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Atmospheric Chemistry and Physics Discussions

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

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In this comment we would like to dwell once again on the issue of heat release to space. In the DP (p. S17433) we stated that the latent heat flux released within the hurricane cannot be radiated to space by the atmosphere with surface temperature $T_s = 300$ K and radiative temperature $T_0 = 200$ K. This means that the hurricane is not a Carnot cycle, because in Carnot cycle all heat received from the heat source at $T = T_s > T_0$ must be given away to the heat sink at $T = T_0$.

In the DP (p. S17433) we estimated the flux of released latent heat using the value of vertical air velocity equal to 10 cm s^{-1}. Referee 1 in his first comment (S7915, hereafter RC1) objected this criticism by noting that the authors' "argument is based on the fact that the latent heat flux in the eyewall of a hurricanes is up to 20 times larger than the radiation emitted atmospheric temperature. This argument is based on the assumption

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that the area where heating and cooling occurs are the same. However, in the case of a hurricane, the regions of high surface energy flux is concentrated near the eyewall (20-50km), which is much smaller than the overall extent of the upper level circulation (500-1000km). The surface energy flux can be fully compensated by radiative cooling as long as the outer radius of the storm is 5 times larger than the radius of the eyewall."

In our third response to Referee 1 (S8193) we noted that the issue of heat release to space and related issues "need to have been solved quantitatively and consistently by the model's author while building the model" and that the brief calculations suggested by Referee 1 are insufficient to solve the problem. Nevertheless, the same objection was later echoed by Dr. Meesters (S8916): "However, this argument has been refuted correctly by Referee 1 (S7915, "energy loss to space"): the radiation to space comes from a cirrus cap which has a far greater horizontal extension than the region where condensation heat is released, so the cloud cap can yield sufficient radiation in spite of its low temperature." Dr. Meesters found "no time to look at the hurricane literature" (Meesters S9060); his statement was not accompanied by numerical estimates altogether.

Here we will show that latent heat release over the overall extent of upper level circulation (500-1000 km) exceeds by more than one order of magnitude heat release to space from the same area and, hence, contrary to the statement of Referee 1, cannot be compensated by radiative cooling.

Assuming the temperature of the upper radiative layer to be $T_0 = 200$ K we have $F_{out} = \sigma_B T_0^4 = 90$ W m^{-2} for the outgoing flux of thermal radiation in the hurricane area.

In the first Authors Comment (S7325, hereafter AC1) we estimated the flux of released latent heat $I = 3.4 \times 10^3$ W m^{-2} using the estimate of precipitation rate $r = 5$ mm hr^{-1} based on the data of Miller (1964, Mon. Wea. Rev., 92: 389) for hurricane Donna (1960), $I = r\rho_l L_v = 3.4 \times 10^3$ W m^{-2}, where $\rho_l = 5.6 \times 10^4$ mol m^{-3} is molar density

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of liquid water, $L_v \approx 44 \times 10^3$ J mol^{-1} is the molar heat of vaporization. The data of Trenberth and Fasullo (2007, J Geophys Res 112: D23107) for hurricane Katrina (2005) describe precipitation rates ***averaged over the hurricane radius of 400 km***, i.e. precisely along the "overall extent of the upper level circulation (500-1000 km)" specified by Referee 1 (RC1). Precipitation rates r depend on wind velocity and range from 2.5 to 5.5 mm hr^{-1}, see Fig. 2 in Trenberth and Fasullo (2007). This means that ***average flux of latent heat release within the entire hurricane area*** is greater than $I = 1.7 \times 10^3$ W m^{-2}, or at least 19 times larger than the flux of thermal radiation into space $F_{out} = 90$ W m^{-2}.

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. Notably, the hurricane is open not only in terms of exported energy, but also in terms of imported energy which is delivered to the hurricane in the form of water vapor (see AC1, p. S7333). This complete energetic openness shows once again that hurricane is not a thermodynamic cycle and not a cycle at all. Instead, as appreciated by Dr. Nobre (S8669), hurricane represents an essentially non-equilibrium and non-stationary release of potential energy ("as in compressed spring") that was previously accumulated in the atmosphere in the form of water vapor.

The above estimates ***have never been attempted within the criticized framework*** that depicts hurricanes as Carnot cycle. Moreover, the processes of Carnot cycle itself, in particular, the two adiabates along one of which most latent heat is released, have never been considered in quantiative terms either. The reader is referred to Authors Comment (S7325) where an explicit treatment of a moist thermodynamic cycle is given and all relevant fluxes of heat are quantitatively estimated.

Since the outgoing flux of heat to space is negligible compared to heat released within

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the hurricane, $\Delta Q_0 \ll \Delta Q_s$, all statements in the DP starting from the last line on p. S17428 and ending with the last line on p. S17429 are correct, as $\Delta Q_0 \ll \Delta Q_s$ implies $\varepsilon \sim 1$ for Carnot efficiency. This refutes the objections pertaining to this section that were put forward by Referee 1 (RC1, p. S7917) and Referee 3 (S8627). However, as we noted earlier in our comments, we are not going to include this part of the DP into the revised paper, because it is a relatively minor issue compared to the others (dissipative heat engine equivalent to perpetual motion machine and the incorrect central formula for mechanical work of the Carnot cycle in the criticized framework) and because we were advised by Referee 2 (S9081) to shorten the critique in the maintext.

The remarkable data of Trenberth and Fasullo (2007) (Fig. 2) also describe latent heat flux from the surface, which appears to range from approximately 200 W m^{-2} to 900 W m^{-2} within the 400 km radius. In the meantime, as noted above, the flux of ***released*** latent heat (estimated from precipitation rates) ranges from 1.5 to over 3×10^3 W m^{-2}. This difference indicates that the impact of the ocean (reflected in the surface latent heat flux) is very minor compared to the energy fluxes within the hurricane. The discrepancy between the two fluxes can be explained accepting, in accordance with the physical approach advanced in the DP, that the major contribution to hurricane's power comes ***not from the ocean*** but from water vapor ***locally accumulated in the atmospheric column prior to hurricane formation***.

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