Review #1 by Ralph Lorenz:

We thank Ralph Lorenz for his constructive comments. In the following, we separated his review into five comments (in ***bold***, numbered) and provide a response to each of them, followed by how we plan to address this comment in the revision.

Comment R1-1. This paper raises the valuable concept of structures in systems (Earth, societal, planetary etc.) and notes that the growth and sustainment of structures should be able to be quantified. This seems like a promising avenue of enquiry, but the present paper fails to adequately develop the concept. While I recognize that an 'ESD ideas' format should encourage advancement of concepts that may not be fully mature, the present very short manuscript really doesn't do enough by itself to merit publication.

Response: Yes, the manuscript is very short -- this is one of the requirements of the ESD Ideas format. We also agree that the concept we propose is not fully mature, which is why we chose this manuscript type. As we will mention in the following, there is a huge gap in Earth system science in terms of formulating structures as the result of work being done. Most processes in the Earth system are not even described in terms of how much work is being done, so it is, obviously, difficult to get some numbers to illustrate this point. It illustrates a huge lack of the basics to even describe such structures in energetic terms.

In our manuscript, we aim to provide the concept to advance towards such a description of structures. We think this fits very well into the category of *ESD Ideas*, because it is novel and innovative. The reviewer makes several constructive remarks that we respond to in the following that will hopefully make the manuscript stronger.

Action: In the revision, we will describe better the challenging context of Earth system processes not being formulated in terms of how much work these perform. We will also aim to strengthen the manuscript by addressing the other points raised by the reviewer as detailed below.

Comment R1-2. In particular, there is a yawning gap – not to say a gross inconsistency in physical dimensions/units – between the (obvious, and qualitatively well-discussed in previous works – e.g. Lineweaver, Bejan and others) structures like vascular networks, sewage systems and flow structures (lines 32-37) and the **energies** discussed in equation 1 in lines 45-52.

Response: We think the reviewer errs here. We could not identify an inconsistency in units of the terms of Equation 1 and the following description. Equation 1 is given by

$$\frac{dU_{structure}}{dt} = u_{structure} \cdot \frac{dA}{dt} + A \cdot \frac{du_{structure}}{dt} = G - D \qquad (1)$$

The individual terms of the equation and their respective units are:

Term	Description	Unit
$U_{structure}$	Net work done to build the structure	J
$dU_{structure}/dt$	Temporal change in $U_{structure}$	J/s or W
$u_{structure}$	Net work done per unit area, $U_{structure}$/A	J/m^2
A	Spatial extent of structure	m^2
dA/dt	Change in spatial extent	m^2/s
G	Power (work done per unit time)	J/s or W
D	Decay of structure	J/s or W

The terms in Eq. 1 have thus the following units

$$\frac{dU_{structure}}{dt}\left[\frac{J}{s}\right] = u_{structure}\left[\frac{J}{m^2}\right]\cdot\frac{dA}{dt}\left[\frac{m^2}{s}\right] + A\left[m^2\right]\cdot\frac{du_{structure}}{dt}\left[\frac{J}{m^2 s}\right] = G\left[\frac{J}{s}\right] - D\left[\frac{J}{s}\right]$$

All terms are in units of J/s, or Watt.

One shortcoming of this formulation, which we noticed since submission, is that some structures, such as turbulence in the atmosphere, do not cover areas, but volumes. In this case, the area *A* would need to be replaced by a volume *V* instead, with $u_{structure}$ being defined as "net work done per unit volume, $U_{structure}/V$". Yet, the underlying formulation and its interpretation would not be affected.

Action: We will clarify the units of Eq. (1) in the revision to make sure that readers can easily see that the units of the equation are consistent. We will also include the last point about volumes for some structures.

Comment R1-3. For each of the environments discussed in section 2, the authors should make at least a token effort to (1) define the physical quantities involved (kinetic energy and viscous dissipation in flow, volume of material and transport rates in geomorphic structures like rivers, metabolic rate and biomass? in plants etc.), …

Response: We would like to point out that the text in section 2 already contains references to some of the physical quantities involved, yet at a condensed level to keep the text short. For turbulent structures, the reference is made to turbulent kinetic energy, a well-defined quantity in meteorology (see e.g., Peixoto and Oort, Physics of Climate, or Stull, An introduction to boundary layer meteorology).

For drainage structures, we agree that we do not mention the forms of energy involved. It involves work done in terms of detachment of sediment and keeping sediment in suspension when it is transported and relocated by water flow. For plant structures, these are being built by plant processes that are driven by the chemical energy generated by photosynthesis. For human structures, it depends which specific structure is being discussed.

Action: We will add text and clarify which forms of energy and work are involved in the revised manuscript and how these are being reflected in the variables associated with the examples.

Comment R1-4. … and (2) identify the destruction mechanisms against which growth must compete – otherwise the paradigm is meaningless.

Response: The suggestion to identify the destruction mechanism is an interesting point. While this is relatively clear for turbulent structures (molecular diffusion) as well as drainage structures (erosion), for plant structures and human-made structures the destruction processes (such as cell death, plant mortality) are more complicated and less physical.

Action: We will mention these destruction mechanisms in the revised version.

Comment R1-5. Then, for at least a couple of these, provide a numerical example or two where these properties, and the resultant timescale, is actually quantified. This exercise, which probably involves half an afternoon, some coffee and a whiteboard, could turn this half-developed 'placeholder' of analogies into a valuable contribution to the literature where the idea is shown to have predictive utility.

Response: We agree that having numerical examples are useful to illustrate this concept. Yet, the challenge is that many Earth system processes are not described in terms of how much work these involve, which is part of the motivation for our manuscript.

In atmospheric science, a demonstration of the concept is relatively straightforward. The generation of kinetic energy has already been described in the context of the Lorenz Energy Cycle, an established, yet relatively marginal topic. From estimates of the Lorenz Energy Cycle, the properties and time scales can be illustrated for the case of atmospheric generation and dissipation. Using estimates from the textbook *Physics of Climate* of Peixoto and Oort (1992), we have an estimate of the mean kinetic energy associated with the large-scale atmospheric circulation of $U_{ke} = 7.3 \times 10^5$ J m^{-2} that is associated with the large-scale structures of high and low pressure systems. The generation rate G is about 2 W m^{-2}, and this yields a time scale of $7.3 \times 10^5/2$ s = 4.2 days. This time scale agrees well with the typical time scale of synoptic activity in the mid-latitudes.

For plant structures, one could develop such a time scale from the chemical energy fixed by plants compared to the standing biomass. Because the conversion efficiency of both is the same, the associated time scale is the same as that derived from the carbon balance. Using typical values of 55 GtC/yr of net primary productivity and a standing biomass in vegetation of about 550 GtC, this yields a time scale of 10 years.

For drainage structures, an energetic framework has not been established, but one could possibly derive a time scale from the sediment mass balance, as the sediment flux encapsulates the work done to detach and sustain sediments in suspension. However, to relate it to structures would require to link this work done to the heterogeneity in topography that was generated by the drainage structure, and this, in turn, would require further analysis. At a qualitative level one would nevertheless expect the resulting time scale to be large, because the removed mass associated with river networks is large, while the input of potential energy by rainfall, some of which fuels sediment detachment and transport, is comparatively small.

Action: We will include these examples in the revision to illustrate the time scales.