A thermodynamical view of the earth climate system

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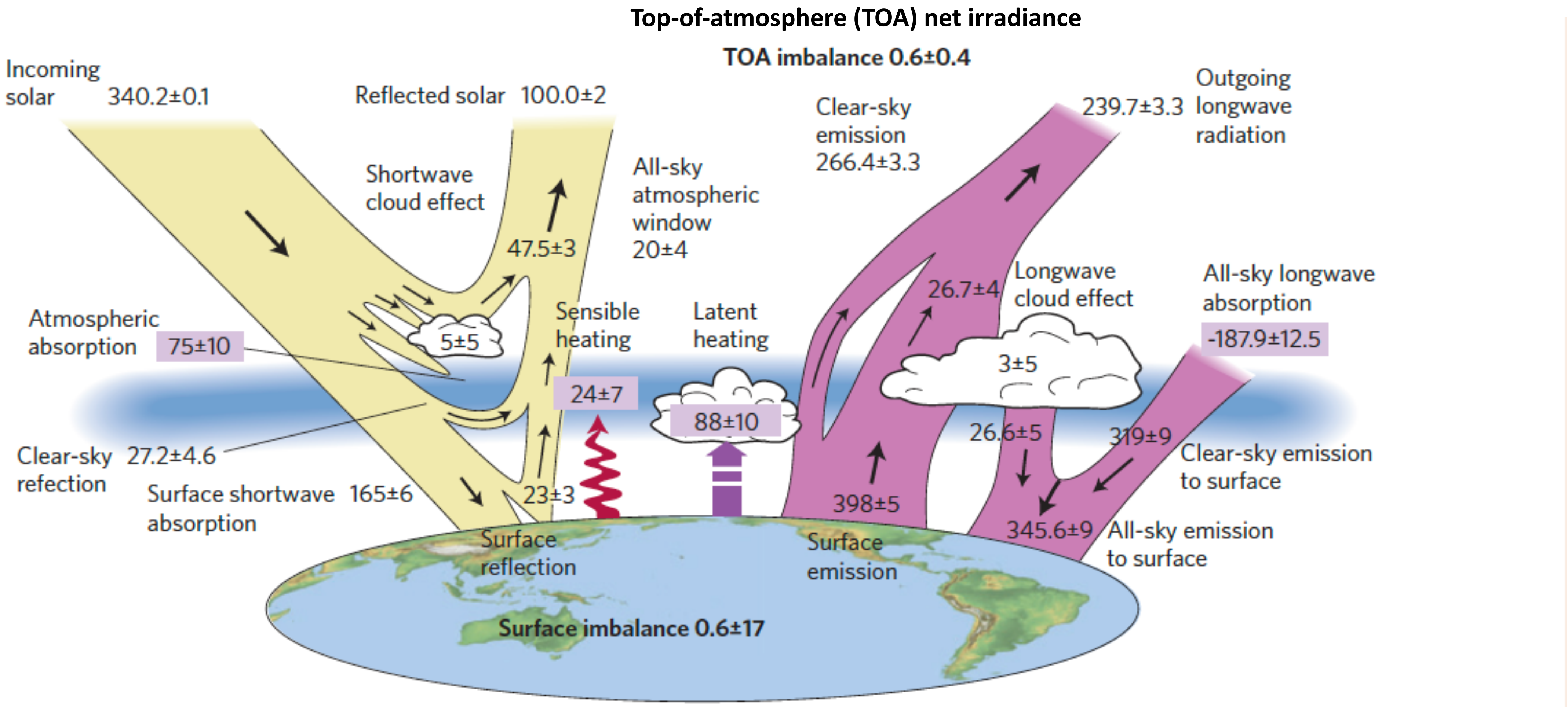
Global annual mean energy budget in Wm^{-2}



Stephens et al. (2012)

The theory of heat radiation (Planck 1913) Chapter 102

and, according to the second principle, the change of the entire entropy is positive or zero. Now the entropy of the body changes by $\frac{Q}{T}$, the entropy of the radiation in the vacuum by

$$\frac{ac}{3}\left(T^3 - T'^3\right).$$

Hence the change per unit time and unit area of the entire entropy of the system considered is

$$\frac{ac}{4}\,\frac{T'^4 - T^4}{T} + \frac{ac}{3}\left(T^3 - T'^3\right) \geq 0.$$

In addition to energy, entropy production within the climate system provides additional insights of understanding climate system

- Outline of this talk
  - Entropy balance equation
  - Entropy production rate by radiative heating and cooling
  - Change of entropy production rate with respect to increasing absorptivity of shortwave irradiance (i.e. decreasing planetary albedo)
  - Irreversible processes contributing entropy production

A thermodynamic view of Earth energy imbalance
A conceptional model to understand an entropy view

Entropy balance equation for the climate system

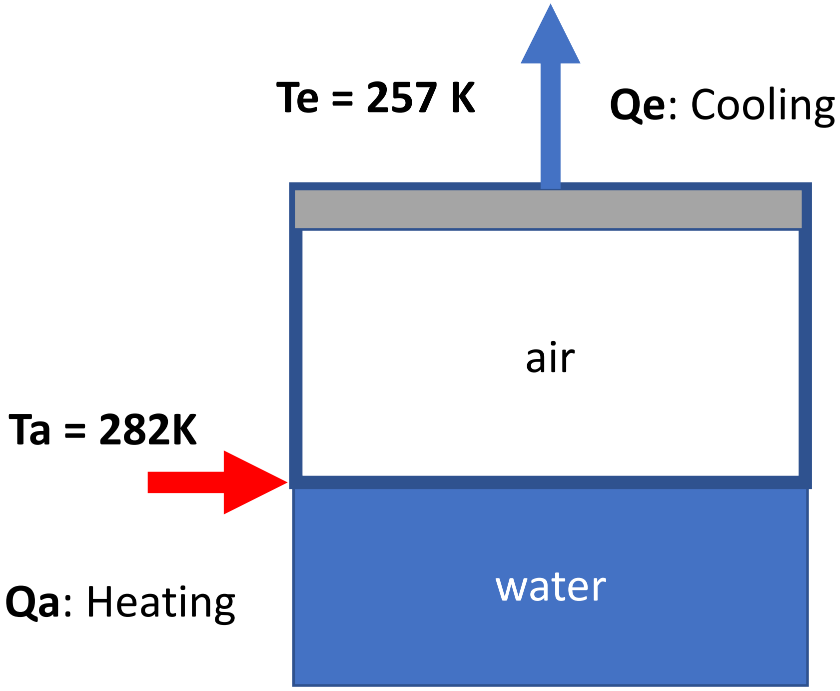
$$\frac{dS}{dt} = \frac{Q_a}{T_a} - \frac{Q_e}{T_e} + \dot{\Sigma}_{\mathrm{irr}}$$

$$\frac{F_{TOA}^{net}}{T_{SST}} = \int \frac{F_{net}^{SW}(z)}{T(z)} dz - \int \frac{T_{trans}(z) F_{up}^{LW}(z)}{T(z)} dz + \dot{\Sigma}_{\mathrm{irr}}$$

$\dot{\Sigma}_{\mathrm{irr}}$ includes entropy produced by all irreversible process in the Earth system

Ta and Te are effective absorption and emission temperatures

The CERES team computes shortwave absorption divide by the layer temperature and longwave emission to space divide by the layer temperature and estimates entropy production rate (Edition 4.1 SYN1deg)



We do not ask how Earth is heated and cooled.

Global annual mean entropy budget

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

Entropy production rate by shortwave absorption
$\frac{Q_a}{T_a}$ = 855 $mW^{-2}K^{-2}$

Entropy production rate by irreversible processes
$\dot{\Sigma}_{irr}$ = 83 m W^{-2} K^{-1}

Entropy production rate by longwave emission to space
$\frac{Q_e}{T_e}$ = 936 $mW^{-2}K^{-1}$

Entropy storage
$\frac{dS}{dt}$ = 2.3 $mWm^{-2}K^{-1}$

Entropy production by irreversible process $\dot{\Sigma}_{irr}$ includes by:

- Heating/cooling by Internal radiation exchange
- Turbulent enthalpy transport
- Frictional dissipation of turbulence
- Frictional dissipation of falling raindrops
- Irreversible phase change, transport, and precipitation of water

Values are derived from Edition 4.1 SYN1deg and EBAF (Gibbins and Haigh 2021)

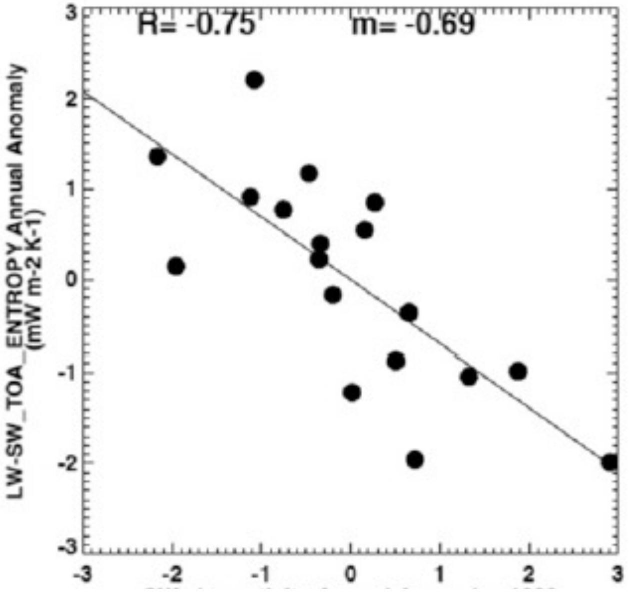
CERES observations

$$\frac{F_{TOA}^{LW,up}}{T_e} - \frac{F_{TOA}^{SW,net}}{T_a} = \dot{\Sigma}_{\mathrm{irr}} - \frac{F_{TOA}^{net}}{T_{SST}}$$

$$\frac{d}{da}\frac{F_{TOA}^{LW\ up}}{T_{skin}} - \frac{d}{da}\frac{F_{TOA}^{SW\ net}}{T_{skin}} = \frac{d\dot{\Sigma}_{\mathrm{irr}}}{da} - \frac{d}{da}\frac{F_{TOA}^{net}}{T_{skin}}$$

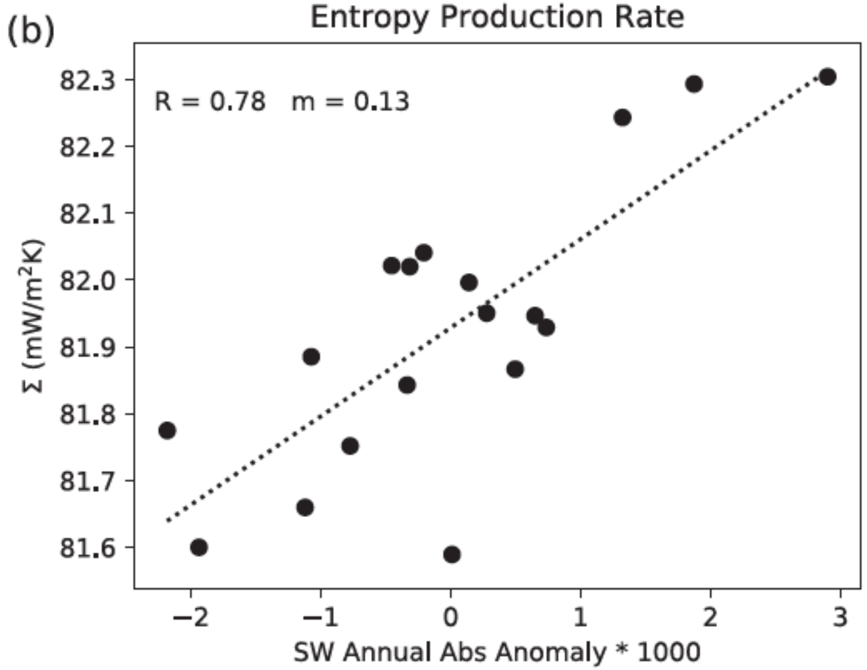
$$\frac{d\dot{\Sigma}_{\mathrm{irr}}}{da}$$

$$\dot{\Sigma}_{\mathrm{irr}} - \frac{F_{TOA}^{net}}{T_{SST}}$$



Absorptivity anomaly × 1000

$$\dot{\Sigma}_{\mathrm{irr}}$$



Gibbins and Haigh 2021

These suggest the inequality of

$$0 < \frac{d\dot{\Sigma}_{\mathrm{irr}}}{da} < \frac{d}{da}\frac{F_{TOA}^{net}}{T_{skin}}$$

or

$$0 < \frac{d\dot{\Sigma}_{\mathrm{irr}}}{da}\frac{da}{dt}\Delta t < \frac{d}{da}\frac{F_{TOA}^{net}}{T_{skin}}\frac{da}{dt}\Delta t$$

where a is absorptivity of Earth

Kato and Rose 2020, 2021; Gibbins and Haigh 2021

We can estimate the change in entropy production by irreversible processes if we know the rate of change of the absorptivity

A parcel model for a deep convective cloud

- A parcel containing moist air is lifted from the lifting condensation level to the level of neutral buoyancy.
- The parcel follow a constant equivalent potential temperature to the level of neutral buoyancy.
- If only entropy production due to water vapor condensation is considered the process is an isentropic process (condensation occurs under saturated conditions in thermal equilibrium)

Entropy production within deep convective clouds

When water vapor condenses under saturated conditions in thermal equilibrium, the process is isentropic.

Other processes changes entropy

Entropy source	**Expression**	**Conditions**	**Entropy change (W kg^{-1} K^{-1})**
Diffusion $\dot{s}_{dif}$ of temperature by air-hydrometeor (liquid) conduction	$\frac{r_i c_l (T_l - T)^2}{T_l T \tau_{cl}}$	Liquid water content 5 g m^{-3} Air temperature 265 K Hydrometeor temperature 275 K Conductive time scale 100 s	5.7×10^{-4}
Diffusion $\dot{s}_{dif}$ of kinetic energy through air-hydrometeor drag force (rain drops)	$r_l \frac{V_{Tl}^2}{\tau_{vl} T}$	Liquid water mixing ratio 0.3×10^{-3} Terminal velocity 10 ms-1 Rain rate 10 mm hr-1	1.1×10^{-4}
Diffusion $\dot{s}_{dif}$ of temperature in moist air	$\frac{k_T}{\rho_a T^2}(\nabla T \cdot \nabla T)$	Conductivity $32\times10^{-4} W m^{-1} K^{-1}$ Temperature gradient 10 K m^{-1}	6.9×10^{-6}
Radiative heating	$\frac{\dot{q}_{rad}}{T}$	Radiative heating 1 K day^{-1} Air temperature 273 K	4.2×10^{-5}

Summary and conclusions

- In addition to energy, entropy production within the climate system provides additional insights of understanding climate system
- Processes associated with clouds and precipitations accounts for most of entropy productions by irreversible processes in the atmosphere.