Trenberth's (2022) Greenhouse Geometry and its Representation on the Earth's Atmosphere Part I. The Physical Science Basis

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Supplementary Video for a talk given at the
EGU General Assembly, 18 April 2024, Vienna, Austria
Session CL2.1 – Earth radiation budget, radiative forcing and climate change
Conveners Martin Wild, Jörg Trentmann, Paul Stackhouse

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Part I
OBSERVATIONS

Chapter 1.1
Trenberth's Greenhouse Geometry

Kevin E. Trenberth (2022):
The Changing Flow of Energy Through the Climate System

Sidebar 3.2: How Does a Greenhouse Effect Work?

(page 30: Earth's Energy Balance)

The answer is:

Imagine two plates in space

Incoming solar radiation: 240 Wm^{-2}

The plate is two-sided: 480 Wm^{-2}

Five panels, four equations.

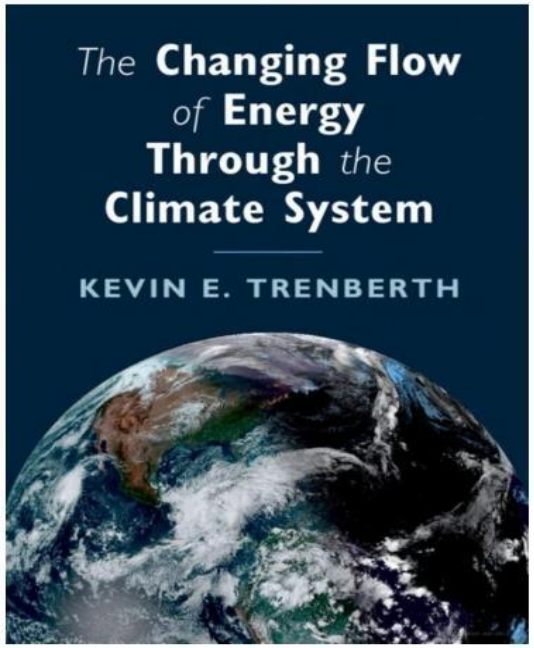


Fig. 3.3. Panel 1

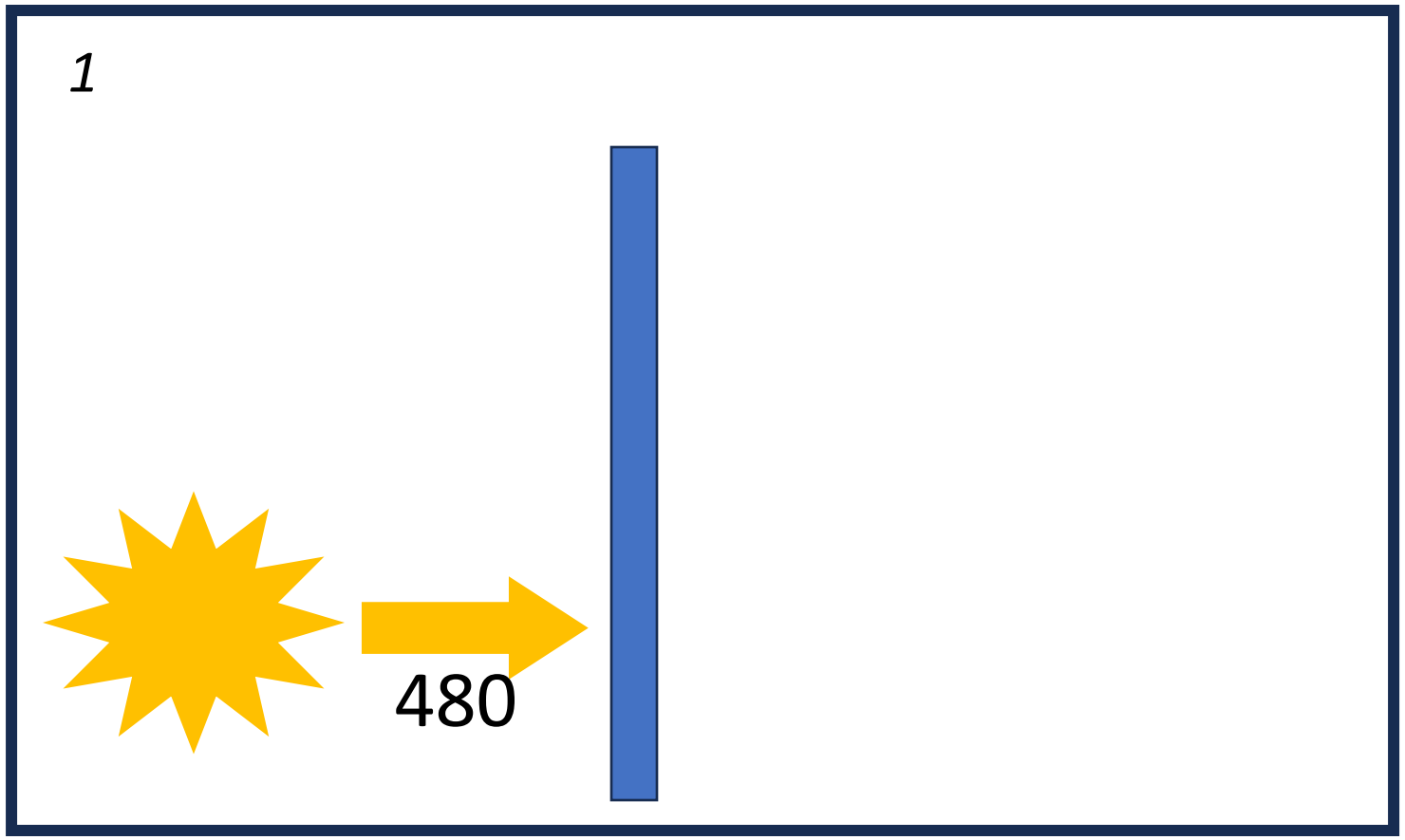


Fig. 3.3. Panel 2

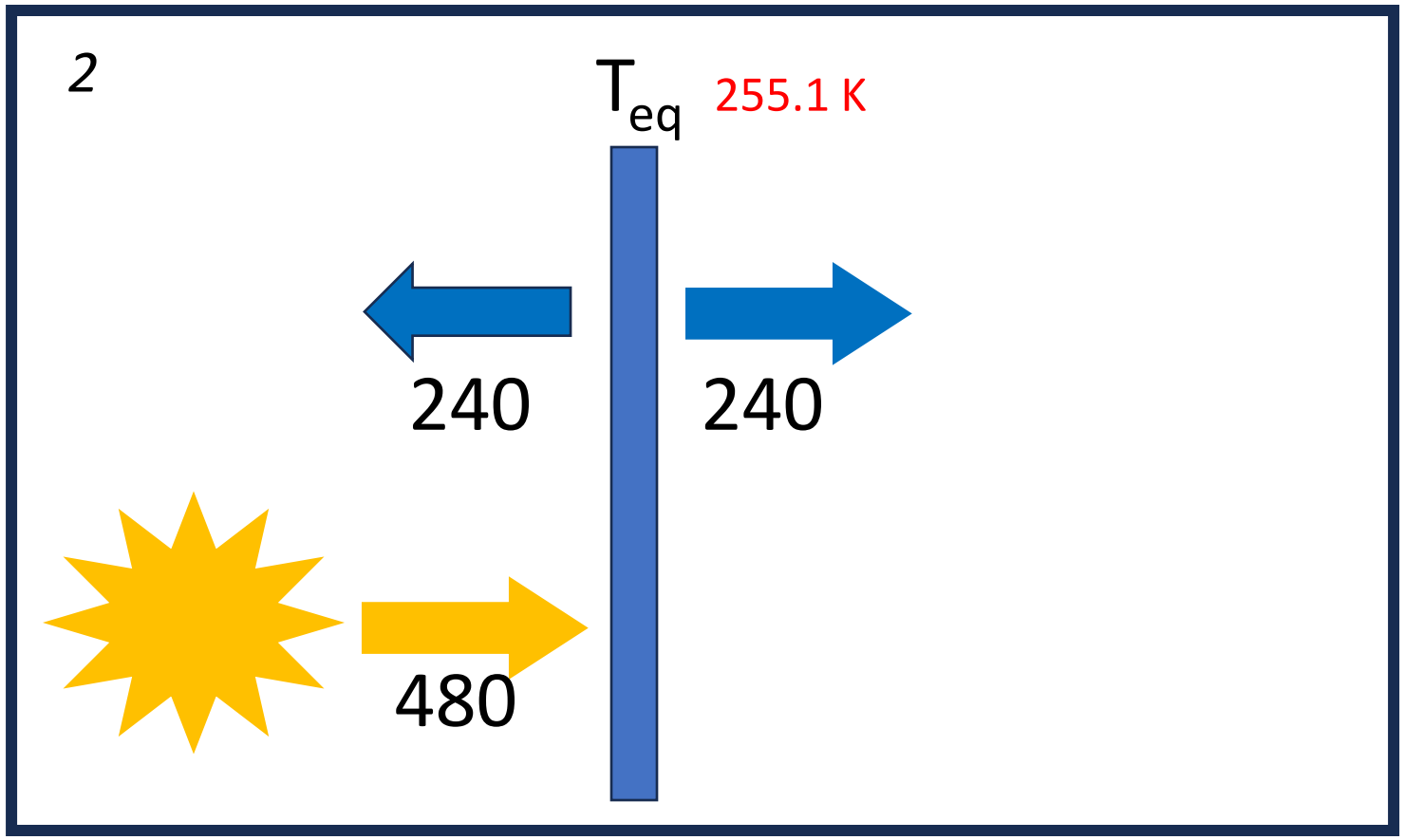


Fig. 3.3. Panel 3

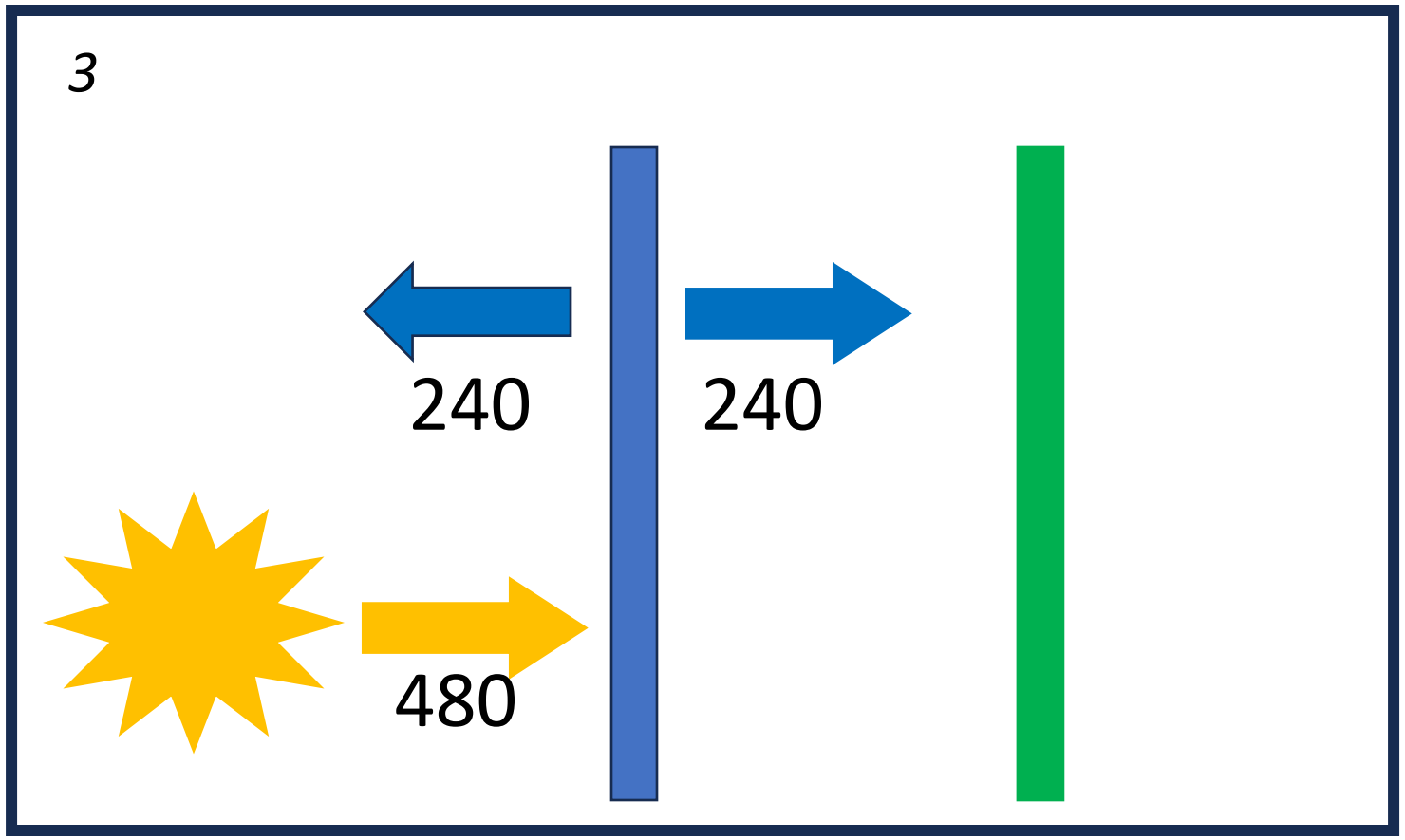


Fig. 3.3. Panel 4

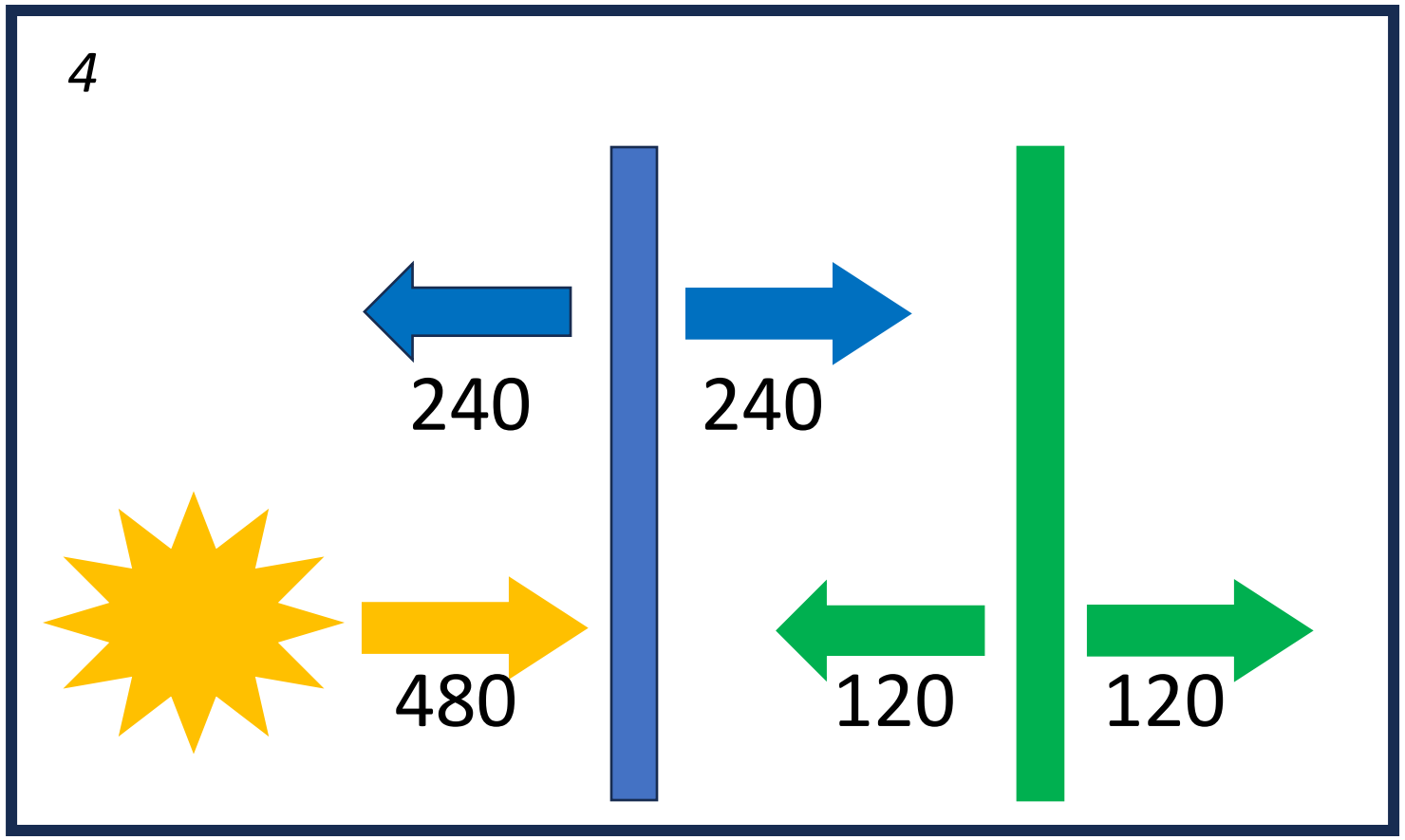
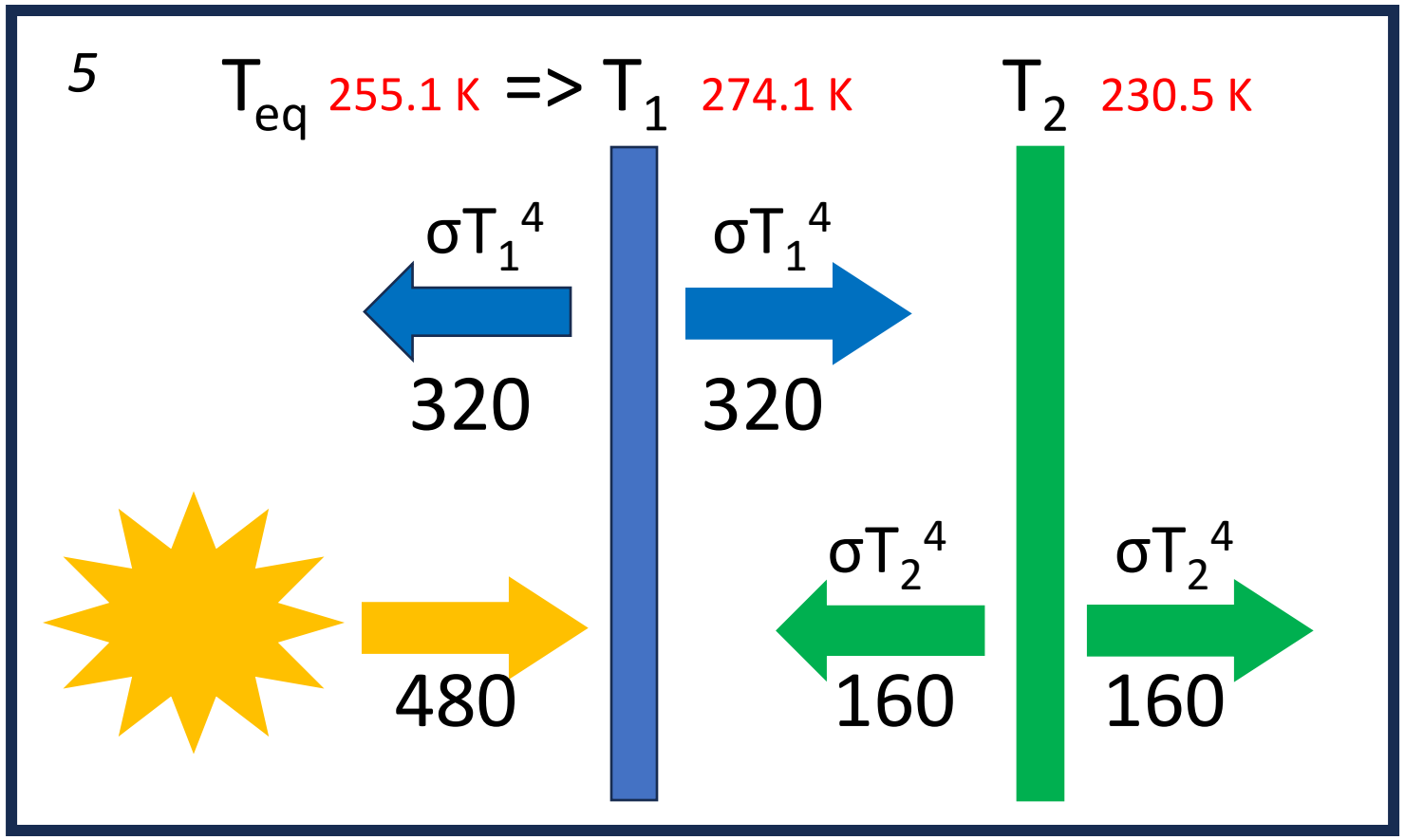
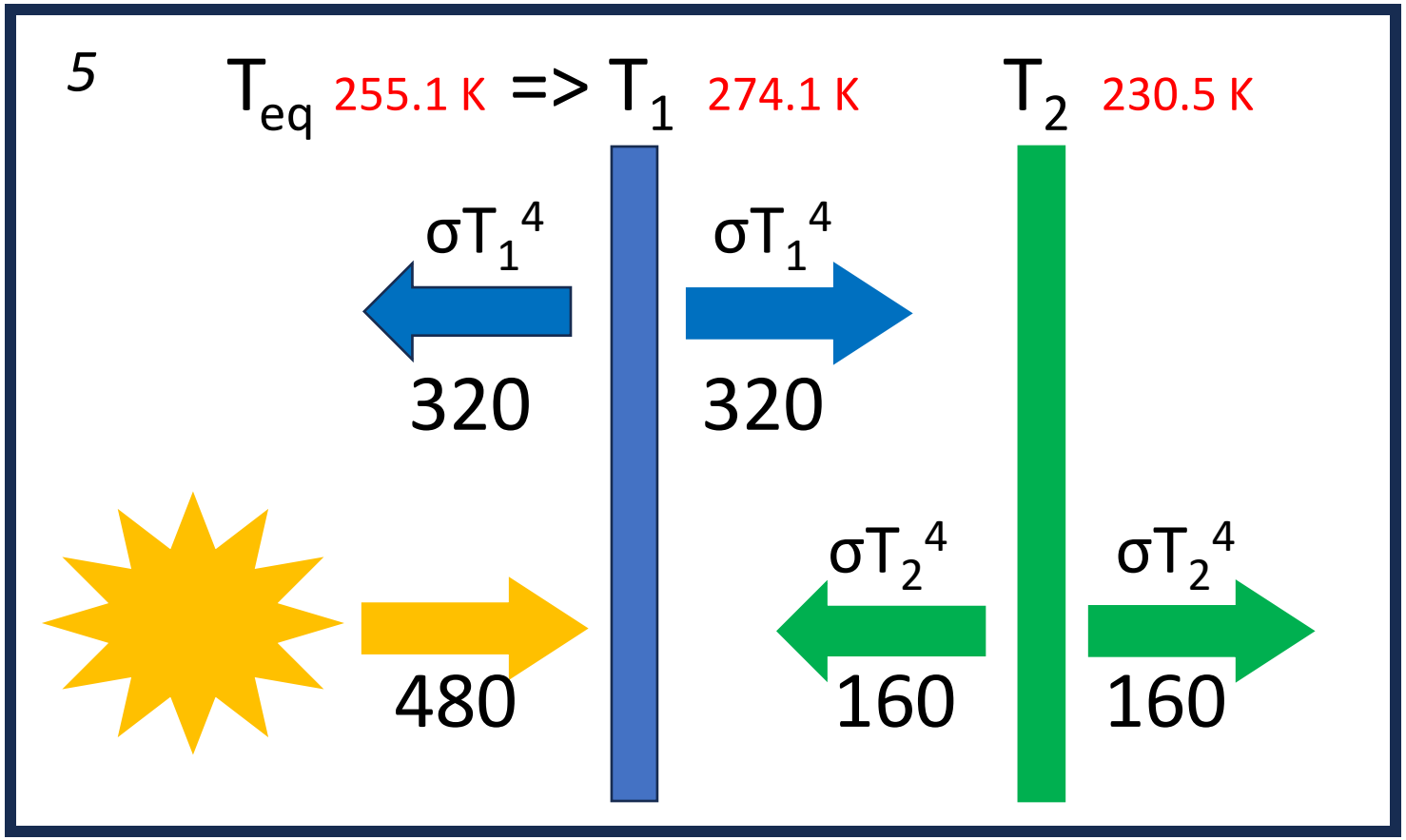


Fig. 3.3. Panel 5: The final state



The final state



$G : F_2 : F_{eq} : F_1 : F_{sol} = 1 : 2 : 3 : 4 : 6$

Trenberth's four equations

(T1) $480\ Wm^{-2} = 2\sigma T_{eq}^4$

(T2) $480\ Wm^{-2} = \sigma T_1^4 + \sigma T_2^4$

(T3) $\sigma T_1^4 = 2\sigma T_2^4$

(T4) $480\ Wm^{-2} = 1.5\ \sigma T_1^4$

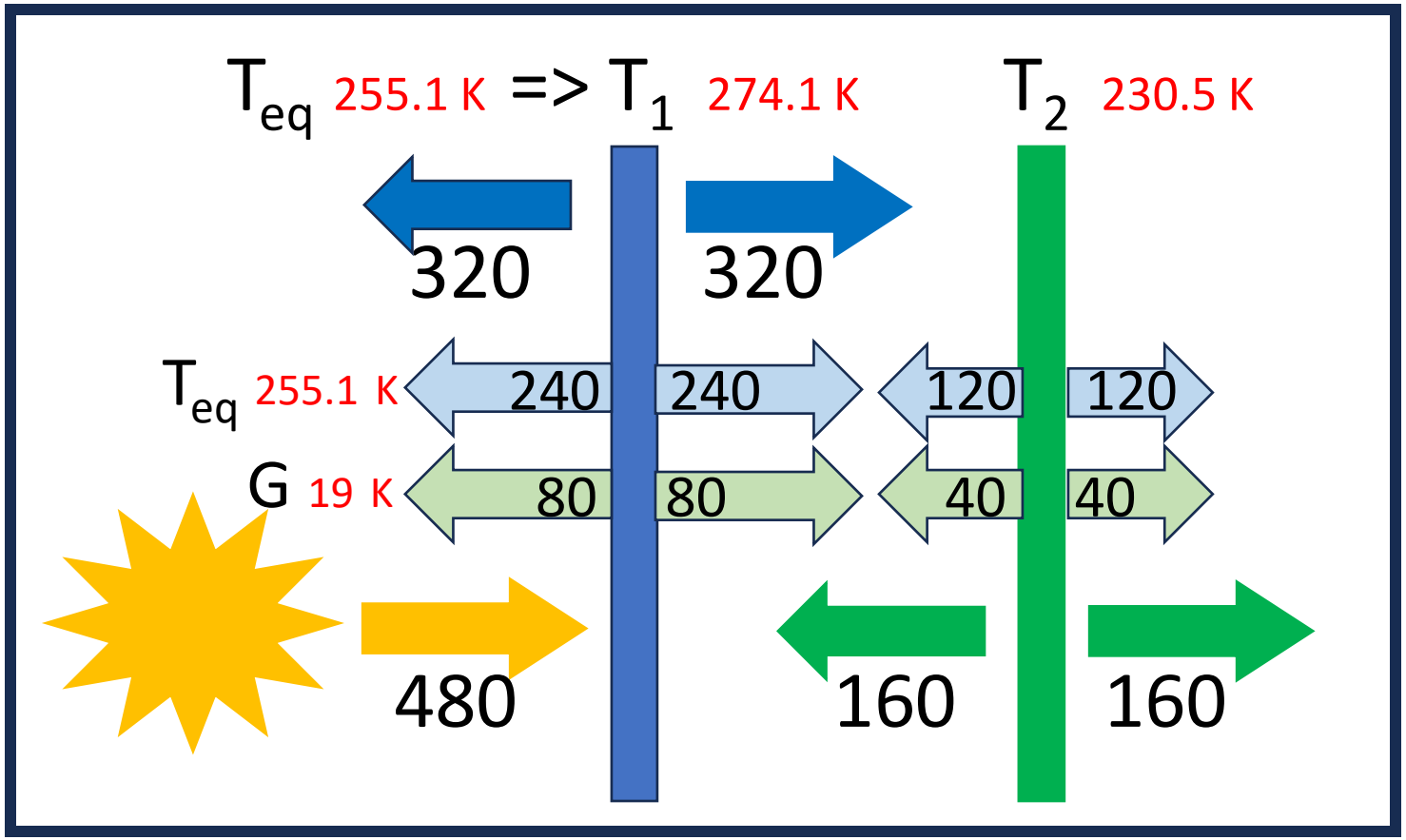
$F_{sol} = 480\ Wm^{-2}$

$F_1 = 320\ Wm^{-2}$

$F_{eq} = 240\ Wm^{-2}$

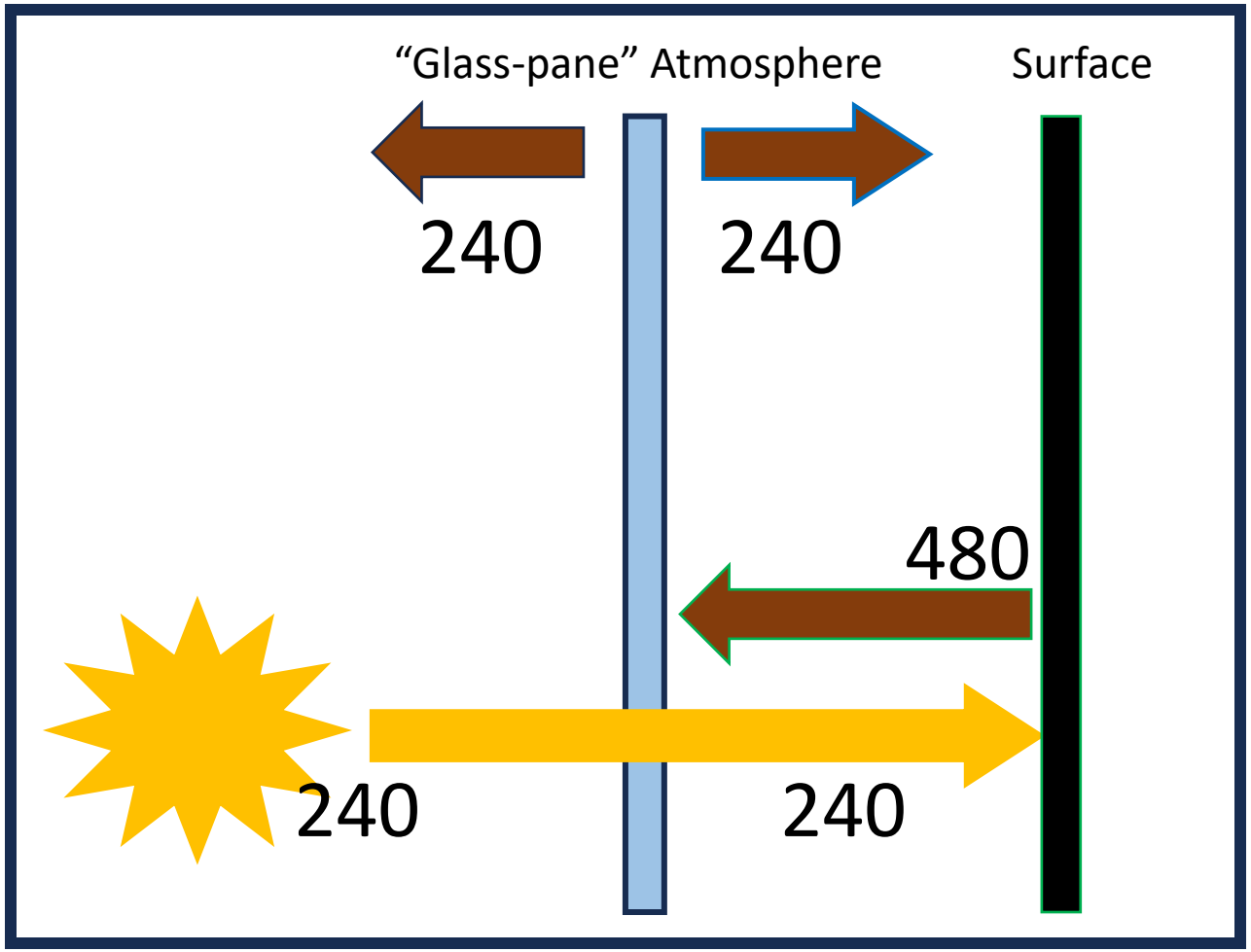
$F_2 = 160\ Wm^{-2}$

$G = 80\ Wm^{-2}$



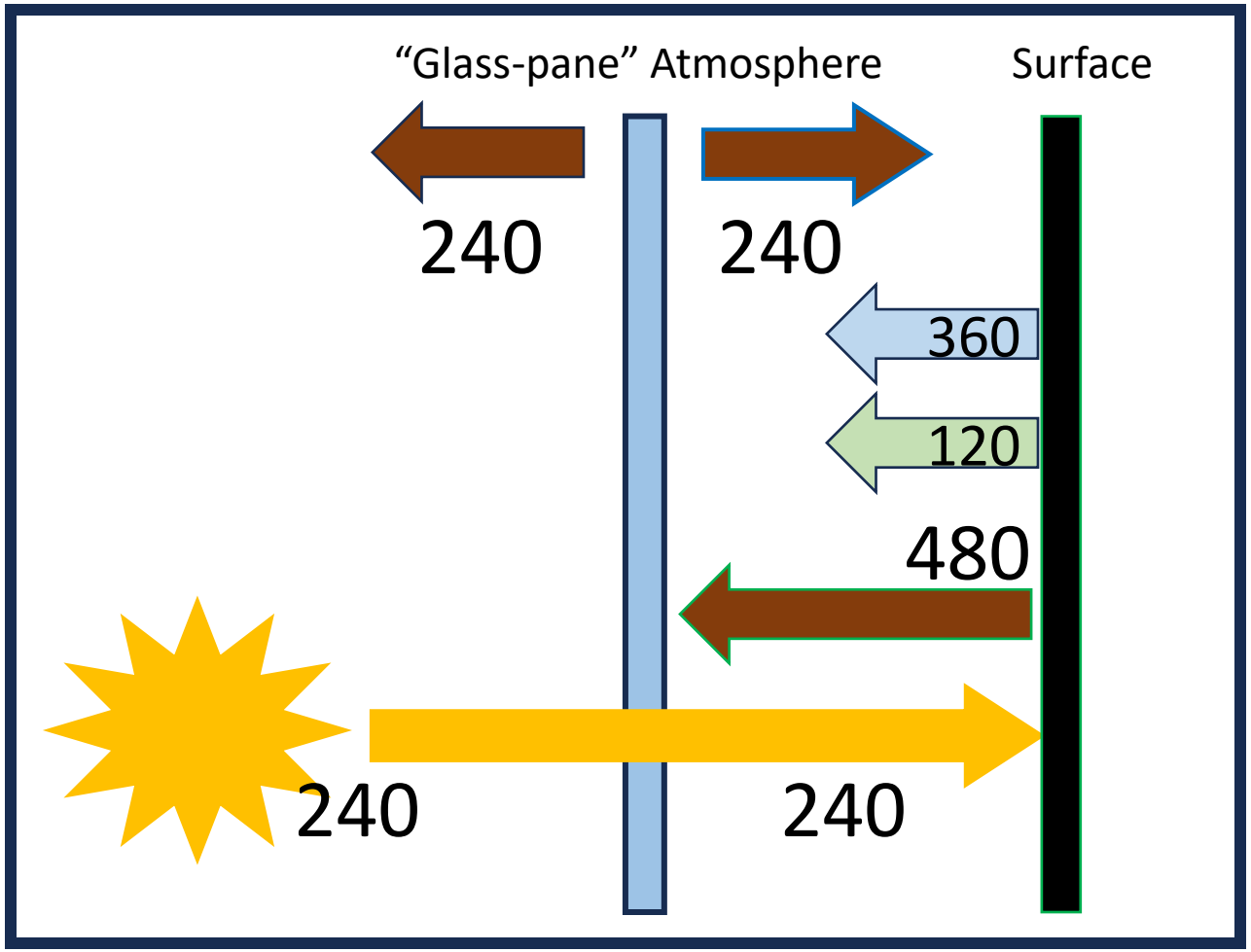
Let me insert the virtual components: 80/240 = 1/3.

$G : F_2 : F_{eq} : F_1 : F_{sol} = 1 : 2 : 3 : 4 : 6$



But that system was open at both sides;

For Earth-like application, a surface and a solar-transparent, IR-opaque „glass-pane” atmosphere should be introduced

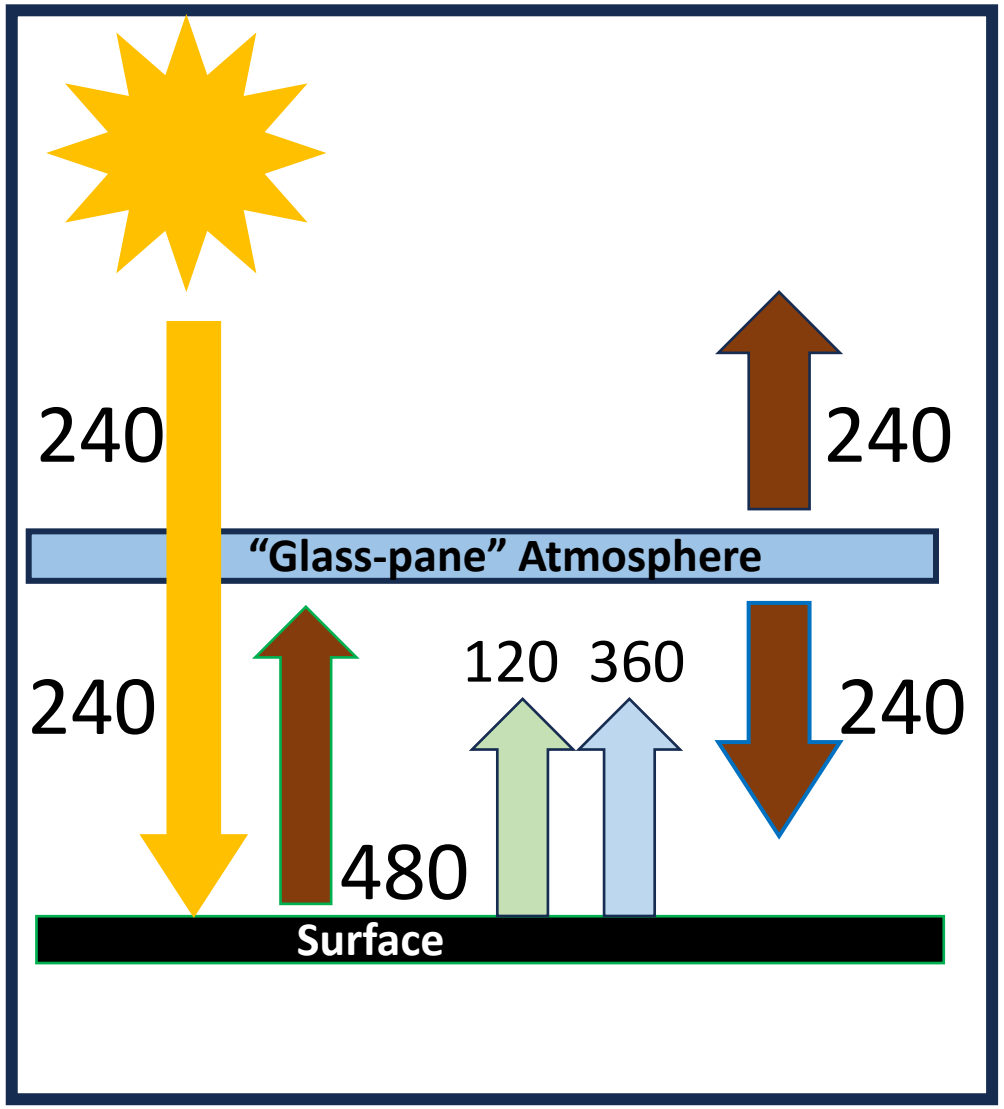


The components:
120/360 = 1/3.

Let’s put it on its feet.

This is the Earth-like geometry.

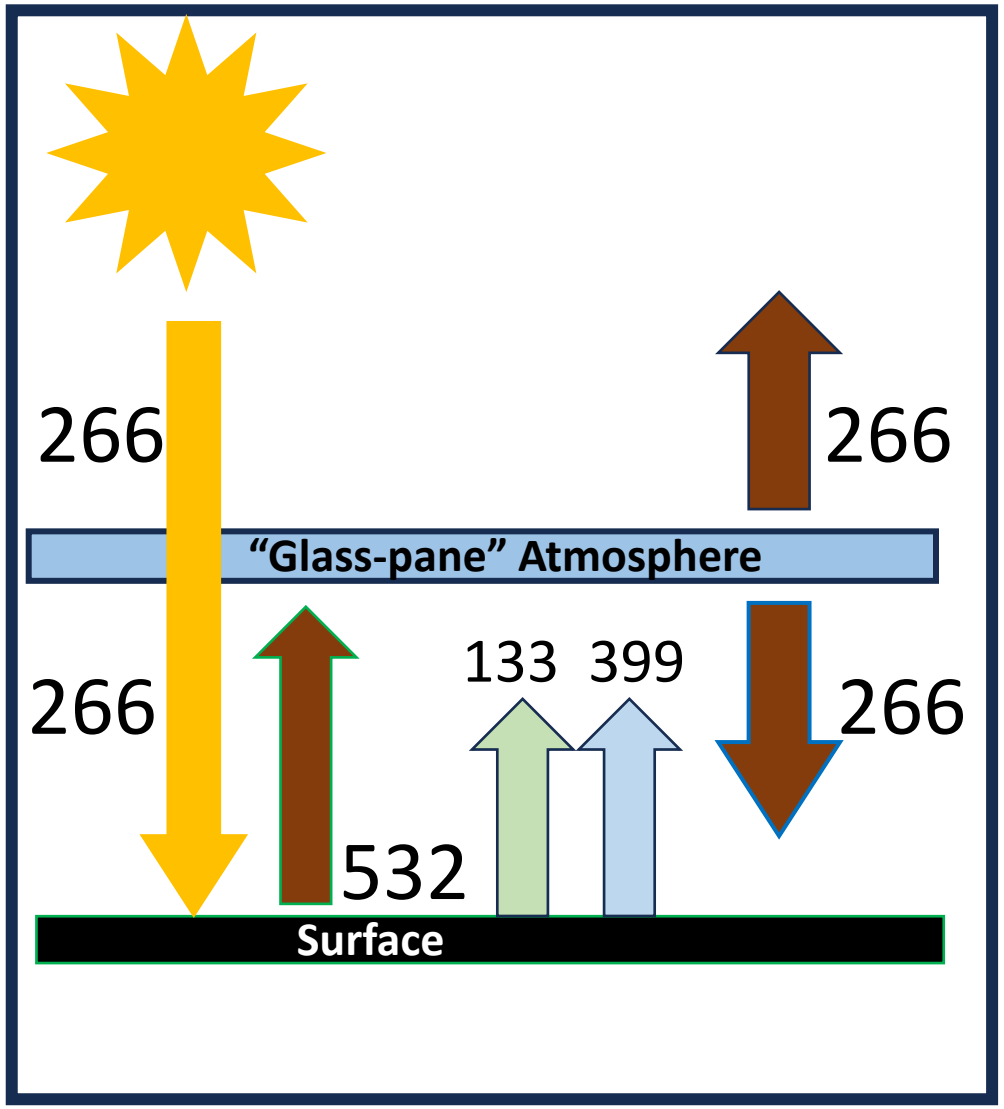
We will compare it to real Earth data.



Let us upcale incoming solar from 240 to 266, (for the clear-sky OLR)

Nothing else was changed, the ratios are the same.

And let us compare this to real-Earth data.



Starting point: the simplest greenhouse geometry, a single-layer atmospheric model

Dennis Hartmann: Global Physical Climatology (1994, 2016) Fig. 2.3

2.5 Greenhouse Effect

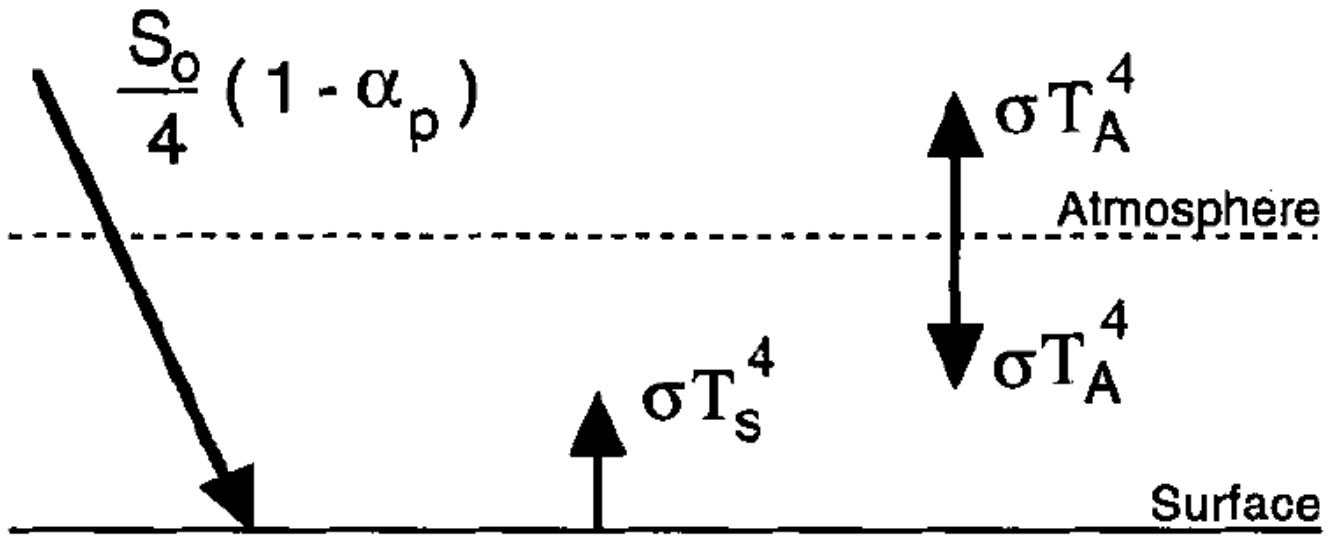


Fig. 2.3 Diagram of the energy fluxes for a planet with an atmosphere that is transparent for solar radiation but opaque to terrestrial radiation.

Starting point: the simplest greenhouse geometry, a single-layer atmospheric model

Dennis Hartmann: Global Physical Climatology (1994, 2016) Fig. 2.3

2.5 Greenhouse Effect

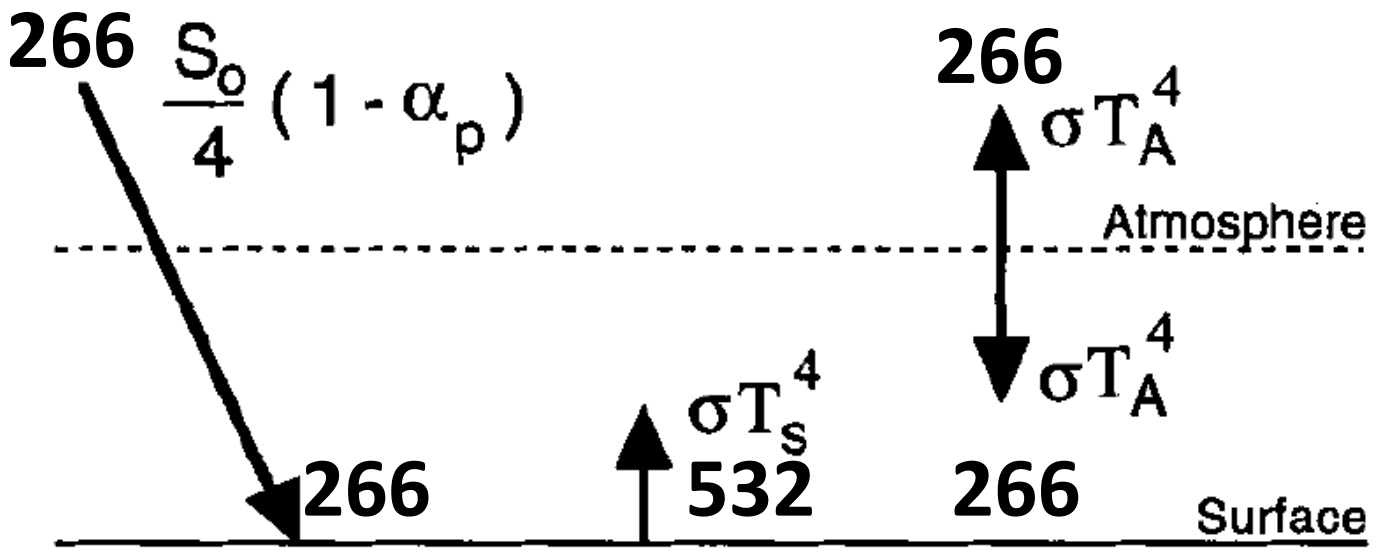
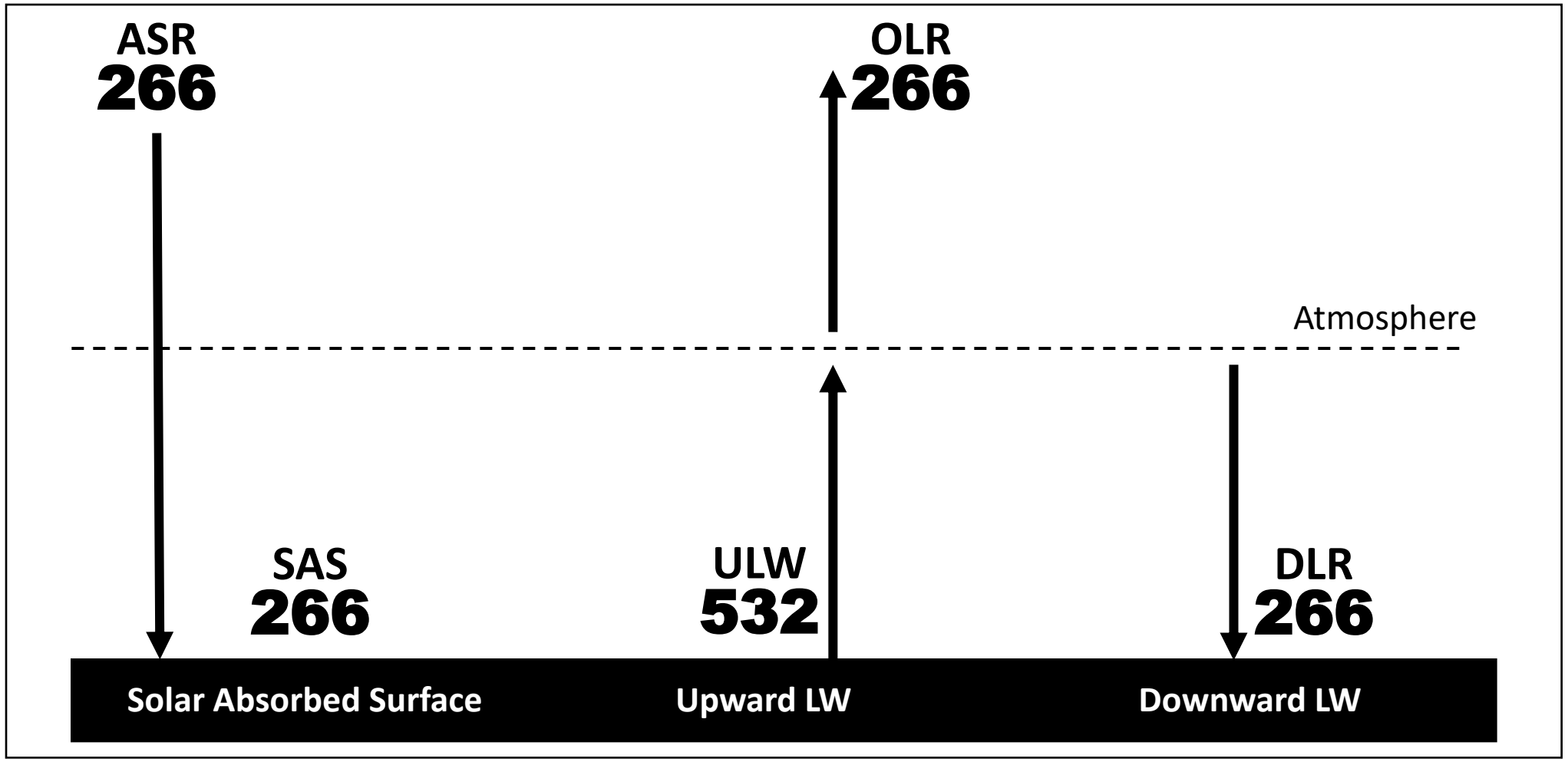


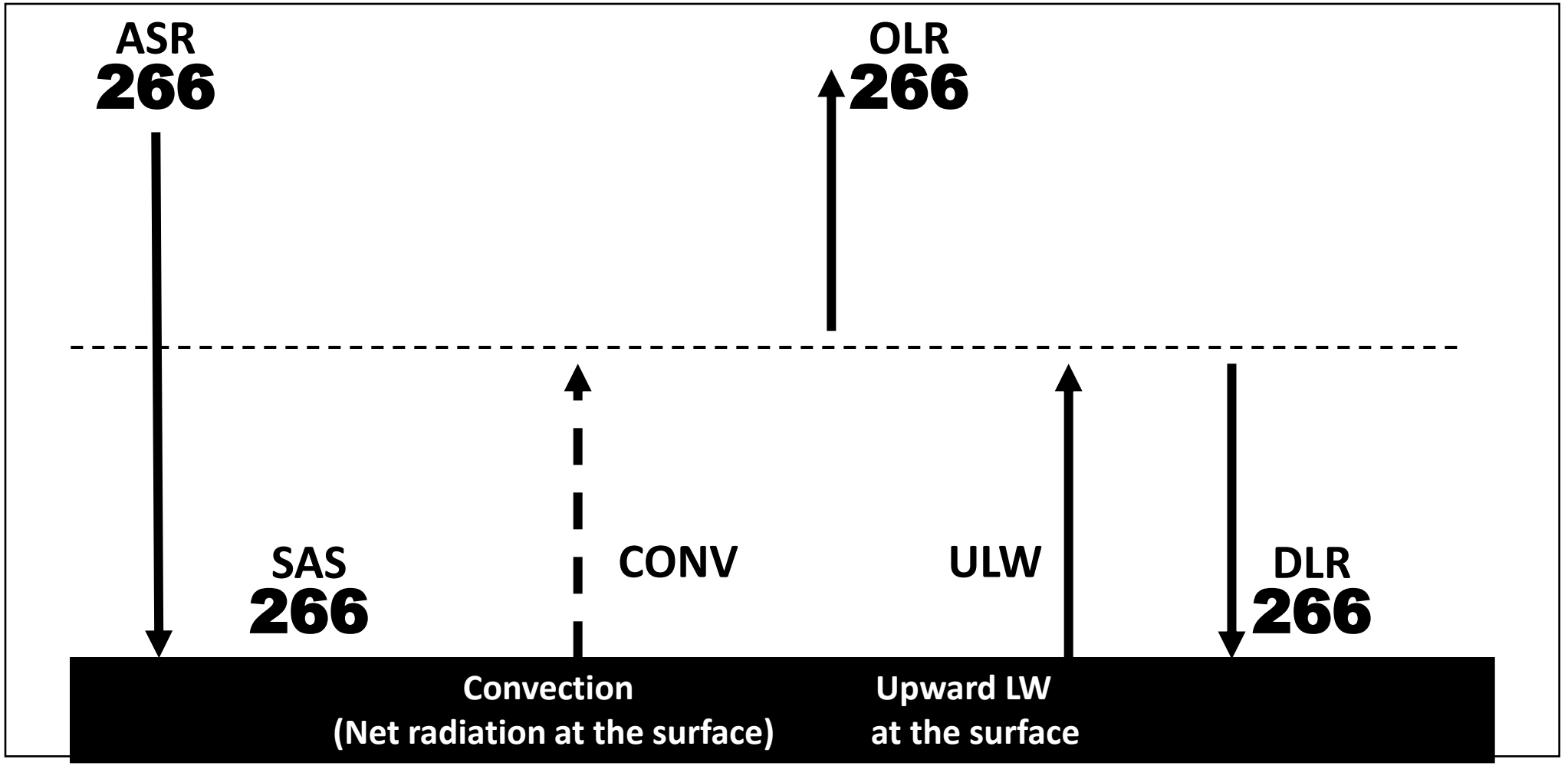
Fig. 2.3 Diagram of the energy fluxes for a planet with an atmosphere that is transparent for solar radiation but opaque to terrestrial radiation.

Single-layer geometry



Simplest greenhouse model

Earth-like atmosphere: Convection
(Net radiation at the surface)



How much is that?

Chapter 1.2
A Constraint on Convection

Emden, 1913

Sitzungsberichte

mathematisch-physikalischen Klasse

der

K. B. Akademie der Wissenschaften

Über Strahlungsgleichgewicht und atmosphärische Strahlung.

Ein Beitrag zur Theorie der oberen Inversion.

Von **R. Emden.**

Vorgelegt von S. Finsterwalder in der Sitzung am 1. Februar 1913.

89) $$T_{\text{Erde}} = 254^0 \sqrt[4]{2{,}2} = 309^0 = +36^0.$$

An der Berührungsfläche Atmosphäre und Erde ergibt sich somit ein Temperatursprung von 20° C, der in Wirklichkeit durch äußere Wärmeleitung stark herabgesetzt wird, namentlich auf Wasser, wo der Wasserdampf mit der Temperatur der Oberfläche in die Atmosphäre übertritt. Auch diese Strahlungstemperatur der Erdoberfläche hat einen durchaus annehmbaren Wert.

MONTHLY WEATHER REVIEW. AUGUST, 1916

RADIATION EQUILIBRIUM AND ATMOSPHERIC RADIATION.[1]

[1] *Emden, Robert*, in Sitzungsb., K. bayerische Akad. d. Wissens., Munchen, 1913, 43:55–142.

Emden also calculates from equations (4) and (5) that the temperature of the lowest atmospheric layer is 15.8°C and that the temperature of the ground is 36°C. The discontinuity in temperature of 20 degrees is in reality greatly diminished by conduction of heat and evaporation.

Discontinuity = 20 °C = Convection

RADIATIVE TRANSFER IN A FINITE GRAY ATMOSPHERE

JEREMIAH P. OSTRIKER*
Yerkes Observatory
Received June 10, 1962; revised January 15, 1963

and the temperature at the ground layer is

$$T(\tau_1) \equiv T_1 = T_b \left(\frac{\tau_1 + \frac{2}{3}}{\tau_1 + \frac{4}{3}}\right)^{1/4} = T_b \left[1 - \tfrac{1}{2}\left(\frac{T_e}{T_b}\right)^4\right]^{1/4}. \qquad (15)$$

Here we see that there will be a discontinuity in the temperature between the lowest layer of the atmosphere (T_1) and the ground (T_b). This discontinuity, although somewhat

a similar problem, Emden (1913) found the same type of discontinuity.

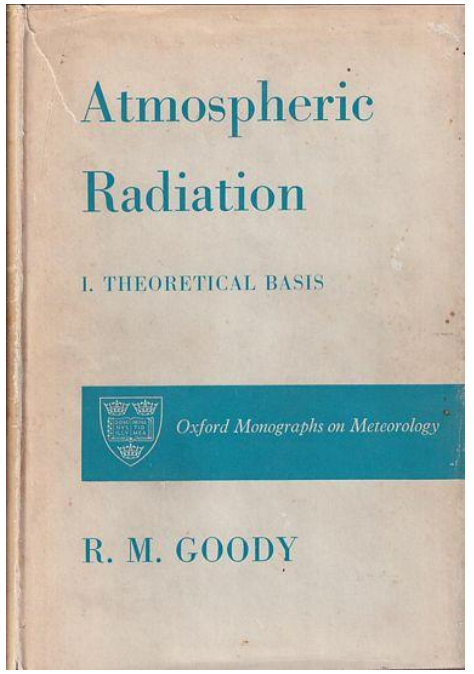
Discontinuity $\boxed{T_b^4 - T_1^4 = T_e^4/2}$ independent of τ

R. Goody: Atmospheric radiation. Theoretical basis. Oxford, 1964

$$F_\nu/2\pi = J_\nu(0) - B^*_\nu(0) = B^*_\nu(\tau^*_\nu) - J_\nu(\tau^*_\nu). \qquad (2.115)$$

Note that if the medium is in thermodynamic equilibrium ($J_\nu = B_\nu$), equation (2.115) requires a discontinuity in B_ν (i.e. a *temperature discontinuity*) at both boundaries.

the step in B always equals $F/2\pi$



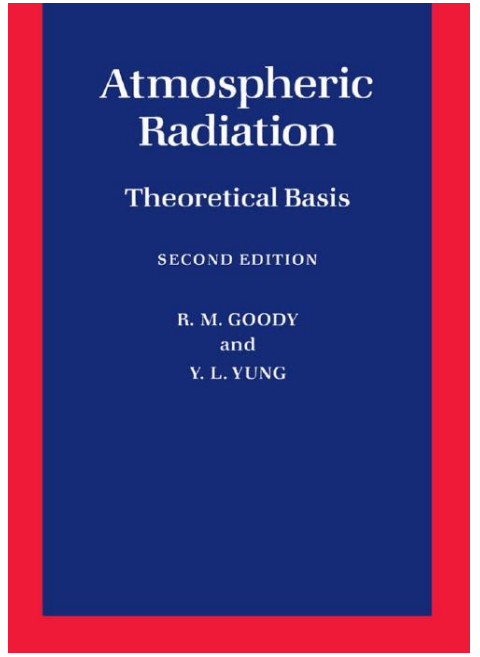
Goody – Yung: Atmospheric radiation. Theoretical basis. Oxford, 1989

$$F/2\pi = B(0) - B^*(0) = B^*(\tau_1) - B(\tau_1). \qquad (2.146)$$

Equation (2.146) requires a discontinuity in the Planck function, implying a discontinuity of temperature, at the boundary.

2. There are discontinuities,

$$\Delta B = \frac{F_S}{2\pi},$$ **DISCONTINUITY = OLR/2**

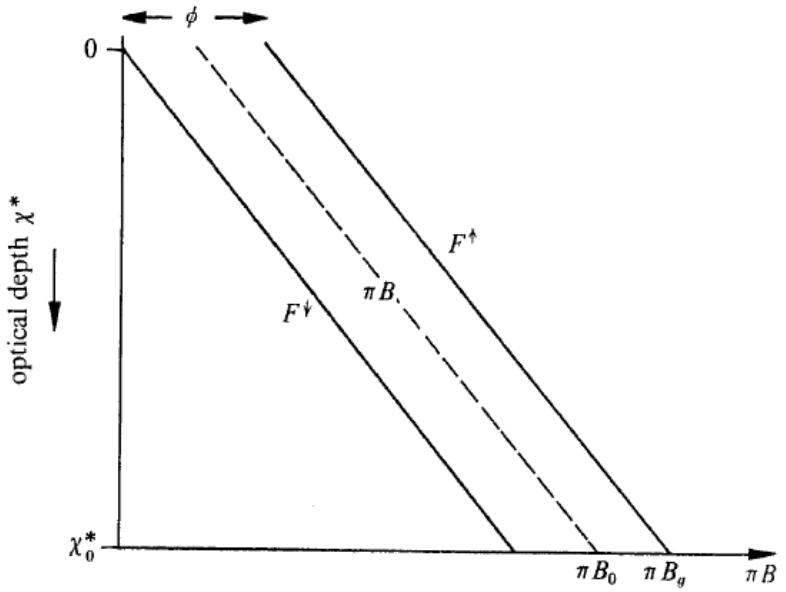


John Houghton: The Physics of Atmospheres
Cambridge (1977, 1986, 2002) Eq. 2.13

At the bottom of the atmosphere where $\chi^* = \chi_0^*$, $F^\uparrow = \pi B_g$, B_g being the black-body function at the temperature of the ground. It is easy to show that there must be a temperature discontinuity at the lower boundary, the black-body function for the air close to the ground being B_0, and

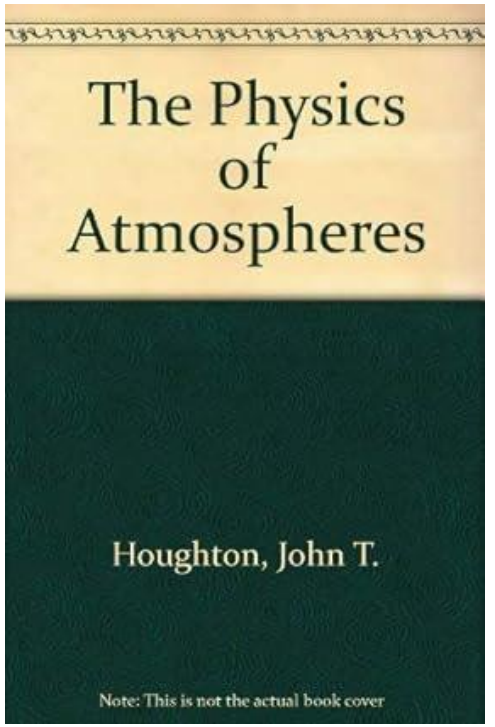
$$B_g - B_0 = \frac{\phi}{2\pi} \qquad (2.13)$$

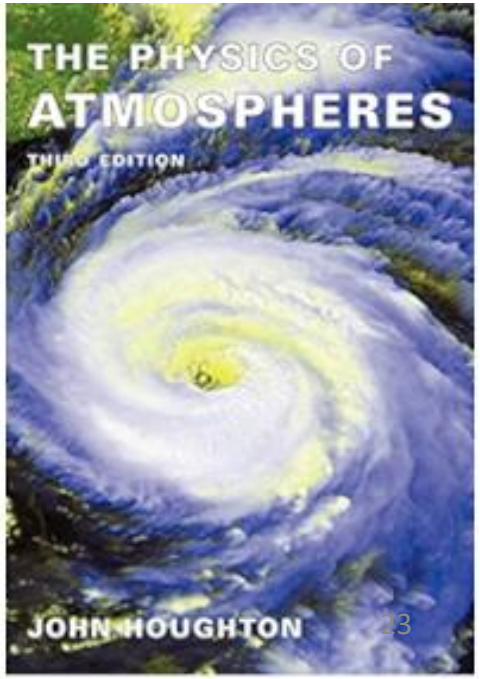
DISCONTINUITY = OLR/2
(independent of the optical depth)

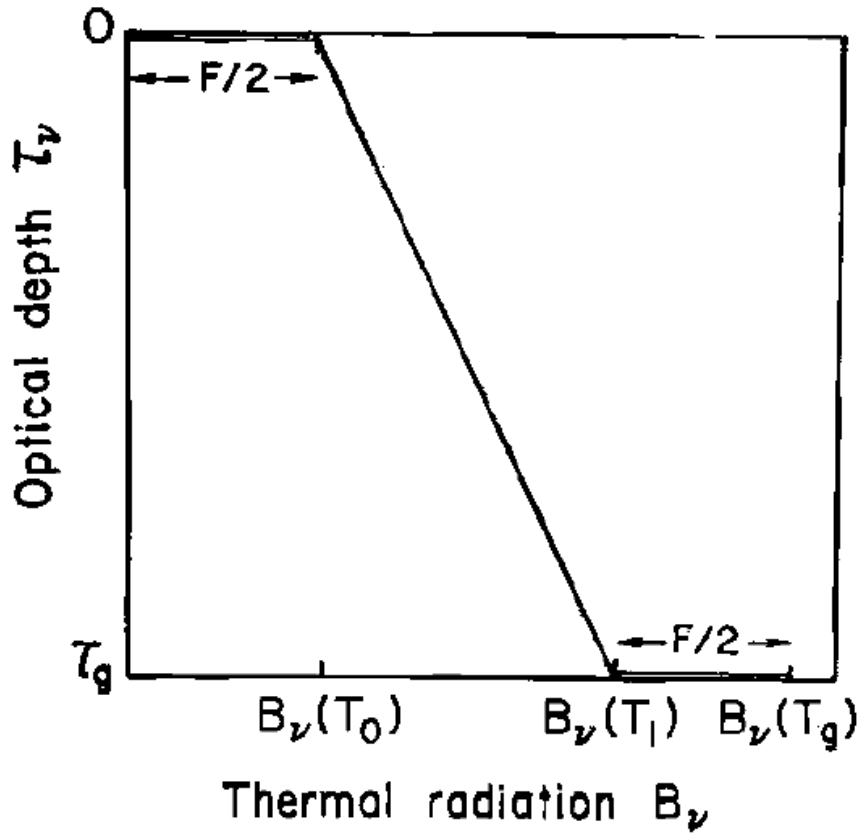


such a steep lapse rate is very unstable with respect to vertical motion, and will soon be destroyed by the process of *convection*

Discontinuity = Convection = OLR/2



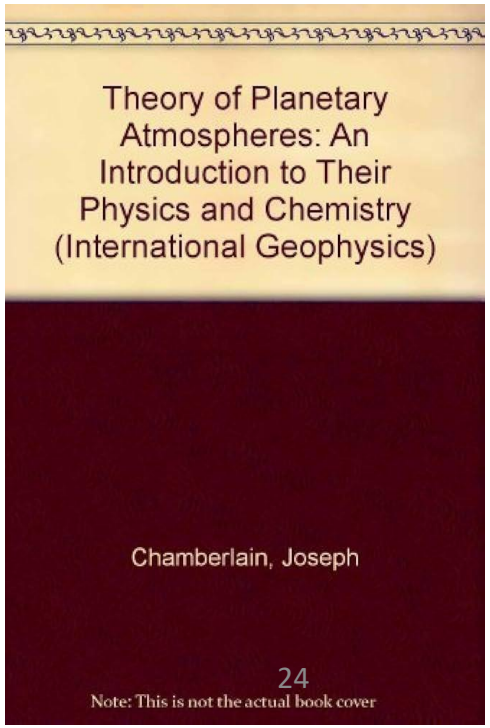




Joseph Chamberlain
Theory of Planetary Atmospheres (1978, 1987)
Academic Press, Fig. 1.4, Eq. 1.2.29

Fig. 1.4 The MRE solution for $T(\tau)$, presented as $B_\nu(T)$ vs. τ. Note the discontinuity at the ground and the finite skin temperature at $\tau = 0$.

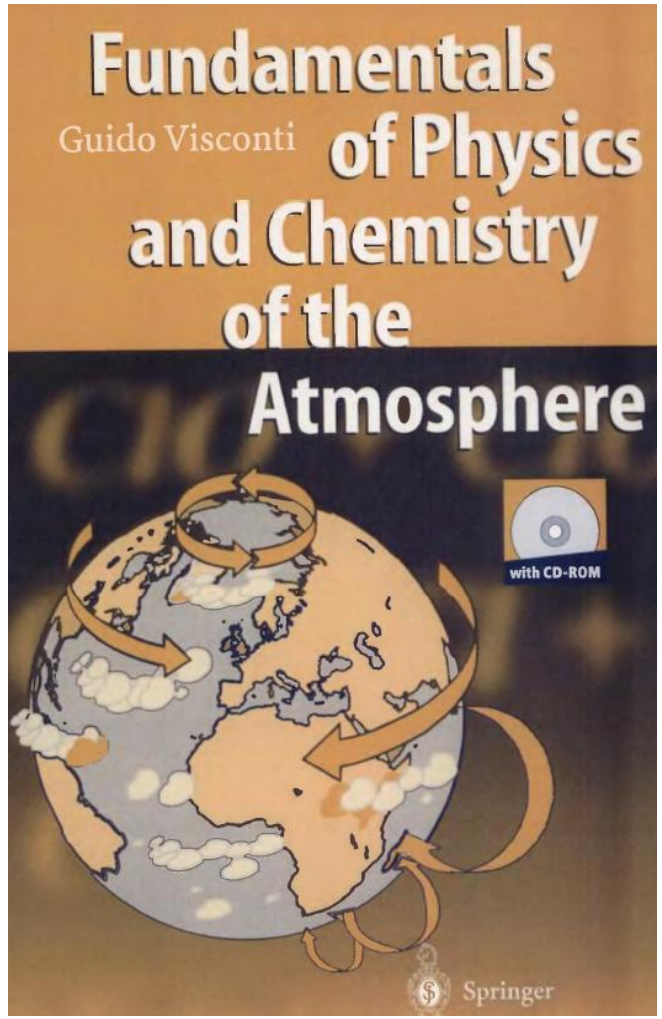
DISCONTINUITY = OLR/2
(independent of τ)



Hence the upward intensity at the ground is

$$I_g^+ \equiv B_\nu(T_g) = B_\nu(T_1) + \tfrac{1}{2}F_\nu \qquad (1.2.29)$$

Visconti: Fundamentals of Physics and Chemistry of the Atmospheres
Springer (2001)



$$T^4 = \frac{T_e^4}{2}\left(\frac{3}{2}\tau + 1\right) \qquad (3.47)$$

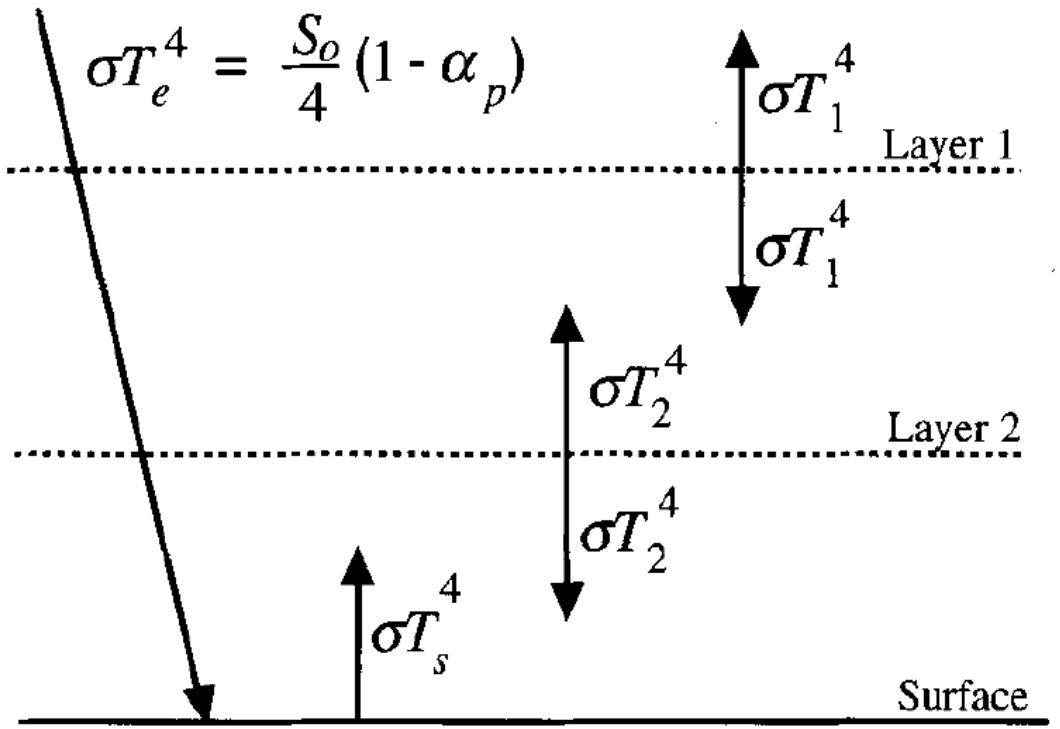
where τ has been replaced by its effective value. An interesting consequence of this solution is to discover what happens at the surface, where the optical thickness is τ^* and the temperature is T_s; we have

$$F^{\uparrow}(\tau^*) = \sigma T_s^4 = \frac{1}{2}\sigma T_e^4\left(\frac{3}{2}\tau^* + 2\right) \qquad (3.48)$$

The temperature at the bottom of the atmosphere at τ^* is given by Equation (3.47), so that we have a discontinuity between the air temperature and that of the surface

$$T_s^4 - T(\tau^*) = T_e^4/2 \qquad (3.49)$$

DISCONTINUITY = OLR/2
(independent of τ)



$$\sigma T_2^4 = 2\sigma T_1^4 \qquad (3.48)$$

$$\sigma T_1^4 + \sigma T_s^4 = 2\sigma T_2^4 \qquad (3.49)$$

$$\frac{S_0}{4}(1-\alpha_p) + \sigma T_2^4 = \sigma T_s^4 \qquad (3.50)$$

$$\varepsilon\sigma T_s^4 + \varepsilon\sigma T_2^4 = 2\varepsilon\sigma T_{SA}^4 \qquad (3.54)$$

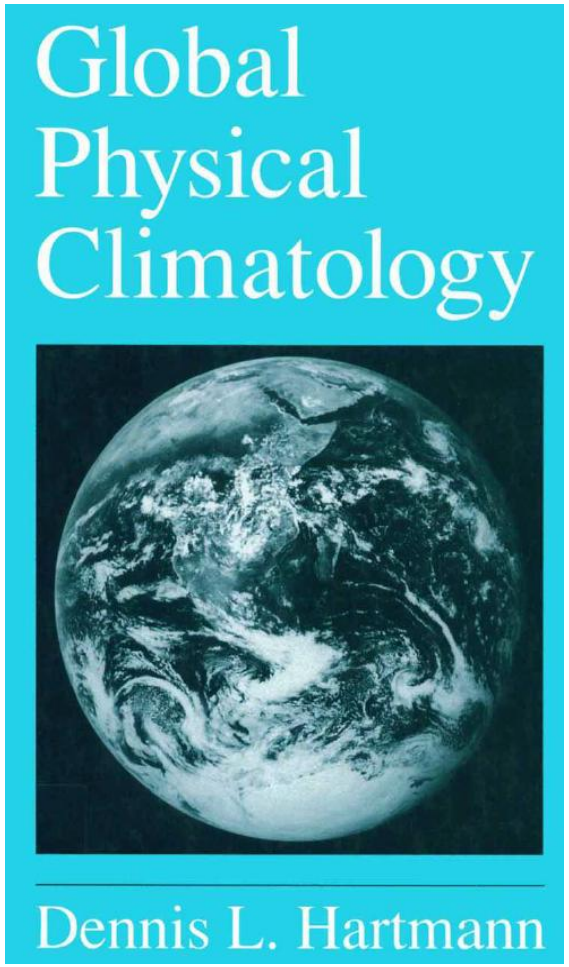


Fig. 3.10 Diagram of simple two-layer radiative equilibrium model for the atmosphere–Earth system, showing the fluxes of radiant energy.

Dennis Hartmann: Global Physical Climatology. Academic Press (1994, 2016)

Fig. 3.10 Eqs. (3.48, 3.49, 3.50 and 3.54)

With Hartmann's data, the equation is justified within 0.31 Wm^{-2}

Emission temperature T_e = 255 K
Air adjacent to surface T_{SA} = 320 K
Surface temperature T_S = 335 K

σT_S^4	–	σT_{SA}^4		$= \sigma T_e^4/2$
$5.67\,[(3.35)^4 - (3.20)^4]$				$= 5.67(2.55)^4/2$
714.11	–	594.54	= 119.56	= 119.87 – **0.31** Wm^{-2}

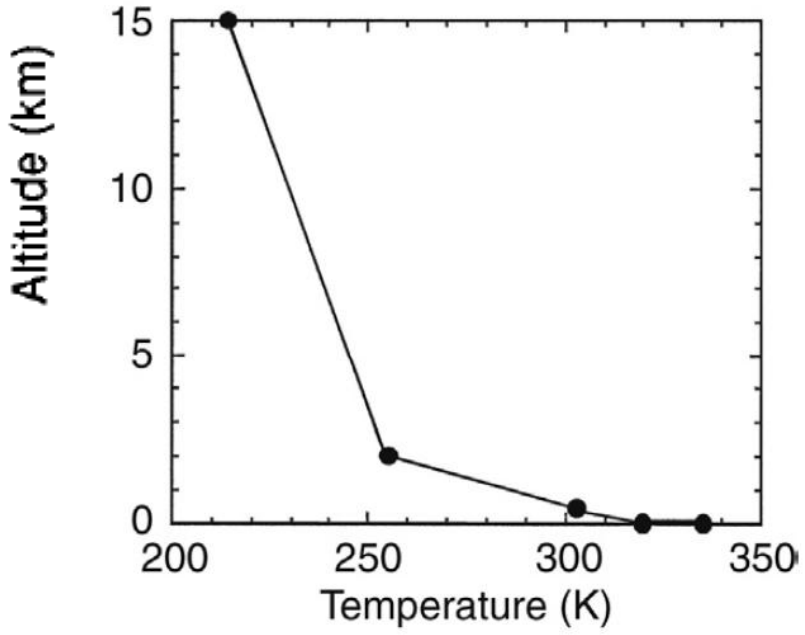
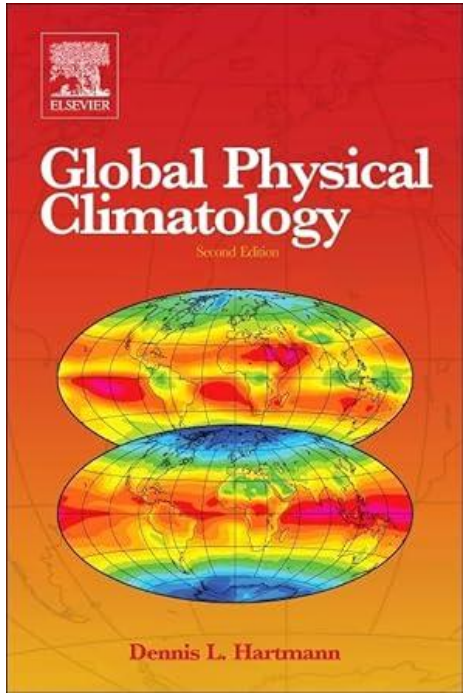


Fig. 3.11

Dennis Hartmann: Global Physical Climatology
Academic Press
(1994, 2016)
Fig. 3.11



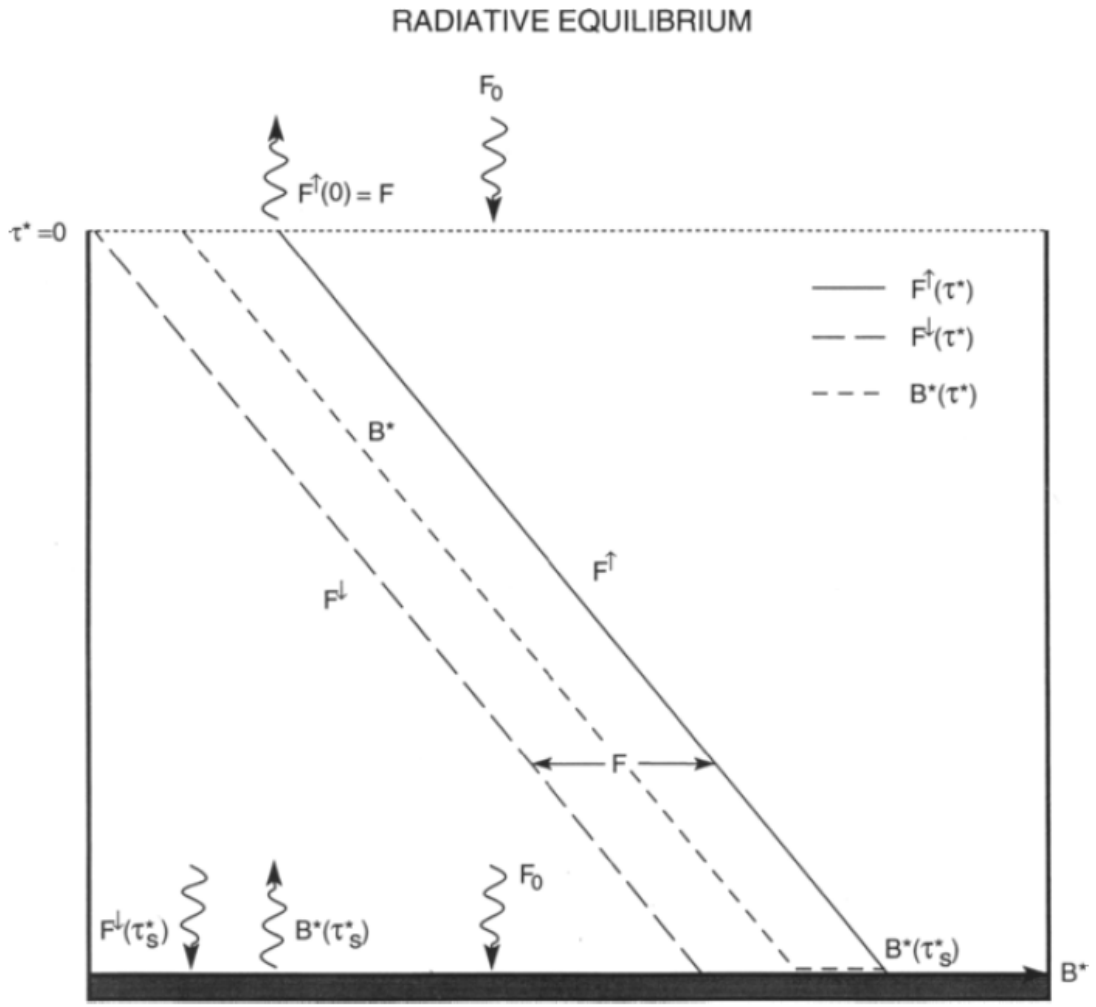
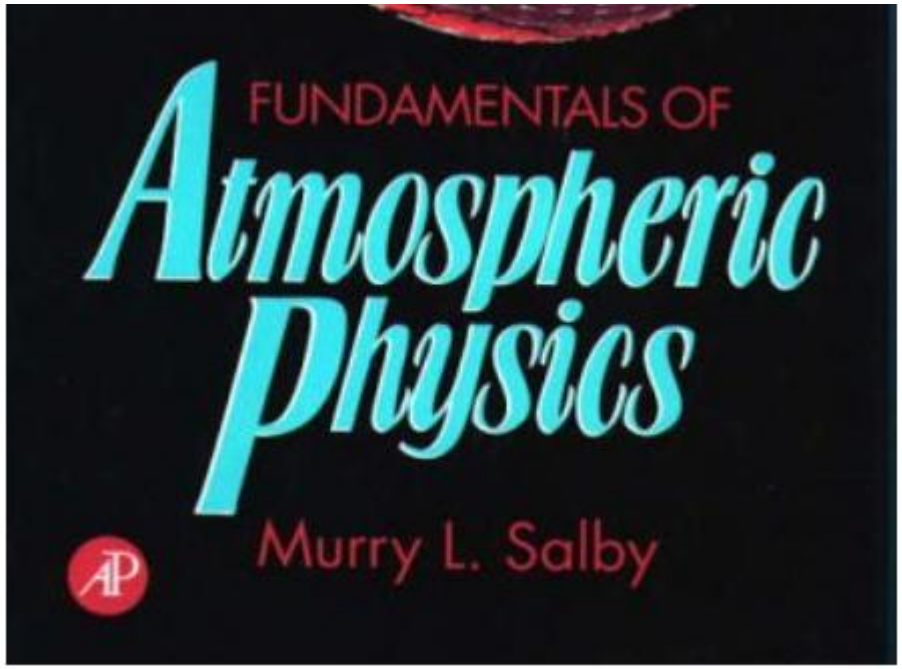


Figure 8.20 Upwelling and downwelling fluxes and emission in a gray atmosphere that is in radiative equilibrium with an incident SW flux F_0 and a black underlying surface. *Note:* the emission profile is discontinuous at the surface.



M. Salby: Fundamentals of Atmospheric Physics
Academic Press, 1996

$$B^*(T_s) = B^*(\tau_s^*) + \frac{F_0}{2}. \qquad (8.67)$$

According to (8.67), the temperature predicted by radiative equilibrium is discontinuous at the surface, the ground being warmer than the overlying air.

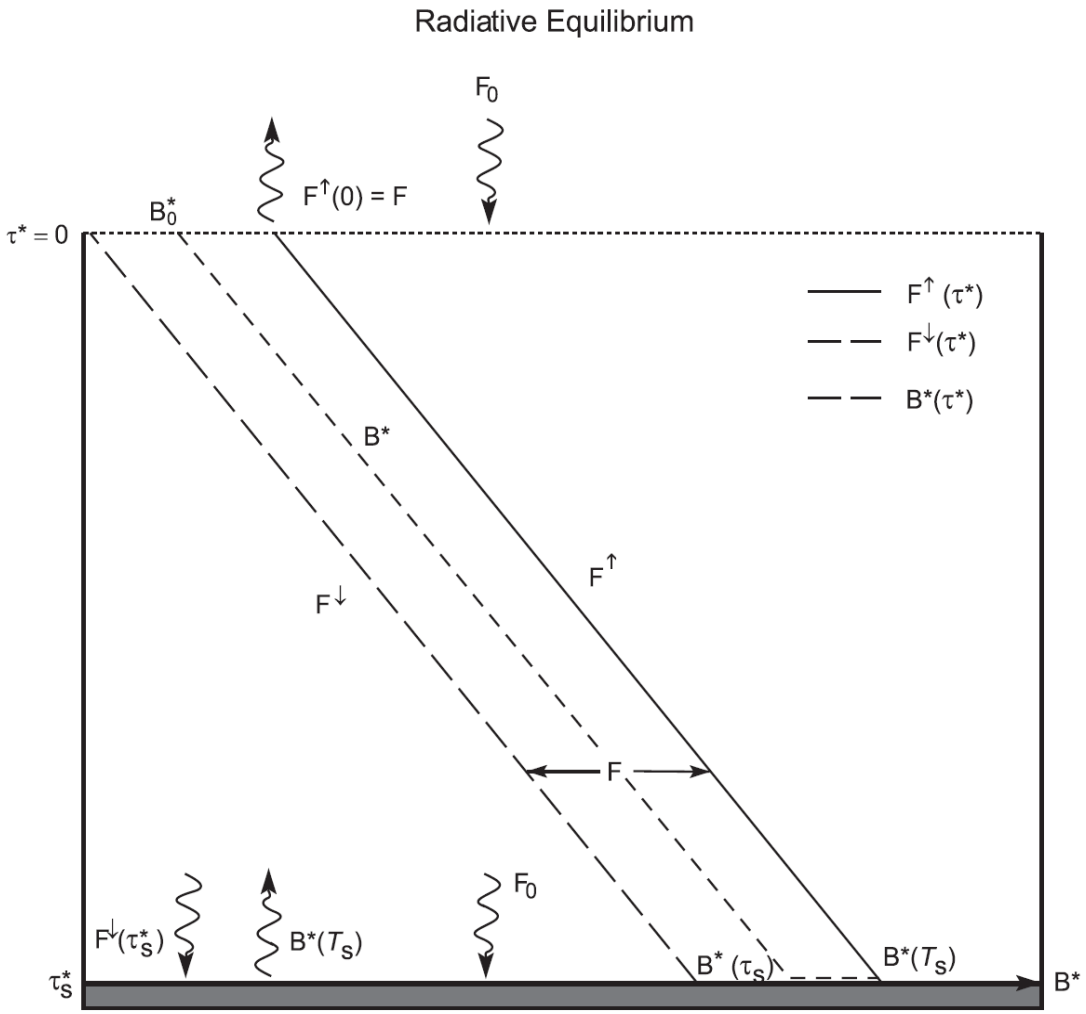
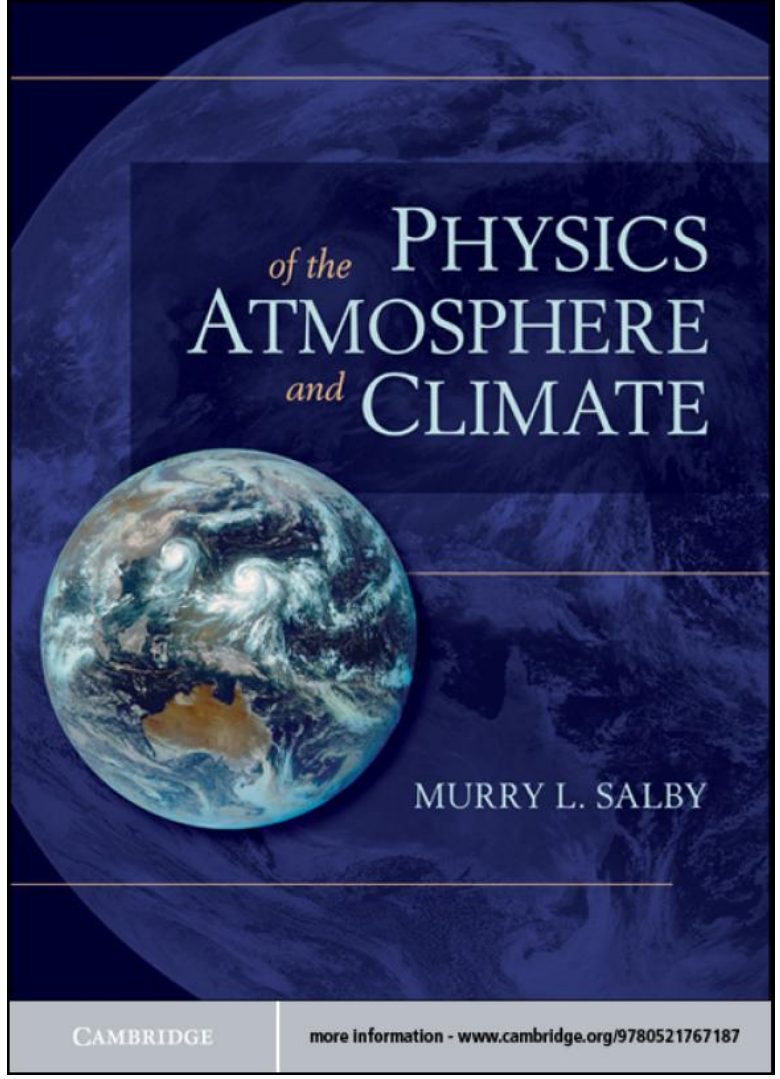


Figure 8.20 Upwelling and downwelling LW fluxes and LW emission in a gray atmosphere that is in radiative equilibrium with an incident SW flux F_0 and a black underlying surface. Note: the emission profile is discontinuous at the surface.



M. Salby: Physics of the Atmosphere and Climate
Cambridge, 2012

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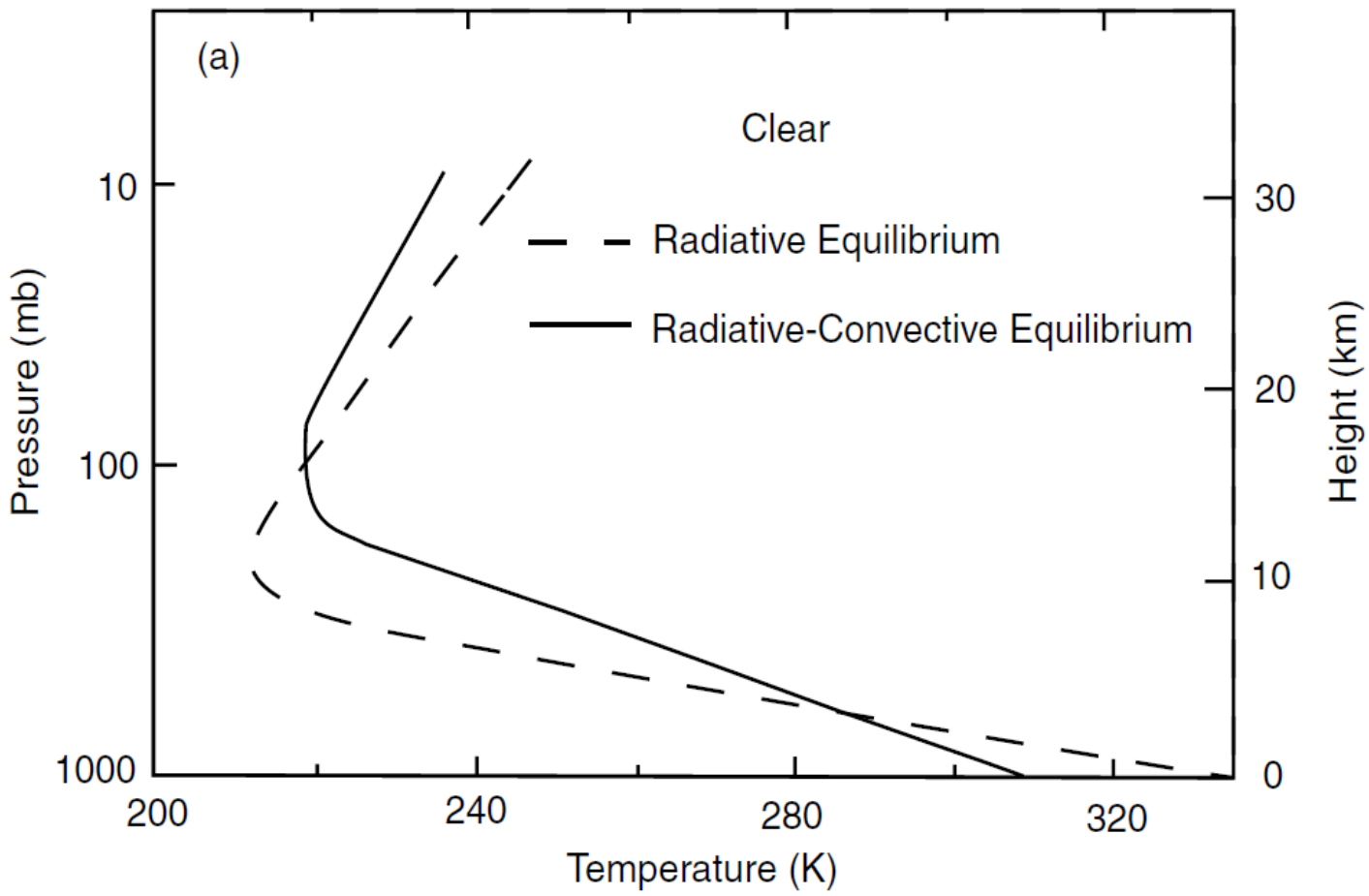
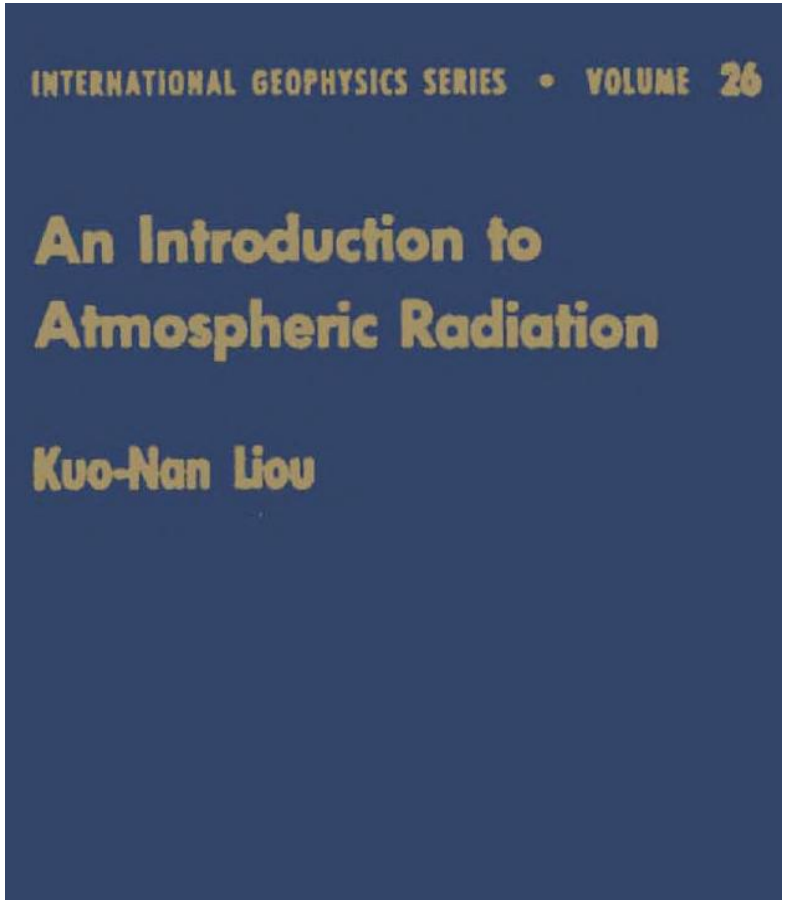
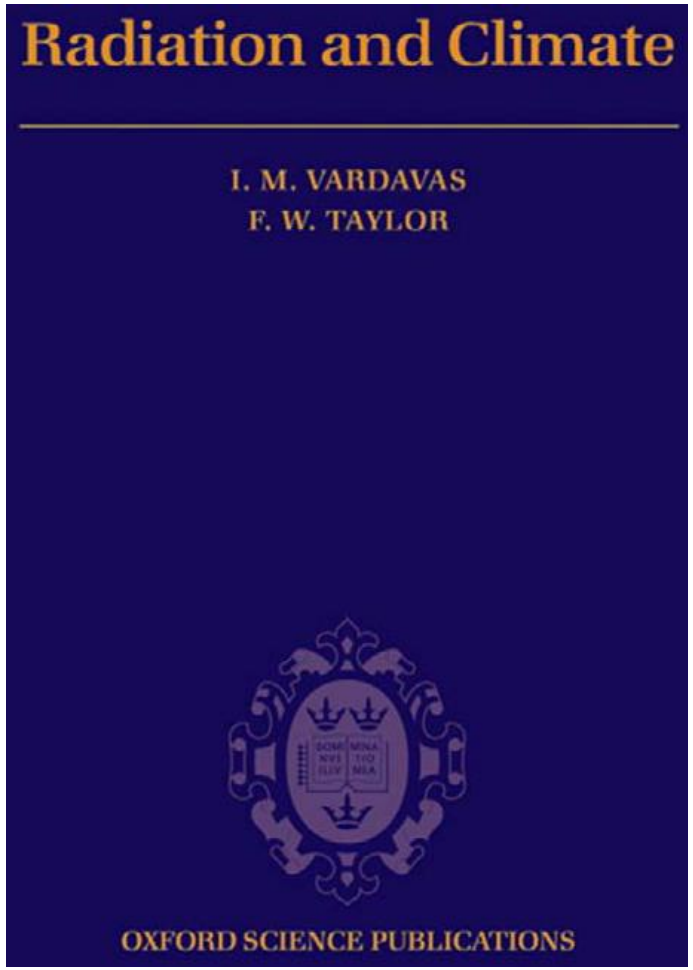
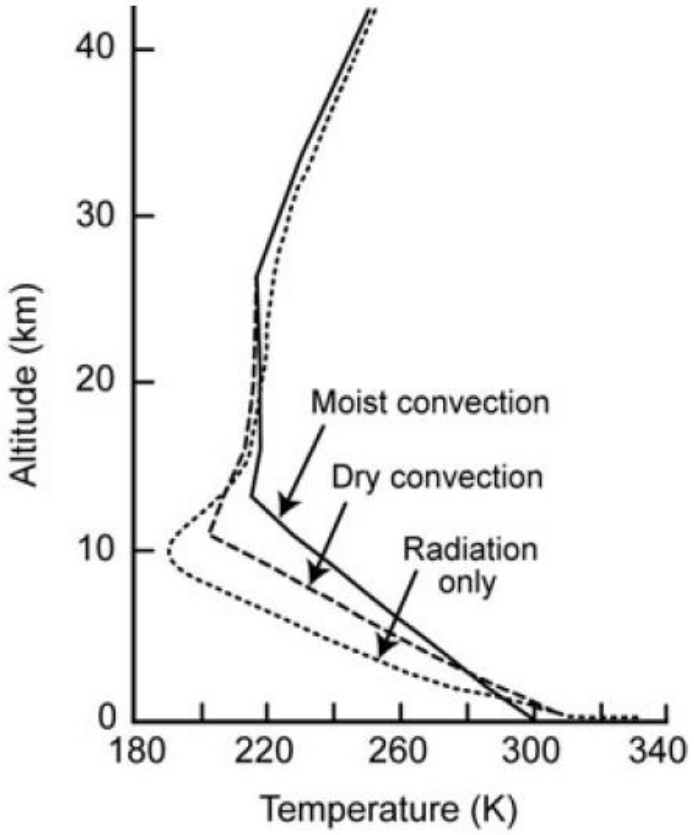


Figure 8.9 Vertical distributions of radiative and radiative–convective equilibrium temperatures in clear (a) and average cloud (b) conditions, simulated from a one-dimensional radiative–convective climate model.

Liou: An Introduction to Atmospheric Radiation
Academic Press (1980, 2002)







Vardavas and Taylor:
Radiation and Climate
Oxford (2007) Fig. 2.11

An atmosphere in radiative equilibrium (see Fig. 2.11) produces essentially a discontinuity (of about 20 K) between the Earth's surface temperature and the near–surface atmospheric temperature.

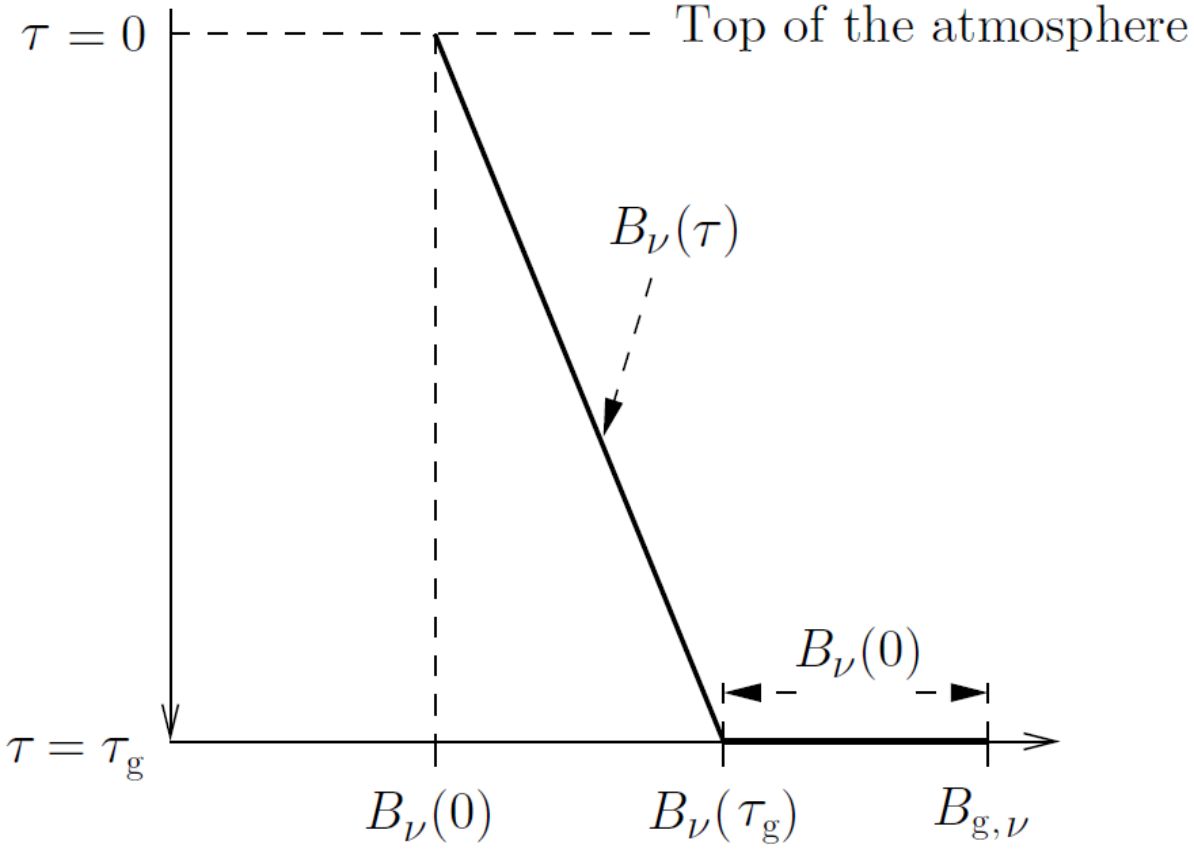
Thus the mean intensity can be expressed as

$$J = I^{+} - f/2\pi.$$

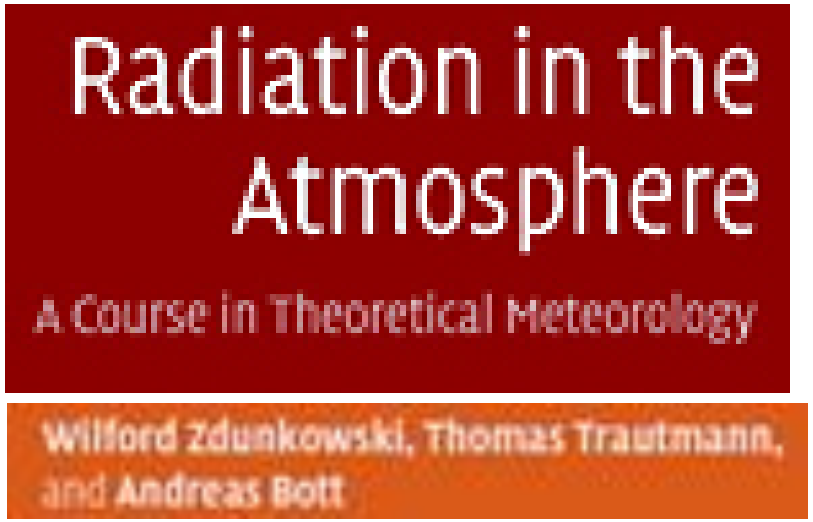
DISCONTINUITY = OLR/2

FIG. 2.11. Representative vertical temperature profiles calculated assuming (top curve) convective equilibrium in a moist atmosphere, (middle) convective equilibrium in a dry atmosphere, and (bottom) radiative equilibrium. (See Manabe and Wetherald 1967)

Two-stream methods for the solution of the RTE



Zdunkowski, Trautmann and Bott
Radiation in the Atmosphere
Cambridge (2008) Fig. 6.7



DISCONTINUITY = OLR/2, independent of τ

$$B_{g,\nu} = B_\nu(\tau_g) + \frac{1}{2\pi} E_{net,\nu}$$

observe a discontinuity of the curve expressing a temperature jump ΔT_g between the surface temperature T_g and the lowest atmospheric layer $T(\tau_g)$, i.e.

$$\Delta T_g = T_g - T(\tau_g) > 0 \qquad (6.155)$$

Marshall and Plumb
Atmosphere, Ocean and Climate Dynamics
Academic Press (2008)

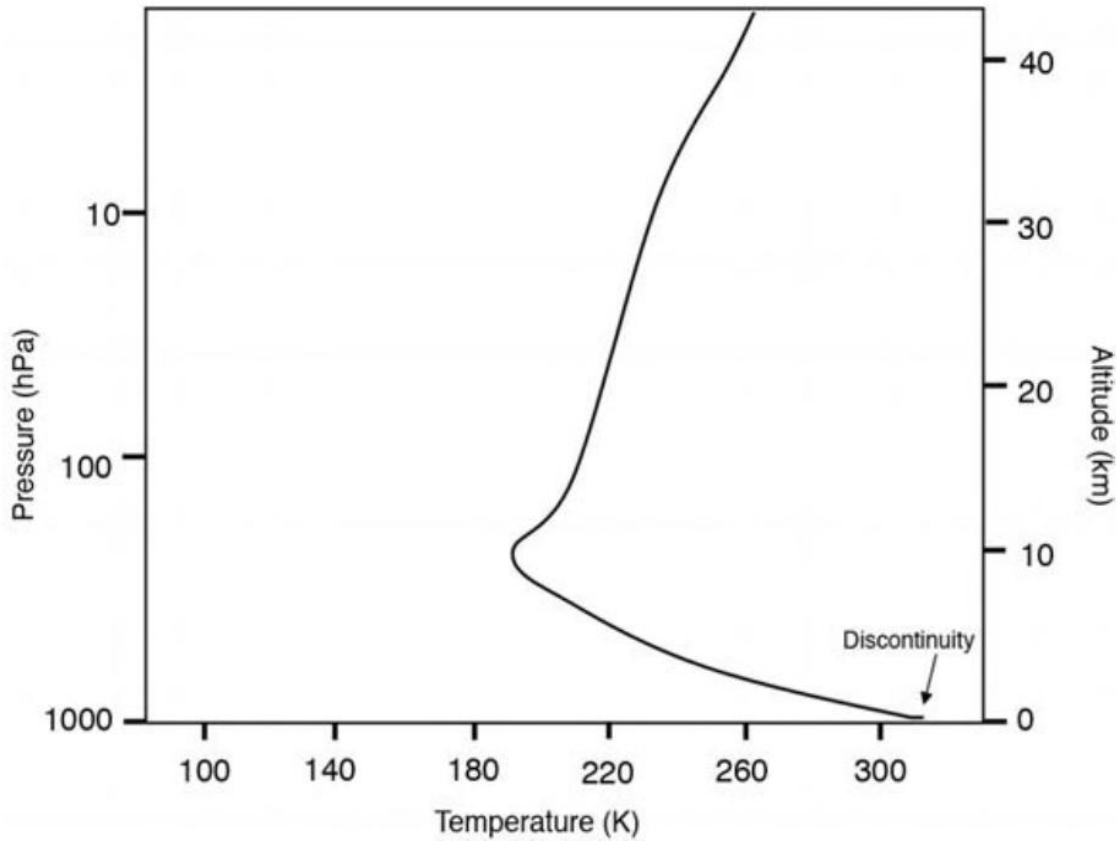


Figure 2.11

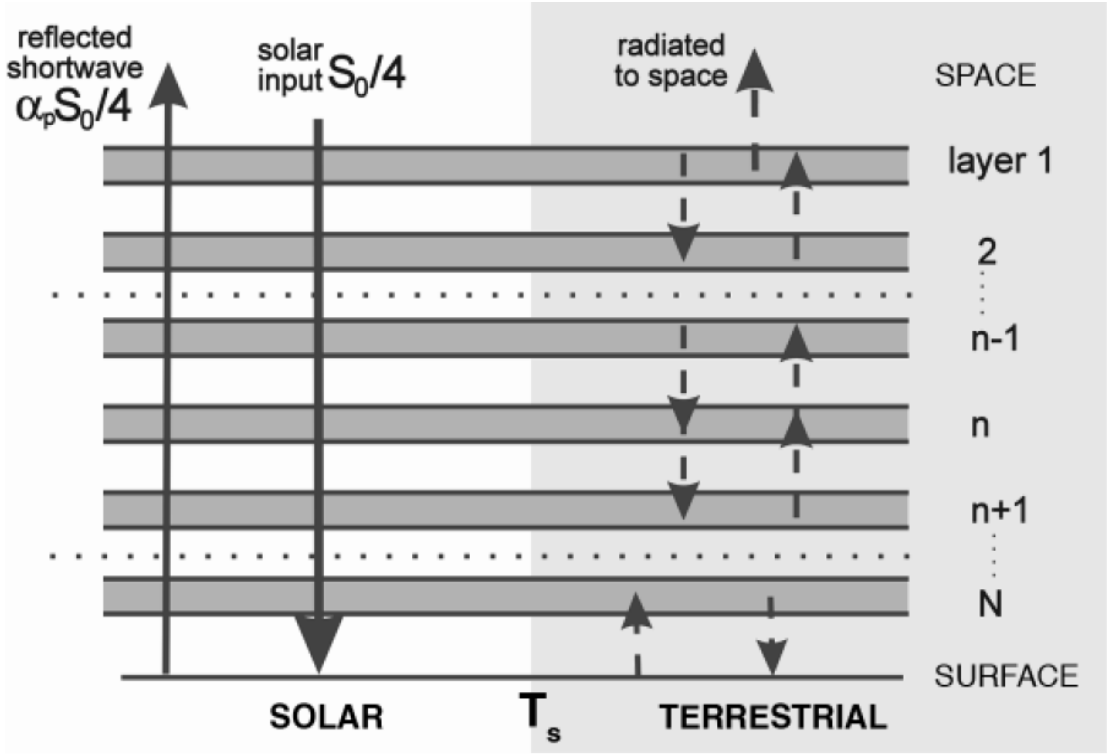


Figure 2.12. An atmosphere made up of N slabs

Problem: $2T_n^4 = T_{n+1}^4 + T_{n-1}^4$

$$T_s = (N+1)^{1/4} T_e$$

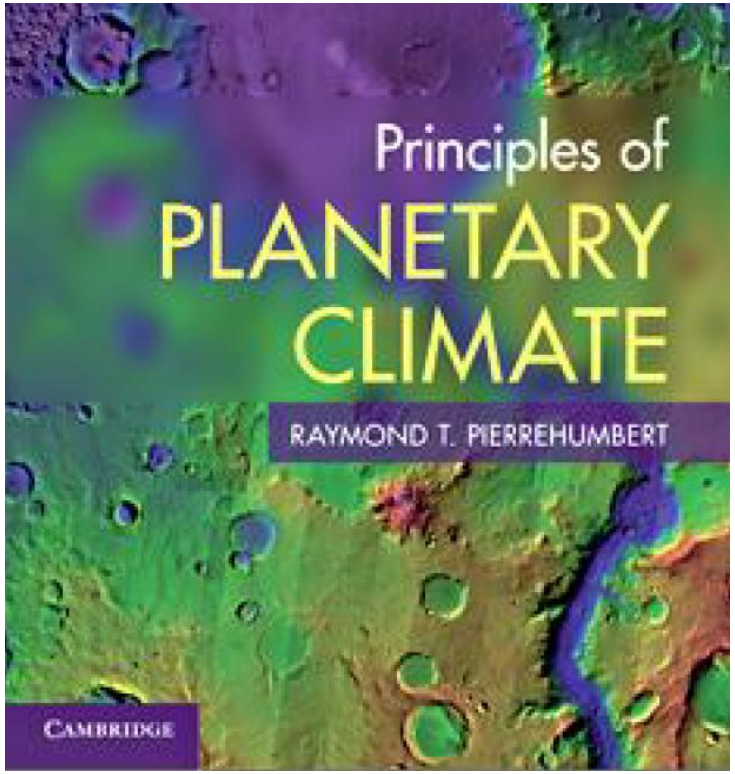
$$(\Rightarrow T_s^4 - T_{sa}^4 = T_e^4/2)$$

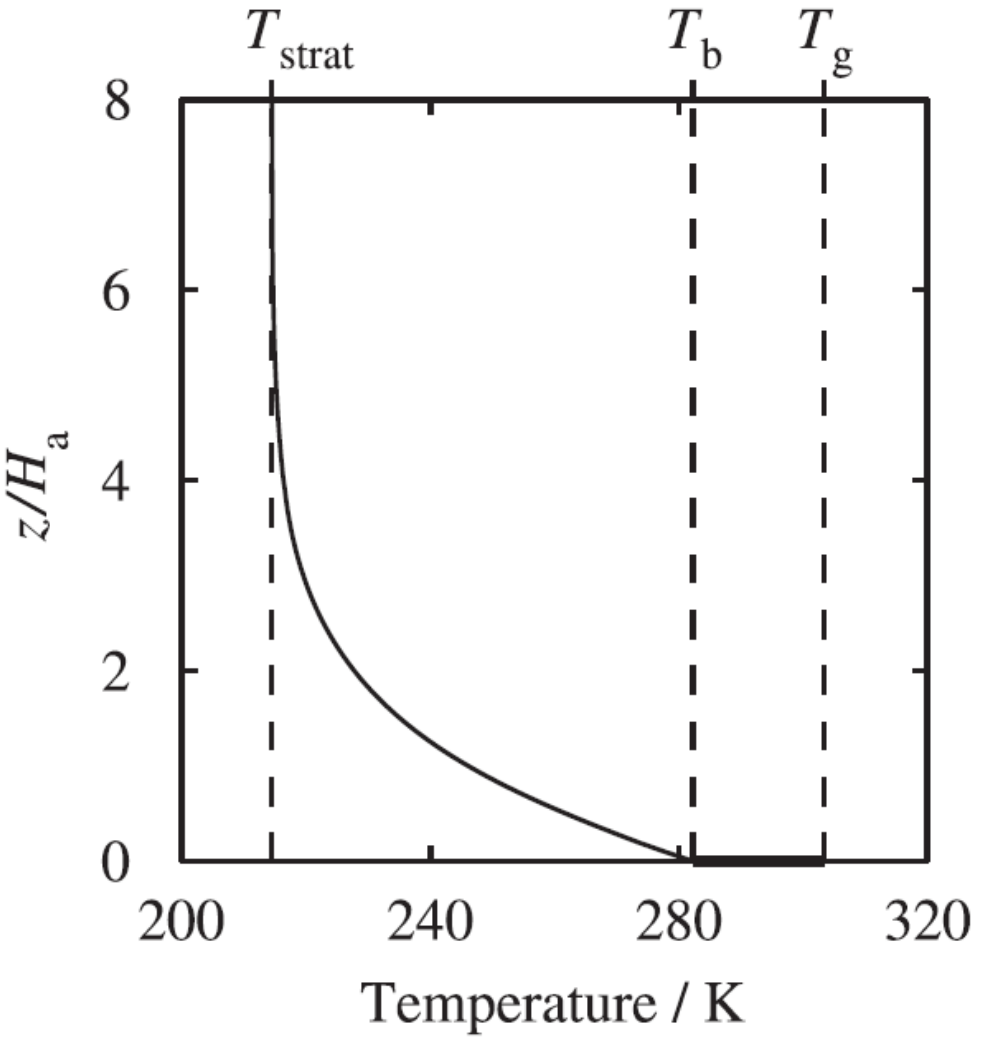
Raymond Pierrehumbert: Principles of Planetary Climate.
Cambridge (2008) Eq. 4.45

Let's now compare the surface temperature with the temperature of the air in immediate contact with the surface. From Eq. (4.42) we find that the low-level air temperature is determined by $\sigma T(0)^4 = (1-\alpha)S \cdot \left(\frac{1}{2} + \frac{1}{2}\tau_\infty\right)$. Taking the ratio,

$$\frac{T(0)}{T_g} = \left(\frac{\frac{1}{2} + \frac{1}{2}\tau_\infty}{1 + \frac{1}{2}\tau_\infty}\right)^{1/4} \qquad (4.45)$$

DISCONTINUITY = $(1 - \alpha)S/2$ = OLR/2
(independent of τ)



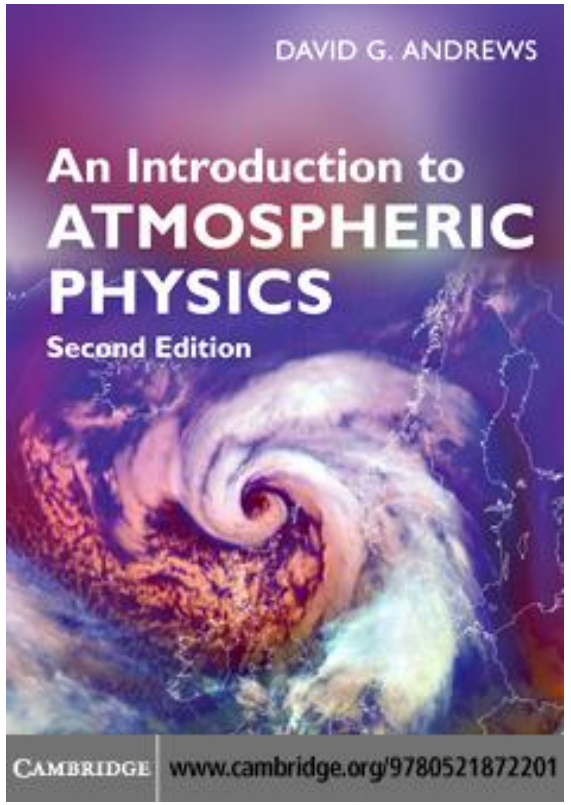


Andrews: An Introduction to Atmospheric Physics
Cambridge (2010), pp 85-86.

$$T_b \equiv T_e \left(\frac{1 + \chi_g^*}{2} \right)^{1/4}$$

$$T_g \equiv T_e \left(\frac{2 + \chi_g^*}{2} \right)^{1/4}$$

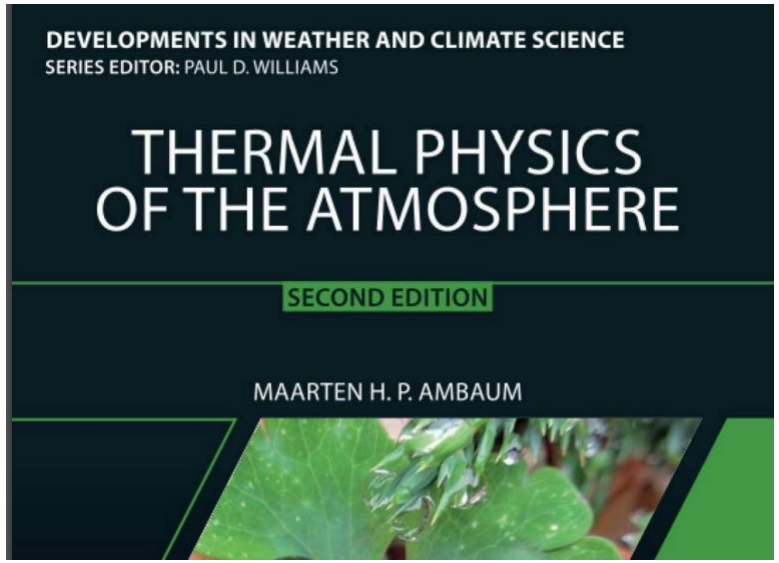
$$T_g^4 - T_b^4 = T_e^4/2$$



DISCONTINUITY = OLR/2 (independent of the optical depth)

discontinuity between the bottom of the atmosphere and the ground.

Inclusion of convection in the model removes the temperature discontinuity



ELSEVIER RMetS Royal Meteorological Society

Copyright © 2021 Royal Meteorological Society.

These two budget equations can be combined by eliminating $L_{\downarrow 0}$ to find

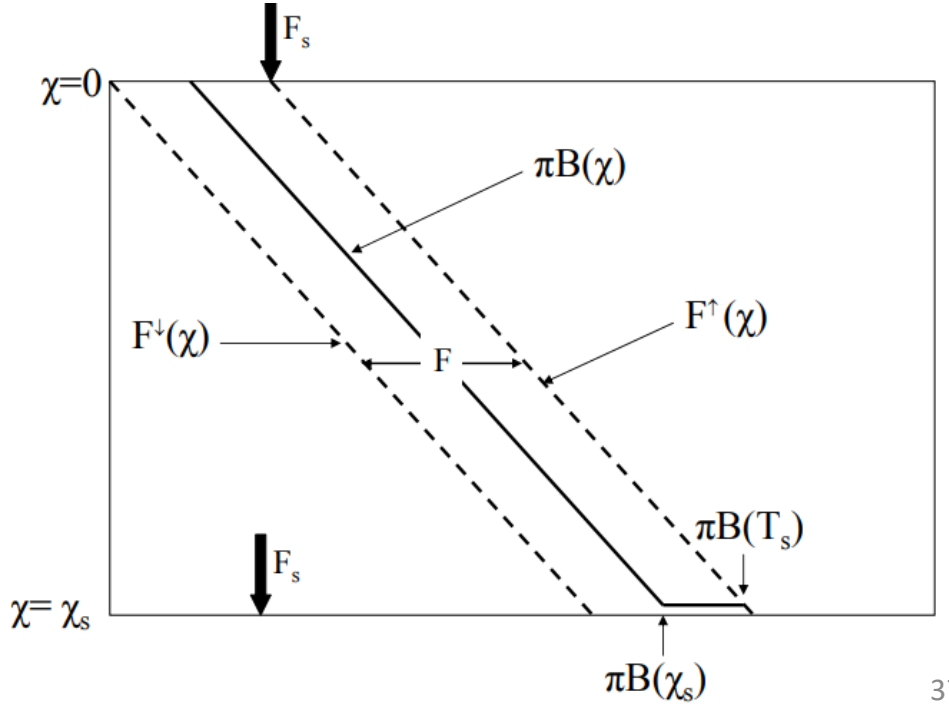
$$\sigma T_E^4 = \sigma T_S^4 + S_{n0}/2. \qquad (10.56)$$

So we find that under radiative equilibrium the surface temperature is higher than the temperature of the adjoining atmosphere. This temperature discontinuity is unstable in practice and there will be turbulent heat exchange which will remove the temperature discontinuity. This instability of the radiative state is a driver of surface layer turbulence: the radiation will force the lower part of the boundary layer, the surface layer, towards instability and this tendency is compensated by turbulent fluxes near the surface.

University Lecture Notes

- “This expression implies that there is a temperature discontinuity between the surface and the cooler lowest layer of the atmosphere.” (Manchester Univ.)
- “surface temperature exceeds that of the overlying air by an amount of $F_0/2$. It only occurs because we have assumed that the only heat fluxes are those due to radiation, so there is no conduction and no turbulent convection”

$$\pi B(T_s) = \pi B(\chi_s) + F_s/2.$$



Final TP Profile

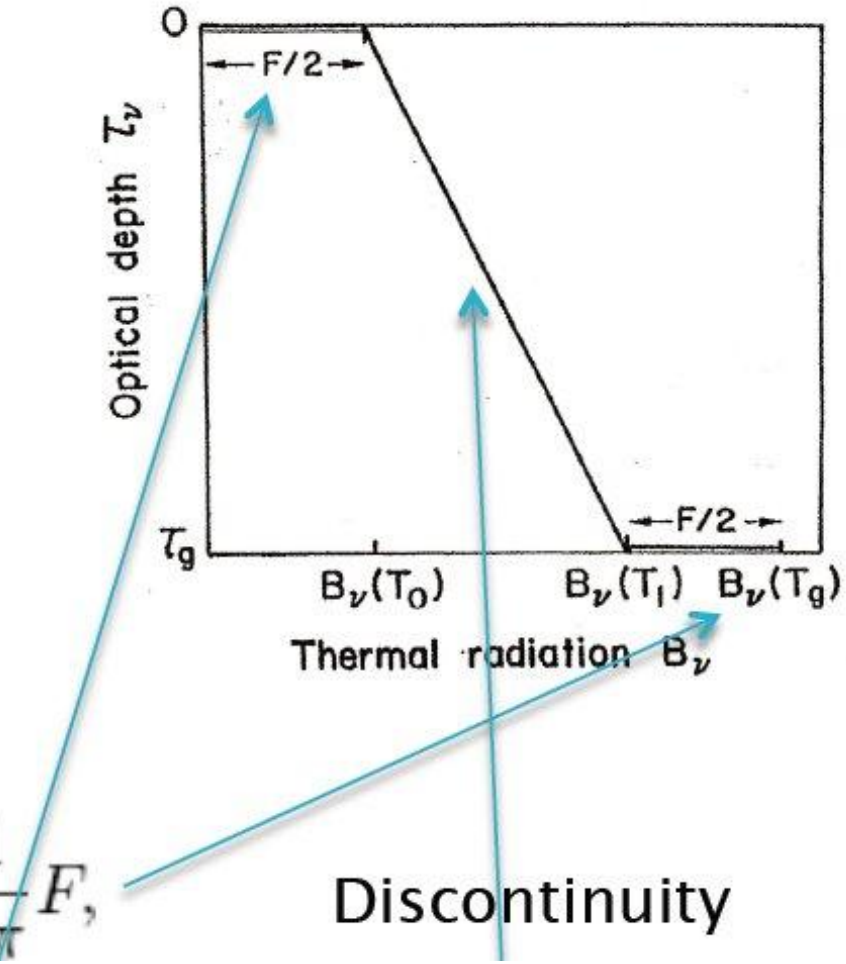
Expressions for intensity:

$$I^+ = B(T) + \frac{1}{2\pi}F$$

$$I^- = B(T) - \frac{1}{2\pi}F$$

Boundary Conditions:

At the Ground: $I_g^+ = B(T_g) = B(T_1) + \frac{1}{2\pi}F,$



Kerry Emanuel
MIT, 2014

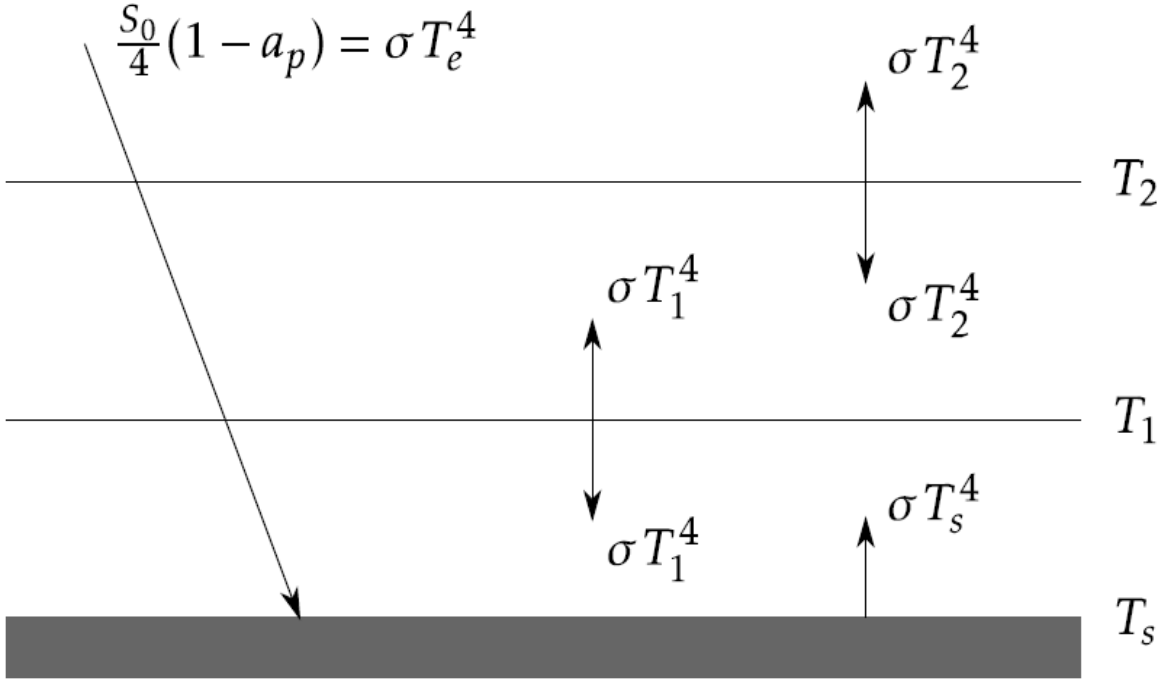


Figure 8: Radiative fluxes in a model with an atmosphere that consists of two layers that are completely transparent to solar radiation and completely opaque to terrestrial radiation

$$\varepsilon_a \sigma T_s^4 + \varepsilon_a \sigma T_1^4 = 2\varepsilon_a \sigma T_a^4,$$

discontinuous emissivity entails a discontinuity in temperature. In radiative equilibrium, the surface atmospheric temperature is generally different from the temperature of the surface. Radiation drives the system into thermodynamic disequilibrium, which in reality is counteracted by heat diffusion or fluid motion. But this effect can be experienced in a desert during the day, where the sand is typically much hotter than the air at 2 m above ground.

Harvard, 2018

We have got the temperature structure in the atmosphere as a function of τ. Now consider energy balance at the surface (looks familiar?),

$$B(T_s) = F_0 + F^{\downarrow}(\tau_s)$$

From their definitions, we have

$$F^{\downarrow} = \frac{1}{2}\left(\bar{F} - F\right)$$

As the net flux F is constant and equal to F_0, and use Eq. (14), we have:

$$B(T_s) = B(\tau_s) + \frac{F_0}{2}$$

Note the jump at the surface.

University exam task

RADIATIVE EQUILIBRIUM EXERCISE

Key Concepts:
Radiative Flux
Eddington's Equation (2-stream approximation)
Grey approximation to absorption coefficient
Radiative Equilibrium
Discontinuity in surface boundary condition

惑星大気学_放射
(2022-05-02)

(3.10)(3.11)より

$$\underbrace{B^*(T_S)}_{\text{地表面}} = \underbrace{B^*(\tau_s^*)}_{\text{大気下端}} + \frac{F^0}{2}$$

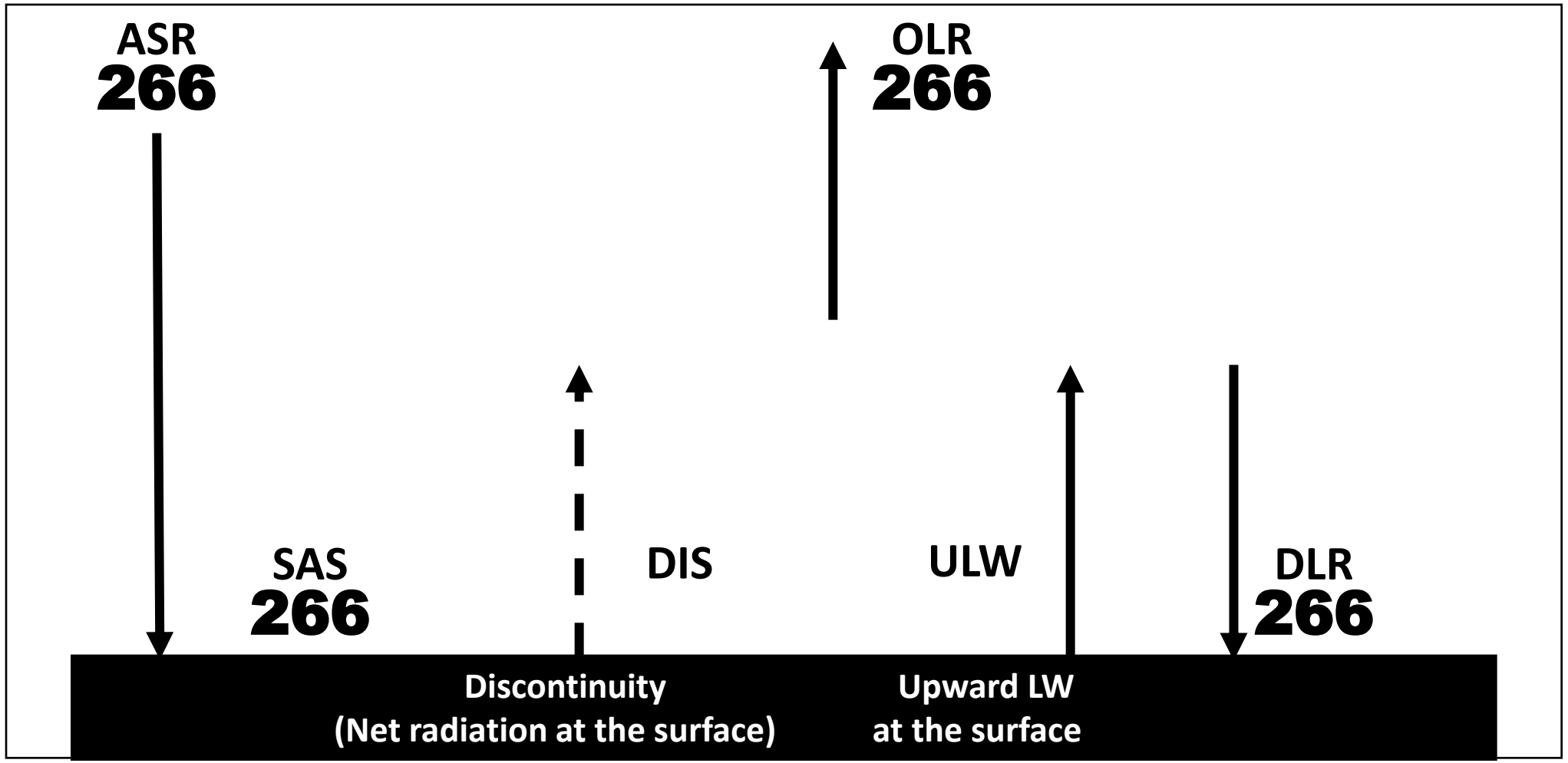
放射平衡では大気下端の温度と地表面温度は不連続になる。($B^* = \sigma T^4$ に注意)

From (3.10)(3.11)

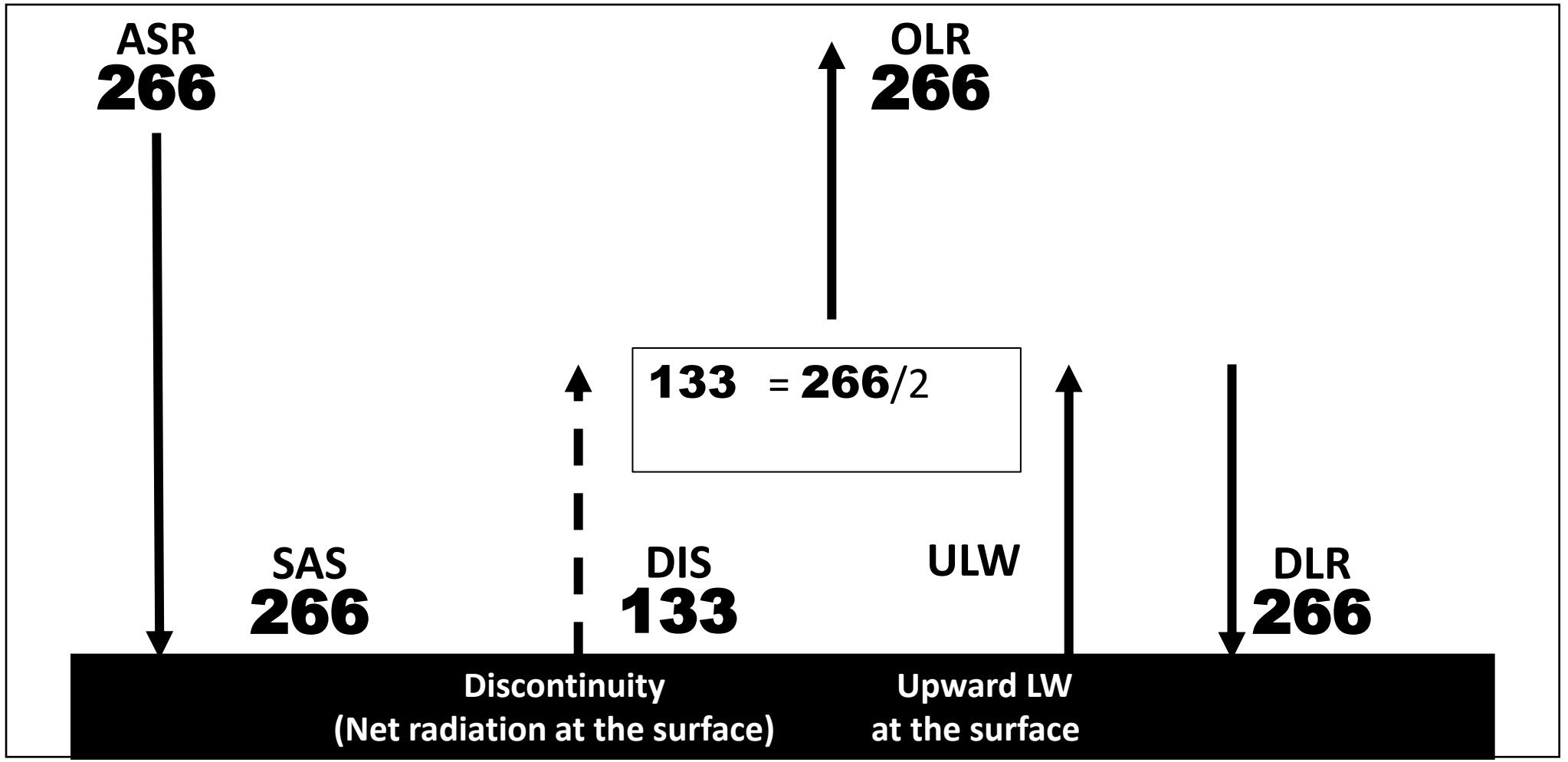
$$\underbrace{B^*(T_S)}_{\text{surface}} = \underbrace{B^*(\tau_s^*)}_{\text{bottom of atmosphere}} + \frac{F^0}{2}$$

A temperature discontinuity exists at the surface. (Note that $B^* = \sigma T^4$)

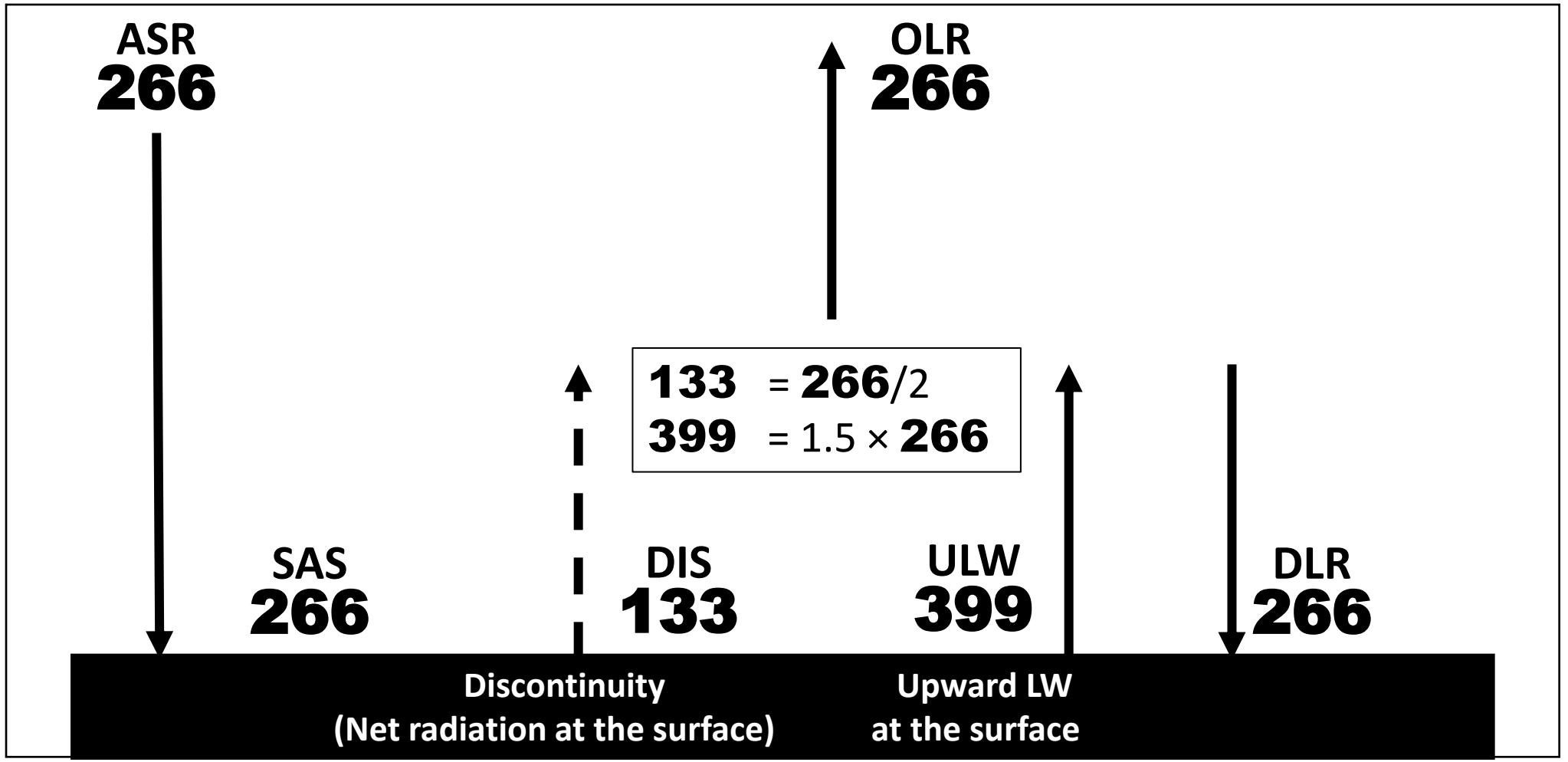
Discontinuity = OLR/2



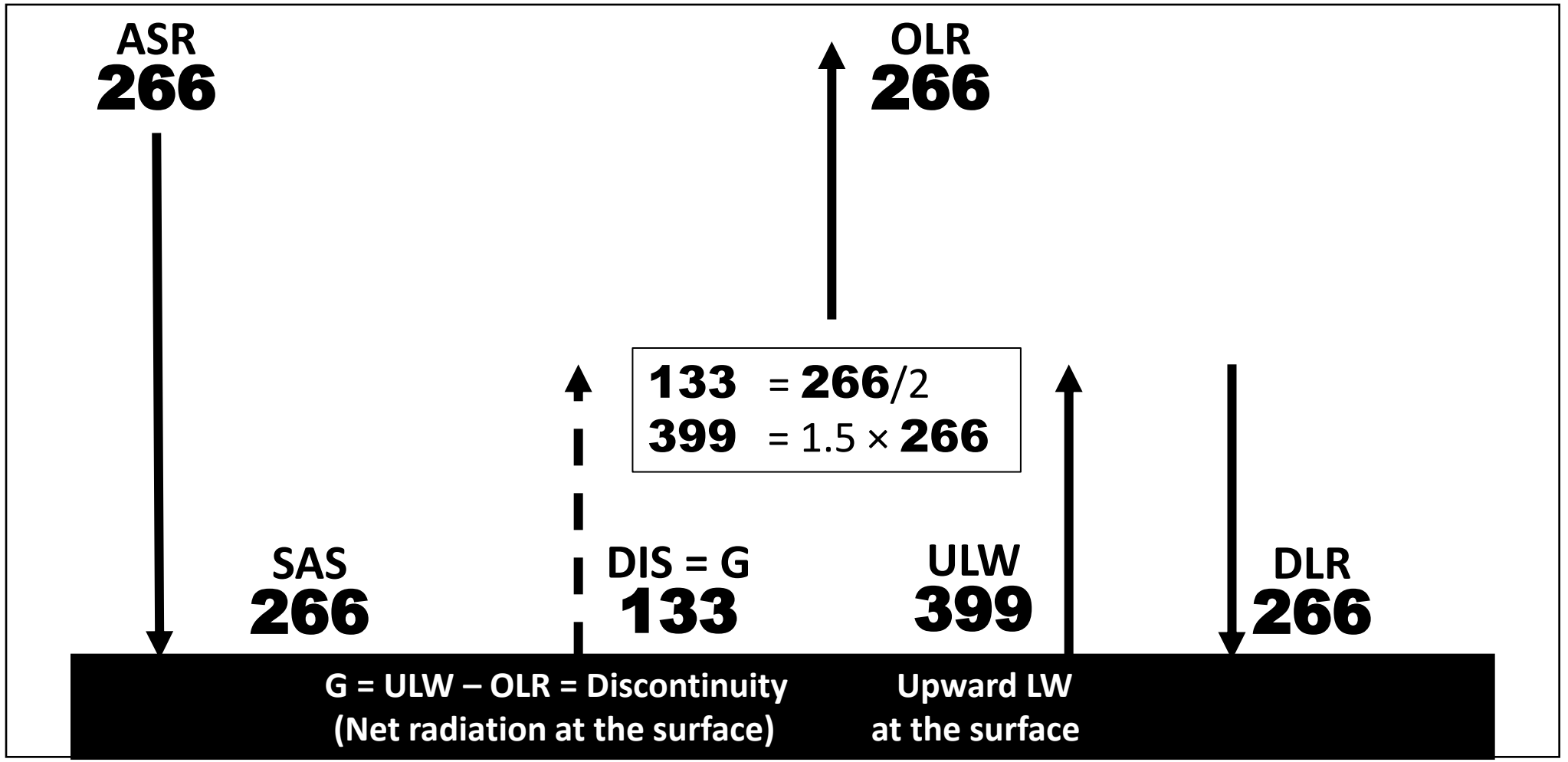
Discontinuity = OLR/2



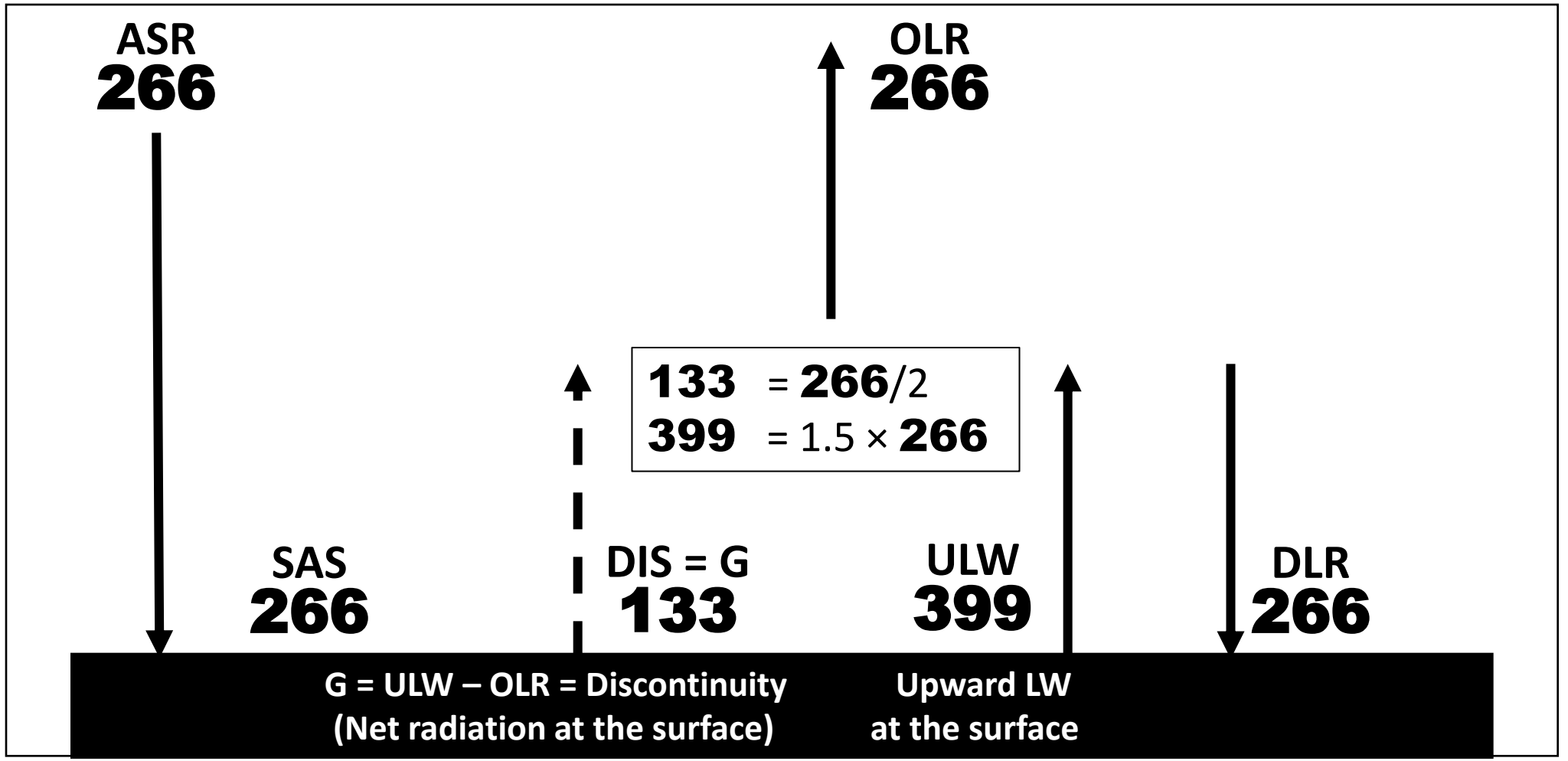
Discontinuity = OLR/2 =>
Surface Upward LW (ULW) = 1.5 OLR



Discontinuity = OLR/2 =>
ULW – OLR = G = OLR/2



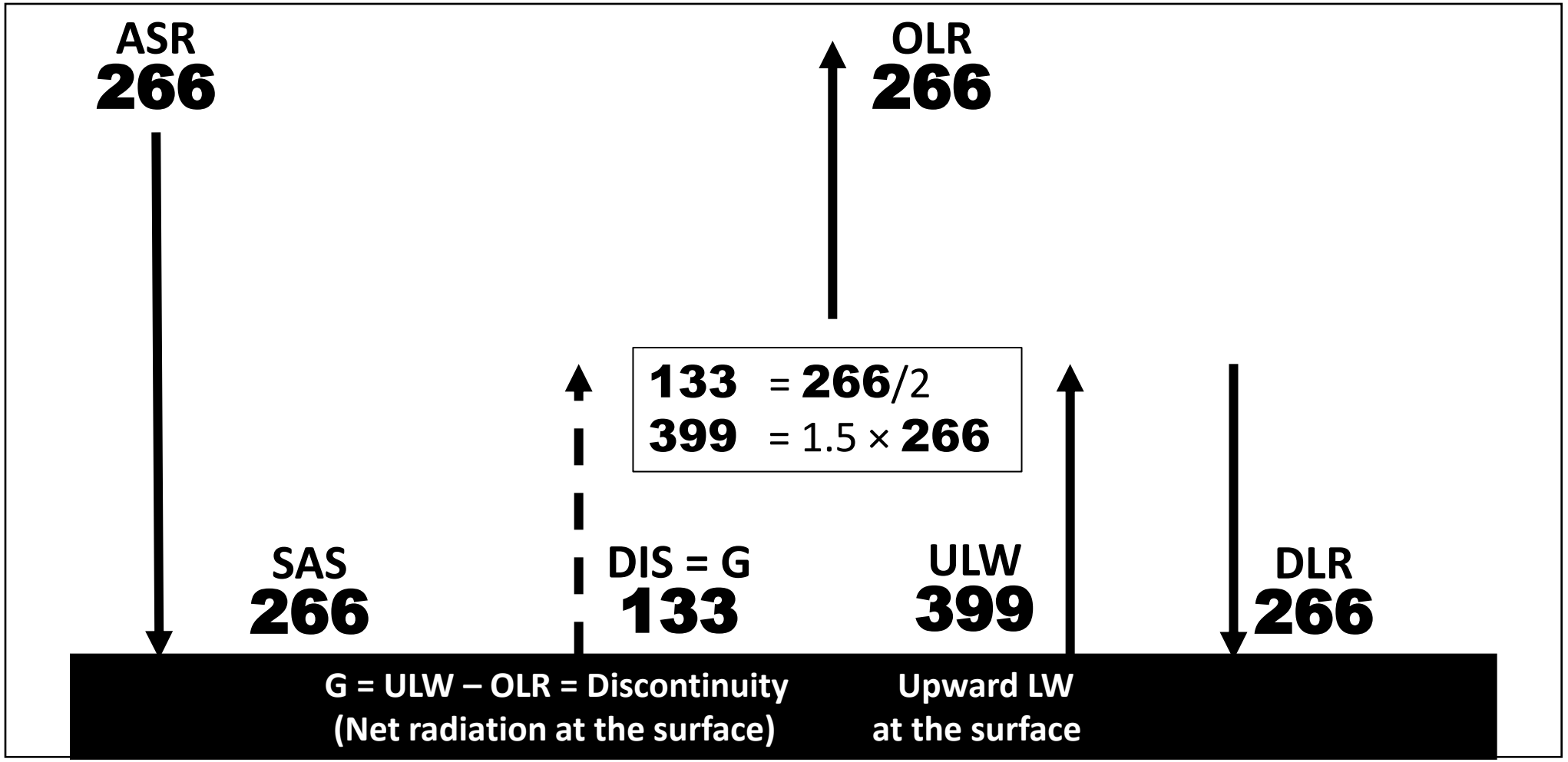
Discontinuity = OLR/2 =>
ULW – OLR = G = OLR/2



(T1) 532 = 2 × 266, (T2) 532 = 399 + 133, (T3) 266 = 2 × 133, (T4) 399 = 1.5 × 266

[(T1) 480 = 2 × 240, (T2) 480 = 360 + 120, (T3) 240 = 2 × 120, (T4) 360 = 1.5 × 240]

Discontinuity = OLR/2 =>
ULW – OLR = G = OLR/2

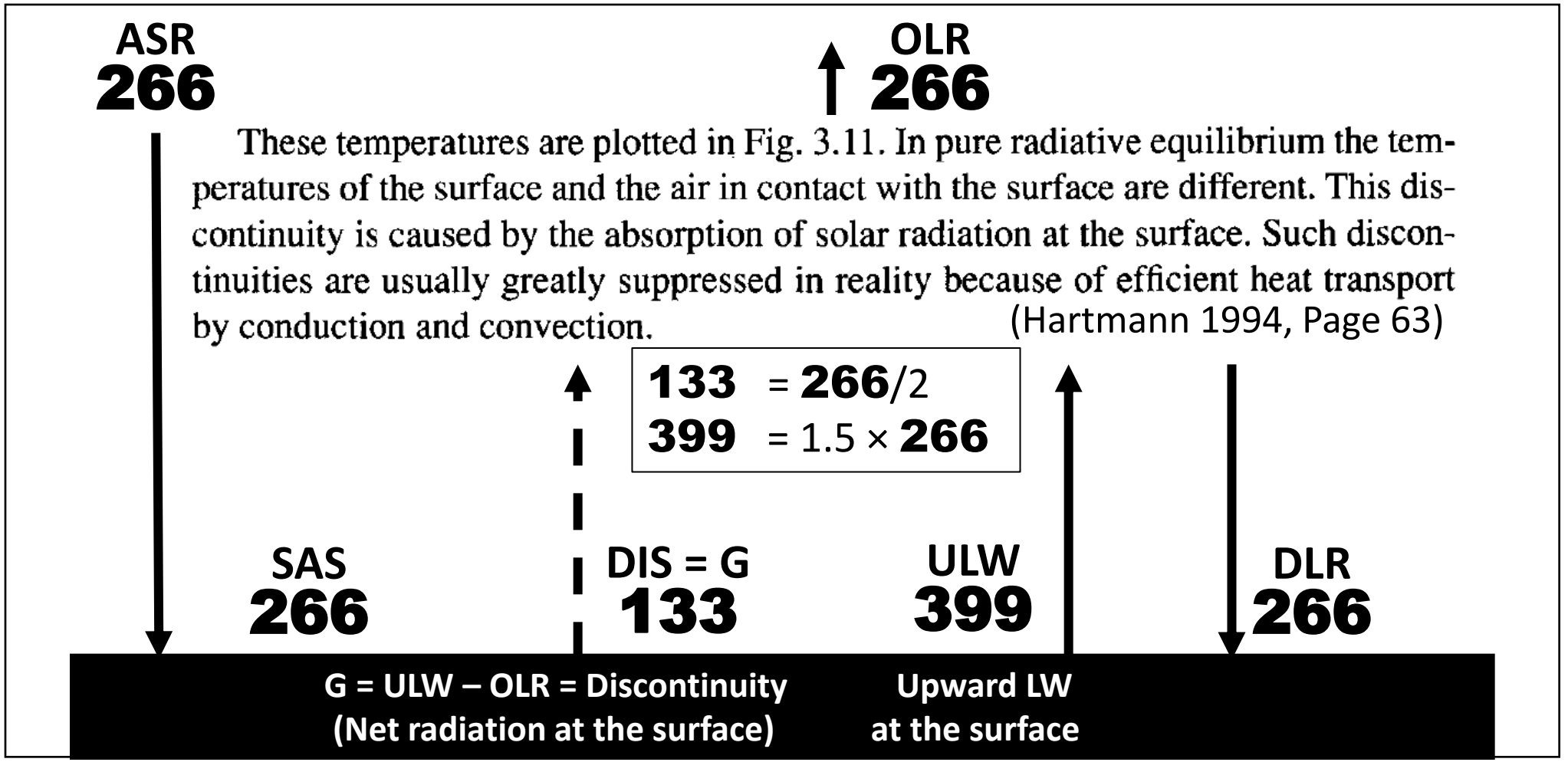


(T1) 532 = 2 × 266, (T2) 532 = 399 + 133, (T3) 266 = 2 × 133, (T4) 399 = 1.5 × 266

Hartmann Eq. (3.48) Eq. (3.49) Eq. (3.50) Eq. (3.54)

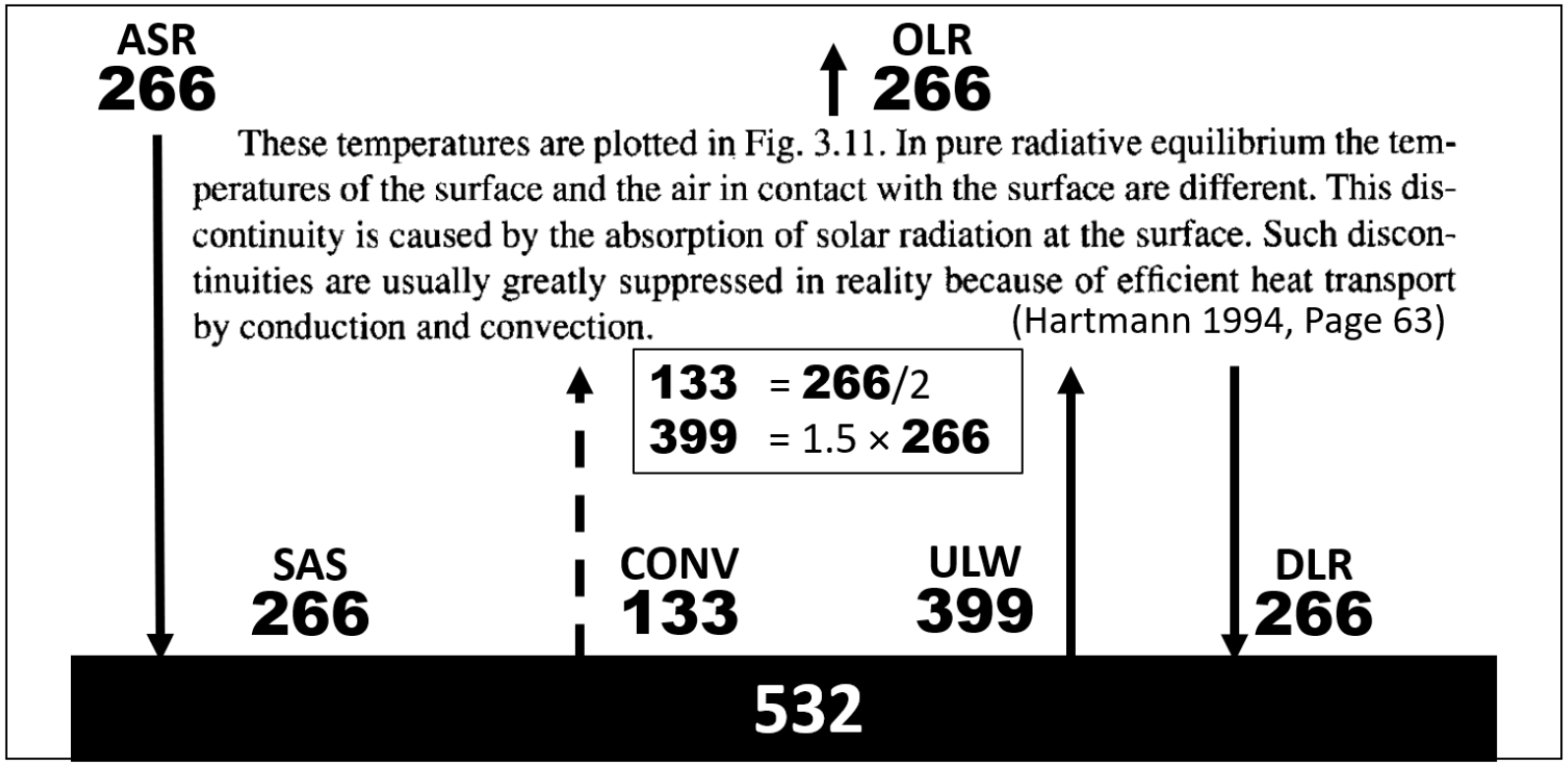
Discontinuity = CONVECTION

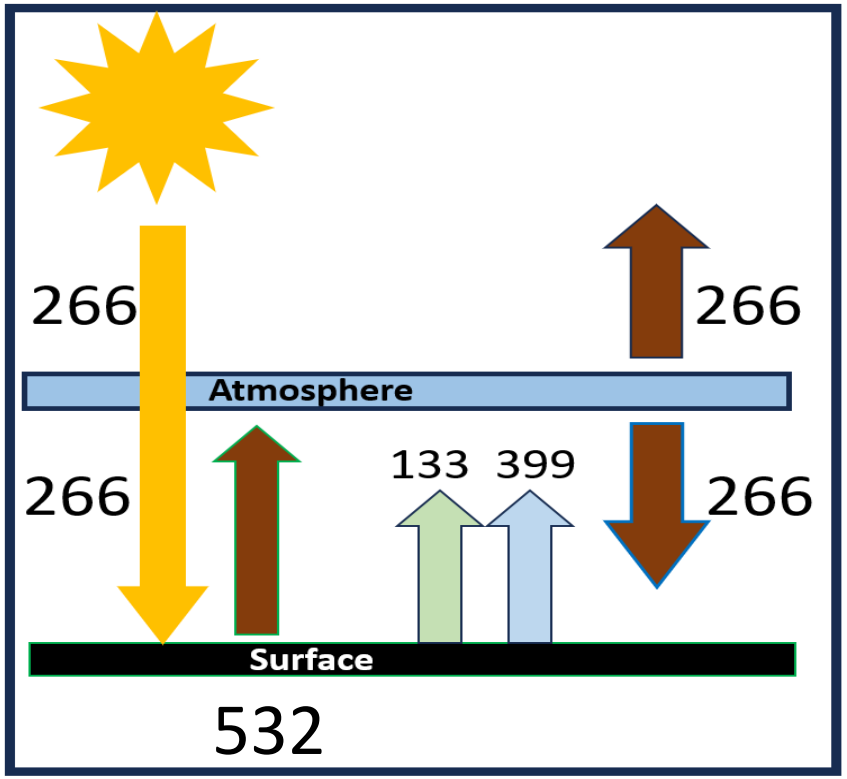
CONVECTION = OLR/2 = G, ULW = 1.5 OLR



(T1) 532 = 2 × 266, (T2) 532 = 399 + 133, (T3) 266 = 2 × 133, (T4) 399 = 1.5 × 266

Hartmann Eq. (3.48) Eq. (3.49) Eq. (3.50) Eq. (3.54)





133 : 266 : 399 : 532 = 1 : 2 : 3 : 4

Real Earth atmosphere

CERES_EBAF-Surface_Ed2.8

Data Quality Summary (March 27, 2015)

March 2000 through February 2010

Discontinuity = Net radiation at the surface = OLR/2

Real Earth atmosphere

CERES_EBAF-Surface_Ed2.8

Data Quality Summary (March 27, 2015)

March 2000 through February 2010

Discontinuity = Net radiation at the surface = OLR/2

Surface (SW down – SW up + LW down – LW up) (clear-sky) = OLR/2

243.9 – 29.7 + 316.0 – 398.0 = 265.7/2

Real Earth atmosphere

CERES_EBAF-Surface_Ed2.8

Data Quality Summary (March 27, 2015)

March 2000 through February 2010

Discontinuity = Net radiation at the surface = OLR/2

Surface (SW down – SW up + LW down – LW up) (clear-sky) = OLR/2

243.9 – 29.7 + 316.0 – 398.0 = 265.7/2 – 0.6 Wm^{-2}

Loeb et al. (2012): Earth heat uptake for July 2005–June 2010 is 0.58 ± 0.38 Wm^{-2}

Real Earth atmosphere

CERES EBAF Edition 2.8 Global Means (Mar 2000 – Feb 2016)

Upward LW radiation at the surface = 3OLR/2

Surface LW up = 1.5 OLR

398.40 = 1.5 × 265.59

Real Earth atmosphere

CERES EBAF Edition 2.8 Global Means (Mar 2000 – Feb 2016)

Upward LW radiation at the surface = 3OLR/2

Surface LW up = 1.5 OLR

$398.40 = 1.5 \times 265.59 + 0.015\ Wm^{-2}$

Real Earth atmosphere

CERES EBAF Edition 2.8 Global Means (Mar 2000 – Feb 2016)

G = ULW – OLR = 399 – 266 = 133

g = 1/3

G = 398.40 – 265.59 = 132.81

g = 132.81/398.40

Real Earth atmosphere

CERES EBAF Edition 2.8 Global Means (Mar 2000 – Feb 2016)

G = ULW – OLR = 399 – 266 = 133

g = 1/3

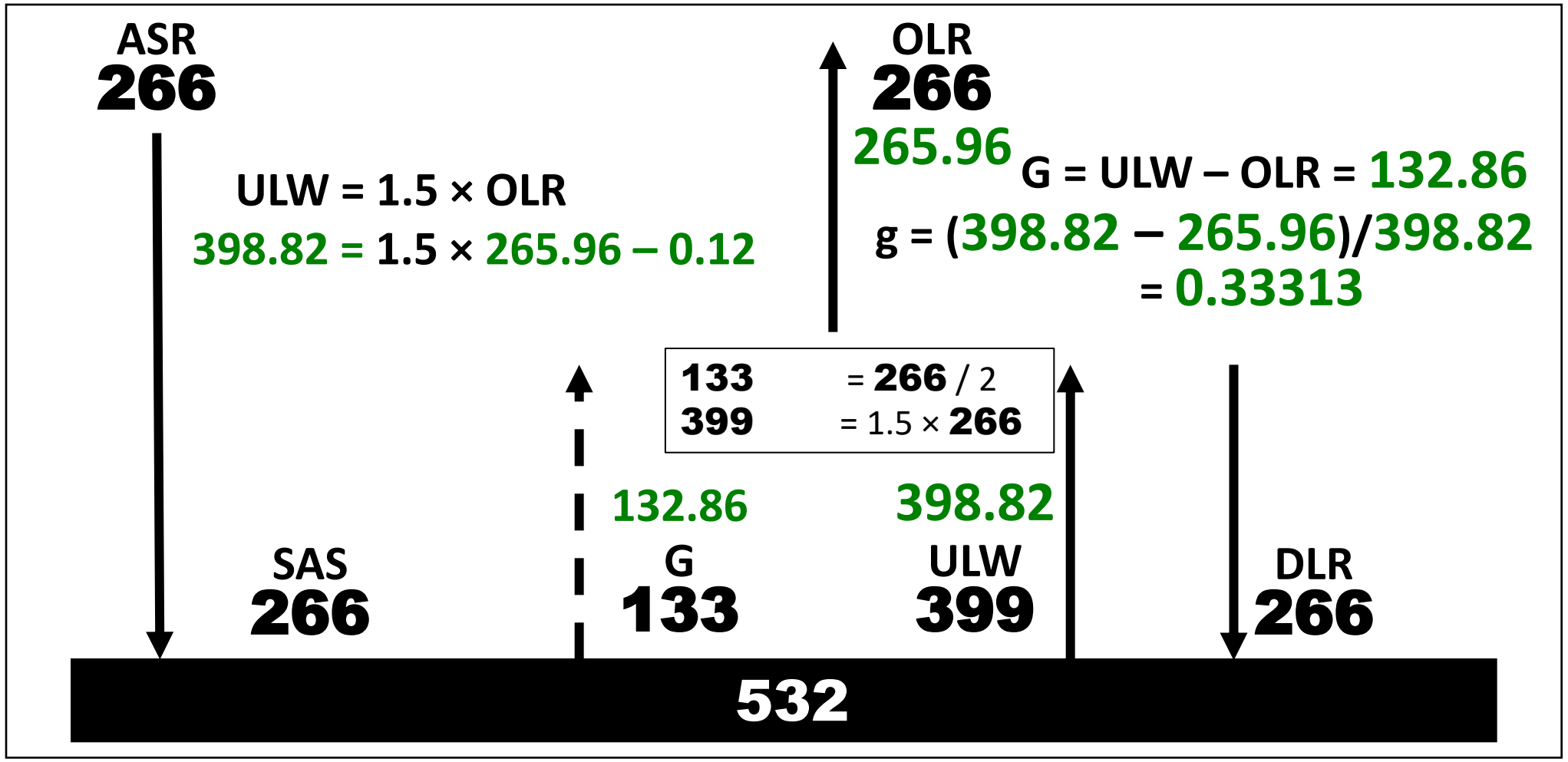
G = 398.40 – 265.59 = 132.81

g = 132.81/398.40 =

0.333358

The Greenhouse Effect, clear-sky. Geometry: black, Real Earth: green

G = ULW – OLR = 399 – 266 = 133, g = G/ULW = 1/3



Real Earth: CERES EBAF Edition 4.2, V2 data (Jan 2001 – Dec 2023) in **green**

Geometric (theoretical) clear-sky g =
Real Earth (observed) clear-sky g = 1/3

- Raval and Ramanathan (1989) g ~ 0.33
- Ramanathan and Inamdar (Frontiers of Climate Modeling, 2006): "The global average G_a is 131 Wm^{-2} or the normalized g_a is 0.33, i.e., the atmosphere reduces the energy escaping to space by 131 Wm^{-2} (or by a factor of 1/3)."
- Stevens and Schwartz (2012) G = 131.5 Wm^{-2} g = 0.331
- Stephens et al. (2012) G = 131.6 Wm^{-2} g = 0.331
- Hartmann (2016) G = 131 Wm^{-2} g = 0.331
- Stephens and L'Ecuyer (2015) G = 132.3 Wm^{-2} g = 0.332
- CERES EBAF Ed2.8 (2017) G = 132.81 Wm^{-2} g = 0.33336
- CERES EBAF Ed4.2 (2024) G = 132.80 Wm^{-2} g = 0.33313

CONVECTION = Net radiation at the surface
Net radiation at the surface = OLR/2

It is there in standard university textbooks and lecture notes.

CONVECTION = Net radiation at the surface
Net radiation at the surface = OLR/2

It is there in standard university textbooks and lecture notes.

But it is missing from

- Manabe and Strickler (1964)
- Manabe and Wetherald (1967)
- The Charney Report (1979)
- Theory of Climate (1983)
- The IPCC Reports (1990-2021)
- Sensitivity studies
- Forcing and feedback estimates
- Global energy budget assessments
- Climate models, GCMs and CMIPs
- Future climate projections …

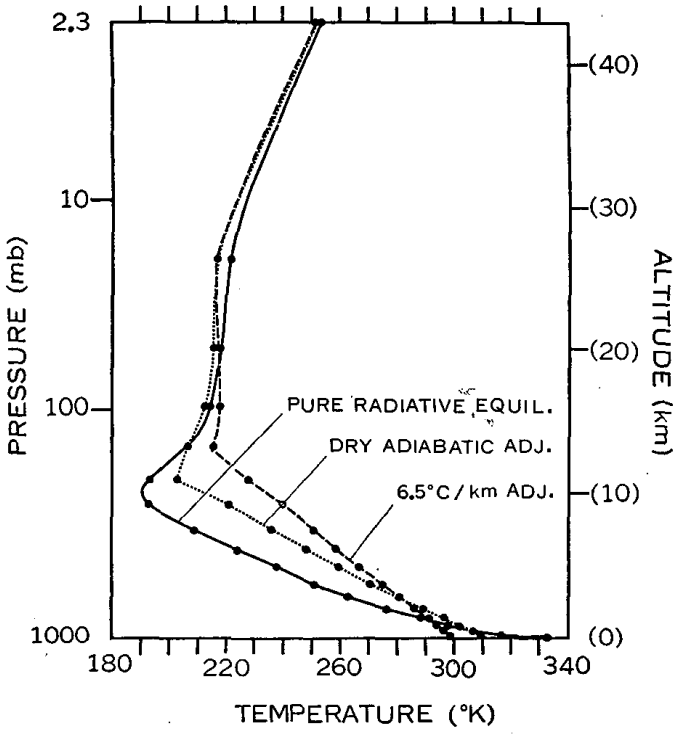


FIG. 4. The dashed, dotted, and solid lines show the thermal equilibrium with a critical lapse rate of 6.5 deg km^{-1}, a dry-adiabatic critical lapse rate (10 deg km^{-1}), and pure radiative equilibrium.

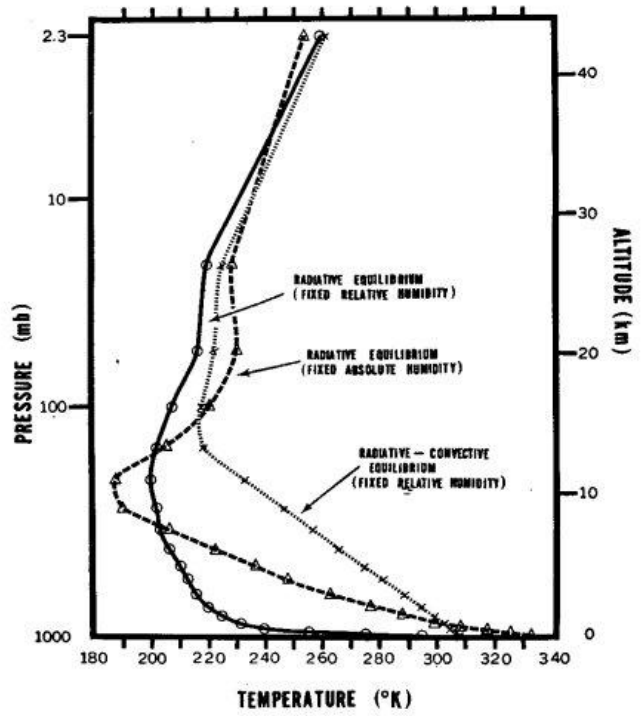


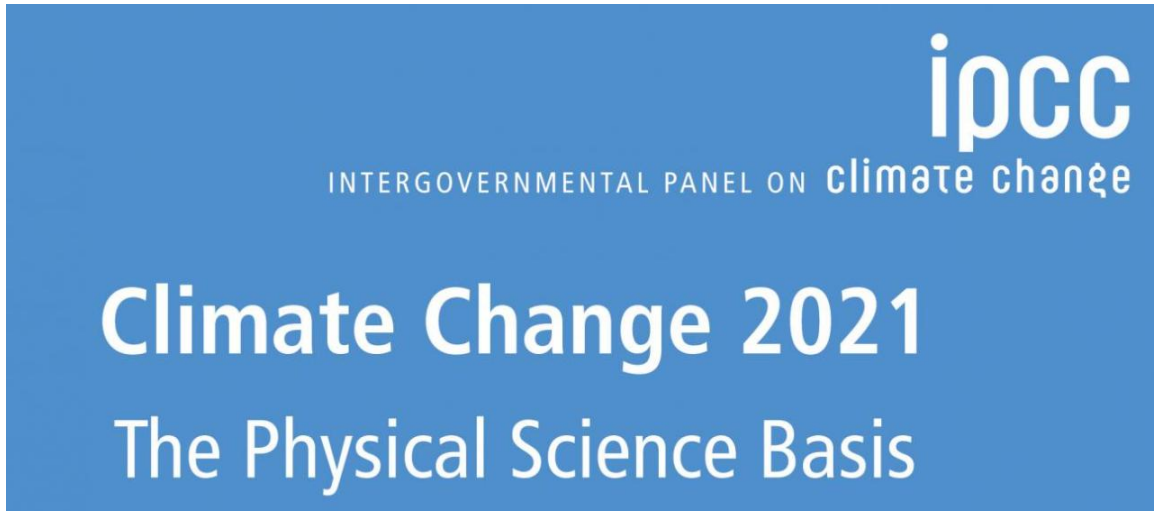
FIG. 5. Solid line, radiative equilibrium of the clear atmosphere with the given distribution of relative humidity; dashed line, radiative equilibrium of the clear atmosphere with the given distribution of absolute humidity; dotted line, radiative convective equilibrium of the atmosphere with the given distribution of relative humidity.

CONVECTION = Net radiation at the surface
Net radiation at the surface = OLR/2

It is there in standard university textbooks and lecture notes.

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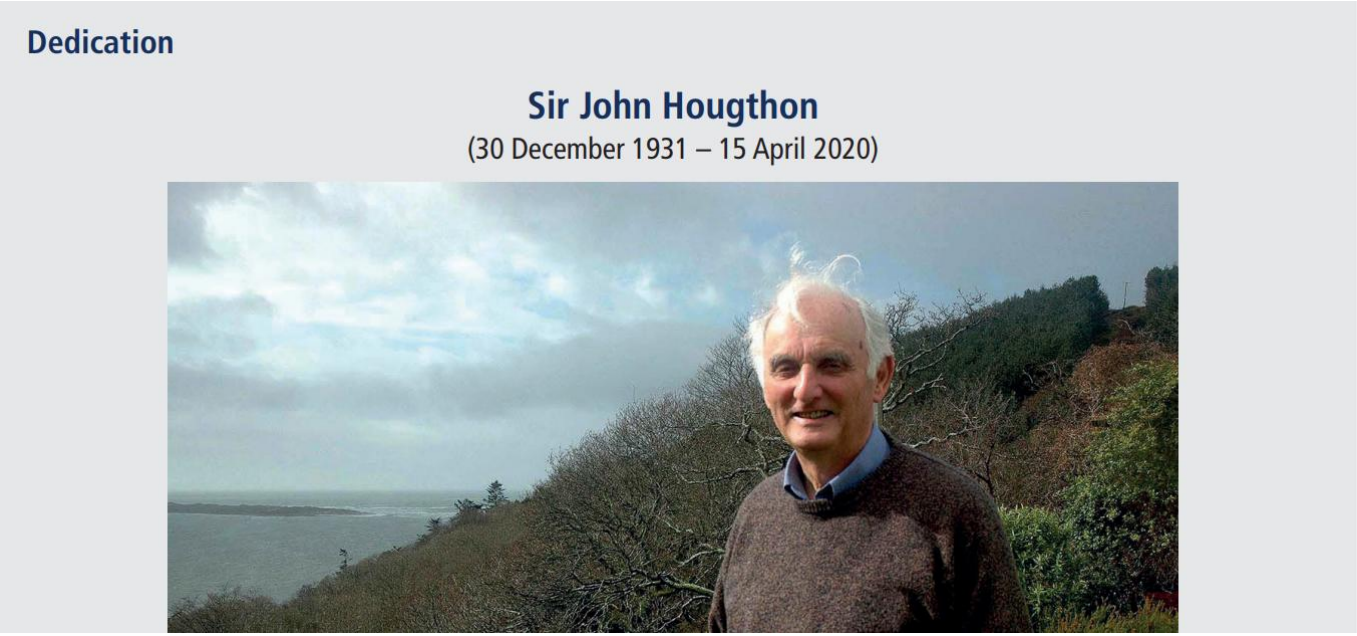
CAMBRIDGE UNIVERSITY PRESS

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CONVECTION = Net radiation at the surface
Net radiation at the surface = OLR/2

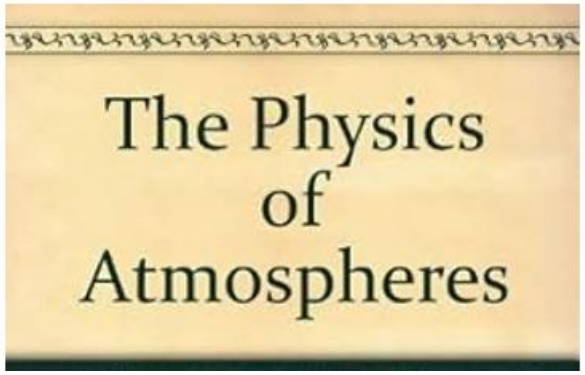
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- Future climate projections …

$$B_g - B_0 = \frac{\phi}{2\pi} \qquad (2.13)$$

Net radiation at the surface = Convection = OLR/2



Cambridge University Press
1977, 1986, 2002

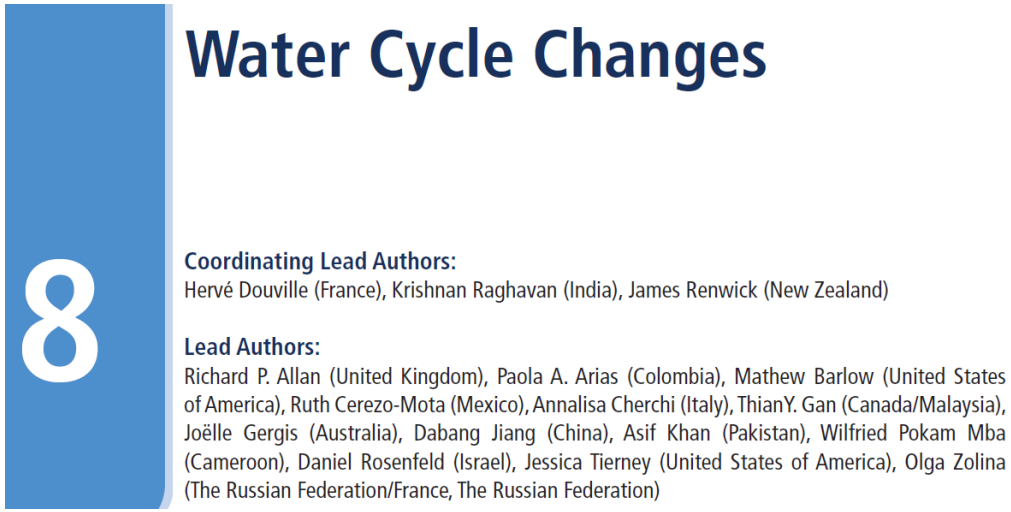


CONVECTION = Net radiation at the surface
Net radiation at the surface = OLR/2

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- Future climate projections …


8

Water Cycle Changes

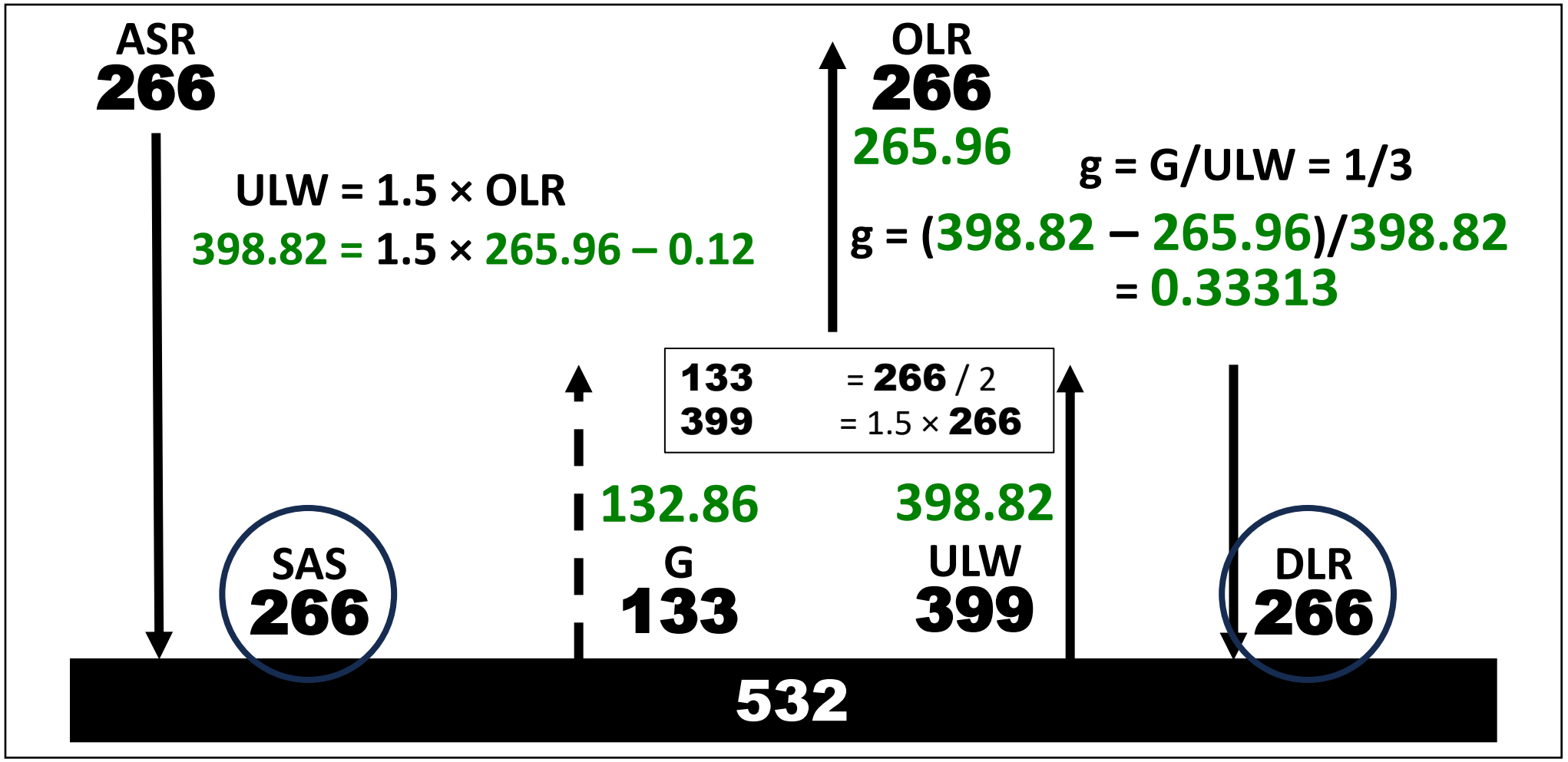
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Without the constraint
Convection = OLR/2
water cycle change assessments
and climate projections
cannot be accurate.

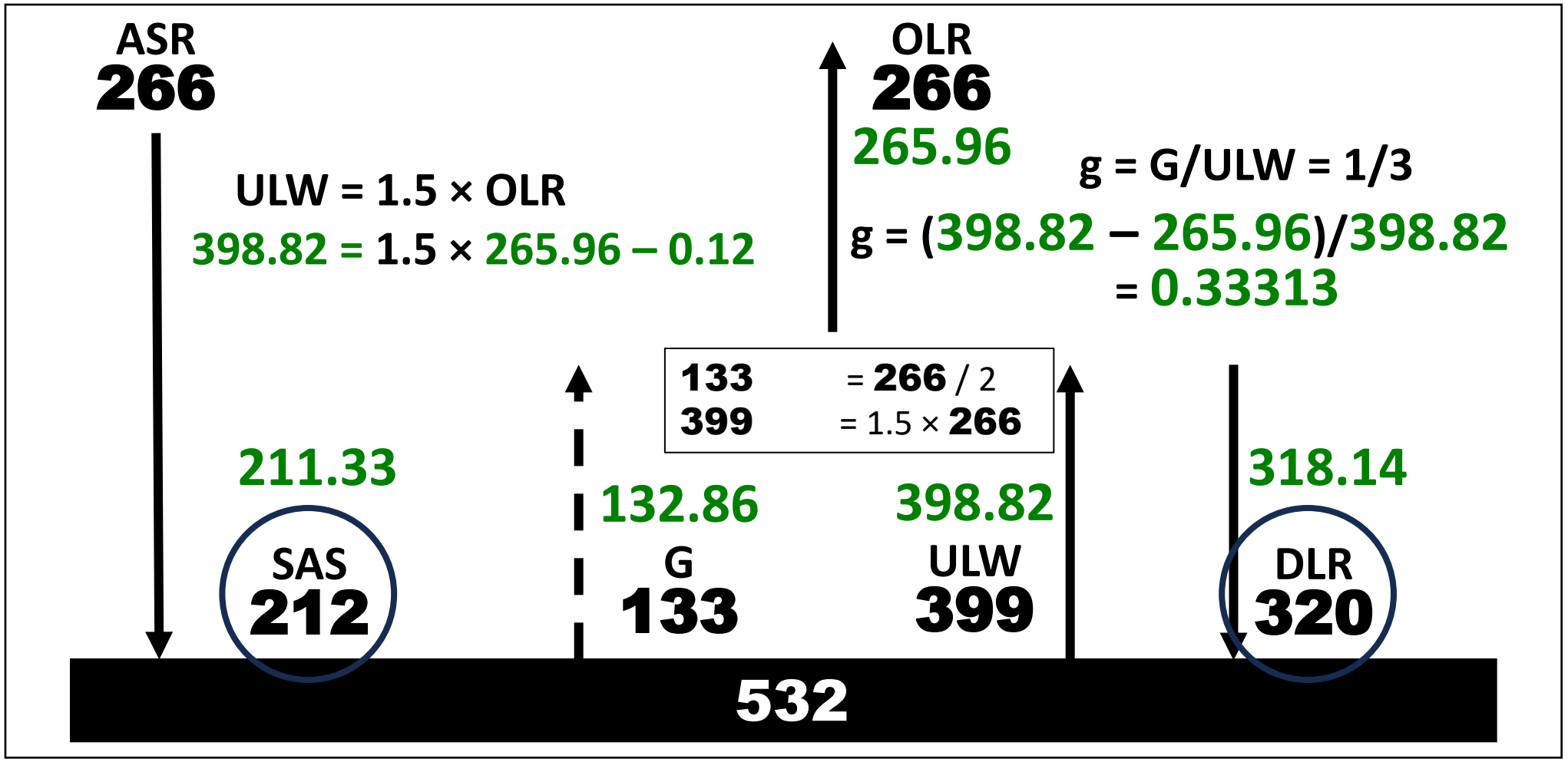
Chapter 1.3
Clear-sky extension

Now what about with SAS and DLR?



Real Earth: CERES EBAF Edition 4.2, V2 data (Jan 2001 – Dec 2023) in **green**

Now what about with SAS and DLR?



Real Earth: CERES EBAF Edition 4.2, V2 data (Jan 2001 – Dec 2023) in **green**

	G	OLR	ULW	TOT
Trenberth's Earth-like	133	266	399	532
Ratio (clear-sky)	**1**	**2**	**3**	**4**
ULW = **3** = 398.75	132.92	265.83	398.75	531.67
CERES EBAF Ed4.2	132.80	265.95	398.75	529.39
Difference	0.12	-0.12	0.0	2.28

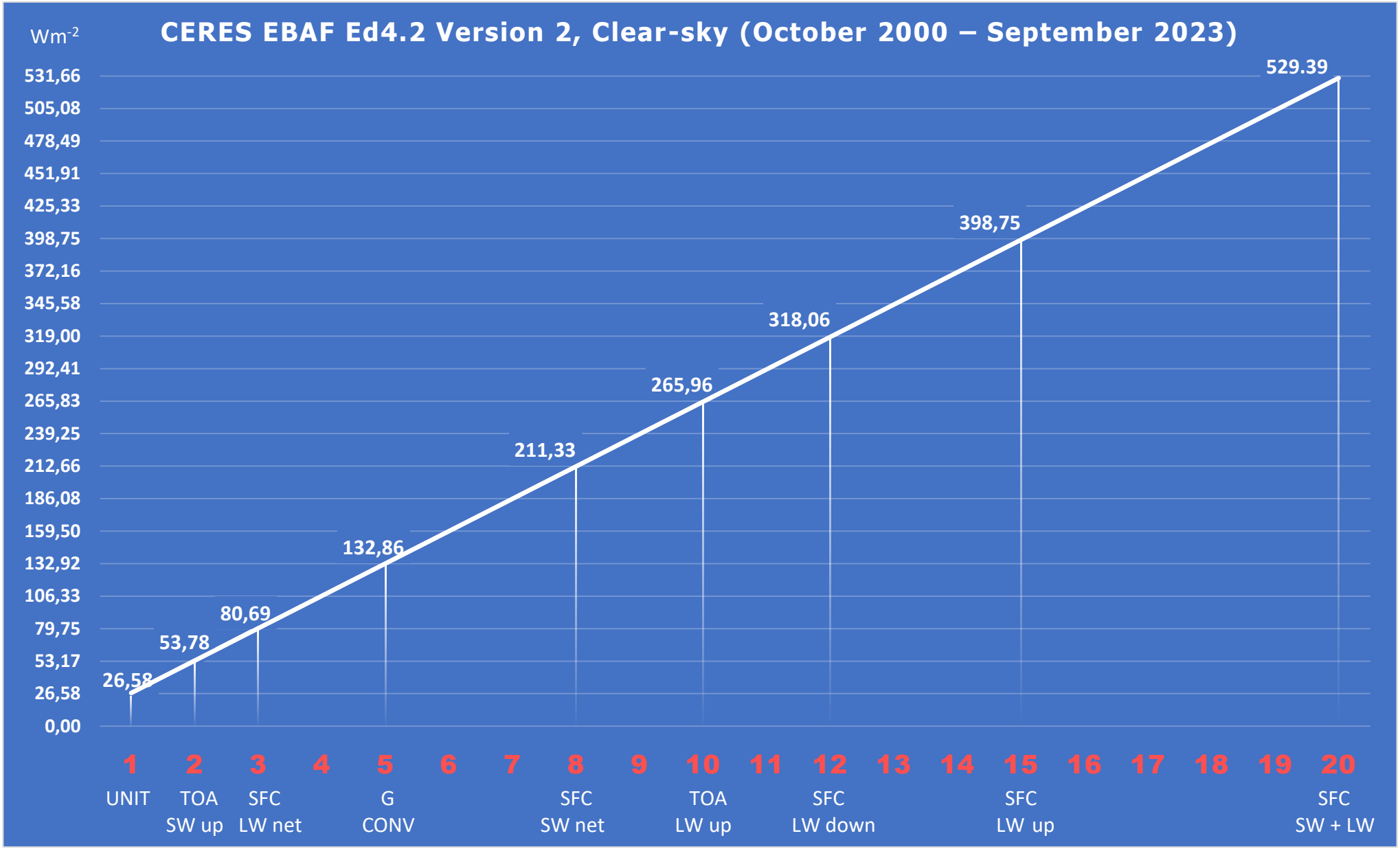
CERES EBAF Edition 4.2, Version 2 (release date 2 January 2024), Oct 2000 – Sept 2023

Insert Surface SW Net = **8**, Surface LW Down = **12**

	G	SFC SW Net	OLR	SFC LW Down	ULW	TOT
Ratio (clear-sky)	**1**		**2**		**3**	**4**
Extended	**5**	**8**	**10**	**12**	**15**	**20**
15 = ULW = 398.75	132.92	212.67	265.83	319.00	398.75	531.67
EBAF Ed4.2	132.80	211.33	265.95	318.06	398.75	529.39
Difference	0.12	1.34	-0.12	0.94	0.0	2.28

Insert Surface SW Net = **8**, Surface LW Down = **12** (**1** = 26.583 Wm^{-2})

	G	SFC SW Net	OLR	SFC LW Down	ULW	TOT
Ratio (clear-sky)	**1**		**2**		**3**	**4**
Extended	**5**	**8**	**10**	**12**	**15**	**20**
15 = ULW = 398.75	132.92	212.67	265.83	319.00	398.75	531.67
EBAF Ed4.2	132.80	211.33	265.95	318.06	398.75	529.39
Difference	0.12	1.34	-0.12	0.94	0.0	2.28


CERES EBAF Ed4.2 Version 2, Clear-sky (October 2000 – September 2023)
Wm-2
531,66
505,08
478,49
451,91
425,33
398,75
372,16
345,58
319,00
292,41
265,83
239,25
212,66
186,08
159,50
132,92
106,33
79,75
53,17
26,58
0,00
26,58
53,78
80,69
132,86
211,33
265,96
318,06
398,75
529.39
1 UNIT
2 TOA SW up
3 SFC LW net
4
5 G CONV
6
7
8 SFC SW net
9
10 TOA LW up
11
12 SFC LW down
13
14
15 SFC LW up
16
17
18
19
20 SFC SW + LW

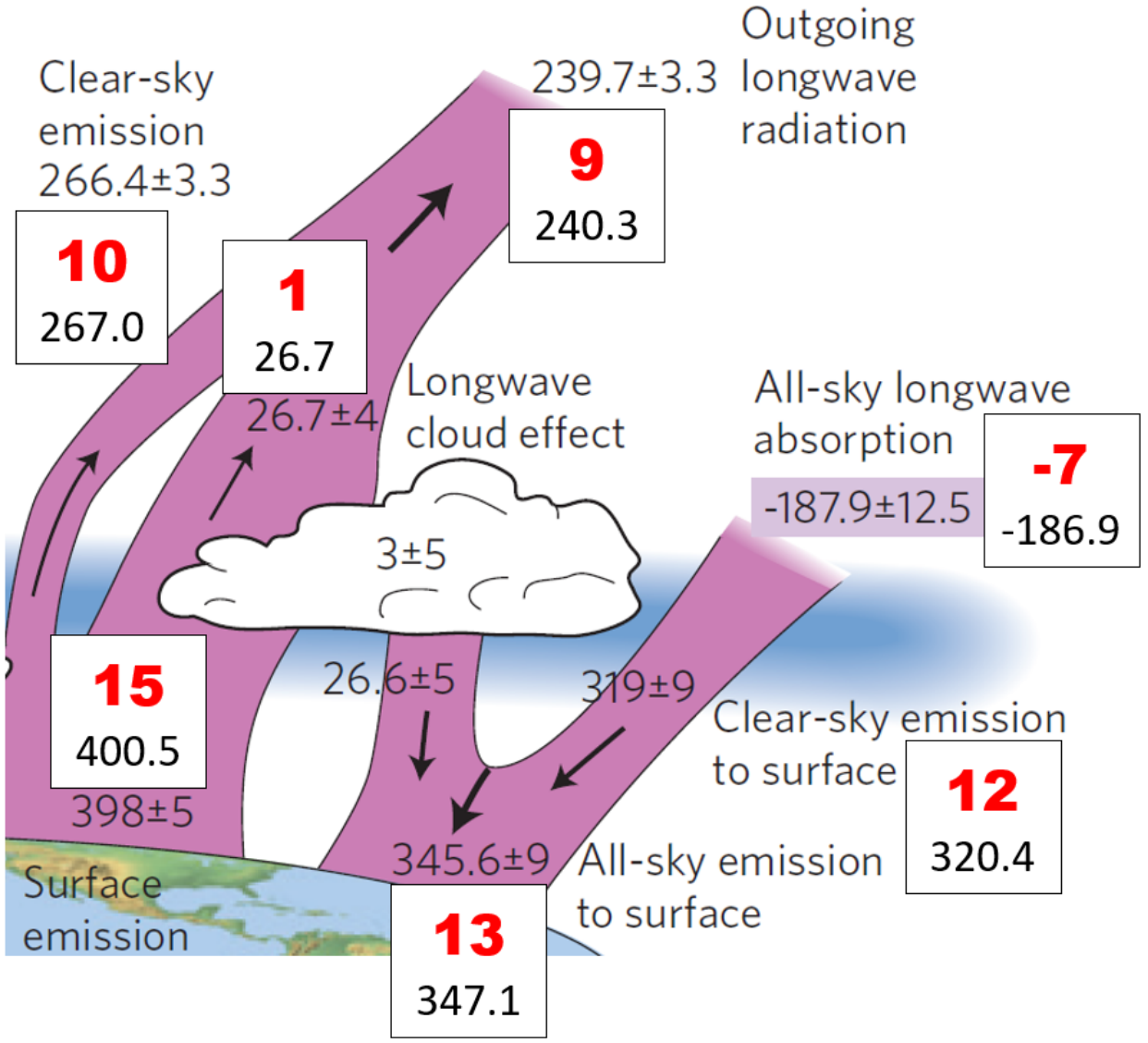
Chapter 1.4
All-sky extension

All-sky extension

An update on Earth's energy balance in light of the latest global observations

Nature Geosci 2012

Graeme L. Stephens[1*], Juilin Li[1], Martin Wild[2], Carol Anne Clayson[3], Norman Loeb[4], Seiji Kato[4], Tristan L'Ecuyer[5], Paul W. Stackhouse Jr[4], Matthew Lebsock[1] and Timothy Andrews[6]

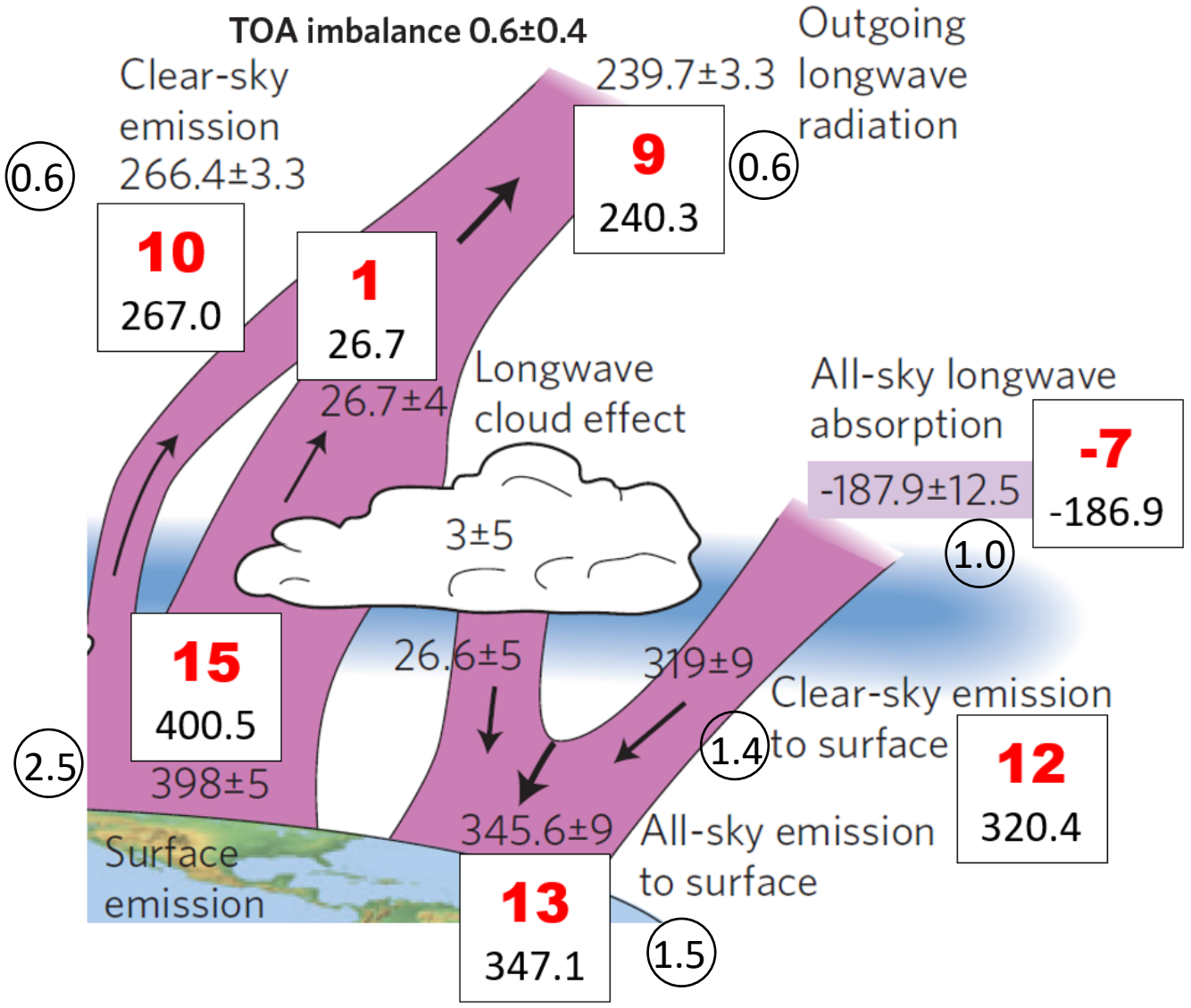


All-sky extension

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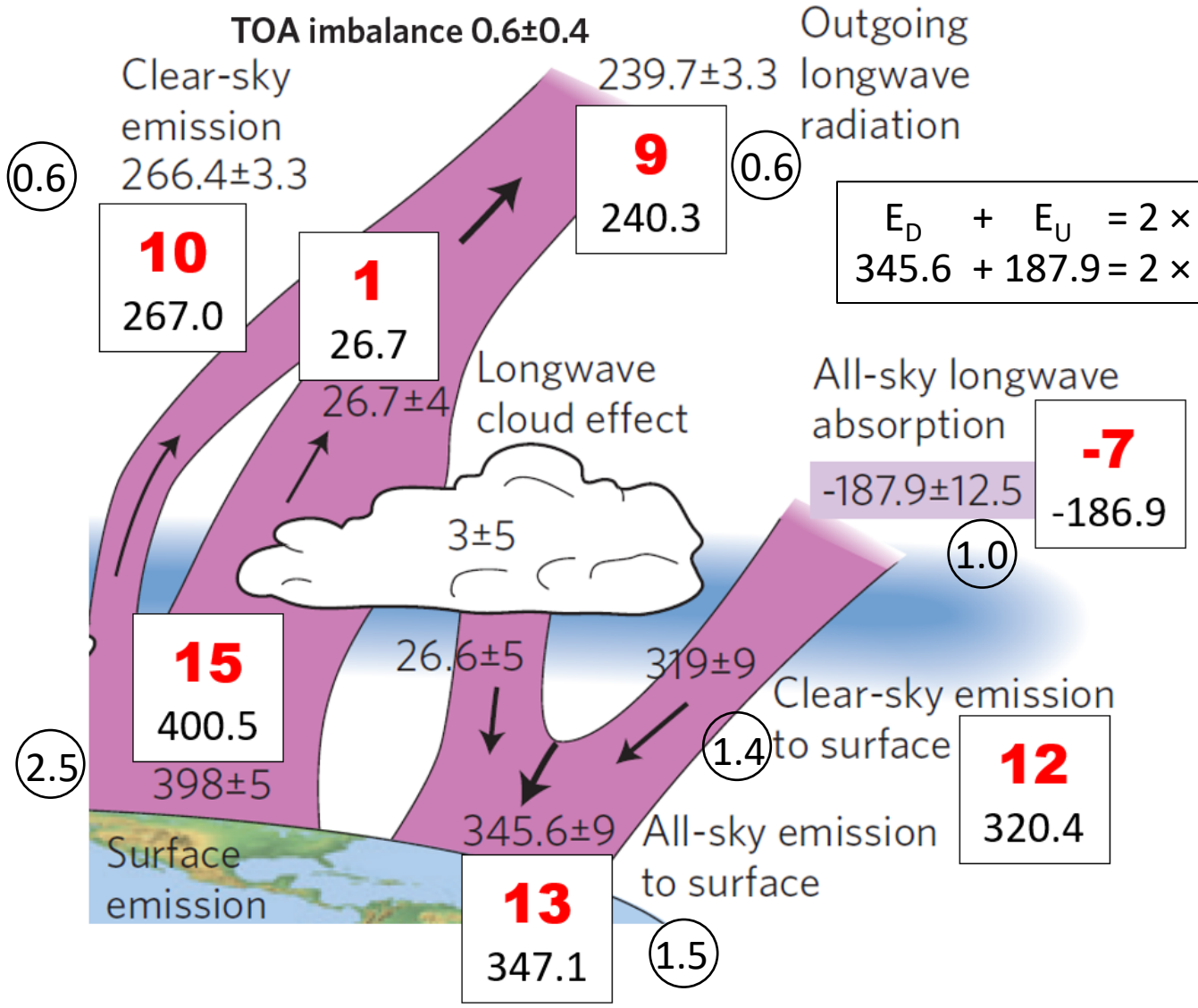


All-sky extension

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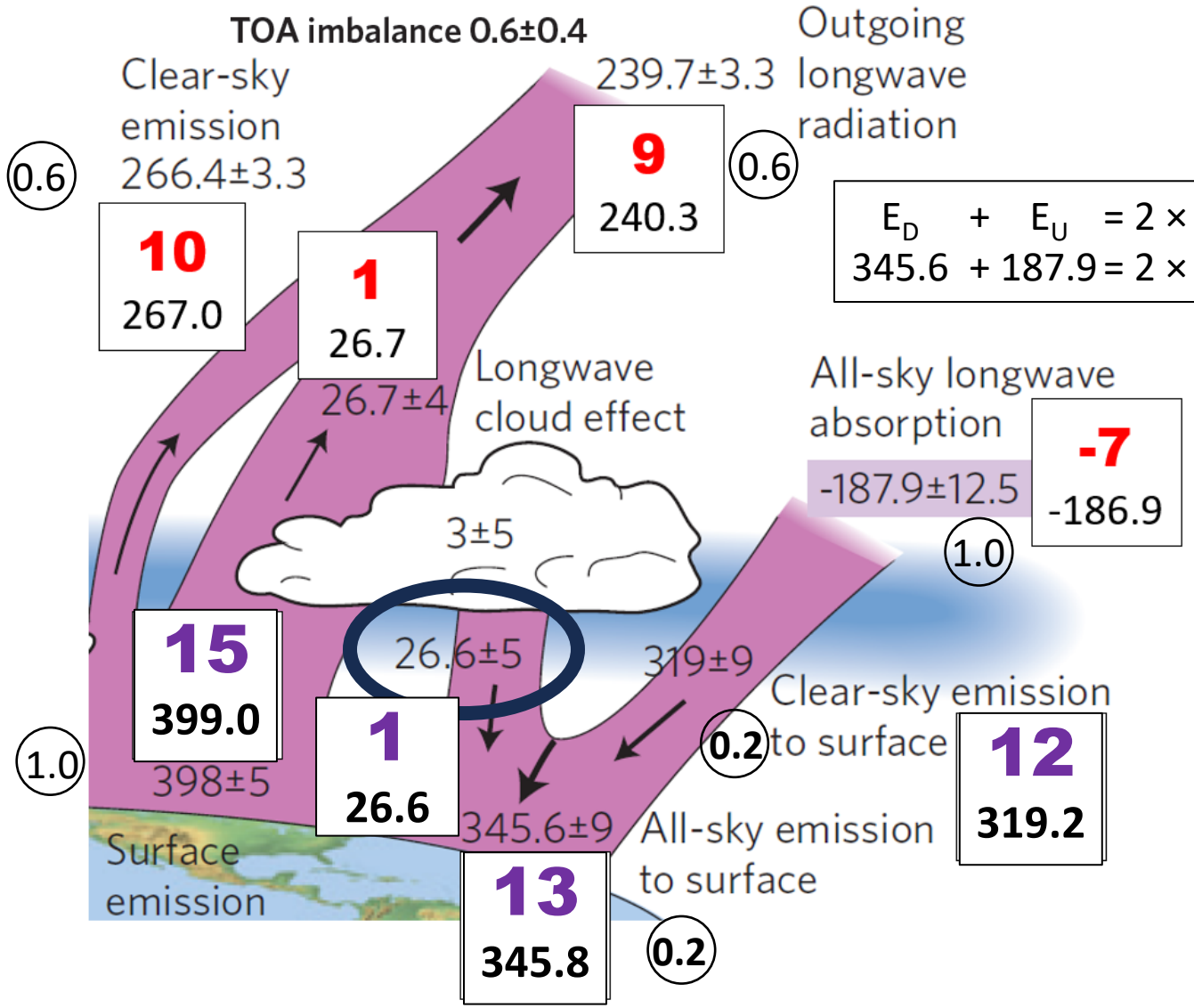
$$E_D + E_U = 2 \times E_T + IMB$$
$$345.6 + 187.9 = 2 \times 266.4 + 0.6 + 0.1$$

All-sky extension

An update on Earth's energy balance in light of the latest global observations

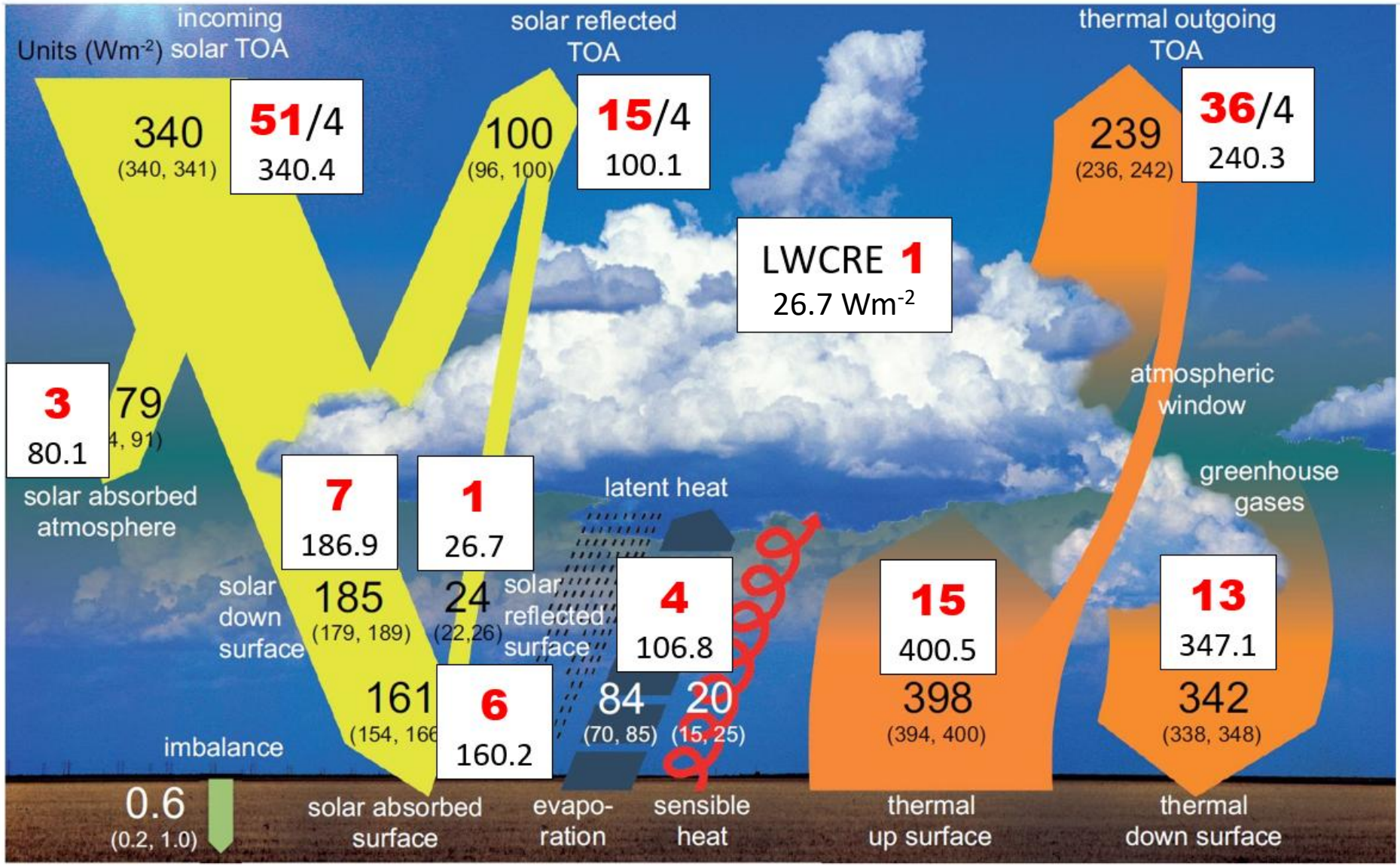
Nature Geosci 2012

Graeme L. Stephens[1*], Juilin Li[1], Martin Wild[2], Carol Anne Clayson[3], Norman Loeb[4], Seiji Kato[4], Tristan L'Ecuyer[5], Paul W. Stackhouse Jr[4], Matthew Lebsock[1] and Timothy Andrews[6]



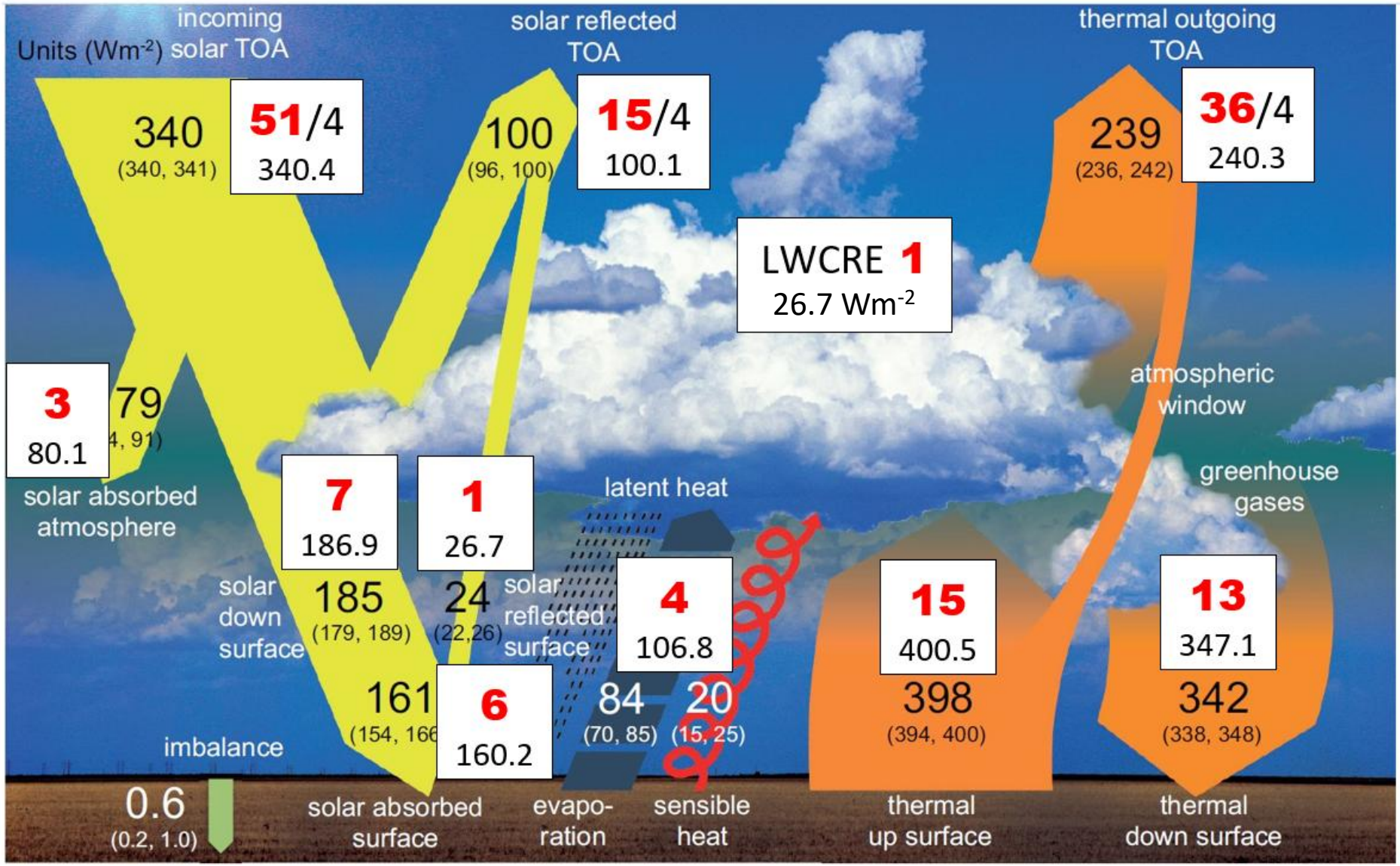
$$E_D + E_U = 2 \times E_T + IMB$$
$$345.6 + 187.9 = 2 \times 266.4 + 0.6 + 0.1$$

(All-sky) IPCC AR5 (2013) (based on Wild et al. 2013)



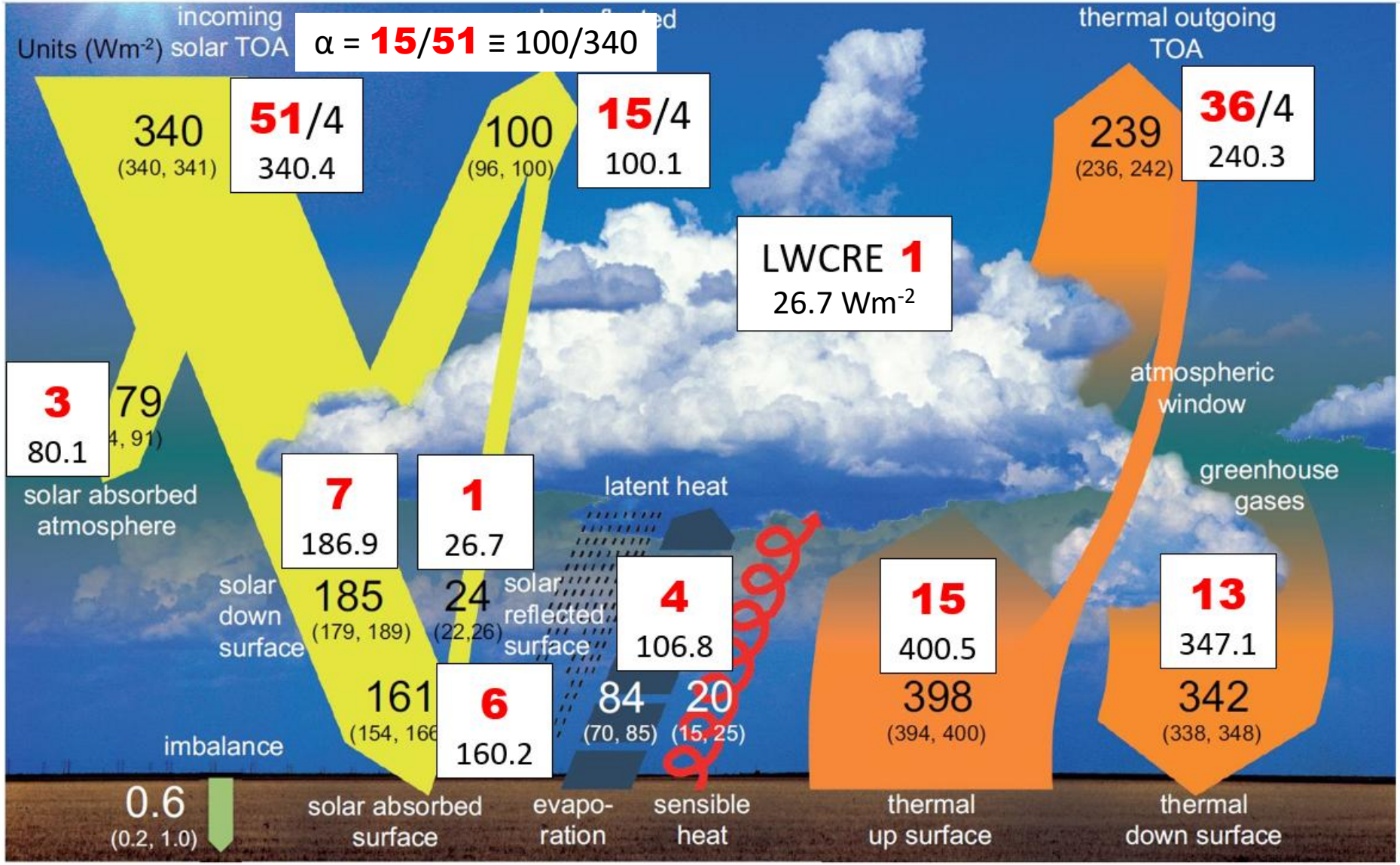
(All-sky) IPCC AR5 (2013) (based on Wild et al. 2013)

TSI
51
1361.7
Wm^{-2}



(All-sky) IPCC AR5 (2013) (based on Wild et al. 2013)

TSI
51
1361.7
Wm^{-2}



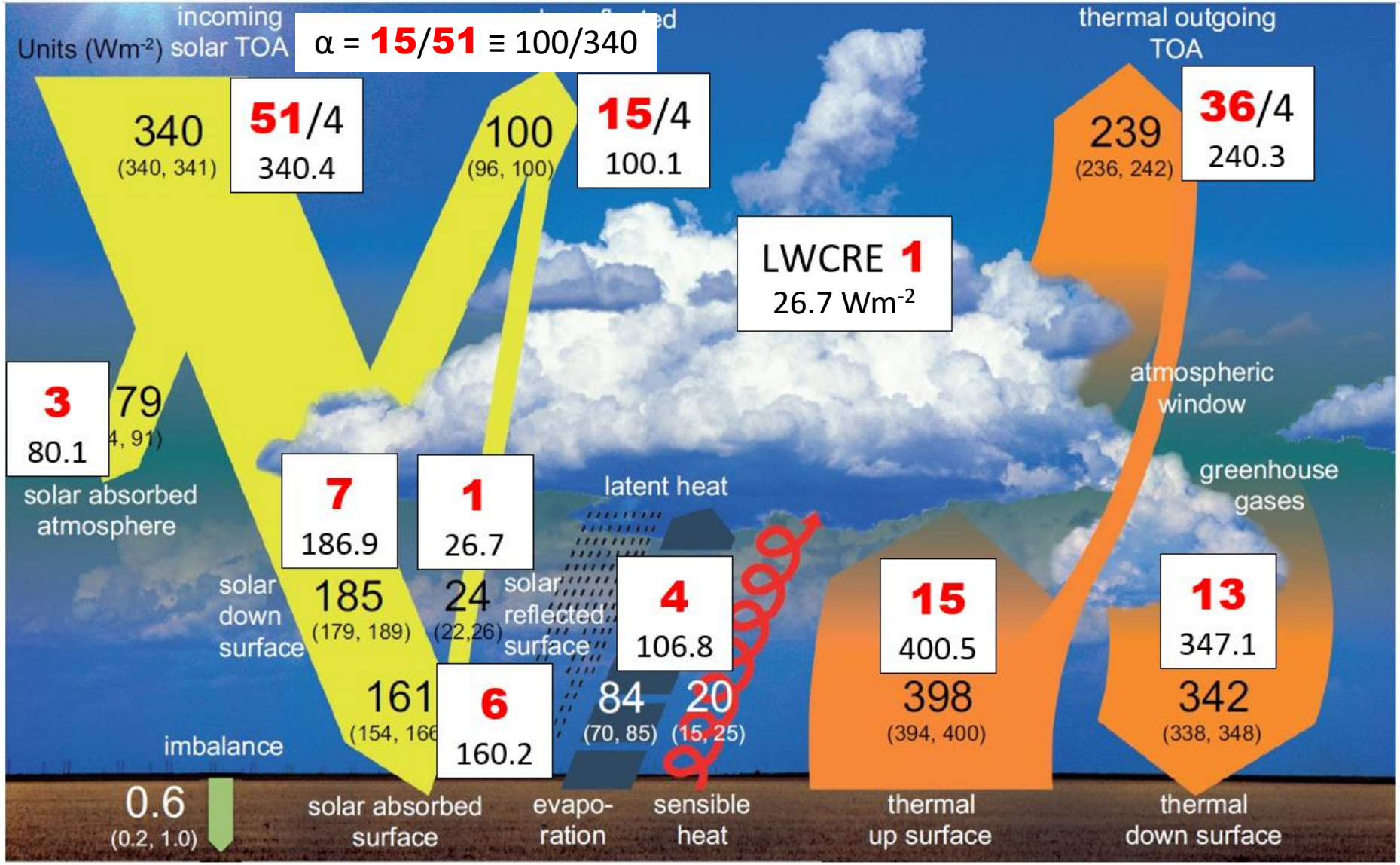
(All-sky) IPCC AR5 (2013) (based on Wild et al. 2013)

TSI
51

Solar flux

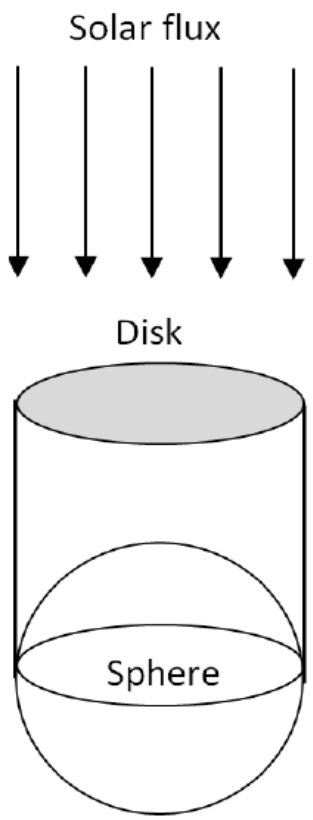
Disk

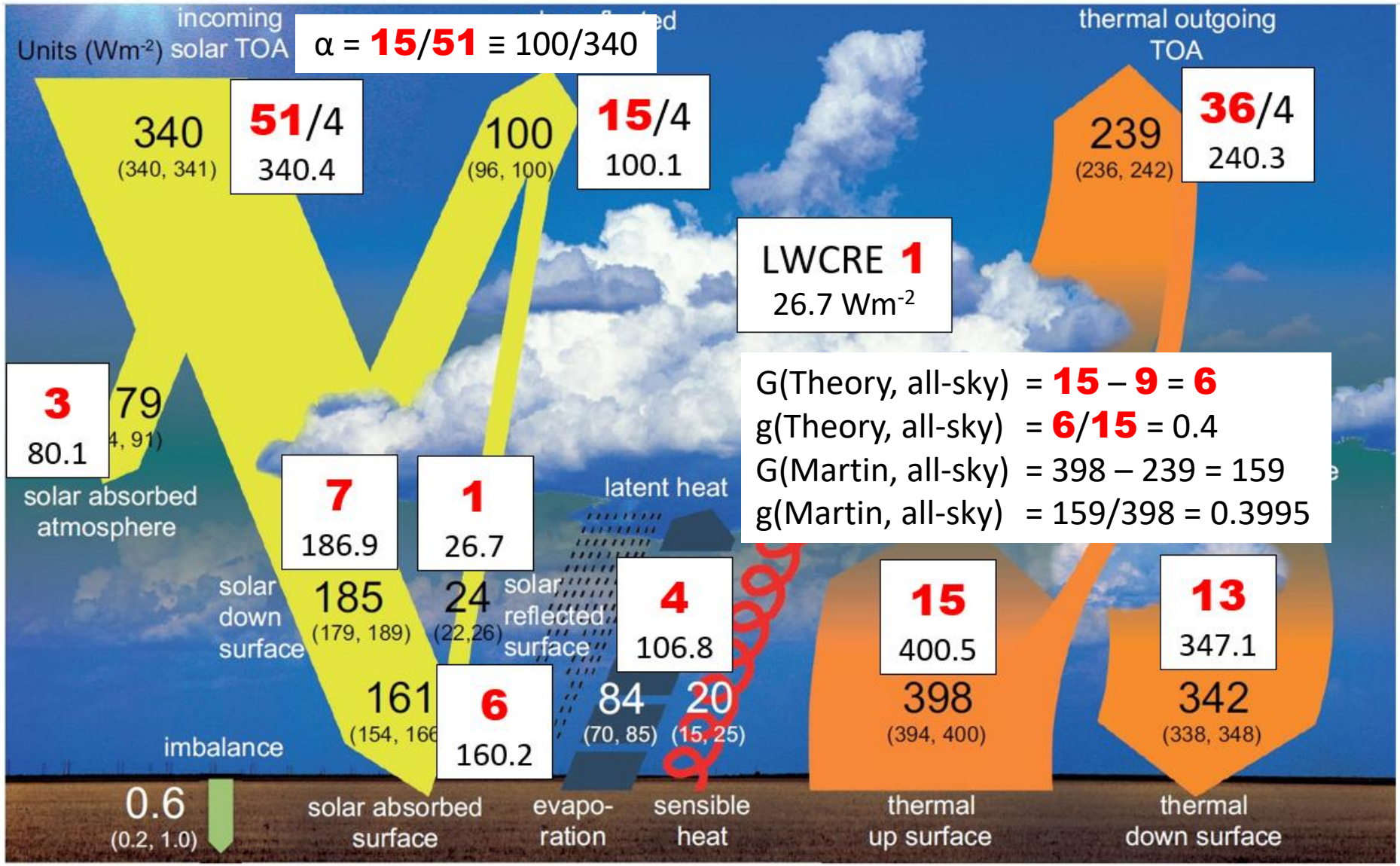
Sphere



(All-sky) IPCC AR5 (2013) (based on Wild et al. 2013)

TSI
51

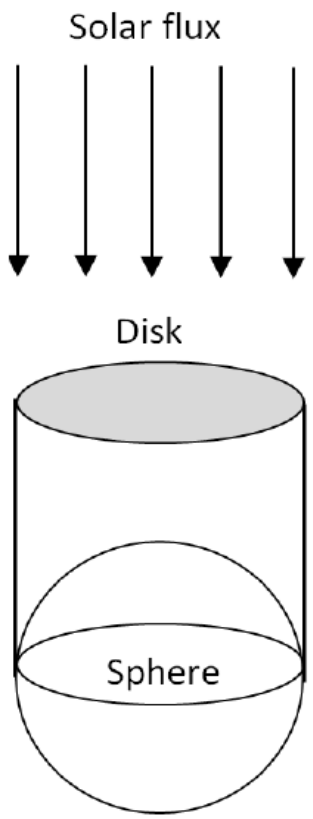


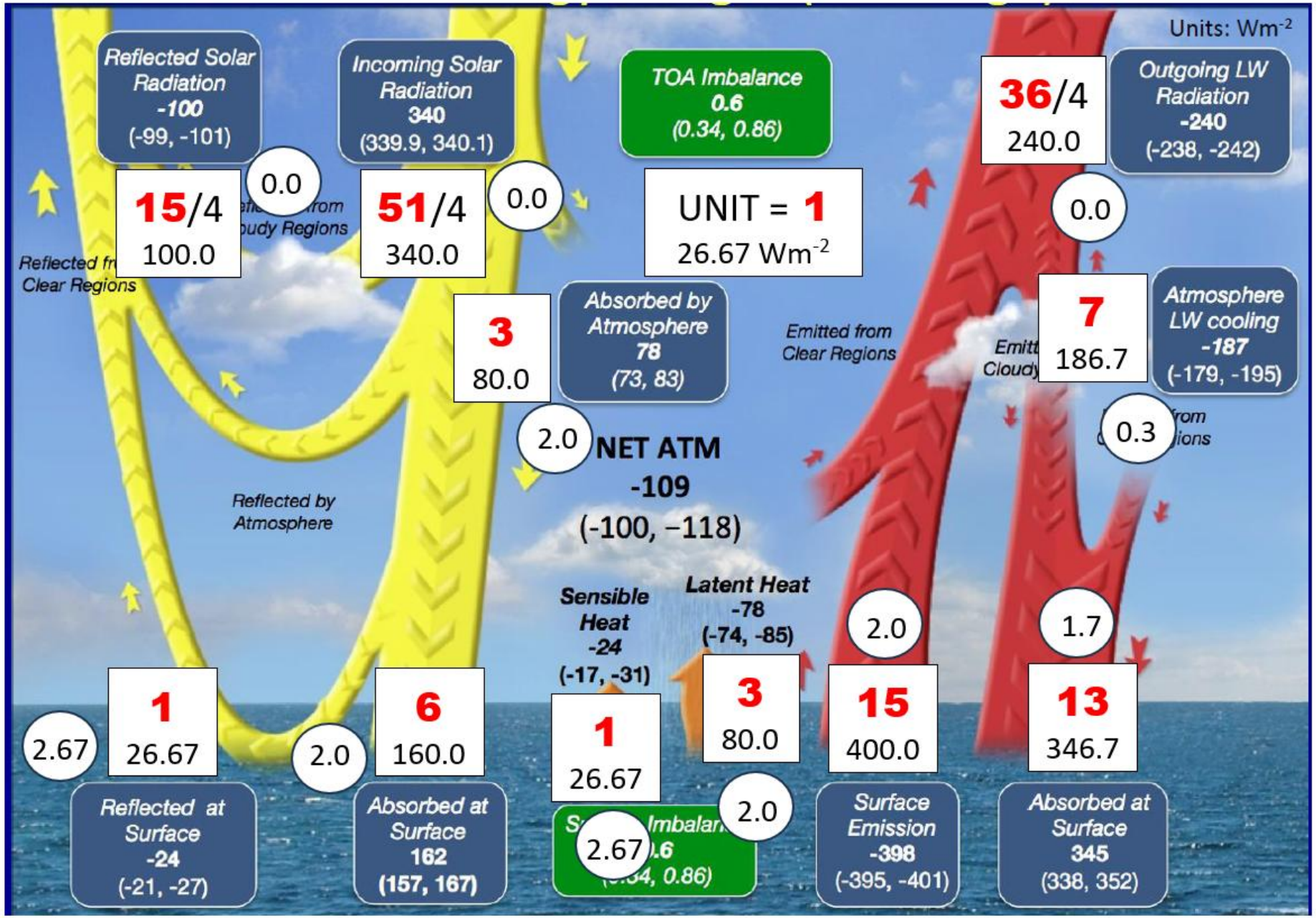


Loeb (2014) CERES EBAF

TSI

51





Langley Colloquium Series & Sigma Series Lecture, NASA LaRC, 2014

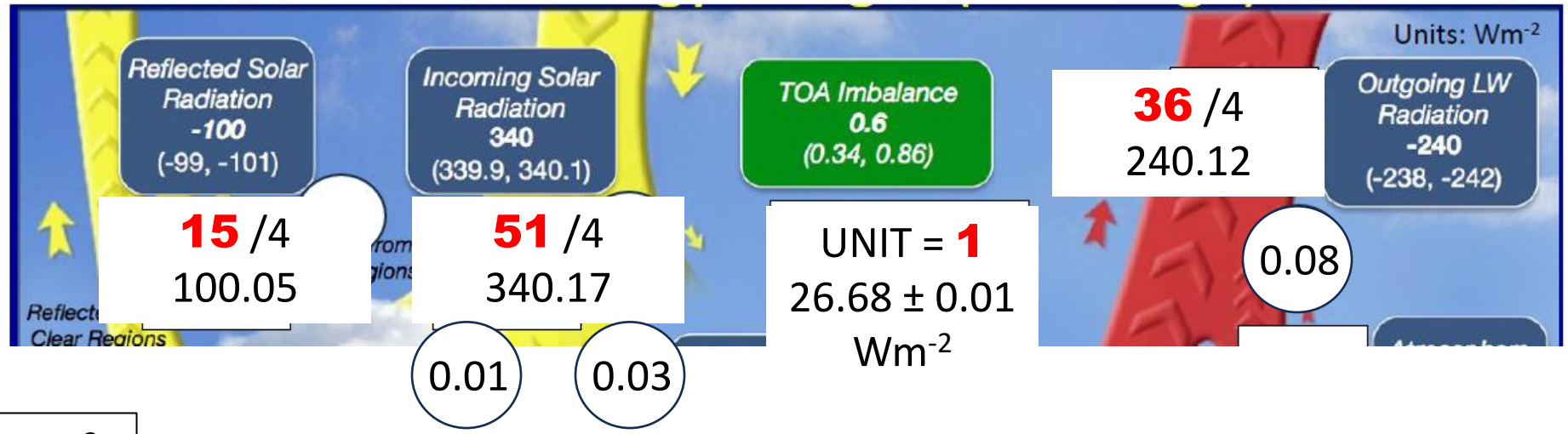
Data from Loeb (2014)

Unit = 26.67 Wm^{-2}	N	N × unit [Wm^{-2}]	Loeb [Wm^{-2}]	Diff [Wm^{-2}]
Incoming Solar	**51**/4	340.0	340	0.0
Reflected Solar	**15**/4	100.0	100	0.0
Outgoing LW	**36**/4	240.0	240	0.0
SW Absorbed by Atm	**3**	80.0	78	-2
SW Absorbed at Surface	**6**	160.0	162	2
Atmosphere LW Cooling	**7**	186.7	187	0.3
NET Atmosphere	**4**	106.7	109	2.3
Sensible Heat	**1**	26.67	24	-2.67
Latent Heat	**3**	80.0	78	-2
LW Surface Emission	**15**	400.0	398	-2
LW Absorbed at Surface	**13**	346.7	345	-1.7

Loeb (2024) CERES EBAF

TSI = 1360.68

51



TSI = 1360.8 ± 0.5 Wm^{-2}
(Kopp and Lean 2011)

Table 3 Average solar irradiance, ASR, −OLR and Net TOA radiation in Wm^{-2} for the first and most recent decades of CERES observations

	Solar irradiance	ASR	−OLR	NET
03/2000–02/2010	340.14	240.7	−240.2	0.53
01/2013–12/2022	340.16	241.6	−240.6	1.05
Difference	0.02	0.9	−0.4	0.52

Observational Assessment of Changes in Earth's Energy Imbalance Since 2000 *Surveys in Geophysics (2024)*

Norman G. Loeb[1] · Seung-Hee Ham[2] · Richard P. Allan[3] · Tyler J. Thorsen[1] · Benoit Meyssignac[4] · Seiji Kato[1] · Gregory C. Johnson[5] · John M. Lyman[5,6]

Part II
THEORY

Chapter 2.1
Constructing a Greenhouse

Single-layer atmosphere: the simplest greenhouse geometry

Dennis Hartmann: Global Physical Climatology (1994, 2016) Fig. 2.3

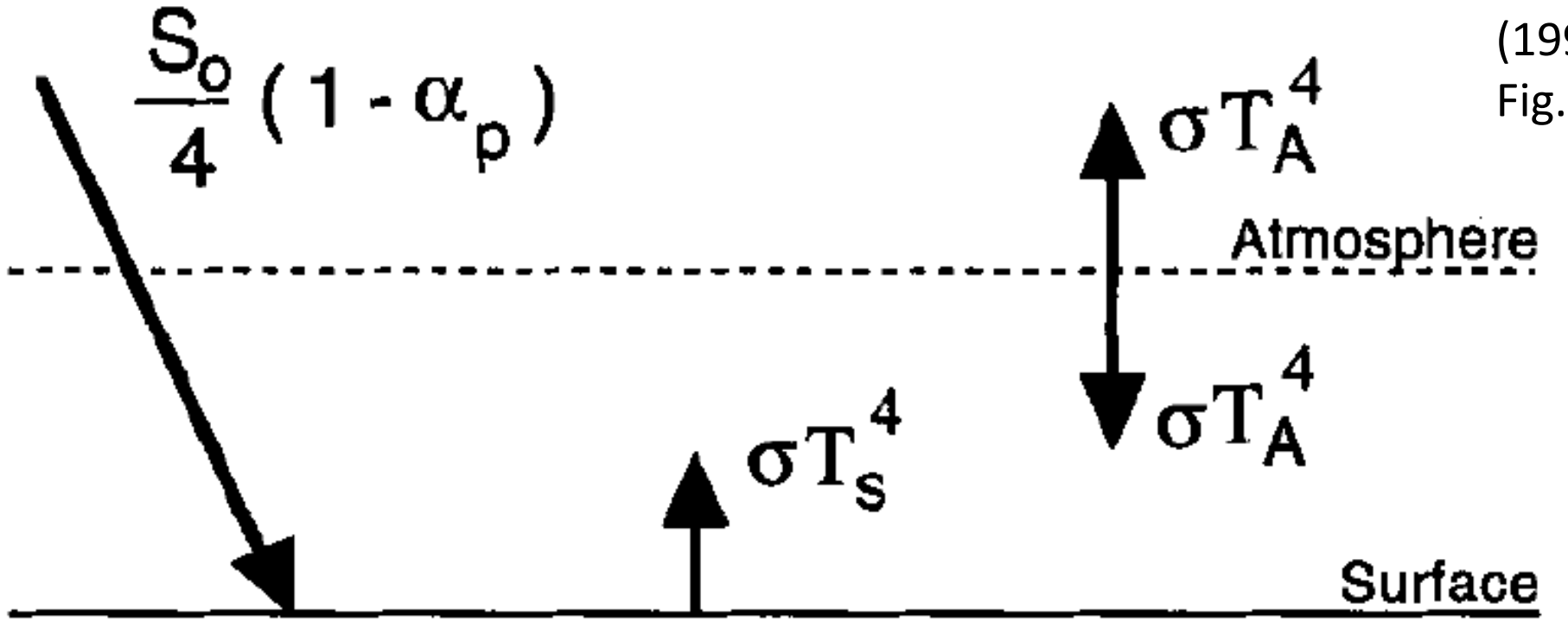
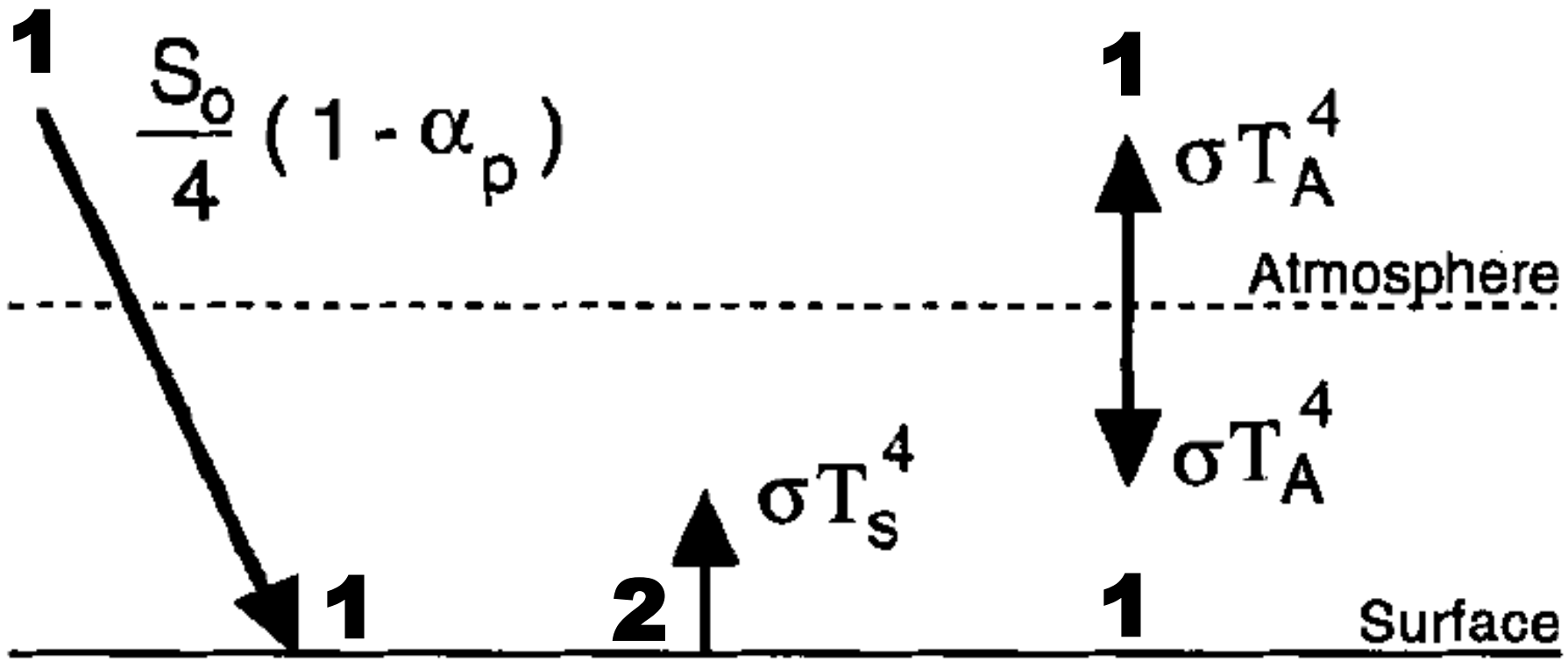
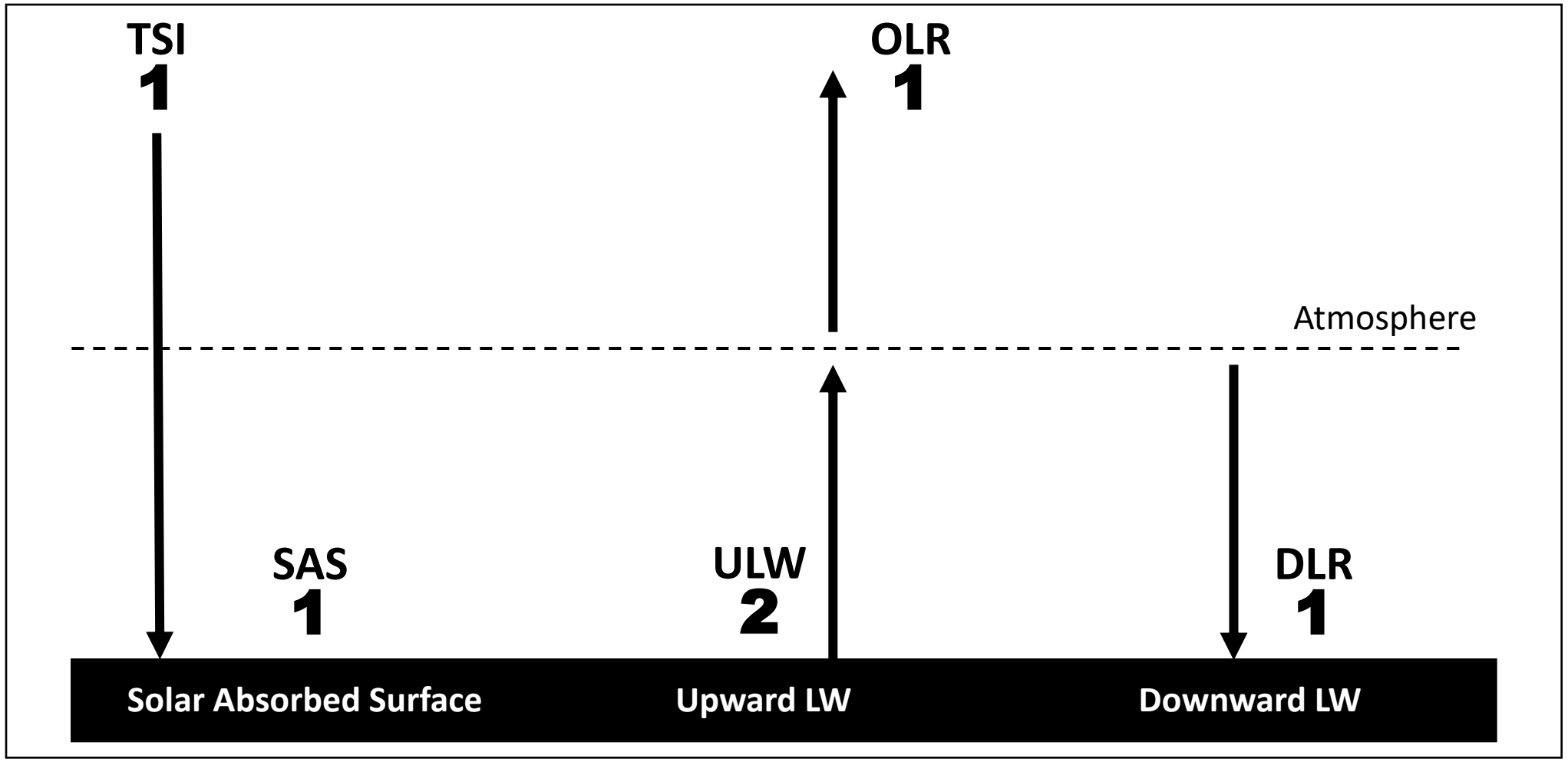


Fig. 2.3 Diagram of the energy fluxes for a planet with an atmosphere that is transparent for solar radiation but opaque to terrestrial radiation.

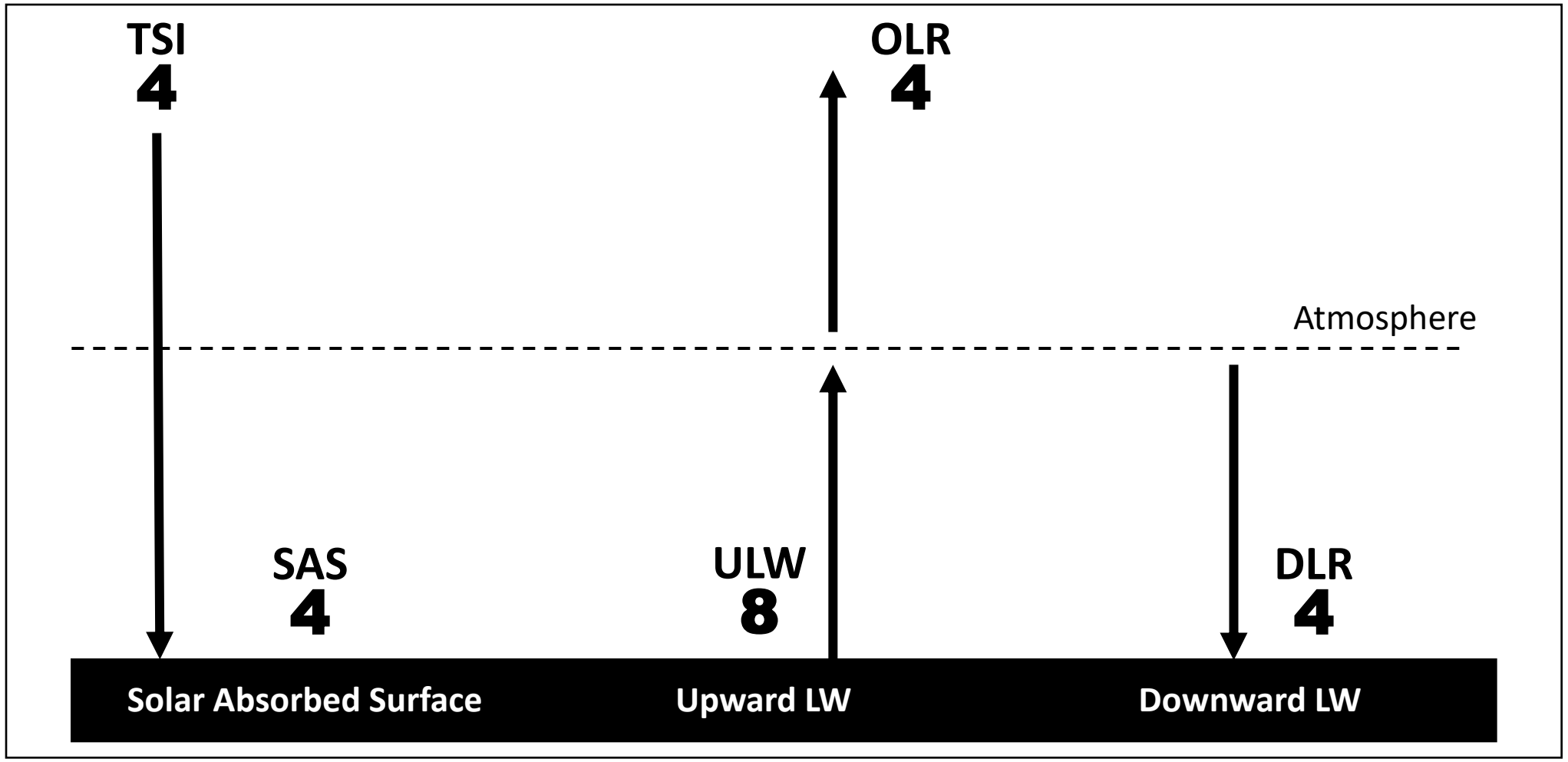
Single-layer atmosphere: the simplest greenhouse geometry



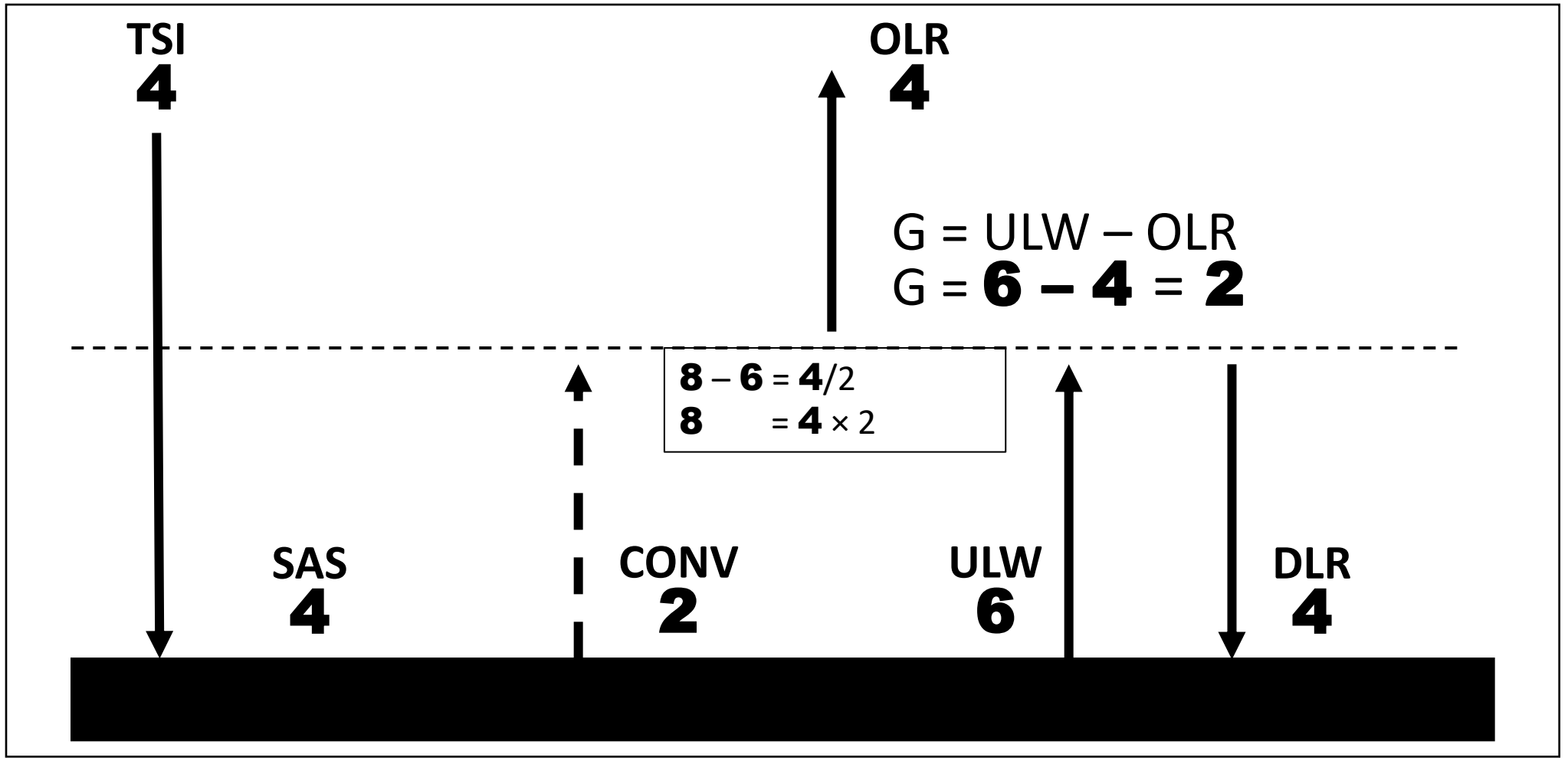
Single-layer atmosphere: the simplest greenhouse geometry



Multiply the unit by 4

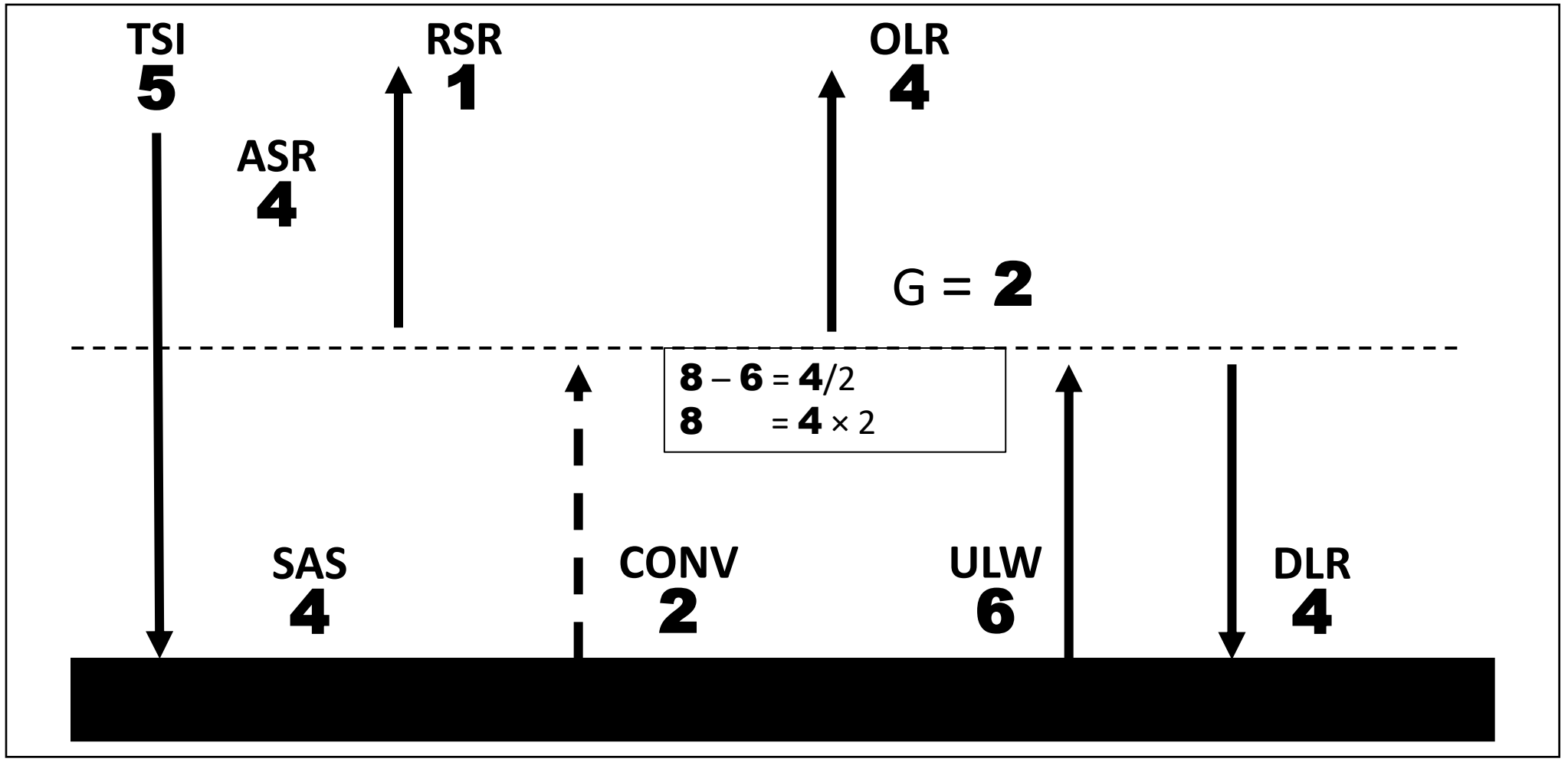


Introduce CONVECTION

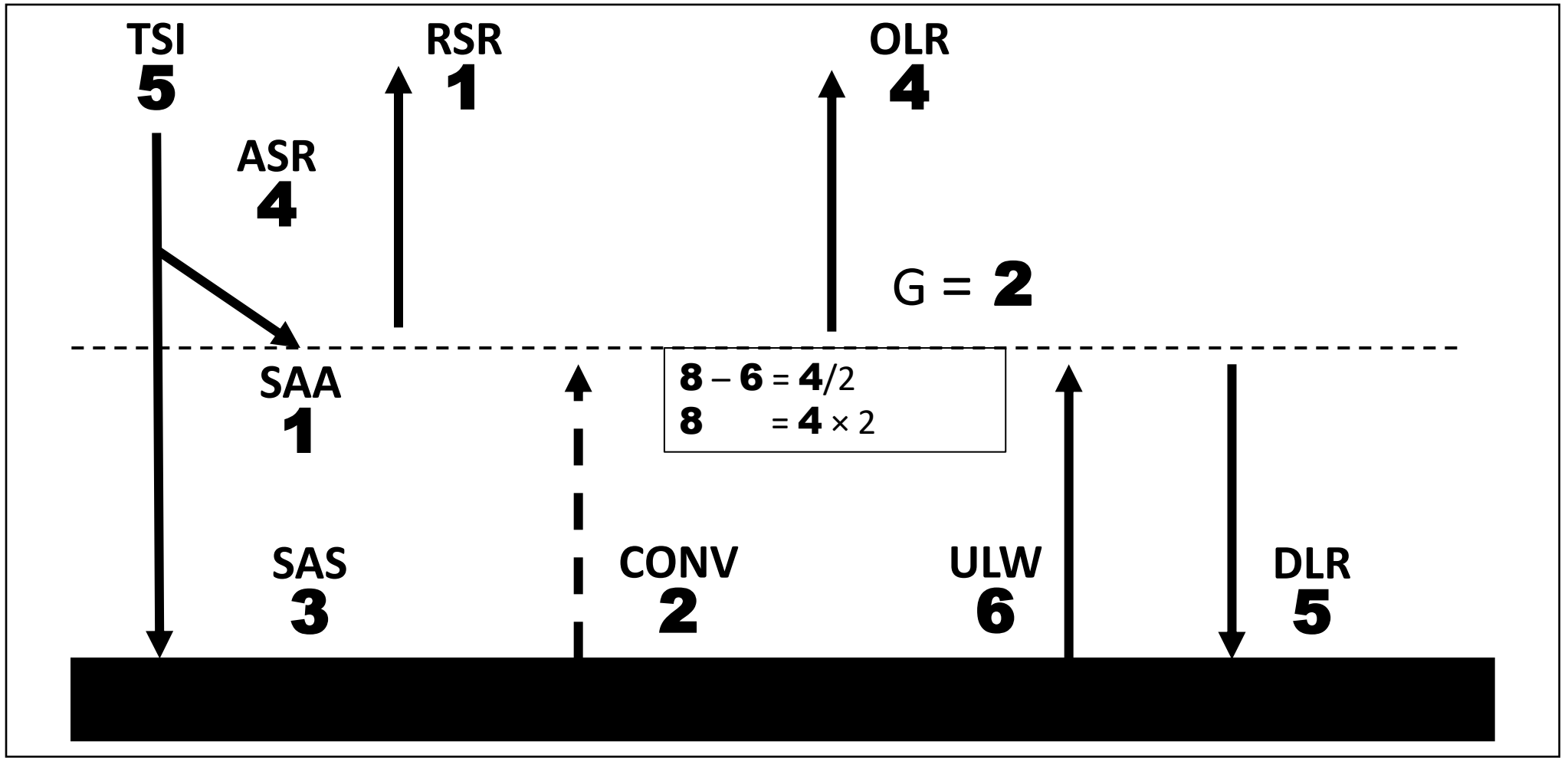


SFC Net (CONV) : OLR : ULW : SFC Tot = 1 : 2 : 3 : 4

Add 1 for RSR and TSI

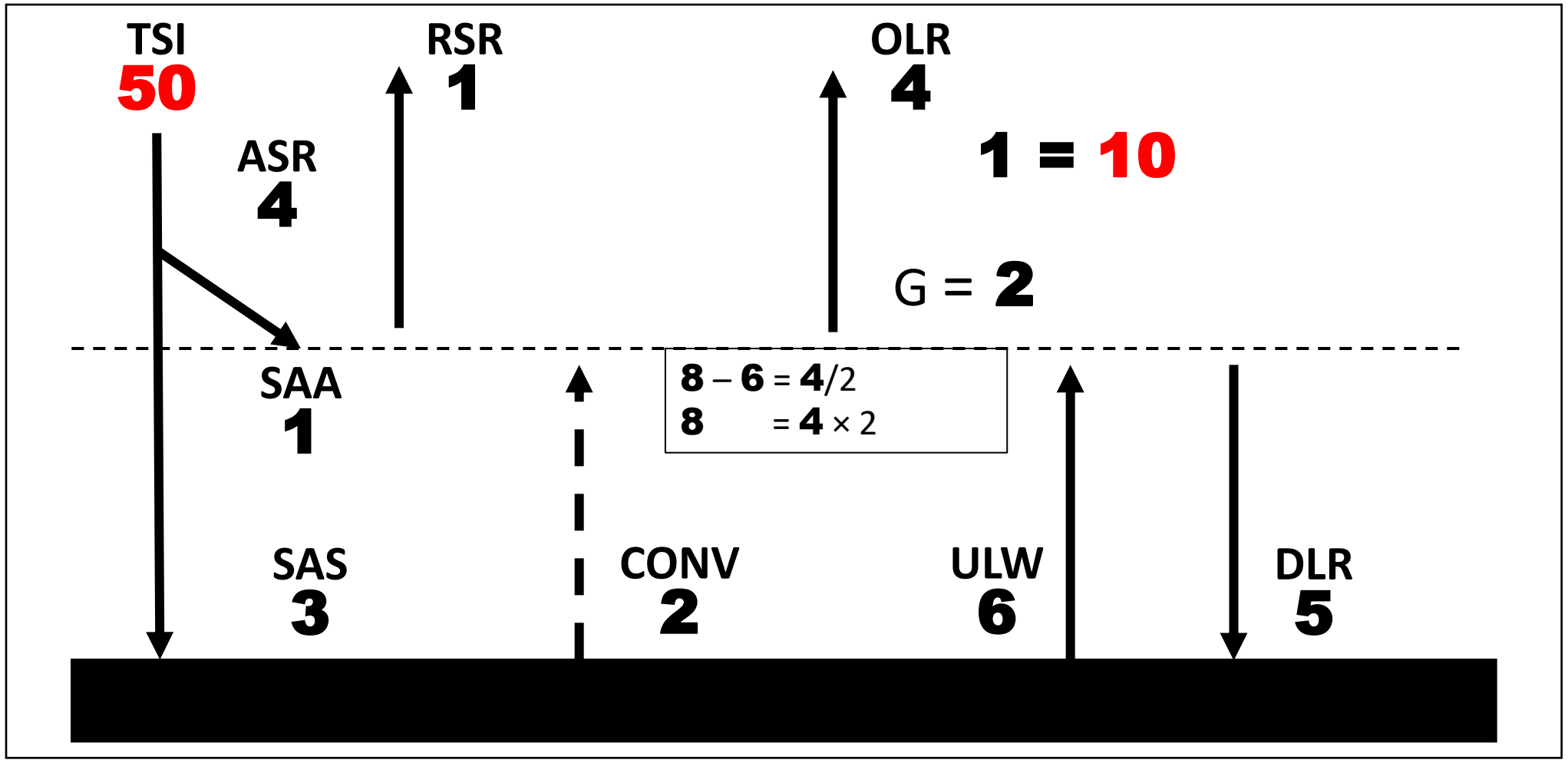


Absorb 1 in the atmosphere, 3 at the surface

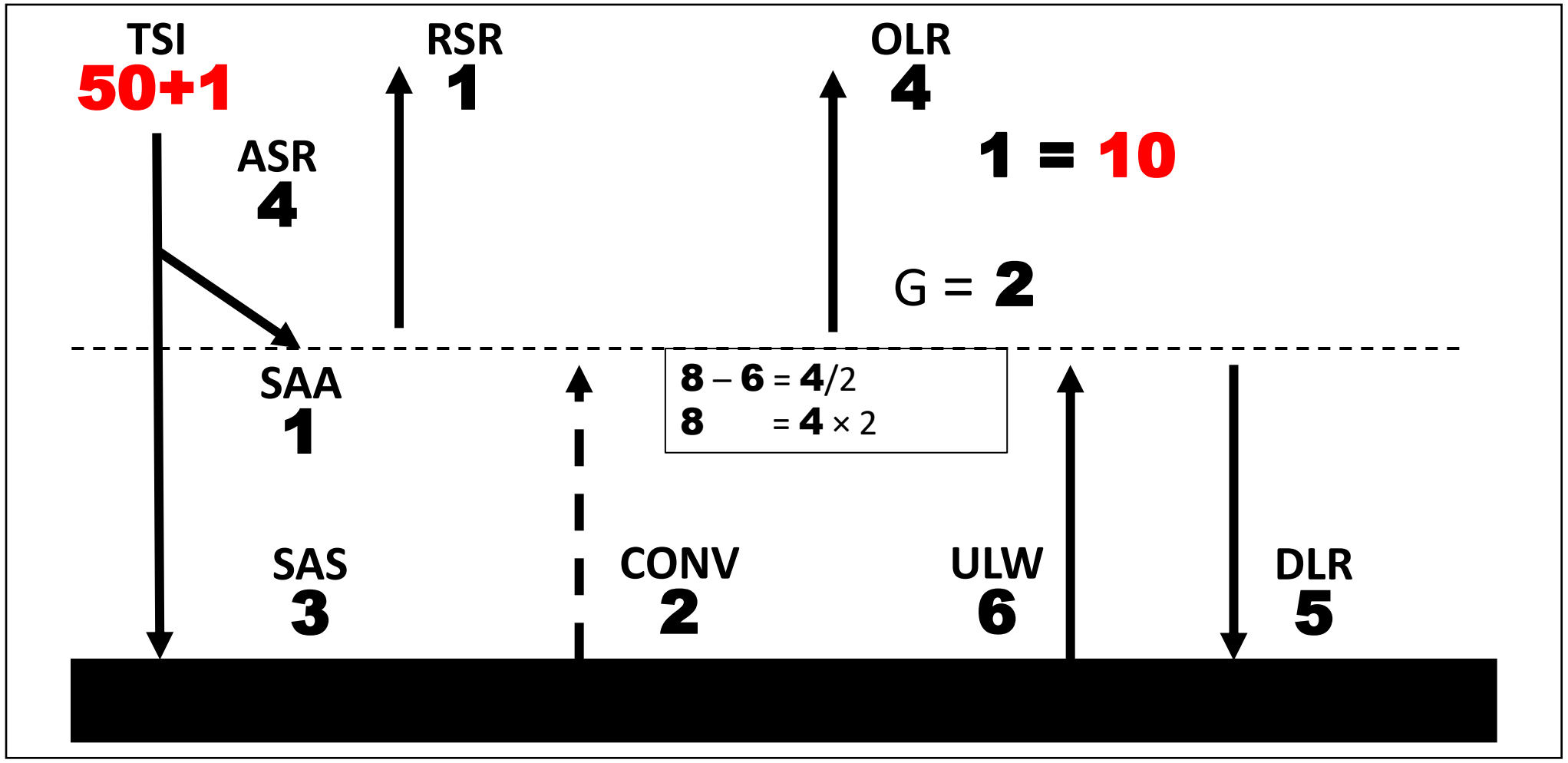


SAS is decreased, DLR is increased by 1

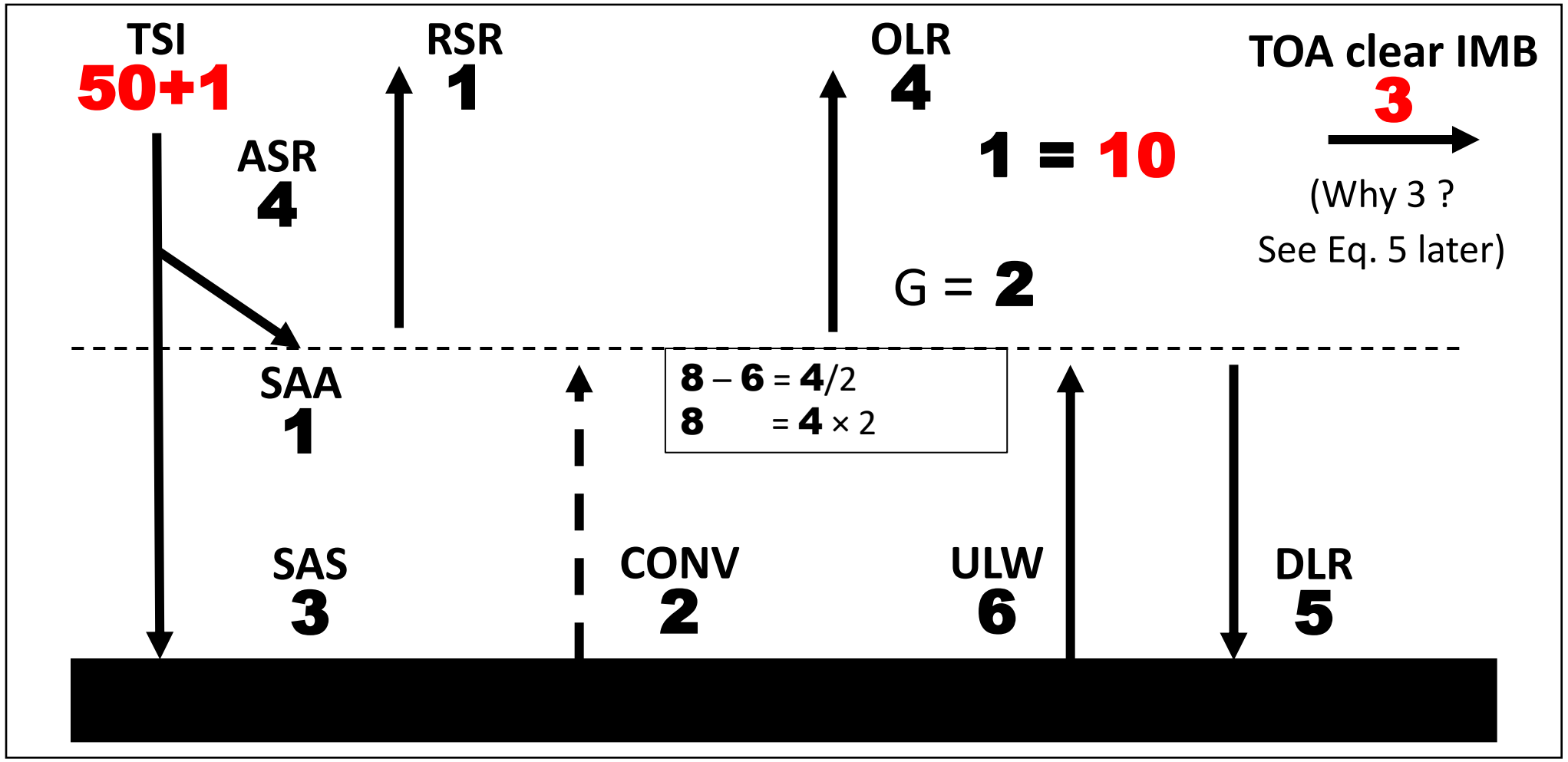
Calibrate to TSI: 1 => 10



Remember, TSI was 51

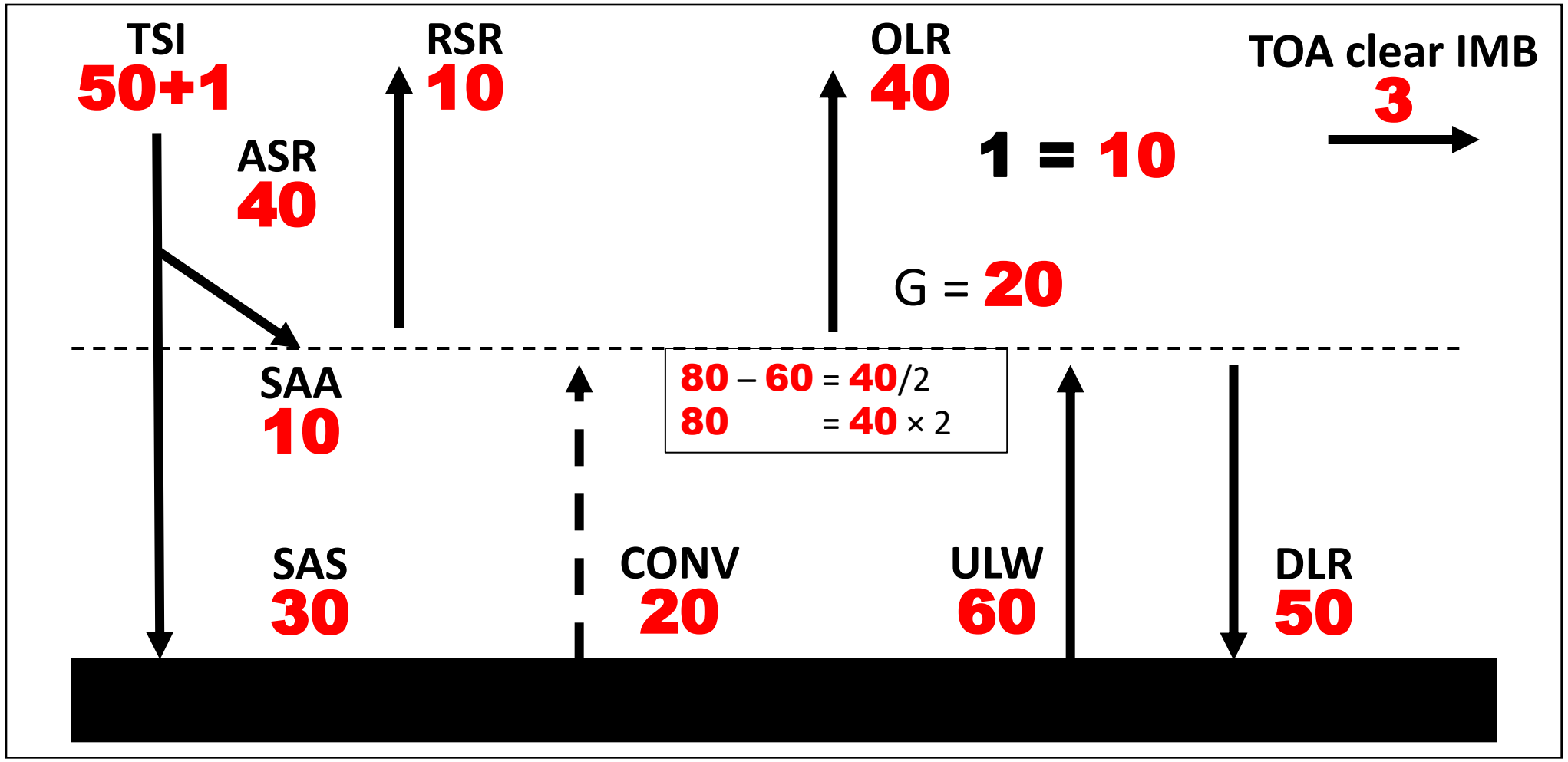


Add 1 to TSI and send 3 to clouds



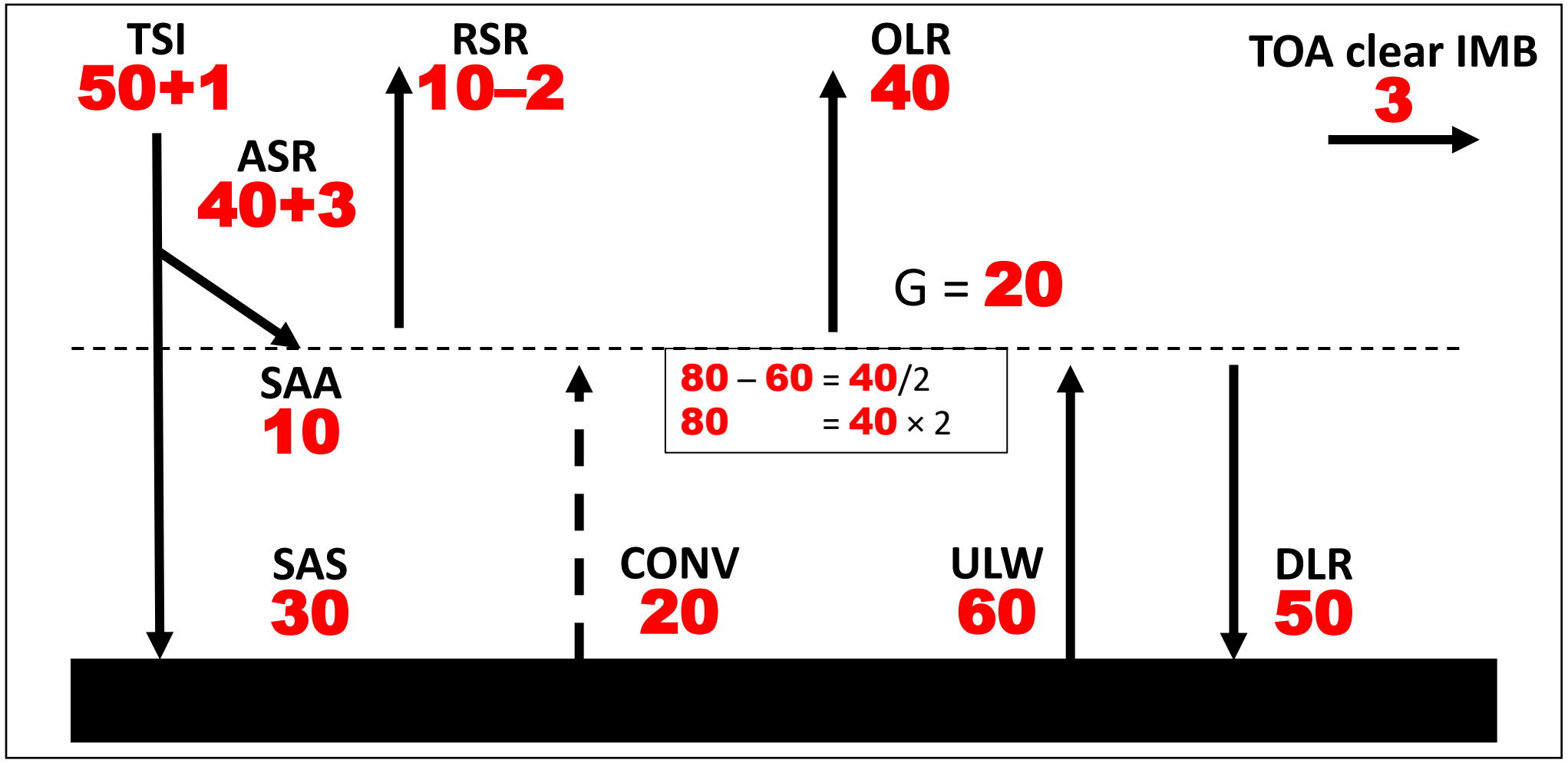
Hiatus at TOA is 2

Convert to red units

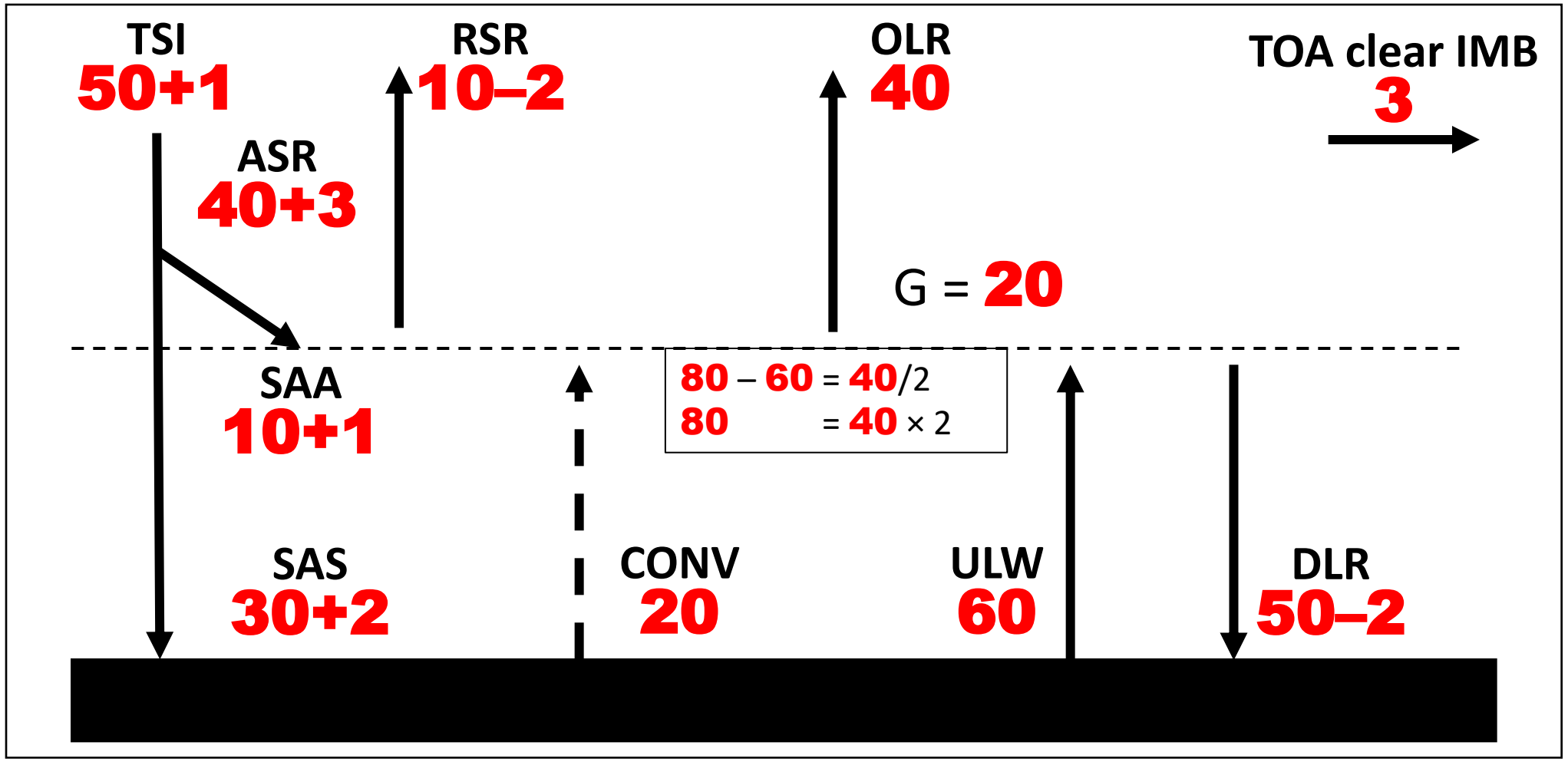


Hiatus is 2

Solution of the hiatus: Reflect 2 less, Absorb 3 more

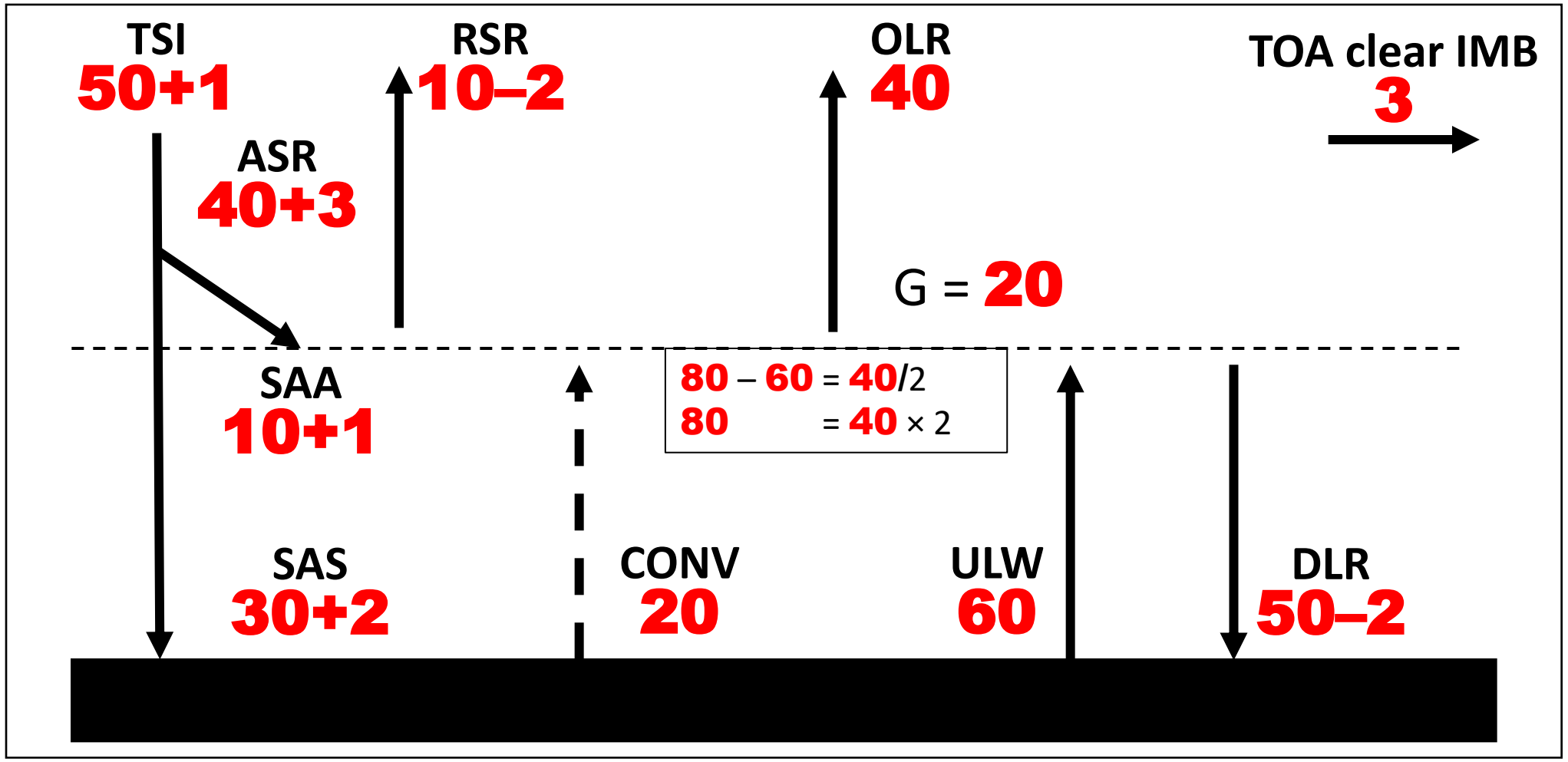


Redistribute absorption



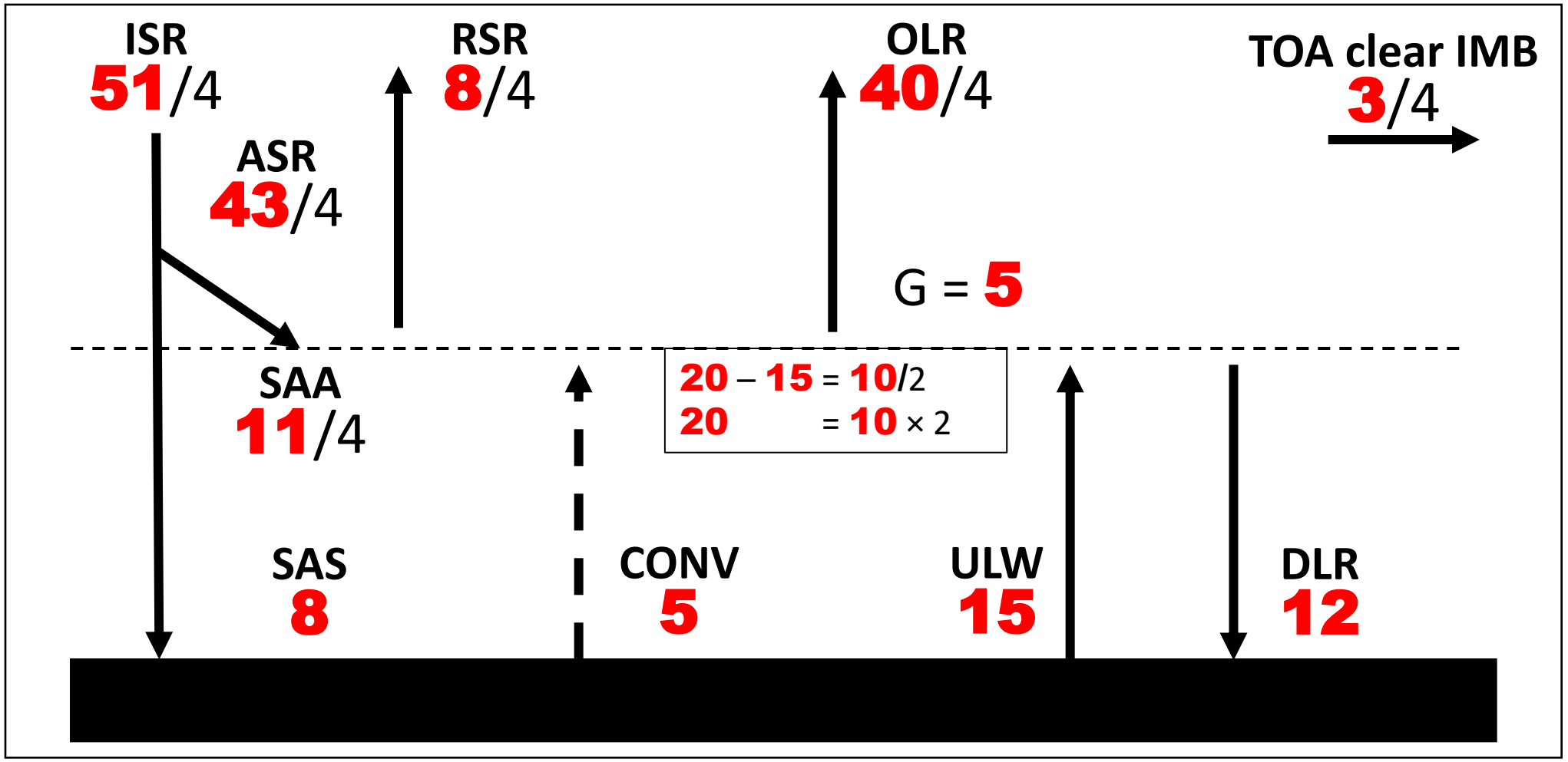
Absorb **1** more in the atmosphere, **2** at the surface

Ready. The Architexture of a Greenhouse.



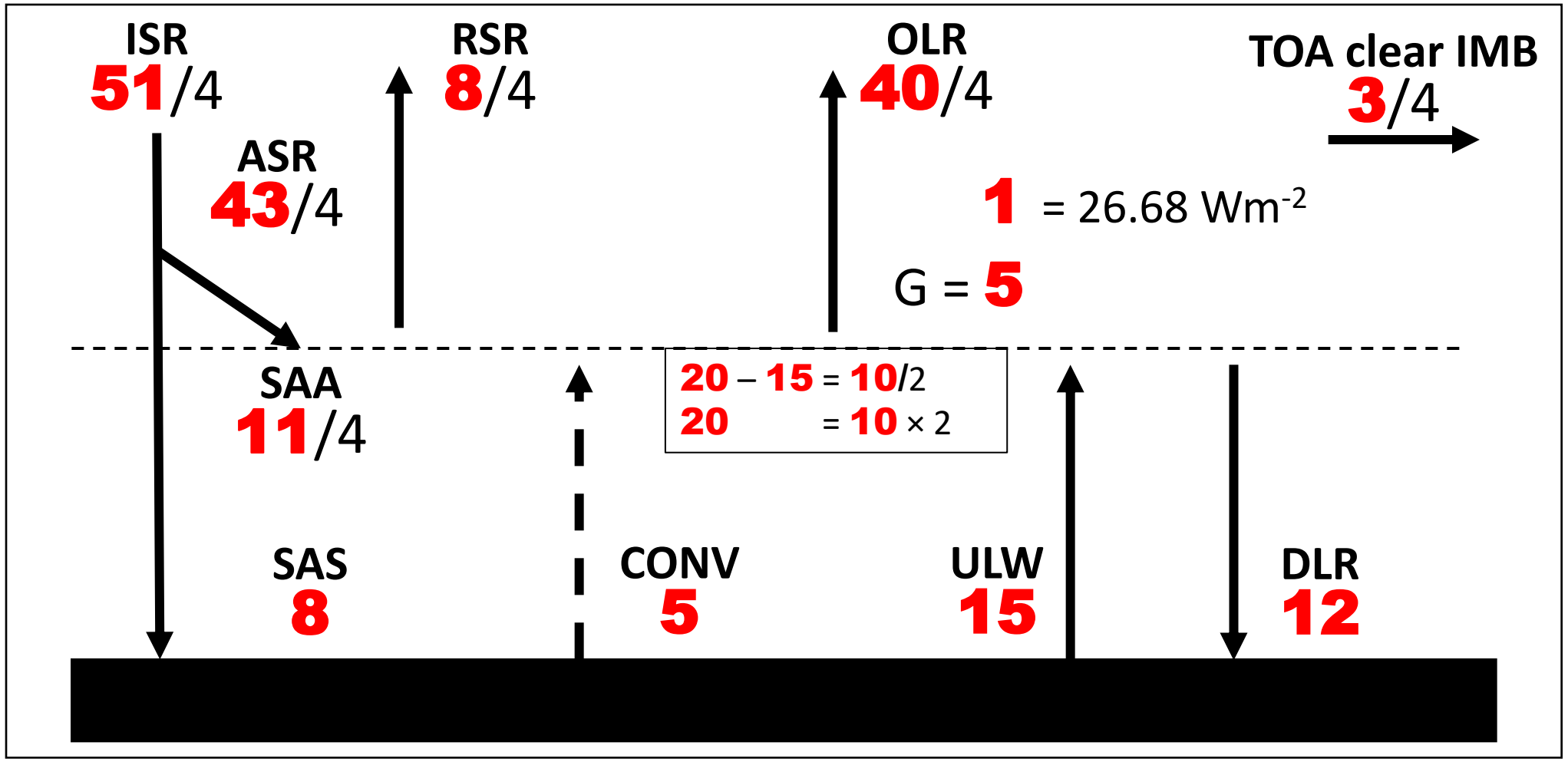
Geometric clear-sky system on the disk.

Divide by 4 for spherical weighting



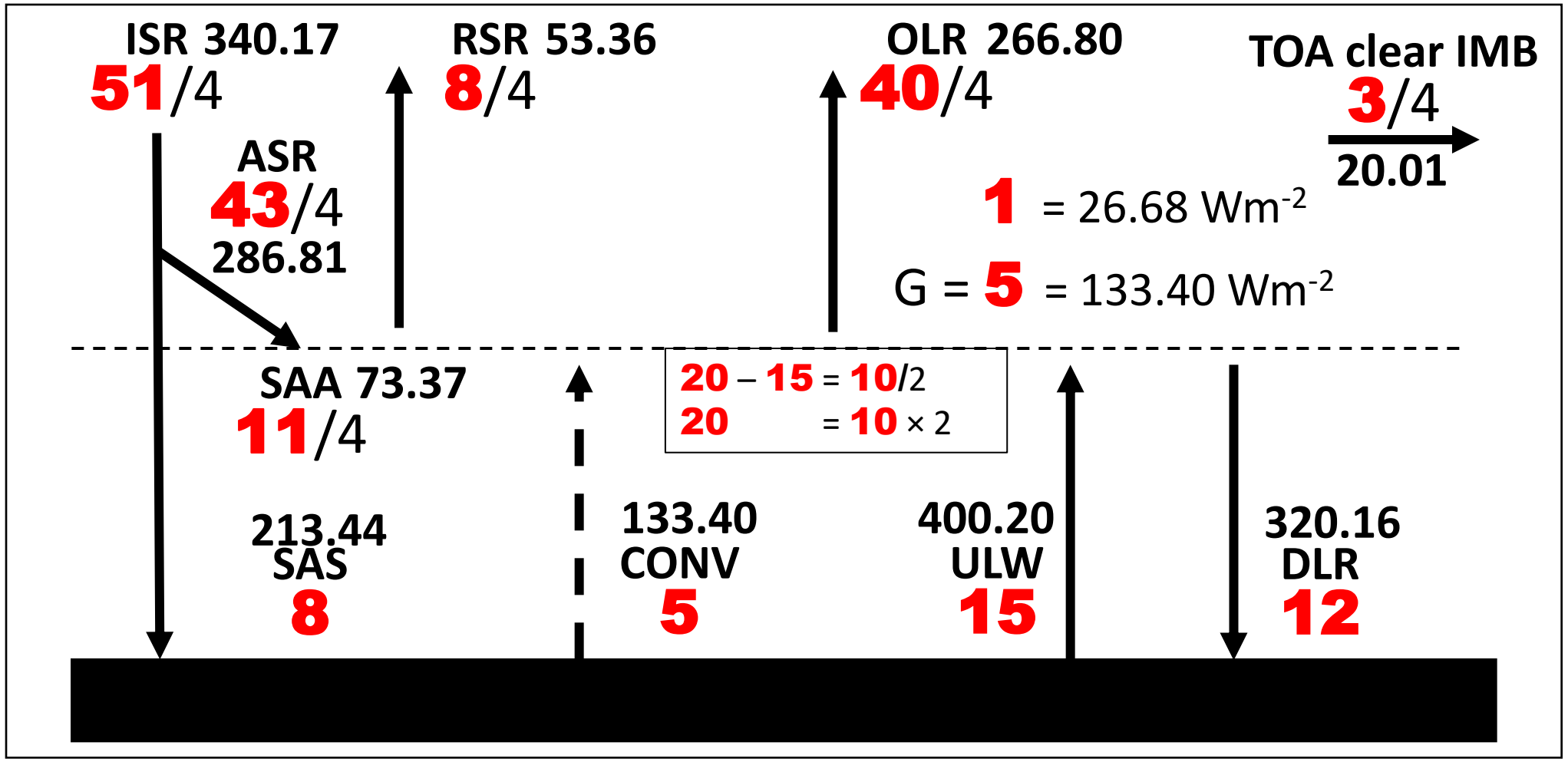
Geometric clear-sky system on the sphere.

Divide by 4 for spherical weighting



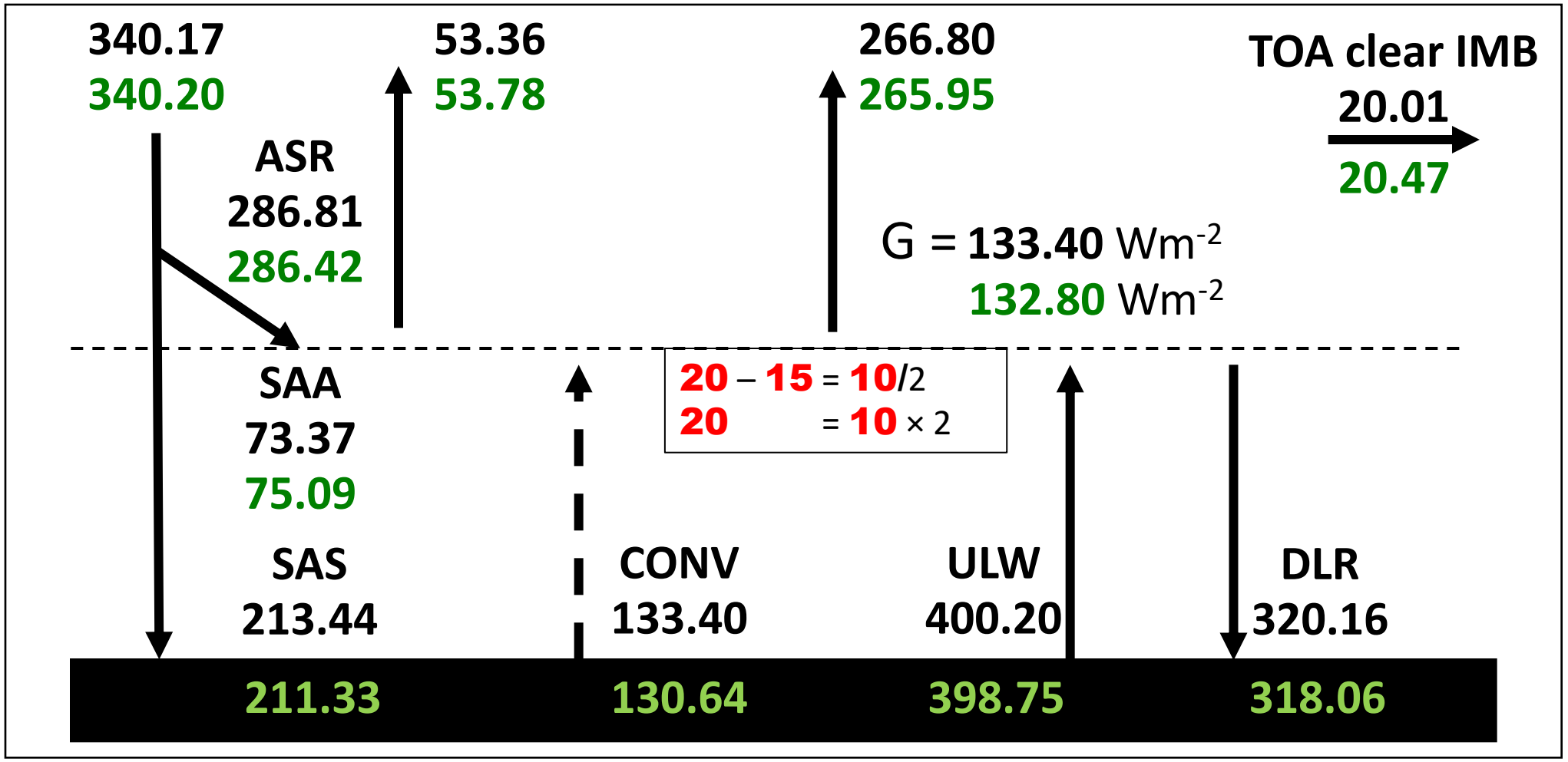
Geometric clear-sky system on the sphere.

Substitute the values in Wm^{-2}



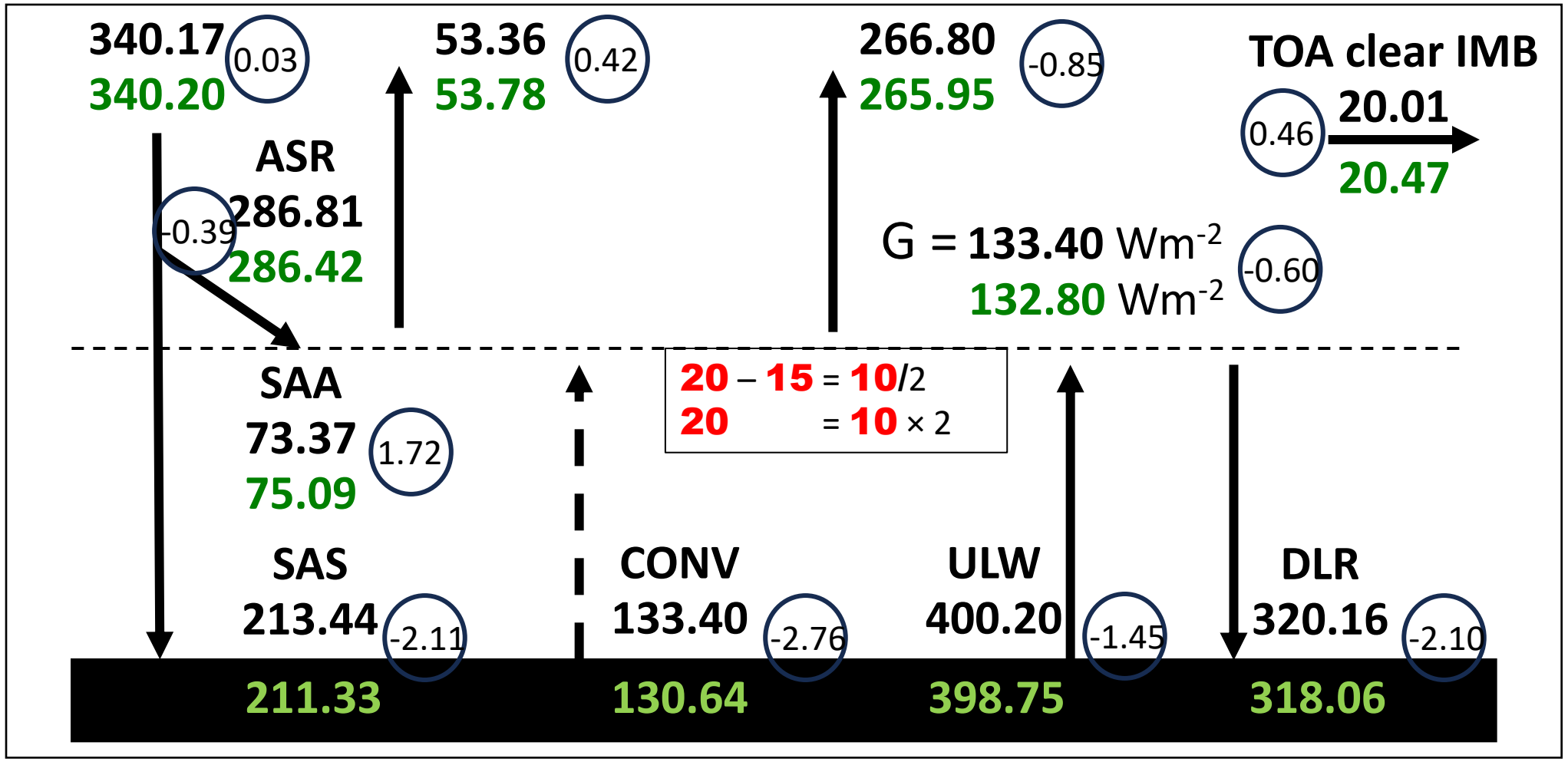
Geometric clear-sky system on the sphere.

TSI = 51 = 1360.68 Wm^{-2} (spherical), 1361.84 Wm^{-2} (geodetic)



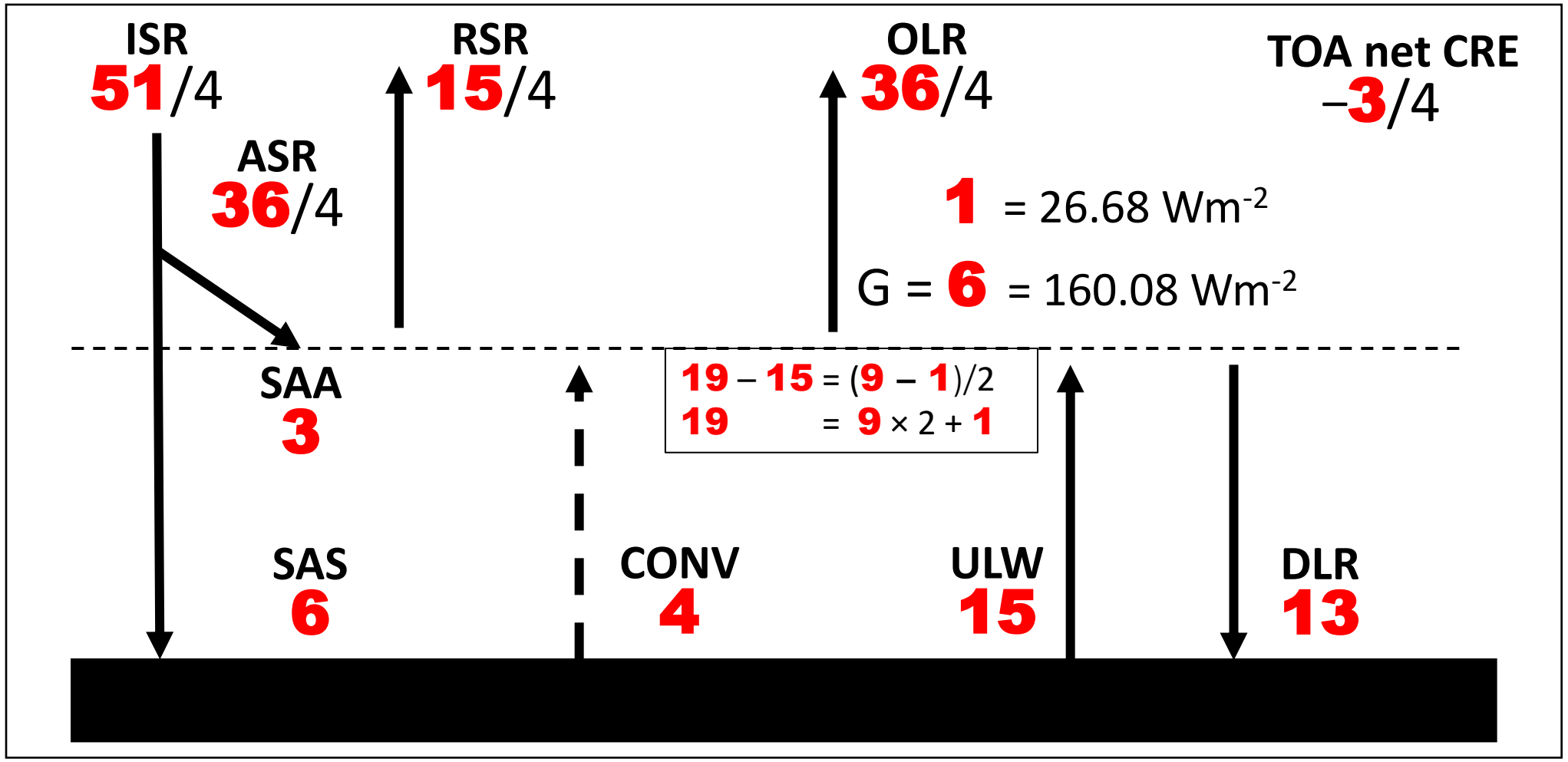
Clear-sky. Geometry in black, EBAF Ed4.2 V2 in green

TSI = 51 = 1360.68 Wm^{-2} (spherical), 1361.84 Wm^{-2} (geodetic)



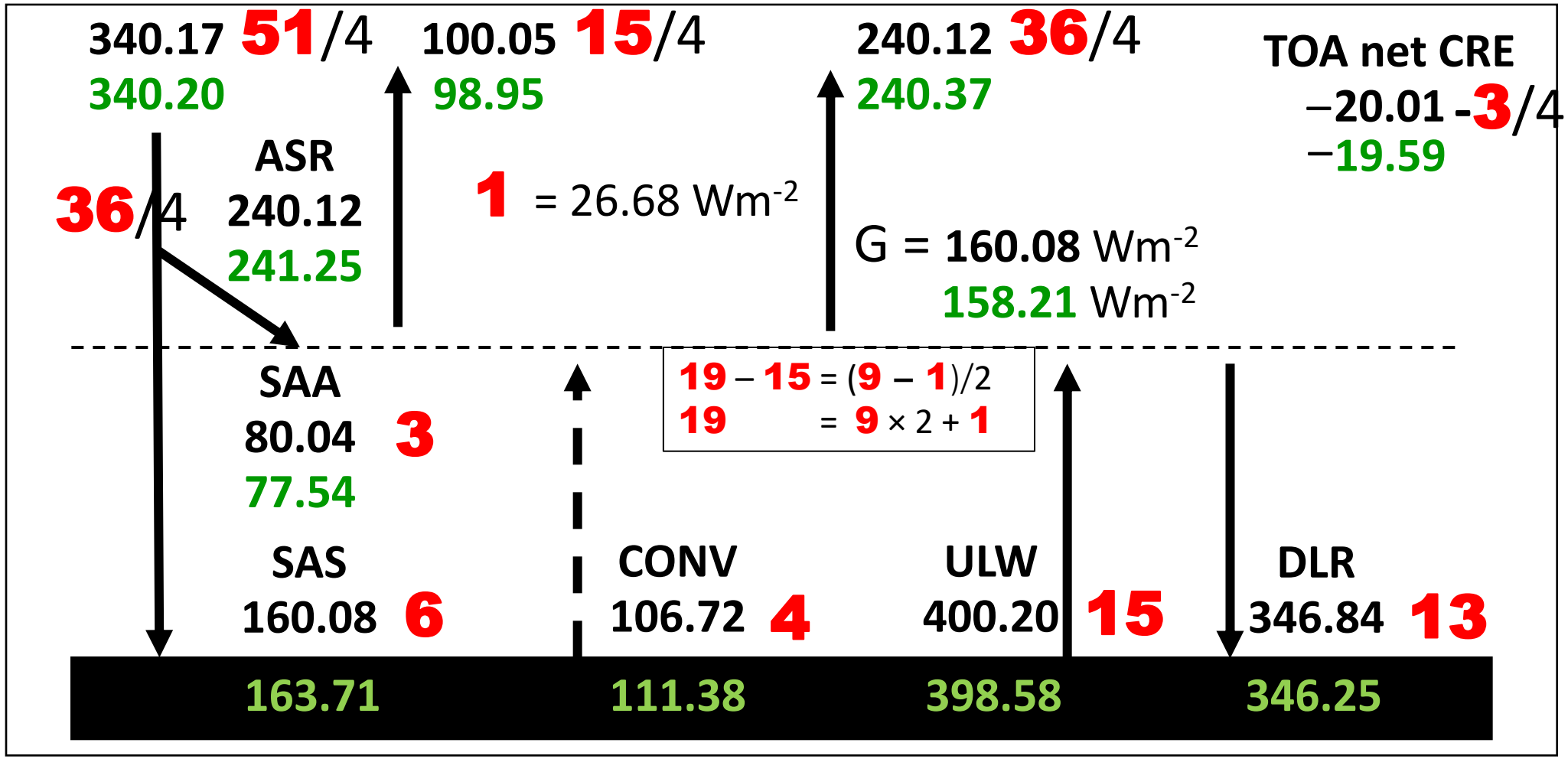
Largest difference 2.76 Wm^{-2} (CONV)

All-sky: OLR 40/4 => 36/4, RSR => 15/4



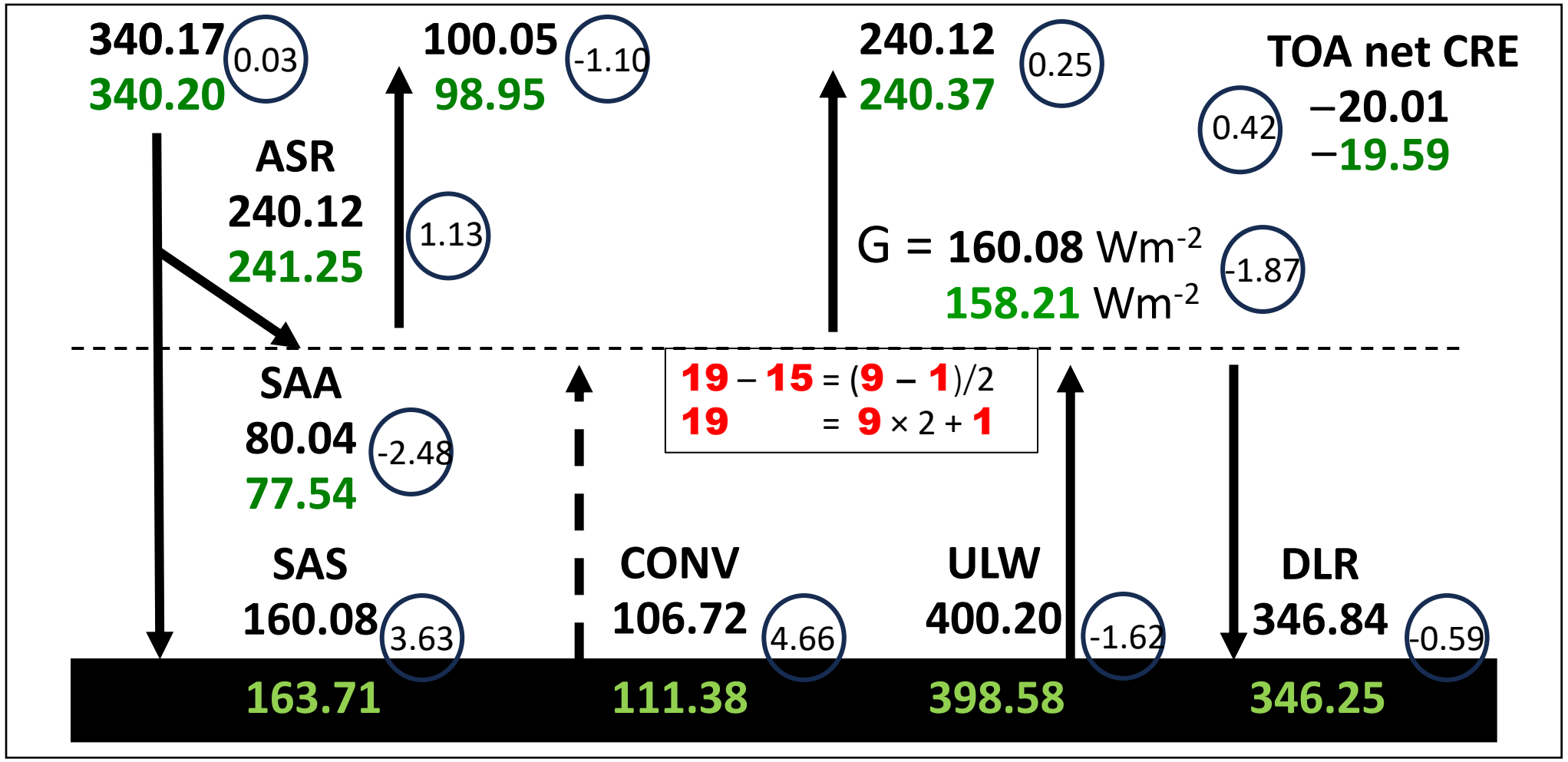
All-sky on the sphere.

TSI = 51 = 1360.68 Wm^{-2} (spherical), 1361.84 Wm^{-2} (geodetic)



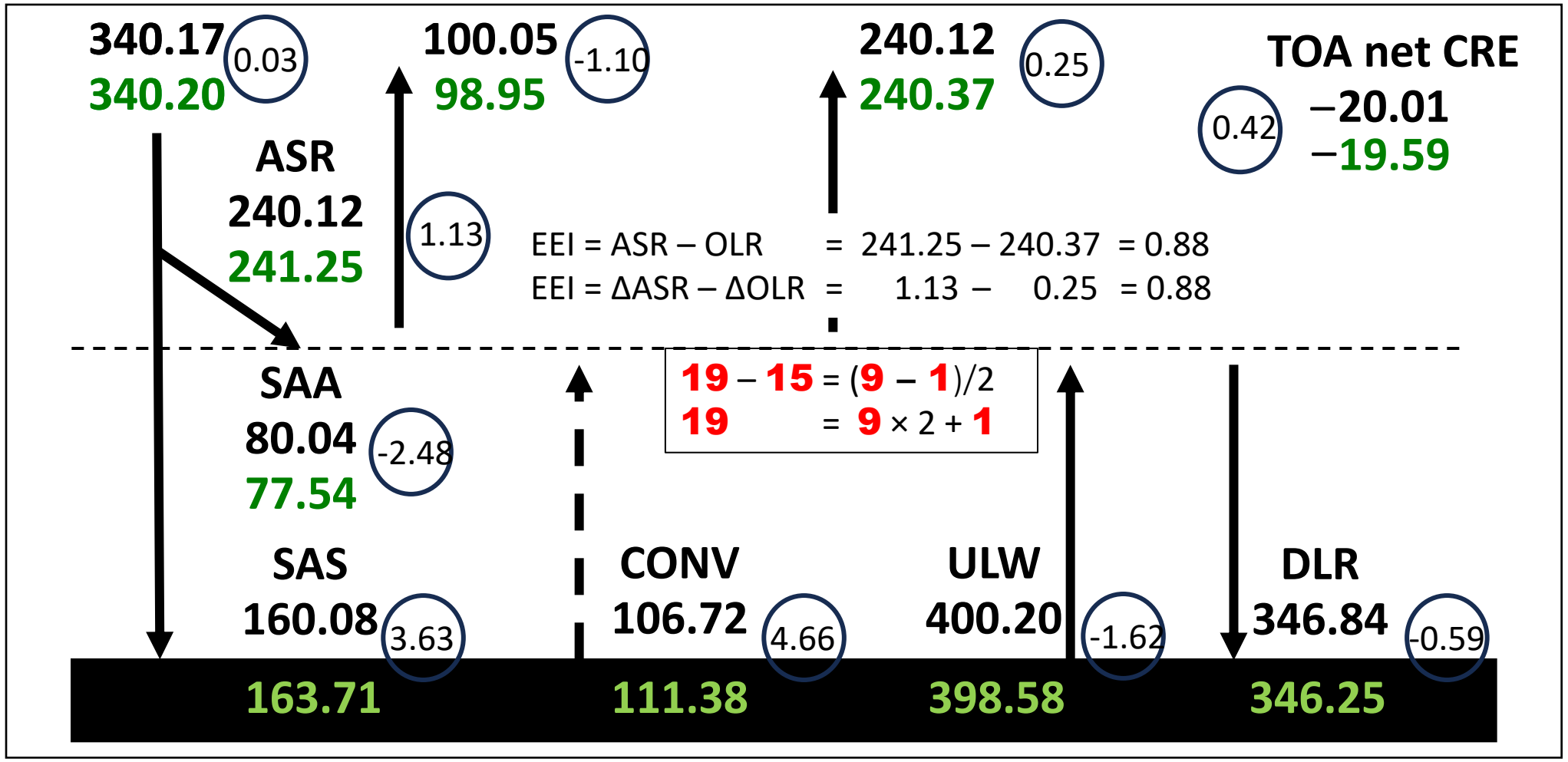
All sky. Theory in black, EBAF Ed4.2 V2 in green

TSI = 51 = 1360.68 Wm^{-2} (spherical), 1361.84 Wm^{-2} (geodetic)



Largest difference 4.66 Wm^{-2} (CONV)

TSI = 51 = 1360.68 Wm^{-2} (spherical), 1361.84 Wm^{-2} (geodetic)



EEI = ASR – OLR = ΔASR – ΔOLR = 0.88 Wm^{-2}

Table 2-1. Geometry vs CERES observation for global mean clear-sky fluxes
CERES EBAF Edition 4.2, version 2, October 2000 - September 2023 (W m^{-2}), clear-sky

Eq. (1) SFC SW+LW Net = OLR/2 **8** + **12** – **15** = **10**/2 (Schw 1906, Eq.11; Houghton 1977, Eq. 2.13)
Eq. (2) SFC SW+LW Tot = 2OLR **8** + **12** = 2 × **10** (Schw 1906, Eq.11; Houghton 1977, Eq. 2.15 at τ = 2)

Unit = 1 = 26.68 Wm^{-2}	**Clear-sky**	**N**	**N × Unit**	**EBAF Ed4.2**	**Difference**
Clear-Sky TOA	SW insolation	**51**/4	340.17	340.20	0.03
	LW	**40**/4	266.80	265.95	-0.85
	SW	**8**/4	53.36	53.78	0.42
	Net	**3**/4	20.01	20.42	0.41
Clear-sky Surface	LW down	**12**	320.16	318.06	-2.10
	LW up	**15**	400.20	398.75	-1.45
	LW Net	**-3**	-80.04	-80.69	-0.65
	SW Net	**8**	213.44	211.33	-2.11
	SW + LW Net	**5**	133.40	130.64	-2.76

Table 4-1. Geometry vs observation for global mean TOA and surface fluxes and CREs for CERES EBAF Edition 4.2 V2 for October 2000 to September 2023 (W m^{-2}), all-sky, **1** = 26.68 Wm^{-2}

Eq. (3) SFC SW+LW Net = (OLR – LWCRE)/2 **6** + **13** – **15** = (**9** – **1**)/2 (Schw 1906, Eq.11; Houghton 1977, Eq. 2.13 incl L)

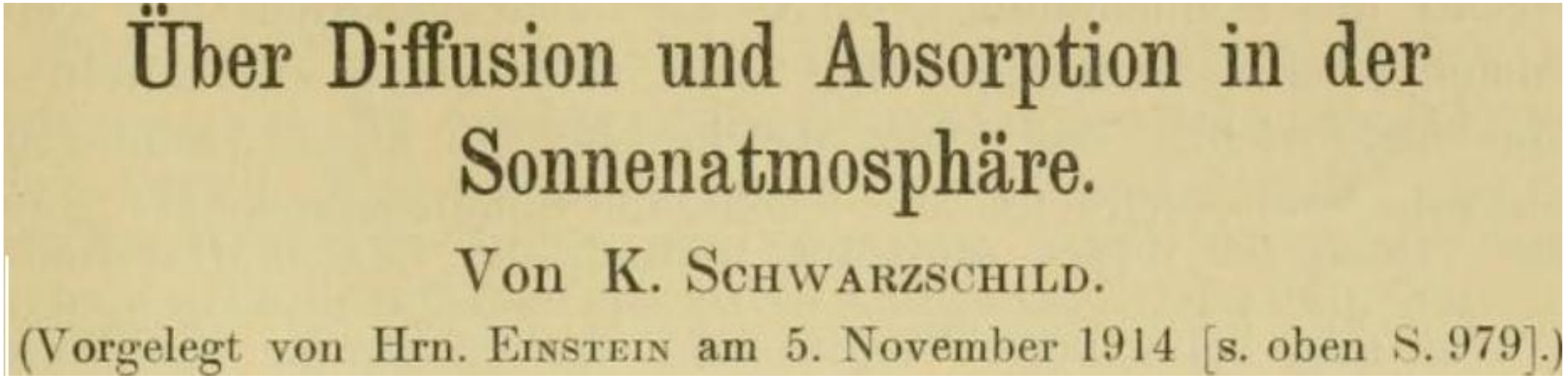
Eq. (4) SFC SW+LW Tot = 2OLR + LWCRE **6** + **13** = 2 × **9** + **1** (Schw 1906, Eq.11; Houghton 1977, Eq. 2.15 at τ = 2 incl L)

TSI = 51	**All-sky**	**N**	**N × Unit**	**EBAF Ed4.2**	**Diff**
TOA	SW insolation	**51**/4	340.17	340.20	0.03
	SW up	**15**/4	100.05	98.95	-1.10
	LW up	**36**/4	240.12	240.37	0.25
	TOT Net	0	0	0.88	0.88
Surface	SW Net	**6**	160.08	163.71	3.63
	LW down	**13**	346.84	346.25	-0.59
	LW up	**15**	400.20	398.58	-1.62
	LW Net	-**2**	-53.36	-52.33	1.03
	TOT Net	**4**	106.72	111.38	4.66
	CRE				
TOA	SW	-**7**/4	-46.69	-45.17	1.52
	LW	**1**	26.68	25.58	-1.10
	Net	-**3**/4	-20.01	-19.59	0.42

Chapter 2.2
Equations and their Solution



- Max Planck chaired a meeting in Berlin on Nov. 5. 1914, where
- Einstein delivered a paper in the absence of the author,
- Karl Schwarzschild, who served as a soldier in World War I.



- This is the paper that introduced the equation of radiation transfer.

In an earlier paper, Schwarzschild (1906) presented the two-stream approximation to the same problem:

Ueber das Gleichgewicht der Sonnenatmosphäre

Von

K. Schwarzschild.

Vorgelegt in der Sitzung vom 13. Januar 1906.

On the Equilibrium of the Sun's Atmosphere

by K. Schwarzschild

(Presented at the meeting of the Berlin Academy of Sciences on January 13, 1906)

$$E = \frac{A_0}{2}(1 + \bar{\tau}), \qquad A = \frac{A_0}{2}(2 + \bar{\tau}), \qquad B = \frac{A_0}{2}\bar{\tau}. \qquad (11)$$

E emission of a layer, A upward beam, B downward beam

A_0 emerging flux at TOA, τ optical depth

$$E = \frac{A_0}{2}(1 + \bar{\tau}), \qquad A = \frac{A_0}{2}(2 + \bar{\tau}), \qquad B = \frac{A_0}{2}\bar{\tau}. \qquad (11)$$

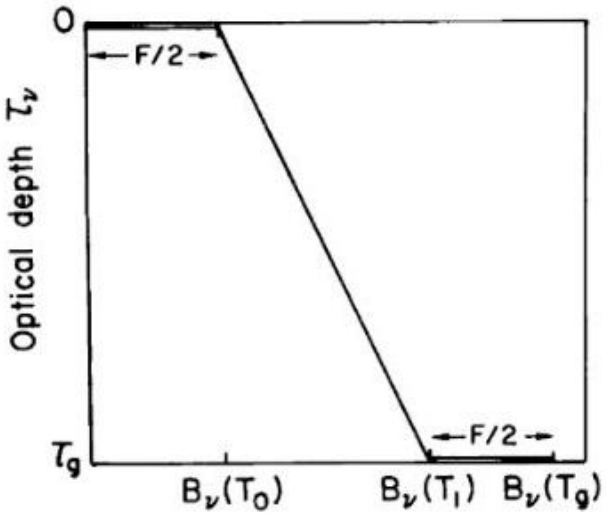
Eq. (1) $A - E = \Delta A = A_0/2$ Net radiation at the surface, independent of τ

Goody (1964, Eq. 2.115) $F_\nu/2\pi = J_\nu(0) - B^*_\nu(0) = B^*_\nu(\tau^*_\nu) - J_\nu(\tau^*_\nu).$

Houghton (1977, 1986, 2002, Eq. 2.13)

The Physics of Atmospheres.
Cambridge Univ Press

$$B_g - B_0 = \frac{\phi}{2\pi}$$



Chamberlain (1978, Fig. 1.4)

Theory of Planetary Atmospheres.
Academic Press

Fig. 1.4 The MRE solution for $T(\tau)$, presented as $B_\nu(T)$ vs. τ_ν. Note the discontinuity at the ground and the finite skin temperature at $\tau = 0$.

Hence the upward intensity at the ground is

$$I_g^+ \equiv B_\nu(T_g) = B_\nu(T_1) + \tfrac{1}{2}F_\nu$$

$$\Delta B_g = B_g - B_0 = B_{eff}/2 \quad = \quad \text{SFC (SW + LW) net} = \text{SH + LH} = \text{OLR}/2$$

- Radiative Equilibrium: Discontinuity; Radiative-Convective Equilibrium: Convection + Evaporation (Emden 1913)
- Net radiation at the surface and the corresponding convective activity are set unequivocaly to OLR/2

J. Houghton: The Physics of Atmospheres. Cambridge, 1977

In a plane parallel atmosphere uniform in the horizontal consider first absorption of radiation along the vertical co-ordinate z. The law of absorption (sometimes known as Lambert's law or Bouguet's law) states that the absorption which occurs when radiation of intensity I (units: power per unit area per unit solid angle) traverses an elementary slab of atmosphere of thickness dz is proportional to the mass of absorber ρdz in unit cross-section of the slab (ρ being the density of absorber) and to the incident intensity of radiation itself. Thus

$$dI = -Ik\rho\, dz \tag{2.1}$$

where k is the absorption coefficient. Integrating (2.1) leads to

$$I = I_0 \exp\left(-\int k\rho\, dz\right) \tag{2.2}$$

The equation for radiative transfer through the slab, which includes both absorption and emission, is sometimes known as *Schwarzchild's equation*

$$dI = -Ik\rho\, dz + Bk\rho\, dz$$

or

$$\frac{dI}{d\chi} = I - B \tag{2.3}$$

$$\frac{d}{dz}(F^{\downarrow} - F^{\uparrow}) = \rho c_p \frac{dT}{dt} \tag{2.4}$$

In equilibrium $dT/dt = 0$, and integration of (2.4) gives

$$F^{\uparrow} - F^{\downarrow} = \text{a constant } \phi, \text{ the net flux.} \tag{2.5}$$

Further, from (2.3) the transfer equations are

$$\left.\begin{aligned} \frac{dF^{\uparrow}}{d\chi^*} &= F^{\uparrow} - \pi B \\ -\frac{dF^{\downarrow}}{d\chi^*} &= F^{\downarrow} - \pi B \end{aligned}\right\} \tag{2.6}$$

If

$$\psi = F^{\uparrow} + F^{\downarrow} \tag{2.7}$$

equations (2.6) may be written

$$\frac{d\psi}{d\chi^*} = \phi \tag{2.8}$$

$$\frac{d\phi}{d\chi^*} = \psi - 2\pi B \tag{2.9}$$

Since ϕ = constant (from (2.5)) $d\phi/d\chi^* = 0$

and $$\psi = 2\pi B \tag{2.10}$$

which on substitution into (2.8) gives

$$B = \frac{\phi}{2\pi}\chi^* + \text{constant} \tag{2.11}$$

The boundary condition at the top of the atmosphere ($\chi^* = 0$) is $F^{\downarrow} = 0$, so that here $\psi = \phi$ and, from (2.10), the constant in (2.11) is $\phi/2\pi$, i.e.

$$B = \frac{\phi}{2\pi}(\chi^* + 1) \tag{2.12}$$

At the bottom of the atmosphere where $\chi^* = \chi_0^*$, $F^{\uparrow} = \pi B_g$, B_g being the black-body function at the temperature of the ground. It is easy to show that there must be a temperature discontinuity at the lower boundary, the black-body function for the air close to the ground being B_0, and

$$B_g - B_0 = \frac{\phi}{2\pi} \tag{2.13}$$

Is it valid on Earth's atmosphere?

CERES EBAF Ed2.8, 192 months (Mar 2000 – Feb 2016)
F. Rose et al., 27th STM (2017)

Global Means(Mar2000-Feb2016)

Clear Sky	Ed2.8
TOA SW Insolation	339.87
TOA SW Up	*52.50*
TOA LW Up	*265.59*
SFC SW Down	244.06
SFC SW Up	29.74
SFC LW Down	316.27
SFC LW Up	398.40

Eq. (1) $A - E = \Delta A = A_0/2$

(244.06 – 29.74 + 316.27) – 398.40 = 132.19 = 265.59 /2

Is it valid on Earth's atmosphere?

CERES EBAF Ed2.8, 192 months (Mar 2000 – Feb 2016)
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Loeb et al. (2012): Earth heat uptake for July 2005–June 2010 is 0.58 ± 0.38 Wm^{-2}

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. D8, PAGES 15,311–15,324, AUGUST 20, 1991

The Earth's Radiation Budget and Its Relation to Atmospheric Hydrology
1. Observations of the Clear Sky Greenhouse Effect

GRAEME L. STEPHENS AND THOMAS J. GREENWALD

Mihalas, 1978; *Goody and Yung*, 1989]

$$\sigma T_s^4 = \sigma T_e^4 \, [2 + 3\tau^*/2] \qquad (1)$$

and

$$\sigma T_*^4 = \sigma T_e^4 \, [1 + 3\tau^*/2] \qquad (2)$$

$$\sigma T_s^4 - \sigma T_*^4 = \sigma T_e^4 \; .$$

$$E = \frac{A_0}{2}(1 + \bar{\tau}), \qquad A = \frac{A_0}{2}(2 + \bar{\tau}), \qquad B = \frac{A_0}{2}\bar{\tau}. \qquad (11)$$

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$$\sigma T_s^4 - \sigma T_*^4 = \sigma T_e^4 \, . \quad /2$$

$$E = \frac{A_0}{2}(1 + \bar{\tau}), \qquad A = \frac{A_0}{2}(2 + \bar{\tau}), \qquad B = \frac{A_0}{2}\bar{\tau}. \qquad (11)$$

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and

$$\sigma T_s^4 = \sigma T_e^4\,[2 + 3\tau^*/2] \quad /2$$

$$\sigma T_*^4 = \sigma T_e^4\,[1 + 3\tau^*/2] \quad /2$$

$$\sigma T_s^4 - \sigma T_*^4 = \sigma T_e^4\,. \quad /2$$

$$B^*(\tau_1) = \frac{\sigma\theta_g^4}{\pi} = \frac{-F_S(2 + 3\tau_1/2)}{2\pi},$$

$$B(\tau) = \frac{\sigma\theta(\tau)^4}{\pi} = \frac{-F_S(1 + 3\tau/2)}{2\pi},$$

$$\Delta B = \frac{F_S}{2\pi}$$ (*Goody and Yung*, 1989)

$$E = \frac{A_0}{2}(1 + \bar{\tau}), \qquad A = \frac{A_0}{2}(2 + \bar{\tau}), \qquad B = \frac{A_0}{2}\bar{\tau}. \qquad (11)$$

Observations of the Earth's Radiation Budget in relation to atmospheric hydrology
4. Atmospheric column radiative cooling over the world's oceans

JGR (1994)

Graeme L. Stephens,[1] Anthony Slingo,[2] Mark J. Webb,[2] Peter J. Minnett,[3] Peter H. Daum,[3] Lawrence Kleinman,[3] Ian Wittmeyer,[1] and David A. Randall[1]

$F\uparrow(\tau_S) = \sigma T_S^4 = F_\infty\,(2 + \tau_S)/2$ (Stephens et al. 1994, Eq. 5a)

$F\downarrow(\tau_S) = F_g \quad = F_\infty\,\tau_S/2$ (Stephens et al. 1994, Eq. 5b)

These equations, with $F_0(\tau_S) = \sigma T_0^4 = F_\infty(1 + \tau_S)/2$, are equivalent to the three terms in Schwarzschild's (1906, Eq. 11). Therefore, $\Delta\sigma T_S^4 = \sigma T_S^4 - \sigma T_0^4 = F_\infty/2$.

$$E = \frac{A_0}{2}(1 + \bar{\tau}), \qquad A = \frac{A_0}{2}(2 + \bar{\tau}), \qquad B = \frac{A_0}{2}\bar{\tau}. \qquad (11)$$

(Schwarzschild 1906, Eq. 11)

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. D6, PAGES 11,585–11,591, JUNE 20, 1995

Deductions from a simple climate model: Factors governing surface temperature and atmospheric thermal structure

C. P. Weaver and V. Ramanathan

Center for Clouds, Chemistry and Climate, Scripps Institution of Oceanography, La Jolla, California

Temperature discontinuity. Equations (6a) and (6b) predict a temperature jump at the surface:

$$\sigma T_g^4 - \sigma T(\tau^*)^4 = \frac{f_0}{2} \qquad (7)$$

3. Modified Schwarzschild's Grey Model

3.1. Semigrey Model With One Spectral Window

The first modification is a simple extension of the Schwarzschild equations in which we add a spectral window

Temperature discontinuity.

$$\sigma T_g^4 - \sigma T(\tau^*)^4 = f_0 \frac{1}{(2 + \beta D \tau^*)} \qquad (12)$$

Thus, as opposed to the SGM, the modified equation predicts that the discontinuity would decrease as $1/\beta$, as well as

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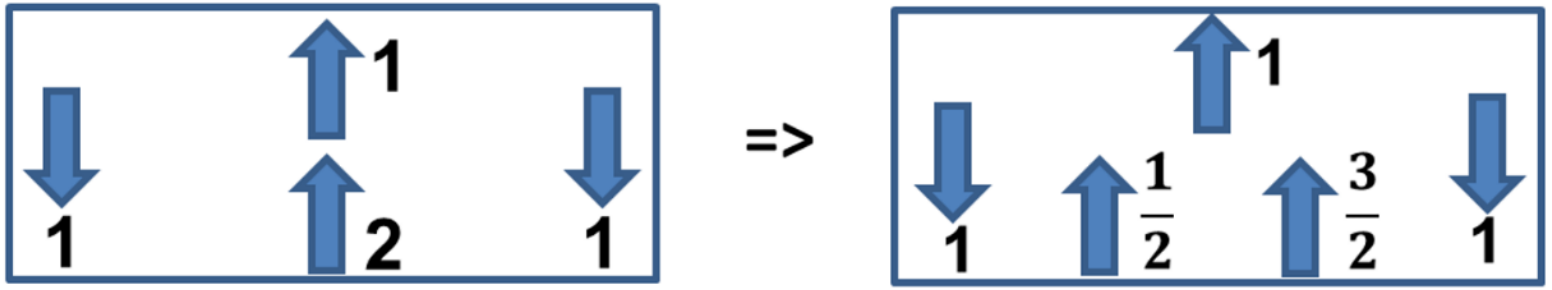
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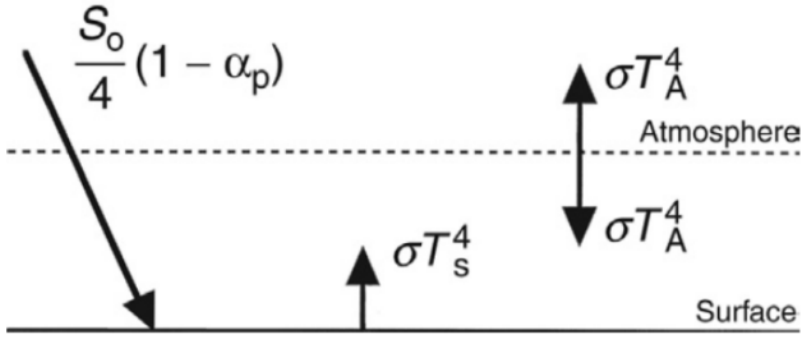
At $\bar{\tau} = 2$

$$E = \frac{A_0}{2}(1 + \bar{\tau}), \qquad A = \frac{A_0}{2}(2 + \bar{\tau}), \qquad B = \frac{A_0}{2}\bar{\tau}. \qquad (11)$$

Eq. (2) $A = 2A_0$ **$E = 3A_0/2$; $B = A_0$**



Eq. (2) $A = 2A_0$ Clear-sky Eq.(1) $\Delta A = A - E = A_0/2$



$\sigma T_s^4 = 2\sigma T_A^4$

Hartmann (1994) Fig. 2.3

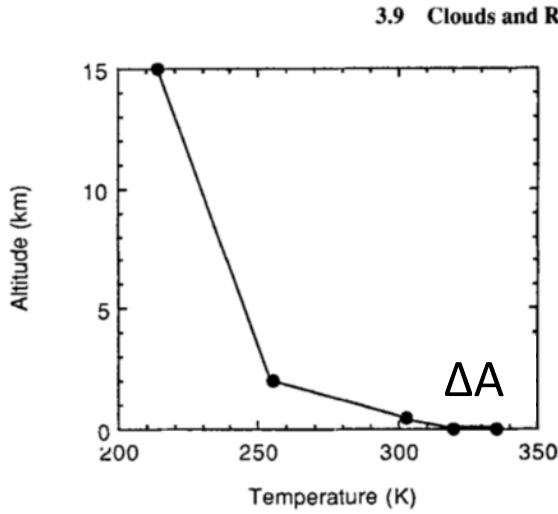


Fig. 3.11

CERES EBAF Ed2.8, 192 months (Mar 2000 – Feb 2016) Global means from Rose et al. (2017), Clear-sky

Eq. (1) $A - E = \Delta A = A_0/2$

$530.59 - 398.40 = 132.19 = 265.59 / 2$ $- 0.60\ Wm^{-2}$

Eq. (2) $A = 2A_0$

$530.59 = 2 \times 265.59$

CERES EBAF Ed2.8, 192 months (Mar 2000 – Feb 2016) Global means from Rose et al. (2017), Clear-sky

Eq. (1) $A - E = \Delta A = A_0/2$

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Eq. (2) $A = 2A_0$

$530.59 = 2 \times 265.59$ $- 0.59\ Wm^{-2}$

$\Delta A : A_0 : E : A = 1 : 2 : 3 : 4$ **(clear-sky) justified within EEI**

NASA CERES data, time period 2005-2015, monthly means

	SW down	SW up	SW abs	LW abs	E(SFC)	OLR	2OLR	Diff
CLIM 1	255.35	31.34	224.01	306.27	530.28	262.43	524.86	5.42
CLIM 2	251.86	29.86	222	307.98	529.98	262.78	525.56	4.42
CLIM 3	246.89	30.09	216.8	311.09	527.89	263.42	526.84	1.05
CLIM 4	242.26	31.63	210.63	315.14	525.77	265.01	530.02	-4.25
CLIM 5	237.33	32.21	205.12	320.27	525.39	267.18	534.36	-8.97
CLIM 6	233.41	28.67	204.74	325.70	530.44	269.05	538.1	-7.66
CLIM 7	231.63	25.72	205.91	328.35	534.26	269.75	539.5	-5.24
CLIM 8	233.65	24.42	209.23	327.05	536.28	269.12	538.24	-1.96
CLIM 9	239.24	25.80	213.44	321.82	535.26	267.58	535.16	0.1
CLIM 10	247.06	29.92	217.14	315.28	532.42	265.25	530.5	1.92
CLIM 11	253.97	33.73	220.24	309.57	529.81	263.26	526.52	3.29
CLIM 12	256.35	33.52	222.83	306.74	529.57	262.38	524.76	4.81
Average	244.08	29.74	214.34	316.27	530.61	265.60	531.20	-0.59

$$(244.08 - 29.74) + 316.27 = 530.61 = 2 \times 265.60 - 0.59$$

Surface energy budget, clear-sky, NASA CERES EBAF Ed4.0 data

Solar absorbed + thermal absorbed = 2 outgoing longwave TOA

$214.2 + 317.6 = 2 \times 268.0 - 4.2\ Wm^{-2}$

$SW\ net\downarrow + LW\ down\downarrow = 2OLR(clear) - 4.2\ Wm^{-2}$

Parameter	TOA Flux adjustment (W/m^2)
Total Net	-4.2

Total SW	1.7
Total LW	2.5
Total Net	-4.2

Creating the all-sky versions

Eq. (1) **SFC Net = A – E = $A_0/2$** (clear-sky, net)

Eq. (2) **SFC Tot = A = $2A_0$** (clear-sky, total at $\tau = 2$)

Separating atmospheric radiation transfer from the longwave cloud effect (LWCRE):

Eq. (3) **SFC Net = A – E = $(A_0 – L)/2$** (all-sky, net, incl LWCRE)

Eq. (4) **SFC Tot = A = $2A_0 + L$** (all-sky, total at $\tau = 2$ incl LWCRE)

The Four Equations

Eq. (1) From Schwarzschild (1906, Eq. 11), net, clear-sky:

$$\mathbf{A - E = \Delta A = A_0 / 2}$$

Eq. (2) From Schwarzschild (1906, Eq. 11) at $\tau = 2$, total, clear-sky:

$$\mathbf{A = 2A_0}$$

Eq. (3) From Schwarzschild (1906, Eq. 11), including LWCRE, net, all-sky:

$$\mathbf{A - E = \Delta A = (A_0 - L) / 2}$$

Eq. (4) From Schwarzschild (1906, Eq. 11) at $\tau = 2$, including LWCRE, total, all-sky:

$$\mathbf{A = 2A_0 + L}$$

The Four Equations

Eq. (1) Houghton (1977, 1986, 2002, Eq. 2.13), net, clear-sky:
$\mathbf{B_g - B_0 = \phi/2\pi}$

Eq. (2) Houghton (1977, 1986, 2002, Eq. 2.15) at $\chi_0^* = 2$, total, clear-sky:
$\mathbf{B_g = 2\phi/\pi}$

Eq. (3) Houghton (1977, 1986, 2002, Eq. 2.13), including LWCRE, net, all-sky:
$\mathbf{B_g - B_0 = (\phi - L)/2\pi}$

Eq. (4) Houghton (1977, 1986, 2002, Eq. 2.15) at $\chi_0^* = 2$, including LWCRE, total, all-sky:
$\mathbf{B_g = (2\phi + L)/\pi}$

Verification of the four equations

CERES EBAF Ed4.1 Version 3, 22 years (April 2000 – March 2022) (Wm^{-2})

Eq. (1) **SFC SW down – SW up + LW down – LW up (clear) = TOA LW (clear)/2**
240.8680 – 29.0724 + 317.4049 – 398.5211 = 266.0122 /2

Eq. (2) **SFC SW down – SW up + LW down (clear) = 2 × TOA LW (clear)**
240.8680 – 29.0724 + 317.4049 = 2 × 266.0122

Eq. (3) **SFC SW down – SW up + LW down – LW up (all) = [TOA LW (all) – LWCRE]/2**
186.8544 – 23.1629 + 345.0108 – 398.7550 = (240.2450 – 25.7672)/2

Eq. (4) **SFC SW down – SW up + LW down (all) = 2 × TOA LW (all) + LWCRE**
186.8544 – 23.1629 + 345.0108 = 2 × 240.2450 + 25.7672

4 decimal places from the netCDF3 file

Verification of the four equations

CERES EBAF Ed4.1 Version 3, 22 years (April 2000 – March 2022) (Wm^{-2})

Eq. (1) SFC SW down – SW up + LW down – LW up (clear) = TOA LW (clear)/2

240.8680 – 29.0724 + 317.4049 – 398.5211 = 266.0122 /2 – 2.3267

Eq. (2) SFC SW down – SW up + LW down (clear) = 2 × TOA LW (clear)

240.8680 – 29.0724 + 317.4049 = 2 × 266.0122 – 2.8238

Eq. (3) SFC SW down – SW up + LW down – LW up (all) = [TOA LW (all) – LWCRE]/2

186.8544 – 23.1629 + 345.0108 – 398.7550 = (240.2450 – 25.7672)/2 + 2.7083

Eq. (4) SFC SW down – SW up + LW down (all) = 2 × TOA LW (all) + LWCRE

186.8544 – 23.1629 + 345.0108 = 2 × 240.2450 + 25.7672 + 2.4450

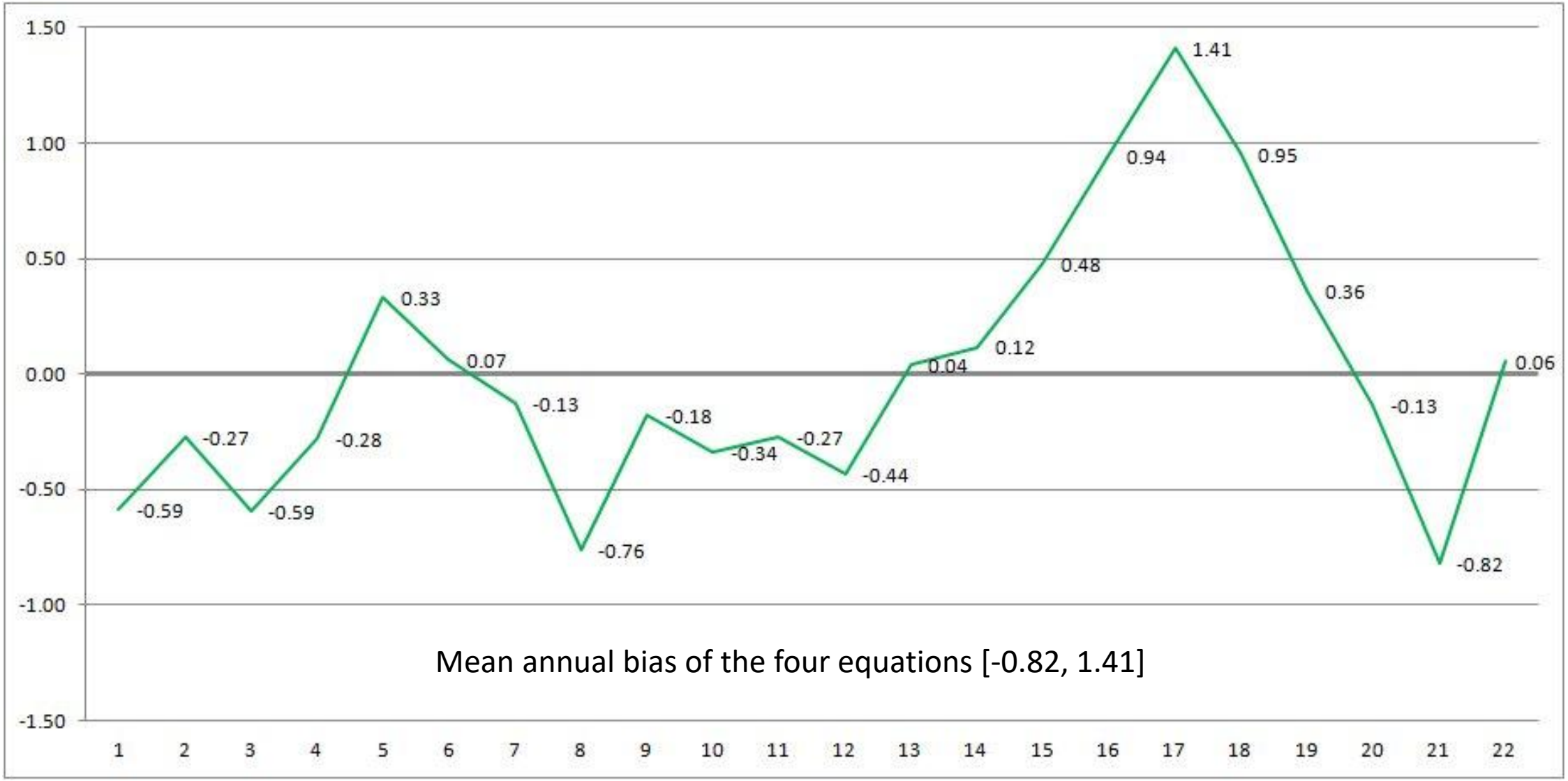
Verification of the four equations

CERES EBAF Ed4.1 Version 3, 22 years (April 2000 – March 2022) (Wm^{-2})

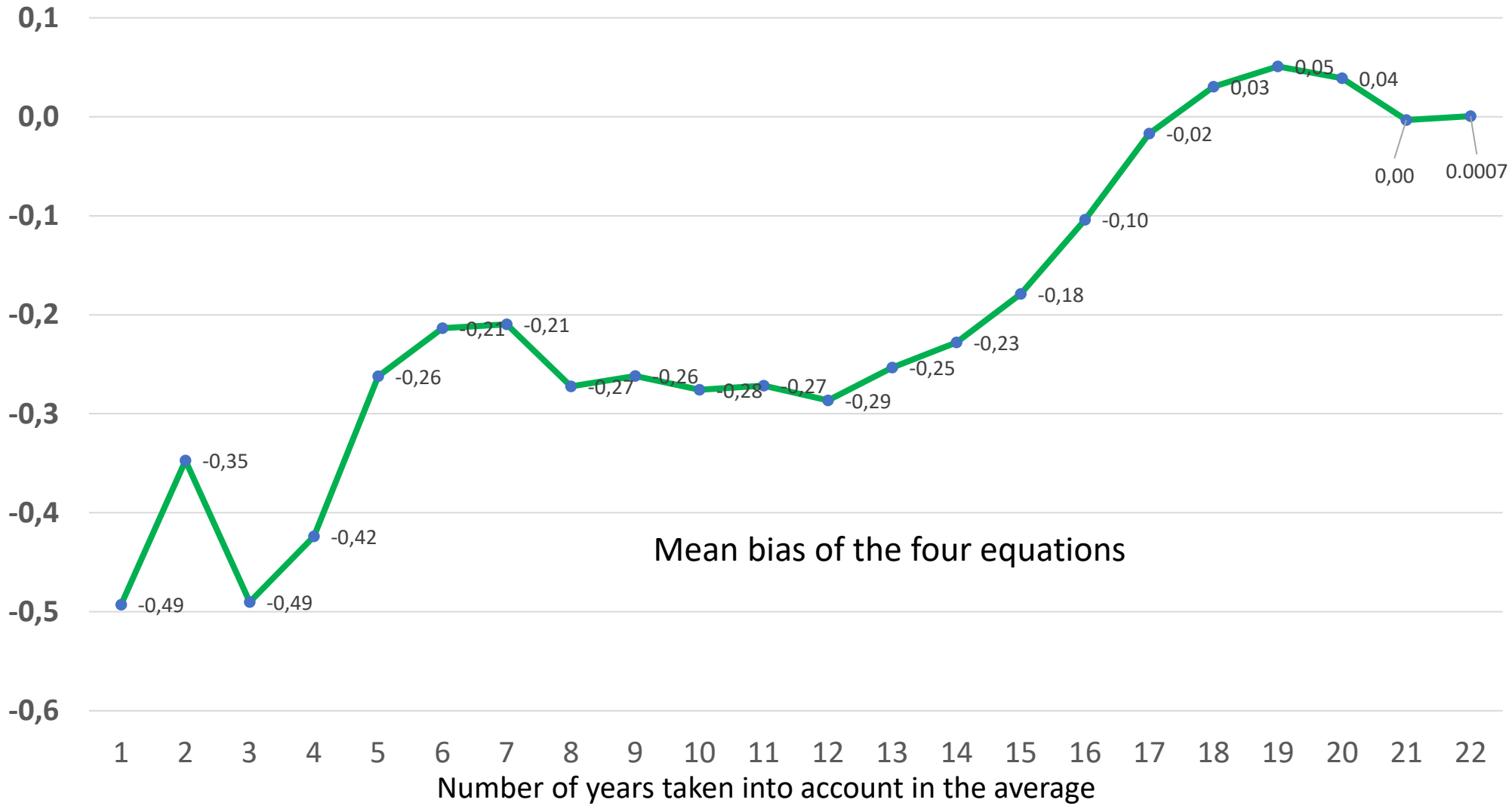
Eq. (1)	**SFC**	**SW down**	**– SW up**	**+ LW down**	**– LW up**	**(clear)**	**= TOA LW (clear)/2**
		240.8680	**– 29.0724**	**+ 317.4049**	**– 398.5211**		**= 266.0122 /2** **– 2.3267**
Eq. (2)	**SFC**	**SW down**	**– SW up**	**+ LW down**		**(clear)**	**= 2 × TOA LW (clear)**
		240.8680	**– 29.0724**	**+ 317.4049**			**= 2 × 266.0122** **– 2.8238**
Eq. (3)	**SFC**	**SW down**	**– SW up**	**+ LW down**	**– LW up**	**(all)**	**= [TOA LW (all) – LWCRE]/2**
		186.8544	**– 23.1629**	**+ 345.0108**	**– 398.7550**		**= (240.2450 – 25.7672)/2** **+ 2.7083**
Eq. (4)	**SFC**	**SW down**	**– SW up**	**+ LW down**		**(all)**	**= 2 × TOA LW (all) + LWCRE**
		186.8544	**– 23.1629**	**+ 345.0108**			**= 2 × 240.2450 + 25.7672** **+ 2.4450**

Mean **0.0007**

Large interannual fluctuations



Approaching zero only after 18 years of averaging

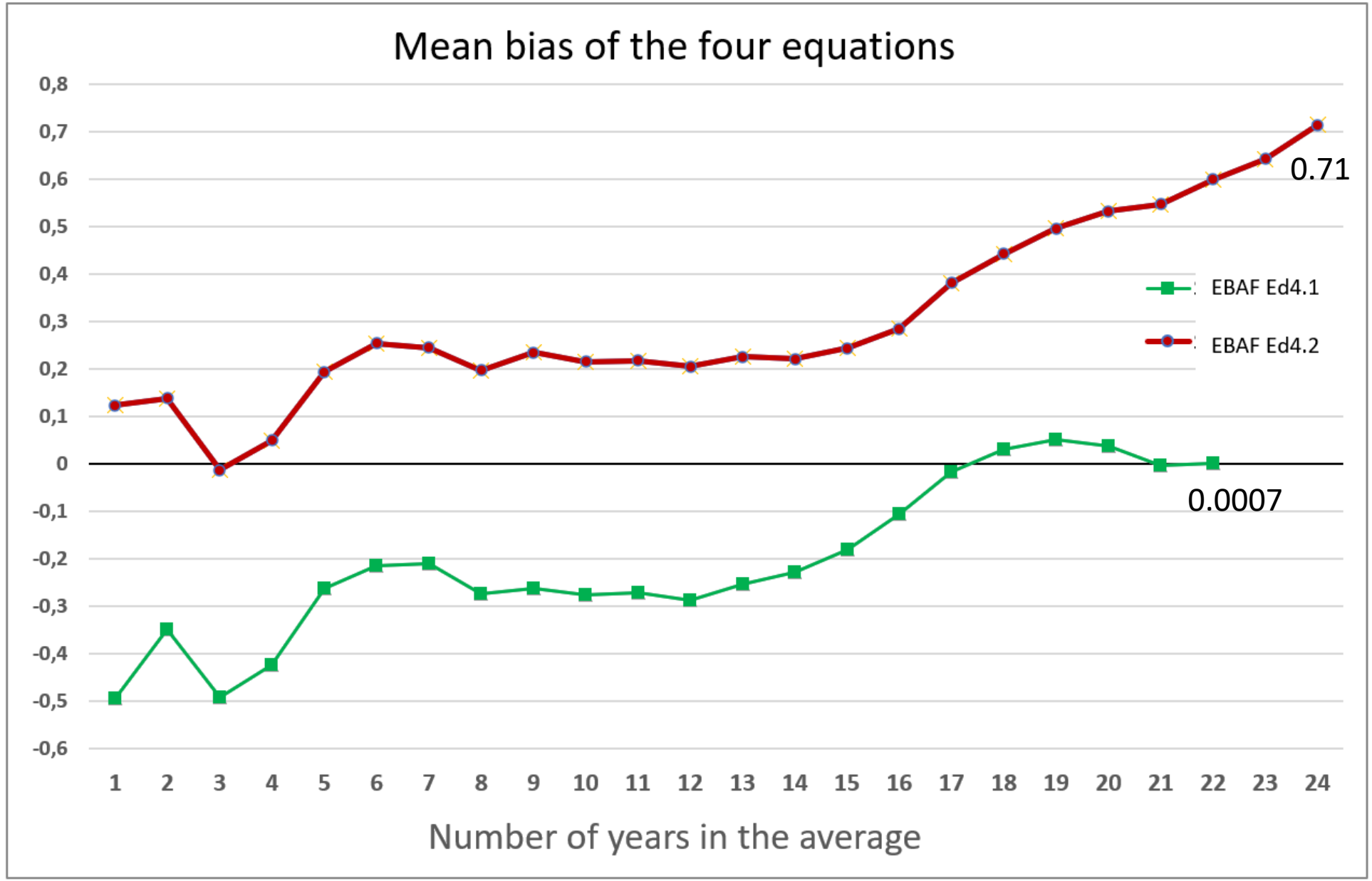


CERES EBAF Ed4.1 Version 3, 22 years (April 2000 – March 2022) (Wm^{-2})
CERES EBAF Ed4.2 Version 2, 22 years (April 2000 – March 2022) (Wm^{-2})
CERES EBAF Ed4.2 Version 2, 24 years (April 2000 – March 2024) (Wm^{-2})

Eq. (1)	**SFC**	**SW down**	**–**	**SW up**	**+**	**LW down**	**–**	**LW up**	**(clear)**	**= TOA LW (clear)/2**
		240.8680	–	29.0724	+	317.4049	–	398.5211		= 266.0122 /2 – 2.3267
		241.0969	–	29.7521	+	317.8744	–	398.5890		= 265.9594 /2 – 2.3495
		241.0514	–	29.7043	+	318.0984	–	398.7742		= 265.9748 /2 – 2.3161
Eq. (2)	**SFC**	**SW down**	**–**	**SW up**	**+**	**LW down**			**(clear)**	**= 2 × TOA LW (clear)**
		240.8680	–	29.0724	+	317.4049				= 2 × 266.0122 – 2.8238
		241.0969	–	29.7521	+	317.8744				= 2 × 265.9594 – 2.6996
		241.0514	–	29.7043	+	318.0984				= 2 × 265.9748 – 2.5042
Eq. (3)	**SFC**	**SW down**	**–**	**SW up**	**+**	**LW down**	**–**	**LW up**	**(all)**	**= [TOA LW (all) – LWCRE]/2**
		186.8544	–	23.1629	+	345.0108	–	398.7550		= (240.2450 – 25.7672)/2 + 2.7083
		187.1451	–	23.4950	+	346.1057	–	398.4220		= (240.3317 – 25.6277)/2 + 3.9818
		187.1756	–	23.4607	+	346.3158	–	398.6162		= (240.3894 – 25.5854)/2 + 4.0126
Eq. (4)	**SFC**	**SW down**	**–**	**SW up**	**+**	**LW down**			**(all)**	**= 2 × TOA LW (all) + LWCRE**
		186.8544	–	23.1629	+	345.0108				= 2 × 240.2450 + 25.7672 + 2.4450
		187.1451	–	23.4950	+	346.1057				= 2 × 240.3317 + 25.6277 + 3.4647
		187.1756	–	23.4607	+	346.3158				= 2 × 240.3894 + 25.5854 + 3.6665

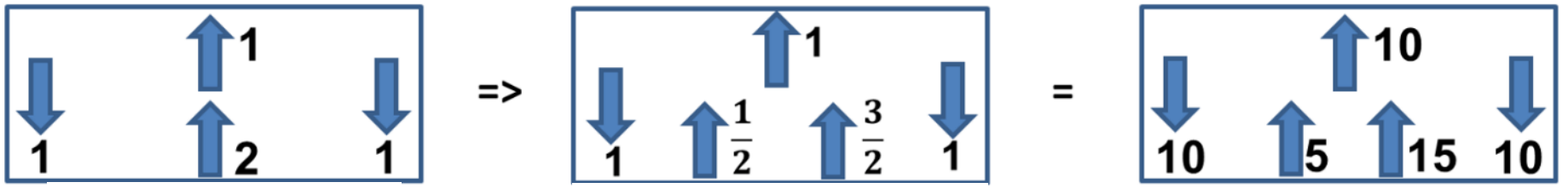
Continuity in Top-of-Atmosphere Earth Radiation Budget Observations
(Loeb et al. 2024, *J Clim*)

Mean 0.0007
0.5994
0.7147

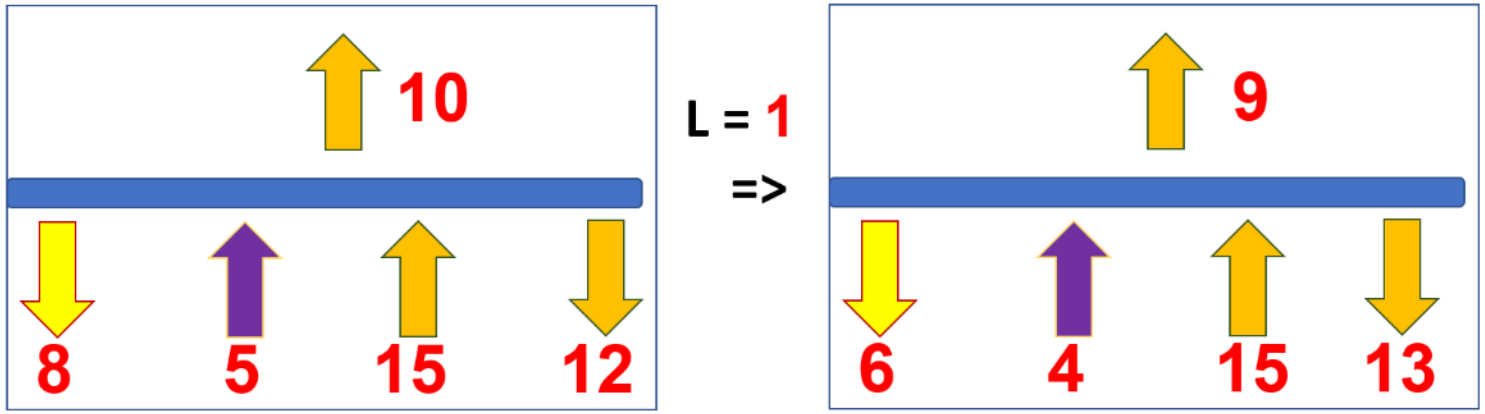

Mean bias of the four equations
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Number of years in the average
EBAF Ed4.1
EBAF Ed4.2
0.71
0.0007

The N-numbers, as solution of the equations

Pure geometry: No reference to GHGs



Eq.(2) $A = 2A_0$ (Clear-sky) Eq.(1) $\Delta A = A - E = A_0/2$



$8 + 12 - 15 = 10 / 2$

$8 + 12 = 10 \times 2$

$6 + 13 - 15 = (9 - 1)/2$

$6 + 13 = 9 \times 2 + 1$

Eq. (1) SFC Net = $A_0/2$

Eq. (2) SFC Tot = $2A_0$

Clear-sky

Eq. (3) SFC Net = $(A_0 - L)/2$

Eq. (4) SFC Tot = $2A_0 + L$

All-sky

The flux components with LWCRE = 1

TOA LW	clear-sky	=	**10**
SFC LW up	clear-sky	=	**15**
SFC LW down	clear-sky	=	**12**
SFC LW net	clear-sky	=	**–3**
SFC SW net	clear-sky	=	**8**
SFC SW+LW net	clear-sky	=	**5**
SFC SW+LW total	clear-sky	=	**20**
G greenhouse effect	clear-sky	=	**5**
SWCRE (surface)		=	**–2**

TOA LW	all-sky	=	**9**
SFC LW up	all-sky	=	**15**
SFC LW down	all-sky	=	**13**
SFC LW net	all-sky	=	**–2**
SFC SW net	all-sky	=	**6**
SFC SW+LW net	all-sky	=	**4**
SFC SW+LW total	all-sky	=	**19**
G greenhouse effect	all-sky	=	**6**
LWCRE (surface, TOA)		=	**1**

Fit model to observation

CERES EBAF Ed4.2 V2, 276 months, Oct 2000 — Sep 2023 data

Best fit: 1 unit = 1 = LWCRE = 26.68 ± 0.01 Wm^{-2}

Earth-like Greenhouse Geometry

Data: CERES EBAF Ed4.2 Version 2, October 2000 – September 2023

Eq. (1) **8** + **12** – **15** = **10**/2; Eq. (2) **8** + **12** = **10** × 2;

Eq. (3) **6** + **13** – **15** = (**9** – **1**)/2; Eq. (4) **6** + **13** = **9** × 2 + **1** **1** = 26.68 Wm^{-2}

TSI = 51 Clear-sky	**N**	**N × Unit (Wm^{-2})**	**EBAF Ed4.2 (Wm^{-2})**	**Diff (Wm^{-2})**
TOA LW up	**40**/4	266.80	265.95	-0.85
TOA SW up	**8**/4	53.36	53.78	0.42
TOA SW net	**3**/4	20.01	20.47	0.46
SFC SW net	**8**	213.44	211.33	-2.11
SFC LW down	**12**	320.16	318.06	-2.10
SFC LW up	**15**	400.20	398.58	-1.62
G	**5**	133.40	132.63	-0.77
TSI = 51 All-sky				
TOA LW up	**36**/4	240.12	240.37	0.25
TOA SW up	**15**/4	100.05	98.95	-1.10
SFC SW net	**6**	160.08	163.71	3.63
SFC LW down	**13**	346.84	346.25	-0.59
SFC LW up	**15**	400.20	398.75	-1.45
G	**6**	160.08	158.38	-1.70

An independent estimate: Clear-Sky Greenhouse Effect at GFDL

LWCRE (geometry) = **1** = 26.68 ± 0.01 Wm^{-2}

G (clear, geo) = **15** – **10** = **5** = 133.40 ± 0.05 Wm^{-2}

G (GFDL AM4) = 133.4 ± 0.6 Wm^{-2}

Quantifying the Drivers of the Clear Sky Greenhouse Effect, 2000–2016

Shiv Priyam Raghuraman ✉, David Paynter, V. Ramaswamy (JGR 2019)

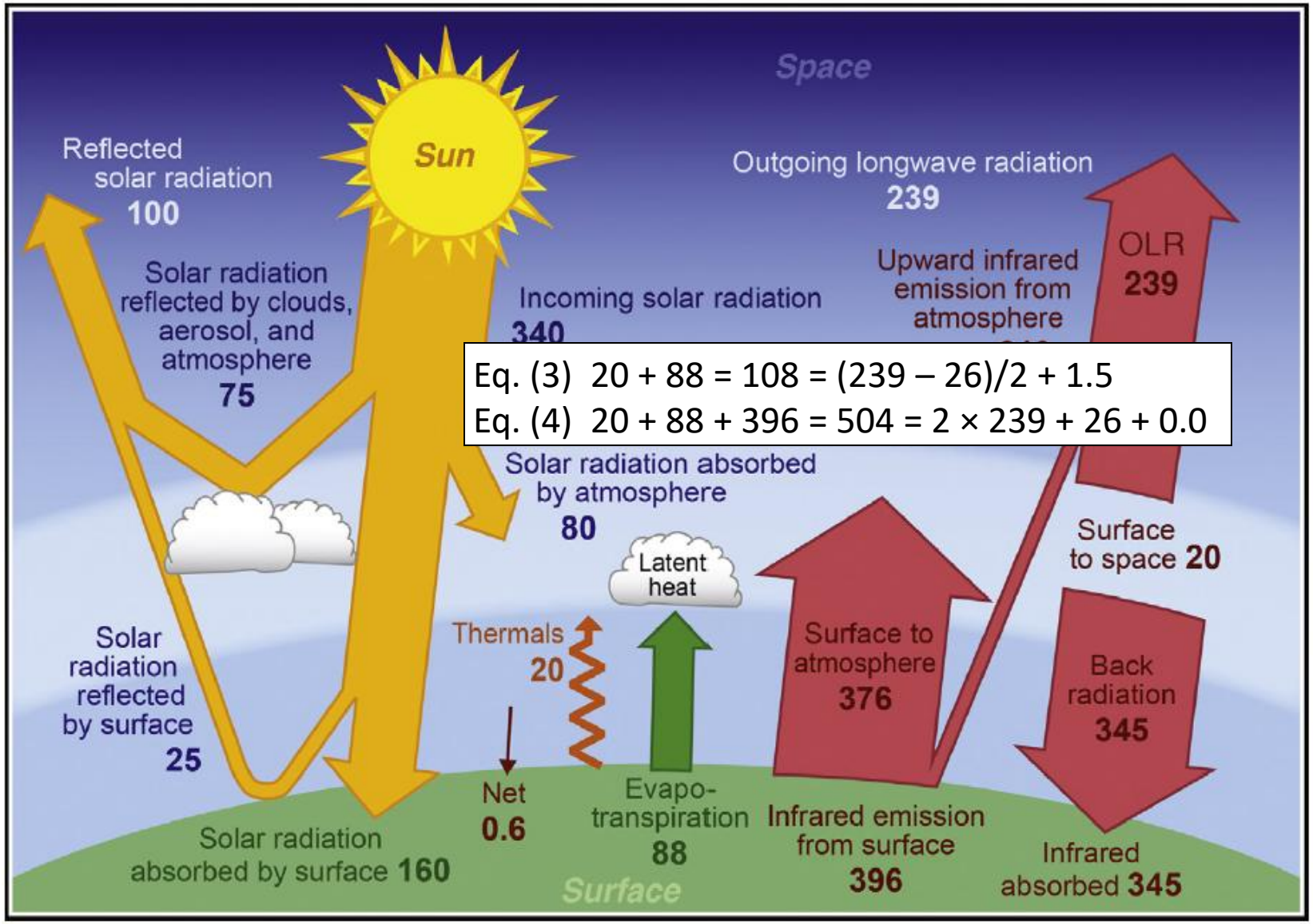
Table 2

Global Mean and Time Mean G Comparison Between Observational, Reanalysis, and Modeling Data Sets Over March 2000 to August 2016

Quantity	ERBE	CE 4.1 "*c*"	CE 4.1 "*t*"	ERA-Interim	GFDL AM4
G_{Oceans}	146 ± 7	131.3 ± 0.5	134.1 ± 0.5	134.8 ± 0.6	135.0 ± 0.5
G	–	129.7 ± 0.6	132.4 ± 0.6	133.1 ± 0.7	133.4 ± 0.6

Chapter 2.3
Checking the Equations and their Solution

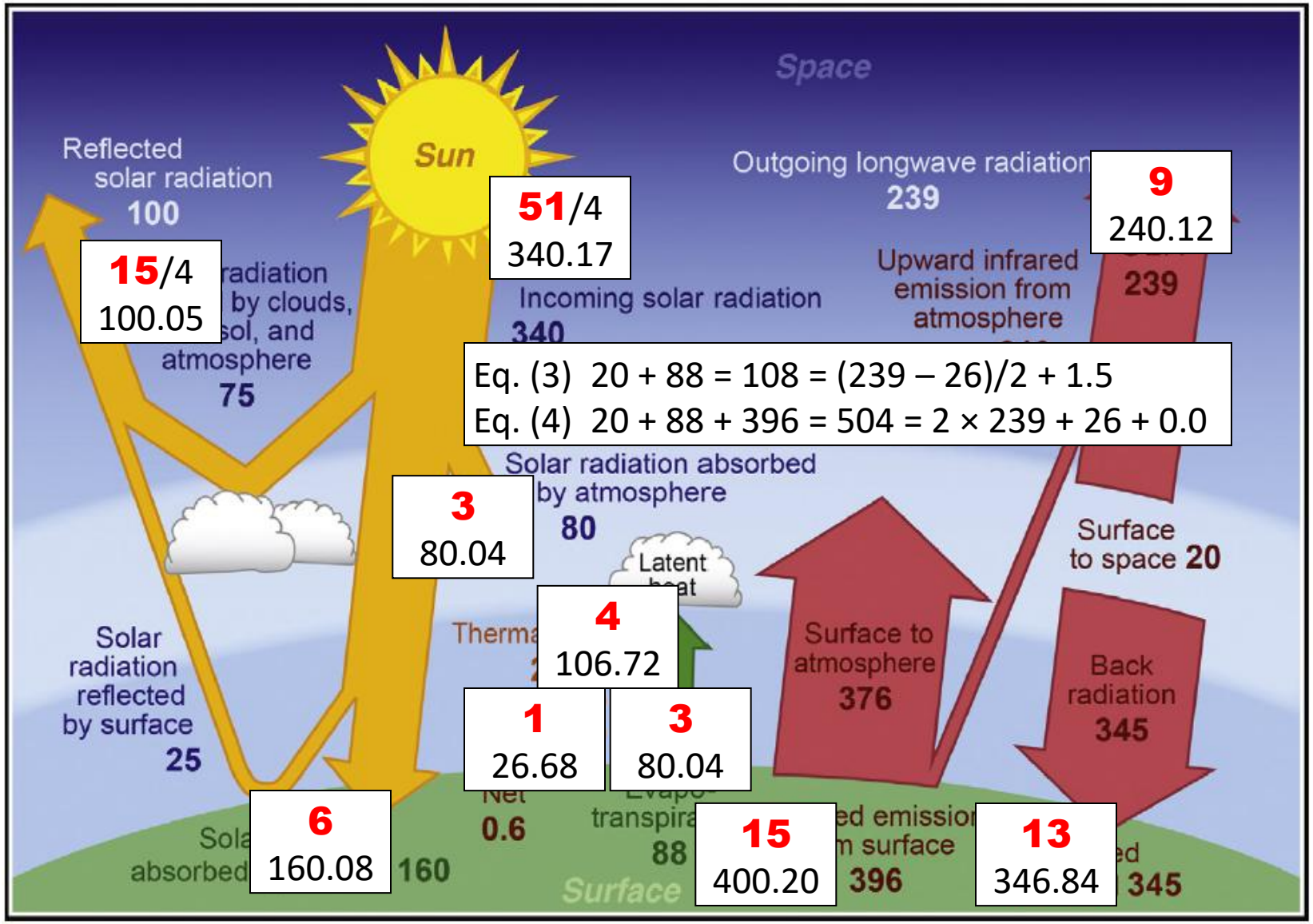
D. Hartmann (IPCC AR5 2013 WGI Ch2 CLA) Global Physical Climatology, 2nd Edition (2016) (all-sky)



Cloud effect
+26

FIGURE 2.4 **Global and annual average radiative and nonradiative energy-flow diagram for Earth and its atmosphere.** Units are Wm^{-2}.

D. Hartmann (IPCC AR5 2013 WGI Ch2 CLA) Global Physical Climatology, 2nd Edition (2016) (all-sky)

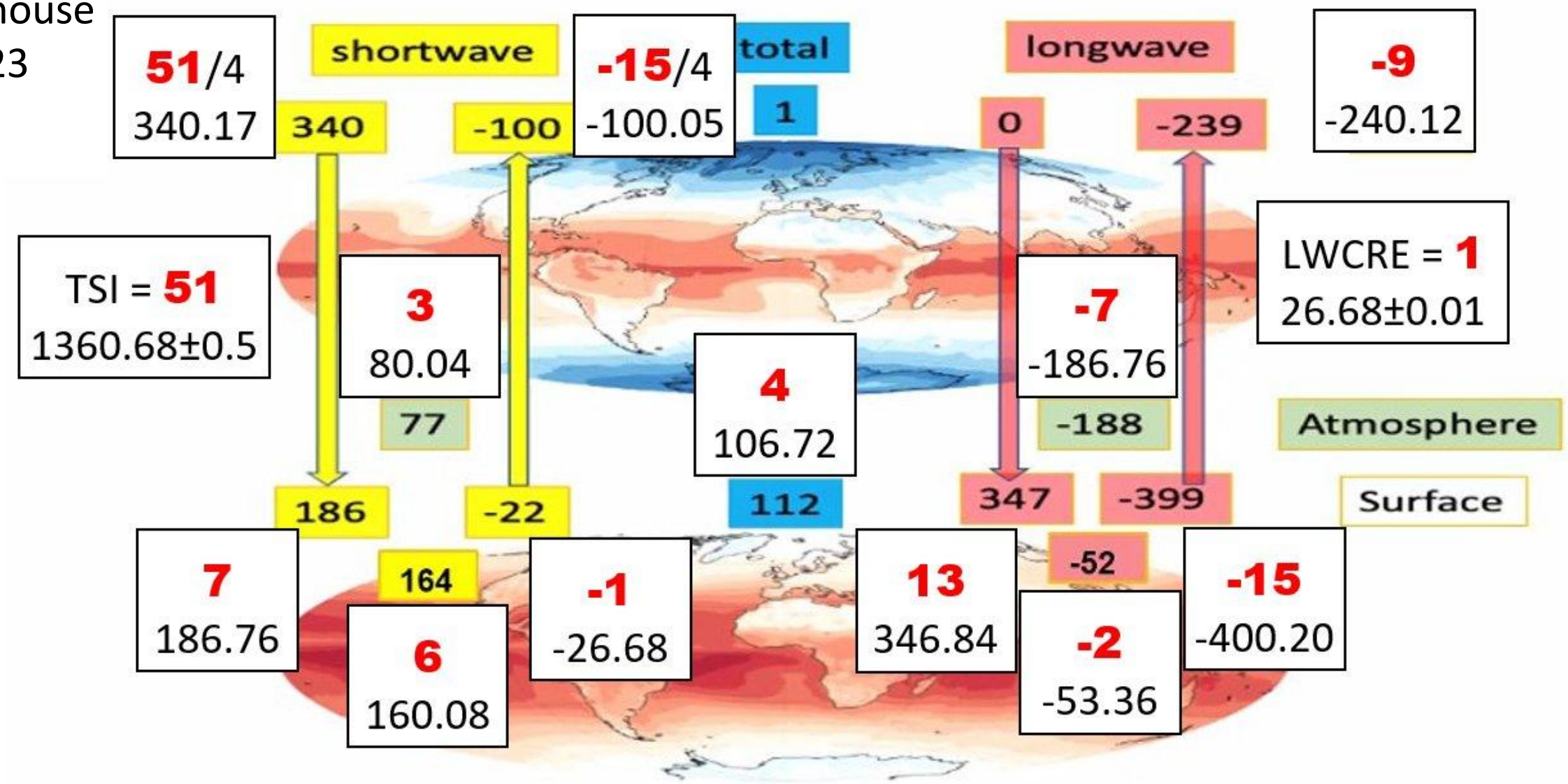


Cloud effect
+26

FIGURE 2.4 Global and annual average radiative and nonradiative energy-flow diagram for Earth and its atmosphere. Units are Wm^{-2}.

GEWEX SRB Rel4-IP: Global Mean Comparisons

P. Stackhouse
EGU 2023
(all-sky)



“Radiative Forcing of Climate”, Meteorological Monographs 2019

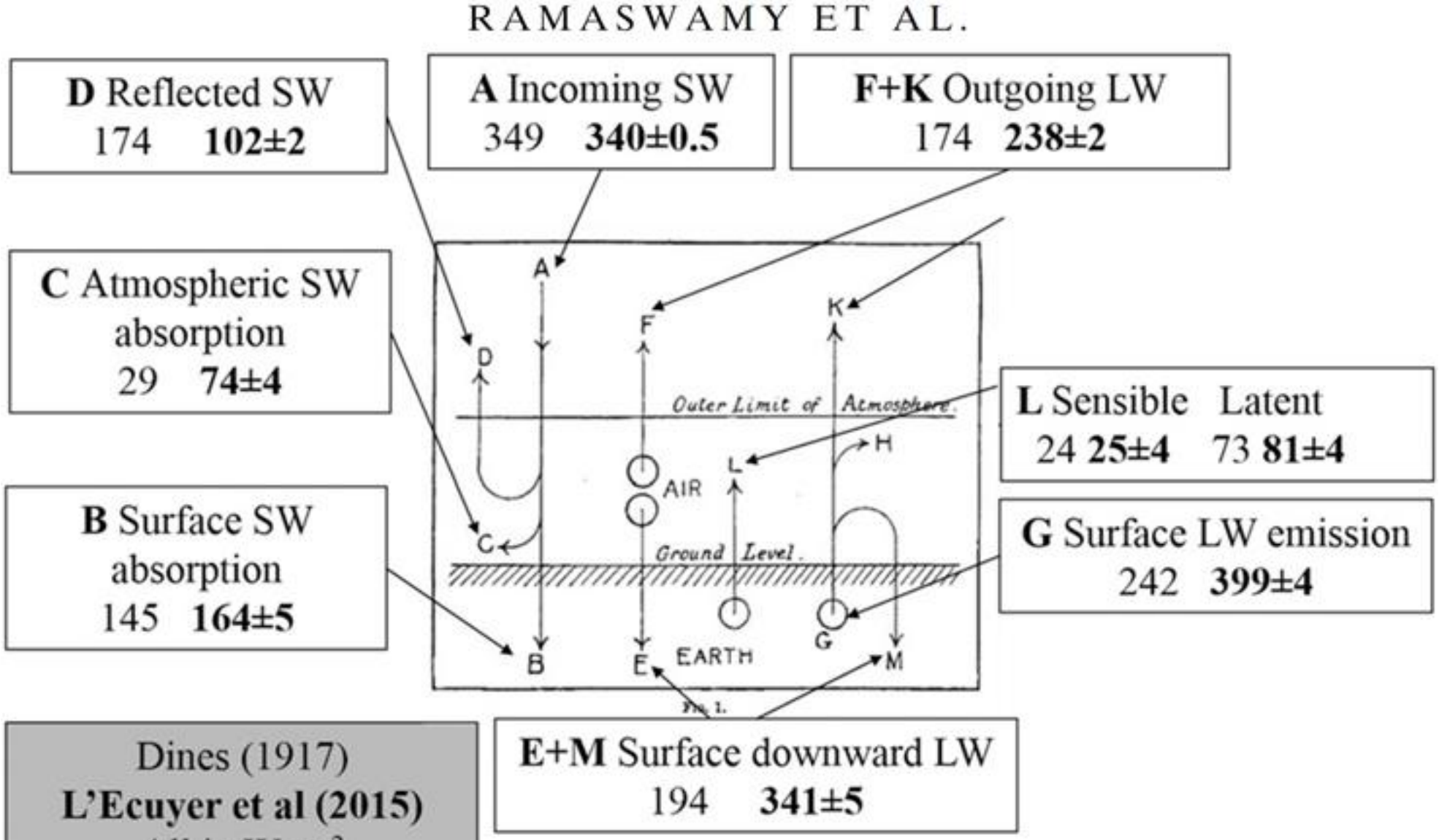


Fig. 14-1.

“Radiative Forcing of Climate”, Meteorological Monographs 2019

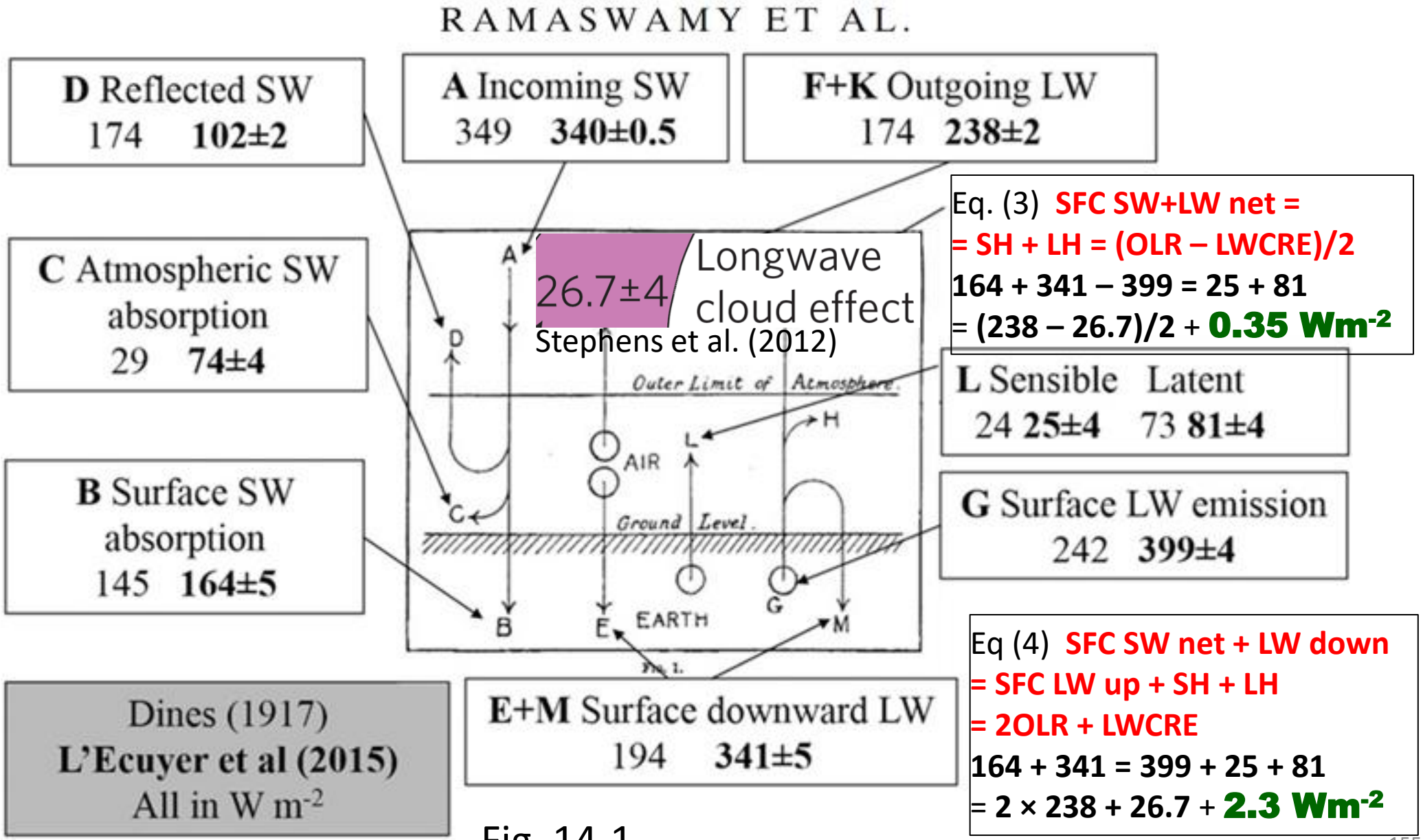
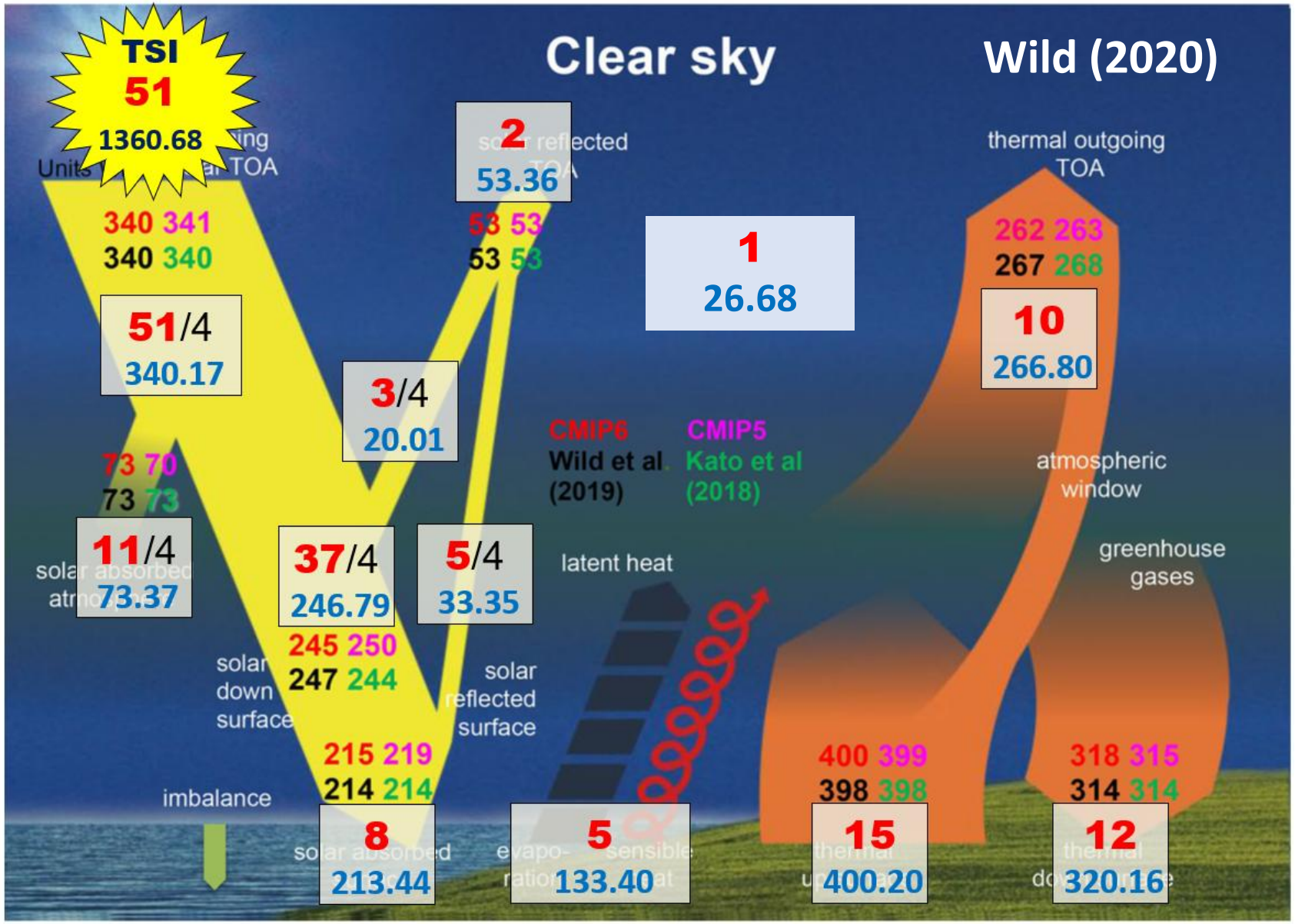
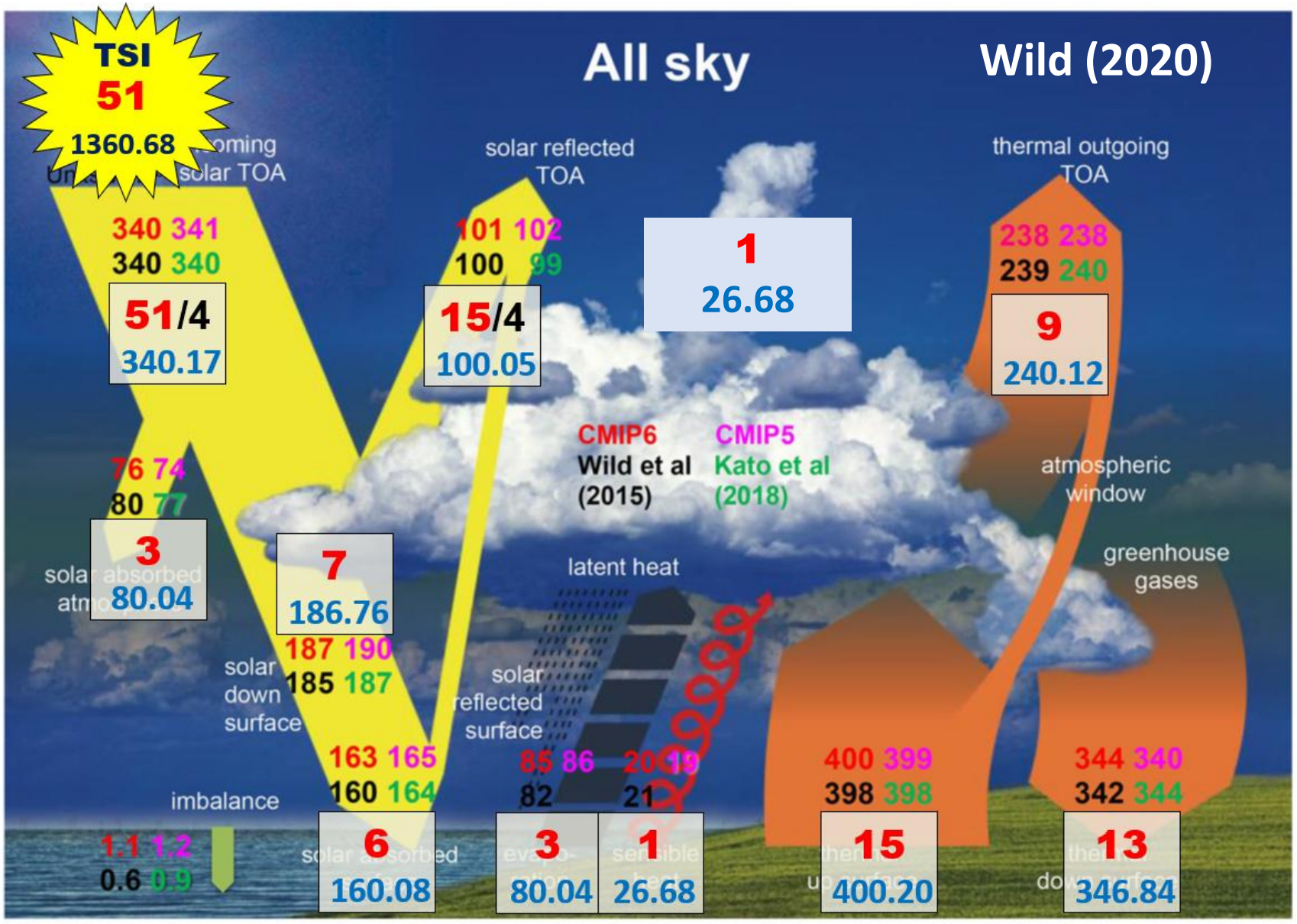


Fig. 14-1.

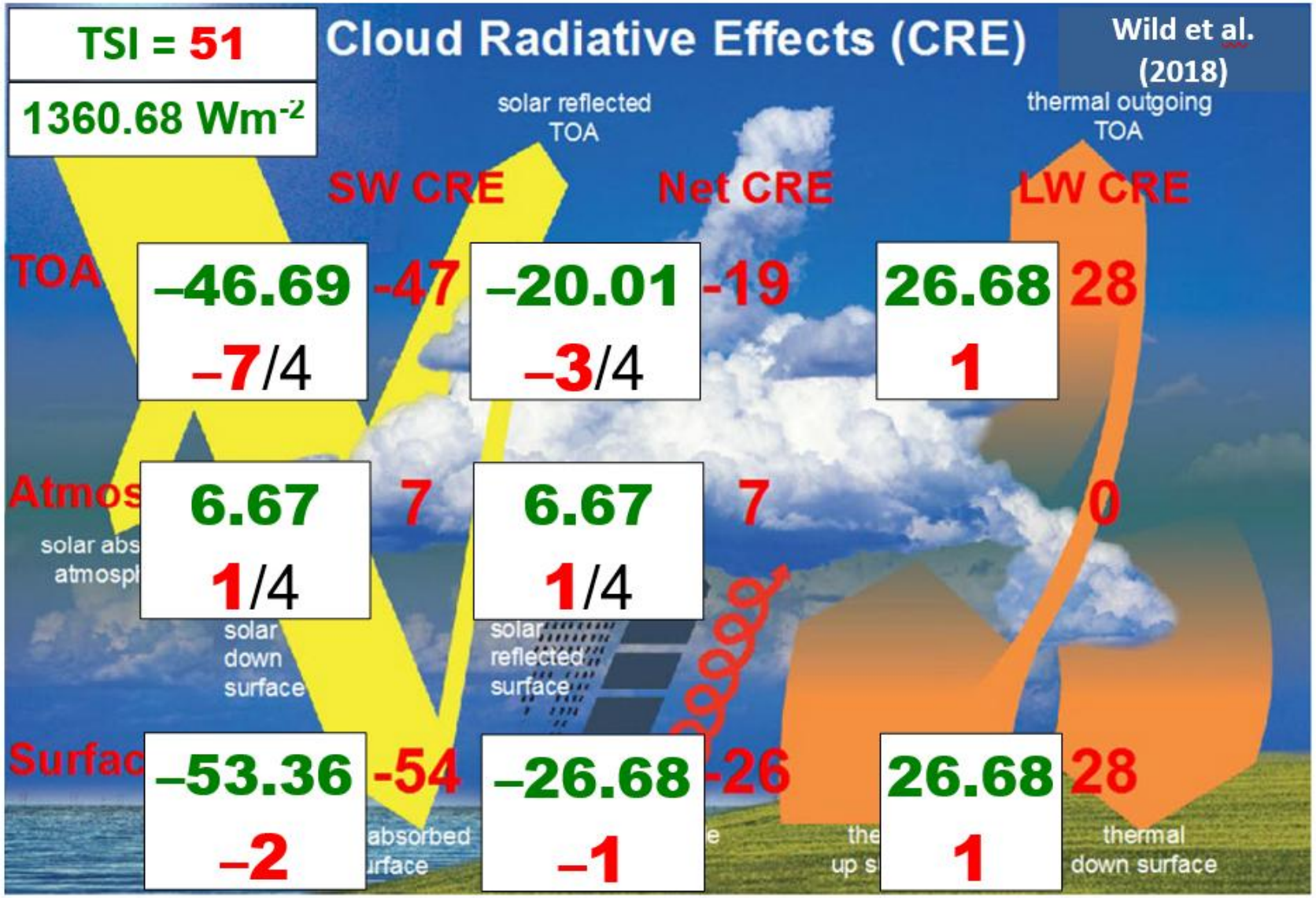
Wild, M. (2020). The global energy balance as represented in CMIP6 climate models. Climate Dynamics (2020) 55:553–577. https://doi.org/10.1007/s00382-020-05282-7.



Wild, M. (2020). The global energy balance as represented in CMIP6 climate models. Climate Dynamics (2020) 55:553–577. https://doi.org/10.1007/s00382-020-05282-7.



Wild, M. et al, (2018). The cloud-free global energy balance and inferred cloud radiative effects: an assessment based on direct observations and climate models. Climate Dynamics https://doi.org/10.1007/s00382-018-4413-y



Wild, M. (2020). The global energy balance as represented in CMIP6 climate models. Climate Dynamics (2020) 55:553–577. https://doi.org/10.1007/s00382-020-05282-7.

	Reference estimates	N	N × unit	CMIP6 mean
TOA				
SW down TOA	340[a], 340[b], 340[c]	51/4	340.17	**340.2**
SW up all-sky TOA	−99[a], −100[b], −102[c]	-15/4	-100.05	**−100.6**
SW absorbed all-sky TOA	241[a], 240[b], 238[c]	36/4	240.12	239.5
SW up clear-sky TOA	−53[a], −53[b]	-8/4	-53.36	−53.0
SW absorbed clear-sky TOA	287[a], 287[b]	43/4	286.81	**287.3**
SW CRE TOA	−46[a], −47[b]	-7/4	-46.69	−47.8
LW up (OLR) all-sky TOA	−240[a], −239[b], −238[c]	-9	-240.12	−238.3
LW up (OLR) clear-sky TOA	−268[a], −267[b]	-10	-266.80	−262.4
LW CRE TOA	28[a], 28[b]	1	26.68	24.1
Net CRE TOA	−18[a], −19[b]	-3/4	-20.01	−23.6
Imbalance TOA	0.7[a]			1.1
Atmosphere				
SW absorbed all-sky atmos.	80[b]. 74[c], 77[d]	3	80.04	**76.0**
SW absorbed clear-sky atmos.	73[b], 73[d]	11/4	73.37	**72.8**
SW CRE atmos.	7[b], 4[d]	1/4	6.67	**3.2**
LW net all-sky atmos.	−183[b], −180[c], −187[d]	-7	-186.76	**−182.1**
LW net clear-sky atmos.	−183[b], −184[d]	-7	-186.76	**−180.9**
LW CRE atmos.	0[b], −3[d]			−1.3
Net CRE atmos.	7[b], 1[d]	1/4	6.67	**1.9**

Wild, M. (2020). The global energy balance as represented in CMIP6 climate models. Climate Dynamics (2020) 55:553–577. https://doi.org/10.1007/s00382-020-05282-7.

Surface				
SW down all-sky surface	185 [b], 186 [c], 187 [d]	7	186.76	**187.4**
SW up all-sky surface	−25 [b], −22 [c], −23 [d]	-1	-26.68	−23.9
SW absorbed all-sky surface	160 [b], 164 [c], 164 [d]	6	160.08	**163.4**
SW down clear-sky surface	247 [b], 244 [d]	37/4	246.79	**244.8**
SW up clear-sky surface	33 [b], 30 [d]	5/4	33.35	30.2
SW absorbed clear-sky surface	214 [b], 214 [d]	8	213.44	**214.6**
SW CRE surface	−54 [b], −50 [d]	-2	-53.36	**−51.2**
LW down all-sky surface	342 [b], 341 [c], 344 [d]	13	346.84	**343.8**
LW up all-/clear-sky surface	398 [b], 399 [c], 398 [d]	15	400.20	−399.9
LW net all-sky surface	−56 [b], −58 [c], −54 [d]	-2	-53.36	**−56.2**
LW down clear-sky surface	314 [b], 314 [d]	12	320.16	**318.0**
LW net clear-sky surface	−84 [b], −84 [d]	-3	-80.04	**−81.7**
LW CRE surface	28 [b], 30 [d]	1	26.68	25.5
Net CRE surface	−26 [b],−20 [d]	-1	-26.68	**−25.4**
Net radiation surface	104 [b], 106 [c], 110 [d]	14	106.72	107.2
Latent heat flux	−82 [b], −81 [c]	-3	-80.04	−85.3
Sensible heat flux	−21 [b], −25 [c]	-1	-26.68	**−20.1**

The Global Energy Balance as Represented in Atmospheric Reanalyses

Martin Wild · Michael G. Bosilovich

Surveys in Geophysics 2024 https://doi.org/10.1007/s10712-024-09861-9

Energy balance component	Reference Estimates Wm^{-2}	Recent Reanal r Reanal Wm^{-2}		N	N×unit
TOA					
SW down	340[a], 340[b], 340[c]	340.9	340.8	51/4	340.17
SW up all-sky	−99[a], −100[b], −102[c]	−101.3	−100.7	-15/4	-100.05
SW absorbed all-sky	241[a], 240[b], 238[c]	239.6	240.1	36/4	240.12
SW up clear-sky	−53[a], −53[b]	−51.3	−52.5	-8/4	-53.36
SW absorbed clear-sky	287[a], 287[b]	289.4	288.2	43/4	286.81
SW CRE	−46[a], −47[b]	−48.8	−47.7	-7/4	-46.69
LW up (OLR) all-sky	−240[a], −239[b], −238[c]	−243.4	−241.5	-9	-240.12
LW up (OLR) clear-sky	−268[a], −267[b]	−265.8	−265.2	-10	-266.80
LW CRE	28[a], 28[b]	22.4	23.9	1	26.68
Net CRE	−18[a], −19[b]	−26.5	−23.8	-3/4	-20.01
Imbalance	0.7 [a]	−3.9	−1.5	0	0
Atmosphere					
SW absorbed all-sky	80[b], 74[c], 77[d]	76.1	75.9	3	80.04
SW absorbed clear-sky	73[b], 73[d]	73.6	72.8	11/3	73.37
SW CRE	7[b], 4[d]	2.7	3.1	1/4	6.67
LW net all-sky	−183 [b], −180[c], −187[d]	−184.2	−181.6	-7	-186.76
LW net clear-sky	−183[b], −184[d]	−182.0	−181.4	-7	-186.76
LW CRE	0[b], −3[d]	−1.4	0.3	0	0
Net CRE	7[b], 1[d]	1.3	3.4	1/4	6.67

Energy balance component	Reference Estimates Wm^{-2}	Recent Reanal r Reanal Wm^{-2}		N	N×unit
Surface					
SW down all-sky	185 [b], 186 [c], 187[d]	187.8	189.2	7	186.76
SW up all-sky	−25 [b], −22[c], −23[d]	−24.4	−25.0	-1	-26.68
SW absorbed all-sky	160 [b], 164 [c], 164[d]	163.4	164.2	6	160.08
SW down clear-sky*	247[b], 244[d]	246.8	247.8	37/4	246.79
SW up clear-sky*	33[b], 30[d]	31.0	32.4	-5/4	-33.35
SW absorbed clear-sky	214[b], 214[d]	215.8	215.3	8	213.44
SW CRE	−54[b], −50 [d]	−51.5	−50.8	-2	-53.36
LW down all-sky	342[b], 341[c], 344[d]	339.1	338.2	13	346.84
LW up all-sky/ clear-sky	−398[b], −399[c], −398[	−398.3	−398.1	-15	-400.20
LW net all-sky	−56[b], −58[c], −54[d]	−59.3	−59.9	-2	-53.36
LW down clear-sky	314[b], 314[d]	314.7	314.3	12	320.16
LW net clear-sky	−84[b], −84[d]	−83.9	−83.9	-3	-80.04
LW CRE	28[b], 30[d]	23.7	23.6	1	26.68
Net CRE	−26[b], −20[d]	−27.7	−27.2	-1	-26.68
Net radiation	104[b], 106[c], 110[d]	104.1	104.3	4	106.72
Latent heat flux	−82[b], −81[c]	−88.7	−86.0	-3	-80.04
Sensible heat flux	−21[b], −25[c]	16.0	−17.5	-1	-26.68
Surface Imbalance	0.6 [b], 0.5[c]	−0.6	0.7	0	0

Stephens et al. (BAMS, 2023)
The First 30 Years of GEWEX
Fig. 2

Rn = LE + H
is shown.
The constraint
Rn = LE + H =
(OLR – LWCRE)/2 (all-sky)
is not menioned but taken
into account in Fig. SB3

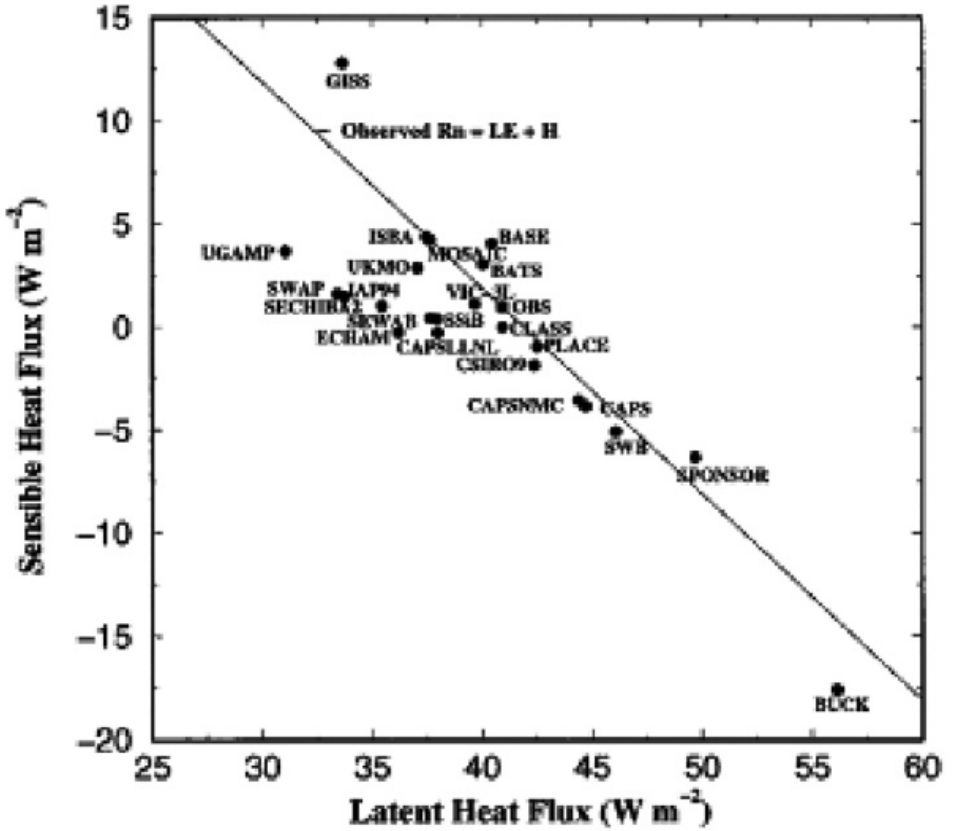


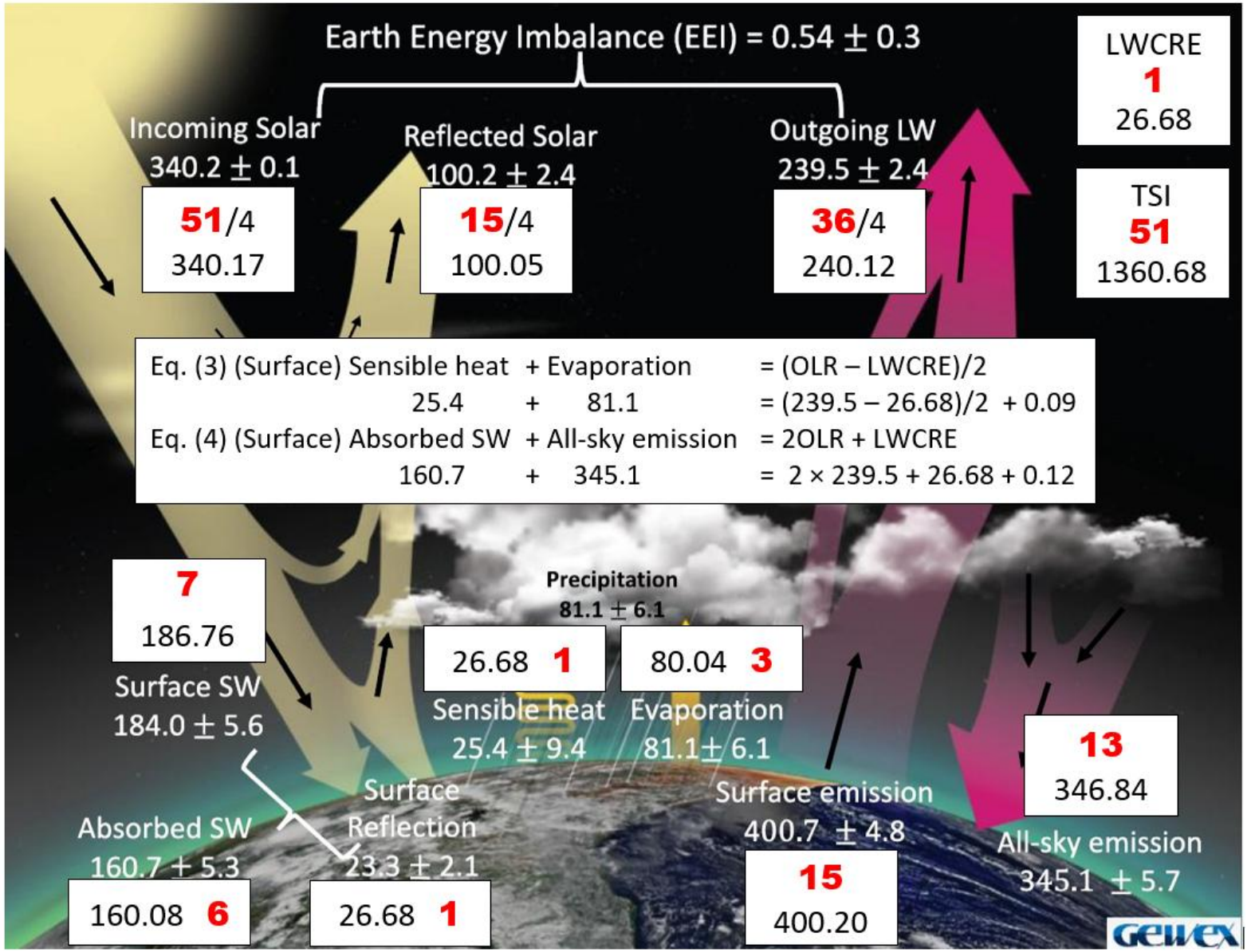
Fig. 2. Comparison of LSMs and observations is a philosophy of GLASS that has been sustained from the outset. In this example (from Chen et al. 1997), annually averaged surface sensible (*H*) vs latent heat (LE) fluxes (W m^{-2}) are shown. The observed annual net radiation (Rn) is 41 W m^{-2} and the line shown is this net radiation value expressed as the sum of the two coordinates with any single point falling on the line being simply the surface energy balance relation Rn = LE + *H*.

30 Years of GEWEX (BAMS 2023)

Stephens et al. (2023, Fig. SB3)

Eq. (3)
Rn = LE + H =
81.1 + 25.4 =
(OLR – LWCRE)/2
= (239.5 –26.68)/2
+ 0.09 Wm^{-2}

(LWCRE = 26.7±4 Wm^{-2} in Stephens et al. 2012)



Transcript of slide #163

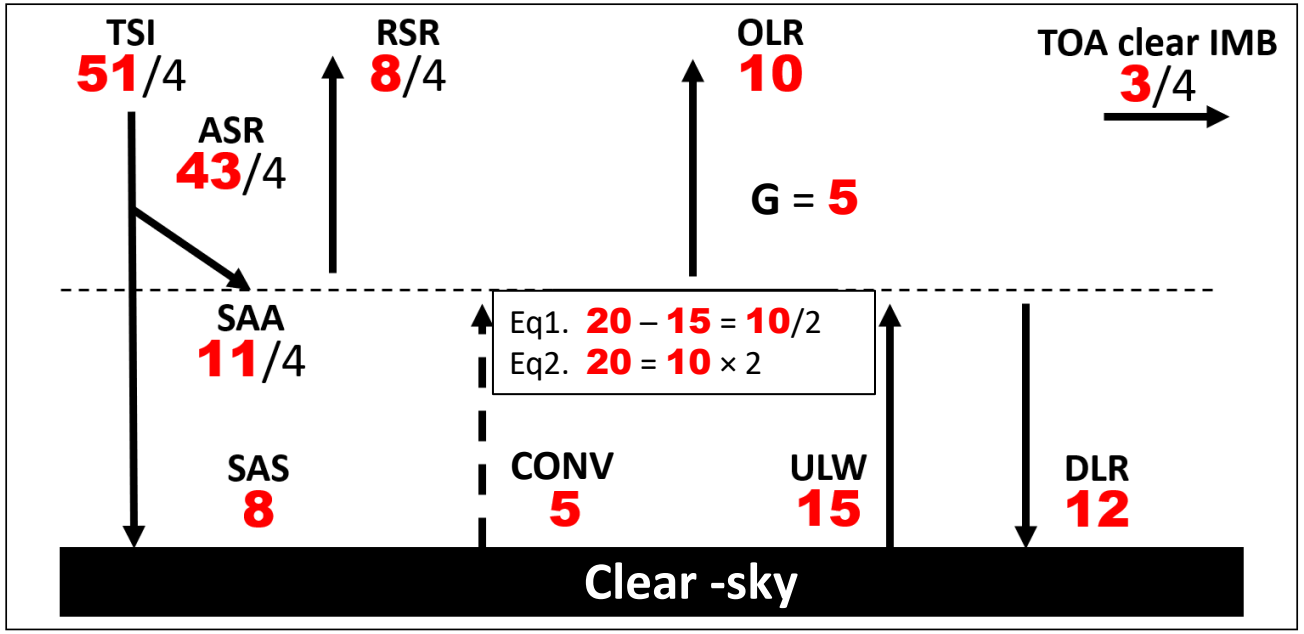
“Let me declare here my expectation.

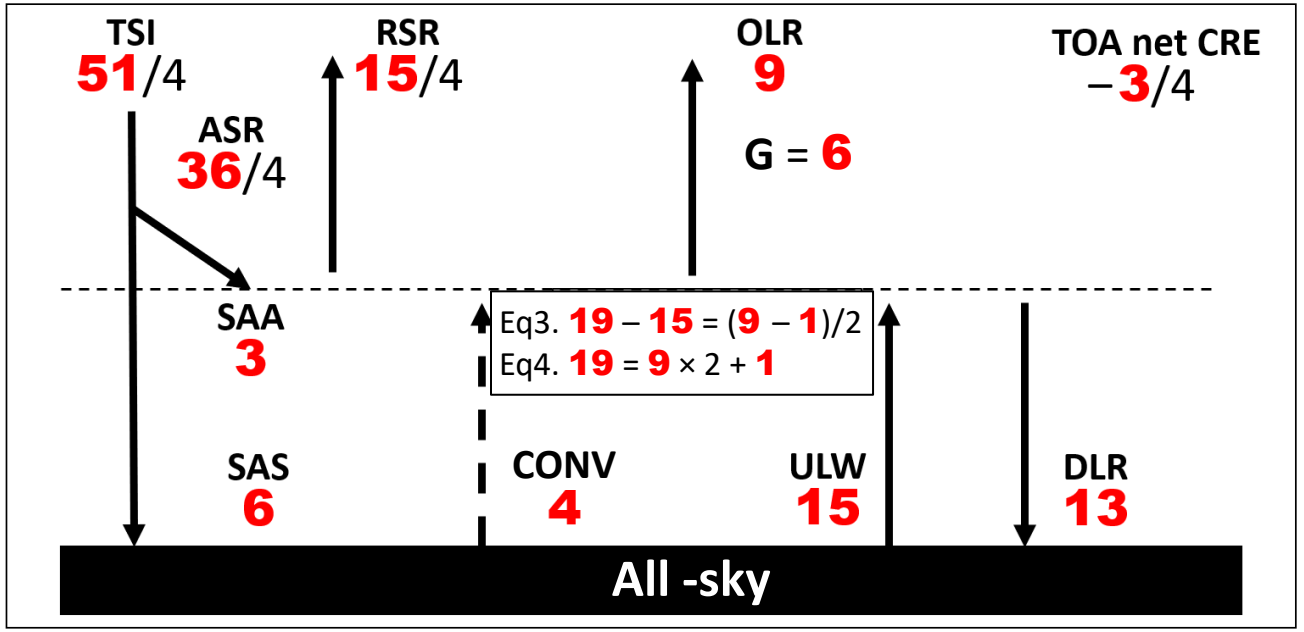
Since this study was published, officially, in the Bulletin of the American Meteorological Society, I expect that

- Every future climate change assessment, or
- Global energy budget estimate, or
- Climate sensitivity study, or
- Forcing and feedback computation

Shoud satisfy these two constraint equations with this exemplary accuracy, and

Should take into account the integer system.”


TSI
51/4
RSR
8/4
OLR
10
TOA clear IMB
3/4
ASR
43/4
G = 5
SAA
11/4
Eq1. 20 – 15 = 10/2
Eq2. 20 = 10 × 2
SAS
8
CONV
5
ULW
15
DLR
12
Clear -sky


TSI
51/4
RSR
15/4
OLR
9
TOA net CRE
–3/4
ASR
36/4
G = 6
SAA
3
Eq3. 19 – 15 = (9 – 1)/2
Eq4. 19 = 9 × 2 + 1
SAS
6
CONV
4
ULW
15
DLR
13
All -sky

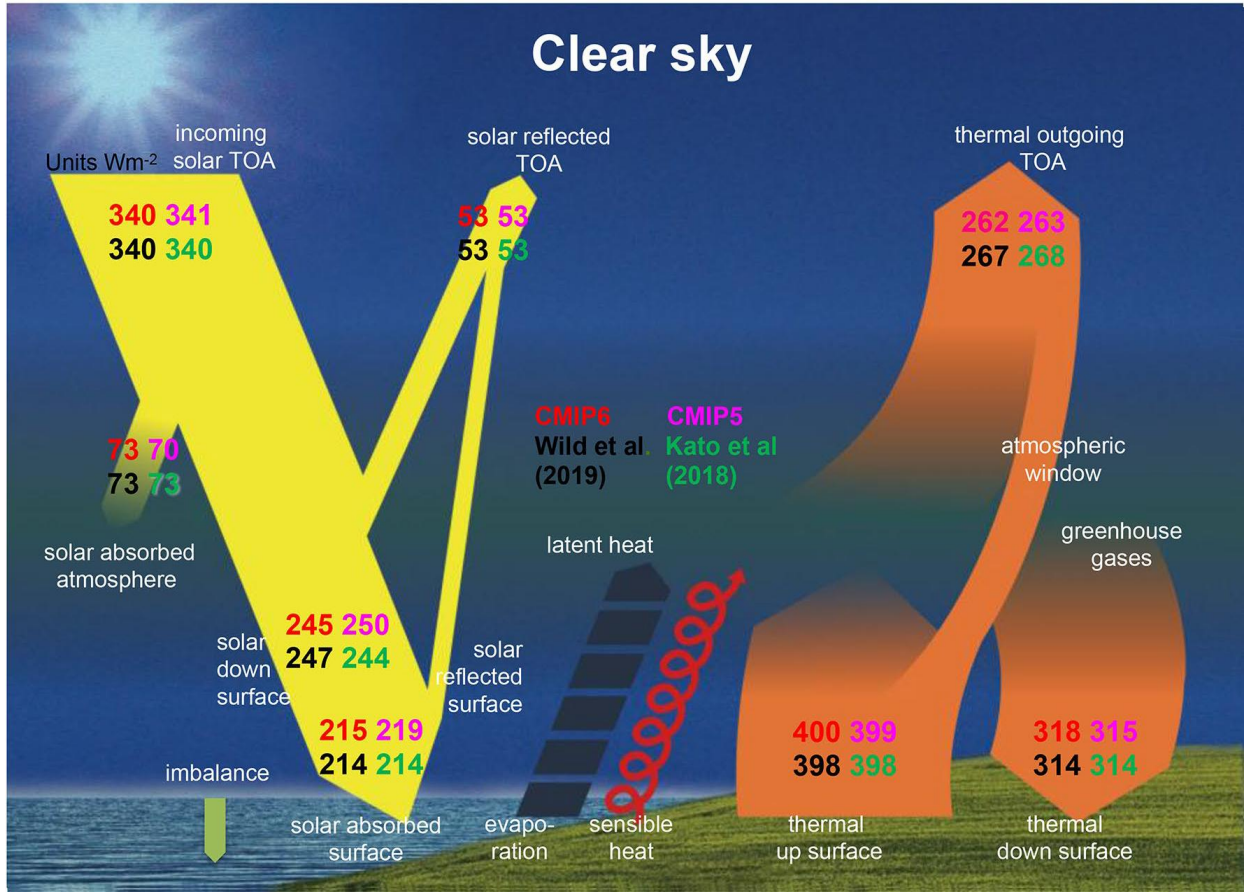
Transcript of slide #165

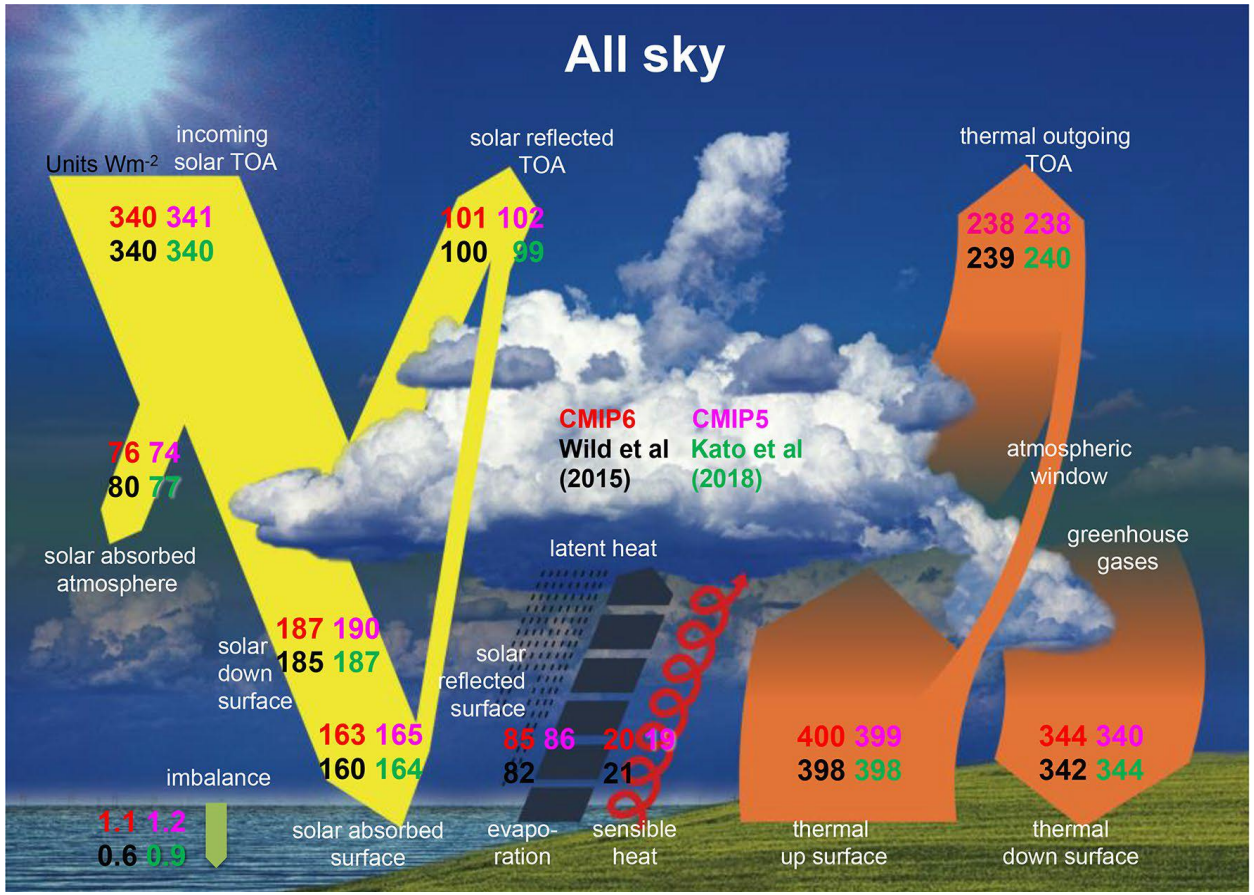
“So here we are.

- Radiative transfer principles define the governing equations;
- The governing equations define the radiative processes;
- The radiative processes define the net radiation at the surface;
- The net radiation at the surface defines the convective process;
- And the convective process defines the atmospheric properties to generate and maintain the required greenhouse effect.

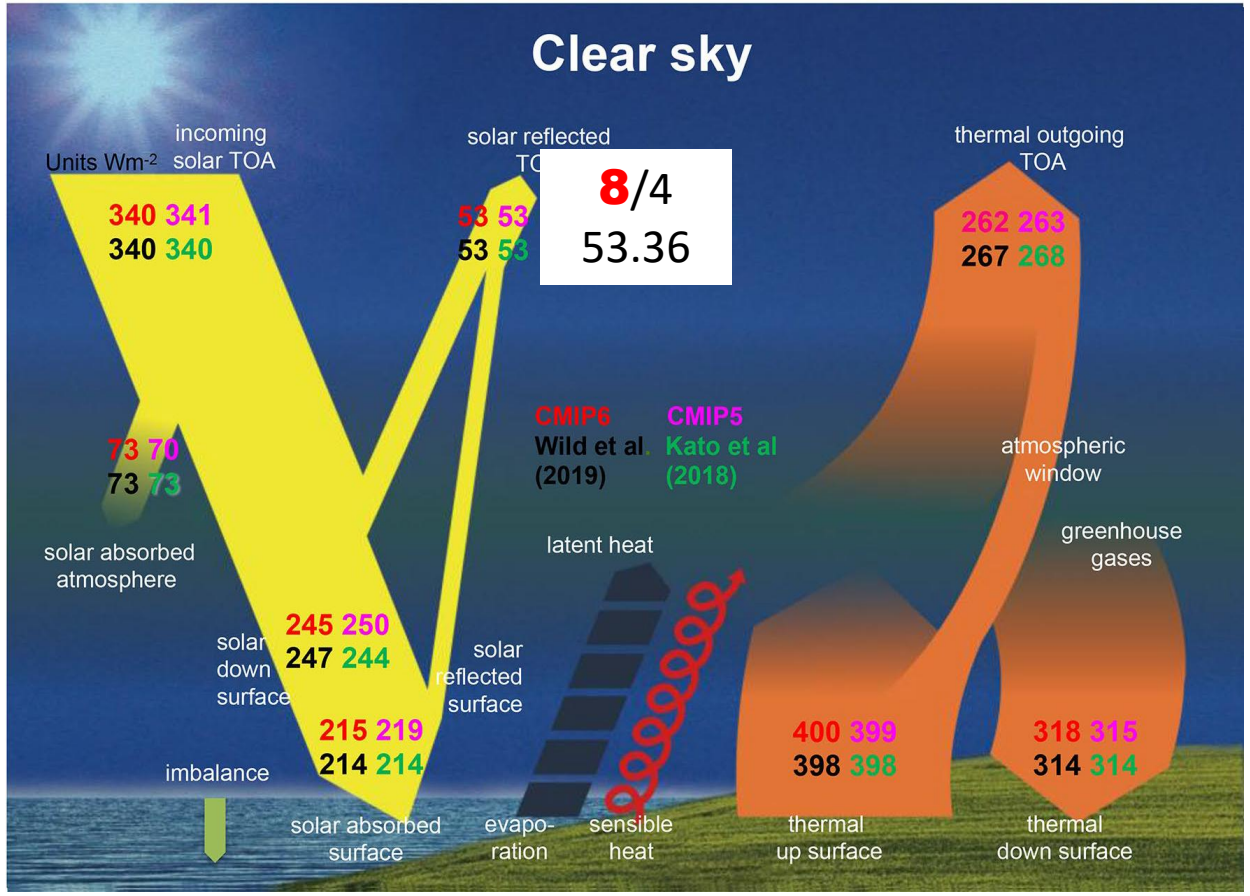
Not the other way around.”

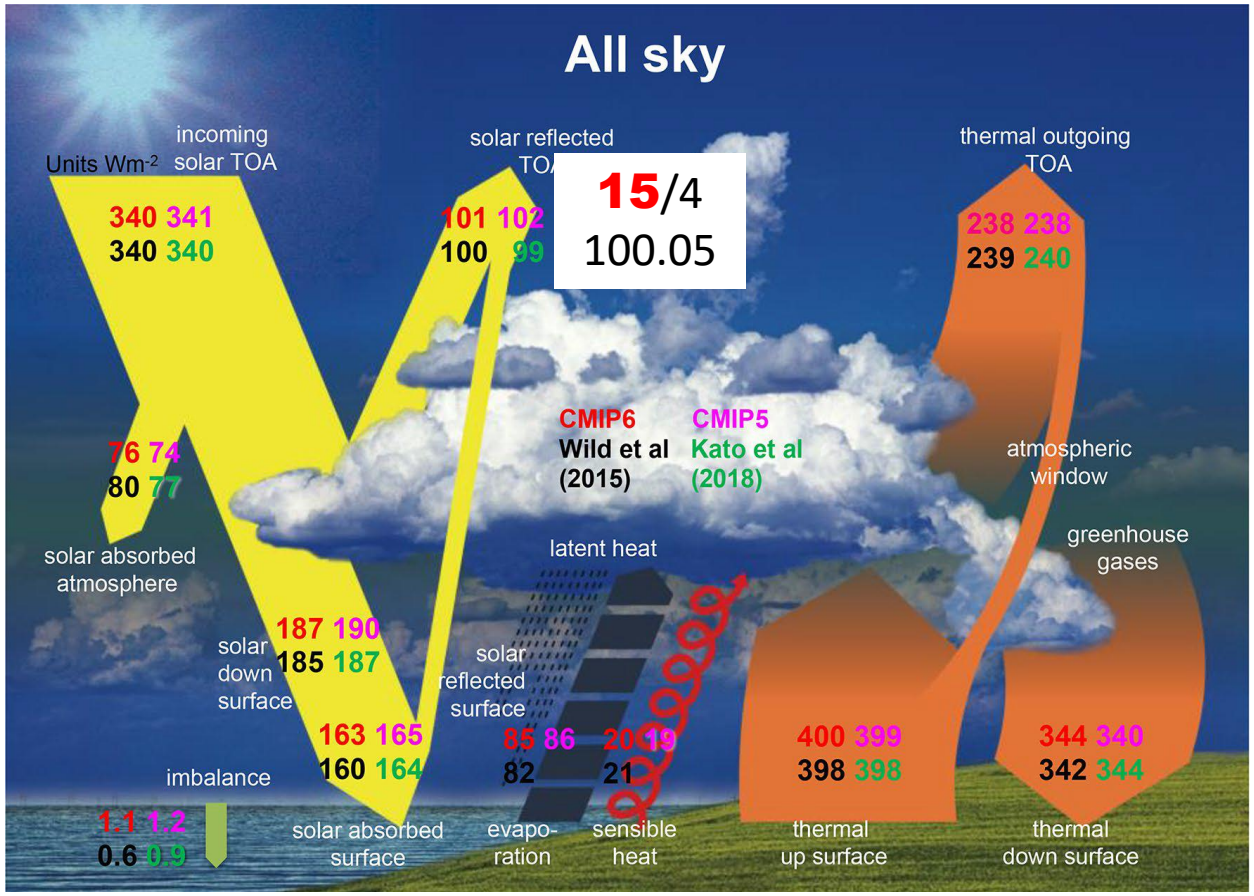
The Most Challenging Feature:



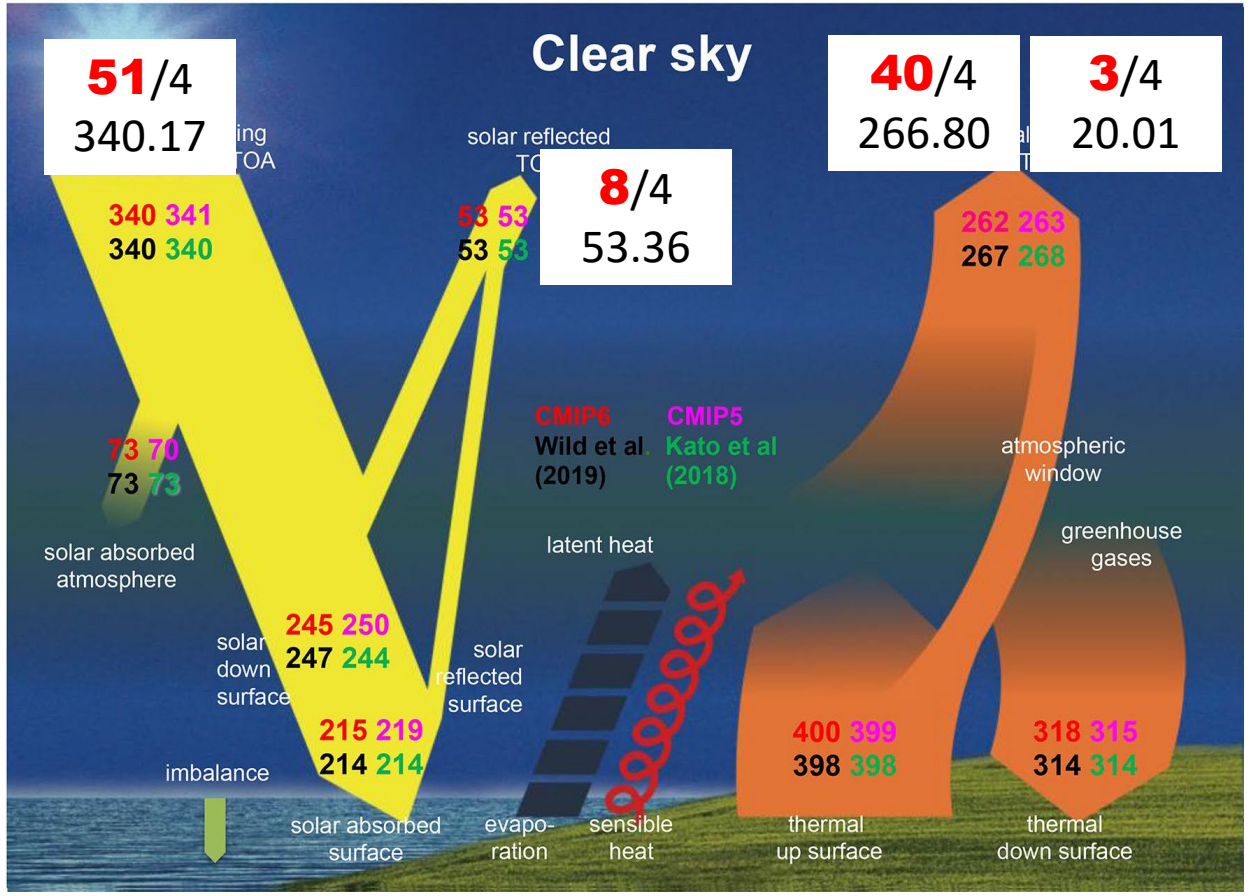


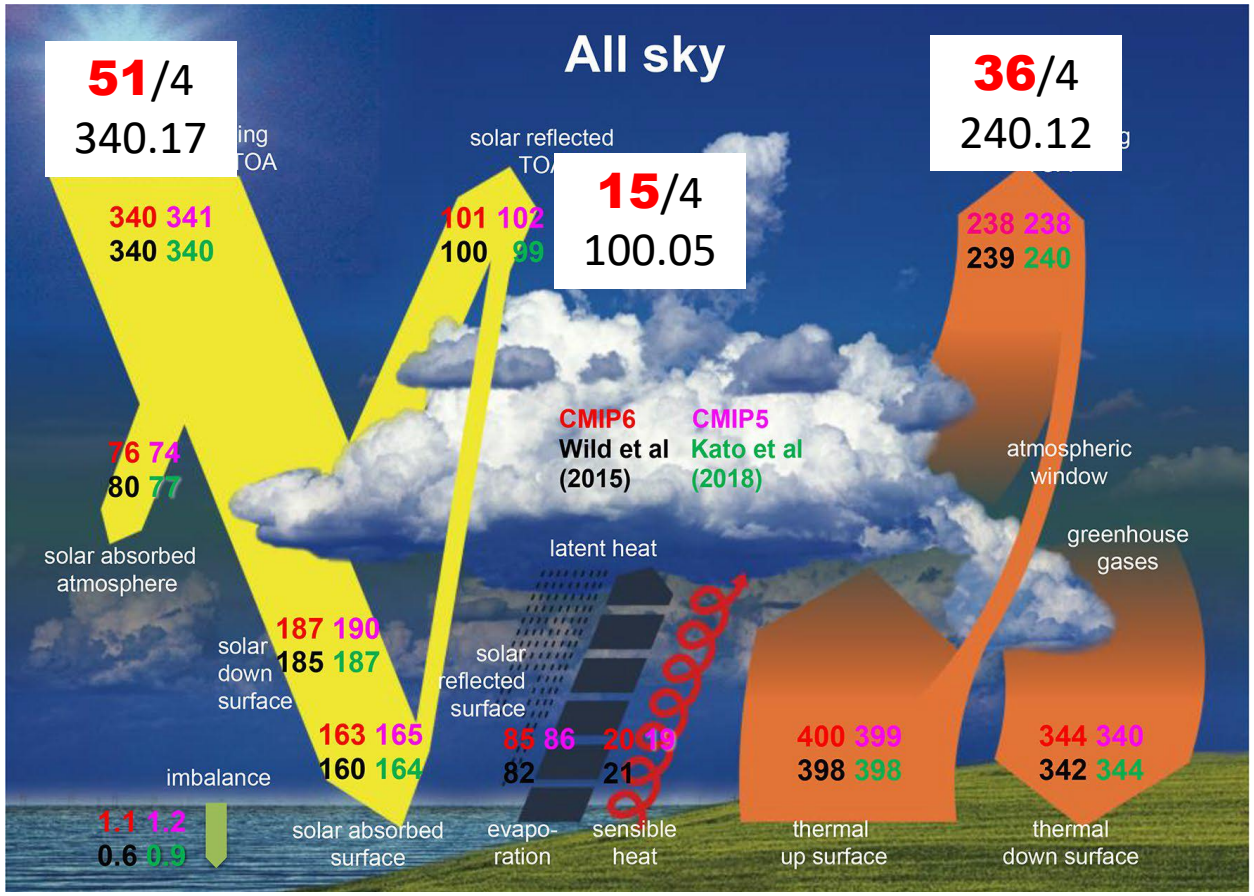
Integer Positions for Solar Reflection at TOA





Allowing to include TSI in the Integer System





Allowing to include TSI in the Integer System

