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- Rainpower and ocean-derived power that fuels a hurricane are comparable
- Rainpower lessens maximum hurricane intensity by 10–30%

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- Supporting Information S1

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Effect of rainpower on hurricane intensity

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Abstract Rain pours in a hurricane at a rate of some 2 km^3/d, the equivalent of river Ganges cascading from the sky. The "rainpower," or energy per unit time that is lost to friction as rain falls through a hurricane, has not been quantified, and its effect on hurricane intensity remains unknown. Here we use satellite data to show that the rainpower is on the same order of magnitude as the ocean-derived power that fuels the hurricane. By coupling the satellite data to a suitably modified version of the Carnot-heat-engine model of hurricanes, we estimate that rainpower lessens hurricane intensity by 20% on average, bringing the predicted intensities of North Atlantic hurricanes into a much improved accord with a 30 year record of observations. Our findings have implications for weather and climate change forecasting.

1. Introduction

The most inert part of a hurricane, the cylindrical "eye" (radius ≈ 50 km), is walled in by the most active, the tubular "eyewall." The eyewall is thin (thickness ≈15 km) and roughly 50 times less voluminous than the entire hurricane (radius ≈ 300 km). And yet nowhere in a hurricane do wind and rain clash more intensively than within the narrow confines of the eyewall, and the eyewall may be regarded as the dynamical heart of a hurricane.

Upward through the eyewall flows the updraft, a hurricane's vertical wind, carrying heat and water vapor from the base of the eyewall (at sea level) to the upper reaches of the eyewall (up to 20 km above sea level). The updraft feeds on an ocean surface-hugging, inward spiraling wind. Even as this inward spiraling wind closes around the base of the eyewall, where it bends upward and turns into the updraft, it attains a mean velocity that is the highest mean velocity anywhere in the hurricane and serves as the conventional measure of hurricane intensity. Thus, hurricane intensity is a characteristic wind velocity closely linked to the eyewall.

Also closely linked to the eyewall are the most profuse rains in a hurricane. Colossal quantities of ocean-derived water vapor are blown upward by the updraft, only to condense high in the eyewall and fall back onto the updraft as torrential rains. Thus, rain and wind are intertwined within the eyewall, and rain is likely to affect hurricane intensity. Nevertheless, the ways in which rain and other phenomena might affect hurricane intensity are poorly known [*Wang and Wu*, 2004; *Kepert*, 2010], and improving intensity prediction has remained a long-standing challenge in hurricane forecasting [*Rappaport et al.*, 2012].

It has been argued that rain might affect hurricane intensity via the latent heat [see, e.g., *Rodgers et al.*, 1994]. As water vapor condenses to rain within the updraft of an eyewall, latent heat is released which helps propel the updraft, which in turn increases the supply of water vapor and so forth. Thus, according to this argument, rain increases hurricane intensity via the latent heat.

Here we argue that rain may also affect hurricane intensity via the rainpower, or the energy per unit time that is lost to friction as rain falls through a hurricane. Before we can ascertain the effect of rainpower on hurricane intensity, we must quantify the rainpower.

2. Rainpower in Hurricanes

Consider a rainy atmosphere. The weight of the raindrops is in balance with the frictional drag of the air, and the power lost to friction per unit volume of rainy atmosphere, primarily in the form of turbulent kinetic energy in the wakes of the raindrops [*McDonald*, 1954; *Lorenz and Rennó*, 2002], can be computed as $\rho g R$ [*Pauluis et al.*, 2000]. Here ρ is the raindrop density, g is the gravitational acceleration, and R is the rain rate—the familiar "millimeters per hour" of weather forecasts but measured in a frame of reference fixed to the air.

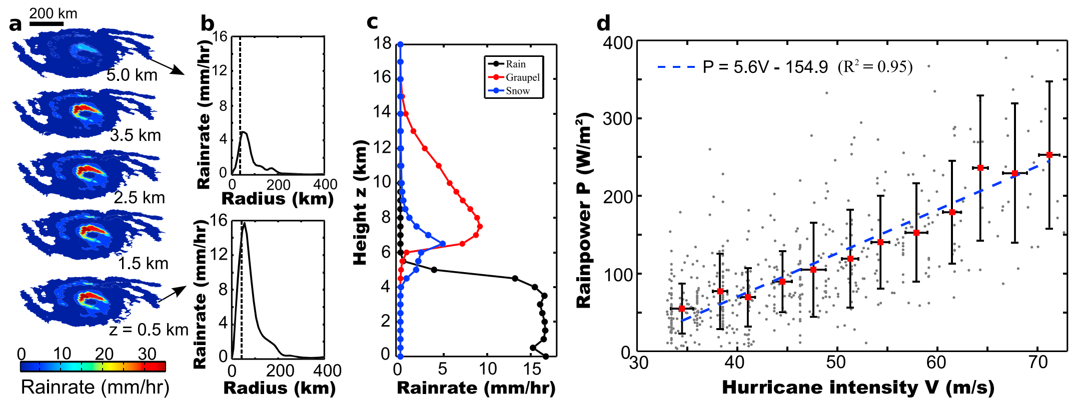

Figure 1. Analysis of the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager satellite data (see supporting information). (a) Typical areal distributions of rain rate at various heights z above the ocean (Hurricane Gordon, 13 September 2006). (b) Typical radial profiles of rain rate computed by azimuthal averaging of the corresponding areal distributions. The rain rate peaks in the eyewall (marked by a dotted line). (c) Typical vertical profile of eyewall rain rate, $R_w(z)$. Although in the text we refer only to rain, precipitation occurs also in the form of graupel and snow, and TRMM satellite data include vertical profiles of eyewall rain rate for each form of precipitation, as shown here. (d) Rainpower P versus hurricane intensity V. Each dot represents a data point (V, P). To every hurricane in the North Atlantic Basin, 1997–2013, there correspond several data points sampled over the entire lifetime of the hurricane. Values of P are computed from the satellite data by using equation (1) with three additive terms: one for rain (ρ = 1000 kg/m^3), one for graupel (ρ = 600 kg/m^3), and one for snow (ρ = 100 kg/m^3). Values of V are obtained from the National Hurricane Center's extended best track database [*Demuth et al.*, 2006]. A cross represents the average of the data points (V, P) contained in one of the bins in a set of bins of equal width δV; the bar of the cross spans two standard deviations of V, and the post two standard deviations of P. The dashed line is a parameterization of P as a linear function of V, obtained by a linear regression fit.

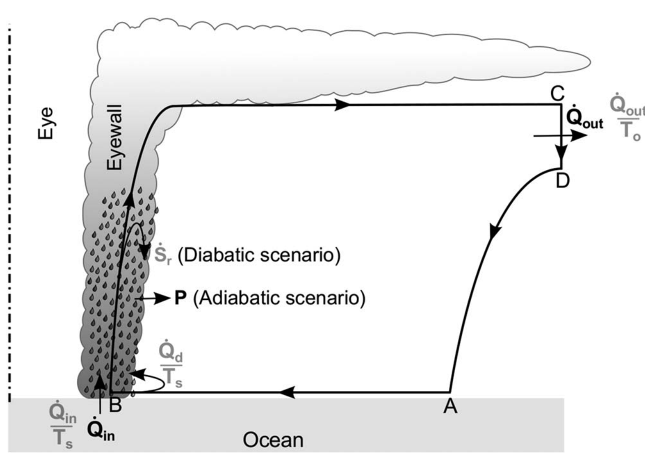

Figure 2. A hurricane as a heat engine. The working fluid consists of dry air and water vapor. We show the sources and sinks for energy using darker font and the sources and sinks for entropy using lighter font. The ocean-derived power, $\dot{Q}_{\text{in}}$, is the engine's heat source, which is at the temperature of the ocean, T_s; the heating from frictional dissipation of turbulent winds at the ocean surface, $\dot{Q}_d$, is not an external source of energy but, rather, an internal source of entropy [*Bister et al.*, 2010] (isothermal expansion in segment A→B). Note that $\dot{Q}_{\text{in}}$ and $\dot{Q}_d$ are concentrated at the base of the eyewall [*Emanuel*, 2003]. In the adiabatic scenario, a parcel of working fluid travels pseudo-adiabatically to the top of the hurricane, and some water vapor condenses in the form of rain (pseudo-adiabatic expansion in segment B→C). The conversion of latent heat into sensible heat (attendant on condensation) does not change the total entropy of the working fluid [*Emanuel*, 2003]; the pseudo-adiabatic assumption accounts for the loss of mass in the form of rain. There follows a nearly isothermal compression in which power $\dot{Q}_{\text{out}}$ is radiated to outer space at the temperature T_o, where $T_o < T_s$ (segment C→D). The cycle is closed [*Emanuel*, 2003] by adiabatic compression back to the surface of the ocean (segment D→A). The cycle remains unchanged for the diabatic scenario—except for segment B→C, where the rainpower, after conversion to heat, acts as an internal source of entropy.

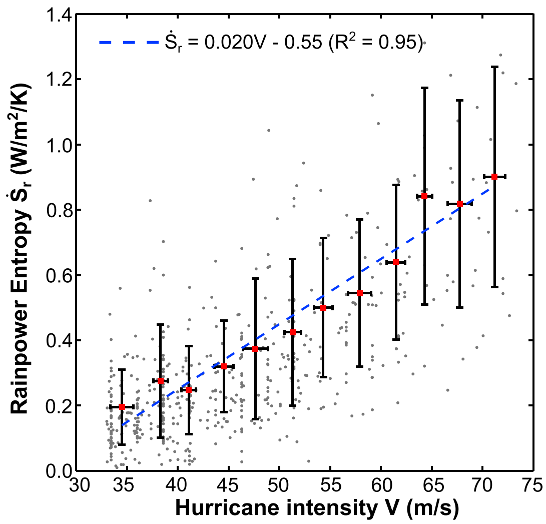

Figure 3. The entropic contribution from rainpower $\dot{S}_r$ versus hurricane intensity V. Each dot represents a data point (V, $\dot{S}_r$). To every hurricane in the North Atlantic Basin, 1997–2013, there correspond several data points sampled over the entire lifetime of the hurricane. Values of $\dot{S}_r$ are computed from the satellite data by using the relation, $\dot{S}_r = \rho g \int_0^H \frac{R_w}{T_e} \mathrm{d}z$, with three additive terms: one for rain, one for graupel, and one for snow. For the vertical profile of the temperature in the eyewall, $T_e(z)$, we use $T_e(z) = T_s - 6.5z$, where z is measured in kilometers [*Vergados et al.*, 2014]. Values of V are obtained from the National Hurricane Center's extended best track database [*Demuth et al.*, 2006]. A cross represents the average of the data points contained in one of the bins in a set of bins of equal width δV; the bar of the cross spans two standard deviations of V and the post two standard deviations of $\dot{S}_r$. The dashed line is a parameterization of $\dot{S}_r$ as a linear function of V, obtained by linear regression fit.

Now we turn to the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager satellite data (Figure 1). From Figures 1a and 1b we verify that in a hurricane, at any given height above the ocean, z, the rain rate peaks in the eyewall, to which we restrict our attention. A typical vertical profile of the eyewall rain rate, $R_w(z)$, is shown in Figure 1c. The rainpower (or power lost to friction per unit area of eyewall in plan view), P, can be computed by integrating $\rho g R_w(z)$ from the base of the eyewall, $z = 0$, to the upper reaches of the eyewall, $z = H$ [*Pauluis and Dias*, 2012]:

$$P = \rho g \int_0^H R_w(z) \mathrm{d}z. \tag{1}$$

For every hurricane in the North Atlantic Basin, 1997–2013, we compute P and plot it against the attendant hurricane intensity, V. The plot of P versus V is shown in Figure 1d.

Let us compare P to the ocean-derived power (sensible heat + latent heat) that fuels a hurricane, $\dot{Q}_{\mathrm{in}}$. The first estimates of $\dot{Q}_{\mathrm{in}}$ for $V > 50$ m/s have been recently extracted from field data [*Bell et al.*, 2012]. For $V = 52$ m/s (a category 3 hurricane), for example, $\dot{Q}_{\mathrm{in}} \approx 750$ W/m^2. From Figure 1d, the corresponding $P \approx 120$W/m^2. The rainpower is on the same order of magnitude as the ocean-derived power that fuels a hurricane.

From the positive correlation between P and V evinced in Figure 1d, it is tempting to argue that the effect of rainpower is to increase hurricane intensity. And yet positive correlation might not signify causality nor can the effect of P on V be understood in isolation from other aspects of a hurricane's thermodynamics, to which we now turn.

3. Thermodynamics of Rainpower

Emanuel's Carnot-heat-engine model of hurricanes [*Bister and Emanuel*, 1998; *Emanuel*, 2003] is based on the notion that, thermodynamically, a hurricane is a gigantic heat engine [*Riehl*, 1950]. Given a suitable set of climatological and oceanic data (consisting of mean sea level pressure, vertical profiles of air temperature and humidity, and sea surface temperature), the model can be used to estimate the maximum intensity over the lifetime of a hurricane. Although the model is predicated on numerous simplifying assumptions [see, e.g., *Bryan and Rotunno*, 2009; *Kepert*, 2010], it provides a lucid framework in which to assess the effect of various factors on hurricane intensity and has been widely employed to that end.

To include rainpower in Emanuel's model, we consider two contrasting scenarios (Figure 2). In the adiabatic scenario, the turbulent wakes of the raindrops do not decay to heat within the eyewall. (In this case, the rainpower leaves the heat engine as output work.) In the diabatic scenario, the turbulent wakes of the raindrops decay to heat within the eyewall and contribute locally to the production of entropy. (In this case, the rainpower feeds back into the heat engine.) To each scenario, there corresponds a specific form of the equation of energy balance and a specific form of the equation of entropy balance, as we discuss next.

In the adiabatic scenario, the equation of entropy balance [*Bister et al.*, 2010] reads

$$\frac{\dot{Q}_{\mathrm{in}}}{T_s} + \frac{\dot{Q}_d}{T_s} = \frac{\dot{Q}_{\mathrm{out}}}{T_o}. \tag{2}$$

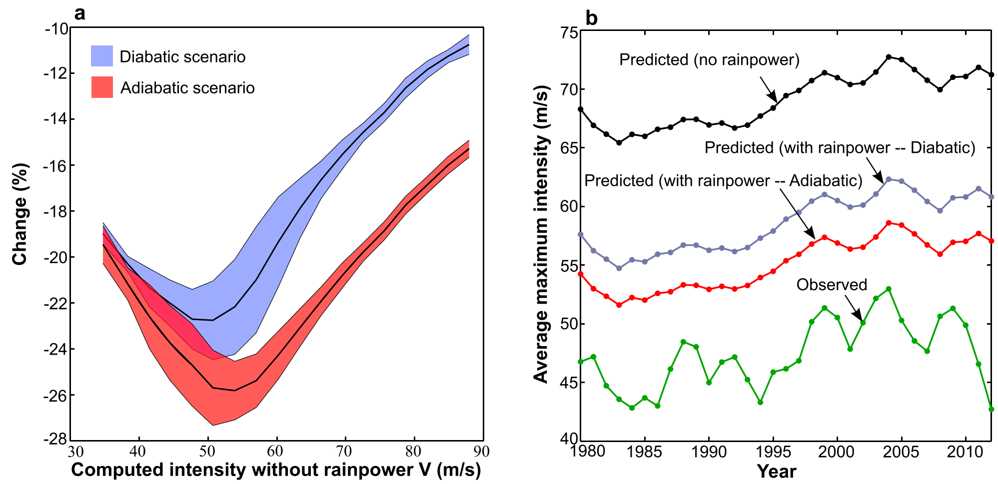

Figure 4. Effect of rainpower on hurricane intensity. (a) Change in intensity due to rainpower versus intensity without rainpower. Individual data points (not shown) are computed by using the model with rainpower (for both scenarios, adiabatic and diabatic) and the model without rainpower (see text), from individual sets of climatological and oceanic data (monthly averages at each grid point in the MDR of the North Atlantic Basin (10–20°N, 20–80°W), months of August to October (the peak hurricane season), 1979–2013). The width of the colored band spans two standard deviations of the percent change in V. (b) Average Maximum Intensity (AMI) of hurricanes in the North Atlantic Basin, 1979–2013. The observed AMIs are computed from the National Hurricane Center's best track database (HURDAT). The predicted AMIs are computed by using the model with rainpower (for both scenarios, adiabatic and diabatic) and the model without rainpower, from monthly climatological and oceanic data in the MDR of the North Atlantic Basin, averaged over the peak hurricane season. The raw time series are filtered using a three-point smoothing window to exclude high-frequency temporal fluctuations. Note that in computing the intensity with rainpower (Figures 4a and 4b), we assume that the parameterizations of Figures 1d and 3, which are based on rain data for 1997–2013, can be used for 1979–2013. This assumption has but a minor effect on the results in Figure 4a (see Figure S1 in the supporting information); as for Figure 4b, this assumption can only affect the results before 1997.

If $\dot{Q}_{in}$, $\dot{Q}_d$, and $\dot{Q}_{out}$ are parameterized as functions of V, equation (2) may be solved for V. For $\dot{Q}_{in}$ and for $\dot{Q}_d$, we use the standard parameterizations of Emanuel's model [*Emanuel*, 2003], namely, $\dot{Q}_{in} = \rho_a C_K V(k^* - k)$ and $\dot{Q}_d = C_D \rho_a V^3$, where C_K and C_D are dimensionless transfer coefficients for enthalpy and momentum, respectively, ρ_a is the density of air, k is the actual enthalpy of the boundary layer, and k^* is the saturation enthalpy of air at the ocean surface. As for $\dot{Q}_{out}$, we turn to the energy balance, $\dot{Q}_{in} - \dot{Q}_{out} = P$ and use our own parameterization for P (Figure 1d).

In the diabatic scenario, the equation of entropy balance reads

$$\frac{\dot{Q}_{in}}{T_s} + \frac{\dot{Q}_d}{T_s} + \dot{S}_r = \frac{\dot{Q}_{out}}{T_o}, \tag{3}$$

where $\dot{S}_r$ is the entropic contribution from the rainpower, $\dot{S}_r = \rho g \int_0^H \frac{R_w}{T_e} dz$, where $T_e(z)$ is the vertical profile of the temperature in the eyewall. As before, if $\dot{Q}_{in}$, $\dot{Q}_d$, $\dot{S}_r$, and $\dot{Q}_{out}$ are parameterized as functions of V, equation (3) may be solved for V. For $\dot{Q}_{in}$ and for $\dot{Q}_d$ we use the standard parameterizations; for $\dot{S}_r$, we use our own parameterization (Figure 3). As for $\dot{Q}_{out}$, we turn to the energy balance, $\dot{Q}_{in} - \dot{Q}_{out} = 0$.

We solve the equations using a modified version of Emanuel's code (see supporting information). The transfer coefficients are $C_D = 0.002$ [*Donelan et al.*, 2004] and $C_k = 0.0016$ (which correspond to $C_k/C_D = 0.8$ [*Emanuel*, 1995]). To account for the effect of friction on surface winds, we reduce the computed intensity by 20%, as suggested by *Emanuel* [2000].

4. Effect of Rainpower

To quantify, via the modified Carnot-heat-engine model, the effect of rainpower on hurricane intensity, we have compiled numerous sets of climatological and oceanic data from the Main Development Region (MDR) of the North Atlantic Basin, 1979–2013. For each set of climatological and oceanic data, we compute two hurricane intensities, V and V', using the model without rainpower and the model with rainpower, respectively.

(In actuality, we compute two values of V': one for the adiabatic scenario and the other for the diabatic scenario.) In Figure 4a we plot the percent change in intensity versus the intensity (i.e., $100 \times (V' - V)/V$ versus V). The effect of rainpower varies with intensity and is more prominent at intermediate intensities, regardless of scenario (adiabatic or diabatic); on the whole, it amounts to a 10–30% reduction in intensity.

Varying climate sustains hurricanes of varying intensities. To study the influence of climate on hurricane intensity, we focus on the Average Maximum Intensity (AMI) of hurricanes in the North Atlantic Basin. We define AMI as the average of the maximum lifetime intensities attained by all hurricanes during the peak hurricane season in a given year. For the period 1979–2013, we compute a time series of observed AMIs, a time series of predicted AMIs (model without rainpower) and two time series of predicted AMIs (model with rainpower, both for adiabatic scenario and for diabatic scenario). The effect of rainpower is to shift the magnitude of the predicted AMIs substantially closer to the observations (Figure 4b).

5. Conclusions

In conclusion, although the rainpower is roughly proportional to hurricane intensity (as we have shown in Figure 1d), the effect of rainpower is not to increase but to lessen hurricane intensity. This apparent paradox has a simple explanation: the effect of rainpower cannot be ascertained from Figure 1d, which is based on satellite data of actual hurricanes, wherein the turbulent processes associated with rainpower are always active. Rather, the effect of rainpower must be computed using a hurricane model in which the rainpower may be switched on or off—allowed or not allowed to alter the thermodynamic economy of the hurricane. Here we have used modified versions of the Carnot-heat-engine model of hurricanes and have found that the effect of rainpower is to lessen hurricane intensity—by an average of 20% as per our estimation.

The conclusion that rainpower lessens hurricane intensity is in accord with recent findings on the overall dynamics of the atmosphere [*Pauluis and Dias*, 2012]. It is also in accord with a notable characteristic of the Carnot-heat-engine model, namely, that hurricane intensities computed using this model correspond to "potential intensities," which are interpreted as theoretical upper bounds on the maximum intensities registered over the lifetime of actual hurricanes. In fact, the observed maximum intensity of a hurricane is typically well below the computed potential intensity, for given climatological and oceanic conditions [*Emanuel*, 2000; *Wang and Wu*, 2004]. Modified versions of the model have recently been used to ascertain the lessening of potential intensity due to two factors not included in the model: vertical wind shear [*Tang and Emanuel*, 2012] and ocean cooling [*Lin et al.*, 2013]. Our work reveals the importance of rainpower, another factor not included in the model. A unified theory of potential intensity that accounts for these and other factors may yield realistic predictions of hurricane intensities and provide valuable guidance in weather and climate change forecasting, hazard prevention, and policy making.

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