Hurricanes: A Century of Scientific Progress

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1. Introduction

In the early 20th century, at the same time that the theories of relativity and quantum mechanics were being developed, there was essentially no basic understanding of the physics of hurricanes. The energy cycle that sustains such storms was not known, nor were the factors that controlled their movement. What was known about the structure and behavior of hurricanes was inferred largely from visual observations of clouds and damage patterns, and it was widely believed that the storm circulation extended upward only a few kilometers. By the end of the century, the structure and behavior of hurricanes had been thoroughly quantified, thanks to rapid technological progress that brought about such wonders as aircraft, radar and satellites, and the basic physics of the storms themselves as well as their intricate substructure had come to be well understood. This new understanding, coupled with the invention and rapid development of the computer, made it possible to forecast the motion of hurricanes with such accuracy that, given modern communications and transportation, loss of life from hurricanes has been virtually eliminated in the developed world.

This chapter chronicles the extraordinary progress in the scientific understanding of hurricanes through the 20th century. We begin with a brief review of progress through World War II, which marked an important turning point in the science of meteorology, and continue with an account of the rapid progress made in the first two decades after the war. Section 4 discusses the very influential CISK theory that was developed in the 1960s. The detailed synthesis of storm structure and behavior made possible by a suite of new observing systems is described in section 5, while the enormous progress in numerical modeling of hurricanes is reviewed in section 6. Subsequent sections describe the ramp-up to the present state of understanding of various aspects of hurricanes, including their genesis, intensification, movement and transition to extratropical storms, their interaction with the ocean, and their control by and possible feedback on various oscillations in the climate system. An assessment of where we stand today, including outstanding challenges, is provided in the concluding section.

2. Progress Through the Second World War

By the early 19th century, it had become well established that hurricanes are vortical storms. Arguably, the native inhabitants of the Caribbean region already understood this at the time of Christopher Columbus's voyages, given the detailed knowledge he obtained from them about the sequence of winds...enough to allow him to ride out a hurricane during his 4th voyage to the New World. That hurricanes have rotary wind fields was not firmly established, however, until the American scientist William Redfield published his observations in the early nineteenth century (Redfield, 1831).

An important step toward understanding the physics of hurricanes was the development of the first law of thermodynamics in the mid 19th century and the discovery of the latent heat of vaporization. Among the pioneers in applying these principles to meteorology was the American scientist James Pollard Espy. Observing that cyclones are invariably associated with clouds and precipitation, Espy came to believe that such storms are powered by the liberation of the latent heat of vaporization, and undertook extensive laboratory experiments designed to determine what we now refer to as the moist adiabatic lapse rate. His work is particularly remarkable when it is recognized that the formulation of the science of thermodynamics took place during the 1840s and 1850s, and the first law of thermodynamics was not introduced to meteorology until the 1860s. But already in 1841, Espy had concluded that the moist adiabatic lapse rate is "about five-eighths of a degree for one hundred yards of ascent, when the dew point is about 70 degrees" (Espy, 1841). This is a remarkably good estimate considering the equipment and techniques he had at his disposal. Espy went on to deduce that if the environmental lapse is greater than the moist adiabatic lapse rate, convection may occur, and he believed that it was such convection that led to the formation of middle latitude cyclones.

It is an historical irony that the "thermal theory of cyclones", as the body of theory developed by Espy and his followers came to be known, was advanced in an attempt to explain extratropical cyclones when in fact it bears a remarkable resemblance to the idea of Conditional Instability of the Second Kind (CISK), which was developed in the 1960's as a theory of tropical cyclogenesis (see section 4). Consider this exposition of the thermal theory of cyclones by Loomis (1846):

> *"The heat liberated in the formation of this cloud raises the thermometer, causing a more decided tendency of the air inward toward the region of condensation....Relative elevation of temperature under the cloud gives increased velocity to the inward current of air. More cloud is thus formed, heat liberated....Thus the storm gains violence by its own action."*

Compare this to CISK, as described by Charney and Eliassen (1964):

> *"We should consider [the depression and the cumulus cell] as supporting one another---the cumulus cell by supplying the heat for driving the depression, and the depression by producing the low-level convergence of moisture into the cumulus cell."*

In fact, theoretical meteorology would be pre-occupied with explaining extratropical cyclones for at least the next hundred years, with almost no serious theoretical work devoted to hurricanes until the 1940's. A practical advance was made, however, in the work of Father Benito Viñes, a Jesuit priest who came to Cuba in 1870 to serve as director of the meteorological observatory of the Royal College of Belen, in Havana. Father Viñes worked tirelessly to establish a network of meteorological observing stations in Cuba and around the Caribbean, and issued the first of many hurricane warnings in 1875. In 1877 he published his collected notes on hurricane behavior, "Apuntes Relativos a los Huracanes de las Antilles", which was soon published as "Practical Hints in Regard to West Indian Hurricanes" by the U.S. Army Signal Corps' national weather service (see Viñes, 1885).

Up through about the 1930's, several texts on hurricanes argued, mostly on the basis of the quick diminution of winds after landfall, that the storm circulation must be quite shallow, extending no higher than about 3 km. Haurwitz (1935) pointed out, on the basis of hydrostatics, that such a circumstance would require extremely high temperatures at low levels in the core. According to Bergeron (1954), arguments that tropical cyclones must be shallow appeared as late as 1948.

3. Watershed Years: 1943-1964

On 27 July 1943, Army Air Corps Colonel Joseph B. Duckworth took an AT-6 trainer from an airfield in Texas and, together with Lieutenant Ralph O'Hair, became the first to penetrate the eye of a hurricane in an airplane. This marked the beginning of hurricane reconnaissance, which became routine by the late 1940's (see Chapter 3). At about the same time, the very first radar images (Wexler, 1947) of tropical cyclones revealed the structure of precipitation, showing for the first time an unambiguous depiction of the eye and spiral rainbands. Newly acquired measurements from aircraft and radar, as well as reports from ships and surface stations and occasional balloon soundings, allowed post-war meteorologists to construct reasonably accurate pictures of the geometry, circulation and kinematic and thermodynamic structure of hurricanes as well as a variety of tropical weather systems. These showed without a doubt that hurricanes are warm core systems that extend through the entire depth of the troposphere and perhaps into the lower stratosphere. The odd idea that hurricanes extend upward only a few kilometers from the surface was forever laid to rest.

The first reasonably accurate description of the energy cycle of tropical cyclones appeared in a paper by Herbert Riehl (1950), recently arrived at the University of Chicago from New York, having been sent there from Germany by his family in the 1930's. To the best of this author's knowledge, this is the first paper in which it is explicitly recognized that the energy source of hurricanes arises from the *in situ* evaporation of ocean water[1]. By the next year, another German scientist, Ernst Kleinschmidt, could take it for granted that "the heat removed from the sea by the storm is the basic energy source of the typhoon" (Kleinschmidt, 1951). Kleinschmidt also showed that thermal wind balance in a hurricane-like vortex, coupled with assumed moist adiabatic lapse rates on angular momentum surfaces, implies a particular shape of such surfaces. He assumed that a specified fraction, q, of the azimuthal velocity that would obtain if angular momentum were conserved in the inflow, is left by the time the air reaches the eyewall, and derived an expression for the maximum wind speed:

$$v_{\max}^2 = 2E\frac{q^2}{1-q^2}, \qquad (1.1)$$

where E is the potential energy found from a tephigram, assuming that air ascending in the eyewall has acquired some additional enthalpy from the ocean. Kleinschmidt did not provide a specific method for estimating this enthalpy increase, and (1.1) is sensitive to the arbitrary value of q specified.

In his widely circulated textbook, now regarded as a classic, Riehl (1954) described hurricanes as heat engines and showed that for air ascending in the eyewall to be appreciably warmer than that of the distant environment, a condition for conversion of potential to kinetic energy, the inflowing air had to acquire enthalpy from the underlying surface.

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[1] Byers (1944) recognized that the observation of nearly constant temperature following air flowing down the pressure gradient near the surface implies a sensible heat source from the ocean. The existence of isothermal inflow has been called into question by more recent observations.

The work of Riehl and his colleagues, most notably Joanne Malkus, arguably culminated in the publication of two papers in the early 1960's: Malkus and Riehl (1960) and Riehl (1963). The first of these once again emphasized that the horizontal temperature gradients that sustain tropical cyclones arise from heat transfer from the ocean. Making use of the fact that the horizontal pressure gradient is very weak at the top of the storm, near the tropopause, that temperature lapse rates are very nearly moist adiabatic in the eyewall, and that the temperature of lifted parcels is a function of their boundary layer equivalent potential temperature, Malkus and Riehl (1960) calculated a relationship between the surface pressure fall from the environment to the inner edge of the eyewall:

$$\delta p_s = -2.5\delta\theta_{eb}, \tag{1.2}$$

where δp_s is the surface pressure drop in millibars, and $\delta\theta_{eb}$ is the increase in equivalent potential temperature, in Kelvins. The horizontal isobaric height gradient was assumed to vanish at 100 mb. This is a simple quantitative relationship showing explicitly the relationship between a measure of hurricane intensity and the increase in boundary layer entropy necessarily arising from sea-air enthalpy transfer. Riehl (1963) showed that (1.2) is well verified in observations of actual storms (with a best-fit coefficient of 2.56) and extended the Malkus and Riehl work in several ways. First, he made use of the deduction made by Riehl and Malkus (1961) that outside the eyewall, where latent heat release is weak, conservation of potential vorticity integrated over a volume capped by an isentropic surface above the boundary layer leads to the conclusion that the curl of the surface stress must vanish, which for an axisymmetric vortex gives

$$r\tau_\theta = constant, \tag{1.3}$$

where τ_θ is the azimuthal component of the surface stress. Given that the latter varies nearly as the square of the wind speed, (1.3) implies that

$$v_\theta \sim r^{-1/2}, \tag{1.4}$$

where v_θ is the azimuthal wind speed. Using (1.4) and assuming cyclostrophic balance gives an approximate expression for the pressure drop from some outer radius, r_o, to the radius of maximum azimuthal winds, r_i:

$$v_{\max}^2 \simeq -\rho\delta p_s, \tag{1.5}$$

where $v_{\max}$ is the maximum azimuthal wind speed and ρ is a mean air density in the boundary layer. Eliminating δp_s between (1.5) and (1.2), and using an estimate of ρ gives

$$v_{\max} \simeq 14.1\left(\delta\theta_{eb}\right)^{1/2}, \tag{1.6}$$

where $v_{\max}$ is in $m\,s^{-1}$.

In the next step, Riehl estimated $\delta\theta_{eb}$ from conservation of entropy and angular momentum in the inflow. I will slightly abbreviate and generalize his derivation here. Assuming that both entropy (θ_e) and angular momentum (*M*) are vertically uniform in the boundary layer, integration of the conservation equations for entropy and angular momentum through the depth of the boundary layer gives

$$\psi \frac{\partial \theta_e}{\partial r} = C_k \left(\theta_{es} - \theta_e\right) r \left|V\right|, \tag{1.7}$$

and

$$\psi \frac{\partial M}{\partial r} = -r^2 \tau_\theta, \tag{1.8}$$

where ψ is the mass streamfunction of the secondary flow at the top of the boundary layer, C_k is an enthalpy transfer coefficient, θ_{es} is the saturation equivalent potential temperature of the sea surface, $\left|V\right|$ is a surface wind speed, and *M* is the absolute angular momentum per unit mass, given by

$$M = r v_\theta + \frac{1}{2} f r^2 \tag{1.9}$$

Eliminating ψ between (1.7) and (1.8) gives

$$\frac{\partial \theta_e}{\partial r} = -\frac{C_k \left(\theta_{es} - \theta_e\right)}{r \tau_\theta} \left|V\right| \frac{\partial M}{\partial r}. \tag{1.10}$$

Recall from (1.3) that $r\tau_\theta$ is assumed constant. Also assuming that $\left|V\right| \simeq v_\theta$, using (1.4) to express v_θ as

$$v_\theta = v_{\max} \left(r_i \big/ r \right)^{1/2},$$

and using (1.9) for M, we can integrate (1.10) from r_i to some outer radius, r_h, to get

$$\delta\theta_{eb} \simeq \frac{C_k \left(\theta_{es} - \theta_e\right)}{2 r \tau_\theta} v_{\max} \left[v_{\max} r_i \ln \frac{r_h}{r_i} + \frac{4}{3} f r_i^{1/2} \left(r_h^{3/2} - r_i^{3/2} \right) \right], \tag{1.11}$$

where we have assumed that $\left(\theta_{es} - \theta_e\right)$ does not vary with radius. Now using $r\tau_\theta \simeq r_i C_D v_{\max}^2$, where C_D is the drag coefficient, we can write (1.11) as

$$\delta\theta_{eb} \simeq \frac{C_k\left(\theta_{es}-\theta_e\right)}{2C_D}\left[\ln\frac{r_h}{r_i}+\frac{4}{3}\frac{fr_i}{v_{\max}}\left(\left(\frac{r_h}{r_i}\right)^{3/2}-1\right)\right]. \tag{1.12}$$

Noting that, from (1.3), $r_i v_{\max}^2 = r_h v_h^2$, where v_h is the wind speed at radius r_h, making the approximation that $r_i << r_h$, and substituting (1.12) into (1.6) gives

$$v_{\max}^2 \simeq 100\frac{C_k}{C_D}\left(\theta_{es}-\theta_e\right)\left[\ln\left(\frac{r_h}{r_i}\right)+\frac{4}{3}\frac{fr_h}{v_h}\right], \tag{1.13}$$

which is equation (27) from Riehl (1963), except that Riehl assumed that $C_D = C_k$.

Note that this, together with $r_i v_{\max}^2 = r_h v_h^2$ (from (1.3)), gives a transcendental equation for the maximum wind speed as a function of the degree of thermodynamic disequilibrium between the ocean and atmosphere, the Coriolis parameter, and the wind velocity at some specified radius. (Riehl goes on to make what in my view is a somewhat circular argument that there is another dynamical limit on the relationship between $v_{\max}$ and r_i which, together with (1.13), determines the radius of maximum wind and an outer radius at the same time.) We shall show in section 7 that Riehl comes very close, in (1.13), to an energetic limit on hurricane intensity[2].

At about this time, Miller (1958) developed a theory for the minimum central pressure in hurricanes. Miller also starts by assuming a moist adiabatic eyewall, but explicitly

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[2] In some sense, Malkus and Riehl (1960) came even closer. Their equation (33) invokes conservation of θ_e along a boundary layer streamline, yielding

$$v\frac{\partial\theta_e}{\partial s} = C_k v\frac{\theta_{es}^* - \theta_{ea}}{h},$$

where θ_{es}^* is the saturation θ_e of the sea surface, θ_{ea} is the θ_e of the ambient boundary layer air, h is the boundary layer depth, and the differentiation is along a streamline. Note that I have changed the notation for consistency, and that Malkus and Riehl unintentionally omitted the factor h. Combining this with (1.2) gives

$$-v\frac{\partial p}{\partial s} = 2.5C_k v\frac{\theta_{es}^* - \theta_{ea}}{h}. \qquad \text{(a)}$$

This is essentially the unnumbered equation after (33) in Malkus and Riehl. They also wrote down an expression (their equation 35) for conservation of energy along a streamline in the boundary layer:

$$-v\frac{\partial p}{\partial s} = C_D\rho\frac{v^3}{h}. \qquad \text{(b)}$$

Had they eliminated pressure between (a) and (b), they would have obtained the correct expression for maximum wind speed, our (7.2), albeit with fixed thermodynamic efficiency. Instead, they combined (b) with a balance equation for sensible heat along a boundary layer streamline, to obtain a peculiar relationship between maximum wind and air-sea temperature difference (their equation 36).

ignored any increase in entropy from the outer region into the eyewall, opting instead to assume that the eyewall air starts out at sea surface temperature and with a relative humidity of 85%. Miller then estimated a vertical profile of temperature in the eye itself by assuming dry adiabatic descent modified by mixing with the eyewall air, along the line of reasoning explored by Malkus (1958). Once the eye temperature profile is constructed, the central surface pressure is calculated hydrostatically, assuming a level of zero horizontal pressure gradient at the standard pressure level nearest the level of neutral buoyancy for undilute pseudo-adiabatic ascent in the environment. The calculated central pressures were in good agreement with the minimum pressures recorded in a limited sample of intense hurricanes.

It is important to note here that Miller's work departs in a significant way from the line of reasoning adopted by Riehl and Malkus. The latter had emphasized the crucial importance of enthalpy transfer from the ocean, while Miller regarded the hurricane as resulting from the release of conditional instability of the ambient atmosphere, requiring no enhanced air-sea enthalpy flux. He quotes Byers (1944) statement that compared the hurricane to "one huge parcel of ascending air" and states in his opening sentence that "the principal source of energy of the tropical storm is the release of the latent heat of condensation", a statement rather precisely analogous to a claim that elevators are driven upward by the downward force on the counterweights: both statements are simultaneously true to first order and completely miss the point. In hindsight, Miller's estimate of the maximum intensity of hurricanes is energetically inconsistent. As the eyewall entropy is no larger than that of its environment, there can be no conversion of potential to kinetic energy in the secondary circulation of the storm; at the same time, the eye itself contains descending air with high temperature, a process that converts kinetic to potential energy. Thus Miller's energy cycle in the net absorbs rather than produces kinetic energy and thus cannot maintain a system against dissipation. But in an important sense, Miller's analysis presaged the CISK thinking that became the dominate paradigm for tropical cyclone physics after 1964 (section 4).

The decade of the 1950s witnessed rapid progress in understanding and predicting hurricane motion. The general idea that tropical cyclones move with the vertically averaged background flow was already evident in the work of Father Viñes and was well known by the time of World War II. By the end of the 1940s, however, Davies (1948) and Rossby (1949) had established that vortices alter the vorticity distribution in their environment such as to induce a poleward and westward drift of cyclonic vortices.

Perhaps the most important technological development of the 1950s was the advent of numerical modeling, beginning with the work of Jule Charney, Ragner Fjørtoft and John von Neumann at the Advanced Study Institute in Princeton (Charney et al., 1950). They had run a simple barotropic model of the atmosphere to produce a series of 24 hour forecasts of the 500 mb height field. Not long afterwards, the first numerical prediction of hurricane movement was accomplished by Akira Kasahara at the University of Chicago, using a barotropic model to forecast the evolution of the background flow with the hurricane vortex removed, supplemented with a routine that predicted the vortex motion relative to the background flow (Kasahara, 1957). Forecasts of two storm were made out to 48 hours. This work inaugurated a long and productive period of research and development on the numerical prediction of hurricane motion.

The network of surface and upper air stations that rapidly expanded during the war also led to the discovery of such tropical phenomena as easterly waves and to a new phase of research on tropical cyclogenesis. Two particularly important post war papers were those of Riehl, (1948) and Palmén (1948). The latter demonstrated that hurricanes only develop over ocean water where the air temperature exceeds 27^o C but not within 5 degrees latitude of the equator. He also showed that these regions are conditionally unstable, whereas other parts of the Tropics (or during other seasons) are generally stable. Riehl (1948) emphasized that tropical cyclones always form from pre-existing disturbances, and in this and subsequent work argued that the interaction of lower tropospheric disturbances with upper tropospheric troughs of tropical or extratropical origin is a key ingredient in tropical cyclogenesis. Another approach to examining the interaction between nascent or developed hurricanes with their environment was initiated by Pfeffer (1955), who argued that the initial spin-up of the circulation could be diagnosed in terms of eddy angular momentum fluxes into the storm.

These early investigators rejected the notion the tropical cyclones could begin spontaneously. In what is, in my view, an enormously prescient work, Bergeron (1954) tackled the problem of why tropical cyclogenesis requires a finite amplitude seed disturbance. Citing recent findings from the Thunderstorm Project (Byers and Braham, 1948), Bergeron pointed out that groups of convective storms are always accompanied by *cool, anticyclonic outflow* near the surface, which stabilizes the atmosphere and mitigates against the formation of a cyclone. He postulated that were this to occur over sufficiently warm ocean, the evaporatively cooled outflow would be re-heated by contact with the sea, leading in some cases to what he termed the 'inverting' of the cyclone, during which enough enthalpy is added from the ocean to initiate convection and inflow of high enthalpy air. Following the earlier work of Riehl and Kleinschmidt, he again emphasized the need to increase the enthalpy of the inflowing air. Bergeron anticipated by more than three decades the finding that cold, low entropy convective downdrafts prevent most tropical disturbances from becoming tropical storms.

4. CISK

A review of the literature on hurricanes published during the first two thirds of the twentieth century reveals a striking separation between tropical meteorologists and the rest of the meteorological community. Bernard Haurwitz, Horace Byers, Tor Bergeron and Carl-Gustav Rossby all made substantial but brief contributions to the science of hurricanes; of the authors of the major works on hurricanes published through 1963, only Herbert Riehl and Ernst Kleinschmidt published important work outside of tropical meteorology. Arguably, this separation of disciplines traces back to the failure of the thermal theory of cyclones, developed in the middle of the 19th century, to explain the dynamics of extratropical cyclones. Already in 1877, Elias Loomis, a protege of Espy and one of the original proponents of the thermal theory, expressed his doubts regarding the validity of that theory, stating that “It seems safe to conclude that rainfall is not essential to the formation of areas of low barometer, and is not the principal cause of their formation or their progressive motion” (Loomis, 1877). By the early 20th century, the thermal theory of extratropical cyclones was dead; as expressed by the American scientist, Frank Bigelow, “The fact is that storms are produced by *horizontal convection* more than by *vertical convection*” (Bigelow, 1906). The great success of the Norwegian School, led by Vilhelm Bjerknes, and the subsequent linear theories of extratropical cyclogenesis by Charney and Erik Eady in the late 1940s showed that most of the observed properties of middle latitude storms could be explained without reference to condensation of water vapor. “As long as one is concerned with waves of small enough amplitude, the vertical motions will not be of sufficient magnitude to cause condensation, so that this factor may also be ignored" stated Jule Charney in his famous paper on baroclinic instability (Charney, 1947). Thus Charney continued the tradition begun by Loomis of downplaying the effects of phase change of water on extratropical dynamics, a tradition that may be said to continue to this day.[3] The rapid progress and consequent popularity of extratropical meteorology in the decades after WWII led to the decline of moist processes, and especially of moist thermodynamics, in university curricula; by the 1970s it was quite possible to obtain a doctorate degree in meteorology without having had any serious exposure to thermodynamics involving phase change of water.

But it was Charney and his Norwegian colleague, Arnt Eliassen, who in 1964 brought extratropical dynamicists back into tropical meteorology. During the previous year, Vic Ooyama of New York University spent some time at MIT with Charney, discussing with Charney his ideas about cumulus convection and hurricanes. They published separate papers (Charney and Eliassen, 1964; Ooyama, 1964) evincing more or less the same idea, which became known as CISK (conditional instability of the second kind), a term introduced in the Charney and Eliassen paper.

CISK almost certainly had its roots in the failure of early attempts to simulate tropical cyclone intensification with numerical models, as reviewed by Yanai (1964).
In each of these early attempts, a conditionally unstable atmosphere was used in the initial condition; invariably, the model developed grid-scale motions that represented its attempt to release the instability. In no case did the simulations proceed long enough for a vortex develop.

With hindsight, we can say that these first attempts to numerically simulate tropical cyclone intensification were grounded in the view that both convection and tropical cyclones result from the release of potential energy stored in the tropical atmosphere, as evidenced by conditionally unstable soundings. But it was known since at least the paper by Bjerknes (1938) that convectively unstable updrafts seek very small scales, whereas a tropical cyclone's inner core is appreciably wider than a typical convective cloud.

Charney and Eliassen (1964) and Ooyama (1964) attempted to solve this by arguing that tropical cyclones represent an organized mode of release of conditional instability, with the convergence of the cyclone's Ekman boundary layer serving as the organizing agent. They maintained that the rate-limiting factor for the growth of the cyclone-scale circulation was the advective supply of latent heat. From Charney and Eliassen (1964):

> *"We should look upon the pre-hurricane depression and the cumulus cell not as competing for the same energy, for in this competition the cumulus cell must win; rather, we should consider the two as supporting one another---the cumulus cell by supplying the heat energy for driving the depression, and the depression by producing the low-level convergence of moisture into the cumulus cell."*

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[3] Erik Eady, whose paper (Eady,1949) is cited together with Charney (1947) as the foundation of the theory of baroclinic instability, worried about the effects of condensation, noting that baroclinic growth rates calculated by ignoring condensation are too small. In a widely ignored portion of his otherwise well-known paper, Eady included the effects of a pre-existing, zonally oriented band of saturated air in his linear analysis of baroclinic growth, and noted the strong tendency toward frontogenesis at the boundaries of the cloudy zone as well as an increase in the rate of growth.

A key concept that emerges in this work is the idea that organized latent heat release drives a circulation, which in turn feeds moisture into the system; the key feedback is between latent heating and moisture supply. Charney and Eliassen demonstrated this concept using a two-layer model in which the magnitude of the heating was taken proportional to the Ekman-induced vertical velocity at the top if the boundary layer, while the heating itself was applied at two model layers. Thus, while the vertically integrated heating is taken to be proportional to some measure of the circulation, its vertical distribution is determined by other means, or simply specified.

Later work by other scientists showed that the vertical distribution of heating is crucial in CISK models. Broadly, if the vertical heating function is sufficiently weighted toward high altitudes, the most rapidly growing disturbances have comparatively large scale. In Charney and Eliassen's two-layer model, the heating was taken to be the same at both levels and the linear growth rate peaks at the smallest scale, albeit with a broad plateau out to scales of a few hundred kilometers.

Almost absent from Charney and Eliassen's paper was any mention of the supply of enthalpy from the sea surface, which had been regarded as so crucial by the Riehl-Malkus-Kleinschmidt school; passing mention is made of the role of the ocean in keeping the boundary layer at ambient humidity. Ironically, the major role of the surface in CISK is as a momentum sink, supplying the drag necessary to produce Ekman convergence. The linear growth rates in CISK are actually greater over land than over ocean, thanks to the larger drag coefficient.

The CISK formulation draws attention away from the supply of energy to tropical storms and replaces it with a concern for the supply of moisture. In effect, it takes for granted the existence of a large reservoir of available potential energy in the tropical atmosphere, and puts the release of that energy into a mathematical straight jacket, forcing it to occur on large scales. The difference between the Riehl-Malkus-Kleinschmidt view and that entailed in CISK is illustrated in Figure 1. In CISK, buoyancy is generated by large-scale convective overturning, releasing the available potential energy of the ambient atmosphere; in the Riehl-Malkus-Kleinschmidt view, the warmth of the inner region is directly related to the elevation of boundary layer entropy by surface fluxes. The critical unstable feedback in CISK is between the large-scale circulation and the convection; in the older view it is between the circulation and the surface fluxes.

It would be difficult to overstate the enormous influence of the CISK paper. Now, for the first time, there was a simple mathematical formulation for representing the collective effects of cumulus clouds on larger scale circulations; so simple that a first year graduate student could easily formulate linear models of tropical disturbances. Before long, extratropical meteorologists[4] who would not formerly have been caught dead with moisture on their hands were enthusiastically describing all manner of circulation systems using the CISK framework. But as the number of papers on CISK multiplied, so to did the its conceptual interpretations. Some stuck to the idea that organized convection is "caused" by moisture convergence, others came to see it as a way of accounting for the need for vertical motion at the top of the boundary layer to overcome convective inhibition. By the early 1980s, the different flavors and

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[4] The present author not excepted

interpretations of CISK had become so profuse as to lead one of the theory's developers to state that the term had lost any definite meaning (Ooyama, 1982).

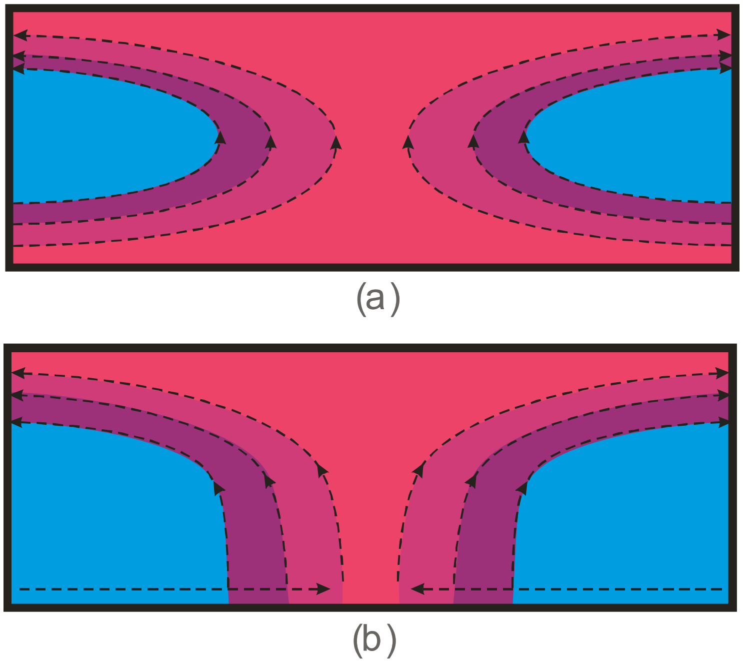

Figure 1: Distributions of saturation moist entropy above the boundary layer and moist entropy in the boundary layer of a hurricane. In the CISK view (a), the warmth of the core is owing to the upward advection of high entropy air from the boundary layer, while in the Riehl-Malkus-Kleinschmidt view (b) the warmth of the core results from enhanced enthalpy transfer from the ocean, giving an increase in entropy in the inflowing boundary layer air. In (a) the ambient atmosphere must be conditionally unstable; (b) can work within a conditionally neutral environment.

Charney and Eliassen's simple representation of cumulus convection was extended by Kuo (1965, 1974) to allow for vertically continuous atmospheres, so that it could be applied in complex models. In Kuo's scheme, as in Charney and Eliassen's, the vertically integrated heating is taken to be proportional to the moisture convergence by the large-scale (explicitly resolved) flow; but Kuo additionally required that the column be conditionally unstable for convection to occur. Because of this switch, the scheme exhibits "jerky" behavior... as soon as an individual column becomes even infinitesimally unstable, convective heating is switched on at a finite rate determined by the local degree of moisture convergence; conversely, as soon as a column becomes even slightly stable, convection is abruptly switched off. Among other consequences, this has a tendency to lead to the formation of artificial "grid point storms" in numerical models (Emanuel and Raymond, 1993), since conditional instability can (artificially) accumulate in regions of moisture divergence, to be released explosively at the onset of convergence.

In many ways, the advent of CISK was a setback for tropical meteorology and for the study of hurricanes in particular. It took the background tropical atmosphere, as many did before and have done since, as a clear, conditionally unstable atmosphere in which large-scale circulations, like tropical cyclones, are particular modes of the release of instability. It ignored the fact that a tropical atmosphere with no large-scale circulation comes into a state of radiative-convective equilibrium in which clouds are continuously releasing available potential energy at the rate it is generated by radiative cooling of the atmosphere and surface fluxes. Such a state should be the natural basic state for the study of tropical circulation systems, just as a balanced zonal flow serves as a natural basic state for the study of baroclinic waves in middle latitudes. And, as shown by Betts (1982) and others, such a state has very little available potential energy. Indeed, the evidence available to date (see e.g. Emanuel et al., 1994) suggests that the interaction between large-scale circulations and convection *per se* is a stable one; growth of large-scale circulations appears to require variable surface fluxes, ocean surface temperature gradients, or variations in longwave radiation owing to variations in clouds and water vapor. This is entirely consistent with the findings of Bergeron (1954), that convective showers, whether individually or in clusters, produce low entropy, anticyclonic outflow near the surface.

Ten years after the publication of the original CISK papers, Arakawa and Schubert (1974) unveiled a new convection scheme based, as almost all successful turbulence schemes are, on the quasi-equilibrium of turbulence kinetic energy rather than of moisture. It is telling that today almost all operational weather prediction centers have abandoned Kuo-type convection schemes in favor of schemes that either explicitly require or implicitly bring about a statistical equilibrium between generation and consumption of buoyancy. The artificial suppression of the release of conditional instability in regions of moisture divergence, allowing instability to accumulate artificially, and the awkwardness of predicting the evolution of water vapor in a framework that assumes its equilibrium, caused many problems in forecast models using Kuo-type schemes that were largely alleviated in the switch to buoyancy-based convective schemes.

Although papers using the CISK framework continue to be published, the weight of evidence suggests that it is a false hypothesis. The numerical modeling work beginning in the late 1960s should have laid CISK to rest, but for reasons explored in section 6, it did not do so entirely.

5. Synthesis of New Observations

The second half of the 20th century saw a rapid increase in the number and quality of observations of hurricanes. Although aircraft reconnaissance was introduced during World War II, the early measurements of meteorological quantities were fairly crude. For example, without inertial navigation or Doppler radar to determine ground speed, surface wind speeds were estimated visually through the late 1950s. (See Landsea, 1993, for a discussion of the wind speed biases in the pre-Doppler ground speed era.) But by the mid 1960s, both kinematic and thermodynamic quantities were being measured with reasonable accuracy by a combination of reconnaissance aircraft and dropsondes deployed therefrom. On great advantage of aircraft reconnaissance in the period was the use of high-altitude aircraft such as a B-57; this allowed an investigation of the properties of the outflow layers of hurricanes. Such capability disappeared in the late 1960s and was not replaced until NOAA purchased Gulfstream IV in the late 1990s.

A great step forward came in 1960, when the first image of a hurricane was transmitted from a polar orbiting satellite. By the 1970s, virtually all tropical cyclones (with the possible exception of some of the elusive, so-called “midget” storms) that formed anywhere were recorded by satellite observations. This provided an almost immediate improvement in warnings, since before satellites, quite a few storms went undetected through at least part of their life, owing to the paucity of non-satellite observations over much of the tropical oceans.

It is not our purpose here to provide a review of the history of observational development, for that is done within Chapters 2, 3 and 11 in this volume; rather, we here discuss the synthesis of hurricane structure and behavior that the new observations made possible.

By the late 1960s, the axisymmetric structure of mature hurricanes had been well determined by aircraft and dropsonde observations. It had been known for some time that hurricanes are warm core vortices; the aircraft data showed that much of the horizontal temperature gradient is concentrated in the eye and eyewall and that in the upper troposphere, the eye temperature can be 15 K warmer than their environment at the same pressure. In strong hurricanes, the cyclonic flow in the lower and middle troposphere can be nearly axisymmetric, but the upper level anticyclonic is usually highly asymmetric, often concentrated in one or more outflow jets.

An example of the detailed picture of tropical cyclones developed by the late 1960s is given in Figure 2, which shows the distribution with radius and pressure of the (pseudo-adiabatic) equivalent potential temperature, constructed from aircraft measurements at five altitudes: 500 m, 750 mb, 650 mb, 500 mb and 180 mb. The aircraft flew “butterfly” patterns at most of these levels; the figure represents an average over what were regarded as the front (NW) and rear (SE) sectors of the storm.

The large number of aircraft missions into hurricanes that had occurred by the late 1970s permitted the construction of a composite view of the thermodynamic and kinematic structure of hurricanes (Frank, 1977a, b), while by the early 1980s, increasingly detailed and high quality measurements from research aircraft allowed for a more detailed synthesis of hurricane structure (Jorgensen, 1984; Weatherford and Gray, 1988) and also led to descriptions of the statistical properties of convective updrafts and downdrafts in hurricanes (Gray, 1965; Jorgensen et al., 1985). With the advent of airborne Doppler radar, the science of hurricanes took a big step forward, yielding unprecedented views of the detailed kinematic structures of the storm and accompanying mesoscale features (Marks and Houze, 1987). The invention of lightning detection networks allowed for a detailed mapping of lightning in hurricanes near land, showing interesting relationships to the structure and evolution of the storms (Molinari et al., 1994).

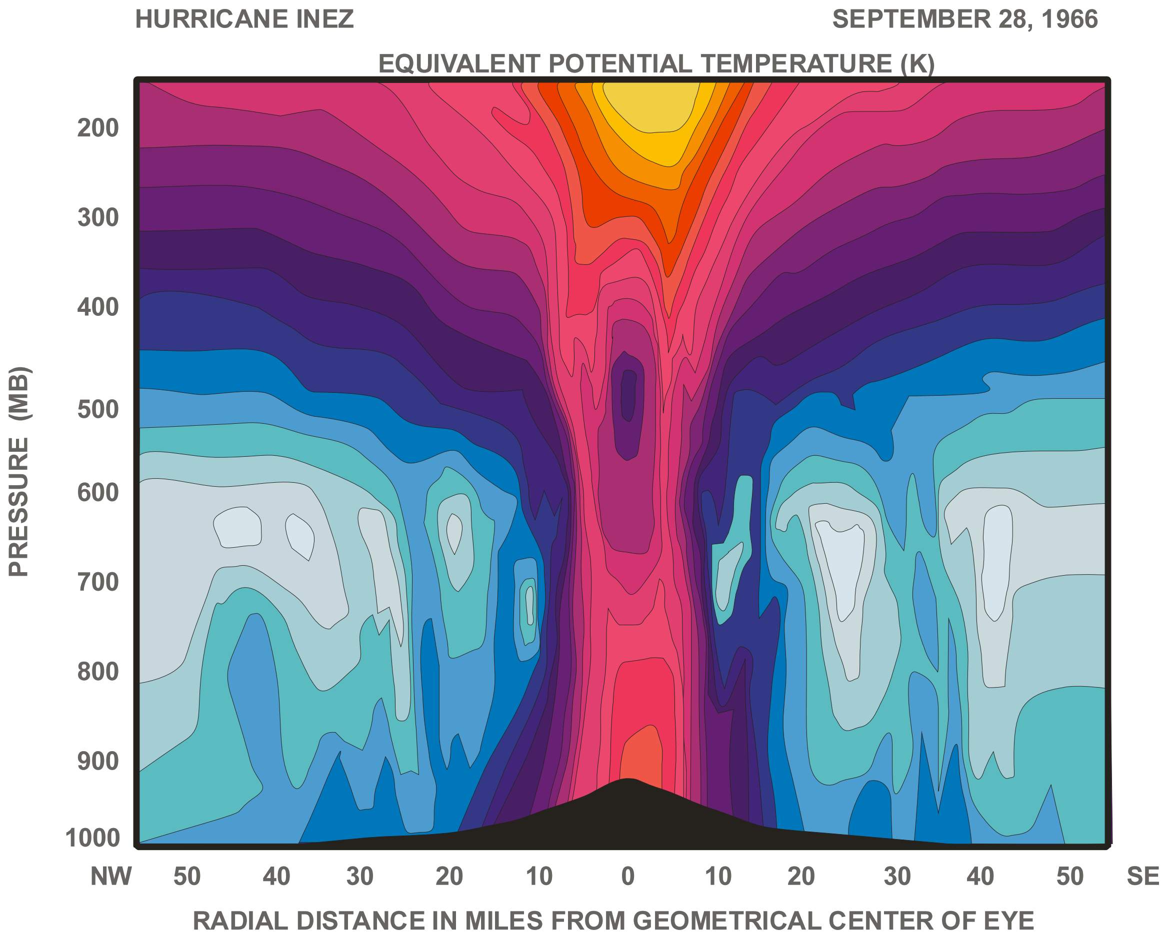

Figure 2: Equivalent potential temperature (K) as a function of pressure and radius from the center of Hurricane Inez on 28 September, 1966, based on aircraft data at 500 m, 750 mb, 650 mb, 500 mb and 180 mb. Contours are at intervals of 2 K with a minimum value of 336 K (light blue) and a maximum value of 376 K (yellow). After Hawkins and Imbembo (1976).

The increasing abundance of aircraft data together with better and better analyses of the large-scale environments of tropical cyclones led to greatly enhanced understanding of the control of hurricane structure, intensity and movement by the large-scale environment, thanks largely to the work of William Gray and his colleagues at Colorado State University. The movement of hurricanes was related observationally to environmental flows (George and Gray, 1976; George and Gray, 1977; Chan et al., 1980), and the environments of developing systems were compared to those that did not develop (McBride and Zehr, 1981). Progress was made toward understanding environmental influences on tropical cyclone size, structure and intensity (Holland and Merrill, 1984; Merrill, 1984; Merrill, 1988). This work showed, among other things, the important influence of environmental wind shear on tropical cyclone intensity change.

Observations of the effects of hurricanes on the upper ocean also came to light in the 1960s. Beginning with the work of Leipper (1967), it became obvious that hurricanes have a profound effect on the uppermost 200-300 m of the ocean, deepening the mixed layer by many tens of meters, cooling the surface temperature by as much as 5^{o} C, and causing near-inertial surface currents of 1-2 ms^{-1}, detectable at depths up to at least 500 m (Withee and Johnson, 1976). By the early 1980s, Price (1981) had established that most of the cooling is owing to entrainment, caused by turbulence generated from the strong shear of the near-inertial currents across the base of the mixed layer. This nicely explains the observation that much of the cooling is offset to the right of the storm's track (in the northern hemisphere), where the turning of the wind stress as the storm passes resonates with inertial oscillations.

6. The Era of Numerical Modeling

In the late 1950s, two tracks of numerical modeling efforts were begun. The first, beginning with Kasahara (1957), sought to understand and predict the motion of existing storms using barotropic models. The other, starting with Kasahara (1961), set out to understand the development and intensification of tropical cyclones using axisymmetric models with thermodynamics.

The track model development begun by Kasahara continued progressively with further encouraging work reported by Kasahara (1959, 1960), and Birchfield (1960, 1961), culminating in the first operational hurricane track prediction model by Sanders and Burpee (1968). While these models were increasingly successful, they met stiff competition from statistical forecasting methods, which were also improving rapidly (see Chapter 4 in this volume). But by 1995, the U.S. National Weather Service had adopted the Geophysical Fluid Dynamics Laboratory hurricane prediction system (Kurihara et al., 1998), a triply nested, high resolution primitive equation model, which consistently out-performed statistical methods of track forecasting. As the forecast models rapidly improved, lack of observations started to become a significant factor in limiting the quality of the forecasts and the models themselves became tools for exploring what kind of observations could best improve the forecasts. For example, Burpee et al. (1996) showed that data collected from dropwindsondes deployed from reconnaissance aircraft significantly improved track forecasts.

Modeling the intensity and intensification of hurricanes progressed somewhat more slowly. After many unsuccessful attempts to model the intensification of hurricanes (see section 5), a breakthrough came with the publication of Ooyama (1969). Ooyama used an axisymmetric model whose vertical structure consists of a boundary layer of fixed thickness surmounted by two layers of variable thickness. Surface enthalpy and momentum fluxes are calculated using bulk aerodynamic formulae, assuming a fixed ocean temperature, and cumulus convection is represented by a scheme that in some respects resembles that of Kuo (1965, 1974) in that the rate of convective heating depends on boundary layer moisture convergence, but it also depends on the degree of conditional instability and the relative humidity above the boundary layer. Ooyama did not include a representation of radiative cooling of the atmosphere.

Figure 3 shows the evolution of the maximum azimuthal wind speed in Ooyama's control simulation, together with another run in which surface enthalpy flux was eliminated. Both the structure and temporal evolution of the storm simulated by the control experiment strongly resemble those found in nature, though the rapid decline following peak intensity is not always observed and, in this model, is likely owing to the lack of radiative cooling...no steady state can be achieved when a heat source is active in the absence of a heat sink.

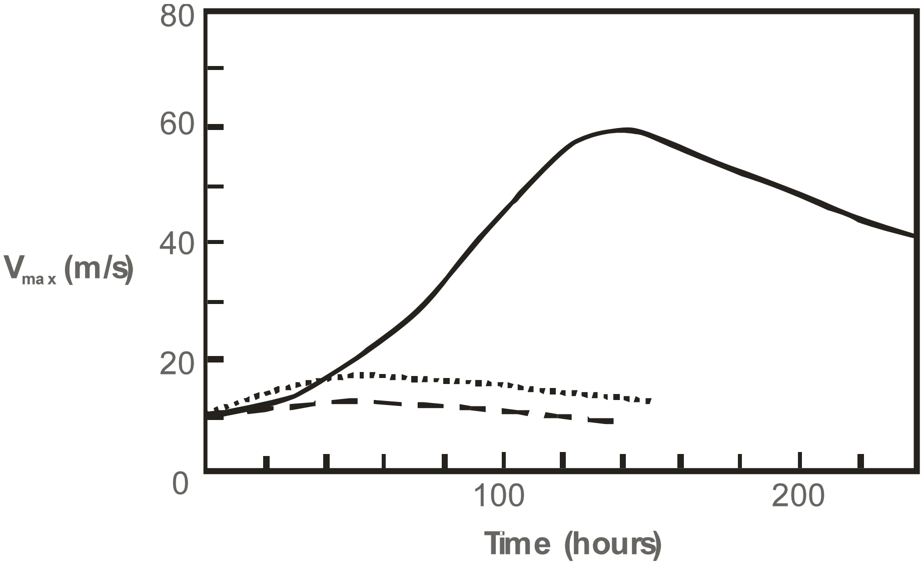

Figure 3: Evolution of the maximum wind speed in the lower layer of Ooyama's model, for three experiments: The control run (solid) and two runs with no surface enthalpy flux. The second of these (dotted) has enhanced conditional instability of the initial state. After Ooyama (1969).

A series of experiments presented in Ooyama (1969) showed, consistent with the Riehl-Malkus-Kleinschmidt view, that the intensity of the model storm varies directly with the coefficient of enthalpy transfer and inversely with the drag coefficient. (See eq. (1.13), although Riehl assumed that $C_k = C_D$ in his derivation.) Subsequent work by Rosenthal (1971) and much later by Emanuel (1995b) confirmed this dependence of maximum wind speed on the exchange coefficients, and Craig and Gray (1996) demonstrated that the rate of intensification exhibits a similar dependence on these coefficients, with more rapid intensification for *smaller* drag coefficient, in contradiction with the predictions of CISK.

And yet Ooyama's 1969 paper left an opening for adherents of CISK. The initial condition in the numerical experiments was strongly conditionally unstable: an ambient boundary layer parcel would be about 10 K warmer than its environment when lifted to the top layer. This is why there is some slight intensification of the initial vortex, even when the surface enthalpy exchange is omitted (see Figure 3). Ooyama himself proved that the initial state was linearly unstable to tropical cyclone-like perturbations, and there is every indication that the very early development of the vortices in his simulations was indeed owing to CISK. Axisymmetric models with no surface enthalpy fluxes whatsoever and enough conditional instability do indeed produce intense vortices (Yamasaki, 1977), though it is not clear whether this is at least partially a consequence of forcing convection into an axisymmetric straight jacket[5]. (The fact that we do not observe tropical cyclone-like disturbances in demonstrably unstable air over land is telling.) As recently as five years ago, Ooyama's 1969 simulations were held up as supporting the idea of CISK (Stevens et al., 1997).

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[5] Yamasaki's simulated vortex was of very small dimensions, with a radius of maximum winds of only about 5 km.

The use of a linearly unstable initial state must with hindsight be regarded as a weakness of the Ooyama work. It has been known at least as far back as Riehl (1948) that tropical cyclones always develop from pre-existing disturbances, such as easterly waves or frontal disturbances, suggesting that the tropical atmosphere is indeed linearly stable to tropical cyclones. The work of Dengler and Reeder (1997) shows that had Ooyama taken his initial state to be conditionally neutral, he would have found that development would only occur if a vortex of sufficient amplitude is used in the initial condition, an aspect more in keeping with observations. (That finite amplitude vortices can intensify to full hurricane strength in an environment in statistical equilibrium was demonstrated by Rotunno and Emanuel (1987).) Nonetheless, there can be no question that Ooyama's work was an important development in understanding and simulating hurricane development.

Following the publication of Ooyama's 1969 paper, work on numerical simulation of hurricane development and structure progressed rapidly. By the late 1970s, computer speed had improved to the point that cumulus convection could be explicitly (albeit crudely) simulated in an axisymmetric model (Rosenthal, 1978)[6], and the first three-dimensional simulations were published (Anthes, 1971). These latter showed, for the first time, the development of spiral rainbands in the simulations. By the 1980s, simulations were being performed with nonhydrostatic models incorporating complex microphysics, including ice physics (Lord et al., 1984; Willoughby et al., 1984), and by the end of the century, three-dimensional, nonhydrostatic models were simulating very realistic structure of actual storms (Liu et al., 1992). An example of such a simulation is shown in Figure 4, using the nonhydrostatic MM5 model run at 1.67 km horizontal grid spacing.

Although there was rapid progress in modeling hurricanes from 1969 onward, it took until 1995 for the skill of track forecasts from a numerical model to overtake that of statistical methods (see Chapter 4 for a complete review of these developments). Much of this gap can be attributed to the structure of research and operational meteorology in the U.S., which leaves neither a clear path nor a system of incentives to bring research products into operational use, a circumstance recently condemned by the U.S. National Academy of Sciences, in their report, dramatically subtitled "Crossing the Valley of Death" (National Research Council, 2000). A notable exception is the development and operational implementation of the Geophysical Fluid Dynamics Laboratory (GFDL) model (Kurihara et al., 1998), the first numerical model to beat statistical models in track forecast skill. But, at the time of this writing, the skill of hurricane intensity forecasts made by numerical models has yet to overtake that of statistical schemes, thus it is clear that there is a long road ahead.

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[6] As a curious historical footnote, Rosenthal discovered that he did not need to parameterize convection in his tropical cyclone simulations because in one such simulation he inadvertently omitted the cumulus scheme and found that the model developed a reasonable storm anyway.

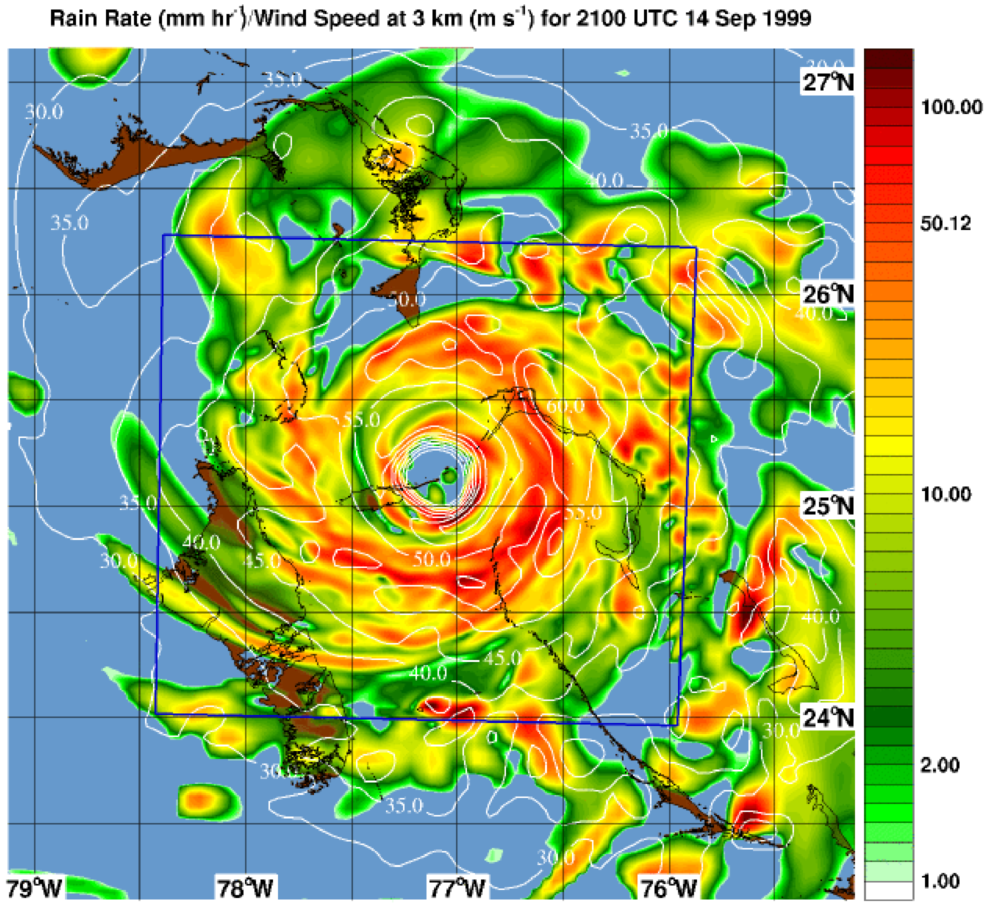

Figure 4: Rain rate (colors) and wind speeds above 30 ms^{-1} (white contours) from a simulation of Hurricane Floyd, 1999, using the nonhydrostatic MM5 model run at 1.67 km horizontal grid spacing. Note the spiral rainbands and the outer and inner eyewalls. Figure courtesy of Dr. Shuyi Chen.

7. Back to the Ocean

By the late 1980s, the failure of CISK to explain or predict the major features of tropical cyclones, including their scale and dependence of intensity and intensification on the environment, led to a renewed interest in the Riehl-Malkus-Kleinschmidt view of local surface enthalpy flux as the primary energy source for tropical cyclones. Observations of the entropy distribution (e.g. Figure 2) made it clear that there is a strong surface entropy source under the eyewall; indeed, Figure 2 more strongly resembles Figure 1b than it does 1a. Douglas Lilly[7] and, independently, Emanuel (1986) developed analytic models of the nonlinear, axisymmetric steady state tropical cyclone. Lilly's approach was based on the conservation of energy and angular momentum along streamlines, whereas Emanuel's assumed, as had Kleinschmidt, that the vortex is neutral to slantwise moist

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[7] Unpublished manuscript

convection. They both derived essentially the same expression for the maximum wind speed:

$$v_{\max}^2 = \frac{T_s - T_o}{T_s}\frac{C_k}{C_D}\left(k_s^* - k_a\right), \tag{7.1}$$

where T_s is the sea surface temperature, T_o is an entropy-weighted average outflow temperature at the top of the storm, k_s^* is the saturation (moist) enthalpy of the sea surface and k_a is the enthalpy of the ambient boundary layer at a nominal altitude of 10 m. Later, Bister and Emanuel (1998) recognized that dissipative heating in the boundary layer is an important heat source in hurricanes. Inclusion of dissipative heating changes (7.1) to

$$v_{\max}^2 = \frac{T_s - T_o}{T_o}\frac{C_k}{C_D}\left(k_s^* - k_a\right). \tag{7.2}$$

The subtle difference here is that the outflow temperature, T_o, appears in the denominator instead of T_s, giving a greater intensity as some of the waste heat is recycled into the front end of the heat engine. Equation (7.2) can be derived from the assumptions of thermal wind balance and neutrality of the vortex to slantwise convection, and alternatively by equating the dissipation of kinetic energy,

$$D \sim C_D v_{\max}^3,$$

to the generation of mechanical energy,

$$G \sim \frac{T_s - T_o}{T_s}\left(C_k v_{\max}\left(k_s^* - k_a\right) + C_D v_{\max}^3\right)$$

where the first factor in the generation is the thermodynamic efficiency of the Carnot cycle, and the last factor is the contribution of dissipative heating.

Equation (7.2) is in many respects similar to (1.13) from Riehl (1963), with the same dependence on the ratio of the exchange coefficients and the ambient thermodynamic disequilibrium between the ocean and atmosphere (though here expressed in terms of enthalpy rather than entropy). But there are two differences: unlike (1.13), (7.2) has no dependence on outer radius, radius of maximum wind, or wind speed at some particular radius; and the Riehl's factor of 100 is replaced by a modified thermodynamic efficiency. Riehl's assumption that parcels become neutrally buoyant at 100 mb has been replaced by an explicit dependence on outflow temperature, which, since hurricanes are subcritical vortices, depends on the level of neutral buoyancy of air ascending in the eyewall. Also, Riehl's use of a power law dependence of wind on radius has been replaced by the assumption of thermal wind balance and slantwise neutrality (or, equivalently, of an assumption of energy equilibrium); this gets rid of the factor in brackets in (1.13).

The relation (7.2) suggests a strong sensitivity of hurricane intensity to those boundary layer processes that determine the exchange of enthalpy and momentum with the ocean, and ocean temperature near the eyewall, which can strongly affect $k_s^* - k_a$. The predictions of (7.2) are in good accord with numerical experiments, beginning with those by Ooyama (1969) and Rosenthal (1971) and continuing with many others in the 1990s, in which the exchange coefficients are simply specified. Unfortunately, little is known about how these coefficients behave at high wind speeds in nature. As is apparent in Figure 2, most of the entropy increase in the inflow occurs very near the eyewall; it is here that hurricanes are sensitive to the exchange coefficients. (Note that for this reason, the centers of hurricanes can approach very near to land before their intensity begins to diminish.) Measurements at low to moderate wind speeds suggest that the drag coefficient increases with wind speed, owing to increased surface roughness, but the enthalpy exchange coefficient remains approximately constant (Large and Pond, 1982); when extrapolated to hurricane wind speeds, this would yield a ratio C_k / C_D too small to explain the observed intensity of hurricanes (Emanuel, 1995b). This suggests that other physical processes must come into play to enhance the enthalpy exchange and/or diminish drag. Andreas and Emanuel, (1999) suggested that the relevant mechanism is re-entrant sea spray, which transfers significant amounts of enthalpy to the air. As of this writing, there is much on-going research on air-sea exchange at extreme wind speeds.

The sensitivity of (7.2) to local perturbations of sea surface temperature can be seen by noting that under average tropical conditions, a local decrease of sea surface temperature of only 2.5^{o} C suffices to bring $k_s^* - k_a$ to zero. (But note that large-scale gradients of sea surface temperature are associated with similar gradients in k_a, so that $k_s^* - k_a$ may remain approximately constant over large areas of undisturbed ocean.) This would suggest that the observed ocean cooling of order 1^{o} C under the storm core could have a significant feedback on hurricane intensity. But the first simulation of a hurricane using an coupled ocean-atmosphere model, by Chang and Anthes (1979), showed little effect of the ocean feedback on storm intensity, leading to a period of roughly two decades during which ocean feedback was regarded as unimportant, except perhaps for storms crossing the wakes of previous storms. (In hindsight, the model used by Chang and Anthes had too coarse a resolution and was integrated for too short a period to see appreciable effects from ocean feedback.) Interest in ocean feedback was renewed after publication of papers by Sutyrin and Khain (1984), Gallacher et al. (1989), Khain and Ginis (1991), Bender et al. (1993), and Schade and Emanuel (1999), all of whom used advanced coupled models to demonstrate that ocean feedback has a first-order effect on hurricane intensity. By the end of the century, Emanuel (1999) had demonstrated that the intensity of many hurricanes could be accurately predicted using even a very simple atmospheric model coupled to an essentially one-dimensional ocean model (Schade, 1997), as long as storms remain unmolested by adverse atmospheric influences such as environmental wind shear, which has been shown to be a statistically significant predictor of intensity change (DeMaria and Kaplan, 1997). An example comparing coupled and uncoupled hindcasts of a hurricane is shown in Figure 5.

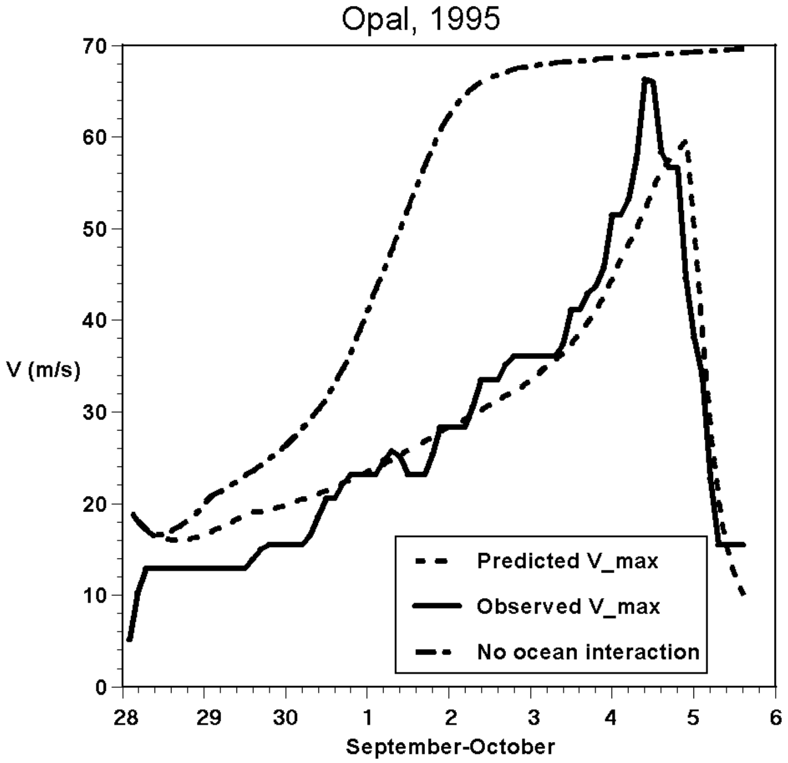

Figure 5: Evolution of the maximum wind speed in Hurricane Opal of 1995, compared to simulations with and without coupling with the ocean. From Emanuel (1999).

As of this writing, the skill of intensity forecasts using coupled models is closing in on that of statistical models, which are still superior. Experience suggests that numerical guidance will eventually dominate, when the speed of computers makes it possible to simulate hurricanes using three-dimensional coupled models of the very high resolution necessary for simulating the fine scale structure of the eyewall and rainbands.

8. Hurricane Motion

During the last three decades of the 20th century, the physics of hurricane motion were refined and extended from the early work of Rossby (1948). Work on the barotropic theory of hurricane motion was advanced by Holland (1982), Chan (1984), DeMaria (1985), Chan and Williams (1987), and Fiorino and Elsberry (1989), among others, and Smith and Ulrich (1990), Smith (1991), and Smith and Weber (1993) developed analytic expressions for the motion of barotropic vortices. Hurricanes are baroclinic vortices, however, and often occur within large-scale environments that have vertical and lateral wind shear. This shear can have multiple effects on storm motion. Shapiro (1992) emphasized the connection between shear and the background potential vorticity distribution, which can have a profound effect on the distribution and intensity of the so-called “beta gyres” that arise in pure form in barotropic simulations with uniform background vorticity gradients. Wu and Emanuel (1993) emphasized the effect of plumes of low potential vorticity swept downshear from the vortex at upper levels and later tried to find evidence of these and beta gyres in real data (Wu and Emanuel, 1994a,b). The combined effect of a background potential vorticity gradient and the interaction between the upper level anticyclone and the lower level cyclone was also explored by Flatau et al. (1994). Shear can also tilt the cyclonic potential vorticity anomaly associated with hurricanes, giving rise to complex motion (Jones, 2000; Smith et al., 2000). All these effects are arguably contained in advanced numerical forecast models, such as the GFDL model (Kurihara et al., 1998), which in their performance have outrun the advance of physical understanding, which still poses a strong challenge.

9. Mesoscale Structure of Hurricanes

Since the earliest radar images of hurricanes (Wexler, 1947) showed the beautiful spiral rainbands than accompany them, there has been a vigorous effort to characterize and understand mesoscale structure in hurricanes. Radar, satellite and aircraft observations have revealed a plethora of mesoscale structures in tropical cyclones. We review progress in understanding these in the following subsections.

a. Spiral rainbands

Spiral rainbands were probably first noticed on radar and many theories have been formulated to explain them. Senn and Hiser (1959) noticed in radar observations that spiral bands seem to form near the eyewall and propagate outward, assuming a quasi-stationary position with respect to the storm. They also noted that the spirals were not organizations of pre-existing convective cells, but the latter tend to develop and decay within the bands. The first theory to explain these observations was advanced by Abdullah (1966). He proposed that spiral bands represent outward propagating inertia-gravity waves, originating in the core of hurricanes. His hypothesis was bolstered by a diagnosis of spiral bands that appeared in early three-dimensional numerical simulations Dierecks and Anthes (1976) that showed that they were indeed inertia-gravity waves, and by a linear stability analysis of baroclinic circular vortices by Kurihara (1976). We point out here that the inertia-gravity waves in the Dierecks and Anthes study may have been exaggerated by the imposition of a rigid upper boundary in the simulation, which does not permit the upward propagation of wave energy that would otherwise occur to some degree. In a series of papers, (Willoughby 1977, 1978a, 1978b, 1979) Hugh Willoughby showed that inward propagating inertia-gravity waves would be amplified by conservation of wave activity, eventually being absorbed in the eyewall and at a critical level in the outflow. He also argued that waves could be excited at the periphery of storms by their interaction with environments in which the wind varies with altitude or in the horizontal. In a later paper, Willoughby et al. (1984) suggested that the principal spiral rain band that is observed to remain quasi-stationary with respect to the storm might be formed at the boundary between recirculating air in the core and air that flows through the system in outer regions.

Another hypothesis for spiral rainbands arose as a result of laboratory experiments performed by Faller (1963), which showed that laminar Ekman boundary layer flow spontaneously develops spiral bands. These bands were explained by Lilly (1966) as manifestations of two different types of linear instability; one is a Rayleigh-type instability resulting from an unstable distribution of horizontal vorticity in the boundary layer, while the other is more nearly akin to inertial instability. Fung (1977) proposed that spiral rainbands in hurricanes arise from a cooperative interaction between such boundary layer instabilities and deep moist convection.

Yet another theory of spiral bands was proposed by McDonald (1968), who suggested that they were manifestation of Rossby waves that propagate on the strong radial potential vorticity gradient outside the core. A complete theory of vortex Rossby waves has been worked out by Montgomery (1997), and Guinn and Schubert (1993) also suggested that the spiral bands are a result of breaking Rossby waves, leading to the production of long, thin filaments of potential vorticity that spin out from the eyewall to form the spiral bands.

Much of the extant theory of spiral bands has been worked out for adiabatic motions, reflecting our poor understanding of the interaction between cumulus convection and larger scale circulations. The relevance of such theories to the observed phenomenon has been questioned by Schade (1994), who pointed out that condensation and evaporation produce such strong sources and sinks of potential vorticity as to render suspect theories based on its conservation; indeed, the first-order balance is between diabatic production and frictional dissipation of potential vorticity.

Improved observations from reconnaissance aircraft led to a better analyses of the structure and behavior of spiral bands. By the early 1980s, the mesoscale structure of the bands had been well documented (Barnes et al., 1983). Detailed distributions of moist entropy and airflow around spiral bands were published by Powell (1990 a,b); these showed that, like squall lines, there are strong interactions between rain-cooled air flowing out of the convection at low levels, and strong boundary layer wind shear. Robe and Emanuel (2001) proposed that spiral rainbands are essentially squall lines whose local orientation is dictated by the direction of the boundary layer wind shear, such that the component of shear normal to the bands is optimum in the sense defined by Rotunno et al. (1988).

b. Concentric eyewalls

Radar imagery and aircraft data also revealed the existence of nearly circular rainbands that tend to form outside the eyewall and then contract inward, eventually replacing the existing eyewall. Double eyewalls had been noticed on radar images at least as early as 1961 (Jordan and Schatzle, 1961), but the first thorough analyses were presented by Willoughby et al. (1982), who also showed that the outer eyewalls are associated with secondary wind maxima, which also amplify as the outer eyewalls contract, eventually becoming the dominant wind maximum. This eyewall replacement cycle can be responsible for large fluctuations in storm intensity, and seems to be a feature of particularly intense storms. It is thought, for example, that the exceptional destructiveness of Hurricane Andrew in south Florida in 1992 was partially owing to the timing of its landfall with respect to an eyewall cycle (Willoughby and Black, 1996). Hawkins (1983) suggested that outer eyewalls might form as a consequence of the interaction of the low level storm circulation with mountainous islands. Numerical models have successfully simulated eyewall cycles (Lord et al., 1984; Willoughby et al., 1984), which seem to be more intense when ice physics are included in the model. The evolution of concentric eyewalls appears to depend in models on the same feedback between wind and surface enthalpy flux that drives the storm as a whole (Emanuel, 1995a).

c. Secondary vortices

Detailed reconstructions of hurricane wind fields, made possible with ground-based and airborne Doppler radar, as well as aircraft data and examination of hurricane damage, show that hurricanes are frequently accompanied by small-scale, transient vortices usually embedded in the eyewall. Some of these may significantly increase the damage done by strong winds (Willoughby and Black, 1996). Lewis and Hawkins (1982) described hurricane eyewalls that seemed to consist of a series of line segments, forming squares or polygons, and by the mid 1980s, Marks and Houze (1984) had documented the existence of mesocyclones in the eyewall, using airborne Doppler radar observations. Small scale velocity structures are often made visible as tilted striations on the inner edge of the eyewall cloud (Bluestein and Marks, 1987). The first theoretical studies of these phenomena were published only very recently (Schubert et al., 1999; Kossin et al., 2000) and strongly suggest that at least some of these vortices result from the unstable distribution of vorticity that results from the contraction of the eyewall.

Forecasters had known from early experience that landfalling hurricanes are often accompanied by an outbreak of tornadoes, especially in certain quadrants of the storm (Hill et al., 1966). Later research (McCaul, 1991) suggests that strong wind shear in the boundary layer, associated with strongly curved hodographs, is responsible for producing supercell-like convective storms, especially in the right-front quadrant, in spite of the absence of large convective available potential energy.

10. The Genesis Problem

Perhaps no facet of hurricanes has proven more vexing than that of understanding and predicting their genesis. There is not even widespread consensus on the definition of the term, though, very broadly, it is usually applied to systems undergoing a transition from some non hurricane-like disturbance, such as an easterly wave or frontal trough, to a more symmetric, warm-core cyclone with a low pressure center at the surface. From the earliest studies (Riehl, 1948), it was recognized that all tropical cyclones originate in some independent disturbance. As described in section 3, Bergeron (1954) pointed out that groups of convective showers usually produce cool, anticyclonic outflow at the surface, thus preventing any spontaneous cyclogenesis near the surface. This is consistent with the analyses by Gray (1979) and McBride (1981), indicating that the secondary circulation in tropical cloud clusters exports moist static energy to the environment. When numerical models are initialized using environments in statistical equilibrium (as opposed to those with large convective available potential energy stored by virtue of a capping inversion), a finite amplitude disturbance is required to initiate intensification by wind-surface flux feedback (Rotunno and Emanuel, 1987; Emanuel, 1989; Dengler and Reeder, 1997), consistent with the observation that genesis must be triggered by an external disturbance.

While Palmén (1948) had established that tropical cyclones form only over sufficiently warm ocean water, little further was done on delineating the character of environments conducive to genesis until the work of Gray, (1968), who showed that genesis only occurs in environments characterized by small vertical shear of the horizontal wind, and also favors regions of large low-level vorticity. By the end of the 1970s, Gray had established a set of conditions that are apparently necessary (though by no means sufficient) for genesis (Gray, 1979). In addition to the two aforementioned factors, Gray argued that larger values of the Coriolis parameter, the heat content of the upper ocean (reflecting the depth of the ocean mixed layer), and the relative humidity of the middle troposphere all favor genesis.

The early investigators, such as Riehl and Bergeron, argued about whether tropical cyclones arise on pre-existing troughs, such as fronts, or from disturbances in the upper troposphere. Later observations showed that there are many routes to genesis, including nearly classic baroclinic development (Bosart and Bartlo, 1991), interaction of easterly waves or other low-level disturbances with tropical upper tropospheric troughs (Ramage, 1959; Sadler, 1976; Montgomery and Farrell, 1993) and, possibly, accumulation of wave energy in diffluent large-scale flow (Shapiro, 1977; Sobel and Bretherton, 1999).

Another body of theory developed around the idea that patches of high vorticity associated with individual convective systems can, under certain circumstances, merge to form a more powerful incipient cyclone. This idea may have started with Fujiwhara's 1923[8] proposal that genesis involves the fusion of several small vortices, and has been revived recently (Ritchie and Holland, 1993; Simpson et al., 1997). (See Chapter 12 in this volume for a more thorough discussion of this). Montgomery and Enagonio (1998), Moller and Montgomery (1999), and Moller and Montgomery (2000) showed that small-scale patches of potential vorticity introduced into the flow field of a larger-scale vortex were quickly axisymmeterized, in the process feeding their energy into the vortex scale flow. This suggests that mesoscale convective systems that develop outside the eyewall may help intensify the storm as a whole.

The central problem in genesis is the transformation of an existing disturbance into a system operating on the feedback between surface enthalpy fluxes and surface wind. Any complete theory must account for the fact that such transformations are relatively unusual and, in any event, only occur under the conditions reviewed by Gray (1979). Bergeron (1954) had concluded that, under normal circumstances, convective downdrafts quench any nascent tendency for the boundary layer moist entropy to increase; he suggested that if, by some means, the surface cyclone could be made strong enough, the inward Ekman drift would overcome the anticyclonic outflow, leading to a positive feedback between surface enthalpy flux and wind, and transformation into a warm core system. But it has become clear from a series of numerical experiments (Emanuel, 1989; Emanuel, 1995a) and a field experiment (Emanuel, 1994; Bister and Emanuel, 1997) that a necessary condition for genesis is the establishment of a mesoscale column of nearly saturated air in the core of the system, so that cumulus convection rising into this air cannot produce low entropy downdrafts. Any environmental influence that disrupts the formation of such a saturated column will prevent genesis and weaken any existing system. Clearly, the ventilation of low entropy air in the middle troposphere through a nascent system will have this effect, as first pointed out by Simpson and Riehl (1958); this nicely explains why vertical shear is inimical to genesis. In axisymmetric models, the establishment of a mesoscale saturated column appears also to be a sufficient condition for genesis (Emanuel, 1995a). An important remaining question is how such a column can be established, and the various mechanisms described in the previous paragraph could all work in this direction. The same axisymmetric models show that a cyclonic circulation of sufficient strength at the surface can ultimately give rise to genesis, after a gestation period in which the friction and downdrafts weaken the circulation, while at the same time Ekman pumping and

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[8] Cited in Bergeron (1954), page 144, but no detailed reference is given.

associated convection moistens a deep column in the core of the system. But detailed observations of Hurricane Guillermo in the eastern North Pacific in 1991 (Bister and Emanuel, 1997) show that, in that development, the saturation was achieved by evaporation of rain falling from a stratiform anvil system associated with a mesoscale convective complex, and that downward advection of angular momentum in the mesoscale downdraft was an important ingredient in the subsequent genesis. It is by no means clear, however, that such a mechanism is at work in all or even most cases of genesis. This conclusion reflects the paucity of field experiments dedicated to the problem of tropical cyclogenesis.

11. Extratropical Transition

When tropical cyclones move into higher latitudes, they often regenerate as baroclinic systems, sometimes achieving great intensity and causing injury and damage. A celebrated case is that of Hurricane Hazel of 1954, which re-developed as it moved over the eastern U.S. and caused damage as far from the coast as Toronto. This event was studied by Palmén (1958), who concluded that both the high moisture content and circulation associated with the tropical storm were essential to the strong rejuvenation of the system. Palmén's findings were corroborated by Anthes (1990) using detailed numerical simulations of the event. Extratropical transition poses a formidable problem for forecasters, as even today's numerical models often miss or underpredict redevelopment owing to the difficulty of correctly handling water vapor, cumulus convection, and the often very small scale of the circulation at low levels.

In recent years interest in extratropical transition has been itself rejuvenated. A number of recent studies (Bosart and Lackmann, 1995; Harr and Elsberry, 2000; Harr et al., 2000; Klein et al., 2000; Thorncroft and Jones, 2000; McTaggart-Cowan et al., 2001) have cast the transition problem within a contemporary dynamical framework. This shows that at least part of the re-development is owing to the superposition of the intense, low-level potential vorticity anomaly associated with the former tropical cyclone with an upper tropospheric potential vorticity anomaly of extratropical origin. But there is large variation for case to case; in other cases, there may not be a strong upper level anomaly, but interaction of the tropical cyclone circulation with pre-existing gradients of potential vorticity at the tropopause, or with strong surface temperature gradients, sometimes plays an important role. Equally intriguing, but less well understood, is the role of the water vapor anomaly associated with the tropical disturbance eluded to by Palmén (1958). Bosart and Lackmann (1995) note the importance of a deep column of nearly-saturated, conditionally neutral air in the redevelopment they studied, while McTaggart-Cowan et al. (2001) show, using sensitivity experiments with a numerical model, that the pre-existing, low-level potential vorticity anomaly associated with the tropical cyclone was not a major factor in the re-development case they examined, suggesting the importance of some other factor or factors associated with the tropical system. The role in extratropical transition of the deep, mesoscale column of nearly saturated air invariably associated with tropical cyclones needs to be better understood.

12. Hurricanes and Climate

> *"Another problem, of much more far-reaching consequences, presents itself. What kind of secular changes may have existed in the frequency and intensity of the hurricane vortices of the Earth? And what changes may be expected in the future? We know nothing about these things, but I hope [to] have shown that even quite a small change in the different factors controlling the life history of a hurricane may produce, or may have produced, great changes in the paths of hurricanes and in their frequency and intensity. A minor alteration of the surface temperature of the sun, in the general composition of the earth's atmosphere, or in the rotation of the earth, might be able to change considerably the energy balance and the balance of forces within such a delicate mechanism as the tropical hurricane. During certain geological epochs, hurricanes may have been just as frequent as the cyclones of our latitudes, or they may have occurred all over the oceans and within all coastal regions, and they may have been even more violent than nowadays. During other periods they may have been lacking altogether. In studying paleo-climate and paleo-biological phenomena, especially along the coasts of previous geological epochs, it may be wise to consider such possibilities."*
>
> *- Tor Bergeron, 1954*

After Bergeron's striking insight a half century ago, interest in climatic influences on hurricane activity increased through the end of the century. As early as the mid 1950s, Namias (1955) showed that there were strong correlations between interannual fluctuations of Atlantic hurricane activity and changes in the general circulation, particularly in the pattern of long waves. This work was extended and particularized to individual parts of the Atlantic basin by Ballenzweig (1959). Interest remained focused on interannual fluctuations of Atlantic tropical cyclone activity for another three decades. In 1982, Lloyd Shapiro published a pair of papers demonstrating a clear connection between interannual fluctuations in Atlantic hurricane activity and other climate signals, including a measure of the phase of the quasi-biennial oscillation and sea surface temperatures west of Africa (Shapiro, 1982 a,b). Two years later, William Gray showed a strong connection between Atlantic hurricane activity and El Niño (Gray, 1984), and by the early 1990's a strong correlation was found between hurricane activity and rainfall in sub-Saharan Africa (Landsea and Gray, 1992). Saunders and Harris (1997) showed that the particularly active 1995 Atlantic Hurricane season was related to exceptionally warm sea surface temperatures, though Shapiro and Goldenberg (1998) noted that most of this signal might result from a connection between sea surface temperature gradients and vertical wind shear, with only a relatively small part owing to the direct influence of sea surface temperature on cyclone formation. Goldenberg (1996) also argued that the physical link between Atlantic hurricane activity and phenomena such as El Niño and sub-Saharan rainfall is through the effect of these phenomena on vertical wind shear over the genesis regions of the North Atlantic. By the 1980s, the Colorado State University group had started using these signals in an attempt to provide seasonal forecasts of Atlantic tropical cyclone activity (Gray et al., 1992). In the last decade of the century, a strong relationship between Atlantic hurricane activity and the North Atlantic Oscillation was discovered (Goldenberg et al., 2001), giving some hope that decadel variations in hurricane activity might be partially anticipated.

While hurricanes are usually considered to respond passively to climate changes on many times scales, it may be that they are active players in phenomena like the North Atlantic Oscillation. The author (Emanuel, 2001) has argued that much of the thermohaline circulation is actually driven by global tropical cyclone activity. If this proves to be the case, then the variation of hurricane activity with climate may be integral to the physics of such phenomena as the North Atlantic Oscillation.

By the end of the 1980s; it was becoming apparent that average global surface temperature was increasing, perhaps in response to anthropogenically induced increases in greenhouse gases, and the effect of global warming on hurricane activity became a concern. Emanuel (1987) argued that increasing greenhouse gases altered the energy balance at the surface of tropical oceans in such as way as to require a greater turbulent enthalpy flux out of the ocean, thereby requiring a greater degree of thermodynamic disequilibrium between the tropical oceans and atmosphere. Using a single-column radiative-convective model, he argued that the potential intensity of tropical cyclones would increase by about 3.5 ms^{-1} for each 1^{o} C increase in tropical sea surface temperatures, and supported that with a calculation of potential intensity from a global climate model subjected to a doubling of atmospheric CO_2 . Subsequent work by Knutson (1998), using a high resolution tropical cyclone model given boundary conditions from a global climate model, gave a similar estimate for the increase in hurricane intensity that might arise as a consequence of global warming. But the problem of how global climate change might affect the frequency of hurricanes remains largely unsolved. Global climate models appear to give disparate results. For example, the study of Haarsma (1992), using the GCM run by the British Meteorological Office, shows an increase in both the intensity and frequency of tropical cyclones, but the analysis by Broccoli (1990), using the Princeton/GFDL model, shows ambiguous results, with an increase in tropical cyclone activity if cloud-radiation feedback is not included and a decrease in activity otherwise. But it is clear from all these studies that even were the worst scenarios of global warming realized, the expected changes in tropical cyclone activity would be small compared to those arising from the kind of natural variability described in the previous paragraph, at least for the next 50 years. On longer time scales, the effects of global warming might be more serious.

Perhaps the most promising route to understanding the relationship between long term climate change and changes in hurricane activity is through examination of the geological record, as Bergeron had suggested. The budding new field of paleotempestology is just beginning to show how hurricane activity varies on times scales of centuries to millennia. For example, Liu (1993) has taken a series of sediment cores from near-shore lakes and swamps along the U.S. Gulf coast and has been able to deduce the timings of strong landfalling storms by observing sand layers in the cores and carbon-dating them from the surrounding organic matter. He has, in the last decade, developed a record of strong landfalling storms going back more than 3000 years at some sites. Work like this, if extended in space and further back into the past, may reveal how hurricane activity changes on very long time scales, offering an opportunity to understand how such activity is related to global and regional climate change on a variety of time scales.

13. Summary and a Look Ahead

The twentieth century was a time of rapid progress in understanding and predicting hurricanes. Most of this progress came after World War II, when an influx of scientific talent, coupled with rapid advances in technology, catalyzed observational and theoretical development. Much of our current understanding of the genesis and intensification of hurricanes was developed or foreshadowed during the 1950s; the advent of CISK in the following decade was arguably a setback from this earlier work. Numerical modeling revealed the sensitivity of hurricanes to processes such as cumulus convection and surface fluxes, and to factors in the environment, but did not, in and of itself, lead immediately to improved physical understanding. In some cases, such as in the simulation of storms in highly unstable environments but without surface fluxes, numerical simulations simply served to codify bad theory. Notwithstanding this, models eventually proved their utility in track prediction. But the characterization of hurricane structure and behavior improved steadily through the post-war years, thanks to skillful analysis and to the development of new technologies for measuring the atmosphere. Radar, reconnaissance aircraft, and satellites were all critical to the new synthesis that emerged in the second half of the century.

In spite of enormous progress, many facets of hurricane behavior remain poorly understood and predicted. We have not advanced to the point that forecasters can skillfully predict which tropical cloud clusters will become tropical cyclones and which will fade away; nor can we make reliable predictions of extratropical rejuvenation. Forecasts of hurricane intensity change remain notoriously unreliable, reflecting no doubt a poor understanding of the environmental and internal influences on intensity. Predictions of hurricane rainfall remain highly uncertain, and because rain-induced flooding is a major cause of death and injury, as in the Hurricane Mitch tragedy, a better grasp of this problem is essential. We are just beginning to understand the great sensitivity of hurricane activity to interannual to interdecadel climate fluctuations. Understanding the physical connection is central to the scientific problem of hurricanes as well as to forecasts of statistical storm activity on seasonal to decadel time scales. And while the scientific community debates when, if and how much global warming might result from anthropogenic increases in greenhouse gases, it is important for hurricane researchers to understand how climate change in general affects hurricanes. Paleotempestology offers the hope of reconstructing changes in storm activity over thousands and perhaps millions of years; this would be a big step forward toward understanding the relationship between hurricanes and climate.

While we have made great strides forward in scientific research, as a community we have been less successful in recent years in conveying to our representatives both the steps that are necessary for continued progress and the benefits to mankind they would bring. As a result, we bring somewhat less computational firepower to bear on numerical weather prediction than do our European colleagues, who suffer far less in the way of severe weather, while many of our most important observation networks fall into decline. Part of our great success in reducing injury and loss of life from hurricanes is owing to the excellent cooperation that has developed among forecasters and emergency managers at the federal, state and local levels. But we have largely failed to export this expertise to the developing world, which continues to suffer devastating losses from tropical cyclones. Nor, closer to home, have we been very successful in helping to bring about changes in the construction and insurance industries, and in the formulation of zoning restrictions, that would mitigate the greatly increasing economic costs of hurricanes. As scientists, we are not well positioned to bring about these changes. But responsibility for the first step -- communicating the nature of the problem to the public -- lies with us.

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