

# ***Interactive comment on “The Nonequilibrium Thermodynamics of Atmospheric Blocking” by Andrew Jensen***

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I thank the reviewer for the prompt review. I especially thank the reviewer for the helpful comments. I hope that my responses help to satisfy your concerns.

## Major Comments

- The methods used to calculate the entropy balance are not made sufficiently clear. Instead of repeating the derivation of the balance equation from Li et al., 2014 (section 2 is nothing more than a shortened paraphrase of a similar passage from this study, also using the same notation), the author should provide more details on how each of the individual terms of equations 6-8 is computed from the MERRA reanalysis. For instance, how are frictional heating rates and convective fluxes derived? Are these really output variables of the reanalysis?

Reply: I agree that I need to provide the details. I will add them in a future version of the manuscript.

For instance, the surface entropy flux consists of standard variables only.

The only variables that are less standard in the entropy production come from the heating rates. The reanalysis contains temperature tendencies due to friction, moist processes, radiation, etc. These can be converted to heating rates and vertically integrated to calculate the entropy production.

- It is really not enough to present only a few summarizing numbers from the calculation in the form of tables. Spatial fields of the different budget terms should be shown. Otherwise, it is impossible for the reader to get a basic idea of (and also build some trust in) the presented analysis.

Reply: I agree that adding spatial fields will help clarify the manuscript. I will add them, including lateral entropy advection, in order to more comprehensively assess the nature of the blocking events.

- The potential physical relationship between entropy production and atmospheric blocking is totally unclear. If I got this right, the author obviously thinks that blocking is a somehow disordered structure that can be supported by the production of entropy (in contrast to cyclones, which are argued to be maintained by negative entropy fluxes). I don't think that this is the case. An atmospheric blocking is characterized by a largescale, persistent and well-structured anti-cyclonic flow anomaly. As such, it has (at least) the same degree of 'orderliness' as a cyclonic flow anomaly. Also if the flow may have (in certain cases) a somewhat more dissipative character at the boundary of the blocking anomaly, it has to be shown how this dissipation could contribute to the maintenance of the blocking anticyclone.

Reply: I apparently didn't make the my argument and perspective on entropy entirely clear. In a future version of the manuscript I will remedy this. I offer here a summary

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that I hope alleviates any concerns.

The use of the order/disorder description of entropy isn't necessarily the best way to describe blocking. There are only a few sentences mentioning this in the manuscript and I will modify them in a future version. I will also add a discussion highlighting the differences between equilibrium vs. non-equilibrium thermodynamics in blocking.

For example, in the past blocking has often been viewed as an equilibrium state (Charney, DeVore 1979, etc.) or even a quasi-barotropic state. It can be argued that these approaches aren't necessarily realistic. For example, that blocking is not always necessarily best characterized in this way is evidenced by the strong entropy production in the calculations in the manuscript. The calculations here suggest that blocking is closer to a non-equilibrium steady-state, strongly entropy producing with significant boundary fluxes.

Also, I didn't mean to imply that blocking wasn't coherent. It is. The main ideas in the manuscript have been influenced and motivated by an analogy with the characterization of long-lived coherent vortices as maximum entropy structures, such as occur in two-dimensional turbulence (see Turkington et al. 2001, Bouchett and Sommeria 2002, Sommeria 2005). Under certain conditions, including maximum entropy, these vortices can be anticyclonic. Blocking is long-lived with a characteristic lifetime of  $\sim 10$  days with many events more than twice that length so it is long-lived 'coherent vortex'. I chose two such events here. Hence the coherent vortex maximum entropy structure idea. This is an equilibrium concept, while the calculations here suggest that the analogy isn't perfect; but again, it motivated the present study. Again, blocking is closer to a non-equilibrium steady-state, strongly entropy producing coherent vortex with significant boundary fluxes. In a future version of the manuscript I will compare and contrast the two approaches.

- I think the analysis is superficial with regard to the spatial and temporal details. Probably the blocking index used by the author provides information on the exact onset and

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decay of as well as on the region affected by the blocking. Why is everything averaged over the whole months of January and February, and not the specific blocking periods (both with regard to the diagnostic and the fields shown in the figures)? Why is the entropy budget averaged over such a large region, and not only over the blocking area?

Reply: I don't agree that the analysis is superficial. Blocking tends to move slightly during its life-cycle and the region I selected encompasses both of the events entirely. There really isn't a lot of extra 'space' in the averaging.

#### Minor Comments

- Comparing the diagnosed entropy anomalies with annual data does not make much sense given that some of the input fields (in particular the surface fluxes) have a very strong seasonal cycle

Reply: They do have a strong seasonal cycle, which is why I included the variance. I think this shows the anomalous nature of the fields.

-Page 6, first row: A Bowen ratio of 7.46 is very unrealistic for a mainly oceanic region (I don't know exactly what 'rough calculation' means, but in this case this may be too rough).

Reply: The 'rough' calculation was calculated by dividing the sensible heat flux and latent heat flux. The SST anomalies were extreme and the high numbers demonstrate this.

- Tables: Provide units. What does 'total' mean (aren't these temporal averages? Then summing them up does not make much sense)?

Reply: I will provide units. You are right: the 'total' column is confusing and it's really unnecessary. I will remove it.

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