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CONSTRUCTAL LAW, AND THE ALBEDO AND GLOBAL WARMING CONUNDRUM

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Abstract. In the current debate on global warming is under analysis whether the albedo will increase with temperature, and may thus constitute a negative feedback mechanism by increasing the amount of solar radiation reflected into space. This issue is analyzed in this paper in the light of the Constructal Law. In fact, by maximizing the overall conductivity of the processes that lead to the thermalization of the solar energy absorbed on Earth and its subsequent radiation into space at the global average temperature, it is possible to conclude that the albedo should increase with the global temperature, thus constituting a negative feedback mechanism that will help to restrain the increase of global temperature. Additionally, the value found for the rate of variation of the albedo with global surface temperature is very close to the values published in the literature, which were obtained both through satellite data and ground-based observations. Although they result from a preliminary analysis, these results are encouraging towards the implementation of the Constructal Law in the analysis of the climate system.

***Key words*:** Earth's albedo, Global warming, Constructal Law.

1. INTRODUCTION

Earth's albedo is defined as the ratio of radiation reflected by the entire planetary surface to the radiation incident on it. Because the Earth's surface also emits thermal radiation, it is not easy to separate this fraction from that corresponding to the radiation received from the Sun. Currently, two method are used based on data from: (i) Earth Radiation Budget Experiment (ERBE, a set of satellite instruments designed to measure the Earth's energetic balance), and (ii) Earthshine (ES, ground based measurements of reflectance based on the dayside earthlight reflected from the Moon back to the night-time observer [1–3]. Anomalies in the terrestrial albedo are detected through the photometric ratio of the dark (earthshine) to the bright (moonshine) sides of the Moon [1].

The main contributors to the Earth's albedo are clouds, polar ice caps, and desert belts in the two hemispheres. Albedo is a chief modulator of the Earth's climate, because it controls the global energy budget through the amount of radiation reaching the Earth's surface.

The direction of the variation of the Earth's albedo in the last decades, in which an increase in the global temperature has been observed, is currently in dispute. By the beginning of the century, Pallé and co-workers [4] found that albedo anomalies although positive show "a steady decrease in Earth's reflectance from 1984 to 2000, with a strong climatologically significant drop after 1995. From 2001 to 2003, only earthshine data are available, and they indicate a complete reversal of the decline." However, in a later paper [5] they reported an incorrect treatment of outlier data points, which caused an overly large decreasing trend of positive anomalies in the period 1998–2003. Recently, Pallé and co-workers published the results of the analysis of an extended period (1998–2014) in which they sigma-clipped data to remove outlier values lying more than 3σ and 1σ away from the fit to the data (σ stands for standard deviation) [5]. As they explained, clipping was done by fitting all the data and eliminating all data more than 3σ and 1σ away from the fit, respectively. The result is shown in Figs. 1 and 2.

We can observe in both cases the same trend: the albedo (or earthshine) increases with Earth global temperature. In the case of 3σ clipping this trend is more noticeable and of order of $0.5 Wm^{-2}$ in the period (1998–2014), while the value corresponding to 1σ clipping is smaller and of order $0.25 Wm^{-2}$. Moreover, as noted by Pallé and co-workers [5], contrarily to the 3σ clipping case, in the plot corresponding to 1σ clipping both the satellite and ground based data sets from of albedo anomalies are in good agreement over the 14 years they have in common. Therefore, in the following we will use the value of 0.25 Wm^{-2} (1σ clipping) as the earthshine variation with Earth' temperature in the period (1998–2014).

The global Earth temperature anomaly evolution in the period 1998–2014, with respect to the base (averaged) values of the period (1951–1980), is shown in Fig. 3. Data of global temperature anomalies were taken from the GISS Surface Temperature Analysis (GISTEMP) that uses data files from NOAA GHCN v3 (meteorological stations), ERSST v4 (ocean areas), and SCAR (Antarctic stations) [6]. Yearly anomalies represented by the points in Fig. 3 are averages of the values of the respective year, the values of the precedent and subsequent years. The best fit provides 0.0124K/year, as the rate of increase of the global temperature anomaly in the period 1998–2014.

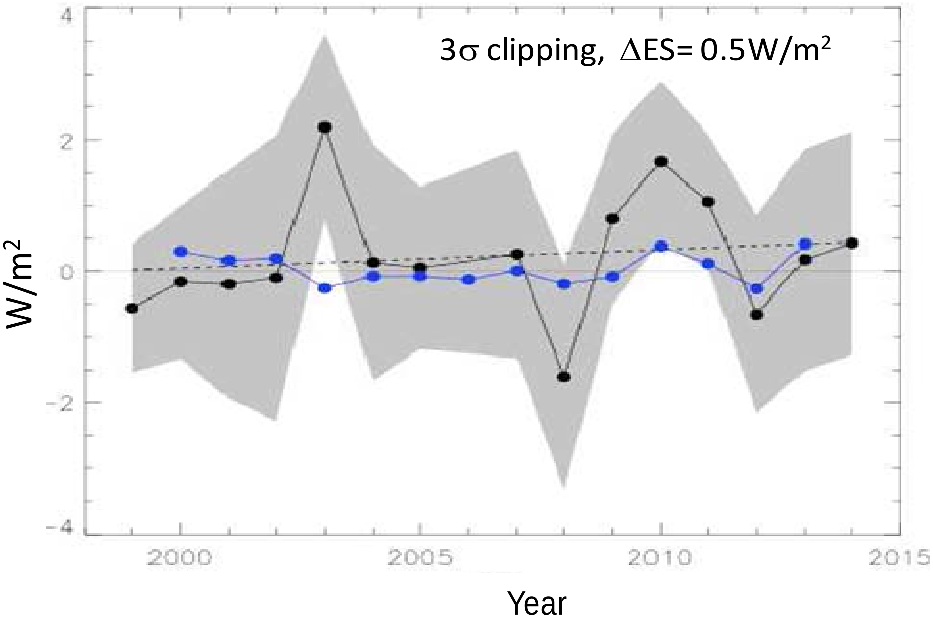

Fig. 1 – Earthshine/albedo anomalies (ΔES), calculated over the mean of the full period (1998–2014) with 3σ clipping expressed as reflected flux in W/m^2. Ground based (black), satellite data (blue), adapted from [5].

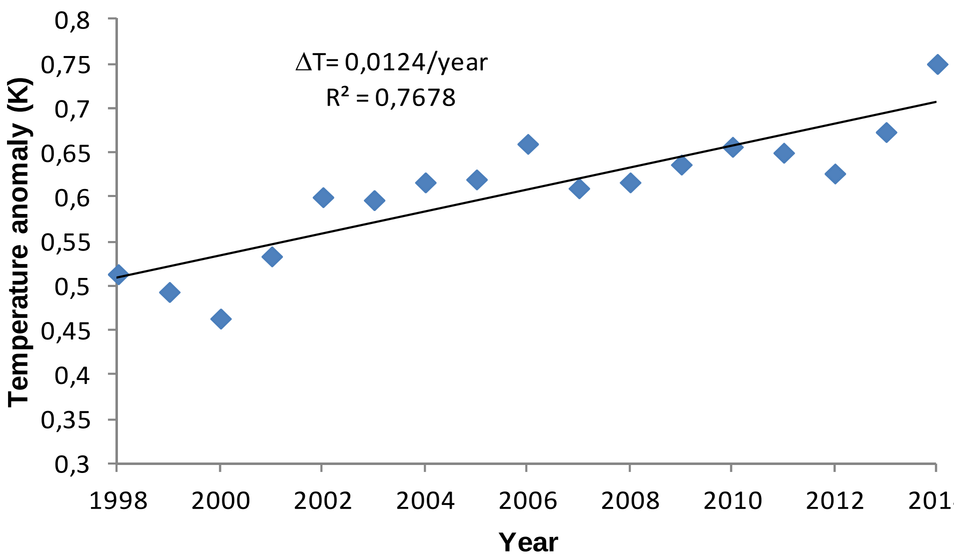

Fig. 2 – Earthshine/albedo anomalies (ΔES), calculated over the mean of the full period (1998–2014) with 1σ clipping expressed as reflected flux in W/m^2. Ground based (black), satellite data (blue), adapted from [5].

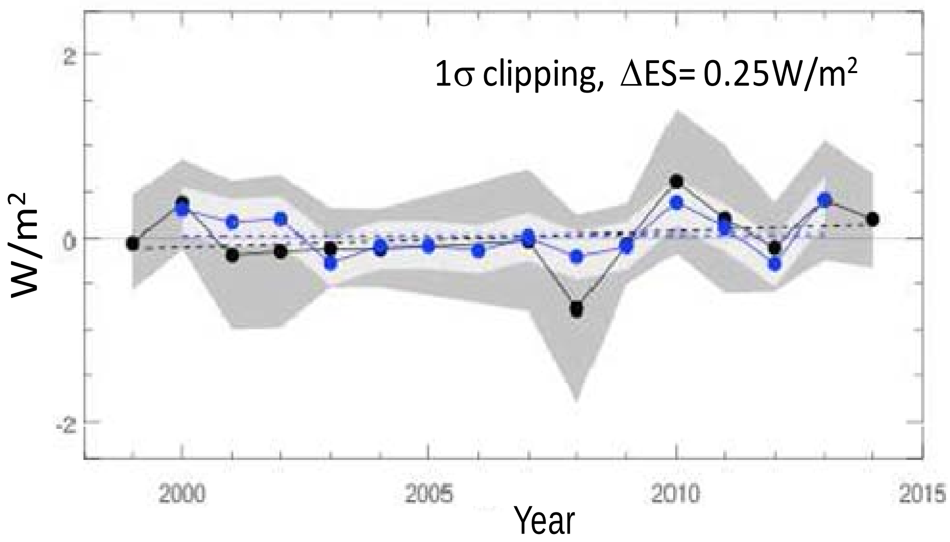

Fig. 3 – Evolution of the global temperature anomaly in the period 1998-2014, with respect to the base period (1951–1980).

2. ANALYSIS OF THE VARIATION OF THE EARTH'S ALBEDO WITH GLOBAL TEMPERATURE IN THE LIGHT OF THE CONSTRUCTAL LAW

Earth's albedo is defined as the ratio of radiation reflected by the entire planetary surface to the radiation incident on it. Because the Earth's surface also emits thermal radiation, it is not easy to separate this fraction from that corresponding to the

Changes in the Earth's albedo are the ultimate result of all processes occurring in the Earth's atmosphere, land and oceans. These processes are very complex and therefore not easy to encompass in analytic models. In this field, only general principles may help dealing with the general behaviour of complex systems. The general principle of maximization of "global flow access", known as the Constructal Law, which was first put forward by Bejan [7] in the form: "For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed (global) currents that flow through it", entails maximization of the global conductivities of complex flow systems under the existing constraints. In the following we will use this statement as the guiding principle in the search for associations between the temperature and the albedo of the Earth.

In that search we will observe the Sun/Earth system from the point of view of an observer placed somewhere in the outer space registering the solar radiation flow hitting the top of the Earth's atmosphere (Q_{sun}), the reflected flux, and the thermal radiation emitted from the Earth to the outer space (Fig. 4). The fraction of the solar radiation absorbed in the Earth atmosphere land and oceans (Q_{in}) powers a cascade of processes on Earth before its thermalisation at the average temperature (T) at which it is emitted into space (Q_{out}). In the course, the exergy of solar radiation flux decreases markedly, or said another way, its entropy increases due to the resistances affecting the many energy transfer processes occurring on Earth.

In Fig. 4, R represents the global resistance of all those processes.

The problem put this way is very simple, however at the cost of lacking of any information on each particular resistance and its contribution to the global entropy generation. In this framework Constructal Law shows its usefulness as a guiding principle, as we discuss below.

In the linear regime [8], the global entropy production rate S_{gen} is given by

$$S_{gen} = F(T)\,Q_{in}\,, \tag{1}$$

where $F(T)$ is the "overall force" driving the heat flow Q_{in} in the course of its thermalisation to the Earth's emission temperature, T.

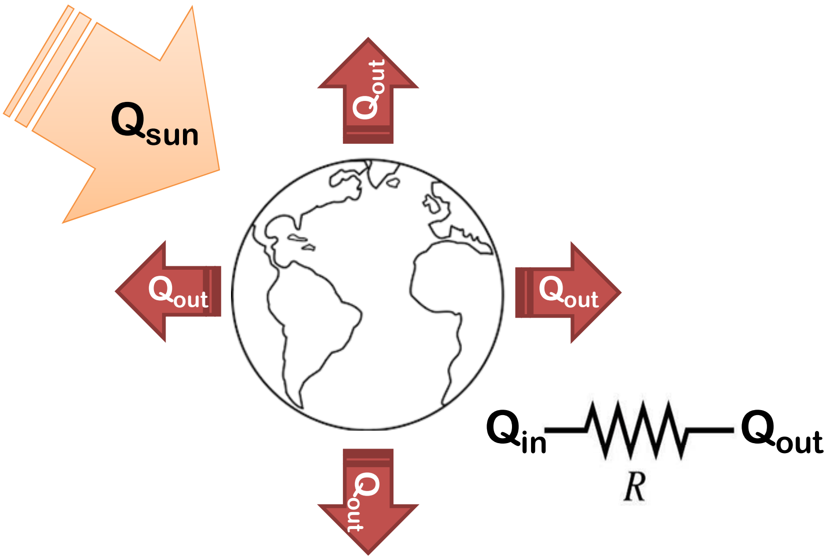

Fig. 4 – Solar radiation power at the top of the atmosphere (Q_{sun}), and terrestrial radiation power emitted from the Earth (Q_{out}). A Global resistance R couples the power absorbed (Q_{in}) and the power emitted (Q_{out}).

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$$Q_{in} = LF\left(T\right), \tag{2}$$

where L is the Onsager's coefficient [8], which clearly has the significance of overall conductance that is just the inverse of the overalll resistance R, shown in Fig.4. In the conditions of the problem depicted in Fig. 4, the global entropy production rate S_{gen} reads

$$S_{gen} = Q_{in} F\left(1/T - 1/_{S}\right), \tag{3}$$

where T_s is the emission temperature of the Sun as a black body. From Eq. (1) it follows that the "overall force" reads:

$$F\left(T\right) = \frac{T_S - T}{T_S T}. \tag{4}$$

Because $\alpha = Q_{in} / Q_{sun}$ represents the faction of the solar radiation reflected from Earth, the solar radiation absorbed in the Earth is given by:

$$Q_{in} = A_p\, f\, \sigma (1 - \alpha)\, T_S^4\,, \tag{5}$$

where A_p is the area perpendicular to the solar radiation flux, T_s, σ, and f are the temperature of the Sun as a black body (5762 K), the Stefan-Boltzmann constant (5.67×10^{-8} Wm^{-2}K^{-4}), the Earth-Sun view factor (2.16×10^{-5}), respectively. Now, from Eqs. (2, 4, 5) it is easy to find the "conductance" (Onsager's coefficient) as

$$L = B\left(1 - \alpha\right)\frac{T_S T}{T_S - T}, \text{ with } B = A_p\, f\, \sigma T_s^4\ . \tag{6}$$

We note that L represents the global conductance associated with the flow Q_{in} under the global driving force $F(T)$ acting between its absorption in Earth and its emission from Earth.

By letting the Earth's emission temperature (T) free, Constructal Law requires the overall "conductance", L, to be maximal (T_s and B fixed). From Eq. (6) that condition is expressed as:

$$\frac{\mathrm{d}\alpha}{\mathrm{d}\tilde{T}} = (1-\alpha)\frac{1}{\left(1-\tilde{T}\right)\tilde{T}}\,, \text{ with } T = \tilde{T}/T_S\,. \tag{7}$$

The dimensionless Eq. 7 shows that albedo and Earth's emission temperature have the same sense of variation, therefore increase in the albedo must be expected as the planetary global temperature increases.
In order to test Eq. 7 in the case of the Earth first we will translate earthshine anomalies (ΔES) into albedo anomalies according to

$$\left(4\Delta ES/SC\right) = \Delta\alpha\,, \tag{8}$$

where SC is the Solar Constant, 1367 Wm^{-2}, and the factor 4 accounts for the fact that solar radiation is reflected/diffused by the entire spherical Earth surface (therefore the anomaly 0.25 Wm^{-2} stands for the average value on the Earth's surface), while the amount of incoming solar radiation is given for the product of the Solar Constant and the area of the Earth perpendicular to the solar radiation flux. Additionally, we take T_s = 5,762 K, the Earth's emission temperature T = 255 K, and α = 0.7, as the value of the albedo currently accepted. We will also consider the observed earthshine anomalies $\Delta ES = 0.25Wm^{-2}$ in the 17 years period (1998–2014) corresponding to 1σ clipping [5] (see also Fig. 3), together with an increase in the global temperature of ΔT = 0.211 K in the same period (see Fig. 3.)

Therefore the observations [5, 6] provide the following rate of variation of albedo with temperature:

$$\left(\frac{\mathrm{d}\alpha}{\mathrm{d}T}\right)_{obs} = 3.5\times10^{-3}\ \mathrm{K}^{-1}. \tag{9}$$

On the other hand, the value calculated from Eq. (7) is

$$\left(\frac{\mathrm{d}\alpha}{\mathrm{d}T}\right)_{CLaw} = 2.9\times10^{-3}\ \mathrm{K}^{-1}. \tag{10}$$

Both results are close and of same order. Given the uncertainty that affects the observed data and, hence the slope of the linear fittings in Figs. 2 and 3, the result anticipated under the Constructal Law is really remarkable as it grounds only on a basic principle applied to a simple model of global solar and terrestrial radiation.

3. CONCLUSIONS

By applying the Constructal Law to a simple model of Earth's incoming solar radiation, reflected radiation and emitted thermal radiation, it is possible to anticipate that the Earth's albedo should increase with the global temperature, thus constituting a negative feedback mechanism that will help to restrain the increase in global temperature by increasing the amount of reflected solar radiation into space. It was found that this theoretical result finds support in recent observations corresponding to the period (1998–2014). The value found for the rate of variation of the albedo with global temperature ($2.9 \times 10^{-3}\mathrm{K}^{-1}$) is very close to the value obtained from data published in the literature ($3.5 \times 10^{-3}\mathrm{K}^{-1}$), which were obtained through both satellite data and ground-based observations. Although they result from a preliminary analysis, these results Together previous ones are encouraging towards the generalized use of the Constructal Law in the analysis of the climate system.

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