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Interactive comment on "On the validity of representing hurricanes as Carnot heat engine" *by* A. M. Makarieva et al.

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Abstract. It is argued, on the basis of detailed critique of published literature, that the existing thermodynamic theory of hurricanes, where it is assumed that the hurricane power is formed due to heat input from the ocean, is not physically consistent, as it comes in conflict with the laws of thermodynamics. It is proposed that intense wind structures like hurricanes and tornadoes can form at the expense of release of potential energy previously accumulated in the atmosphere in the form of partial pressure of water vapor. It is estimated that the local drop of air pressure that arises during condensation of water vapor and its disappearance from the gas phase is large enough to generate velocities up to the maximum of 10^2 $\mathrm{m\,s^{-1}}$ observed in spatially and temporally compact circulation events like hurricanes and tornadoes. On a larger spatial

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scale the same physical effect is shown to produce a stationary circulation pattern with horizontal wind velocities in the order of several $\mathrm{m\,s^{-1}}$.

1. Introduction

Wind velocities in hurricanes and tornadoes reach 30-120 $\mathrm{m\,s^{-1}}$ (Businger and Businger, 2001). The question of how solar energy absorbed by the planetary surface is ultimately transformed into kinetic energy of air masses has long puzzled scientists (Lorenz, 1967). Regarding hurricanes, that admittedly remain a geophysical enigma, it was proposed that the ultimate source of their dynamic power might be heat input from the ocean (Emanuel, 1991, 2003, 2006) and that the hurricane represents a Carnot thermodynamic engine. Briefly, according to the Bernoulli's equation, acceleration of air masses under adiabatic conditions leads to their cooling. If the acceleration occurs along the isothermic oceanic surface, and no drop of air temperature is observed, this means that there is a heat input from the ocean. This heat input is thought to be partly transformed into the kinetic energy of air masses and partly lost to space (heat sink) via radiation of the greenhouse components of the upper atmosphere, the latter being colder than the oceanic surface.

Here we analyze several fundamental physical aspects of this approach. First, in thermodynamic engines the value of heat input is set externally and quantitatively determines all processes within the engine. In the process of isothermal acceleration of air masses over the oceanic surface the value of presumed oceanic heat input is related to wind velocity. In order that wind velocity could be numerically predicted (the main target of hurricane's theory) from the value of heat input, the latter should be determined independently. However, independent physical determinants of oceanic heat input are lacking. We argue that the two existing attempts to overcome this limitation either involved an incorrect integration of Bernoulli's equation (Emanuel, 1991) or based on the dissipative heat engine concept (Emanuel, 2003), the latter to be shown below to violate the second law of thermodynamics.

Second, the power of latent heat release per unit planetary surface within the hurricane area exceeds the power of absorbed solar radiation by many times. Since the power of thermal radiation into space is, via radiative equilibrium, linked to the temperature of the upper atmosphere, in order to release that power into space via thermal radiation one would need atmospheric temperatures greatly exceeding the global mean surface temperature (+15 °C) and the effective temperature of the planet (-18 °C). This would imply heat transfer from a cooler object (oceanic surface) to a warmer object (the radiating upper atmosphere), which is impossible. This means that there is no atmospheric heat sink to space in the hurricane area that would be necessary for the existence of Carnot cycle.

Finally, the assumption that high wind speeds in hurricanes are due to the heat input from the ocean leaves one to seek for different physical mechanisms allowing for the even higher wind speeds observed in tornadoes that develop over the land surface. Could not these high-speed wind structures have a single physical cause? We explore these and related issues and provide a theoretical perspective of quantitatively accounting for hurricanes and tornadoes as adiabatic dynamic processes driven by phase transitions from gas to liquid (water vapor condensation) in the atmosphere. We show that partial pressure of atmospheric water vapor represents a store of potential energy, which can be converted to the kinetic energy of dynamic air motions when water vapor disappears from the gas phase during condensation. The magnitude of the resulting wind velocity depends on the horizontal dimension of the circulation pattern to be formed, with maximum velocities reached in compact events like hurricanes and tornadoes. Large-scale circulation is characterized by lower velocities due to the greater cumulative impact of surface friction forces.

2. The equations of Carnot cycle

We start with a brief consideration of a reversible thermodynamic cycle that involves phase transitions of water vapor. For one mol of substance, the first law of thermodynamics then reads as $dQ = pdv + c_v dT + Ld\gamma$, where dQ is heat increment, p is air pressure, v is molar volume, c_v is molar heat capacity of air at constant volume, T is

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absolute temperature, $\gamma \equiv p_{H_2O}/p$ is the relative partial pressure of saturated water vapor, L is molar energy of vaporization. The last term in this equation, $Ld\gamma$, describes the energy that is spent on evaporation at $d\gamma > 0$ or released during condensation of water vapor at $d\gamma < 0$ in the atmospheric air. Since under realistic conditions $\gamma \ll 1$, the heat capacity of liquid water is neglected.

The cycle consists of two isotherms ($dT = 0$) at $T = T_s$ and $T = T_0$ and two adiabates ($dQ = 0$). Integrating the above equation for all the four processes, we obtain:

$$1, isoth.\, a{-}c: \quad \int_a^c dQ \equiv \quad \Delta Q_s = A_1 + L\Delta_1\gamma; \tag{1}$$

$$2, adiab.\, c{-}o: \quad \int_c^o dQ = \quad 0 = A_2 + c_v(T_0 - T_s) - L\Delta_2\gamma; \tag{2}$$

$$3, isoth.\, o{-}o': \quad \int_o^{o'} dQ \equiv \quad -\Delta Q_0 = -A_3 - L\Delta_3\gamma; \tag{3}$$

$$4, adiab.\, o'{-}a: \quad \int_{o'}^a dQ = \quad 0 = -A_4 + c_v(T_s - T_0) + L\Delta_4\gamma. \tag{4}$$

Here spatial points a, c, o and o' correspond to those in Fig. 1 of Emanuel (1991). All terms in Eqs. (1-4) are defined to be positive. Along the first (warmer) isotherm at $T = T_s$ the air receives heat ΔQ_s, expands and performs work $A_1 \equiv \int_a^c pdv > 0$, some water vapor evaporates, $L\Delta_1\gamma \equiv \int_a^c Ld\gamma = L(\gamma_c - \gamma_a) > 0$. Then the air expands adiabatically and performs work $A_2 \equiv \int_c^o pdv > 0$; as the air cools, water vapor condenses; this is indicated by the minus sign at $L\Delta_2\gamma \equiv \int_o^c Ld\gamma = L(\gamma_c - \gamma_o) > 0$. Air loses heat $\Delta Q_0 > 0$ (hence the minus sign at this term) and compresses along the second (colder) isotherm at $T = T_0 < T_s$; here work is exerted on the air and water vapor condenses, as indicated by the minus signs at $A_3 \equiv \int_{o'}^o pdv > 0$ and $L\Delta_3\gamma \equiv \int_{o'}^o Ld\gamma = L(\gamma_o - \gamma_{o'}) > 0$. Finally, the air compresses adiabatically and warms; work is again exerted on the air, while water evaporates, hence the minus and plus signs at $A_4 \equiv \int_a^{o'} pdv > 0$ and $L\Delta_4\gamma \equiv \int_{o'}^a Ld\gamma = L(\gamma_a - \gamma_{o'}) > 0$, respectively.

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Note that $\oint L d\gamma = L(\Delta_1\gamma - \Delta_2\gamma - \Delta_3\gamma + \Delta_4\gamma) = 0$, i.e., all energy that is released in the reversible moist thermodynamic cycle during condensation is spent on evaporation within the cycle.

For the cumulative work $A \equiv \oint p dv$ performed by the heat engine working on the basis of such a cycle we have from Eqs. (1-4):

$$A \equiv \oint p dv = A_1 + A_2 - A_3 - A_4 = \oint dQ = \Delta Q_s - \Delta Q_0. \quad (5)$$

Summing Eq. (2) and Eq. (4) we have

$$A_2 - A_4 = L(\Delta_2\gamma - \Delta_4\gamma). \quad (6)$$

Differentiating the ideal gas equation $pv = RT$ (here R is the universal gas constant) for the isotherms $dT = 0$ we have $pdv = -vdp$. This allows one to calculate work A (5) by integrating A_1 and A_3 and using Eq. (6):

$$A = RT_s \ln \frac{p_a}{p_c} - RT_0 \ln \frac{p_{o'}}{p_o} + L(\Delta_2\gamma - \Delta_4\gamma). \quad (7)$$

Here low indices at p refer to air pressure in the corresponding points. The efficiency of the cycle $\varepsilon \equiv A/\Delta Q_s$ is calculated from the same equations as work A.

In the simple case of the "dry" Carnot cycle ($\gamma = 0$) the dry adiabate equation relates pressures p_1 and p_2 as $p_1/p_2 = (T_1/T_2)^{c_p/R}$, $c_p = c_v + R$. Since $T_o/T_c = T_{o'}/T_a = T_0/T_s$, we have $p_o/p_c = p_{o'}/p_a$ and, using Eqs. (1-4), most transparently arrive at the well-known result for Carnot efficiency:

$$A = R(T_s - T_0) \ln \frac{p_a}{p_c}, \ \Delta Q_s = RT_s \ln \frac{p_a}{p_c}, \ \varepsilon = \frac{T_s - T_0}{T_s}. \quad (8)$$

The four equations, Eqs. (1-4), contain eight parameters, p_c, p_a, T_s, T_0, p_o, $p_{o'}$, ΔQ_s, and ΔQ_0. Hence, in order to completely solve the problem and to determine work A and efficiency ε, four out of the eight parameters must be preset.

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In Eqs. (1-4) $\gamma \equiv p_{\mathrm{H_2O}}/p$ is understood as relative partial pressure of saturated water vapor; γ is thus a function of temperature and air pressure; relative humidity is equal to unity everywhere in the cycle. The cycle is reversible. If one relaxes this condition, allows relative humidity to take arbitrary values in some points of the cycle, then, in order to solve the problem, one will additionally need to specify γ (now understood as relative partial pressure of unsaturated water vapor) in all such points. For example, if one sets relative humidity to be less than unity in the beginning of the cycle at point a (and leaves it equal to unity in points c, o, o') then, in order to know pressure p_c in the hurricane center c from the consideration of Eqs. (1-4) one will have to specify p_a, T_s, T_0, γ_a *and* any of these: p_o, $p_{o'}$, ΔQ_s or ΔQ_0. (Note that the cycle is not reversible in this case, because evaporation at relative humidity less than unity is an irreversible process.)

3. Specific critique

3.1 Incorrect integration of Bernoulli's equation by Emanuel (1991)

The work of Emanuel (1991) on the theory of hurricanes summarizes much of the previous work; it represents the hurricane as Carnot heat engine. The main result consists in the statement that partial pressure p_c in the hurricane center can be calculated from the known values of p_a, T_s, T_0 and γ_a (see p. 185 of Emanuel (1991), where γ is notated as q and measured in mass rather than pressure units, $q = (M_v/M)\gamma$, where M_v is molar mass of water vapor, M is air molar mass). As we have seen, such a result cannot be obtained from the consideration of the thermodynamic cycle of Eqs. (1-4), which necessitates five rather than four parameters to be preset to find p_c. For example, knowing ΔQ_s in addition to the four parameters listed by Emanuel (1991) would be sufficient.

In order to overcome this limitation, Emanuel (1991) invoked Bernoulli's equation as an additional, fifth equation to the system:

$$d\left(\frac{1}{2}|\boldsymbol{V}|^2\right) + d(gz) + \alpha dp + \boldsymbol{F}\, d\boldsymbol{l} = 0, \quad (9)$$

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where $\boldsymbol{V}$ is velocity vector, g is acceleration of gravity, z is height, $\boldsymbol{F}$ is turbulent friction forces, $\boldsymbol{l}$ is streamline vector, $\alpha \equiv 1/\rho$, p is air pressure, ρ is air mass density.

The following logic was applied: in the stationary case work A generated within the cycle undergoes dissipation and is equal to work of turbulent friction forces $\oint \boldsymbol{F}\,d\boldsymbol{l}$. Work of turbulent friction forces is considered practically negligible on all parts of the trajectory of air masses except for the warmer isotherm $a-c$, i.e. $A = \oint dQ = \oint \boldsymbol{F}\,d\boldsymbol{l} \approx \int_a^c \boldsymbol{F}\,d\boldsymbol{l}$. In order to calculate the last term, Bernoulli's equation was integrated in the following form, see Eq. (15) of Emanuel (1991):

$$A \approx \int_a^c \boldsymbol{F}\,d\boldsymbol{l} = -\int_a^c \alpha dp = R_d T_s \ln\frac{p_a}{p_c}. \tag{10}$$

(Note that this formula is written per unit air mass with $R_d = R/M_d$, where $R = 8.3\ \mathrm{J\,mol^{-1}\,K^{-1}}$ is the universal gas constant. To express A per air mol, as in Eqs. (1-4), R_d should be replaced by R.)

One can see that the velocity term, see the first term in Eq. (9), was ignored by Emanuel (1991) when integrating Bernoulli's equation along the horizontal streamline. In the meantime, this term, $\int_a^c d(|\boldsymbol{V}|^2)/2 = V_c^2 - V_a^2$, makes a major contribution to the considered integral. (In the work of Emanuel (1991, legend to Fig. 1) it is stated that "air begins spiraling in toward the storm center at point a" and then that "...assuming that V is zero at the beginning of the cycle" (Emanuel, 1991, p. 185). Hence, we have $V_a = 0$ and $V_c^2 - V_a^2 = V_c^2$. Eq. (10) is true for $V_c = 0$. In the meantime, Bernoulli's equation is only valid *along the streamline*. Hurricane wind speed reaches its maximum near the hurricane wall, where air starts to spiral in the upward direction. Therefore, the ultimate point along the horizontal streamline $a-c$ where Bernoulli's equation is still valid is located in the vicinity of the point of maximum wind speeds, $V_c = V_{max} \neq 0$. Given these to be of the order of 60 $\mathrm{m\,s^{-1}}$ for comparable $\Delta p = 50$ mbar (see, e.g., Holland (1980, Fig. 5b)) we have $V_c^2 - V_a^2 = V_c^2 = 3600\ \mathrm{m^2\,s^{-2}}$ and $\alpha\Delta p = \Delta p/\rho = 4200\ \mathrm{m^2\,s^{-2}}$. Thus, the term neglected by Emanuel (1991) is of the same order of magnitude as the terms that were retained.)

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The formula for work $A = \oint dQ = \oint T ds = \varepsilon T_s \Delta s$, Eq. (10), that resulted from the incorrect integration of Bernoulli's equation, is incorrect. As discussed above, the correct formula is that of Eq. (7). A helpful observation is that in the "dry" limit ($\gamma \to 0$) the correct formula for work of the "moist" engine, Eq. 7, should tend to Eq. (8) for the work of "dry" engine. Formula (16) of Emanuel (1991) (equivalent to Eq. (10) does not depend on γ altogether; in the dry limit, it overestimates the real work given by Eq. (8) by three times given the characteristic values of $T_s = 300$ K and $T_0 = 200$ K.

The error can be identified at the logical level. Bernoulli's equation contains two additional variables, velocity V and friction force F. By invoking an additional equation for stationarity, $A = \oint dQ = \oint \mathbf{F} d\mathbf{l}$, as done by Emanuel (1991), one gets six equations (Eqs. (1-4), Bernoulli's equation and the stationarity equation) for eleven independent variables, p_c, p_a, T_0, T_s, q_a (γ_a), p_o, $p_{o'}$, ΔQ_s, ΔQ_0, V, F. It is clear that it is necessary to preset *five* parameters to solve the problem. Contrary to the main result of Emanuel (1991), it is impossible to calculate pressure p_c in the hurricane center by presetting only *four* parameters, namely p_a, T_s, T_0 and q_a (γ_a).

3.2 Invoking the dissipative heat engine concept results in the conflict with the second law of thermodynamics

In later works, starting from the work of Bister and Emanuel (1998) and summarized by Emanuel (2003), a different attempt is made to overcome the problem of the incufficient number of equations to determine p_c using the Carnot cycle formalism. The stationarity equation is now written in the following form without involving the unknown magnitude of friction forces F :

$$A = \varepsilon(\Delta Q_s + A). \tag{11}$$

This equation constitutes the basis of the theoretical concept of the dissipative heat engine described by Rennó and Ingersoll (1996) and discussed by Emanuel and Bister (1996), Pauluis et al. (2000), Rennó (2001), Pauluis and Held (2002). In this engine heat ΔQ_A that originates from dissipation of mechanical work A, $\Delta Q_A = A$, is added to the Carnot cycle at the highest temperature $T = T_s$ and recycled within the engine.

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In this engine the modified heat input thus becomes $\Delta Q_{in} = \Delta Q_s + \Delta Q_A = \Delta Q_s + A$. In the result, the efficiency of this cycle rises above Carnot efficiency and, at $T_0 \to 0$, becomes potentially infinite. Indeed, from Eq. (11) we have $A = [\varepsilon/(1-\varepsilon)]\Delta Q_s = [(T_s - T_0)/T_0]\Delta Q_s$, where $\varepsilon = (T_s - T_0)/T_s$ is the Carnot efficiency. The dissipative heat engine has one more remarkable property, namely that the the amount of heat disposed to heat sink at $T = T_0$, which is given by $\Delta Q_{out} = (1-\varepsilon)\Delta Q_{in} = (1-\varepsilon)(\Delta Q_s + A) = \Delta Q_s$, coincides with the amount of heat received from the heat source at $T = T_s$.

We thus have an engine that does not receive any net energy input from the environment, but recirculates dissipated heat to work and back within itself at a potentially infinite rate. Work produced by heat engines can be converted to potential energy of chemical or gravitational nature, or it can be transformed into practically non-dissipating kinetic energy like, for example, the kinetic energy of satellites rotating around the Earth, and stored in those forms. It is possible to recirculate between any two forms of ordered energy, for example, a ball jumping on the elastic surface "recirculates" potential energy to kinetic energy and back (Sherman, 2008). But, as is well-known, the second law of thermodynamics prohibits recirculation of dissipated heat. Additionally, the fundamental Carnot efficiency is, as is equally well-known, the maximum possible efficiency any heat engine can reach.

Conflicting with these fundamental principles, the dissipative heat engine is equivalent to a perpetual motion machine of the second kind. In the dissipative heat engine the mechanical energy of the atmosphere dissipates to heat and is added to Carnot cycle at $T = T_s$, i.e., at the warmer isotherm. For simplicity consider the classical "dry" Carnot cycle ($\gamma = 0$). At the warmer isotherm $T = T_s$ of the Carnot cycle *all heat* ΔQ_{in} introduced to the cycle is converted to mechanical work A_1, $\Delta Q_{in} = \int_a^c p dv \equiv A_1$, see Eq. (1). For the dissipative heat engine this means that $A_1 = \Delta Q_{in} = \Delta Q_s + \Delta Q_A = \Delta Q_s + A$. In other words, some part of work A_1 originates from external heat ΔQ_s, while another part of A_1 represents work that originated from heat ΔQ_A, which, in its turn, came as the product of dissipation of work A at the same temperature. That is,

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work A dissipates to heat and is regenerated back to an equal amount of work (as part of A_1) at one and the same temperature T_s!

Such recycling of dissipated energy is an inherent feature of a perpetual motion machine of the second kind, the one prohibited by the second law of thermodynamics. Indeed, in order to dissipate work A isothermally at $T = T_s$ to heat $\Delta Q_A = A$, the heat produced should be removed from the environment during dissipation (otherwise the environment would warm) to a colder medium with $T_1 < T_s$. The removed heat should be afterwards gained back to the environment to be converted to work. However, this would imply heat transport from the colder to the warmer object, which is physically impossible. (The same logic applies to the "moist" Carnot cycle: since evaporation of water vapor occurs at the expense of thermal energy of molecules of liquid water, heat ΔQ_A originating from dissipation of work A in the atmosphere should be first transferred to the ocean. This is impossible, since in this case the ocean should have been colder than the atmosphere and would have been unable to serve as the heat source of the cycle delivering heat input ΔQ_s to the atmosphere.)

It is noteworthy that in none of the aforementioned publications where the dissipative heat engine was discussed, the processes and equations of Carnot cycle, Eqs. (1-4), were explicitly considered. This might be one of possible reasons for why a concept equivalent to the perpetual motion machine of the second kind has persisted unexposed in the literature, see, e.g., Emanuel (2006), for quite a while.

Turning specifically to the hurricane framework, formula (6) of Emanuel (2003)

$$P = \frac{T_s - T_0}{T_s}\left(2\pi \int_a^c C_k \rho |V| (k_0^* - k) r dr + D\right),$$

where $D = 2\pi \int_a^c C_D \rho |V|^3 r dr$ is "the net dissipation energy" ("the vertically integrated dissipative heating"), see formula (7) and text on p. 84 of Emanuel (2003), as well as the resulting expression for the maximum hurricane wind speed $V_{\max}$,

$$|V_{\max}|^2 \approx \frac{C_k}{C_D} \frac{T_s - T_0}{T_0} (k_0^* - k),$$

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where Carnot efficiency $\varepsilon = \frac{T_s - T_0}{T_s}$ is replaced by $\frac{T_s - T_0}{T_0}$ and which, starting from the work of Bister and Emanuel (1998), is present in works of Emanuel (1999), Emanuel (2003), Emanuel (2005), Emanuel (2006), are incorrect. As explained above, these formulae originate from a concept equivalent to perpetual motion machine of the second kind. (In the notations of Emanuel (2003) $2\pi \int_a^c C_k \rho |V| (k_0^* - k) r dr = \Delta Q_s / t_c$ and $2\pi \int_a^c C_D \rho |V|^3 r dr = D = P = A/t_c$, see formula 6 of Emanuel (2003). Here t_c is time period of one cycle, i.e. Emanuel (2003) considers cycle power rather than energy.)

On the basis of Eq. (11), the stationary hurricane velocity was found from the condition that the turbulence term, assumed to be equal to dissipative heating, grows with velocity in a different manner than does heat input (Emanuel, 2003, p. 85): "Comparing Equation 4 with Equation 5 shows that the dissipation increases as the cube of the wind speed, whereas the heat transfer increases only as the first power of the wind speed, so that eventually the dissipation matches energy production and the storm achieves a quasi-steady state." In reality, we emphasize, if freed from the above inconsistencies, a correct consideration of Carnot cycle does not allow one to know both heat input and pressure difference (from which velocity can be calculated). Heat input must be found from independent physical considerations that do not exist.

3.3 Quantifying heat loss to space

The problems outlined above pertain to the theoretical treatment of the Carnot cycle irrespective of its (in)applicability to the description of hurricanes. There is an additional quantitative consideration that specifically shows that the high-intensity wind structures as hurricanes cannot represent a Carnot cycle with heat input from the ocean and heat loss to space.

The Carnot maximum efficiency formula is only valid for reversible cycles. The reversability of the moist thermodynamic cycle, Eqs. (1-4), implies that moisture that condenses during the moist adiabatic ascent $c - o$ and during the isothermal compression $o - o'$ remains within the air parcel to evaporate back during its adiabatic descent and warming. (Only in this case water vapor will be close to saturation in all phases of

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the cycle. Evaporation at relative humidity less than unity is an irreversible process.) This could only be the case if the flux F_P of removal of the condensed moisture from the atmosphere by rain would either be absent or negligibly small compared to the flux F_{LH} of latent heat release during the adiabatic ascent, which, per unit air volume per cycle, is approximately given by $L\Delta_2\gamma$ in Eq. (2).

Per unit surface area per unit time, the vertical flux of latent heat released in the ascending air masses within the hurricane can be estimated as $F_{LH} = w\Delta\rho_v L$, where $\Delta\rho_v$ is change of water vapor mass density over the height of hurricane circulation h_h, w is the average velocity of the moist adiabatic ascent. Exponential scale height of water vapor distribution being $h_{\mathrm{H_2O}} \sim 2$ km $\ll h_h$, we have $\Delta\rho_v \sim \rho_v$ (i.e. practically all ascending water vapor undergoes condensation). Taking into account that $L = 2.4$ kJ g^{-1}, taking $\rho_v \sim 30$ g m^{-3} at $T_s \sim 300$ K and characteristic vertical velocity of $w \sim 0.06$ m s^{-1} (Emanuel, 1991) we obtain $F_{LH} \sim 4 \times 10^3$ W m^{-2}.

The data of Trenberth and Fasullo (2007) for hurricane Katrina (2005) describe precipitation rates r averaged over the hurricane radius of 400 km, i.e. over the entire spatial scale of the order of 10^3 km occupied by the hurricane. Precipitation rates r depend on wind velocity and range from 2.5 to 5.5 mm hr^{-1}. Miller (1964) reported precipitation rate of about 5 mm hr^{-1} for hurricane Donna (1960). This allows the minimum estimate of latent heat flux F_P corresponding to precipitated moisture as $F_P = r\rho_l L_v = 1.7 \times 10^3$ W m^{-2}, where $\rho_l = 5.6 \times 10^4$ mol m^{-3} is molar density of liquid water, $L \approx 44$ kJ mol^{-1} is the molar heat of vaporization, 1 mm hr^{-1} $= 2.8 \times 10^{-7}$ m s^{-1}.

One can see that the available estimates of F_{LH} and F_P coincide in their order of magnitude illustrating the nearly obvious fact that the major part of moisture condensed within the hurricane is removed from the atmosphere via precipitation.

This important fact has a two-sided implication for the view of hurricanes as a thermodynamic cycle. First, since the air volumes ascending within the hurricane area reach the upper cold atmosphere practically totally depleted of (condensed and precipitated) moisture, the descent of these air volumes can only occur along a dry adiabate, not

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along a moist adiabate, as the irreversibility of the cycle, Eqs. (1-4), prescribes. In such a case relative humidity of the descending air parcels at the sea surface would have been close to zero. This strongly contradicts the observations (relative humidity at the sea surface is around 80%, i.e., close to unity), which indicates that there is a strong admixture of moist air (and, hence, latent heat) into the descending air parcels. This means that there is a very significant import of latent energy (in the order of 10^3 W m^{-2}) from the external environment to the hurricane and that hurricane is not therefore a thermodynamically closed system (cycle). It exchanges not only mass, but also latent energy with the external environment. The statement that "there is little thermodynamic contribution" from the descending leg of the hurricane (Emanuel, 1991), is not supported by the available evidence.

Second, assuming the temperature of the upper radiative layer to be $T_0 = 200$ K (Emanuel, 1991) we have $F_{out} = \sigma_B T_0^4 = 90$ W m^{-2} for the outgoing flux of thermal radiation to space in the hurricane area, $\sigma_B = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is Boltzmann's constant. This is at least 19 times smaller a flux than the flux of latent heat irreversibly released within the hurricane area. In order to radiate this flux to space, the upper atmosphere should have had a temperature of about $T_0 \sim 400$ K. In this case the heat sink would have been warmer than the heat source (the ocean), which is impossible.

Trenberth and Fasullo (2007) remark that Carnot cycle of the hurricane is approximate, as "some of this energy is transported out of the subtropics to higher latitudes before it is radiated to space." The above estimates show that not some, but over 95% (18/19) of energy released within the hurricane is transported away from the hurricane without any interaction with the presumed "heat sink" of the upper atmosphere. As discussed above, the hurricane is open not only in terms of exported energy, but also in terms of imported energy delivered to the hurricane in the form of water vapor. This complete energetic openness indicates that hurricane is not a thermodynamic cycle and not a cycle at all. Instead, as will be argued below, the hurricane represents an essentially non-equilibrium and non-stationary release of potential energy that was previously accumulated in the atmosphere in the form of water vapor.

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References

Bister, M. and Emanuel, K. A.: Dissipative heating and hurricane intensity. Meteorol. Atmos. Phys., 65, 233-240, 1998.

Bolton, D.: The computation of equivalent potential temperature, Mon. Wea. Rev., 108, 1046-1053, 1980.

Businger, S. and Businger, J. A.: Viscous dissipation of turbulence kinetic energy in storms, J. Atmos. Sci., 58, 3793-3796, 2001.

Eastin, M. D., Gray, W. M. and Black, P. G.: Buoyancy of convective vertical motions in the inner core of intense hurricanes. Part I: General statistics, Mon. Weather Rev., 133, 188-208, 2005.

Emanuel, K. A.: An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance, J. Atmos. Sci., 43, 585-604, 1986.

Emanuel, K. A.: The theory of hurricanes, Annu. Rev. Fluid Mech., 23, 179-196, 1991.

Emanuel, K. A.: Thermodynamic control of hurricane intensity, Nature, 401, 665-669, 1999.

Emanuel, K. A.: Tropical cyclones, Annu. Rev. Earth Planet. Sci., 31, 75-104, 2003.

Emanuel, K. A.: Divine wind: The history and science of hurricanes, Oxford University Press, New York, 2005.

Emanuel, K. A.: Hurricanes: Tempests in a greenhouse, Phys. Today, 59, 74-75, 2006.

Emanuel, K. A. and Bister, M.: Moist convective velocity and buyoancy scales, J. Atmos. Sci., 53, 3276-3285, 1996.

Gustavson, M. R.: Limits to wind power utilization, Science, 204, 13-17, 1979.

Hatzianastassiou, N., Matsoukas, C., Fotiadi, A., Pavlakis, K.G., Drakakis, E., Hatzidimitriou, D. and Vardavas, I.: Global distribution of Earth's surface shortwave radiation budget, Atmos. Chem. Phys., 5, 2847-2867, 2005.

Held, I. M. and Soden, B. J.: Water vapor feedback and global warming, Annu. Rev. Energy Environ., 25, 441-475, 2000.

Holland, G. J.: An analytic model of the wind and pressure profiles in hurricanes, Mon. Wea. Rev., 108, 1212-1218, 1980.

Lorenz, E. N.: The nature and theory of the general circulation of the atmosphere, World Meteorological Organization, Geneva, 1967.

Makarieva, A. M., Gorshkov, V. G. and Li, B.-L.: Conservation of water cycle on land via restoration of natural closed-canopy forests: Implications for regional landscape planning, Ecol. Res. 21, 897-906, 2006.

ACPD

8, S11260–S11274, 2009

Interactive Comment

Makarieva, A. M. and Gorshkov, V. G.: Biotic pump of atmospheric moisture as driver of the hydrological cycle on land, Hydrol. Earth Syst. Sci. 11, 1013-1033, 2007.

Makarieva, A. M., Gorshkov, V. G. and Li, B.-L.: Interactive comment on "On the validity of representing hurricanes as Carnot heat engine" by A. M. Makarieva et al., Atmos. Chem. Phys. Discuss., 8, S83408211;S8345, 2008.

Miller, B. I.: A study of the filling of hurricane Donna (1960) over land, Mon. Wea. Rev., 92, 389-406, 1964.

Nobre, P.: Interactive comment on "On the validity of representing hurricanes as Carnot heat engine" by A. M. Makarieva et al., Atmos. Chem. Phys. Discuss., 8, S8669-S8670, 2008.

Pauluis, O., Balaji, V. and Held, I. M.: Frictional dissipation in a precipitating atmosphere, J. Atmos. Sci., 57, 989-994, 2000.

Pauluis, O. and Held, I. M.: Entropy budget of an atmosphere in radiative8211;convective equilibrium. Part I: Maximum work and frictional dissipation, J. Atmos. Sci., 59, 125-139.

Rennó, N. O. and Ingersoll, A. P.: Natural convection as a heat engine: A theory for CAPE, J. Atmos. Sci., 53, 572-585, 1996.

Rennó, N. O.: Comments on "Frictional dissipation in a precipitating atmosphere", J. Atmos. Sci., 58, 1173-1177, 2001.

Samsury, C. E. and Zipser, E. J.: Secondary wind maxima in hurricanes: Airflow and relationships to rainbands, Mon. Weather Rev., 123, 3502-3517, 1995.

Sherman, S. G.: Interactive comment on "On the validity of representing hurricanes as Carnot heat engine" by A. M. Makarieva et al., Atmos. Chem. Phys. Discuss., 8, S8953-S8954, 2008.

Trenberth, K. E. and Fasullo, J.: Water and energy budgets of hurricanes and implications for climate change, J. Geophys. Res., 112, D23107, 2007.

Wurman, J., Straka, J. M. and Rasmussen, E. N.: Fine-scale Doppler radar observations of tornadoes, Science, 272, 1774-1777, 1996.

Zrnić, D. and Istok, M.: Wind speeds in two tornadic storms and a tornado, deduced from Doppler spectra, J. Appl. Meteorol. 19, 1405-1415, 1980.

Interactive comment on Atmos. Chem. Phys. Discuss., 8, 17423, 2008.