Data versus Theory: Absolute Calibration

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CERES Science Team Meeting, April 28, 2022

There is no "groundtruth" for the radiation budget
(Barkstrom et al., 1989)

Data:

CERES EBAF Ed4.1, 21 years
(July 2000 – June 2021)

Theory:

Four equations created from
Schwarzschild (1906, Eq. 11)

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)

Nachrichten Königlichen Gesellschaft Wiss. Göttingen, Math-Phys. Klasse **195,** pp. 41–53.
In "Selected Papers on the Transfer of Radiation" (D. H. Menzel, ed.). Dover, New York.

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

- May be derived from first principles (Milne 1930, Thermodynamics of the Stars)
- Plane-parallel — but that's OK (Loeb-Kato-Wielicki, 2002)

E emission of the layer, ***A*** upward beam, ***B*** downward beam
A_0 emerging flux, τ optical depth

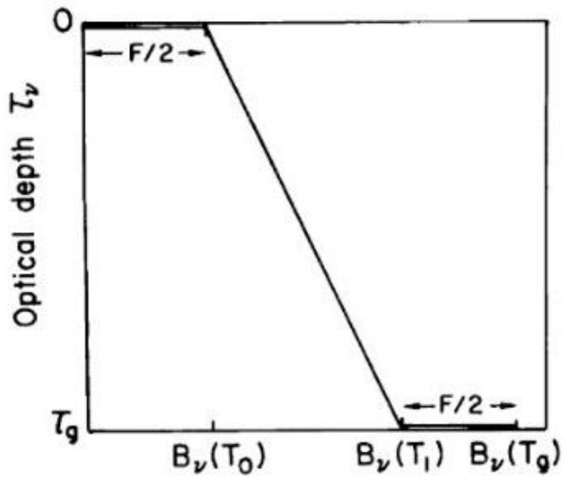
$$E = \frac{A_0}{2}(1 + \bar{\tau}), \qquad A = \frac{A_0}{2}(2 + \bar{\tau}), \qquad B = \frac{A_0}{2}\bar{\tau}. \qquad (11)$$

Eq. (1) $A - E = \Delta A = A_0/2$ Surface net, independent of τ

Houghton (1977, 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 $\tau = 0$.

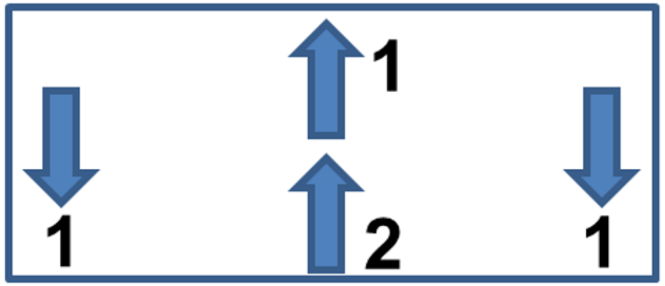
$$\Delta B_g = B_g - B_0 = B_{eff}/2$$

SFC SW+LW net = $H_S + H_L$ = OLR/2

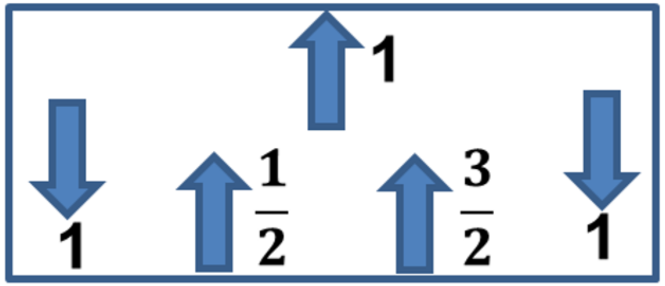
- Radiative Equilibrium: Discontinuity; Radiative-Convective Equilibrium: Convection + Evaporation
- Net radiation at surface sets convective activity to OLR/2
- Missing from Manabe and Wetherald (1967), The Charney Report (1979), IPCC (1990 – 2022) …

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

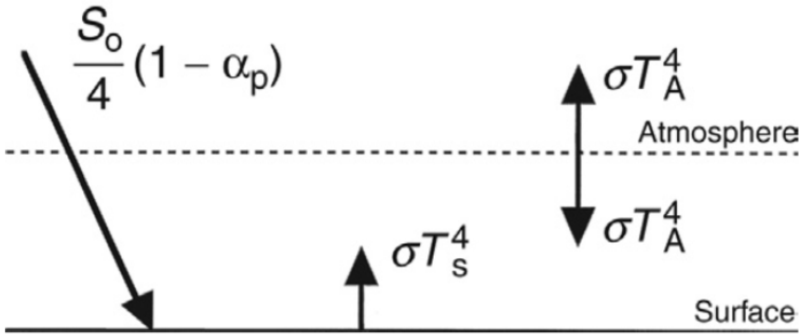
Eq. (2) $\tau = 2$ $\quad$ $\mathbf{A = 2A_0}$ $\quad$ $\mathbf{E = 3A_0/2;}$ $\quad$ $\mathbf{B = A_0}$



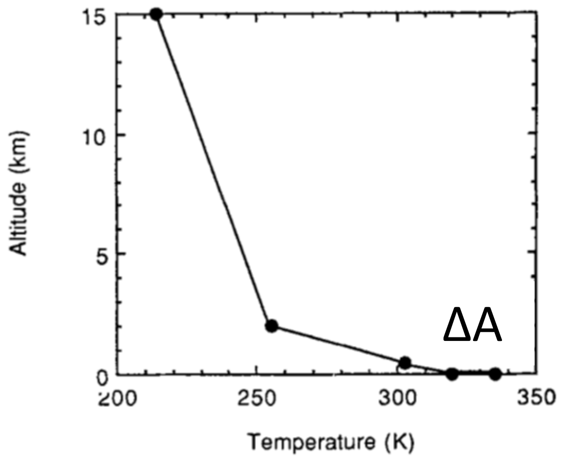
=>



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

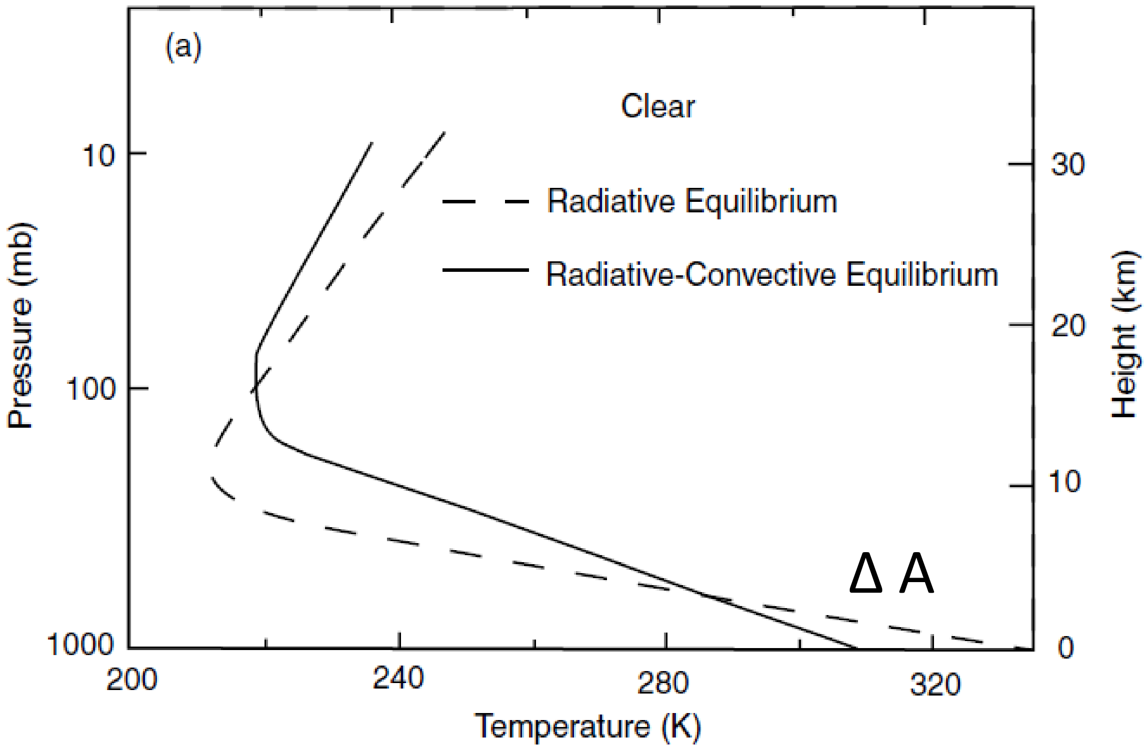


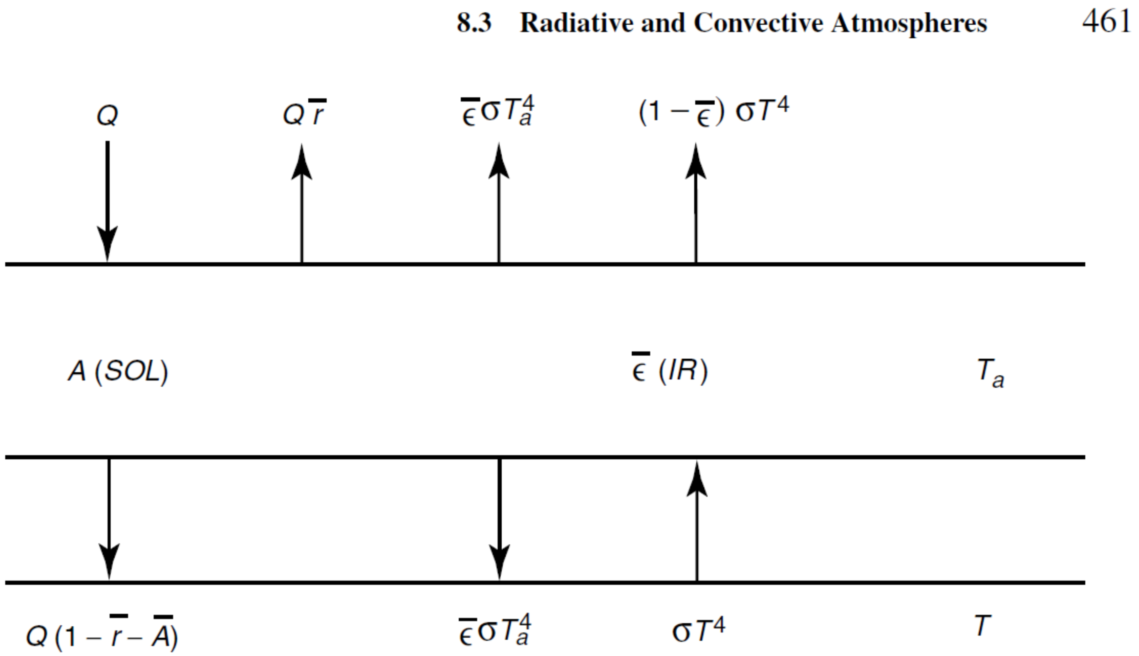
3.9 Clouds and Radiation



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

Fig. 2.3 Hartmann (1994) Fig. 3.11





$2\sigma T_a^4 = \sigma T^4$ if $\varepsilon = 1$

Fig. 8.9 Liou (2002) Fig. 8.8

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

Eq. (2) SFC Total = $A = 2A_0$ if $\varepsilon = 1$

Creating the all-sky versions

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

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

Separating atmospheric radiation transfer from the longwave cloud effect:

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

Eq. (4) **SFC Tot** $= \mathbf{A} = \mathbf{2A}_0 \mathbf{+ L}$ (all-sky, total at $\tau = 2$ incl LWCRE)

Validity of the equations

CERES EBAF Ed4.1 252 months (July 2000 – June 2021)

Eq. (1)	SFC SW down	– SW up	+ LW down	– LW up	(clear)	= TOA LW (clear)/2	
	240.86	– 29.08	+ 317.41	– 398.51		= 266.01 /2	–2.32
Eq. (2)	SFC SW down	– SW up	+ LW down		(clear)	= 2 × TOA LW (clear)	
	240.86	– 29.08	+ 317.41			= 2 × 266.01	–2.83
Eq. (3)	SFC SW down	– SW up	+ LW down	– LW up	(all)	= [TOA LW (all) – LWCRE]/2	
	186.83	– 23.17	+ 345.04	– 398.73		= (240.24 – 25.77) /2	+2.73
Eq. (4)	SFC SW down	– SW up	+ LW down		(all)	= 2 × TOA LW (all) + LWCRE	
	186.83	– 23.17	+ 345.04			= 2 × 240.24 + 25.77	+2.44

Mean bias of the four equations = 0.005

Mean bias of the four equations

CERES EBAF Ed4.1, July 2000 – June 2021

• **Clear-sky (net)**	**ΔEq1 = -2.32**	}	-2.57
• **Clear-sky (tot)**	**ΔEq2 = -2.83**		
• **All-sky (net)**	**ΔEq3 = 2.73**	}	+2.58
• **All-sky (tot)**	**ΔEq4 = 2.44**		

mean = 0.005 Wm^{-2}

• **Net (clear-sky)**	**ΔEq1 = -2.32**	}	+0.20
• **Net (all-sky)**	**ΔEq3 = 2.73**		
• **Tot (clear-sky)**	**ΔEq2 = -2.83**	}	-0.19
• **Tot (all-sky)**	**ΔEq4 = 2.44**		

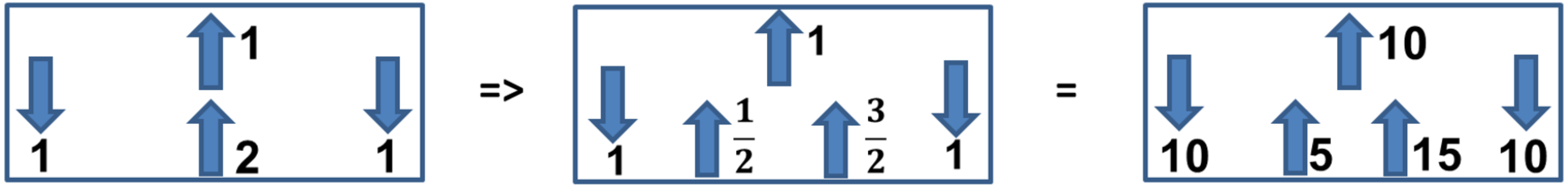
mean = 0.005 Wm^{-2}

252 months (21 running years)

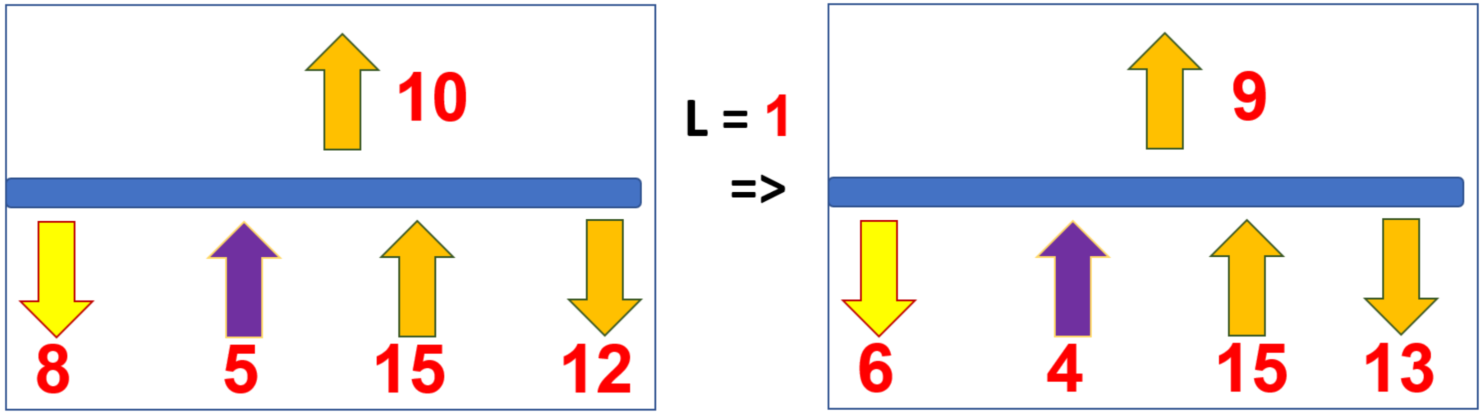
252 months		-14.461	-12.903	-7.183	-4.388	**Min**
21 running years		8.814	4.329	10.615	7.305	**Max**
From	Through	**ΔEq1**	**ΔEq2**	**ΔEq3**	**ΔEq4**	**Mean**
Mar2000	Feb2021	-2.3141	-2.8789	2.7554	2.4197	-0.0045
Apr2000	Mar2021	-2.3153	-2.8694	2.7487	2.4227	-0.0033
May2000	Apr2021	-2.3201	-2.8625	2.7369	2.4208	-0.0062
June2000	May2021	-2.3225	-2.8528	2.7318	2.4275	-0.0040
July2000	**June2021**	**-2.3208**	**-2.8338**	**2.7308**	**2.4425**	**0.0047**
Aug2000	July2021	-2.3234	-2.8241	2.7246	2.4482	0.0063
Sept2000	Aug2021	-2.3285	-2.8172	2.7203	2.4542	0.0072
Oct2000	Sept2021	-2.3245	-2.8014	2.7203	2.4656	0.0150
Nov2000	Oct2021	-2.3199	-2.7854	2.7157	2.4727	0.0208
Dec2000	Nov2021	-2.3187	-2.7689	2.7090	2.4812	0.0256
	Average	**-2.3208**	**-2.8294**	**2.7294**	**2.4455**	**0.0062**

Theoretical equilibrium “groundtruth”

No reference to atmospheric composition



$A = 2A_0$ (Clear-sky) $\Delta A = A_0/2$, $E = 3A_0/2$



$8 + 12 - 15 = 10\ /\ 2$

$8 + 12 = 10 \times 2$

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

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

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

Internal calibration best fit

TOA LW	clear-sky =	**10**		TOA LW	all-sky =	**9**
SFC LW up	clear-sky =	**15**		SFC LW up	all-sky =	**15**
SFC LW down	clear-sky =	**12**		SFC LW down	all-sky =	**13**
SFC LW net	clear-sky =	**–3**		SFC LW net	all-sky =	**–2**
SFC SW net	clear-sky =	**8**		SFC SW net	all-sky =	**6**
SFC SW+LW net	clear-sky =	**5**		SFC SW+LW net	all-sky =	**4**
SFC SW+LW total	clear-sky =	**20**		SFC SW+LW total	all-sky =	**19**
G greenhouse effect	clear-sky =	**5**		G greenhouse effect	all-sky =	**6**
SWCRE (surface)	=	**–2**		LWCRE (surface, TOA)	=	**1**

CERES EBAF Ed4.1, 252 months, July 2000 — June 2021 data, best fit:

LWCRE = 1 all-sky unit = 1 = 26.68 ± 0.01 Wm^{-2}.

Data: July 2000 – June 2021

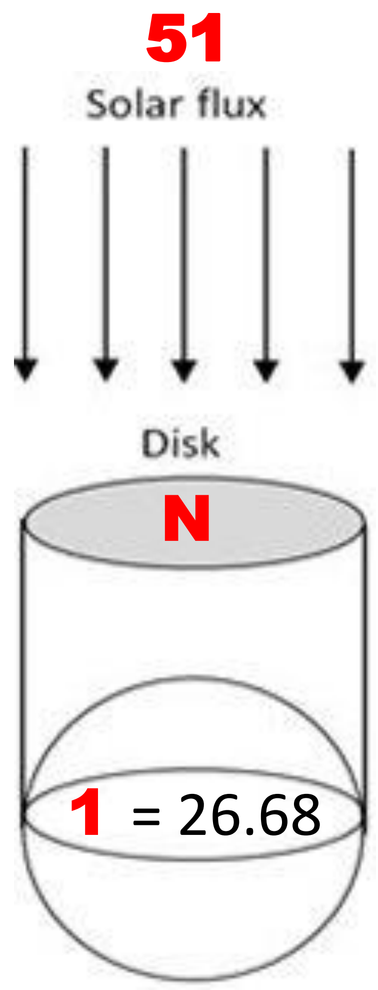
Theory: **1** = 26.68 ± 0.01 Wm^{-2}

Clear-sky	N	N × Unit	Data	Data – Theory
TOA LW up	10	266.80	266.01	-0.79
SFC SW net	8	213.44	211.78	-1.66
SFC LW down	12	320.16	317.41	-2.75
SFC LW up	15	400.20	398.51	-1.69
All-sky				
TOA LW up	9	240.12	240.24	0.12
SFC SW net	6	160.08	163.66	3.58
SFC LW down	13	346.84	345.04	-1.80
SFC LW up	15	400.20	398.73	-1.47
			Mean difference	**-0.81**

Empirical extension: TOA SW up $\in \mathbb{N}$

CERES EBAF Ed4.1, July 2000 – June 2021

TOA Flux (clear-sky with Δ^C)	N	Theory (F_0)	Data (F)	Data – Theory (ΔF)
TOA SW up clear-sky	**8** / 4	53.36	53.72	0.36
TOA SW up all-sky	**15** / 4	100.05	98.98	-1.07
TOA LW up clear-sky	**40** / 4	266.80	266.01	-0.79
TOA LW up all-sky	**36** / 4	240.12	240.24	0.12
TOA SW CRE	**-7** / 4	-46.69	-45.25	1.44
TOA LW CRE	**4** / 4	26.68	25.77	-0.91
TOA Net CRE	**-3** / 4	-20.01	-19.48	0.53
TOA Albedo, clear	**8** / **51**	0.157	0.158	0.001
TOA Albedo, all	**15** / **51**	0.294	0.291	-0.003



Clear-sky: SW up = **8** SW in = **43** LW up = **40** TOA Net IMB = **3**

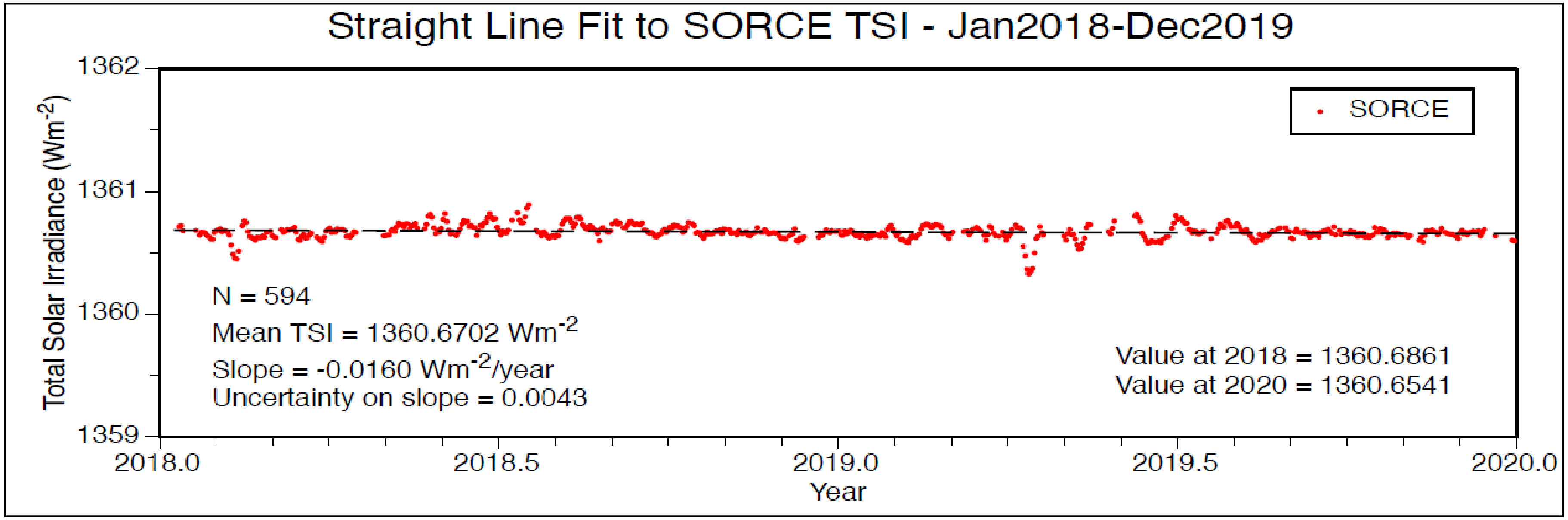
All-sky: SW up = **15** SW in = **36** LW up = **36** TOA Net CRE = **–3**

With TSI = 51, each flux is an integer on the intercepting cross-section disk.

External calibration: SORCE TSI

S. Gupta, D. Kratz, P. Stackhouse, A Wilber:
On Continuation of the Use of Daily TSI for CERES Processing

CERES 33rd Science Team Meeting, April 28, 2020



Mean TSI = 1360.670 Wm^{-2}, value at 2018 = 1360.686 Wm^{-2}

5856	1360.717
5857	1360.699
5858	1360.73
5859	1360.696
5860	1360.698
5861	1360.679
5862	1360.703
5863	1360.693
5864	1360.693
5865	1360.706
5866	1360.726
5867	1360.662
5868	1360.666
5869	1360.658
5870	1360.658
5871	1360.659
5872	1360.61
5873	1360.668
5874	1360.647
5875	1360.643
5876	1360.596
5877	1360.591
5878	1360.655
5879	1360.631
5880	1360.629
5881	1360.635
5882	1360.613
5883	1360.883

SORCE TSI 17-yr mean

```
; data_set_name: SORCE Level 3 Total Solar Irradiance
; date_range: 20030225 to 20200225
; cadence: 24 hours
; version:             19
; number_of_data:           6210
```

- 2003 Feb 25 — 2020 Feb 25
- Number of non-zero data: 5882
- Mean Total Solar Irradiance (TSI) at 1-AU =

1360.883 ± 0.5 Wm^{-2} = **51** => **1** = 26.684 ± 0.01 Wm^{-2} ("SUN unit")

1 × (4/4.0034) = 1 = 26.661 Wm^{-2} ("GEO unit")

This data file was obtained from:
http://lasp.colorado.edu/home/sorce/data/ Kopp, G. (2019), SORCE Level 3 Total Solar Irradiance Daily Means, version 019, Greenbelt, MD, USA: NASA Goddard Earth Science Data and Information Services Center (GES DISC), Accessed 2022/04/12 at doi:10.5067/D959YZ53XQ4C

Same from CERES ISR

CERES EBAF Ed4.1 DQS, 12/9/2021:

20-year mean ISR **=** **339.88 Wm^{-2}**

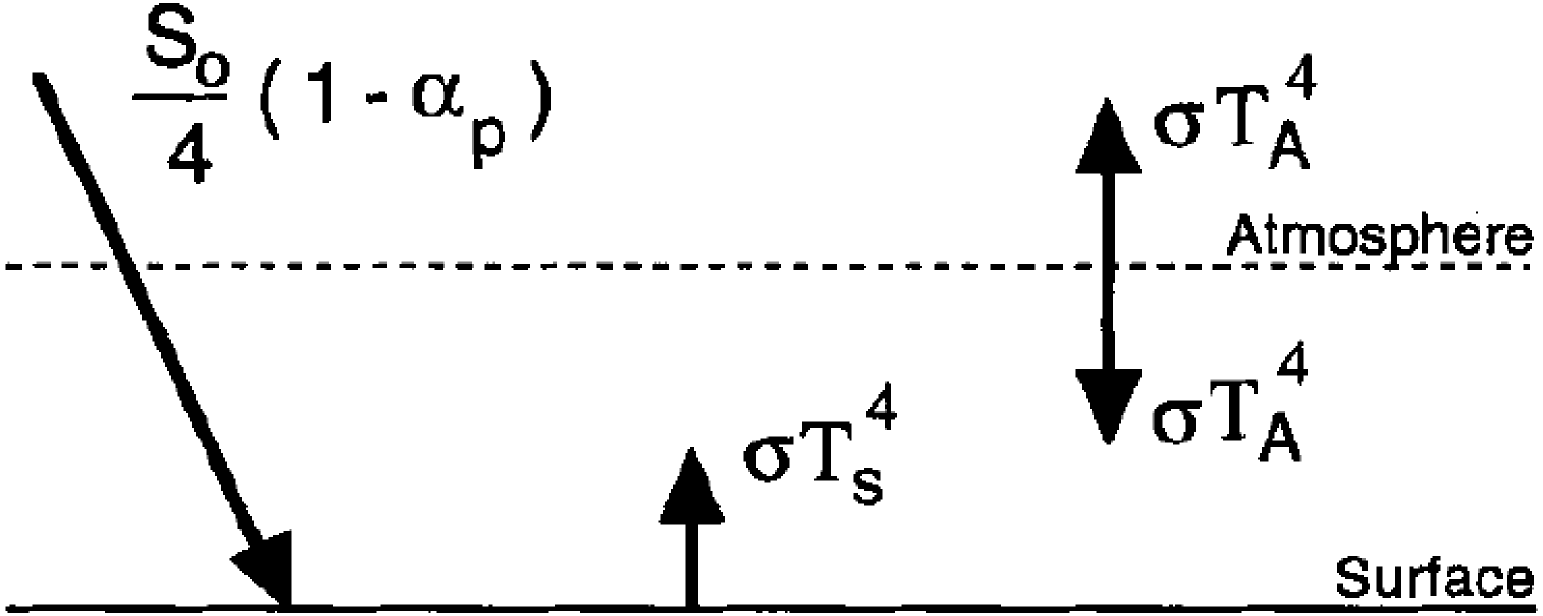
TSI = 339.88 × 4.0034 = **1360.68 = 51**

=> 26.68 = 1 "SUN unit"

Unit with geodetic weighting:

26.68 × (4/4.0034) = **1** = **26.66** Wm^{-2} "GEO unit"

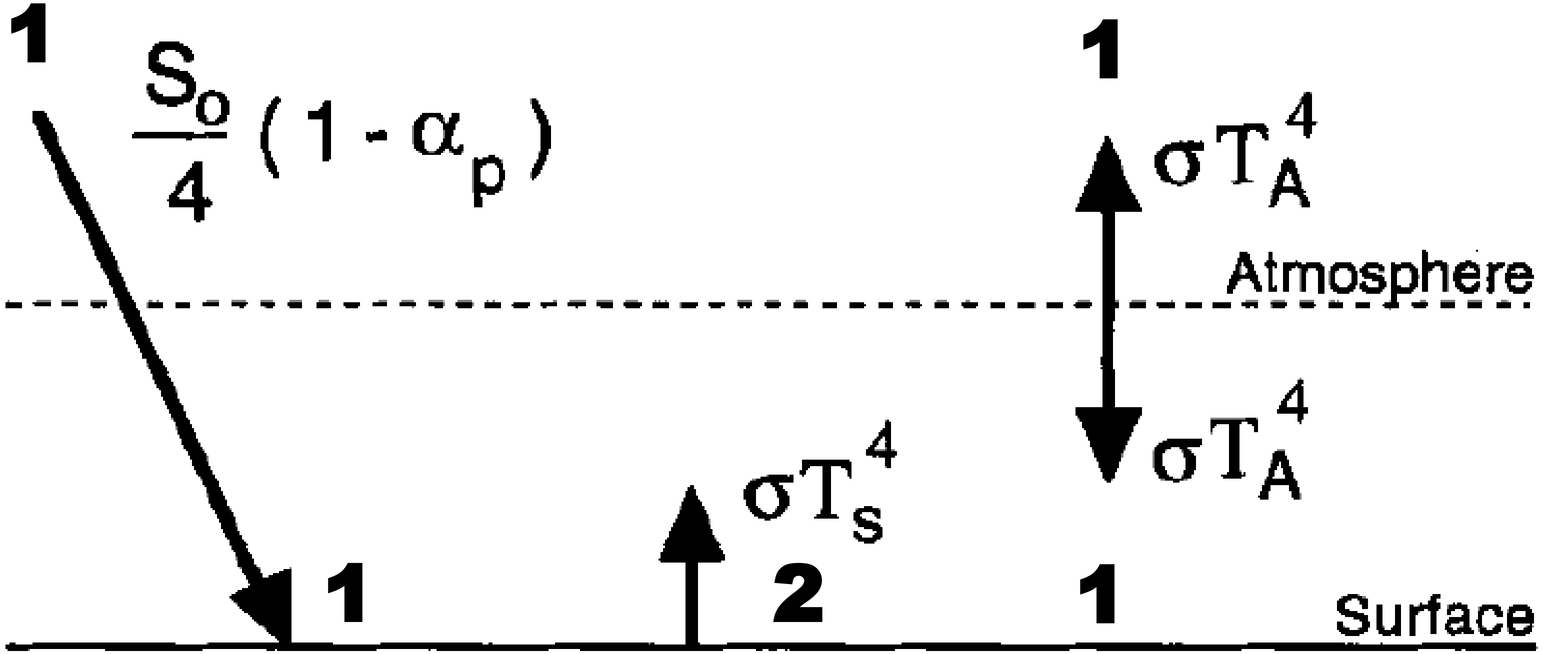
Theory: The simplest greenhouse model



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

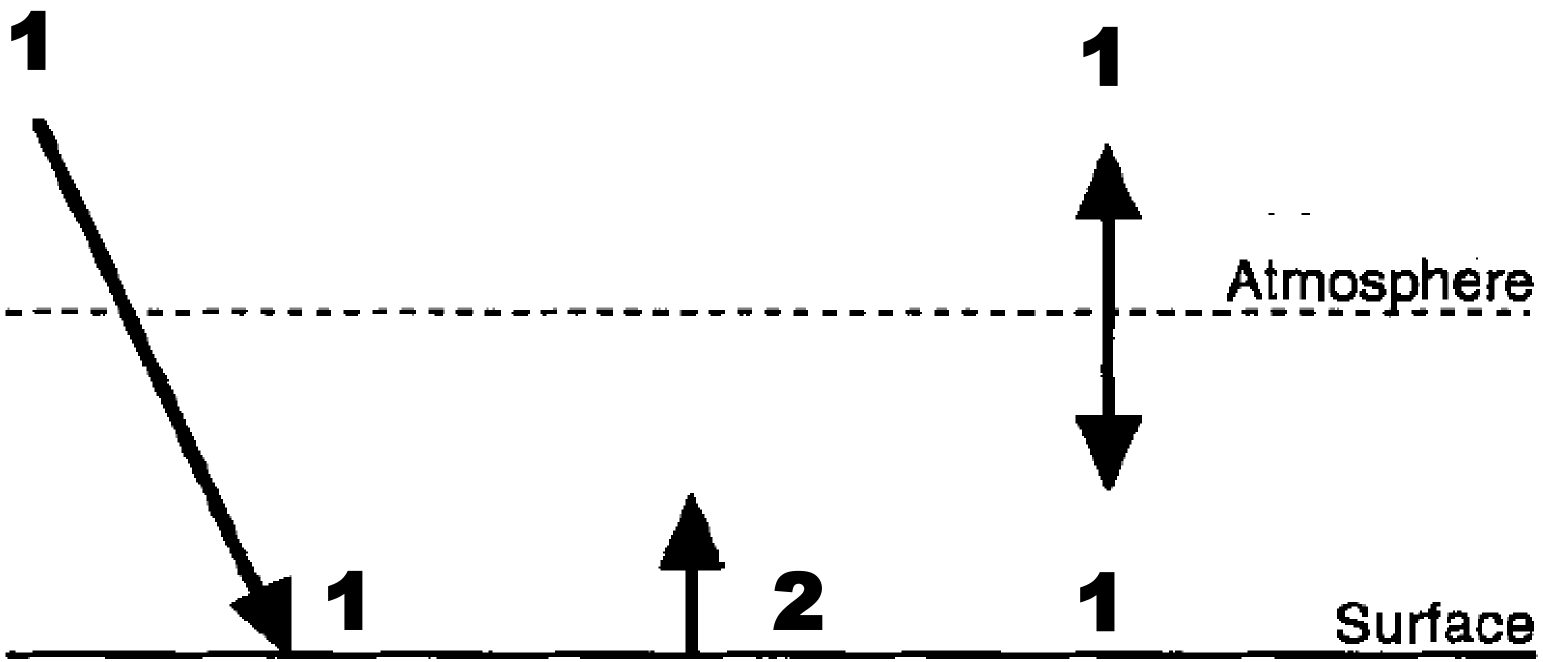
Hartmann (1994, Fig. 2.3)

The simplest greenhouse model

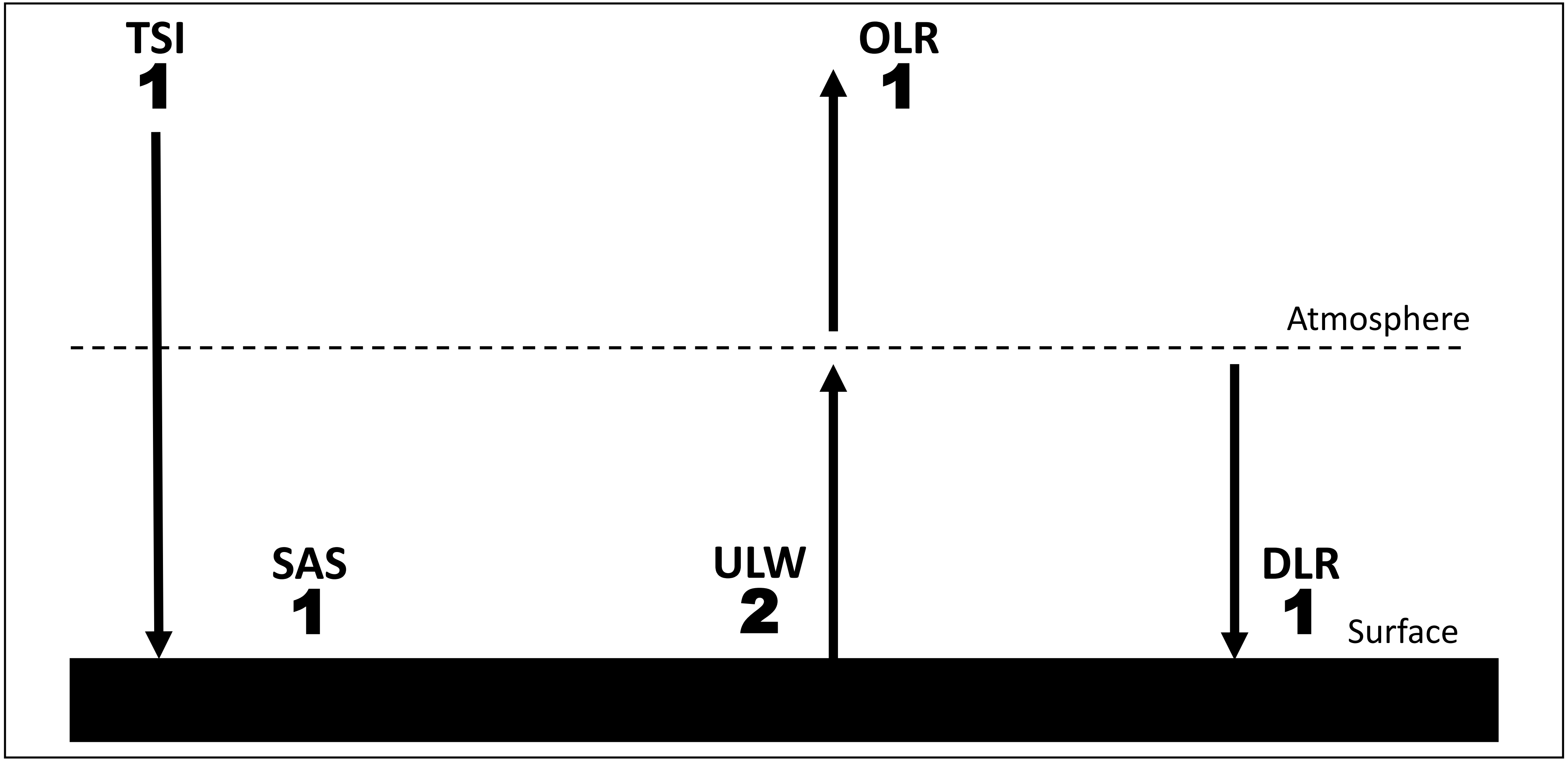


$$\sigma T_s^4 = 2\sigma T_A^4$$

The simplest greenhouse model



Clear-sky on the disk

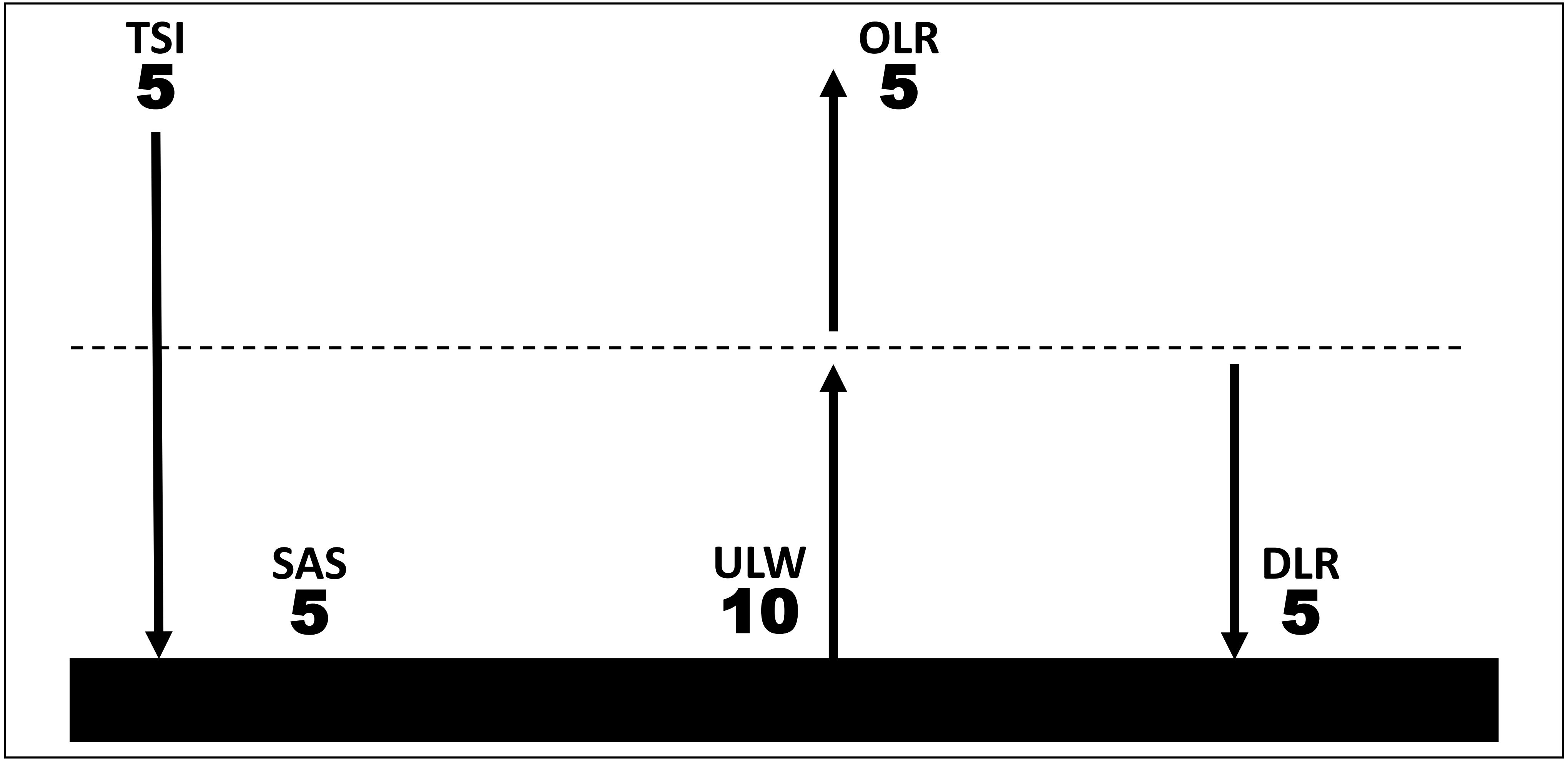


Solar Absorbed Surface

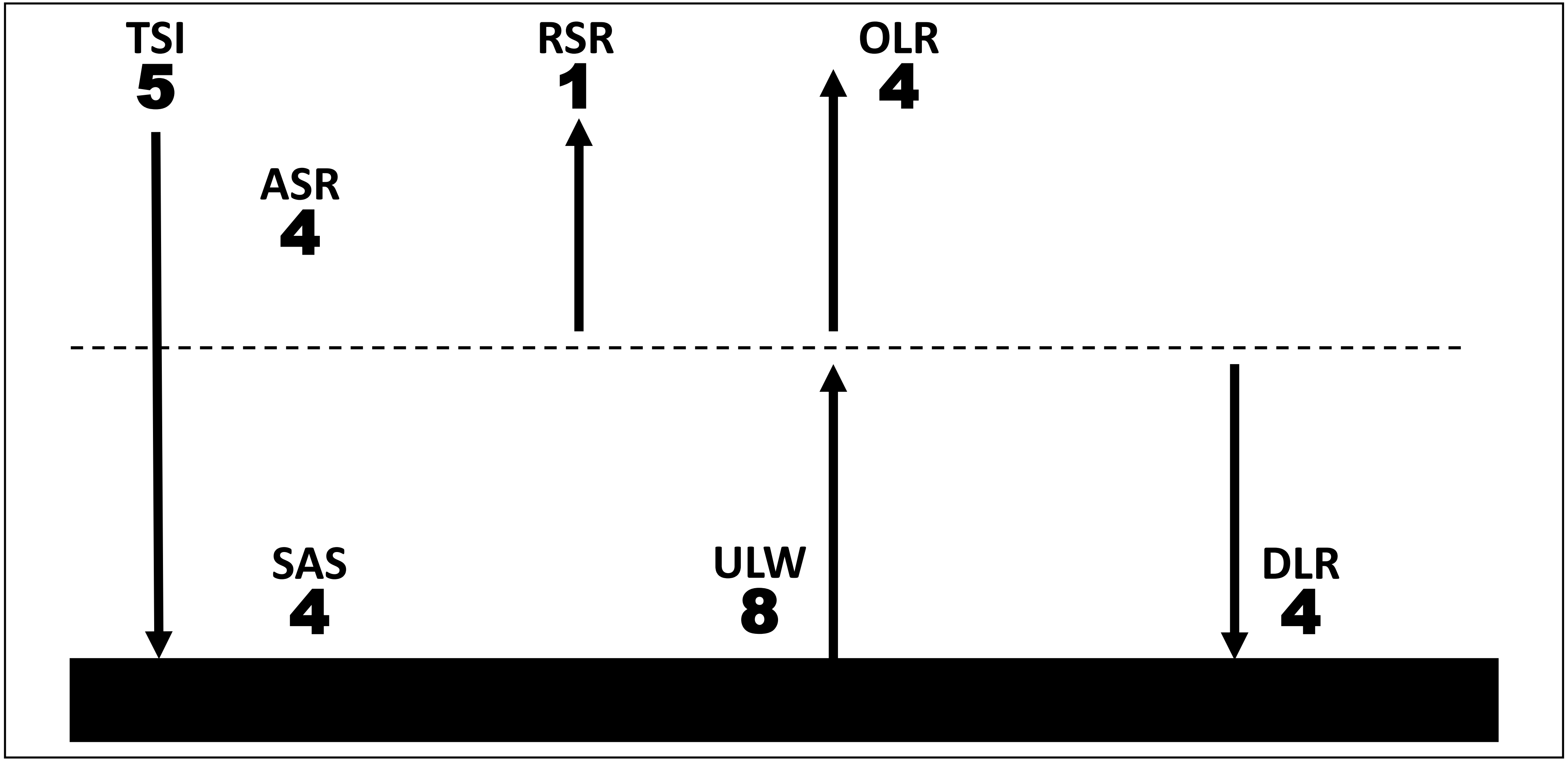
Upward LongWave

Downward Longwave Radiation

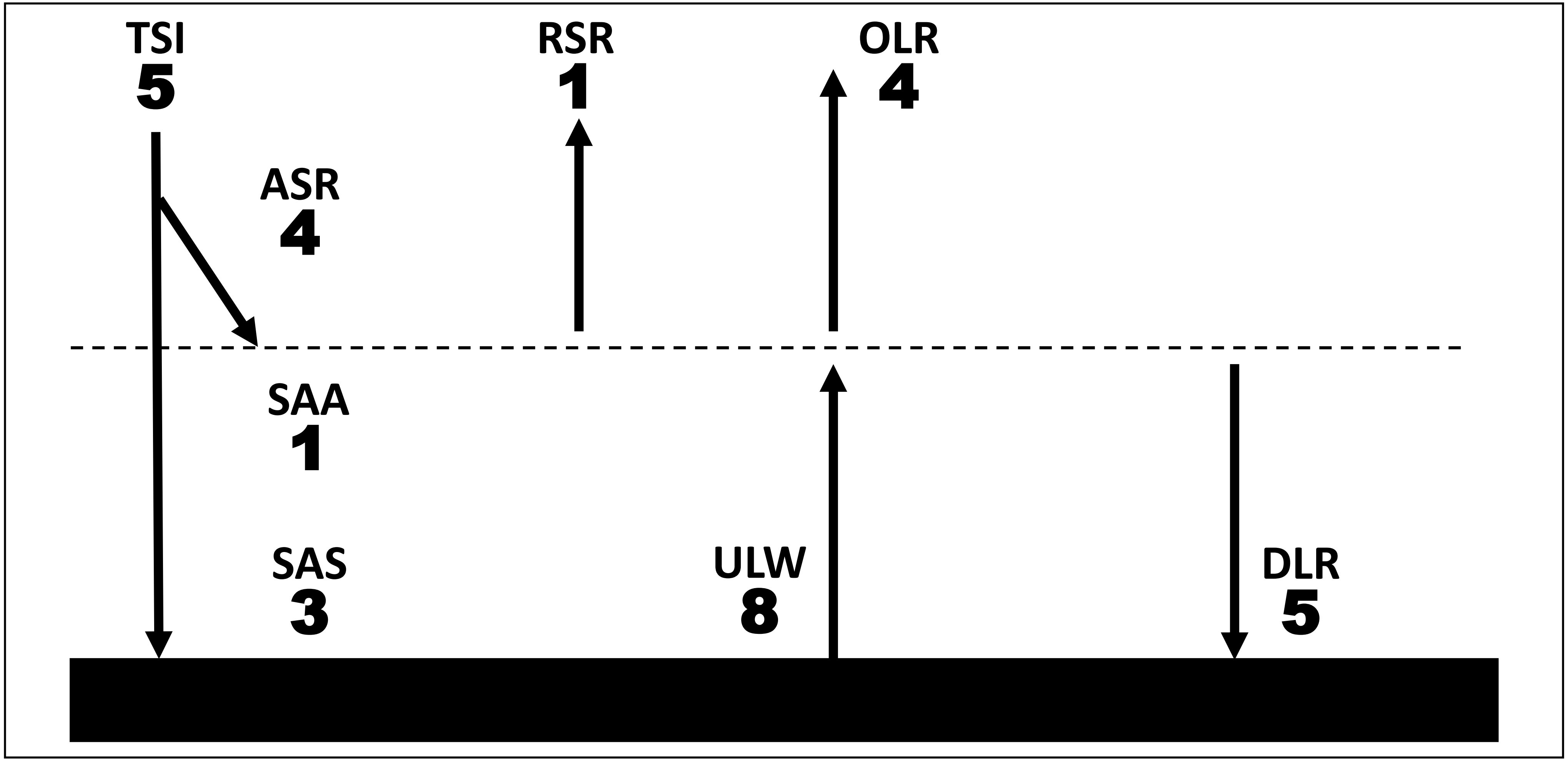
Multiply by 5



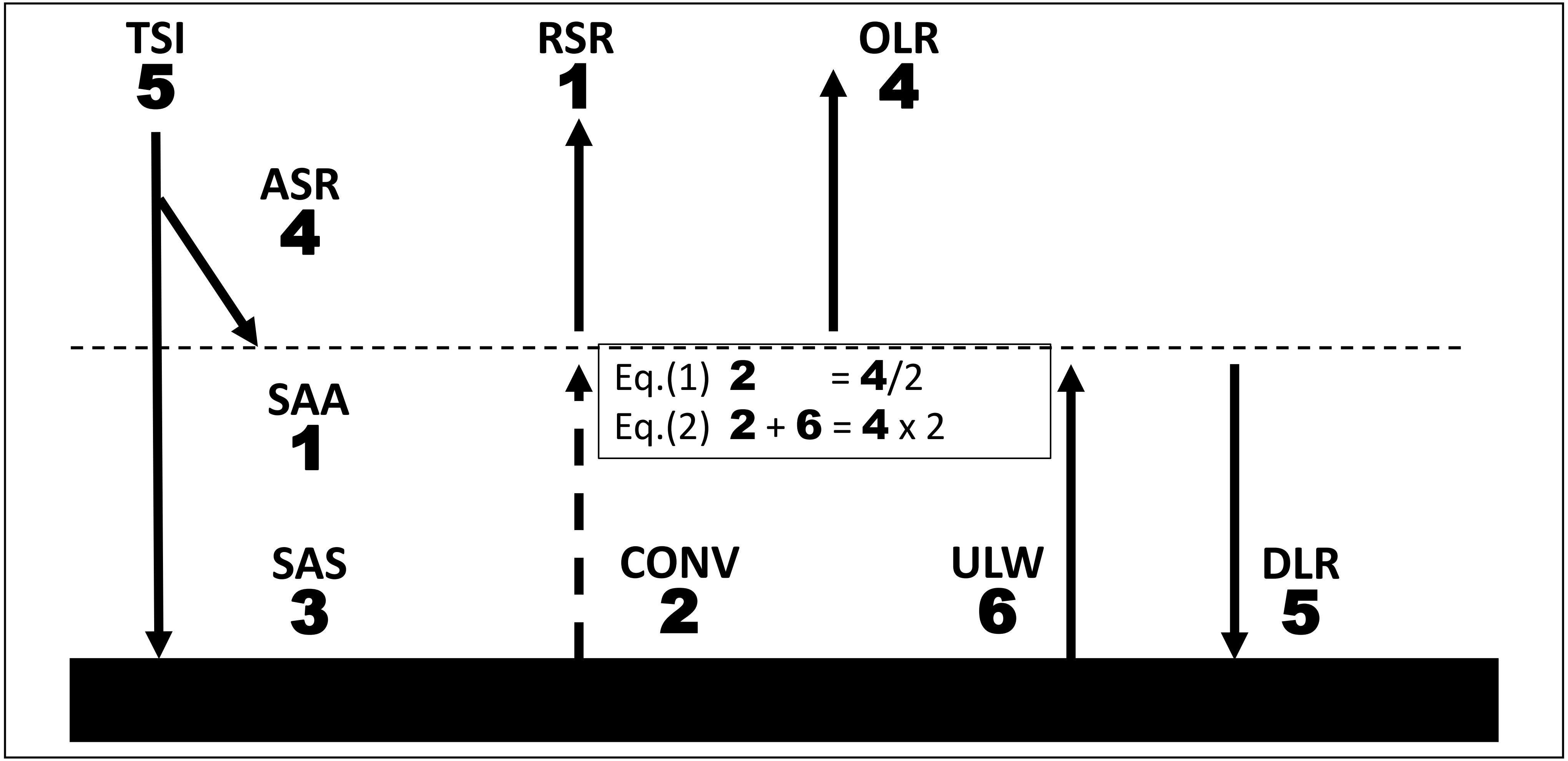
Introduce 1 unit RSR



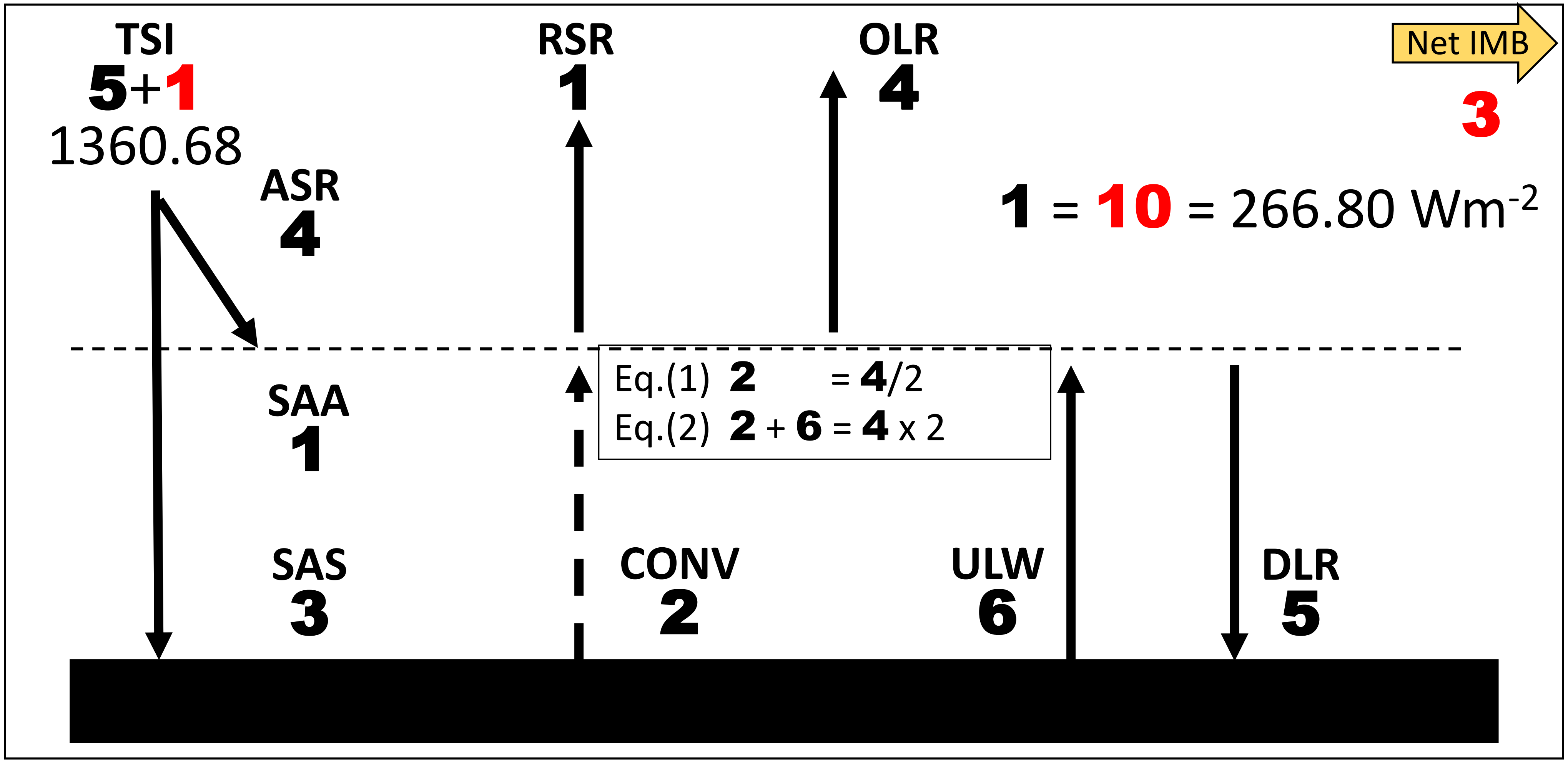
Allow 1 unit Solar Absorption Atmosphere



Add 2 units Convection to satisfy Eqs. (1) and (2)

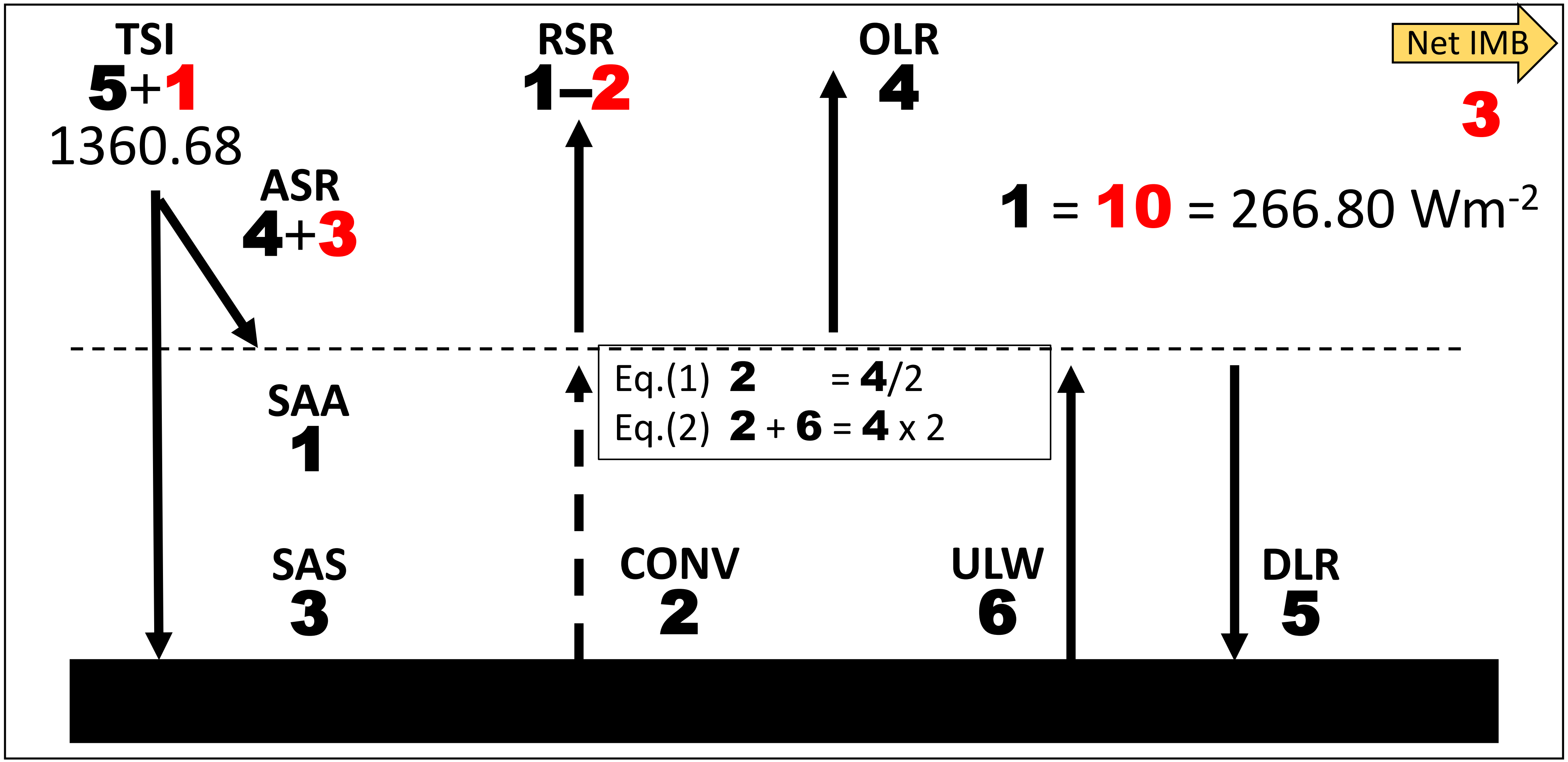


Calibrate to TSI

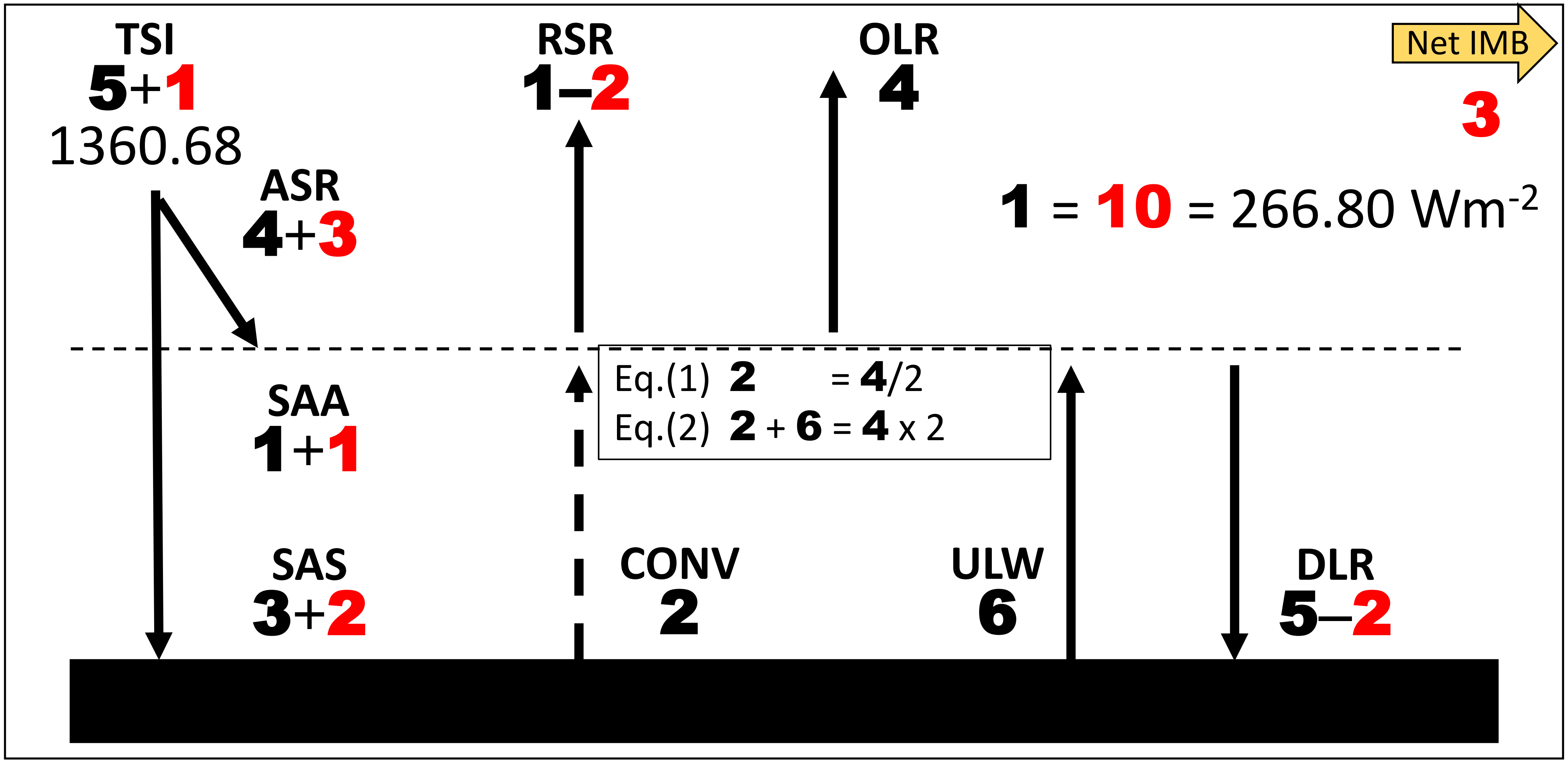


We have 2 "SUN units" hiatus

Reflect 2 less, absorb 3 more

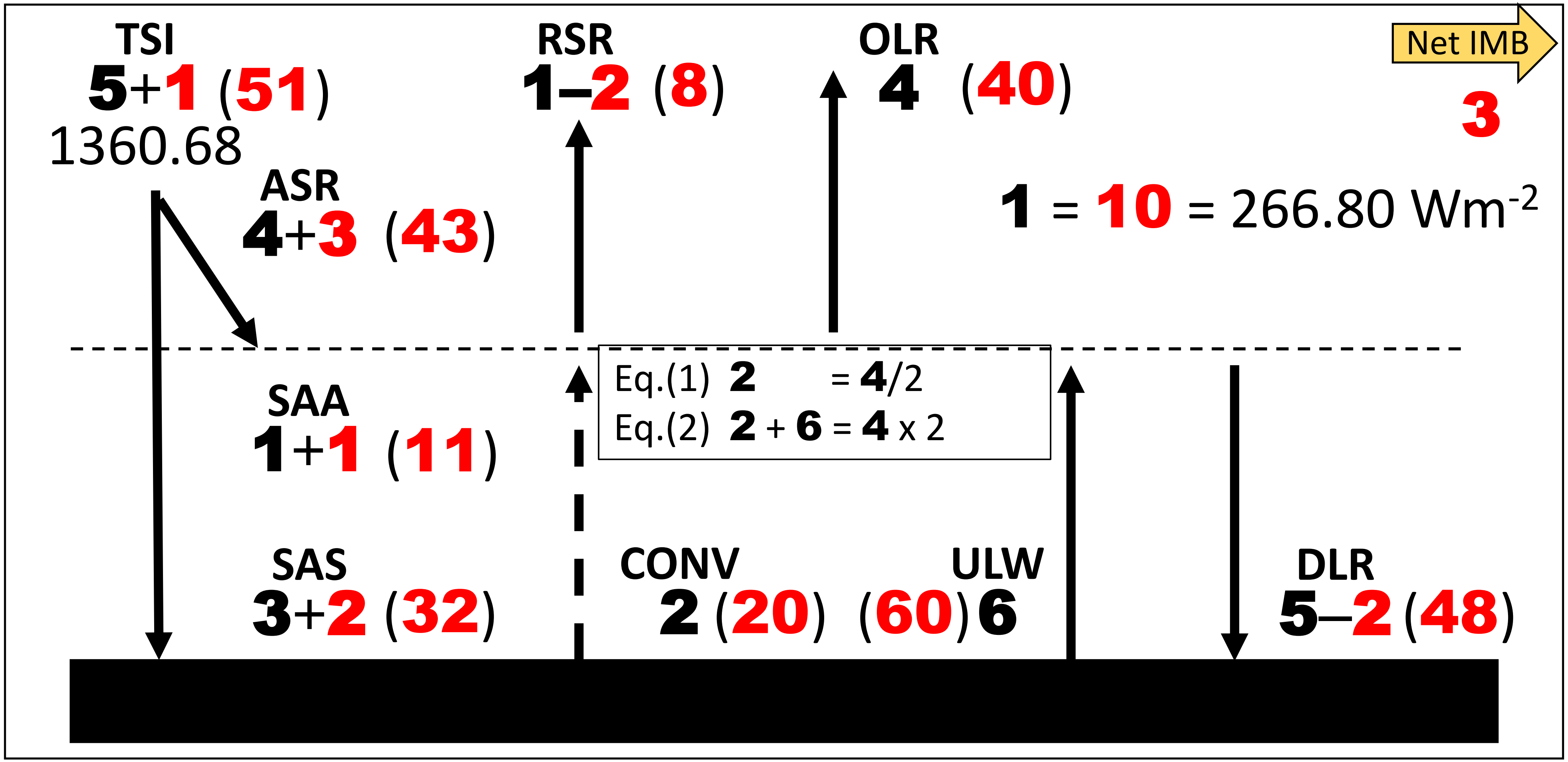


Re-distribute the absorption



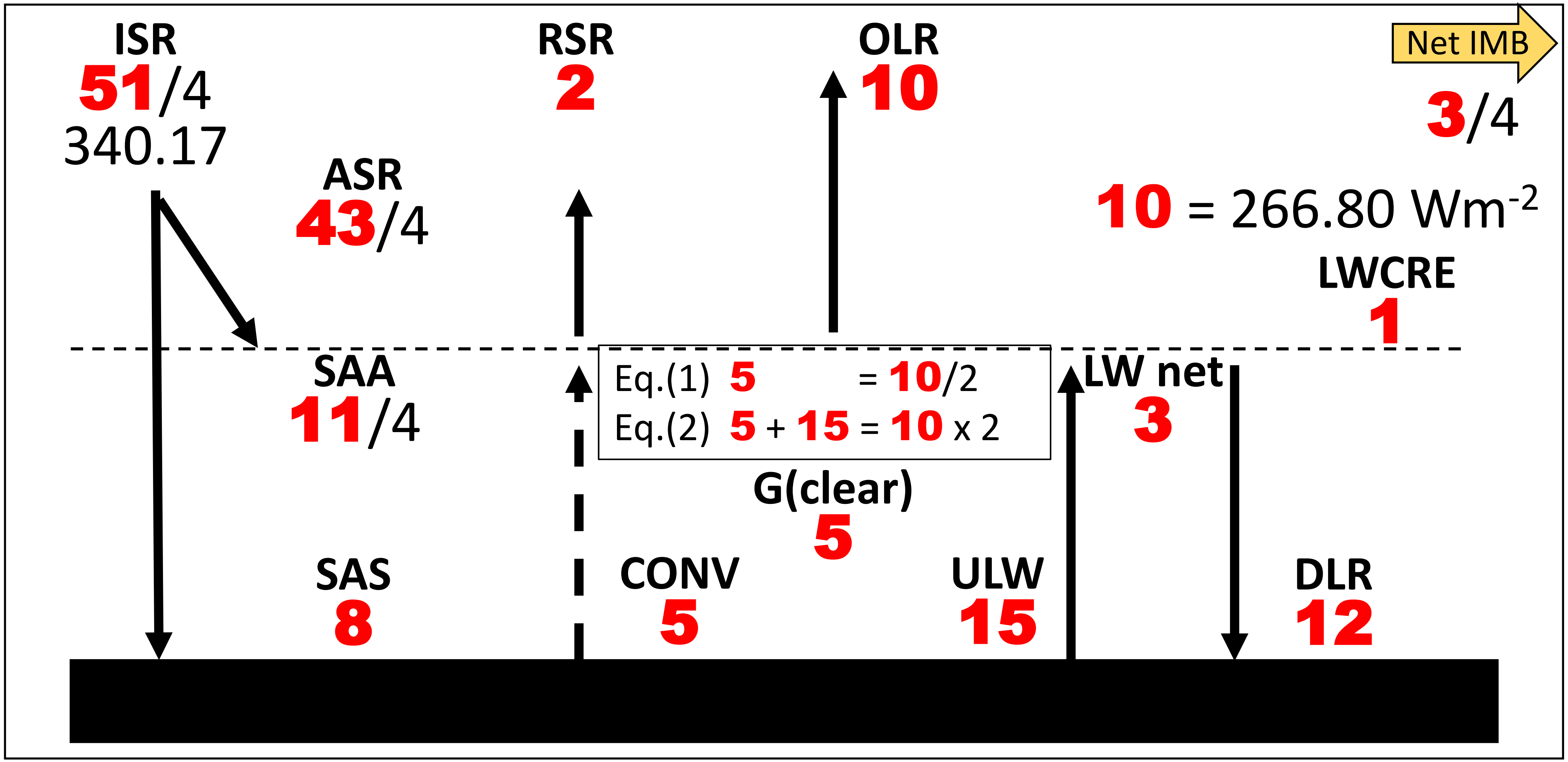
Ready.

Transform to "SUN units"



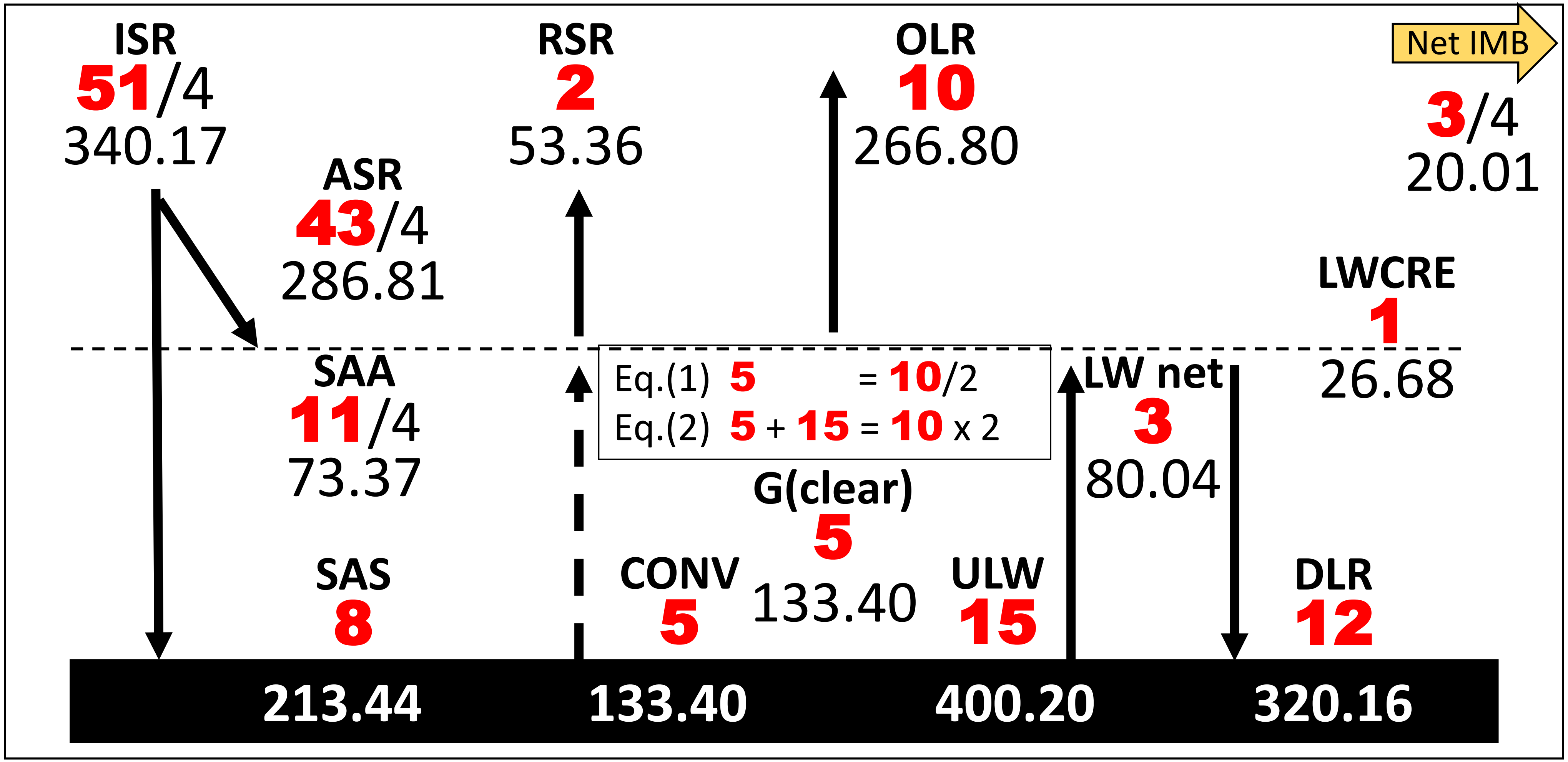
"Groundtruth" on the disk, clear-sky

Divide by 4 for spherical weighting



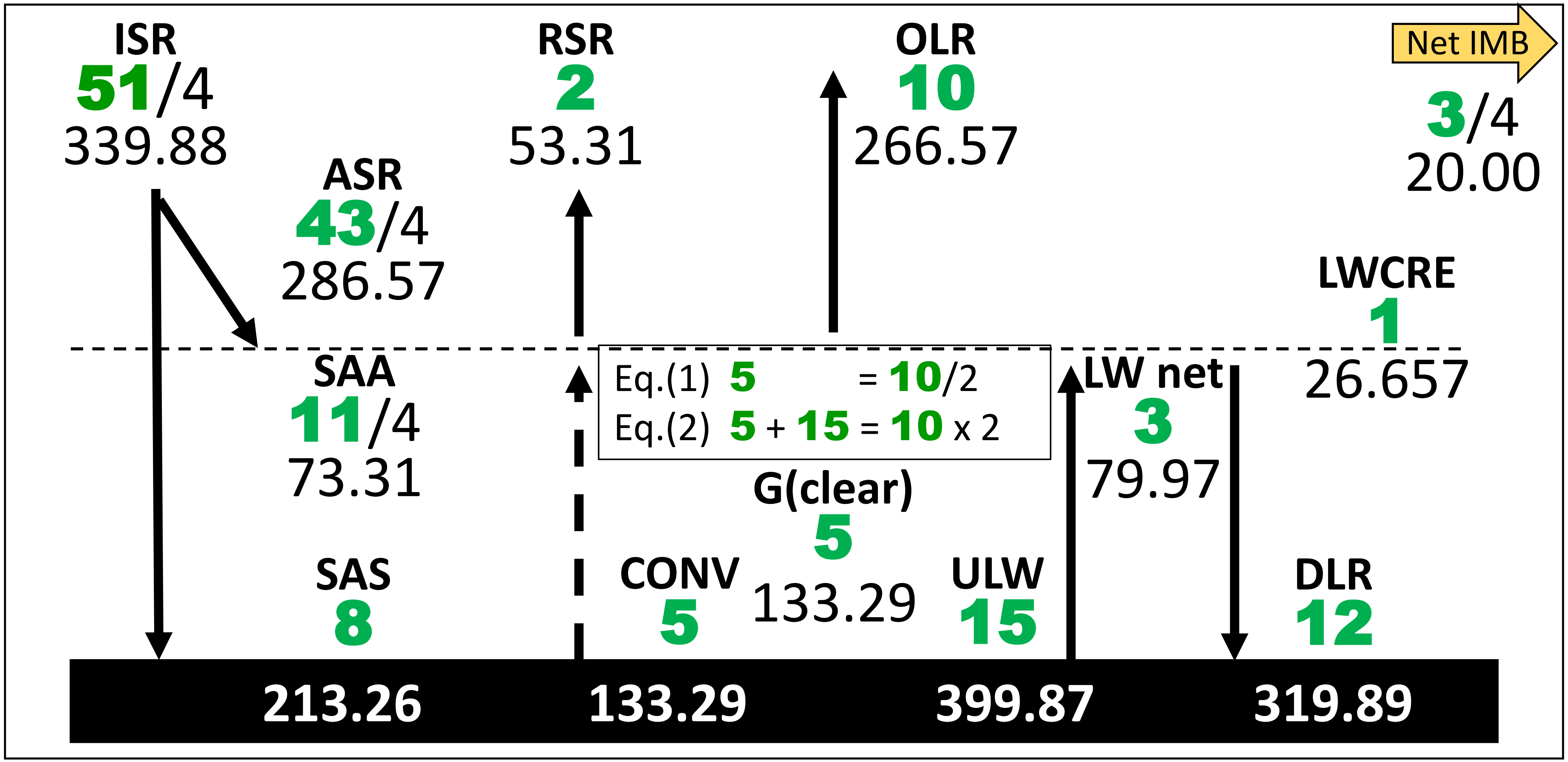
“Groundtruth” on the sphere, clear-sky

Theory: The clear-sky system, sphere



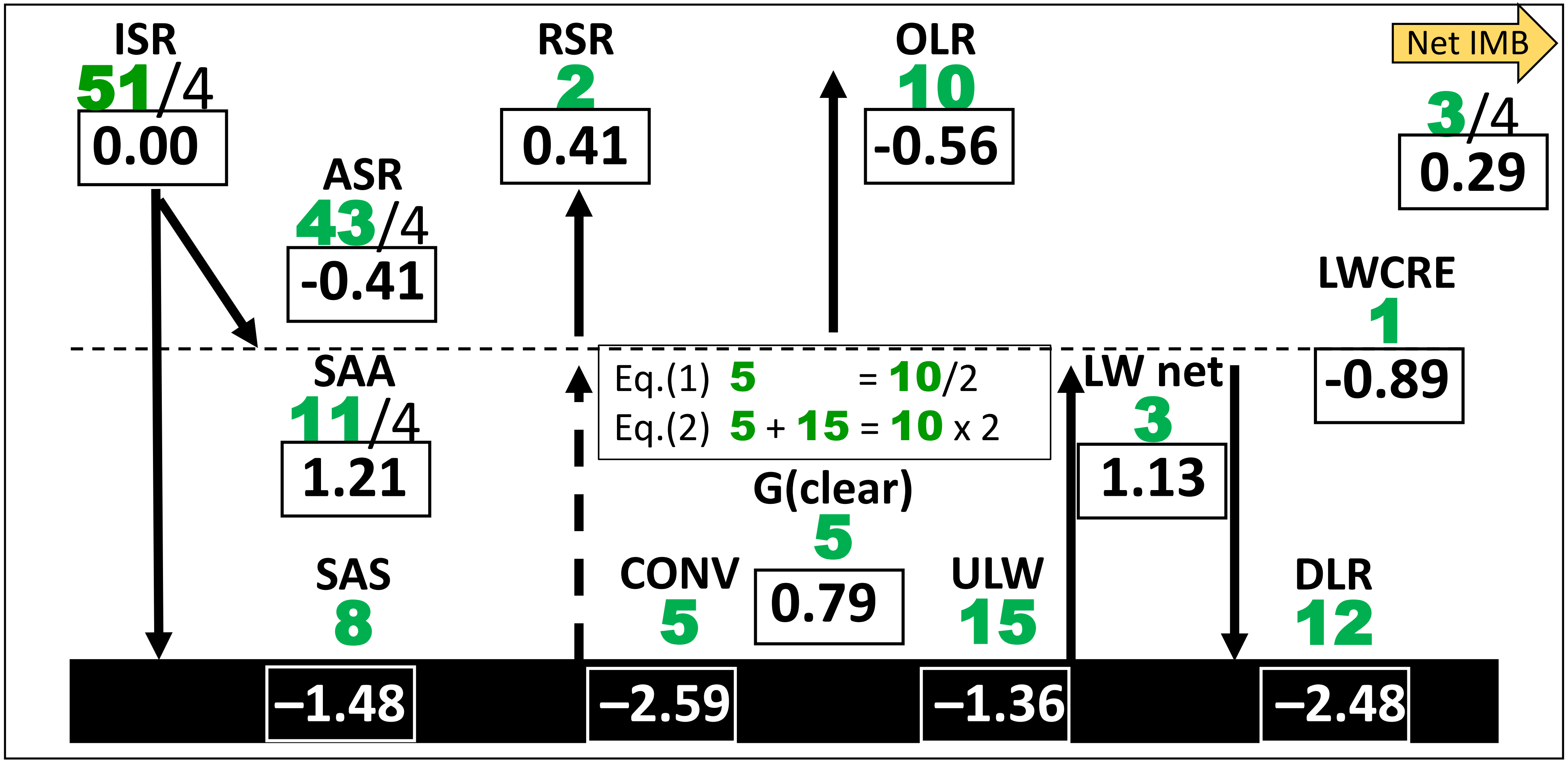
Absolute calibration, clear-sky, sphere

Transform to “GEO units”, 1 = 1 × 4/4.0034



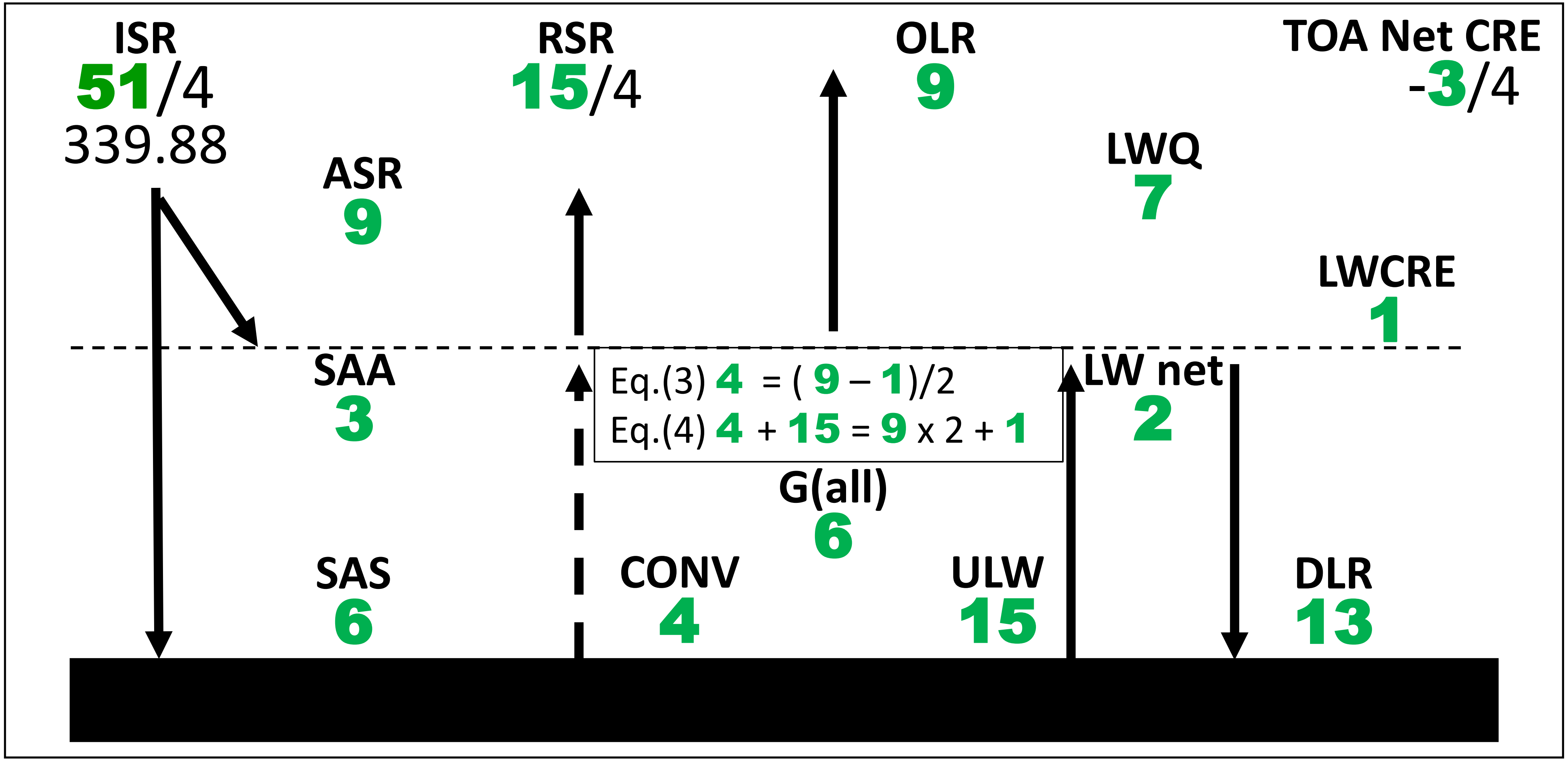
Absolute calibration, clear-sky, geoid

CERES EBAF Ed4.1 21-yr clear-sky minus Theory (Wm^{-2})



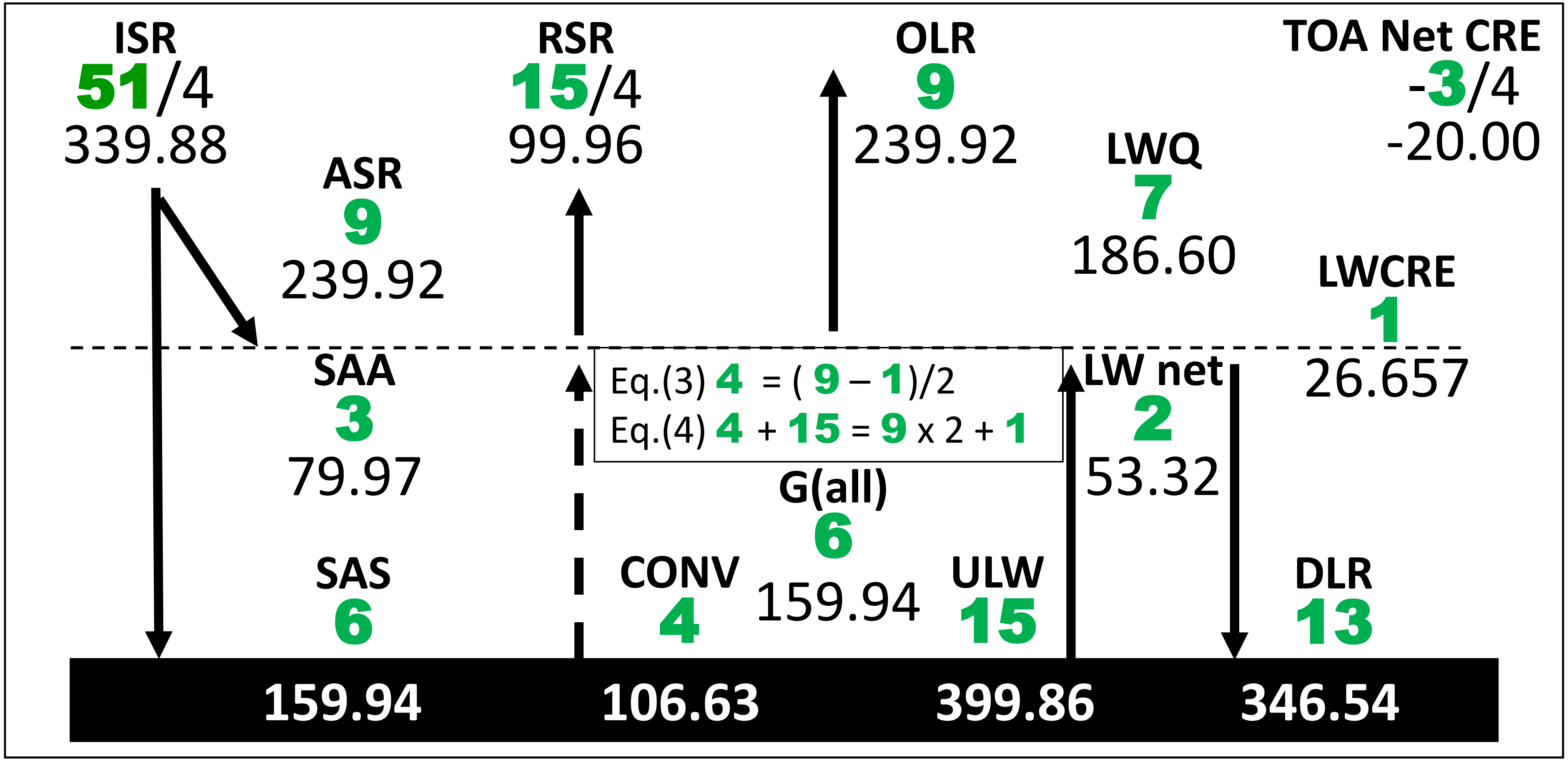
Deviation from theoretical clear-sky equilibrium

Theory: The all-sky system, geoid



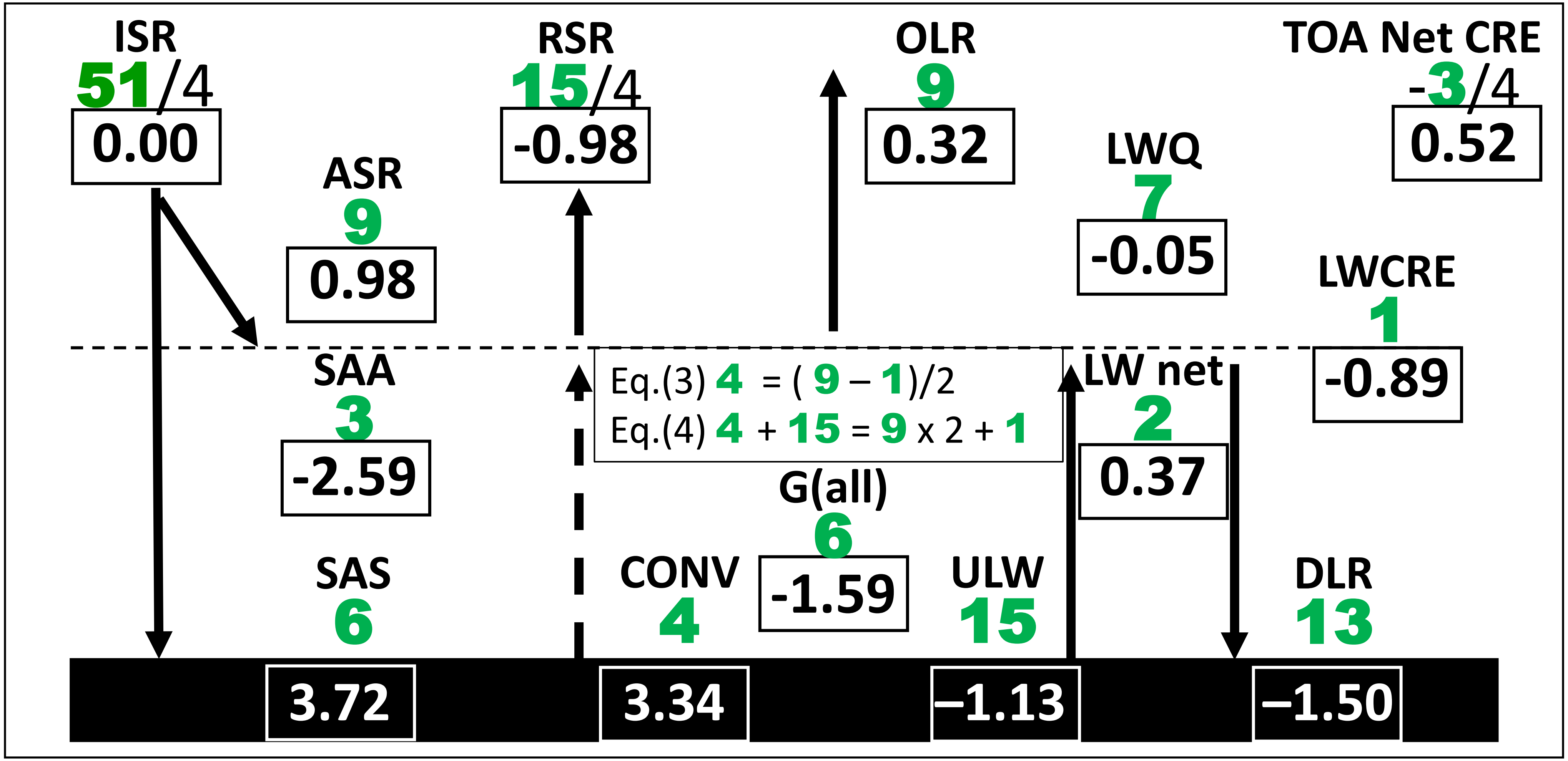
Theoretical equilibrium all-sky “groundtruth”, geoid

Theory: The all-sky system, geoid



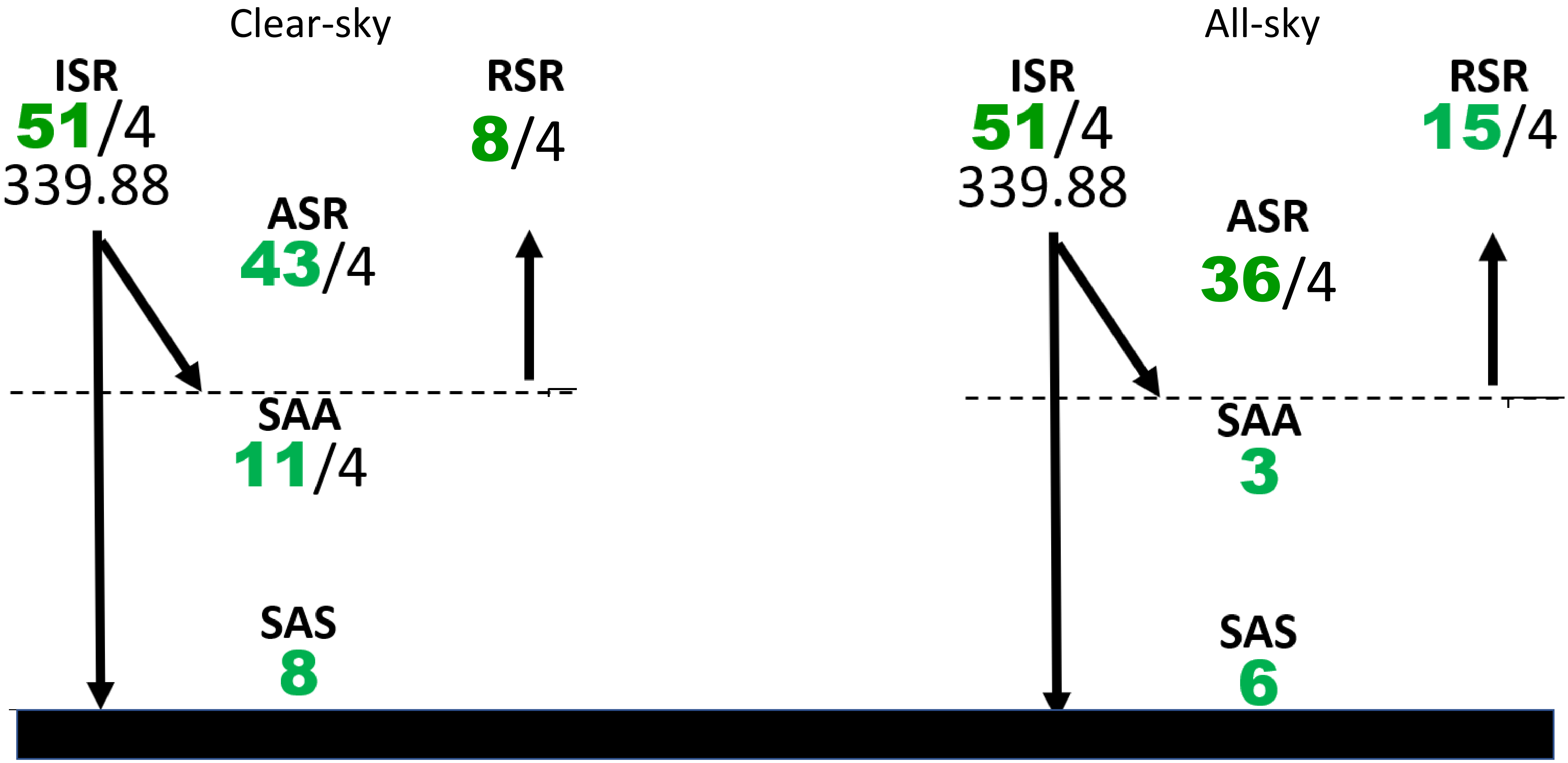
Theoretical equilibrium all-sky absolute calibration, geoid

CERES EBAF Ed4.1 21-yr all-sky minus Theory (Wm^{-2})

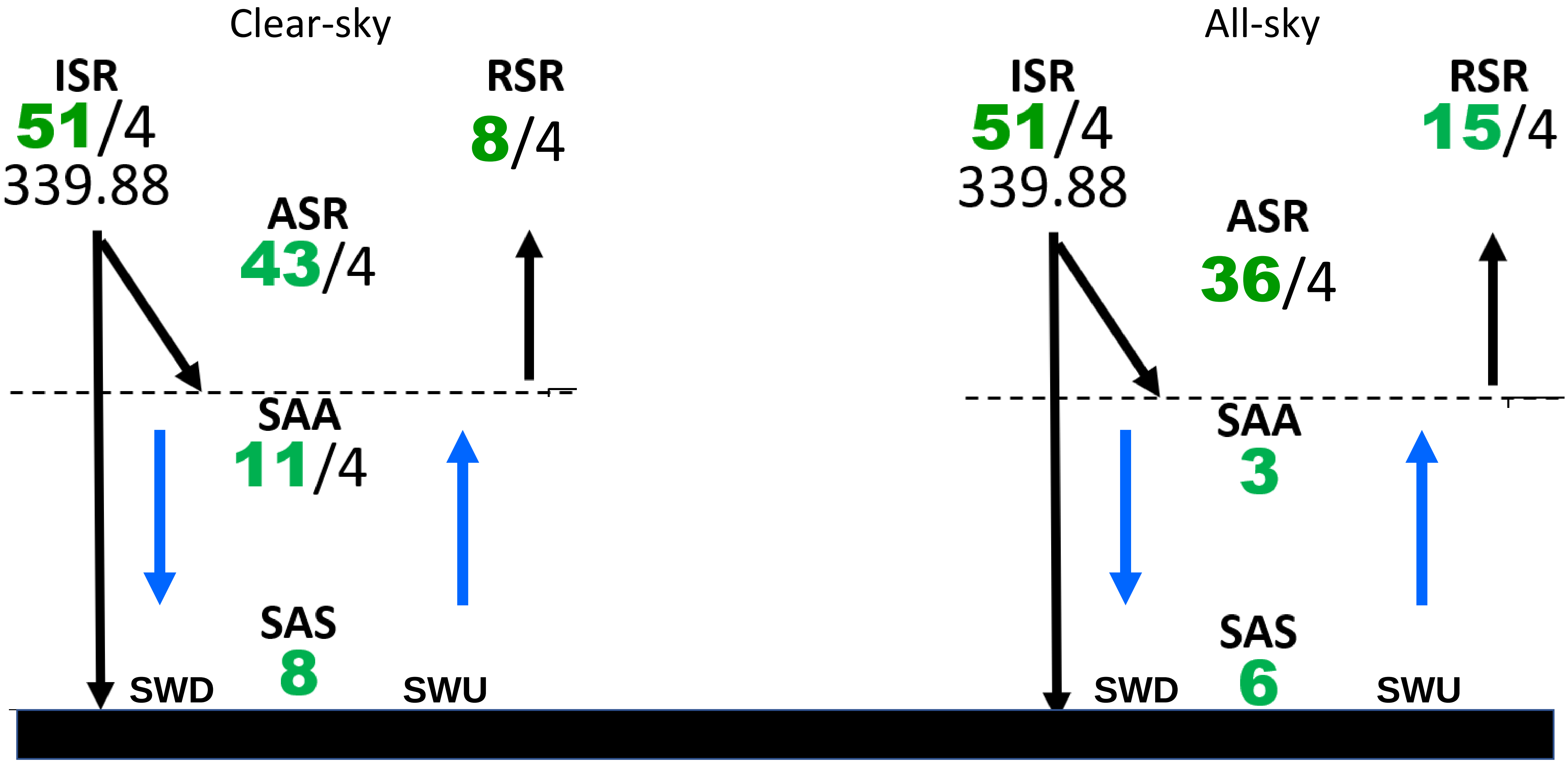


Deviation from theoretical all-sky equilibrium, geoid

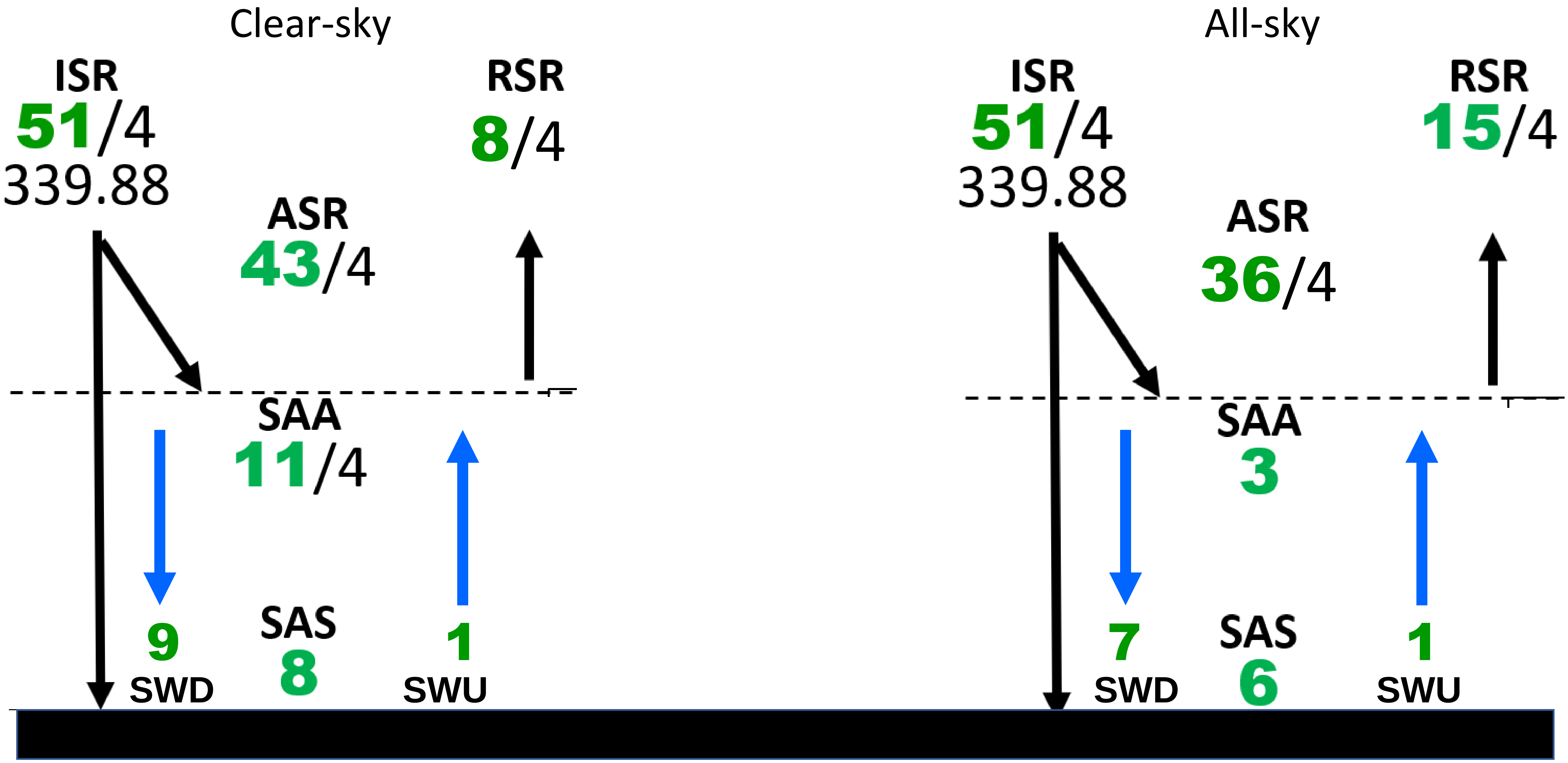
Extras: Surface Solar



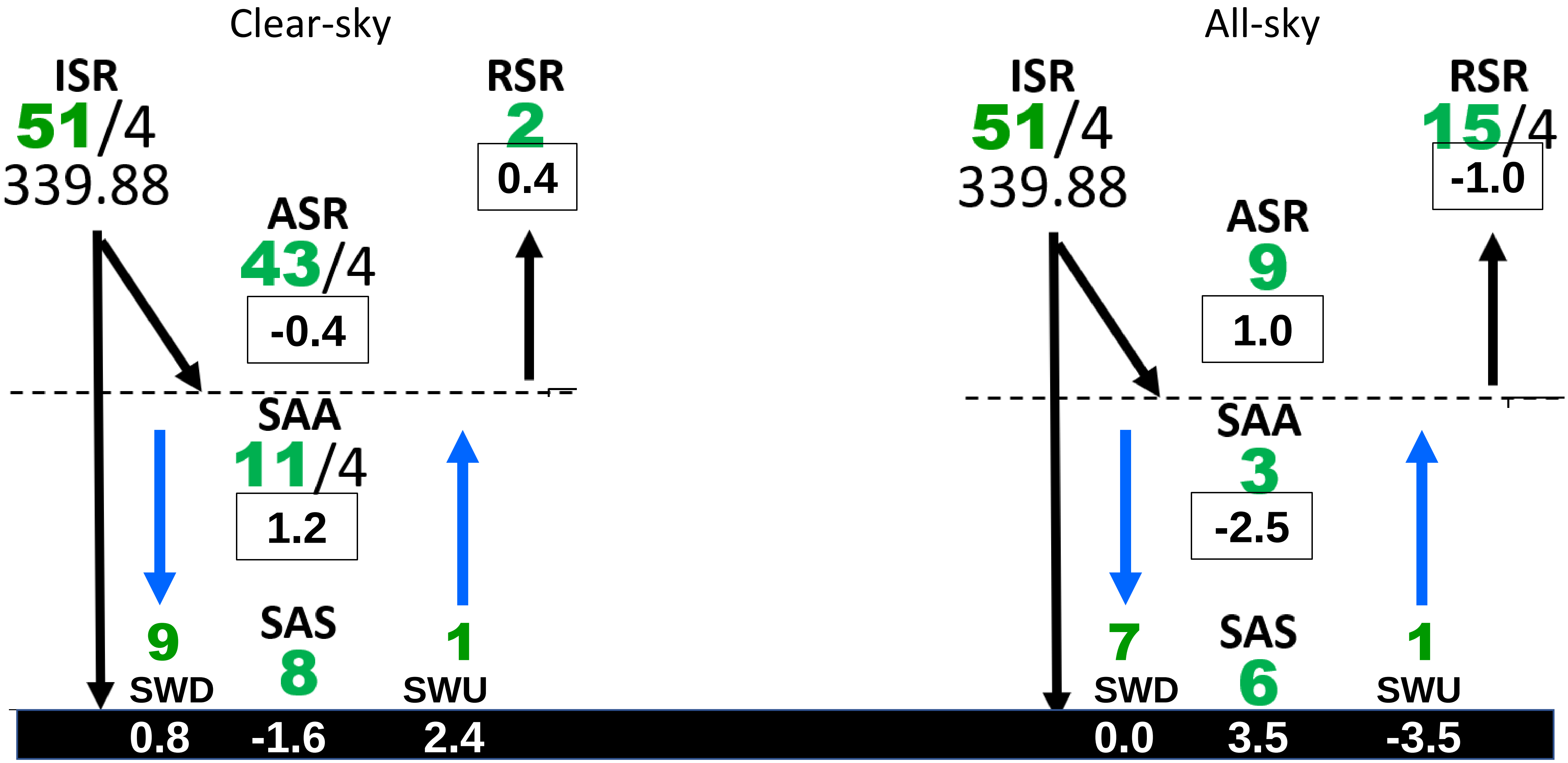
Surface Solar



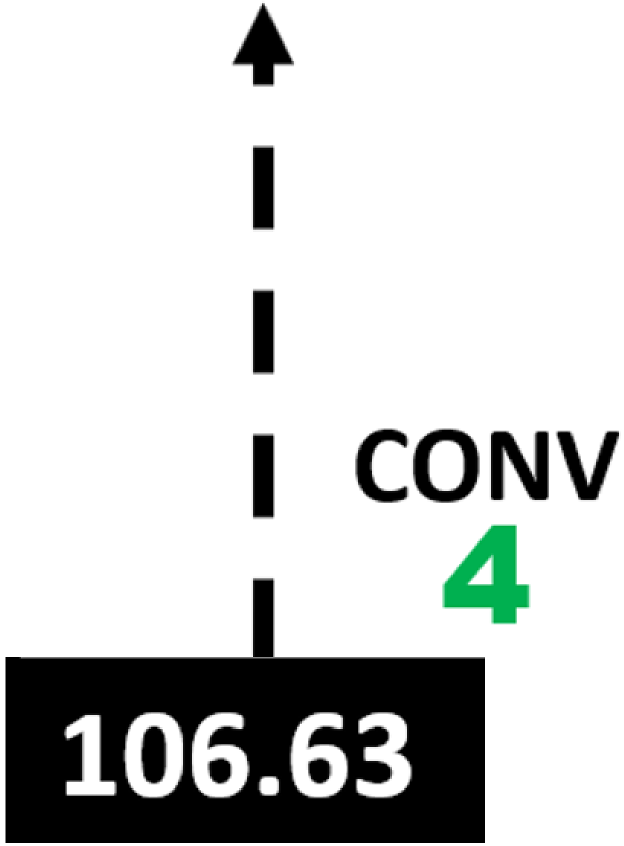
Surface Solar



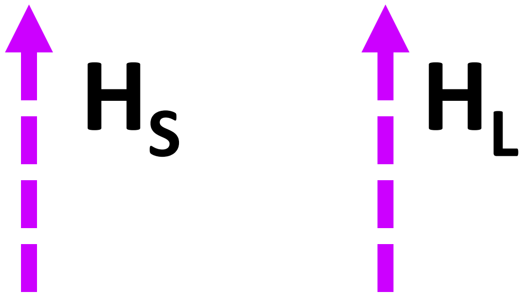
Surface Solar



Convection (All-sky) = **4**

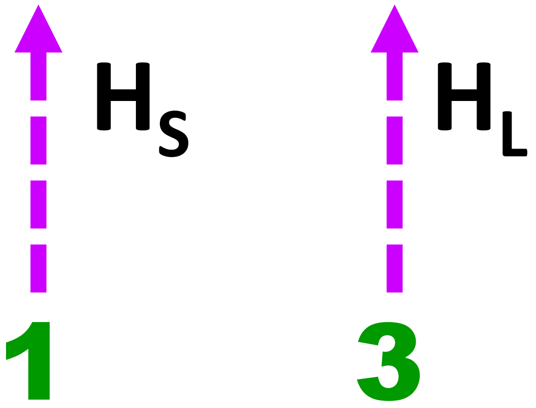


Sensible Heat + Latent Heat (All-sky)



106.63

Sensible Heat + Latent Heat (All-sky) = **1** + **3**



106.63

Sensible Heat + Latent Heat (All-sky) = 1 + 3

H_S H_L

	1	3
Theory	26.66	79.97
L'Ecuyer et al. (2015)	**25**	**81**
Difference	**-1.66**	**1.03**

106.63

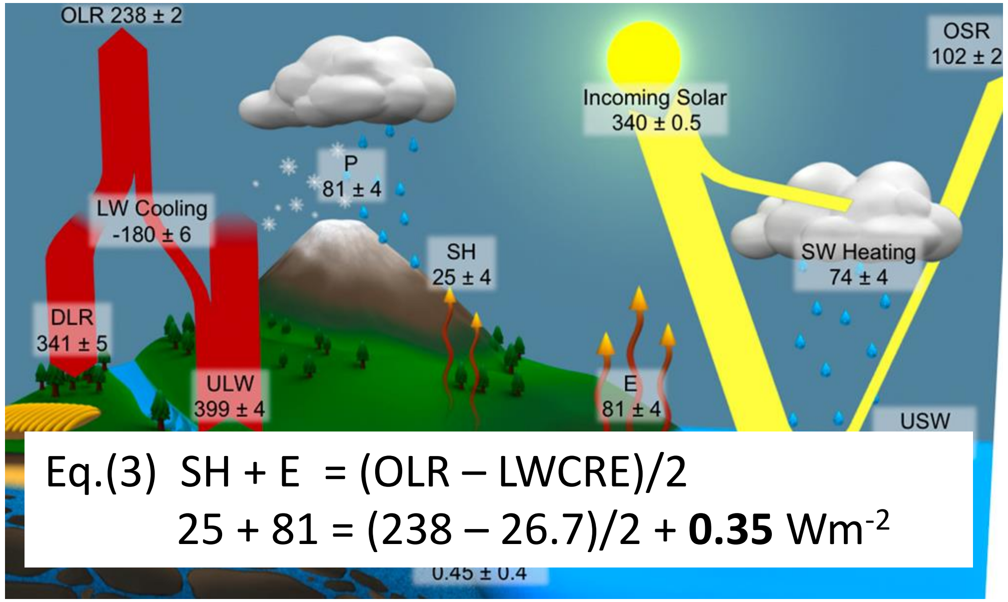
-0.63

Sensible Heat + Latent Heat (All-sky) = **1** + **3**

	H_S	H_L
	1	**3**
Theory	26.66	79.97
L'Ecuyer et al. (2015)	**25**	**81**
Difference	**-1.66**	**1.03**

106.63

-0.63



Eq.(3) SH + E = (OLR – LWCRE)/2

25 + 81 = (238 – 26.7)/2 + **0.35** Wm^{-2}

Data: **Table 2-1**, CERES EBAF Ed.4.1 DQS, clear-sky with Δ^C (July 2005-June 2015)

Theory: Eq. (1) **8** + **12** – **15** = **10**/2; **Eq. (2)** **8** + **12** = **10** × 2; **1** = 26.66 Wm^{-2}

		N	Theory N × Unit	Data Table 2-1	Data – Theory
Clear-Sky TOA	LW	**40**/4	266.6	265.9	-0.7
	SW	**8**/4	53.3	53.8	0.5
	Net	**3**/4	20.0	20.3	0.3
Clear-Sky Surface	LW down	**12**	319.9	317.2	-2.7
	LW up	**15**	399.9	398.2	-1.7
	LW Net	**-3**	-80.0	-81.0	-1.0
	SW down	**9**	239.9	240.7	0.8
	SW up	**1**	26.7	29.1	2.4
	SW Net	**8**	213.3	211.6	-1.7
	SW + LW Net	**5**	133.3	130.6	-2.7

Data: **Table 4-1**, CERES EBAF Ed.4.1 DQS, all-sky (July 2005-June 2015)

Theory: Eq. (3) **6** + **13** – **15** = (**9** – **1**)/2; Eq. (4) **6** + **13** = **9** × 2 + **1**; **1** = 26.66 Wm^{-2}

	All-sky	**N**	Theory **N** × Unit	Data Table 4-1	Data – Theory
TOA	SW insolation	**51**/4	339.9	340.0	0.1
	SW up	**15**/4	100.0	99.1	-0.9
	LW up	**36**/4	239.9	240.1	0.2
	TOT Net	0	0	0.71	0.7
Surface	SW down	**7**	186.6	186.6	0.0
	SW up	**1**	26.7	23.2	-3.5
	SW Net	**6**	160.0	163.3	3.3
	LW down	**13**	346.6	344.8	-1.8
	LW up	**15**	399.9	398.3	-1.6
	LW Net	**-2**	-53.3	-53.5	-0.2
	TOT Net	**4**	106.6	109.8	3.2
	CRE				
TOA	SW	**-7**/4	-46.6	-45.3	1.3
	LW	**1**	26.7	25.8	-0.9
	TOT	**-3**/4	-20.0	-19.6	0.4
Surface	SW	**2**	-53.3	-48.2	5.1
	LW	**1**	26.7	27.4	0.7
	TOT	**-1**	-26.7	-20.8	5.9