quick study

Hurricanes: Tempests in a greenhouse

Kerry Emanuel

Greenhouse gases make Earth's surface hotter than it would be if the planet were simply a blackbody radiator. That additional warming is an important driver of hurricanes.

Kerry Emanuel is a professor of atmospheric sciences at the Massachusetts Institute of Technology in Cambridge, Massachusetts.

The tropics have generally the most benign climates found on Earth, with gentle breezes and small daily and seasonal temperature variations. Why, then, do tropical climates breed the most destructive wind storms known? This brief tutorial explains the paradox and presents an overview of hurricane physics.

The greenhouse effect

Of the solar energy that streams to Earth, about 30% is reflected by clouds or the surface, and an additional small percentage is directly absorbed by atmospheric water—either gaseous or condensed in clouds. The radiation that escapes reflection or absorption in the atmosphere is absorbed by the surface, which transmits energy upward both by radiation and in vast convective currents whose visible manifestations are the beautiful cumulus and cumulonimbus clouds that ply the tropical skyscape. The outgoing photons have much longer wavelengths than the incoming photons, since Earth's surface temperature is far lower than the Sun's. The outgoing IR radiation is strongly absorbed by clouds and by trace amounts of certain gaseous components of the atmosphere, notably water vapor, carbon dioxide, and methane. Those constituents reradiate both upward and downward. Remarkably, the surface receives on average more radiation from the atmosphere and clouds than direct radiation from the Sun. The warming of the surface by back radiation from the atmosphere is the greenhouse effect. Because of it, Earth's surface temperature is some 35 K higher than its effective blackbody temperature. That difference makes hurricanes possible.

The relatively high surface temperature also means that atmospheric radiation exports entropy to space. The reason is that the atmosphere is heated at approximately the surface temperature, but it cools at the much lower effective emission temperature of Earth. In equilibrium, the planet must generate entropy, and the vast majority of that entropy is produced in the atmosphere, mainly through the mixing of the moist air inside clouds with the dry air outside them and through frictional dissipation by falling raindrops and snowflakes. Were it not for moisture in the atmosphere, the entropy would have to be produced by frictional dissipation of the kinetic energy of air molecules. The resulting air motion would be too violent to permit air travel.

Water in the atmosphere thus has a paradoxical effect on climate. It is far and away the most important greenhouse molecule in the atmosphere and is responsible for a surface temperature increase that requires the production of entropy. On the other hand, mixing and irreversible processes associated with precipitation absorb most of the entropy production and spare people from violent winds. But not always.

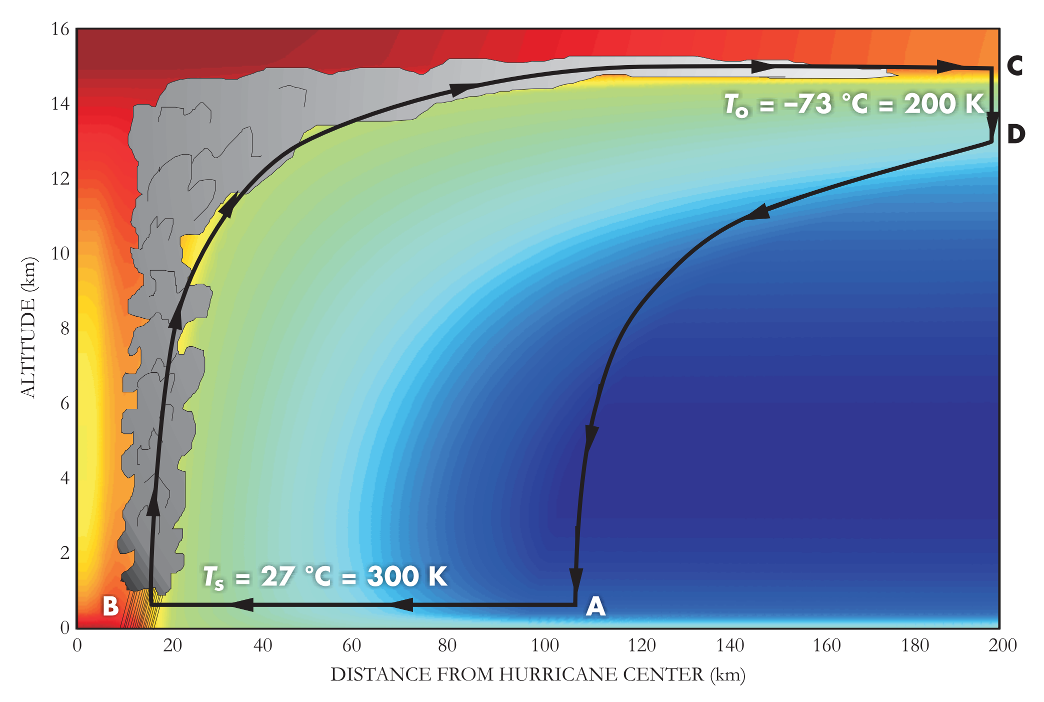
A Carnot engine

In the part of the tropics where the sea surface is warm enough and the projection of Earth's angular velocity vector onto the local vertical axis is large enough, random small-scale convective currents sometimes organize into rotating vortices known as tropical cyclones. In computer models of the tropical atmosphere, such organization can happen spontaneously, but usually only if a combination of ocean temperature and rotation is somewhat higher than those observed in nature. In subcritical conditions, some trigger is necessary to initiate the vortices, and in the terrestrial atmosphere tropical cyclones only develop from preexisting disturbances of independent origin. In mathematical parlance, tropical cyclones may be said to result from a subcritical bifurcation of the radiative–convective equilibrium state. About 10% of them develop in the Atlantic Ocean, where the disturbance is often a 100-km-scale "easterly wave" that forms over sub-Saharan Africa and then moves westward out over the Atlantic. When its maximum wind speed exceeds 32 m/s, it, by definition, becomes a hurricane.

The convective core of a tropical cyclone may be many tens to hundreds of kilometers across, orders of magnitude greater than the few hundred meters' width of an ordinary cumulus cloud. The core's small surface-to-volume ratio, together with the strong stability to horizontal displacement afforded by the inertial stability of its rotation, greatly reduces mixing between cloudy moist air and clear dry air. In a strong tropical cyclone, entropy production by the mixing of dry and moist air is virtually shut down, and dissipation of the wind's kinetic energy takes over as the primary mechanism for producing entropy. Most of the dissipation occurs in a turbulent atmospheric boundary layer within a few hundred meters of the ocean surface.

The mature hurricane is an almost perfect example of a Carnot heat engine whose working fluid may be taken as a mixture of dry air, water vapor, and suspended condensed water, all in thermodynamic equilibrium. The engine is powered by the heat flow that is possible because the tropical ocean and atmosphere are not in thermal equilibrium. This disequilibrium arises because, thanks to the greenhouse effect, the ocean must lose heat by direct, nonradiative transfer to the atmosphere to balance the absorption of solar radiation and back radiation from the atmosphere and clouds. The heat transfer is accomplished mostly by evaporation of water, which has a large heat of vaporization. To maintain substan-

© 2006 American Institute of Physics, S-0031-9228-0608-XXX-X



The hurricane as a Carnot heat engine. This two-dimensional plot of the thermodynamic cycle shows a vertical cross section of the hurricane, whose storm center lies along the left edge. Colors depict the entropy distribution; cooler colors indicate lower entropy. The process mainly responsible for driving the storm is the evaporation of seawater, which transfers energy from sea to air. As a result of that transfer, air spirals inward from A to B and acquires entropy at a constant temperature. It then undergoes an adiabatic expansion from B to C as it ascends within the storm's eyewall. Far from the storm center, symbolically between C and D, it exports IR radiation to space and so loses the entropy it acquired from the sea. The depicted compression is very nearly isothermal. Between D and A the air undergoes an adiabatic compression. Voilà, the four legs of a Carnot cycle.

tial evaporation rates, the air a short distance above the sea surface must be much drier than would be the case were it in equilibrium with the sea.

The figure illustrates the four legs of a hurricane Carnot cycle. From A to B, air undergoes nearly isothermal expansion as it flows toward the lower pressure of the storm center while in contact with the surface of the ocean, a giant heat reservoir. As air spirals in near the surface, conservation of angular momentum causes the air to rotate faster about the storm's axis. Evaporation of seawater transfers energy from the sea to the air and increases the air's entropy.

Once the air reaches the point where the surface wind is strongest—typically 5–100 km from the center of the hurricane—it turns abruptly (point B in the figure) and flows upward within the sloping ring of cumulonimbus cloud known as the eyewall. The ascent is nearly adiabatic. In real storms the air flows out at the top of its trajectory (point C in the figure) and is incorporated into other weather systems; in idealized models one can close the cycle by allowing the heat acquired from the sea surface to be isothermally radiated to space as IR radiation from the storm outflow. Finally, the cycle is completed as air undergoes adiabatic compression from D to A.

The rate of heat transfer from the ocean to the atmosphere varies as vE, where v is the surface wind speed and E quantifies the thermodynamic disequilibrium between the ocean and atmosphere. But there is another source of heat; the dissipation of the kinetic energy of the wind by surface friction. That can be shown to vary as v^3. According to Carnot, the power generation by the hurricane heat engine is given by the rate of heat input multiplied by the thermodynamic efficiency:

If the storm is in a steady condition, then the power generation must equal the dissipation, which is proportional to v^3. Equating dissipation and generation yields an expression for the wind speed:

$$v^2 = \frac{T_s - T_o}{T_o}\,E\,.$$

Here T_s is the ocean temperature and T_o is the temperature of the outflow. Those temperatures and E may be easily estimated from observations of the tropics, and v as given by the above equation is found to provide a good quantitative upper bound on hurricane wind speeds. Several factors, however, prevent most storms from achieving their maximum sustainable wind speed, or "potential intensity." Those include cooling of the sea surface by turbulent mixing that brings cold ocean water up to the surface and entropy consumption by dry air finding its way into the hurricane's core.

The thermodynamic cycle of a hurricane represents only a glimpse of the fascinating physics of hurricanes; more complete expositions are available in the resources given below. The transition of the tropical atmosphere from one with ordinary convective clouds and mixing-dominated entropy production to a system with powerful vortices and dissipation-driven entropy production remains a mysterious and inadequately studied phenomenon. This may be of more than academic interest, as increasing concentrations of greenhouse gases increase the thermodynamic disequilibrium of the tropical ocean–atmosphere system and thereby increase the intensity of hurricanes.

Additional resources

▶ K. Emanuel, *Annu. Rev. Earth Planet Sci.* **31**, 75 (2003).
▶ K. Emanuel, *Divine Wind: The History and Science of Hurricanes*, Oxford U. Press, New York (2005). ■

The online version of this Quick Study provides links to images of hurricanes.