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Interactive comment

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

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Here we address concerns of Referee 2 about the need to consider two bodies for a consistent definition of work. The referee commented as follows: *"In physics, work is defined by force times length, with force being an interaction between TWO objects. Similarly, in thermodynamics, power implicitly involves TWO objects: an engine and an end-user that "dissipates the mechanical energy" and it is easy to define power through the forces acting between these TWO objects. The situation is obviously less clear when considering only ONE object. ... In any case, this is a choice. I strongly disagree with the author's point of view that "power" is a quantity defined a priori from the equations of the fluid. Power can only be defined as the mechanical energetic output of a "power system". Obviously, concerning the atmosphere, the "power system"*

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Discussion paper

is only an abstract part of the atmosphere, that needs to be specified first. I believe this misunderstanding largely explains why the introduction and the definition of "power" is so confusing in this manuscript."

There is a simple and well-studied example of work and power defined for one object – it is a spring. A compressed spring performs work as it expands. If another body is attached to the spring, the spring can perform work on that body. If no other bodies are attached, the spring performs work *on itself*. In this case the potential energy contained in the compressed spring is converted to the kinetic energy of the spring parts. In either case work performed by the spring is the same.

Likewise, when gas expands into vacuum it performs work *on itself* – its potential energy associated with pressure is converted to the kinetic energy of the macroscopic motion. If the expanding air parcel is surrounded by other air parcels, then a certain part of its work can go to compress and/or accelerate and/or warm these surrounding parcels. But, as with the compressed spring, the work itself remains the same – governed by gas pressure and the relative change of the parcel's volume.

We have added this explanation of the physical meaning of the obtained expression for work to Section 2.

For a quantitative insight, consider a compressed spring obeying Hooke's law. For such a spring the normal component of force $F = -ES\Delta l/l$ is proportional to spring extension $\Delta l < 0$, with E being Young's modulus, S the area of the spring's cross-section and l is spring length. Since $\Delta l \equiv l - l_0$, where l_0 is length of uncompressed spring, we have $d(\Delta l)/dt = dl/dt$. As the spring begins to expand, work performed due to the changing spring's length (taken per unit time per unit spring volume $V = Sl$) is $W_s = (F/V)dl/dt = -E(\Delta l/l)(1/l)dl/dt$.

Length l of the spring changes as the velocity difference $\Delta v = v_2 - v_1$ between the two ends of the spring, $dl/dt = \Delta v$. With $l \to 0$ we have $\Delta v/l \to \nabla \cdot \mathbf{v}$ and $W_s = -E(\Delta l/l)\nabla \cdot \mathbf{v}$, where $-E(\Delta l/l) = F/S = p$ is pressure (for details see, e.g., Feynman et al., 1964, Chapter 38). Thus the resulting formula for W_s is analogous to $W_a = p\nabla \cdot \mathbf{v}$ we obtained for work performed per unit time per unit volume by an expanding air parcel (Eq. (8) in Section 2).

Notably, in our formulation of work the referee's requirement that *"the power system is only an abstract part of the atmosphere that needs to be specified first"* is fulfilled – it is specified by choosing the scale at which an air parcel – the power system – is considered, i.e. the scale at which the divergence of velocity is defined. We have emphasized in our article that the definition of work is scale-specific (see paragraph below Eq. (9) in Section 2 and the fifth paragraph "The reason for this contradiction..." after Eq. (15) in Section 3.1) and quantified how its magnitude changes with the changing scale (see Section 5.3).

References

Feynman, R., R. Leighton, M. Sands, and E. Hafner, 1964: *The Feynman Lectures on Physics*, Vol. II. Addison-Wesley.

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