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Seiji Kato ✉; Fred G. Rose

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Global and Regional Entropy Production by Radiation Estimated from Satellite Observations

Seiji Kato[1, a)] and Fred G. Rose[2]

[1]*NASA Langley Research Center, Hampton, Virginia, USA*
[2]*Science System and Applications, Inc., Hampton, Virginia, USA*

[a)] Corresponding author: seiji.kato@nasa.gov

Abstract. The rate of entropy production by Earth's climate system is estimated using satellite-based observations. Based on the entropy estimate, we provide a thermodynamical view of the climate system when the absorptivity of shortwave irradiance increases.

INTRODUCTION

The form of energy changes while flowing through Earth's climate system. Although the magnitude of regional energy flux components significantly varies temporally and spatially, global and annual means are stable. An energy budget diagram that describes annual mean energy fluxes within the climate system [1][2] has less meaning if the variability of global annual mean energy budget is large. While the energy view of Earth's climate system is explored well, a path to look at the climate system thermodynamically has been less taken. In this paper, we provide a thermodynamical view of Earth's climate system, which provides additional insights in understanding important processes driving the climate system.

The equation central to this view is the entropy balance equation [3],

$$\frac{dS}{dt} = \frac{Q_a}{T_a} - \frac{Q_e}{T_e} + \dot{\Sigma}_{irr} \qquad (1)$$

where the left side is the rate of entropy change in the climate system, the first term on the right side is entropy production rate by absorption of the shortwave irradiance, the second term is entropy production rate by the longwave emission to space, and the third term is entropy production rate by irreversible processes. Although Eq. (1) can be applied to a regional scale, we apply Eq. (1) for a global scale in this paper. In Eq. (1), Q_a is the rate of shortwave irradiance absorption, T_a is the global mean absorption temperature, Q_e is the rate of longwave irradiance emission to space, T_e is the global mean emission temperature, and $\dot{\Sigma}_{irr}$ is the entropy production rate by irreversible processes within the system. Processes contribute to the irreversible processes include enthalpy diffusion down the temperature gradient, diffusion of kinetic energy by drag force (e.g. falling raindrops [13]), water phase change under unsaturated conditions, and radiation exchange within the climate system (e.g. between the surface and clouds).

Estimate of entropy production within the climate system

We estimate the entropy production rate using a satellite data product. The product used in this study is the edition 4 Cloud and the Earth's Radiant Energy System (CERES) SYN1deg-month product. We provide brief descriptions of the computation method here, but detailed descriptions are given in Kato and Rose [4].

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SYN1deg data product and entropy computations

The SYN1deg-month product contains hourly irradiances for every equal area grid. The size of equal area grids is 1°×1° from equator to 45° degree latitude and the degree of longitude of the grid increases toward poles. Irradiances for each grid are computed hourly. Hourly cloud properties are derived from MODIS and geostationary satellites by the CERES cloud algorithms [5]. Temperature and humidity profiles are taken from a NASA Global Modeling and Assimilation Office's reanalysis product [6]. Aerosol optical thicknesses are derived from MODIS spectral radiances by the MODIS team. Aerosol optical thicknesses derived by the dark target and deep blue algorithms are averaged. An aerosol transport model that assimilates MODIS aerosol optical thicknesses provides aerosol optical thicknesses under cloudy conditions [7]. Detailed descriptions of the SYN1degree production process are provided by Rutan et al. [8].

Computations of entropy production rate by shortwave absorption (the first term on the right side of Eq. 1) and by longwave emission to space (the second term on the right side of Eq. 1) are similar to irradiance computations in the SYN1deg-month algorithm. The entropy production rate by shortwave irradiance absorption $\frac{Q_a}{T_a}$ is computed by the shortwave irradiance absorption in computational layers divided by their air temperatures. The entropy production rate by longwave emission to space $\frac{Q_e}{T_e}$ is computed by the longwave irradiance transmission from computational layers to space divided by their air temperatures. The absorption of shortwave irradiance by the surface and the longwave irradiance transmitted from the surface to space divided by surface skin temperature are included in these two terms.

Figure 1 shows the annual regional mean entropy production rate by shortwave and longwave irradiances. Larger values occur over tropical ocean where clear-sky conditions are often present.

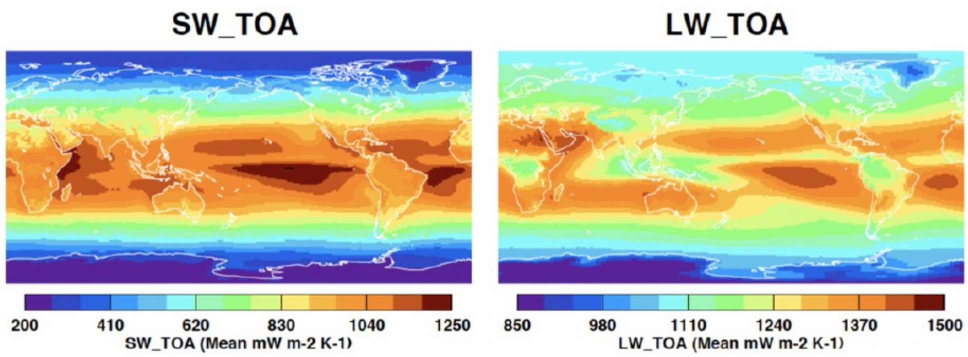

Figure 1: Annual mean entropy production rate (left) by absorption of shortwave irradiance and (right) by emission of longwave irradiance to space in mW m^{-2} K^{-1}. Eighteen years of data from March 2000 through February 2018 are used. (Taken from Kato and Rose, 2020 [4] © American Meteorological Society. Used with permission).

Entropy change due to increasing absorption of shortwave irradiance by Earth

The entropy balance equation states that the entropy stored within the system $\frac{dS}{dt}$ balances with the entropy produced by shortwave absorption, longwave emission to space and irreversible processes. For an annual and global scale, the difference of the shortwave absorption and longwave emission (hereinafter TOA irradiance imbalance) is used to heat ocean [9]. Following Gibbins Haigh [10], therefore, we compute $\frac{dS}{dt}$ by dividing the annual global mean top-of-atmosphere net irradiance by the global mean sea surface temperature.

Figure 2 shows the annual global mean values of $\frac{Q_e}{T_e} - \frac{Q_a}{T_a}$, which is equal to $\dot{\Sigma}_{irr} - \frac{dS}{dt}$, as a function of annual global mean shortwave absorptivity. The absorptivity is defined as the annual global mean absorbed shortwave irradiance divided by the annual global man insolation. Once the data points are fitted by linear regression, the slope of the regression line is negative. However, when $\dot{\Sigma}_{irr}$ as a function of annual shortwave absorption anomalies is plotted in a similar way, the slope is positive [10]. These results imply that

$$0 < \frac{d\dot{\Sigma}_{irr}}{da} < \frac{d}{da}\frac{dS}{dt} \qquad (2)$$

where a is the global mean shortwave absorptivity. This inequality states that the change of irreversible processes due to shortwave absorption change is smaller than the change of entropy storage caused by shortwave absorption change. Because of TOA irradiance imbalance leads to mostly heating ocean, this inequality is consistent with global annual mean radiation budget change.

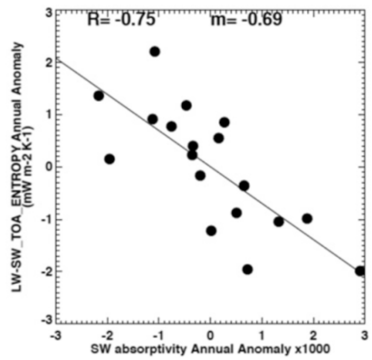

Figure 2: Annual global anomalies of $\frac{Q_e}{T_e} - \frac{Q_a}{T_a}$ as a function of annual global absorptivity anomalies (absorbed shortwave irradiance divided by insolation). Eighteen years of data from March 2000 through February 2018 are used; R and m are, respectively, correlation coefficient and slope. (Taken from Kato and Rose, 2020 [4] © American Meteorological Society. Used with permission).

DISCUSSION

Loeb et al. [11] analyze CERES data and show that TOA irradiance imbalance is increasing with time. This means that the upper bound of the inequality (2) is increasing. The rate of shortwave absorption change derived from CERES data is 0.68 Wm^{-2} dec^{-1}, which is equivalent to a 2.8×10^{-3} absorptivity increase per decade. If we simply take the trend of absorptivity from CERES observations and use the slope of the linear regression line given by Gibbins and Haigh [10] of 0.13 mW^{-2} K^{-1} per 1000 absorptivity change (their Figure 2b), entropy production by irreversible processes changes at the rate of 3.6 mW^{-2} K^{-1} dec^{-1}. This is approximately 0.4% of the annual global mean entropy production by irreversible processes of 83 Wm^{-2} K^{-1}. The value of 83 Wm^{-2} K^{-1} is the value of 76 Wm^{-2} K^{-1} derived in Kato and Rose [4] with a scaling correction described in Gibbins and Haigh [10] and Kato and Rose [12]. The standard deviation of annual global mean entropy production by irreversible processes is approximately 1%. This means that events at one standard deviation become normal within 25 to 30 years. Global mean precipitation increases 2% for 1 K surface temperature increase and surface temperature increase is about 0.2 K per decade. This means that precipitation increase is about 0.4% per decade, which is consistent with this thermodynamical view.

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