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Interactive Comment

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

Anonymous Referee #1

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Review of **On the validity of representing hurricanes as Carnot heat engine** by A. M. Makarieva, V. G. Gorshkov, and B.-L. Li.

The authors offer a critic of the potential intensity theory for hurricanes developed by Kerry Emanuel. The original derivation of this theory by Emanuel (1986) is based on analyzing the structure of a balanced vortex forced by surface energy fluxes. The results of this theory have been often reinterpreted in terms of a classic Carnot cycle (Emanuel 1986, 1988, 2003). While the authors criticize the Emanuel theory for making several fundamental mistakes, I find their criticisms to be mostly based on incorrect interpretations of Emanuel's work.

Dissipative heat engine

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Different versions of the Emanuel theory have been presented over time, under slightly different assumptions. One should be aware of a key difference on versions based on a reversible heat engine framework (Emanuel 1986, 1988, 1991), where the hurricane is viewed as exerting work on its environment', and those based on a dissipative heat engine framework (Bister and Emanuel 1998, Emanuel 2003), where the hurricane generates kinetic energy that is then dissipated internally.

As a dissipative heat engine does not perform any work on its environment, the first law of thermodynamics can be written as:

$$\Delta Q_s - \Delta Q_0 = 0, \tag{1}$$

with ΔQ_s the external energy source at the surface and ΔQ_0 the energy removed at top of the atmosphere. The action A is here the work performed and dissipated internally, and measure in terms of the total dissipation of kinetic energy. As frictional dissipation is an irreversible process, it corresponds to a net entropy production, given by $\frac{A}{T_A}$, where T_A is the temperature at which dissipation occurs. The second law of thermodynamics applied to the cycle can be written as:

$$\frac{\Delta Q_s}{T_s} - \frac{\Delta Q_0}{T_0} + \frac{A}{T_A} = 0. \tag{2}$$

The first two terms on the left-hand side are the entropy change due to the external energy sources, the third term is the entropy production due to frictional dissipation. The sum of these three terms must cancel out as the initial and final states are identical.

Combining the first and second law of thermodynamics yields

$$A = \frac{(T_s - T_0)T_A}{T_s T_0} Q_s. \tag{3}$$

In the hurricane model of **?**, the dissipation occurs at the surface, i.e. $T_A = T_s$, so that the work is indeed given by equation (MGL4).

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MGL argus that the expression for the work in a dissipative heat engine (MGL4) is inconsistent with their version of the first law (equation MGL1). However, they fail to notice that (MGL1) is the implementation of the first law for a reversible heat engine that exerts works on its environment. For a dissipative heat engine, no work is exerted on the outside world, and the first law of thermodynamics should be written as equation (1) above. This issue has been previously discussed in Rennó and Ingersoll(1996), Emanuel and Bister (1996), and Pauluis and Held (2002).

Energy loss to space

In section 3.4, the authors argue that the atmosphere cannot be cooled sufficiently fast to support a hurricane as described by the Emanuel framework. Their 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 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.

Cooling and heating rates themselves are irrelevant to the Carnot cycle. Only the total heating and cooling integrated along the trajectory are taken into considerations. The fact that the cooling occurs over a larger area or longer period of time than the heating has no impact on the thermodynamic cycle.

Efficiency in the Emanuel framework

Section 3.1 argues that the Emanuel framework is thermodynamically inconsistent. However, their arguments is based on the authors' assumption that the efficiency of the cycle is $\epsilon = 1$. This assumption is itself in contradiction with the Emanuel theory, which implies $\epsilon \approx 0.25..0.5$. The authors claim to justify this in section 3.4, but as

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indicated above, the argument is incorrect: the discussion of section 3.1 is based on faulty assumptions.

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