Toward a General Theory of Hurricanes

Kerry A. Emanuel

In all the Indies, I have always found May-like weather," commented Christopher Columbus on his meteorologically lucky first voyage to the New World. For most of us, too, "tropics" brings to mind a similar picture of benign tranquility. On islands such as Hawaii and Tahiti, mean temperatures in summer and winter differ by only a few degrees, and almost all rainfall occurs in brief tropical downpours. Day-to-day variability is also small, with winds and temperatures virtually constant for long periods of time. It is a great irony that these benign climates occasionally produce the earth's most violent storms: hurricanes.

How does the normally serene atmosphere of the tropics produce the world's fiercest storms?

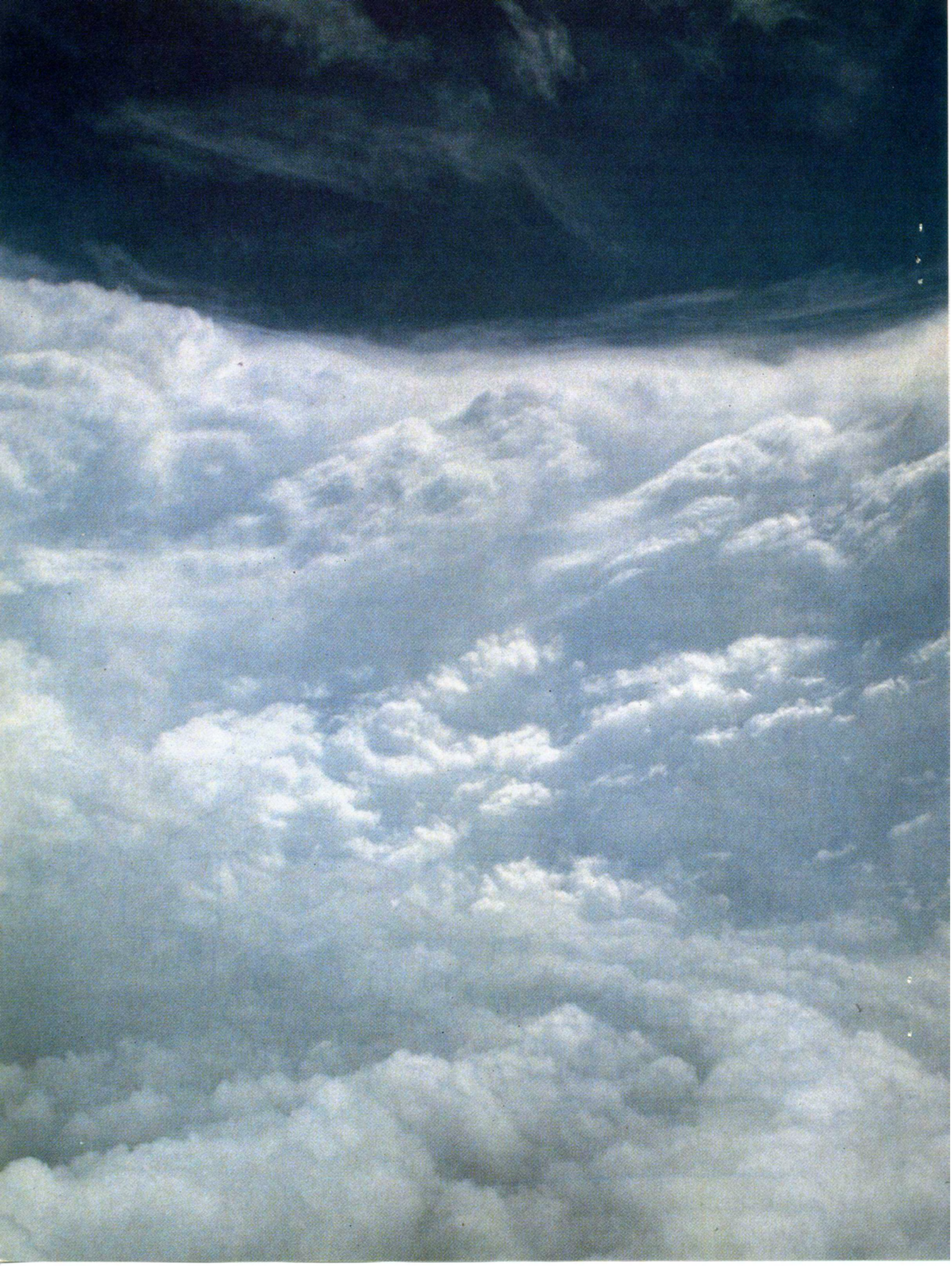
Hurricanes, named after Huracan, a Carib god of evil, rank with earthquakes as the most destructive natural phenomena. (They are also called tropical cyclones and typhoons in other parts of the world.) A single storm killed 300,000 people in Bangladesh in November 1970, and the two worst natural catastrophes in US history were hurricanes (Galveston in 1900 and the 1928 Lake Okeechobee storm). While loss of life in developed countries has been greatly reduced by sophisticated warning systems, property damage is increasing as the population of coastal regions swells. A single moderate hurricane caused more than $1 billion damage along the US Gulf coast in 1986. In a nation preoccupied with minute risks, it is paradoxical that little heed is taken of warnings that some of our major coastal cities are disasters waiting to happen.

To the atmospheric scientist the hurricane is a thing of great beauty and mystery. Each year, scientists venture into the eyes of these great storms in airplanes to collect data for research and forecasting. The sensation of being in the eye is impossible to convey; according to one of the better "eyewitness" accounts I have heard, it is like standing in the midst of a white, slowly revolving coliseum 15 km high and 15 to 150 km across. Some of the feeling is conveyed by Figure 1, a photograph taken in the eye of Hurricane Diana, and by Figure 2, a perspective view of Hurricane Allen reconstructed with visible and infrared imagery from a polar-orbiting satellite. In a radar scan through the center of Hurricane Gloria (Fig. 3), the eye appears as a funnel-shaped, echo-free region surrounded by a sloping wall of intense precipitation. The eye wall is in turn surrounded by a "moat" of relatively weak precipitation, outside of which moderate rain returns. A horizontal radar scan taken from the center of Hurricane Emily (Fig. 3) shows a vortical pattern of precipitation, with the eye in the center.

Figure 1. Hurricanes rank with earthquakes as the most destructive natural disasters, and their origins in the normally serene tropics have been shrouded in mystery. At the same time, they are objects of awesome beauty, as is apparent from this photograph taken in 1984 from a National Oceanic and Atmospheric Administration weather plane in the eye of Hurricane Diana off the North Carolina coast. Being in the eye, with the eye wall towering above and blue sky above that, has been compared to standing in the middle of an immense, revolving white coliseum. (Photograph by Howard Bluestein, University of Oklahoma.)

Despite decades of intensive scientific research, many aspects of tropical hurricanes remain enigmatic, and controversy about their physics persists. Among the more perplexing mysteries is the question of why hurricanes are so rare. Although, as we will see later, the reservoir of potential energy for hurricanes exists over large portions of the tropical oceans for much of the year, it is seldom tapped. Most other storms may be regarded as arising from the linear instability of the time-averaged state of the atmosphere. By "linear" we mean that infinitesimal perturbations upon the mean state will amplify, as shown by an analytic treatment of the linearized form of the governing equations of motion, heat, and mass. The basic west-to-east flow of air in middle and high latitudes is unstable in this sense, giving rise to the numerous cyclones and anticyclones that affect daily weather outside the tropics. But the only common linear instability of the tropical atmosphere is that which produces the ubiquitous cumulus clouds that dot the tropical skyscape. For many years, atmospheric scientists regarded hurricanes as rare manifestations of the same instability that drives cumuli, though attempts to demonstrate this quantitatively always led to cumulus clouds and not to hurricanes. As we shall see, the energy source of the mature hurricane is quite different from that which drives cumulus convection, though questions remain about the energetics of developing storms.

Virtually all theoretical investigations of hurricanes have treated them as phenomena highly specific to the present state of the earth's atmosphere, rather than as part of a general class of geophysical fluid dynamical systems. This paper represents an early attempt to place the physics of hurricanes in a general context. In addition to enhancing our understanding, a general theory



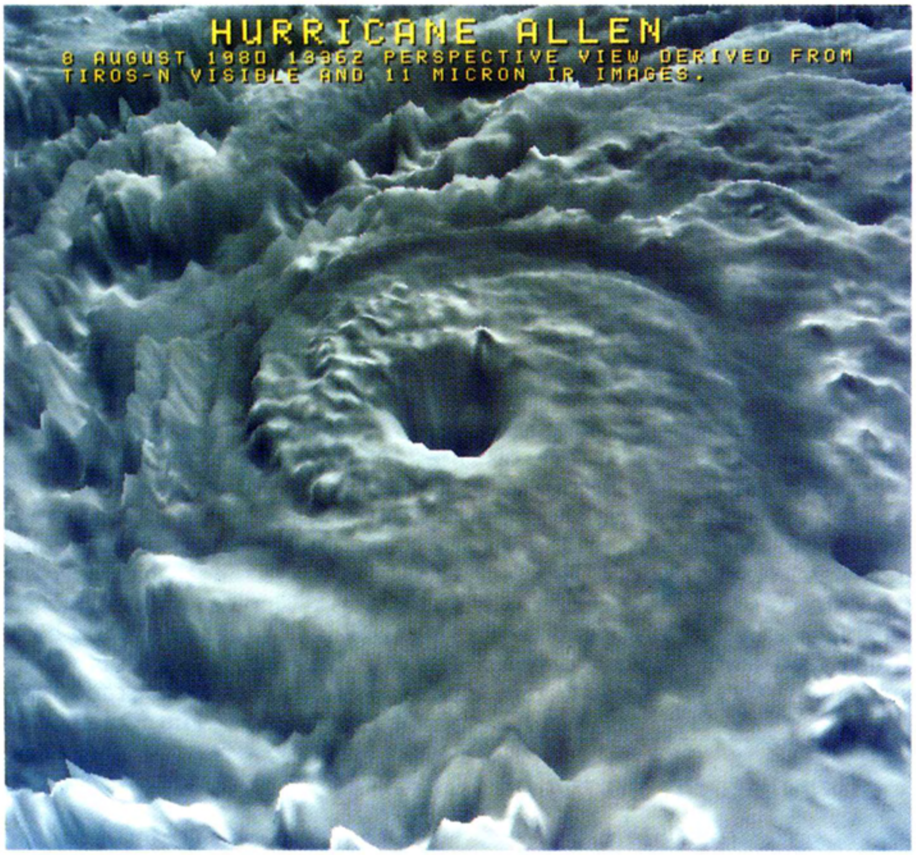


Figure 2. The eye of Hurricane Allen appears as a funnel-shaped hole near the center of this perspective view. The image was constructed using 1-km resolution data from visible and 11-μm infrared instruments on board the TIROS-N polar-orbiting satellite. At the time the data were collected on 8 August 1980, the eye was located over the Gulf of Mexico. Software developed at the NASA/Goddard Space Flight Center uses the infrared data to estimate the height of the cloud tops and visible imagery for coloring and shading to produce the perspective view. (For more information, see Hasler et al. 1985.)

would allow us to predict how the frequency and intensity of these storms would respond to changes in climate. It would also allow us to relate them to seemingly different phenomena such as oceanic storms of the polar night and dust devils, and to address sensibly the question of whether hurricanes are possible in other planetary and in stellar atmospheres. Any valid general theory of hurricanes must account for their observed structure and intensity as well as their rarity, and should make testable predictions about the precise nature of conditions under which they form.

The tropical atmosphere

The normal state of the maritime tropical atmosphere results from a balance among several physical processes: turbulent fluxes of sensible and latent heat from the sea surface; cooling of the atmosphere by infrared radiation to space; transport of heat, moisture, and momentum by cumulus clouds; and horizontal and vertical transport by large-scale atmospheric motions. The relative importance of these processes differs in space and time, but the tropical atmosphere can be broadly divided into four regions, as illustrated in Figure 4. Region 1 contains widely scattered cumulonimbus towers, many of which extend through the entire troposphere (a layer in which temperature is strongly controlled by moist convection and which in the tropics extends upward to about 15 km, containing 80 to 85% of the mass of the atmosphere). Much of the moisture condensed in these clouds falls out as rain, and the large amount of latent heat released when water vapor condenses into liquid water or ice is mostly used to increase the sum of the internal and potential energies of parcels of air ascending through the clouds. The region containing deep clouds generally occurs where the sea-surface temperatures exceed 26°C, though there are exceptions.

Region 2 receives mass near its top from the deep clouds of Region 1. The air slowly subsides, and the loss of the sum of potential and internal energy is balanced by longwave electromagnetic radiation to space. Generally free of clouds, this region covers large parts of the upper troposphere. Since the air entering from Region 1 is at very low temperatures (−60 to −80°C), it contains almost no water vapor, so that Region 2 is exceedingly dry. Air leaves Region 2 by subsiding through the trade inversion—a sharp transition in temperature and water-vapor content—whereupon it enters the trade cumulus layer (Region 3). The trade inversion generally lies between 1 and 3 km altitude. The trade cumuli act primarily to transport water vapor from its source at the sea surface to Region 3. Since these clouds do not normally precipitate, there is no net release of latent heat, and thus the trade cumuli's main effect on the heat balance is through radiational cooling of the cloud surfaces. The loss of potential plus internal energy of air sinking through Region 3 is also balanced by radiation to space, but the air experiences a large increase in water-vapor content from the cumuli.

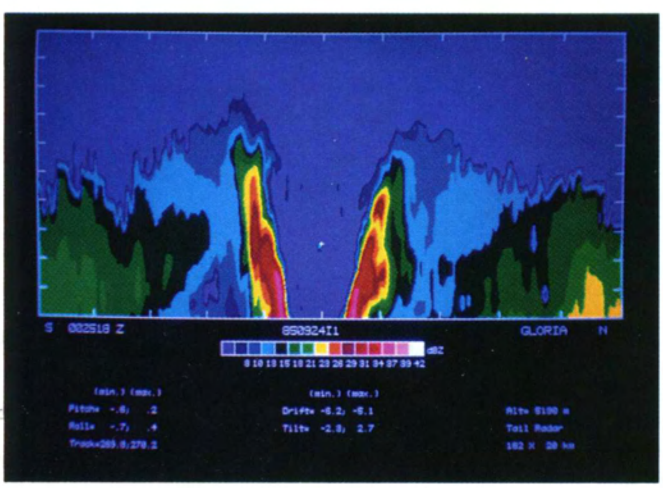
Finally, air enters the subcloud layer, Region 4. Typically only 500 m deep, this layer, as its name implies, lies below the bases of the cumuli and cumulonimbi. Conserved quantities such as water-vapor content and specific entropy (entropy per unit mass) are homogenized in this region by turbulent eddies. For reasons that are not well understood, the water-vapor content of this layer is strongly controlled by a natural humidistat that keeps the relative humidity near the surface between 75 and 80% over a wide range of conditions. Air in Regions 3 and 4 flows toward Region 1, where it ascends within the deep cumulonimbi.

The deep convective clouds of Region 1 are by far the most conspicuous and impressive components of the normal tropical circulation. In the meteorological literature, it is often stated that these deep cumulonimbi "drive" the circulation, but it is more nearly true to say that the clouds result from the circulation, which ultimately arises as a consequence of the sea-surface temperature gradient. The misconception results in part from the huge release of latent heat in the clouds; it is often not recognized that only a tiny fraction of the heat is available for the production of kinetic energy. The circulation is driven not by the small differences between the densities of air within clouds and those of their immediate environment, but rather by the large differences between the temperature of Region 1 and that of Regions 2 and 3, which result from the gradient of sea-surface temperature.

Misconceptions about the role of cumulonimbus clouds have resulted from incorrect treatments of the density of air within such clouds. This is illustrated in Figure 5, which shows a typical vertical profile of temperature (black curve) from balloon soundings made in the deep tropics (Region 1), plotted on a thermodynamic diagram with log pressure on the ordinate and temperature on the abscissa. The dark gray curve shows the temperature that a parcel of air would have if it ascended from the subcloud layer without mixing with its environment. It cools quite rapidly for the first 0.5 km in accord with the first law of thermodynamics, which says that temperature drops with pressure. At about 0.5 km, water vapor begins to condense, and the release of latent heat prevents the parcel's temperature from falling as rapidly above this level. Note that the lifted parcel is substantially warmer than the ambient air through a large depth, except in a small area just above the subcloud layer (around 0.5 km). The lifted parcel would have a substantial positive buoyancy if the density of the air were a function of its temperature alone. The total buoyant energy could then be shown to be proportional to the area enclosed by the dark gray curve and the environmental sounding. The state represented by Figure 5 is said to be conditionally unstable to subcloud layer air; that is, a finite (but small) amount of work must be done to lift the air through the small area where it is colder than its environment; thereafter, it will be positively buoyant and accelerate upward. The small area of stability allows potential energy to accumulate, after which it can be released with great vigor. An example of this is the springtime juxtaposition of desert air on top of humid maritime air over the US plains states, which results in a tremendous accumulation of buoyant energy that, when finally released, may produce severe thunderstorms and tornadoes.

The problem confronting the tropical meteorologist several decades ago was to explain why soundings appeared conditionally unstable even where deep cumulus convection was occurring and to explain further how the untapped remainder might be used to initiate a hurricane. Several theories proposed that cumulus clouds organized in clumps, rather than randomly spaced, could more effectively tap the potential energy reservoir between the subcloud layer and the overlying atmosphere. "Organized convection" became a popular explanation of many large-scale circulation systems, and the idea that hurricanes are caused by the release of latent heat in cumulus clouds is still widely believed (see, for example, the latest *Encyclopaedia Britannica*).

In recent years an altogether different picture of the stability of the tropical atmosphere has emerged. Beginning with the work of Betts (1982), it has been realized that the presence of condensed water in tropical clouds has a decisive influence on their density. While this influence had been known for quite some time, it had not generally been included in computations of parcel stability because it was thought that most condensed water rained out before it could accumulate to the point of having a substantial effect on buoyancy. But rain actually increases the condensed water content of the lower portions of clouds, although it does diminish the content higher up.



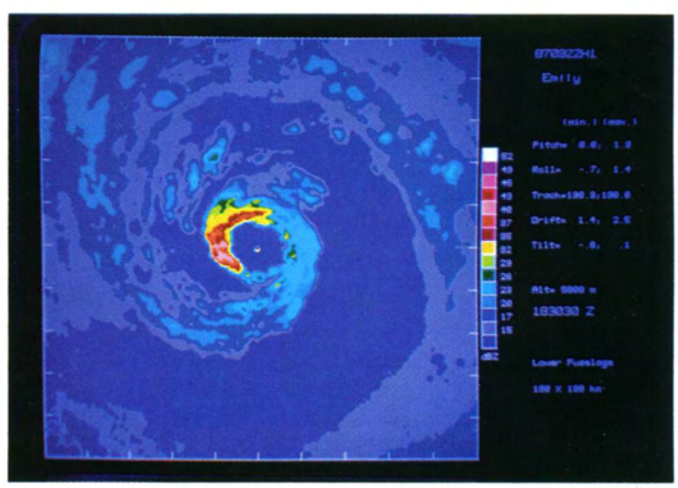


Figure 3. Radar scans help visualize the structure of hurricanes. At the left, a cross section through the eye of Hurricane Gloria on 24 September 1985 shows the reflectivity obtained from an airborne radar located at the position of the white cross. The section is 20 km high and 162 km across. The reflectivity is proportional to the sum of the sixth power of the diameters of water and ice particles in the radar beam and thus is particularly sensitive to large raindrops and graupel. (Cloud droplets are too small to be detected.) Coloring corresponds to equal increments of reflectivity on a log scale, with pink denoting the highest and purple the lowest values. The eye is the funnel-shaped region of low reflectivity at the center. At the right, a horizontal cross section through Hurricane Emily on 22 September 1987 shows a concentration of precipitation in the northwest section of the eye wall. The radar echoes clearly show the nearly circular symmetry of the storm. The airplanes from which these measurements were made are two P-3 Orions used for research and reconnaissance by the Hurricane Research Division of the National Oceanic and Atmospheric Administration's Atlantic Oceanographic and Meteorological Laboratory in Miami.

The light gray curve in Figure 5 shows the virtual temperature of a parcel lifted from the subcloud layer, with no rain-out of condensed water permitted. The virtual temperature is defined including the weight of condensed water, so that comparison of it with environmental temperature (the black curve) accurately reflects the parcel's actual buoyancy. Note that the potential buoyancy of subcloud layer air is very small (the light gray curve is very close to the black curve). Systematic examination of a large number of tropical soundings shows this property to be quite general. Evidently, the tropical atmosphere is convectively adjusted—that is, almost neutrally buoyant with respect to subcloud layer air, being maintained in such a state by the clouds themselves, which rapidly release buoyant energy almost as soon as it is generated by large-scale processes. What little potential energy exists is surely used to drive the clouds themselves against dissipation. There is apparently no atmospheric reservoir of potential energy for hurricanes. What, then, drives the storm?

The energy source of hurricanes

The reservoir of potential energy for hurricanes resides in the thermodynamic disequilibrium between the atmosphere and the underlying ocean. This is reflected in the fact that air immediately above the ocean is subsaturated, yielding a potential for transfer of entropy from sea to air even though the two media are usually at about the same temperature. The true energy source for hurricanes was recognized long ago by Riehl (1954) and others, though their ideas were temporarily submerged during the peak of enthusiasm for the organized convection theory. The first successful numerical simulation of a hurricane, by Ooyama (1969), demonstrated that the thermodynamic disequilibrium between ocean and atmosphere is the sine qua non for the hurricane.

The effectiveness of this source is indicated in Figure 5. The light red curve represents the virtual temperature of air lifted from the subcloud layer after being saturated at the sea-surface temperature characteristic of the region the sounding was taken in. The lifted parcel is now substantially less dense than the ambient environment. If the parcel is not only saturated at sea-surface temperature but forced to undergo an isothermal expansion to a lower pressure characteristic of the eye of a moderate hurricane, its entropy is further increased, and the dark red curve results when that air is lifted. (About half the total entropy increase of air flowing into a hurricane results from isothermal expansion.)

We are now in a position to state with some confidence the basic mechanism that sustains a mature hurricane against dissipation. The energy cycle is illustrated in Figure 6, whose division of regions is similar to that of Figure 4, but with an additional Region 5, the eye. The horizontal scale in Figure 6 is considerably smaller than that of Figure 4, and the sea-surface temperature is approximately constant. Air spirals inward in Region 3 and especially Region 4. It is important to note that the ambient air has an absolute angular momentum with respect to the storm center, by virtue of the earth's rotation. As the air flows inward, it approximately conserves this angular momentum, resulting, in the Northern Hemisphere, in a counterclockwise rotation of the winds about the storm center. Since the rate of evaporation of water increases with surface wind speed, the moisture content of the air increases as it flows inward. In Region 3 this increase is slow because dry air is continually being mixed downward from higher levels. As the inward-flowing air approaches the eye wall

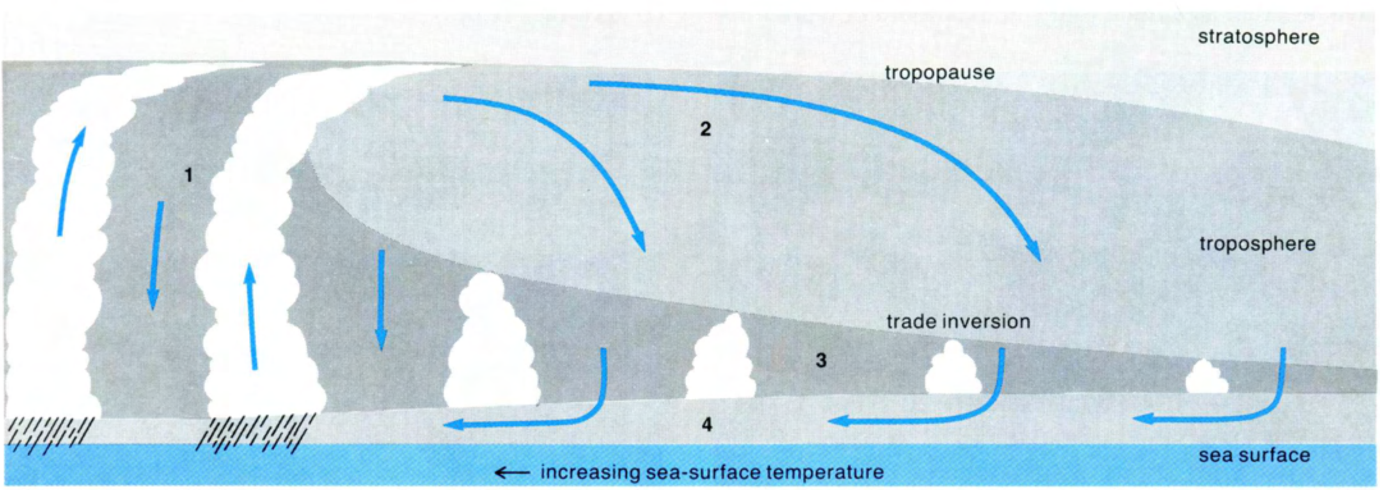


Figure 4. An understanding of the normal state of the maritime tropical atmosphere is a prerequisite to understanding the anomalous occurrence of hurricanes. The mean circulation and structure of the tropical troposphere are shown in this schematic cross section, which covers an area roughly 5,000 km across, spanning about 7°C of sea-surface temperature gradient, from about 22°C to 29°C. The tropopause divides the troposphere and stratosphere at about 15 km altitude over the warmest ocean water.

The average clockwise circulation in this diagram is driven by the gradient of sea-surface temperature. Air ascends within the deep cumulonimbus clouds in Region 1, and the vertically averaged latent heat release (which is proportional to the net precipitation reaching the surface) is used to raise the sum of potential and internal energy of parcels of air. Air flows from Region 1 to Region 2, where it slowly subsides as it loses energy by infrared radiation to space. The very dry air of Region 2 subsides through the trade inversion into Region 3, where it is moistened by mostly nonprecipitating trade cumuli. The air eventually enters the subcloud layer, Region 4, where it receives heat and moisture from the ocean as it flows back toward Region 1. Since the net gain of sensible and latent heat occurs at a higher temperature than it is lost at, there is net mechanical energy available from the cycle; this is used to balance dissipation.

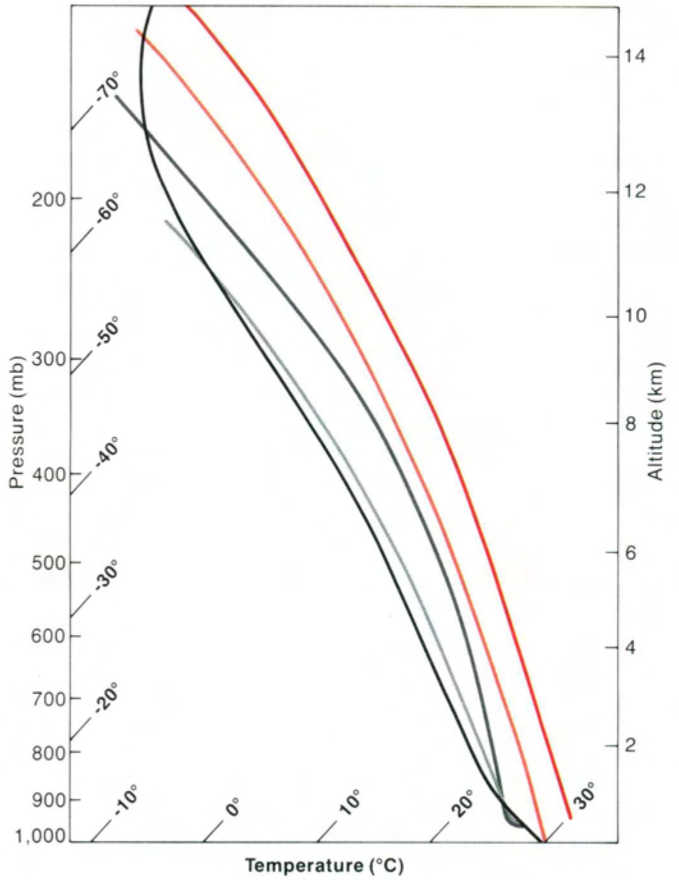


Figure 5. The temperature of the normal tropical atmosphere is compared with that in the interior of hurricanes on this thermodynamic diagram. On such a diagram, pressure decreases upward (the scale on the left records pressure in the standard atmospheric units of millibars), and temperature decreases upward and to the left. A height scale is shown on the right.

The black curve shows the time-averaged virtual temperature as a function of pressure, constructed from a large sample of balloon observations from the Caribbean region in summer (corresponding to Region 1 of Figure 4). The virtual temperature is defined to account for the effect of variable water-vapor content on density (i.e., the actual density is given by p/RT_v, where p is the pressure, R is the gas constant for dry air, and T_v is the virtual temperature). The dark gray curve shows the virtual temperature a parcel would have if lifted from the surface with no heat added other than the latent heat of vaporization. The light gray curve also shows the virtual temperature of a lifted parcel, but in this case the effect of condensed water on density has been accounted for in the definition of T_v.

The light red curve results from the same process, except that the surface parcel has first been brought into thermodynamic equilibrium with the ocean. The dark red curve is constructed in the same manner as the light red curve, but the pressure of the parcel has first been reduced to 950 mb (a typical surface pressure at the center of a moderate hurricane) while its temperature is held constant.

The closeness of the black and light gray curves shows that the density of cumulus clouds is only slightly less than that of their environment, while the dark red curve represents the low density of air ascending in hurricane eye walls. The energy for hurricanes can be shown to be proportional to the area enclosed by the black and dark red curves.

(Region 1), however, it undergoes a rapid increase in moisture content since there is little dry air to mix from aloft.

The air ascending in the eye wall, an outward-sloping ring of intense cumulonimbus clouds located between 10 and 100 km from the center, is much warmer than the distant environment at the same altitude. It is this difference, related directly to the radial variation of water-vapor content in the subcloud layer (Region 4), which drives the storm. The same can be said for the mean circulation shown in Figure 4, but there the lateral variation of subcloud layer entropy is due to the underlying variation in sea-surface temperature rather than to variations in relative humidity at constant temperature. The role of the cumulus clouds in the energy cycle of a hurricane is to redistribute vertically entropy acquired from the ocean.

The warmest air at a fixed altitude within the storm is in the eye (Region 5), which is often free of clouds. The dynamics of the eye are not entirely understood, but the basic process is as follows. The inward-flowing air in Region 4 can never reach the center, because even partial conservation of angular momentum would require the air to spin up to infinite velocity. Thus it stops flowing inward and ascends at a finite radius, leaving an inert core of air. As the eye wall spins up, turbulent eddies transfer angular momentum to the core, causing it to spin up also. Thus the core is mechanically forced by the rotating air in the eye wall. The angular acceleration, acting like a giant centrifuge, impels mass outward, a process which pulls down dry air from near the top of the storm. The warming of the eye wall reinforces this circulation. The adiabatic compression of the downward-flowing air is responsible for the great warmth of the inner eye. It is important to note, however, that the formation of the eye represents a direct sink of energy, although it may indirectly aid the energy-producing circulation.

The hurricane can be regarded as an elegant example of a natural Carnot heat engine (an idealized, reversible thermodynamic cycle that converts heat to mechanical energy). To illustrate this, it is first necessary to define the total entropy content of moist air. This is the sum of the entropies of dry air, water vapor, and suspended liquid water. (We will neglect the small contribution from suspended ice and the effect of water substance on heat capacity. For a more detailed account of the whole process, see Emanuel 1988.) The total entropy per unit mass of air is

$$s = C_p \ln T + \frac{L_v w}{T} - R \ln p. \qquad (1)$$

Here C_p is the heat capacity of air at constant pressure, L_v is the latent heat of vaporization of water, and R is the gas constant of air. T and p are temperature and pressure, while w is the mass of water vapor per unit mass of dry air. The total entropy, s, defined by (1) is conserved in individual parcels of air, except that it can be changed by contact with the ocean and by radiational cooling or heating. It is important to note that s cannot be changed by formation or evaporation of clouds; this will change the individual terms on the right of (1) but not their sum.

Following the circuit illustrated in Figure 6, parcels of air traveling between a (for ambient) and c (for center) receive total entropy from the ocean as a direct consequence of the thermodynamic disequilibrium between ocean and atmosphere. This is the true heat source for the hurricane. The air then ascends through the eye wall while conserving total entropy, and flows outward to large distances where the excess entropy is ultimately lost by radiation to space, symbolically between points *o* (for outflow) and *o′* in Figure 6. The air then slowly returns to the surface.

The entropy gain occurs at the relatively high temperature of the seawater (26 to 30°C), while the loss occurs at the much lower temperatures of the lower stratosphere (−60 to −80°C). According to Carnot's theorem, the thermodynamic efficiency of the heat engine is

$$\epsilon \equiv \frac{T_s - T_o}{T_s}, \tag{2}$$

where T_s is the temperature at which heat is added (here the seawater temperature) while T_o is the mean temperature at which it is lost (the temperature of the lower stratosphere). This efficiency is typically about ⅓, which is much higher than values previously quoted in the literature. Earlier estimates concerned the fraction of total latent heat converted to mechanical energy. But most of the water vapor condensed in the storm derives from the ambient vapor content, whereas it is the latent heat derived from the excess water acquired from the ocean that drives the storm.

Carnot's theorem shows that the total amount of mechanical energy available from a closed circuit through the storm is the total heat input multiplied by the efficiency:

$$E = \epsilon\, T_s(s_c - s_a), \tag{3}$$

where the subscripts *c* and *a* denote evaluation at the respective points in Figure 6. Reference to (1) shows that the entropy increase results only from an increase in water-vapor content (w) and a drop in pressure, since in a tropical hurricane the temperatures at points *c* and *a* are the same.

The maximum available energy given by (3) may be used to calculate the central pressure of a mature storm. This is a useful exercise, since central pressure is strongly related to other quantities of interest such as maximum wind speed. In a steady state hurricane, virtually all the mechanical energy generated from the Carnot cycle is used to balance frictional dissipation at the ocean surface. Locally, the air is driven against friction by a radial pressure gradient, and the total pressure drop is proportional to the total frictional dissipation. Thus the total pressure drop from *a* to *c* in Figure 6 must equal the total mechanical energy from the Carnot cycle:

$$-\int_a^c \alpha\, dp = \epsilon\, T_s(s_c - s_a), \tag{4}$$

where α is the gas volume per unit mass. Using the ideal gas law ($\alpha = RT/p$), the integral in (4) may be evaluated to arrive at

$$RT_s \ln\frac{p_c}{p_a} = -\epsilon\, T_s(s_c - s_a). \tag{5}$$

Since s depends on pressure, (5) is an implicit relation for pressure that requires knowledge of the total increase in water-vapor content from the ambient environment inward to the eye. The water-vapor content, w, depends on pressure, temperature, and relative humidity; thus for a given temperature a lower bound on pressure can be determined from (5) by requiring the surface air at the eye to achieve saturation with respect to water. This lower bound is a function of ϵ, surface temperature, and ambient relative humidity, the last of which measures the degree of thermodynamic disequilibrium between

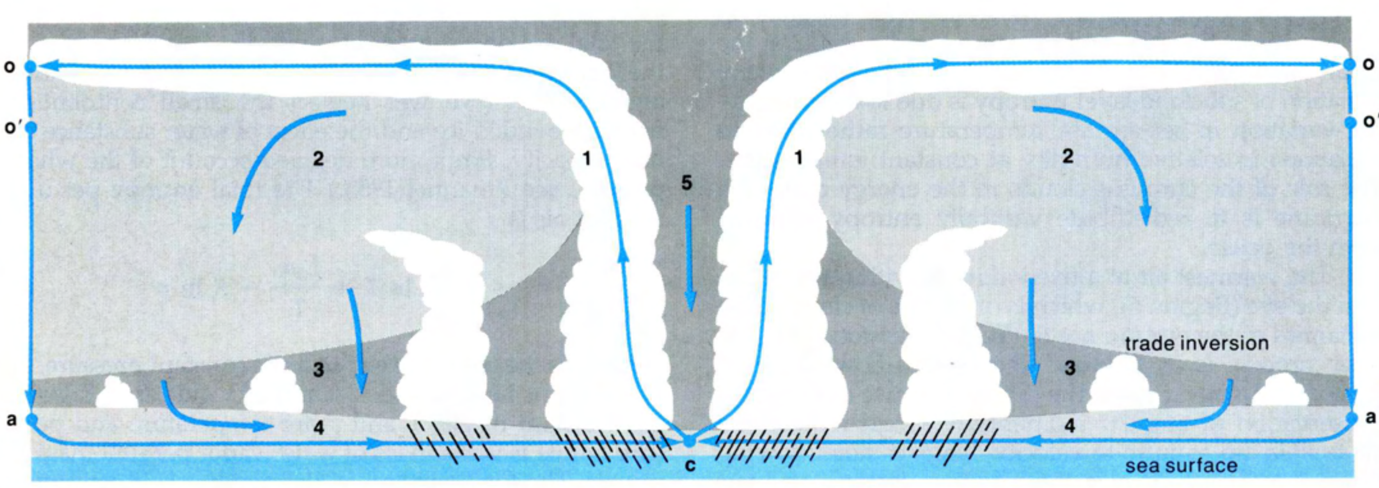


Figure 6. The structure and airflow of a mature hurricane are shown in this cross section, which spans a width of about 1,600 km and a height of 15 km. The regions correspond closely to those of the overall tropical atmosphere shown in Figure 4, but with an additional region of subsiding air in the eye (Region 5). In this case, the sea-surface temperature may be considered constant, but the total entropy content of the subcloud layer (Region 4) increases inward toward the eye as the increasing surface wind speed leads to greater evaporation rates, causing the near-surface air to approach saturation. The total entropy increases from point *a* to point *c* and is approximately conserved during ascent through the eye wall to point *o*. Heat is lost by infrared radiation to space, symbolically between points *o* and *o′*. Because heat is acquired at a much higher temperature than it is lost at, the Carnot heat engine, which converts heat into mechanical energy, is very efficient ($\epsilon \approx$ ⅓). In the steady state, this energy is mostly balanced by frictional dissipation at the surface.

the ocean and the atmosphere.

The lower bound on central pressure over the tropical oceans, which is calculated using (5) from mean September conditions, is shown in Figure 7, together with the measured central pressures of some of the most intense tropical storms on record. Evidently, some hurricanes attain the thermodynamic upper bound on intensity, but many do not.

A more general diagram showing the minimum sustainable central pressure as a function of sea-surface temperature and outflow temperature (the temperature at which entropy is lost by export or by radiational cooling to space) is shown in Figure 8. There is no solution for minimum pressure at sufficiently high sea-surface temperature or low outflow temperature. A detailed analysis (Emanuel 1988) shows that the Carnot engine runs away in this regime because of the pressure dependence of the water-vapor mixing ratio, w: the increase of water-vapor mixing ratio resulting from a decrease in pressure represents more than enough additional entropy to account for the pressure drop. The hypothetical hurricanes, or "hypercanes," of this regime would be intense enough to make dissipation away from the surface important in the energy balance. Numerical simulation of hypercanes has not yet been attempted.

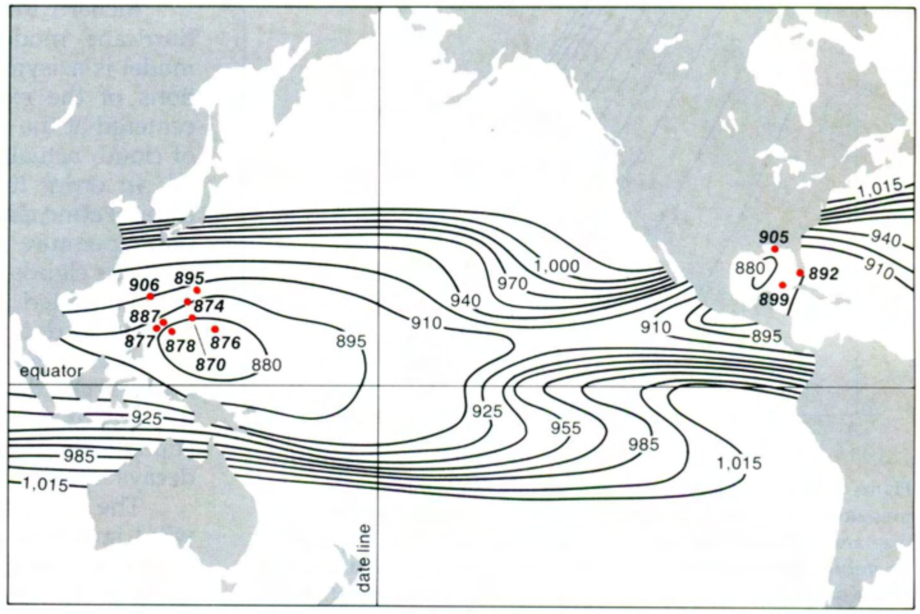


Figure 7. Hurricanes are areas of very low pressure. The tropical oceans are ideal spawning grounds for them, as demonstrated by this map, which shows the minimum sustainable central pressures in tropical storms under September mean climatological conditions over the Pacific Ocean and the Caribbean Sea. The pressures, which have been calculated using Eq. 5, are expressed in millibars, with 1,015 mb assumed to be the normal surface pressure. The dots and italicized numbers show, respectively, the locations and central pressures of some of the most intense hurricanes on record. Tropical storms in the Australian region are not indicated, because they occur during the late Southern Hemisphere summer (February–April).

Why are hurricanes so rare?

It is clear from Figure 7 that much of the tropics can support hurricanes. The comparative rarity of hurricanes is therefore somewhat mysterious.

Forecasters have long known of the existence of several empirical conditions that are necessary but not sufficient for the formation of hurricanes (e.g., see Anthes 1982). The first of these requires the sea temperature to be at least 26°C through a depth of at least 60 m. The temperature requirement is explained by Figure 4: when sea-surface temperatures are less than 26°C, it is likely that the convective layer is too shallow to support an efficient Carnot engine. The depth requirement might at first glance appear to involve the need for a sufficiently large heat reservoir, but the average municipal swimming pool has a higher heat capacity than the entire column of atmosphere above it. The depth requirement is likely due to the tendency of even modest disturbances to mix cold water up from the depths, thus reducing the thermodynamic disequilibrium with the atmosphere. A second requirement is the absence of significant vector changes of the mean wind with height through the troposphere. Wind shear apparently disrupts the connection between the incipient warm core of disturbances aloft and the surface wind, destroying the feedback between surface wind and total entropy content that drives the storms. There are other empirical conditions as well, but even when they are satisfied storm formation usually does not take place.

A clue to the basic limitations on storm formation is revealed by numerical simulations, which are made by integrating the basic equations governing momentum, mass, heat, and water in its various phases. While the continuum equations are well known, it is not possible to resolve by computations all the scales of motion that are important to most fluid dynamical phenomena. For example, the necessity of resolving scales from cumulus clouds all the way up to the diameter of a hurricane would require on the order of 10^7 grid points, and the necessity of resolving the time scale of the cumuli imposes an upper limit of several seconds on each time step. When the number of computational operations per grid point per time step is calculated, the total number of operations that must be performed per unit time is far too large for current computers. It should be added that we have not considered here important processes on much smaller scales. In practice, these small-scale processes are parametrically related to the resolved fields. Current hurricane models crudely resolve the cumulus clouds, but the microphysics of cloud and rain formation and turbulent motions on the subgrid scale are represented by parameterizations.

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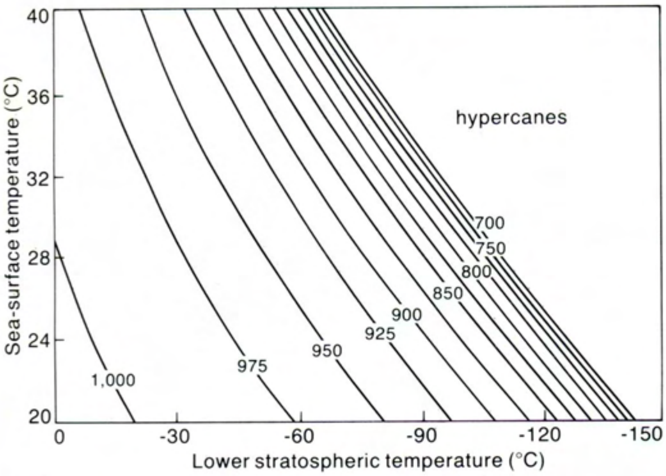

Figure 8. A more general way to assess the low atmospheric pressures associated with hurricanes is demonstrated by this diagram, which shows the minimum sustainable central pressure (in millibars) of tropical storms calculated from Eq. 5 as a function of the sea-surface temperature and the mean temperature of the lower stratosphere. The ambient surface relative humidity is assumed to be 75%. No solutions of Eq. 5 are possible in the region marked "hypercanes" because the mechanical energy produced by the Carnot heat engine is so large that it cannot be balanced by surface friction alone. The intensity of hurricanes in this regime would be limited by internal turbulent dissipation of kinetic energy, presumably at very high wind speeds.

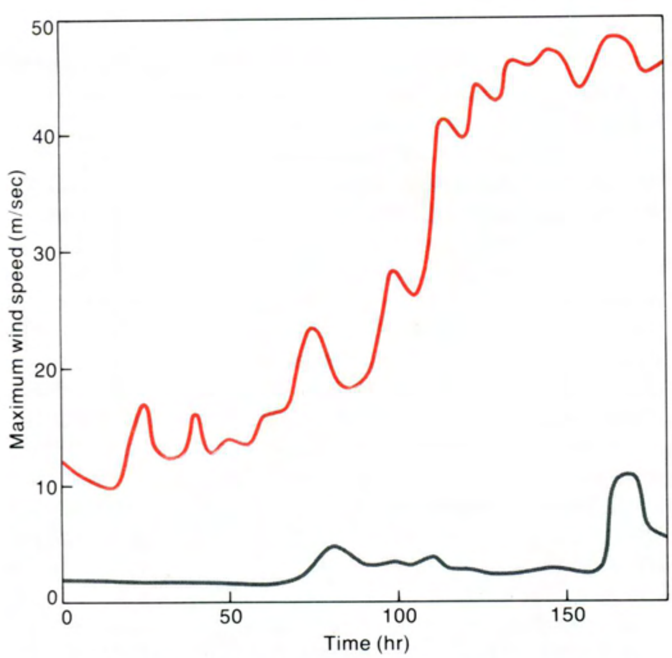

Figure 9. Computer models provide a partial answer to the question of why hurricanes are rare even though the tropical atmosphere has abundant energy to support them. This graph shows the evolution with time of the maximum surface wind speed produced by one such numerical model (Rotunno and Emanuel 1987). The red curve begins with a 12 m/sec amplitude vortex, while the maximum velocity in an experiment that starts with a 2 m/sec amplitude vortex, but is otherwise identical, is shown by the gray curve. The failure of the weak vortex to amplify demonstrates that hurricanes in this model cannot arise out of weak random noise; rather, a vortex of sufficient amplitude must be provided by independent means, such as a large-scale wave or a thunderstorm complex from a middle-latitude continent.

Richard Rotunno and I have developed one such hurricane model (Rotunno and Emanuel 1987). The model is axisymmetric—that is, it does not allow variations of the explicitly calculated fields around circles centered at the storm center. The cumulus clouds (rings of cloud, actually) are explicitly, albeit crudely, simulated. In order to create an environment similar to the tropical atmosphere, we first specified a vertical structure of temperature and moisture that is linearly unstable to cumulus clouds. We then ran the model forward in time and permitted the cumulus clouds to grow and, ultimately, to decay, leaving the model's atmosphere in a state that is neutral to its clouds, as the real atmosphere is to real clouds. We used this new state as the basis of all the experiments. To get a model hurricane started, we superimposed on the basic state a weak vortex which decays upward from the surface.

The evolution with time of the maximum surface wind speed in two of these experiments is shown in Figure 9. The first experiment starts with a maximum wind of 12 m/sec. After about three days, the vortex rapidly intensifies to a nearly steady state amplitude of about 45 m/sec. The minimum pressure achieved is almost exactly equal to that predicted by the Carnot cycle theory described above. The second experiment is identical to the first, except that we started at an amplitude of only 2 m/sec. The model storm does not amplify, even after 150 hours have elapsed. Apparently, the model needs a sufficient "kick" to get a hurricane started.

The need for a strong starting disturbance is consistent with the observation that real hurricanes never start spontaneously, unlike linear instabilities, which arise "like a child from the womb, like a ghost from the tomb," as the English poet Shelley once described the formation of clouds. Rather, some preexisting disturbance of independent origin seems to be necessary. The starting disturbance is often provided by large-scale waves that arise from instabilities of the east-to-west flow over sub-Saharan Africa in summer. Most such "easterly waves" run their course, often as far westward as Florida, without developing into tropical storms. Only occasionally does a wave develop into a hurricane. Other starting disturbances arise from waves on cold fronts that sometimes manage to penetrate into the tropics, and from thunderstorm complexes that occasionally drift out over the ocean from middle-latitude continents.

Why do weak disturbances fail to amplify? While in principle we ought to be able to answer this question from the numerical simulations, the fields that result from highly nonlinear computations are often as inscrutable as nature itself. Although this question remains unanswered, a preliminary analysis suggests the following heuristic view. In order for a vortex to spin up, air must move toward the central axis through a layer that is deep enough so that surface friction will not dissipate most of the initial angular momentum. The part of this converging air that lies above the subcloud layer is quite dry, with a specific entropy somewhat less than that of the subcloud layer. As it converges toward the center it must ascend, and because of its low humidity it does not gain heat from condensation as it rises. This leads to cold air near the vortex center, which tends to oppose further uplift. If surface fluxes, which depend on surface wind speed, have not in the meantime saturated the air through the depth of the inflow layer, the vortex will decay. This description should be regarded as tentative until or unless verified by more precise analysis.

The generic hurricane

Despite the current limitations on our understanding of hurricane genesis, knowledge of the dynamics and energetics of mature storms allows us to generalize from the specific example of tropical hurricanes to the possibility of similar phenomena in other climates and in other atmospheres.

One candidate for hurricanes outside the tropics is, ironically, the polar low, a small, intense cyclone that occurs over certain arctic oceans (such as the Norwegian Sea) in the midst of the polar night (see Rasmussen 1983, for an excellent review). These storms arise suddenly and unpredictably, often wreaking havoc on fishing boats and oil platforms. They form when an exceptionally deep mass of cold air flows out over relatively warm open water, creating a large sea-air thermodynamic disequilibrium. Analysis of the energy potential given by (5) shows that moderately strong hurricanes may indeed be maintained under these circumstances. In this case, most of the total entropy difference between ocean and atmosphere results from the large temperature contrast between the two media rather than from the undersaturation of the surface air.

Another possible example of a generic hurricane is the dust devil, a small whirlwind which forms over heated ground on sunny days. Here again a large thermodynamic disequilibrium between the surface and the air exists. The effective heat capacity of the ground is limited, however, since heat is conducted slowly through soil and sand. This, combined with the shallow depth of the convecting boundary layer and its overall unstable stratification, allows only very small disturbances. It is not known whether the dust devil relies on a feedback between the surface winds it generates and heat transfer from the ground, like a hurricane, or whether it is simply a mode of ordinary convection.

The available energy for hurricanes, expressed by (5), may be used to predict the dependence of hurricane intensity (but not frequency) on climate (Emanuel 1987). Over the warmest parts of the oceans, a change in sea-surface temperature of 1°C will change the minimum sustainable pressure in hurricanes by 15 to 20 mb. Thus the colder ocean waters that may have existed during ice ages would have supported somewhat weaker hurricanes, while an increase of a few degrees (as may occur, for example, as a result of the greenhouse warming associated with an increase of atmospheric CO_2) could cause a substantial increase in the severity of hurricanes.

Finally, we may ask whether hurricanes are possible in other planetary or in stellar atmospheres. For a true hurricane, it is necessary to have an interface between a solid or liquid of high heat capacity and effective conductivity and a liquid or gas of much smaller total heat capacity. The rate of heat transfer between the two media must depend on the wind velocity near the interface. The gas or liquid on top must have a convectively adjusted layer near the interface and exist in a state of significant thermodynamic disequilibrium with respect to the other medium.

These conditions appear to rule out the possibility that the Great Red Spot of Jupiter is a hurricane, as it is generally believed that there are no well-defined phase-transition interfaces within the planet, except perhaps very near the core. Sunspots, though they may involve rotating convection, cannot be true hurricanes since here, too, there are no phase interfaces. The great dust storms that occur episodically on Mars have been compared to hurricanes, but it seems unlikely that the effective heat capacity of the Martian surface could be large enough to drive these circulations. A rough survey of the solar system suggests that hurricanes, like the oceans that breed them, are unique to our own planet.

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