of the inner core is the principal factor in the self-limiting mechanism of intensification, and the nonlinear advective terms in the equation of motion play a crucial role in determining the radius of the eye or that of maximum wind. Many arguments with the linear theory about preferred scales, or short-wave cutoff, are irrelevant to the tropical cyclone. Between the radius of the maximum wind and the Rossby radius of deformation in the outer environment, there is no other scale dynamically significant enough to be "preferred." Only through later work with nonlinear numerical models have the importance of these and other nonlinear processes become properly and specifically understood.

If one regards the acronym CISK to mean strictly the original linear theory, it represents a crude and incomplete idea by the present standard. Some conjectures in Charney and Eliassen were overstated and may have misled the indiscriminating reader. The present author views CISK in terms of the conceptual content that has grown and matured with advances in modeling work. Then, the spirit of CISK as the cooperative intensification theory is valid and alive. It is unfortunate, however, such a view of CISK does not seem to be shared by the majority of users of the acronym. On one hand, there are those who continue on criticisms of CISK as the linear theory, ignoring all the later contributions that have cast a better light on the theory. On the other hand, there are those who attach the acronym CISK to almost anything at their convenience. As the result of this arbitrary practice, the acronym has become a useless term in any sensible communication.

The unfortunate practice started when a certain scheme of parameterizing moist convection, which was only a technical component of the original CISK theory, became known as CISK. For example, in the closure of the balanced model of the tropical cyclone, an assumption (Ooyama, 1963 and 1969) was made that the release of latent heat by moist convection in a vertical column was proportional to the supply of unstable moist air at the bottom of the column (more specifically to the vertical motion at the top of the mixed boundary layer). This assumption is commonly, but confusingly, referred to as the CISK parameterization and attributed to Charney and Eliassen (1964). As a linear theory or a concept, CISK does not require this particular assumption. In fact, Charney and Eliassen use a different assumption that combines the total moisture convergence to a vertical column with the notion of a reduced effective saturation humidity. Furthermore, many numerical models of the tropical cyclone operate on a variety of parameterization schemes, or even without parameterization, simulating the cooperative intensification stage (i.e., the conceptual CISK). Obviously, there are many acceptable ways to parameterize the effects of moist convection for the same purpose, although they are significantly different in terms of both rationale and mathematical format as schemes. The only common denominator of these schemes appears to be the intent to parameterize moist convection in its entire vertical stretch, but even this distinction is blurred since the parameterization in Kurihara's (1975) model is based on a modified moist adjustment hypothesis. Therefore, it is a very confusing practice to call any particular scheme, or a class of schemes, CISK parameterization.

The loose semantics, by itself, is not a serious problem. Unfortunately, however, it has encouraged a far more dangerous practice of calling every mathematical exercise CISK if the theory employs one of those "CISK parameterization" schemes. As it should have been clear from our earlier discussion of closure hypothesis, the mathematical isolation of cooperative instability in the original CISK theory is not derived from the vertical parameterization of convective clouds but from the closure on mesoscale organization that puts individual clouds on the implicit side of the closure. This particular closure is mathematically possible and physically justified only in the context of the frictional boundary layer in an intense balanced vortex. If the quasi-balance constraint is removed from the theory, clouds will reappear on the explicit side, even if the same parameterization is retained. Then, the linear theory becomes, figuratively speaking, too cloudy to see the cooperative mode of instability (i.e., CISK) which should still be present behind the clouds. Nonlinear primitive equation models of the tropical cyclone can actually reach the cooperative intensification stage by integrating over many generations of clouds. If the surface friction is removed from the physical definition of the problem, there will be nothing but clouds (i.e., conditional instability of the *first* kind) in the linear theory albeit CISK in its name. The fact that cumulus parameterization does not eliminate cumulus instability has been known since

Syono and Yamasaki (1966), but many papers of so-called CISK theory are discussing convective clouds in disguise. Wave-CISK (Lindzen, 1974) is a typical example of such non-CISK theories in the literature. If mathematical solutions and interpretive arguments of the paper are carefully examined, we have to conclude that Lindzen's "CISKable" tropics have no clouds. In recognition of this difficulty, the Wave-CISK now takes moist convection as an externally assumed forcing term, making the acronym totally meaningless.

If we are interested in developing a genuine CISK theory for the general state of the tropics, we must consider not just a better parameterization scheme but the possibility of parameterizing mesoscale convective systems or, at least, a more general closure hypothesis than the ones we have now. There will be no easy answers. For the sake of the future, we may attempt to shed a little light on the current difficulty.

Fig. 3 illustrates three processes that are important to moist convection over the tropical oceans. The abscissa is a spectral representation of horizontal scales, which we are interested in for the closure. The ordinate indicates the time rates of the three processes. Specifically, moist convective instability of individual convective clouds is shown as the rate of consumption of unstable moist air in the mixed layer. The clouds are on the implicit side of the closure and are independent of the scale of our interest on the explicit side. A rate of $(1/2\ \text{hour})^{-1}$ is shown by line (c) on the diagram. To maintain convection over the tropical oceans, either continuously or continually, the mixed layer must be maintained by transfer of sensible and latent heat

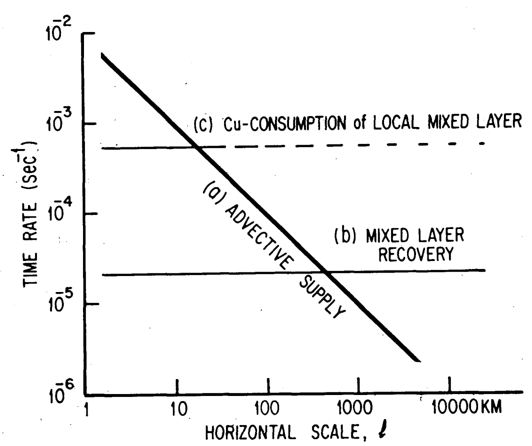

Fig. 3 Scale-dependent relation of three basic processes in organized moist convection.

from the ocean. A typical rate of mixed-layer recovery $(1/2\ \text{day})^{-1}$ is shown by line (b). It is obvious that moist convection cannot continue just by tapping the ocean below. If the convection were to continue in an area for many hours, the required moist air would have to be imported from the mixed layer outside that area. In the case of the tropical cyclone (except for the incipient stage), the advective supply is accomplished by the frictionally induced radial flow, which is on the explicit side of the closure. The advective supply rate, corresponding to $10\ \text{m s}^{-1}$ of the convergent component of wind, is shown by a slanted line (a). For this speed, the convection can be supported continuously over an area of 15 km in linear scale, which may well be the eyewall convection.

In the normal state of the tropical atmosphere, as well as in an incipient cyclone, moist convection can continue for hours in the form of organized systems. This is possible for such a system, when it generates mesoscale circulations to secure the supply of moist air. Squall lines, for example, achieve the supply by moving relative to the mixed layer air. For the closure or parameterization, the problem is entirely different from that in a mature cyclone, since the mesoscale circulation is part of the dynamics to be parameterized, and cannot be put on the explicit side of the closure.

An attempt to apply the closure of CISK to synoptic-scale disturbances, such as the easterly wave, is also dubious, but for a different reason. Since the motion of scales greater than 1000 km may be assumed to be in a quasi-balanced state, the approximation of the Ekman boundary layer is valid. However, as shown in Fig. 3, the boundary-layer convergence in such large scales has practically no effect on moist convection. The evaporative heat supply is the dominant factor that determines the overall activity of moist convection over the large-scale area. Of course, clouds are not necessarily distributed uniformly, but will be organized in mesoscale systems, over which the synoptic-scale field does not have direct control.

6. Conclusion

Progress in tropical cyclone theory and modeling during the past two decades has been reviewed, with emphasis on conceptual understanding. It is hoped that this paper will help to clarify the certain confusion in the current literature about basic problems of the tropical cyclone. The conceptual understanding, of course, does not imply the knowledge that would be sufficient to replicate the real tropical cyclone with numerical models. The models have simulated "realistic" cyclones in all sizes and intensities but, thus far, none that is good enough to be called real. The age-old problems of turbulence and cloud microphysics are still with us. If we choose to calculate clouds and mesoscale systems explicitly, their stochastic nature in the time scale of the tropical cyclone will raise the problem of digesting and properly interpreting enormous numerical results. To those who work with problems of the future, what we have already learned may look miniscule. But, this history tells us, at least, that understanding the problems to be solved is as important as solving them.

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台風の理論およびモデルの発展に伴なう概念的進化

大　山　勝　通
National Hurricane Research Laboratory, NOAA

航空機観測の進歩に伴ない，台風の一般構造およびエネルギー収支については，1960年代の初めごろまでに.かなりよくわかってきた。しかし，これらの知識を力学的に統一して台風の生成発達を説明する理論は容易に生れなかった。現在の台風理解の因となった最初の発達理論が出るためには，力学的問題としての台風の認識，特に種々の要因の相対的重要度，を再考する必要があった。雲のパラメータ化が成功の原因のように云われるが，実は，問題認識上の変化がそのような雲の扱いを一応許されるものとした。雲のパラメータ化を技術的にのみ応用すると，その後の種々の線型理論（いわゆるCISK）に見られるような物理的混乱を引きおこす。一方，台風の理解のためには，線型理論は不充分であり，理論の概念としての妥当性および限度は非線型数値モデルによる実験によってのみ評価されることとなった。数値モデルの進歩により，台風成生の理解のためには，雲のパラメータ化を取り除く必要があることもわかってきた。この論文は，歴史を逆転するかの如く見える最近の発展の裏にある真の進歩を概念的に解明することを目的とする。