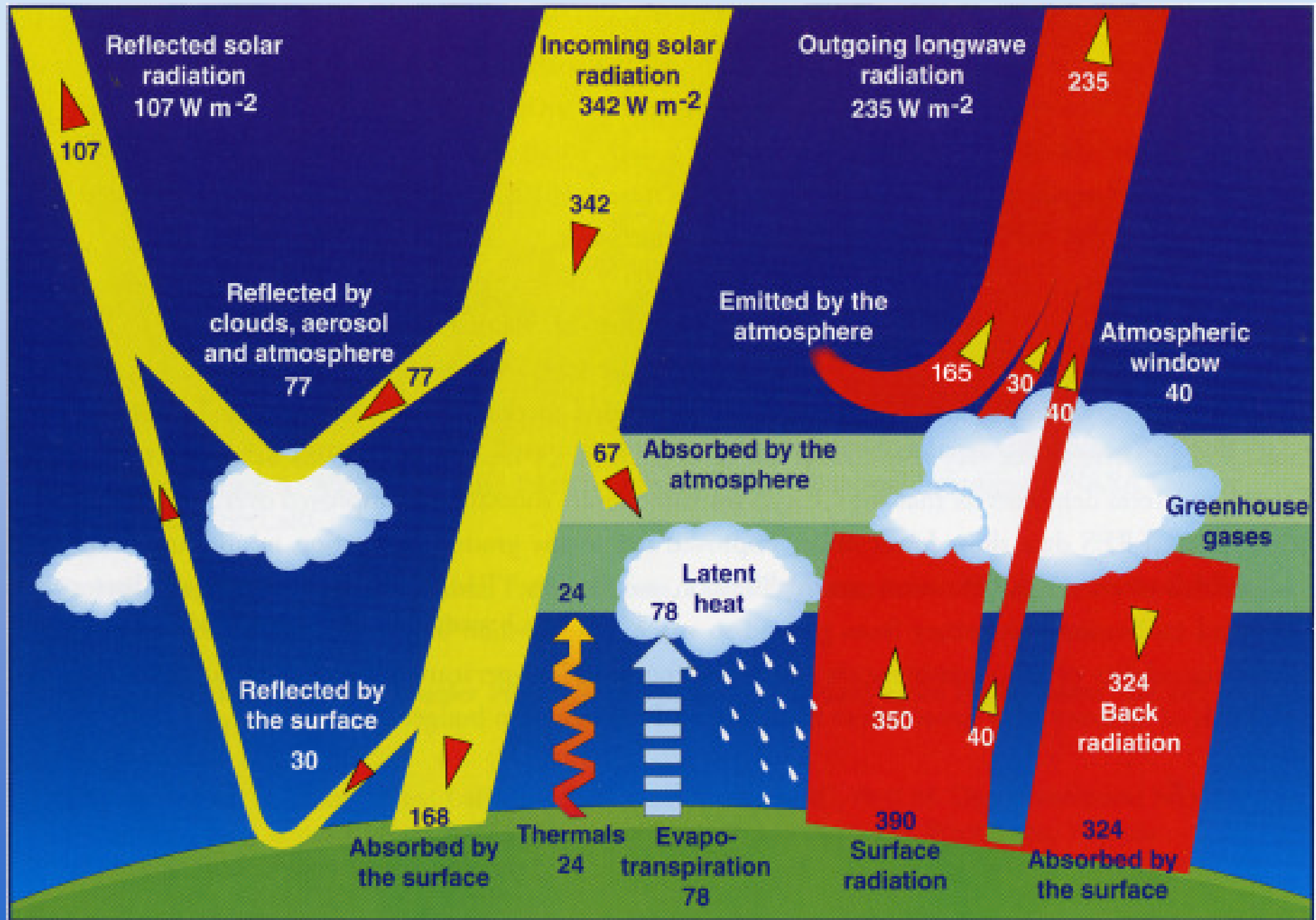


Energy and Entropy Budget

Earth Energy Budget



Source: Kiehl and Trenberth

The Earth's Entropy Budget

<http://vortexengine.ca>

Outgoing entropy flux
radiated from the earth's
atmosphere back to space

$$= 240 \text{ W/m}^2 / 255 \text{ K}$$

$$= 940 \text{ mW}/(\text{K}\cdot\text{m}^2)$$

Radiation
temperature
of the sun
= 5800 K

Radiation absorbed and
emitted by the earth
= 240 W/m^2

Incoming entropy flux from
solar radiation

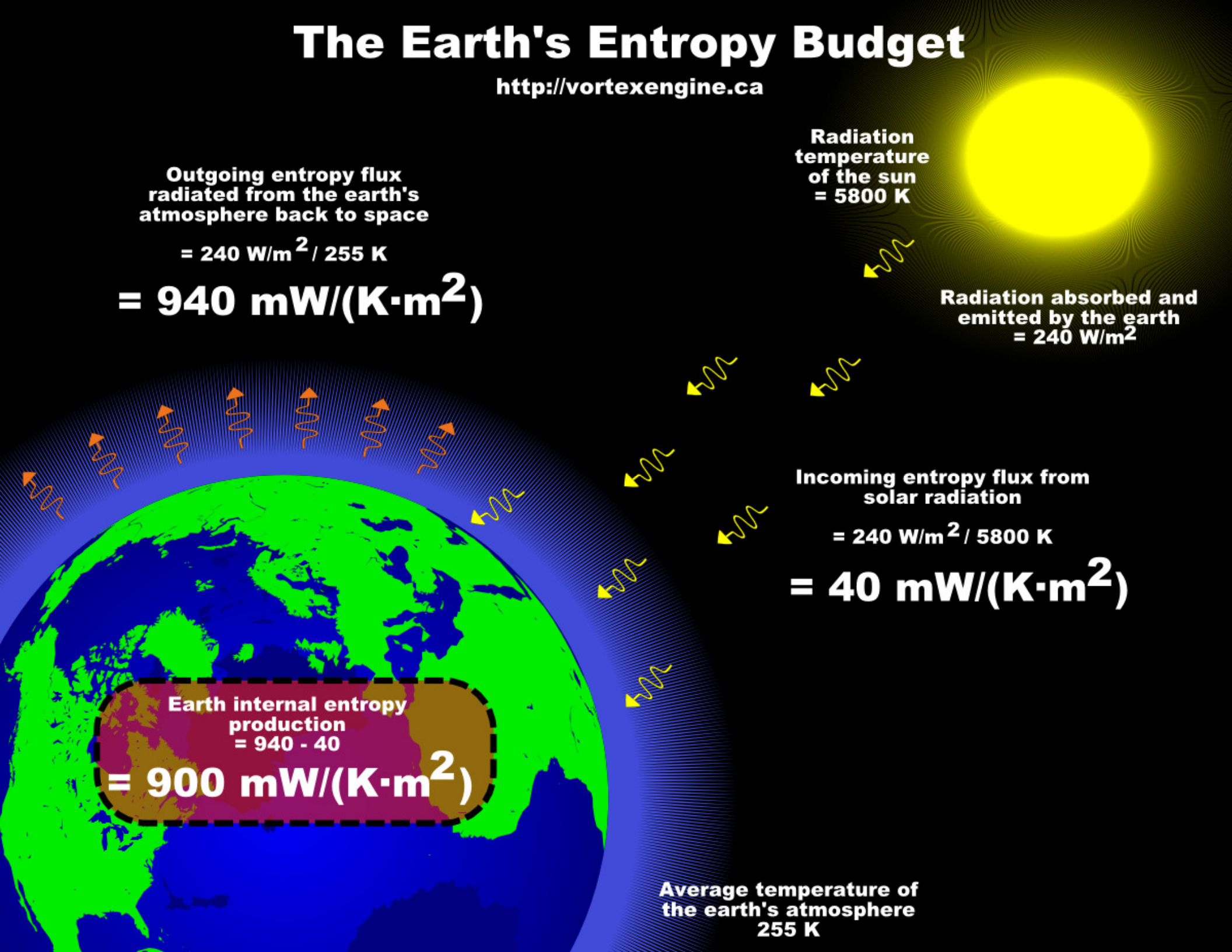
$$= 240 \text{ W/m}^2 / 5800 \text{ K}$$

$$= 40 \text{ mW}/(\text{K}\cdot\text{m}^2)$$

Earth internal entropy
production
= $940 - 40$

$$= 900 \text{ mW}/(\text{K}\cdot\text{m}^2)$$

Average temperature of
the earth's atmosphere
255 K



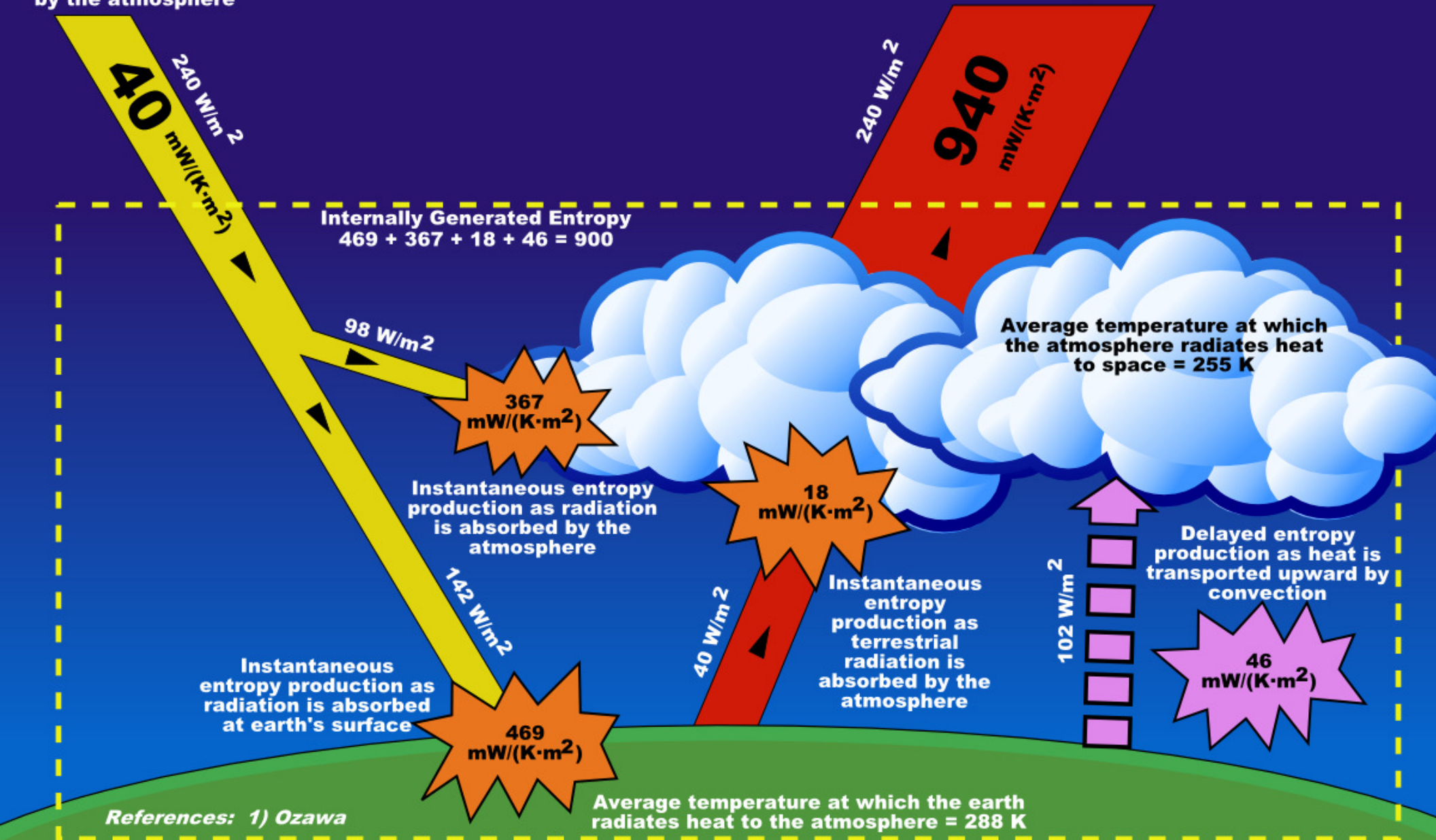
The Earth's Entropy Budget

Internal Entropy Production

<http://vortexengine.ca>

Incoming entropy flux absorbed by either the surface of the earth or by the atmosphere

Outgoing entropy flux emitted by the atmosphere back to space



41, 4 / REVIEWS OF GEOPHYSICS

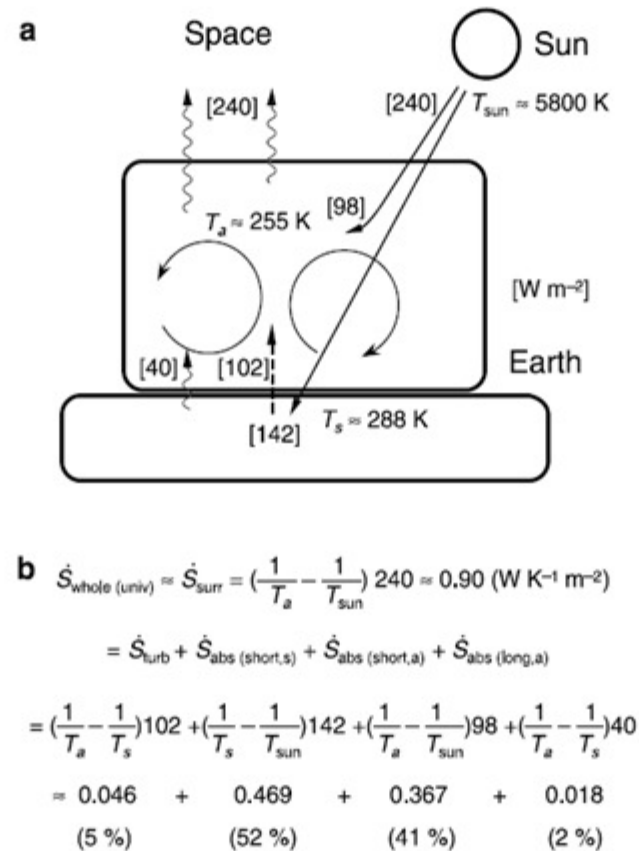
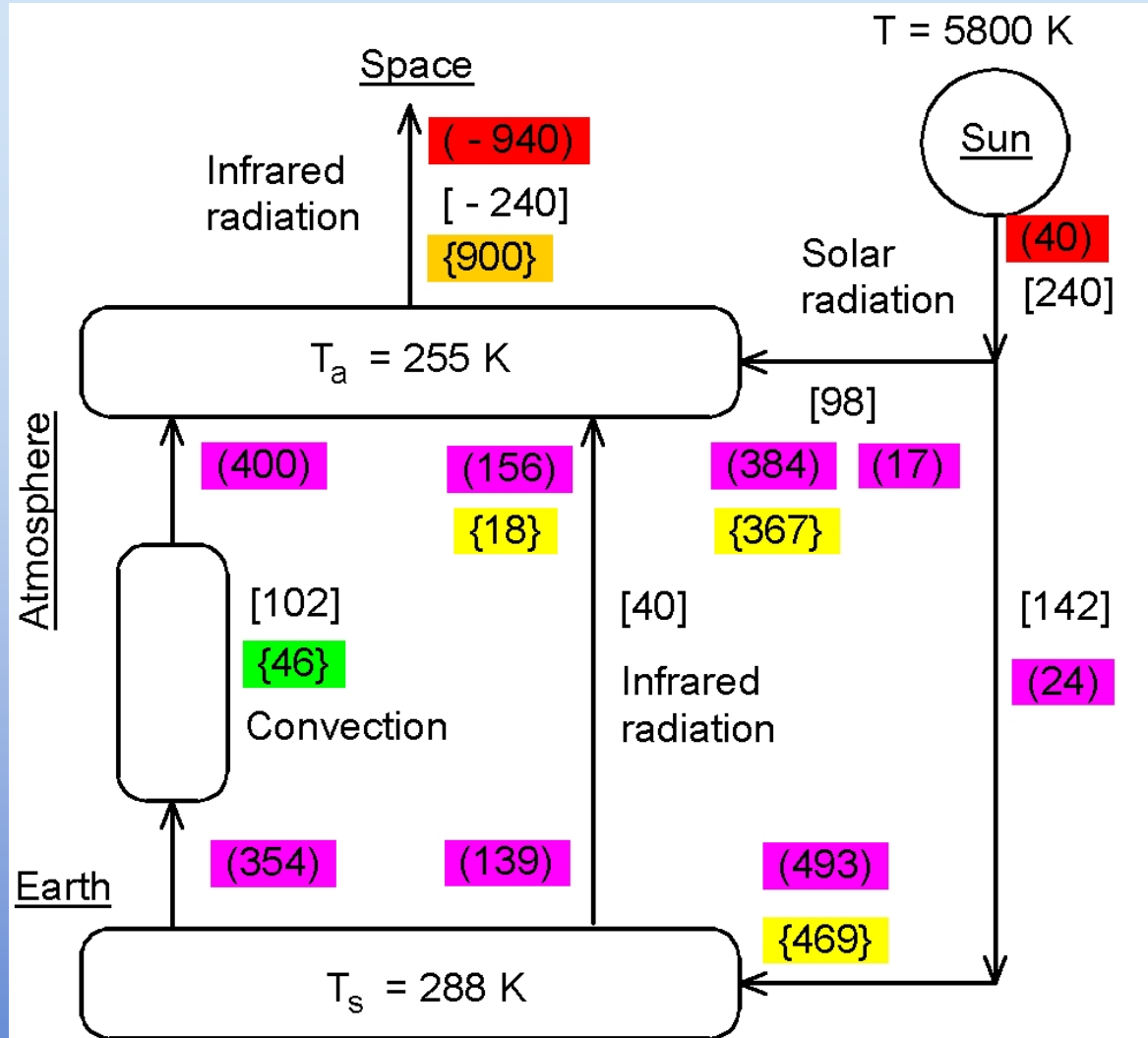


Figure 5. Energy and entropy budgets for the Earth. (a) Global-mean (surface-area mean) energy flux components (i.e., shortwave radiation, longwave radiation, vertical turbulent heat transport), in W m^{-2} . (b) Corresponding rates of entropy production in the whole system (universe) due to the irreversible processes (absorption of radiation, turbulent convection, etc.) in the climate system. The total rate of entropy production is $0.90 \text{ (W K}^{-1} \text{ m}^{-2}\text{)}$.

Earth Entropy Fluxes

and

Earth Internal Entropy Production



Energy flux [W m⁻²]

External entropy flux (mW K⁻¹ m⁻²)

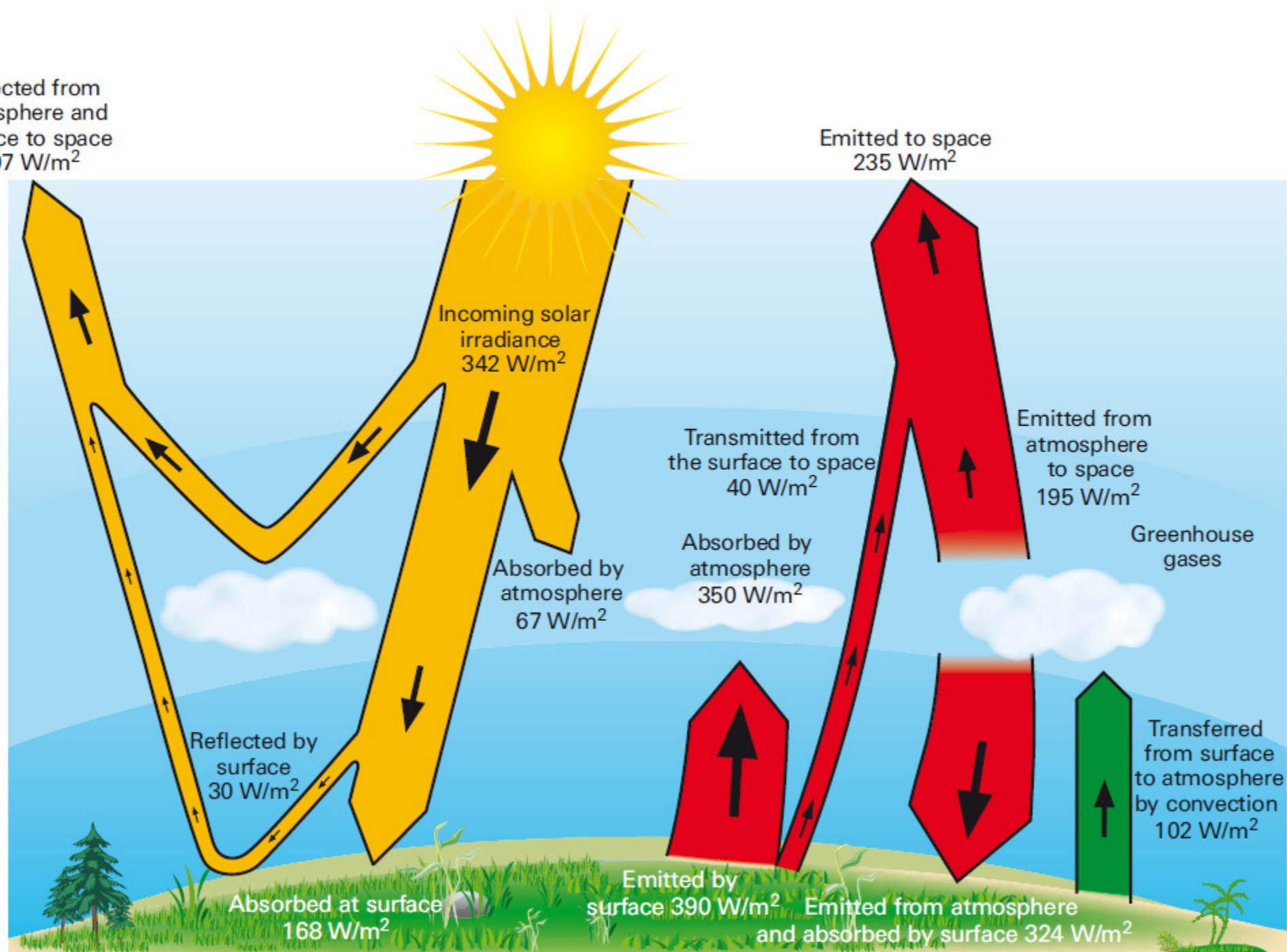
Internal entropy flux (mW K⁻¹ m⁻²)

Internal entropy production by absorption {mW K⁻¹ m⁻²}

Internal entropy production by turbulence {mW K⁻¹ m⁻²}

Internal entropy production total {mW K⁻¹ m⁻²}

Reflected from
atmosphere and
surface to space
 107 W/m^2



Energy and Entropy for Atmospheric convection

Infrared emission

$102 \text{ W/m}^2 @ 255 \text{ K}$

$$S_{eo} = 400 \text{ mW/(K m}^2\text{)}$$

↑ HEAT GIVEN UP

ATMOSPHERE

Irreversibly Internally
generated Entropy

$$S_i = 46 \text{ mW/(K m}^2\text{)}$$

↑ HEAT RECEIVED

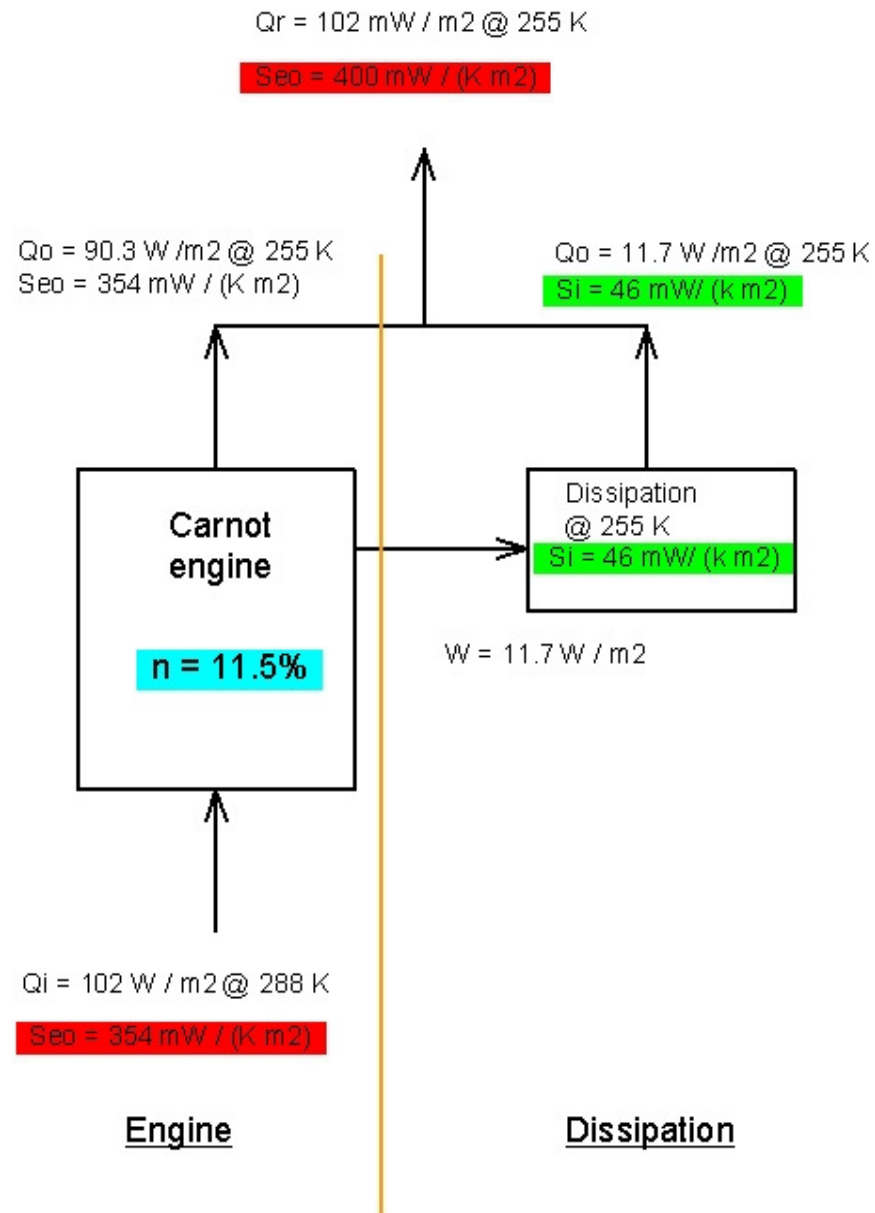
Heat received from earth surface

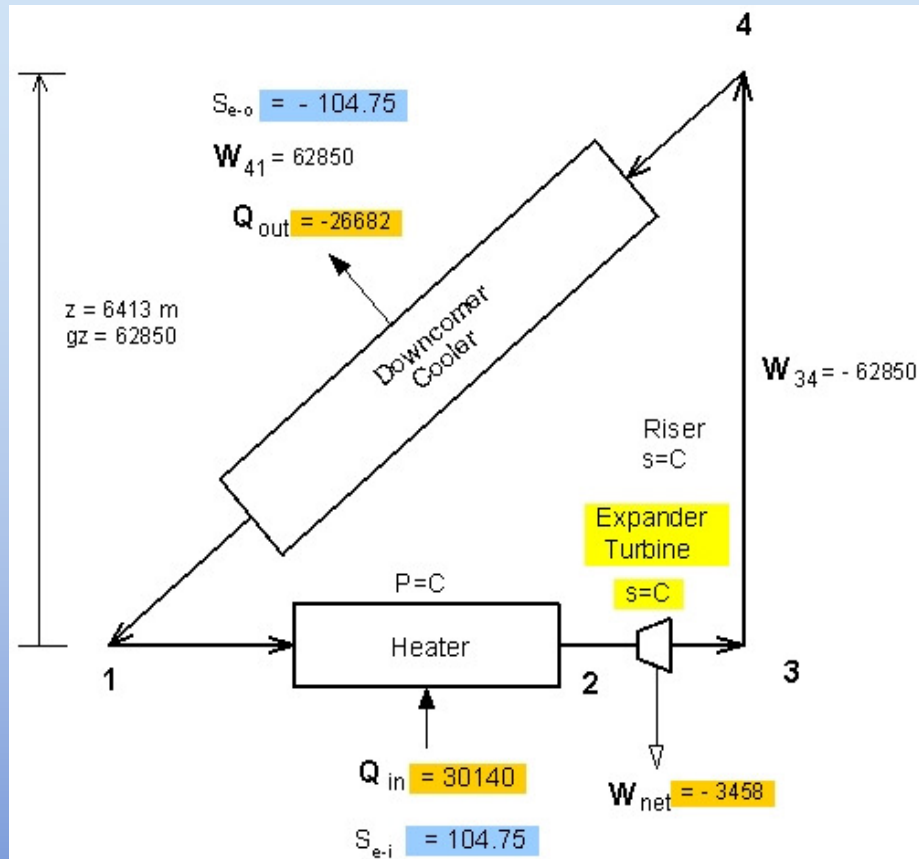
$102 \text{ W/m}^2 @ 288 \text{ K}$

$$S_{ei} = 354 \text{ mW/(K m}^2\text{)}$$

Energy and Entropy

Heat is carried by a Carnot engine followed by dissipation of the work at cold source temperature.





State	P (kPa)	T(K)	s (J/K-kg)	h (J/kg)	Duty (J/kg)
1	100	273	-0.55	-150	30140
2	100	303	104.20	29989	-3458
3	96.08	299.6	104.20	26531	-62850
4	42.32	237	104.20	-36319	36168

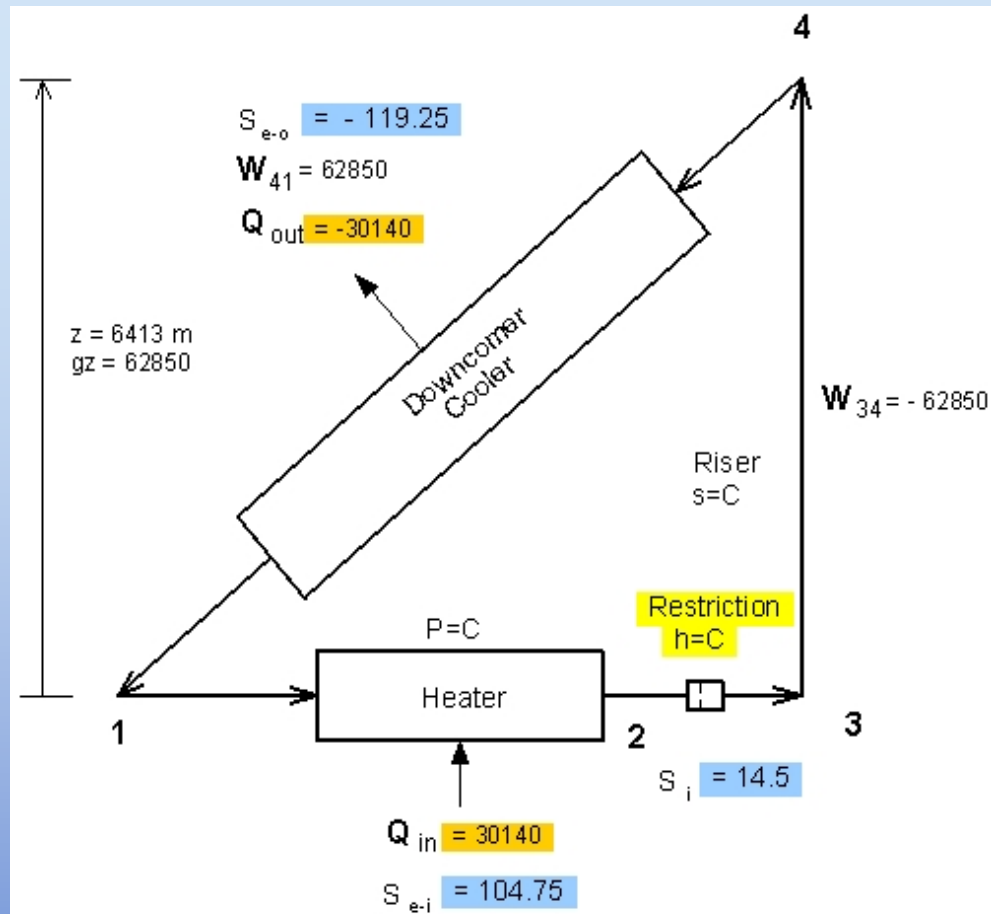
$$T_h = 288 \text{ K}$$

$$T_c = 255 \text{ K}$$

$$\text{Efficiency} = 11.47\%$$

Gravity power cycle - Reversible - Pure Air

Based on: Michaud, L. 2000: Thermodynamic Cycle of Atmospheric Upward Heat Convection. Meteorol. Atmos. Phys. 72, 29-46



State	P (kPa)	T(K)	s (J/K-kg)	h (J/kg)	Duty (J/kg)
1	100	273	-0.55	-150	30140
2	100	303	104.20	29989	0
3	95.07	303	118.70	29989	-62850
4	42.32	240.4	118.70	-32903	32710

$$T_h = 288 \text{ K}$$

$$T_c = 256.7 \text{ K}$$

$$\text{Efficiency} = 0 \%$$

Gravity power cycle - Irreversible - Pure Air

Based on: Michaud, L. 2000: Thermodynamic Cycle of Atmospheric Upward Heat Convection. Meteorol. Atmos. Phys. 72, 29-46

Energy Production Potential of the Atmospheric Vortex Engine

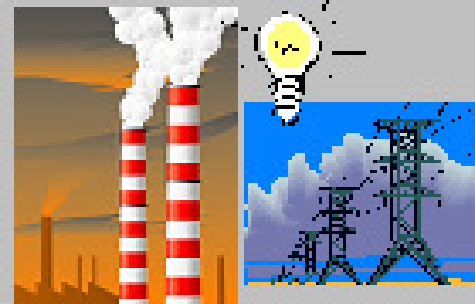
Atmospheric Vortex Engine
mechanical energy production
potential = 6,000 TW (Ref 3)
(Carnot Efficiency 12% $\times$ 52,000
TW = 6,000 TW)

Total incoming
solar radiation =
174,000 TW
(Ref 1)

Atmospheric
upward heat
convection =
52,000 TW
(Ref 1)

Total global energy production rate = 15 TW (Ref 2)

Total global electrical energy
production rate = 2 TW (Ref 2)

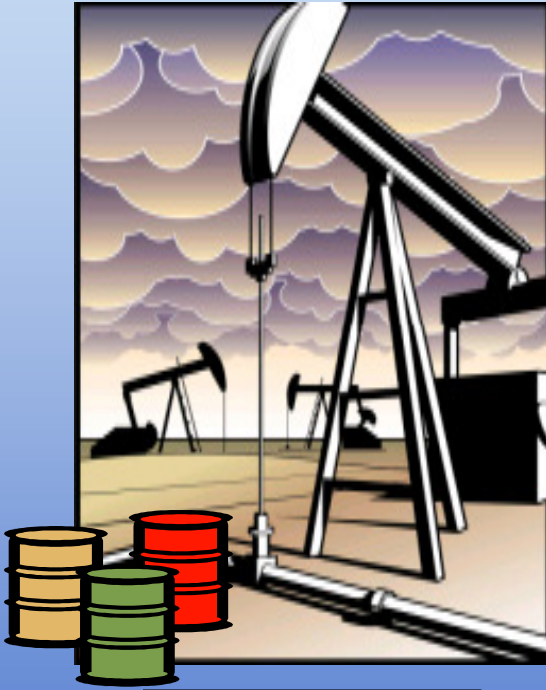


References:

- (1) Tremberth and NASA
- (2) US Department of Energy
- (3) L.M. Michaud

A Comparison of the Earth's Stored Energy Resources

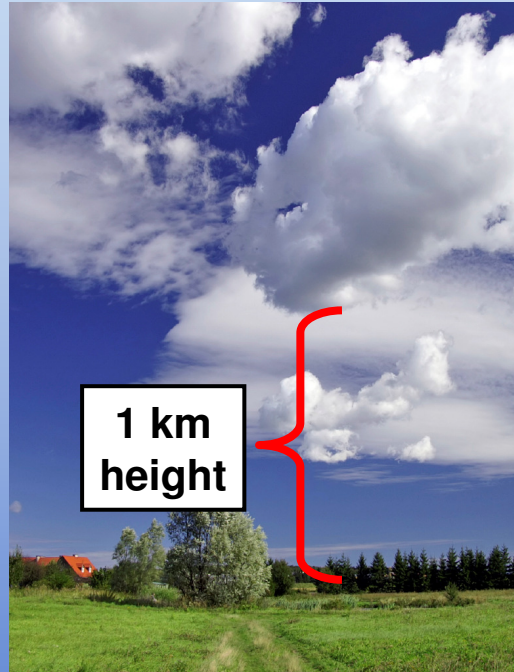
Crude Oil Reserves



$7.3 \times 10^{21} \text{ J}$



Latent heat of water vapor in the bottom kilometer of the atmosphere



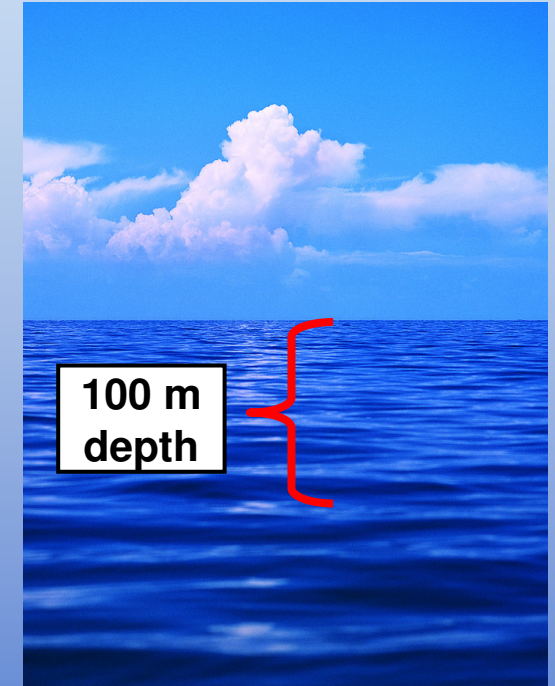
1 km height

$13 \times 10^{21} \text{ J}$



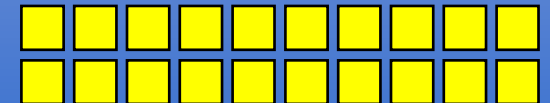
Heat content of tropical ocean water

100 m layer, 3°C



100 m depth

$130 \times 10^{21} \text{ J}$



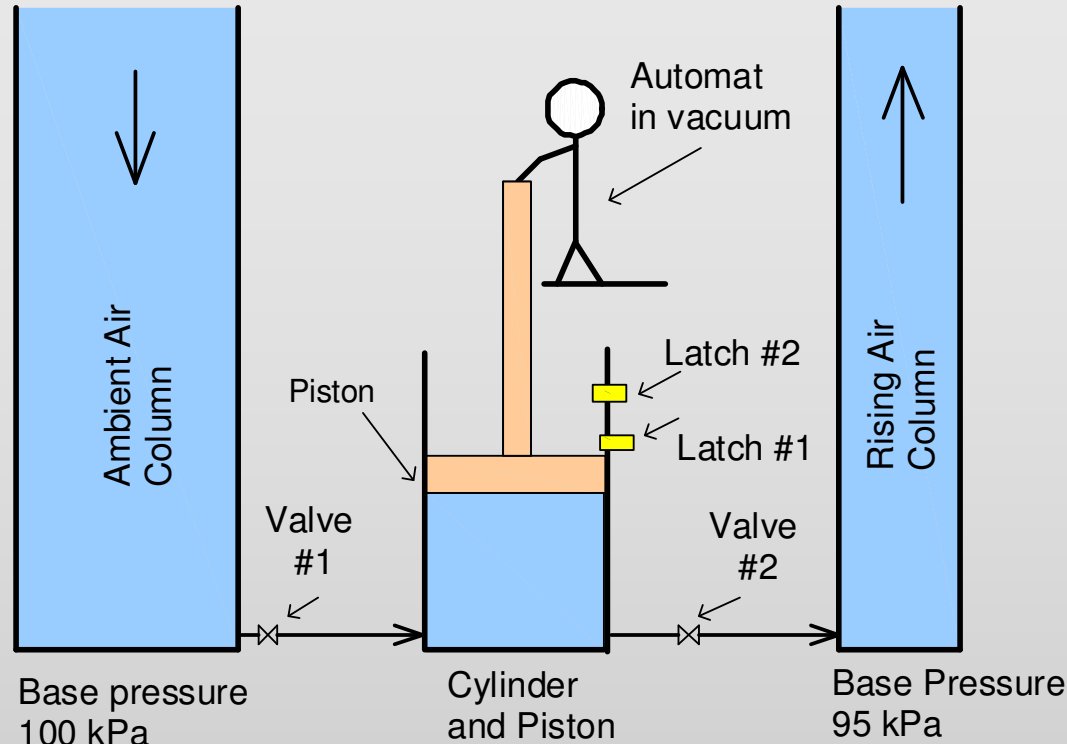
Replenishment times

10^8 years

10 days

100 days

Reversible and Irreversible Expansion



Constrained reversible expansion - Work is produced - No Latch

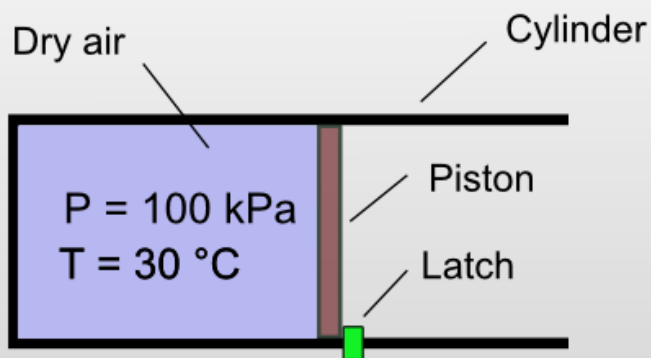
1. Start with piston at bottom of the cylinder, open valve #1,
2. Automat raises piston and let 1 kg of air at 100 kPa in cylinder,
3. Close valve #1,
4. Automat raises piston until cylinder pressure decreases to 95 kPa,
5. Open valve #2,
6. Automat pushes piston to the bottom of the cylinder.

The air temperature decreases.

Unconstrained irreversible expansion - No work is produced - Two Latches

- 1-3. As above except after step 3. set latch #1 and #2, set latch #2 so that the final pressure is 95 kPa,
4. Automat lets go of the piston,
5. Let go latch #1, piston snaps against latch #2 without doing any work,
6. Automat pushes piston to the bottom of the cylinder.

The air temperature does not decrease.

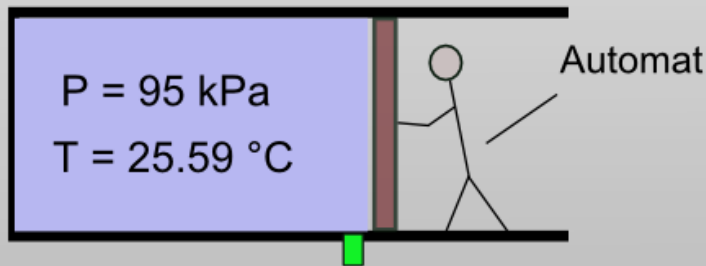


INITIAL CONDITION

Work production requires that expansion be restrained

Ambient pressure: $P = 95 \text{ kPa}$

Initial pressure difference: 5 kPa

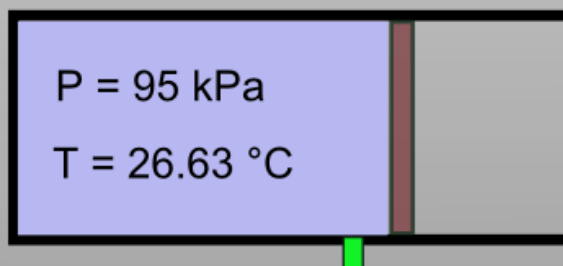


AFTER RESTRAINED
ISENTROPIC EXPANSION

Work against environment 3085 J

Work against automat 1346 J

Total work 4431 J



AFTER UNRESTRAINED
EXPANSION

Work against environment 3384 J

Total work 3384 J

Loss work 1047 J

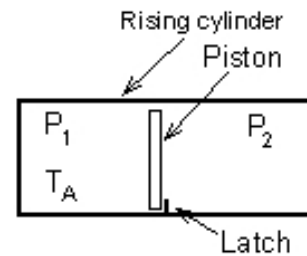
Additional enthalpy of the air 1047 J

Capturing work of expansion produced when the latch lets go requires that the expansion be restrained, otherwise the energy remains in the cylinder.

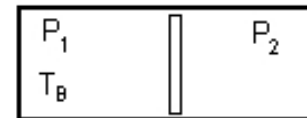
Approximately 22% of the work of expansion is lost no matter how small the initial pressure difference.

Work loss form lack of mechanical equilibrium calculation

Initial Condition



Final Condition



Reversible Expansion

$$T_{BR} = T_A (P_2 / P_1)^k$$

where $k = R / C_p = 2 / 7$

$$W_R = c_p (T_A - T_{BR})$$

Irreversible Expansion

$$T_{BI} = T_A (k (P_2 / P_1) + 1) / (k + 1)$$

from $\Delta h = P_2 (\Delta V)$

$$W_I = c_p (T_A - T_{BI})$$

Loss Work

$$W_{loss\%} = 100 (W_R - W_I) / W_R$$

$$W_{loss\%} = 100 ((k R + 1) / (k + 1) - (R)^k) / (1 - (R)^k)$$

where $R = P_2 / P_1$

Limit $W_{loss\%}$ as R approaches 1 is 22.2%

Therefore 22.2 % of the work that would be produced if the expansion were carried out at mechanical equilibrium is lost as the cylinder is raised irrespective of how small the friction between the cylinder and piston.

2004 Earth Entropy Budget

in: Kleidon, A. and Lorenz, R. D. (eds.) Non-equilibrium thermodynamics and the production of entropy: life, Earth, and beyond. Springer Verlag, in press.
© 2004 Springer Verlag, Heidelberg. ISBN: 3-540-22495-5

1 Entropy Production by Earth System Processes

5

Entropy Sources:

Shown:

- Frictional dissipation
- Latent heating
- Sensible heating

Not shown

- Mixing
- PE of precipitation dissipation
- Diffusion

Answer:

- None of the above:
Free or unconstrained expansion

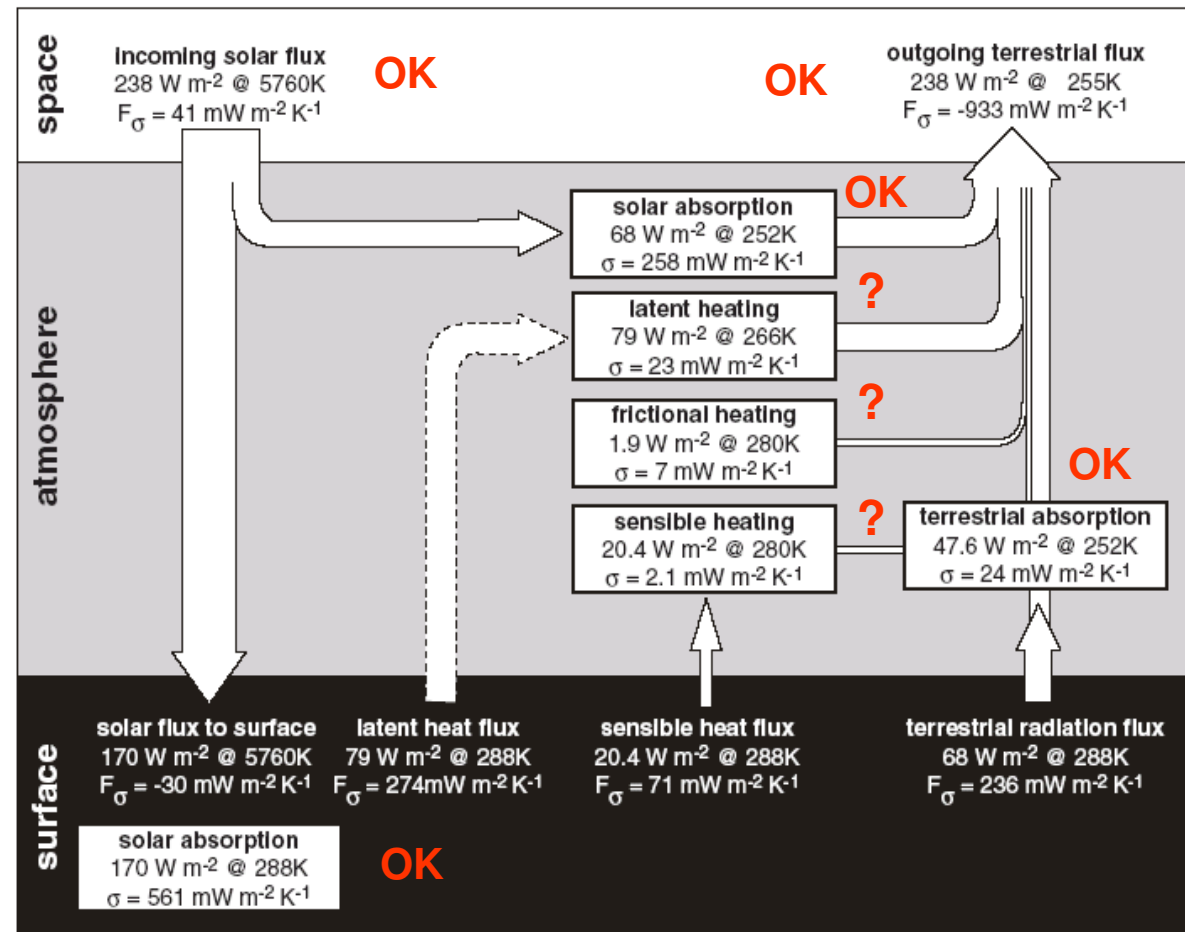


Fig. 1.2. Global budget of entropy production by diabatic Earth system processes. Based on Peixoto et al. (1991). Note that the latent heat flux has been corrected from Peixoto et al.'s estimate