Climate change, in the framework of the Constructal Law

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The first version of the paper has been improved to clarify the points highlighted by the reviewers. With the present paper the authors intend to show that the Constructal Law (CL) can capture basic features of the Earth behavior as a flow system, therefore a new approach for studying the Earth climate can be developed on the basis of the Constructal Law (CL). The issue is not if our simple model makes predictions as accurate as the very complex GCMs but the fact that the application of the CL to the climate system seems to be very promising and open new methodologies for dealing with the climate system.

As a result some parts of the first version of the paper have been re-written, or new text has been added, namely to the sections: **2; 4.1; 4.2** and **5.**

The more specific clarifications that have been made are summarized in the replies to the reviewers below:

Reply to **Reviewer #1**

1. Models of the Earth climate are either simple or complex depending on the number of variables they take into account. If the purpose is to check the impact of global warming on all the climatologic variables, then Global Circulation Models (GCM) are the appropriate models. On the other hand, if that purpose restricts to a single variable as global temperature, T, our simple model seems is competitive. For the case of global temperature the model only needs the radiative balances at the top of the atmosphere together with the global radiative properties of the atmosphere, the albedo and the Earth's greenhouse factor. An additional estimate is needed for the thermal inertia of the Earth, here modeled as an ocean layer of appropriate depth, together with the assumption that latitudinal radiation imbalance is transported along the meridian as any form of enthalpy (the current q) by all the planetary atmospheric and oceanic circulations. In this way there is no need to specify other details, namely the role of transient eddies.

2. Of course, the model presented in our paper is very simple but allows further improvements. This paper has the purpose of highlighting a new way to deal with the Earth global circulations on the basis of Constructal law (CL). We demonstrate that CL can capture the basic tendency of the Earth behavior as a flow system, therefore a new approach for studying the Earth climate can be developed on the basis of CL.

3. The model uses an average speed of the air at the boundaries between the equatorial an polar zones, no matter which specific transport patterns are at that stage (e.g. transient eddies, mesoscale circulations, etc).

About the more specific comments:

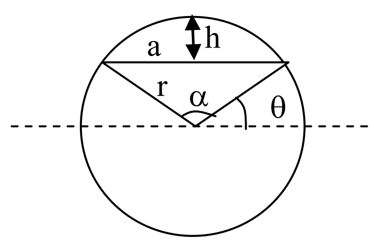
- The f_H defined in eq. (5) depends on the latitude θ and is different from the earth–sun view factor $f = 2.16X10^{-5}$ (constant) in eqs. 33-37.
- In our model, the parameters ρ and γ are global parameters that do not vary with latitude.
- Our simple model assumes symmetry between the Earth hemispheres. It also assumes that "The surface temperature is quasi-steady: it is averaged over many daily cycles and annual cycles, but it changes slowly with the changes in the radiative properties of the atmosphere" (p. 144).

- The corollary follows: "symmetry requires dq = dθ = 0 at the equator". In the real Earth this is approximately true, and the error affecting the evaluation of the global temperature is of second order. However, a further improvement of our simple model might account for the asymmetries between the North and South hemispheres. The ranges of possible changes in the albedo and the Earth's greenhouse factor have been considered in cases (A) and (B) to set the range of the scenarios under analysis.

- *It is unclear how values found in Sec 4.1 are compared to Hansen's results. What does it mean "temp. increase of 1.2 K for an increase of 0.6 K"?* That phrase has been removed and the overall sense has been clarified.

- The comment on Eq. 34 has been clarified before (albedo and the Earth's greenhouse factor are considered constant), and a new eq. (39) has been inserted in the text with the purpose of clarifying the maximization of heat flow.

1) The Earth-Sun factor is obtained from usual geometric relations. For example, for the polar zone we get :



$$A_L = 2\pi \cdot r \cdot h$$

With $h = r - r \cdot \sin\theta$ we get $A_L = 2\pi \cdot r^2 \cdot (1 - \sin\theta)$

$$A_{LP} = \frac{r^2}{2} \cdot \alpha - \frac{a(r-h)}{2} = \frac{r^2}{2} \cdot 2\left(\frac{\pi}{2} - \theta\right) - \frac{2r\sin\left(\frac{\pi}{2} - \theta\right)\left(r - (r - r \cdot \sin\theta)\right)}{2}$$

Hence we get

$$A_{LP} = r^2\left(\frac{\pi}{2} - \theta - \sin\theta\cos\theta\right)$$

2) A nomenclature is added to avoid any confusion.

3) $T\infty$ has to be mentioned as it is the temperature of the cold source (see Fig. 1) so that it should normally appear in equations (6) and (9) if not simplified.

4) T_{scale} is constant while t_{scale} depends on the ocean depth taken into account as part of effective Earth's inertia. This is discussed in section 4.

5) The changes are made.

6) The difference is due to the 2-box model as what is called "polar zone" in our model is of course wider than the commonly known polar zone. This is of course also the case for the equatorial zone.

7) The step changes considered in the albedo and the greenhouse factor were: (A) $\delta\rho$=0.002 with $\delta\gamma$=0.011, and (B) $\delta\rho$=0.002 with $\delta\gamma$ =0.005.

A small change in the albedo was considered due to the fact that it is influenced by two competing trends: the area with snow and ice cover is expected to diminish while water evaporation is expected to increase the global cloud cover. We considered greater changes in the greenhouse factor to accommodate possible scenarios arising from uncertainties on content of atmospheric greenhouse gases.

8) a revised version of this section is proposed:

Although coming from a simple model, these results are consistent with those based on complex meteorological models. Indeed, the results found for case (A) and case 3 for inertia are closed to that found by Hansen et al. (2005), using the global climate model of the NASA Goddard Institute of Space Studies to simulate the climate evolution for the 1880-2003 period. Hence, they have reported that 85 % of the heat storage occurs above 750 m depth. The depth taken into account for thermal inertia calculation in case 3 (917 m) is of the same order of magnitude. In their calculation, the overall temperature increase is 1.2 K which is close to what we have found for case (A) with ΔT_H = 1.16 K and ΔT_L = 1.11 K. Concerning the Earth's energy imbalance, our results differ from Hansen's as our change in albedo and greenhouse factor is of step-change type, which of course differs from the evolution of CO_2 atmospheric concentration. Hence, Hansen et al. have found an overall energy imbalance of 1.8 W.m-2 relative to 1880, while we have found a value of 3.6 W.m-2 at year 0 which corresponds to the year 1880 in Hansen's work.

9) The word continuous refers to the fact that there is no plateau, contrary to the case 4.2

10) Year 2000 corresponds to 120 years elapsed since 1880 which in our case is year 0.
There is a typo in the text and the reviewer is right. The correct equation giving γ is :

$$\gamma = 0.411 + \frac{0.022(\tilde{t} - 3.45)}{3.45}$$

This change was made in the final version of the manuscript.

Reply to **Reviewer #2**

1) The model contains a number of simplifying [..]

The authors want to stress out that heat is advected through the atmosphere and not through the material Ocean as explained page 249. Furthermore, it was assumed pure sensible heat exchange (no condensation nor evaporation occurs).

2) The model is first solved [..]

The step change is of course not representative of the GHG emission history. However, it allows to get some information on the time constants of the system.

3) Comparison to Hansen's work

The authors agree with the reviewer comments that our results do not fully match those presented in Hansen's work. Indeed, on Hansen's result basis we have: +0.6 K and +0.8 W/m2 since 1950. With our model the +0.6 K variation is linked with a +1.04 W/m2 (+0.011 in gamma) or never reached (+0.0055 in gamma). The duration to reach theses values depends on the ocean layer depth taken into account. To match the 50 year of Hansen's model, the depth should be around 450 m (1/6 of the 2750 m). The authors agree that the model could be improved as suggested: refinement of inertia description, refined law for ρ or γ evolution as a function of the latitude and time, etc. This will be of interest and will be done in our future work. At this stage, section 4.1 and 4.2 have been modified to take into account the reviewer comments:

Section 4.1: *The energy imbalance is the highest initially [3.67 W/m2, case (A)], while it is still significant [1.47 W/m2, case (A)] when 60% of the temperature response is reached. The scenarios A and B were used to test the sensitivity of the present model to changes in the albedo and earth greenhouse factor. The results allow interesting comparisons with those from other models. Although coming from a simple model, these results are consistent with those based on complex meteorological models. For example, using the global climate model of the NASA Goddard Institute of Space Studies to simulate the climate evolution for the 1880-2003 period, Hansen et al. (2005) have found an overall temperature increase of 1.2 K and an energy imbalance reaching 0.85 $\pm$ 0.15 W/m2 for an overall energy imbalance of 1.8 W/m2 relative to 1880. The overall temperature increase is similar that our value found in case (A). The authors report as well that 85% of the heat storage occurs above 750 m depth. The depth taken into account for thermal inertia calculation in case 3 (917 m) is of the same order of magnitude, so that only case 3 is studied in what follows.*

Section 4.2: *Taking into consideration the results found by Hansen et al. (2005), the reported variations are +0.6 K and +0.8 W/m2 since 1950. With our model the +0.6 K variation is linked with a +1.04 W/m2 (+0.011 in γ, case A) or never reached (+0.0055 in γ, case B)*

The duration to reach theses values depends on the ocean layer depth taken into account. To match the 50 year of Hansen's model, the depth should be around 450 m (1/6 of the 2750 m) and not 917 m as chosen in section 4.1.

From these comparisons, we can conclude that our model can roughly match the results found with more detailed models. Some leads to improve the models would consist in refining the way Earth inertia is taken into account and the equations governing the γ and ρ evolutions.

4) Difference between the evolution of the pole and equator temperature

As the evolution of ρ and γ is similar for the pole and the equator zones, the difference might come from the difference of variation of the surface to volume ratio. Indeed, for the polar it varies as $6/(R.(2+\sin\theta))$ while for the equatorial zone it varies as $6/(R.(3-\sin^2\theta))$. For example, with $\theta = 57°$ we get $2.11/R$ m^2/m^3 for the pole and $2.61/R$ m^2/m^3 for the equator. Hence the heat flux received per m^3 will be higher at the equator than at the pole, other parameters being constant.

This will be discussed and addressed more precisely in our future work with an improved model.