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Interactive comment on "Quantifying the global atmospheric power budget" *by* A. M. Makarieva et al.

A. M. Makarieva et al.

ammakarieva@gmail.com

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We thank our referees for their excellent comments and apologize for the delay in addressing them. The first two authors had been in a field trip completely disconnected from the electronic world from April 24th (at which time no comments were yet available) until yesterday. We have just asked the Editor to re-open and if possible extend the discussion for one month giving the referees an opportunity to react to our replies if needed. We aim to respond to all the comments within the nearest days.

Before addressing the specific comments of the referees, below is an addition to Section 1 that is to replace the second paragraph on p. 2 in the revised manuscript. We believe that it sets the scene for our study more specifically and provides a unified perspective on several key propositions of the referees.

"Our motivation here is to clarify what is meant by *atmospheric power* and how we can assess it from observations in a moist atmosphere. We found that the available literature provides no clear answer. One approach to define atmospheric power is to consider the rate at which the kinetic energy of winds dissipates to heat. This can be done by assessing the friction term in the equations of motion. In a steady state the rate at which kinetic energy dissipates should be equal to the rate at which it is generated. Then *atmospheric power* can be defined as the *rate at which new kinetic energy must be produced to offset the dissipative effects of friction* (Lorenz, 1967, p. 97).

Following Lorenz (1967, Eq. 102), the atmospheric power (W m^{-2}) in a steady state should be defined as

$$W_I \equiv -\frac{1}{\mathcal{S}}\int_{\mathcal{M}} \mathbf{v}\cdot\nabla p \alpha d\mathcal{M} = -\frac{1}{\mathcal{S}}\int_{\mathcal{V}} \mathbf{v}\cdot\nabla p d\mathcal{V}, \quad (1)$$

Here p is air pressure, $\mathbf{v}$ is air velocity, $\alpha \equiv 1/\rho$, ρ is air density, $\mathcal{S}$, $\mathcal{M}$ and $\mathcal{V}$ are, respectively, Earth's surface area, total mass and total volume of the atmosphere, $d\mathcal{M} = \rho d\mathcal{V}$. Laliberté et al. (2015) termed W_I atmospheric *work output*. Sometimes atmospheric power is also referred to as *global wind power* (e.g., Marvel et al., 2013) or *kinetic energy dissipation* (Boville and Bretherton, 2003).

Lorenz (1967, Eq. 102) proposed an additional formulation for kinetic energy production, which was adopted by many researchers:

$$W_{II} \equiv -\frac{1}{\mathcal{S}}\int_{\mathcal{V}} \mathbf{u}\cdot\nabla p d\mathcal{V}, \quad (2)$$

where $\mathbf{u}$ is horizontal velocity of air. For a recent use of this formulation, see, e.g., Huang and McElroy (2015) and references therein. According to Lorenz (1967), $W_I = W_{II}$.

On the other hand, it is possible to formulate atmospheric power from a thermodynamic viewpoint as work per unit time, while work in the atmosphere is performed by the air

parcels that change their volume. With this reasoning according to Pauluis and Held (2002, Eq. 4) the atmospheric power should be defined as

$$W_{III} \equiv \frac{1}{\mathcal{S}} \int_{\mathcal{V}} p \nabla \cdot \mathbf{v} d\mathcal{V}. \tag{3}$$

Pauluis and Held (2002) referred to W_{III} as to *mechanical work* (per unit time).

Meanwhile, according to Vallis (2006, Eq. 1.65), work done per unit mass is $pd\alpha$. Then total work performed by the atmosphere per unit time is[1]

$$W_{IV} \equiv \frac{1}{\mathcal{S}} \int_{\mathcal{M}} p \frac{d\alpha}{dt} d\mathcal{M}. \tag{4}$$

Here

$$\frac{dX}{dt} \equiv \frac{\partial X}{\partial t} + \mathbf{v} \cdot \nabla X \tag{5}$$

is the material derivative of the considered property X.

As we discuss below, for a dry hydrostatic atmosphere obeying the continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = \dot{\rho} \tag{6}$$

with $\dot{\rho} = 0$, all four definitions of atmospheric power are equal, $W_I = W_{II} = W_{III} = W_{IV}$. In an atmosphere with a water cycle, the source term $\dot{\rho}$ is not zero[2]. Here gas (water vapor) is created by evaporation and destroyed by condensation with a local rate $\dot{\rho} \neq 0$ (kg m^{-3} s^{-1}). As we will show, in this case each of the four candidate expressions W_I, W_{II}, W_{III} and W_{IV} are distinct.

[1]Definition (4) for atmospheric power was endorsed by two referees of this work, see doi 10.5194/acp-2016-203-RC2 and 10.5194/acp-2016-203-RC4.

[2]Referee 1 rightfully pointed out that using the dot for the source term is potentially confusing, since in some texts the dot indicates partial derivative over time. We have however retained this dotted notation for the sources to ensure consistency in notations with the study of Laliberté et al. (2015) which we examine in detail.

To our knowledge, these distinctions have not been previously highlighted and examined. Which definition, if any, represents the "true power" of a moist atmosphere and is consistent with the thermodynamic interpretation of work? We show that confusion between definitions results in inconsistencies and errors in estimating atmospheric power and contributes to misunderstandings of the atmospheric power budget.

In Section 2 we explore how the derivation of an expression for global atmospheric power is affected by phase transitions etc."

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