Hurricanes

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09:49)

0.3 Potential intensity

The mechanism of hurricanes has been described as a “heat engine,” which converts heat to the kinetic energy of the strong hurricane winds. The source of heat is the condensation of water evaporated from the ocean, and the sink of energy is mostly dissipation due to friction of hurricane winds with ocean's surface. Using this framework one can estimate the maximum expected wind speed of hurricanes, and how it might change in a warmer climate.

Energy/power dissipation in a hurricane.
The dissipation of energy in a hurricane is largely due to friction between winds and the ocean surface. In general, the work done by a force is equal to the force times the distance over which the force is applied. The energy dissipated by the wind friction force per unit time is therefore the wind friction force times the distance divided by the time it takes the winds to cover that distance, or the friction force times the wind velocity. The friction force per unit area between the winds and the surface is estimated as $C_D\rho V_s^2$, where V_s is the wind speed (m/s), C_D (nondimensional) is an

empirical constant and ρ the air density (kg/m^3). Multiplying by the wind velocity to obtain the energy dissipation per unit area per unit time, we find the dissipation rate to be $D = C_D \rho V_s^3$, and the integral of this quantity over the hurricane area is the total energy dissipation per unit time. A time series of this quantity is referred to as the power dissipation index (PDI). The work done by the hurricane wind friction force on the surface is also a measure of the destructiveness of the hurricane, making the PDI a useful measure of the expected damage caused by hurricanes.

Saturation specific humidity for a warming SST

As a reminder, the saturation specific humidity, $q^*(T,P)$, is the maximum possible mass (kg) of water vapor in one kg of moist air at a temperature T and a pressure P, given by the Clausius-Clapeyron relation (box 2.1). Note that q^* is exponential in the temperature, as shown in Figure 3a. When the temperature is 30°C the saturation specific humidity is 27.5 gr/kg, and a mere one degree warming leads to a very significant 6% increase in the saturation specific humidity. Figure 3b,c show the historical SST in the main development area of hurricanes in the Atlantic, and the predicted SST there according to the RCP8.5 scenario, as well as the expected resulting saturation specific humidity. We next estimate how the anticipated increase in saturation specific humidity for a warmer SST may affect the projected maximum possible hurricane strength.

Energy input into a hurricane

Water evaporated from the ocean surface into a hurricane is transported upward in the hurricane eye wall surrounding its center. The rising air expands at the lower pressures it encounters, cools, and this leads to condensation. The condensation involves the release of latent heat, fueling the hurricane. Ultimately, this heat is drawn from the warm upper ocean which is cooled by the evaporation process, and which is the main source of heat for the hurricane. The evaporation per unit area, per unit time, into the hurricane is calculated as $C_k V_s (q^*(T,P_s) - q_a)$, where V_s is the surface wind speed, T is the surface air temperature (°K) assumed equal to the SST, $q^*(T,P_s)$ the saturation specific humidity at the surface, in units of kg moisture per kg of moist air, q_a the atmospheric surface specific humidity and C_k is a nondimensional empirical "bulk coefficient" for evaporation. This evaporation is equivalent to a heat input of $L\rho C_k V_s (q^*(T,P_s) - q_a)$, where L is the latent heat of evaporation/condensation (J/kg), and ρ the air density (kg/m^3). The fraction ε of this heating converted into kinetic energy of the winds is the "efficiency" in transforming heat to kinetic energy, and is further discussed below. The net input of kinetic energy into the hurricane due to evaporation, per unit time, is, therefore,

$$G = \varepsilon \cdot L \cdot C_k \rho V_s \cdot (q^*(T,P_s) - q_a) = \varepsilon \cdot L \cdot C_k \rho V_s \cdot q^*(T,P_s)(1 - RH),$$

where $RH = q_a / q^*(T,P_s)$ is the atmospheric relative humidity at the surface, and we note that the energy input G is a function of the SST via the dependence of the surface saturation moisture on temperature.

Efficiency of converting heat to wind energy

A four-stage heat engine was imagined by Carnot as a piston filled with gas and attached to a reservoir of heat. By heating and cooling the gas in the piston, it is made to expand and contract, turning the heat input into work done by the piston. As part of this "Carnot cycle" of heating and cooling, heat is provided to the heat engine at a high temperature T_H, some of the heat is converted to kinetic energy and some is lost to the environment at a low temperature T_C, due to the imperfect efficiency of the engine. The maximum possible efficiency can be shown to be $\varepsilon = (T_H - T_C)/T_H$. For Hurricanes, $T_H = SST$ is temperature of the heat source (the ocean surface). T_C is the average temperature at which heat is lost by the hurricane via radiation by air at the top of the storm. The taller a hurricane is, the lower is the temperature T_C at its top and thus, the greater the thermodynamic efficiency. For a typical hurricane, with $SST \approx 30°\text{C} = 303$ K and $T_C \approx 200$ K, we find the maximum expected efficiency to be $\varepsilon \approx 1/3$.

Hurricane as a Carnot cycle

To justify the use of Carnot efficiency to estimate the energy conversion efficiency in a hurricane, consider the flow of air in a hurricane, along the surface toward the center, up in the eye wall near the storm center, outward at the top of the storm and back down toward the surface, as an analogue of the compression and expansion of gas in a piston in a Carnot heat engine. Stage (1) of the Carnot cycle involves isothermal expansion of the gas-filled piston while absorbing heat from the external reservoir, countering the adiabatic cooling that would have occurred due to the expansion. This corresponds in a hurricane to air acquiring heat (in the form of latent heat from surface evaporation) as it flows along the surface around and toward the center of the storm, at a warm surface temperature T_H. Stage (2) is adiabatic expansion of the piston with no heat exchanges with the external reservoir, doing work and cooling. This is analogue in a hurricane to air rising up near the storm center, releasing latent heat and cooling adiabatically. Stage (3) is isothermal compression in which the piston motion compresses the air while releasing heat to an external cold reservoir to counter the adiabatic heating due to compression. In a hurricane, this is analogue to the release of heat by the air in a hurricane via radiation, while flowing out of the convective plumes at the top of the storm, and descending and therefore compressing at a temperature T_C. Stage (4), the final step, is adiabatic compression while heating the air in the piston, which is parallel to air descending back to the surface in a hurricane and adiabatically heating.

Estimating maximum wind speed in a hurricane

Setting dissipation to be equal to the energy input ($D = G$), we find $V_s^2 = \varepsilon L q^*(T,P_s)(1-RH)C_k/C_D$. Assuming the ratio of the two bulk coefficients to be about one,

$$V_s^2 = \frac{SST - T_C}{SST} L\, q^*(T,P_s)\,(1-RH) \tag{1}$$

This is the final expression for the potential intensity (V_s) we have been looking for, representing the squared hurricane wind speed on the left in terms of the important factors: (1) evaporation which depends on the saturation specific humidity and on the surface atmospheric relative humidity; (2) conversion of evaporated water to heat as expressed by the constant L, and (3) the efficiency of conversion of heat to kinetic energy as expressed by the ratio involving the warm and cold temperatures within the hurricane. The hurricane velocity estimated this way is exponential in temperature, because of the Clausius-Clapeyron relationship that affects surface evaporation, the energy source for hurricanes in this picture.

Substituting values for the different constants, and assuming the tropical surface atmosphere to be 85% saturated $RH = q_a/q^*(T,P_s) = 0.85$, we find a reasonable estimate for present-day hurricane wind speed,

$$V_s = \left(\frac{1}{3} \times 2260 \times 10^3 \times 0.15 \times \frac{20}{1000}\right)^{1/2} = 47 \text{ m/s} = 169 \text{ km/hour}.$$

Figure 4 shows the estimated wind speed calculated based on the observed and predicted RCP8.5 SST in the Atlantic main development area. Some small strengthening is already expected due to the warming experienced by the MDR (blue line), and more is anticipated by year 2100 (orange line). Of course, the anticipated increase is subject to a possible modification by the changing shear due to El Niño and other factors.

Notes

1 The image on the chapter title page is of “Dramatic Views of Hurricane Florence from the International Space Station from 9/12,” posted to Flickr by NASA Goddard and licensed under the Creative Commons Attribution 2.0 Generic license, downloaded from wikimedia.

1 Thanks to high school student Jonathan Vardi for preparing observations and model output, and writing several codes that are used in this chapter.

4 For more details on the mechanisms by which vertical shear disrupts hurricanes, see, for example, Frank and Ritchie (2001) and Riemer et al. (2010).

4 The results in Figure 2 are based on the ERA5 reanalysis product of the European Center for Mid-range Weather Forecasting (ECMWF). The relation between wind shear in the North Atlantic MDR during El Niño and La Niña events is analyzed, for example, by Zhu et al. (2012).

5 The derivation of potential intensity follows Kerry Emanuel’s web page, see also Emanuel (1986).

7 El Niño’s irregularity, which limits its predictability, was suggested to be a result of either a nonlinear chaotic behavior driven by the seasonal cycle (Tziperman et al., 1994; Jin et al., 1994), or stochastic-like atmospheric weather forcing (Kleeman and Moore, 1997; Penland and Sardeshmukh, 1995).

8 The efficiency of converting heat to kinetic energy is different, of course, from that of an ideal Carnot engine, see Bister et al. (2011).

11 The strengthening of hurricanes frequently occurs when a particular upper-level potential vorticity disturbance interacts with a low-level developing hurricane, see for example Montgomery and Farrell (1993). This is an example of the more general concept of rapid storm development via what’s known as “transient amplification” (Farrell, 1988; Farrell and Ioannou, 1996).

11 The analysis of the correlation between PDI and SST in the main development area in the North Atlantic during the hurricane season, shown in Figure 5, follows Emanuel (2005). The data used here to calculate the PDI are from the AOML/NOAA HURDAT2 dataset, https://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html.

13 The analysis in Figure 6 follows Kossin et al. (2020), and the data are from the supplementary information to that paper. Thanks to high school student Veer Gadodia for doing the analysis and helping to prepare the plot.

13 The concept of error type I and type II has been used in the context of observed and predicted hurricane strength by Knutson et al. (2020, 2019).

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