Data versus theory update

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Data

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

Theory

Four equations based on
Schwarzschild (1906, Eq. 11)

Ueber das Gleichgewicht der Sonnenatmosphäre

Von

K. Schwarzschild.

Vorgelegt in der Sitzung vom 13. Januar 1906.

Schwarzschild, K. (1906) On the Equilibrium of the Sun's Atmosphere.
Nach. K. Gesell, Wiss. Göttingen, Math-Phys. Klasse **195,** pp. 41–53.
In "Selected Papers on the Transfer of Radiation" (D. H. Menzel, ed.). Dover, New York.

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

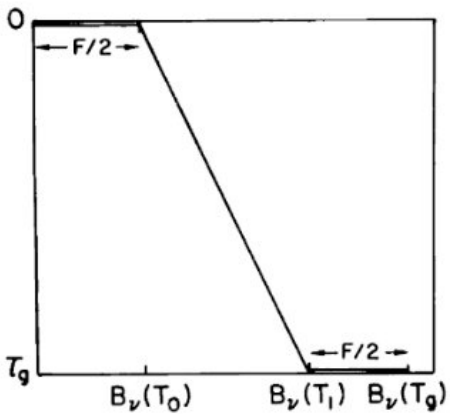
E emission of the layer, A upward beam, B downward beam, A_0 emerging flux, m „Optische masse"

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

Eq. (1) $\mathbf{A - E = \Delta A = \frac{A_0}{2}}$ (net, clear-sky)

- In radiative equilibrium: discontinuity
- In radiative-convective equilibrium: convection (Emden 1913)
- = OLR/2, independently of the optical depth
- Planetary application in standard textbooks:

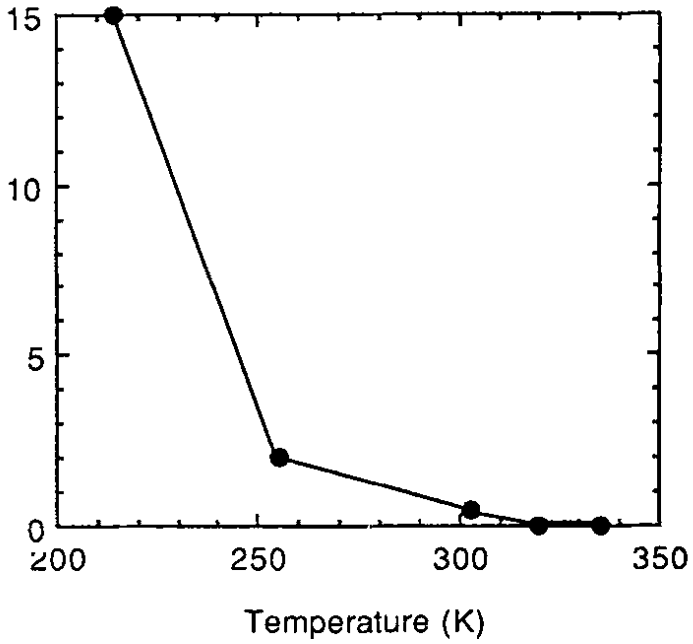
- Houghton	(1977, Eq. 2.13):	$\mathbf{B_g - B_0}$	$\mathbf{= \phi/2\pi}$
- Goody and Yung	(1989, Eq. 2.146):	$\mathbf{B^*(\tau_1) - B(\tau_1)}$	$\mathbf{= F/2\pi}$
- Andrews	(2000, Eqs. 3.42-3.43):	$\mathbf{\sigma(T_g^4 - T_b^4)}$	$\mathbf{= F_0/2}$
- Pierrehumbert	(2008, Eqs. 4.44-4.45):	$\mathbf{\sigma(T_g^4 - T(0)^4)}$	$\mathbf{= (1-\alpha)S/2}$



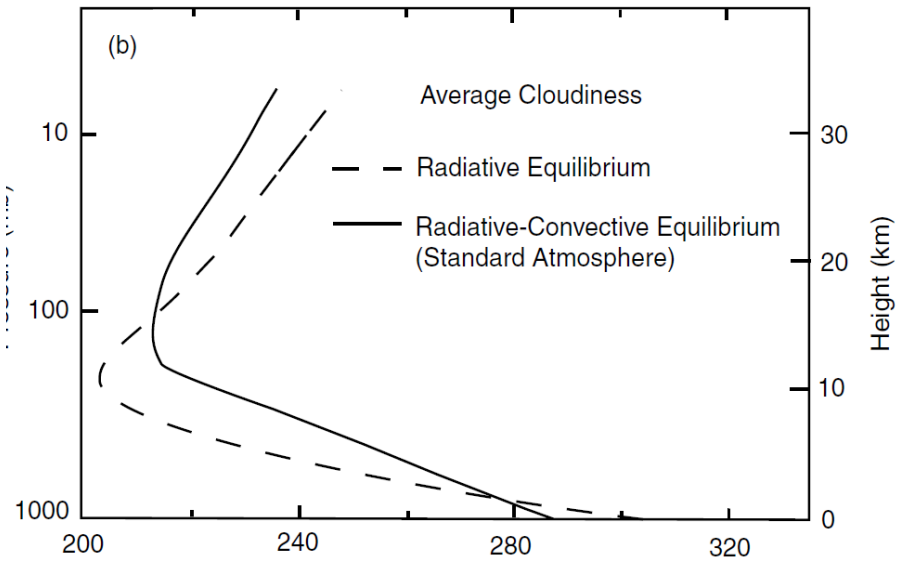
- Missing from Manabe-Wetherald (1967) convective adjustment
- Missing from Hasselmann's (1976) stochastic model
- Missing from IPCC (1990) — (2021)

Radiative Equilibrium: Discontinuity
Radiative-Convective Equilibrium: Net Flux

Hartmann (1994)
Global Physical Climatology



Liou (2002)
An Introduction to Atmospheric Radiation



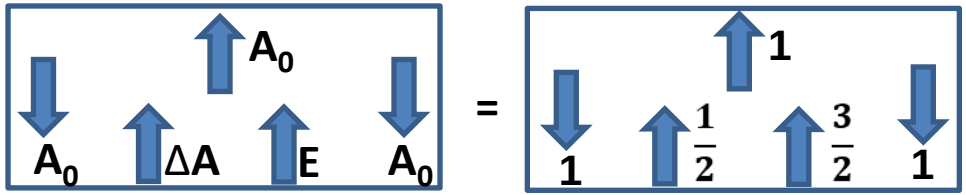
$$\textbf{Eq. (1)} \quad \mathbf{A - E = \Delta A = \frac{A_0}{2}}$$

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

Eq. (2) $\mathbf{A = 2A_0}$, $\mathbf{E = 3\frac{A_0}{2}}$, $\mathbf{B = A_0}$ (total, clear-sky)

Particular case at $\tau = 2$ (needs explanation)

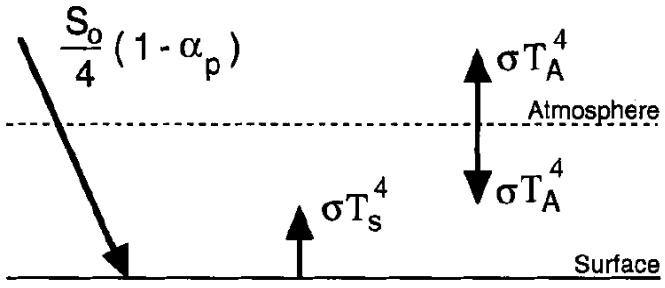
$$\Delta A : A_0 : E : A = \frac{1}{2} : 1 : \frac{3}{2} : 2$$



Hartmann (1994)
Global Physical Climatology

$$\frac{S_0}{4}(1-\alpha_p)+\sigma T_A^4=\sigma T_s^4 \quad \Rightarrow \quad \sigma T_s^4=2\sigma T_e^4$$

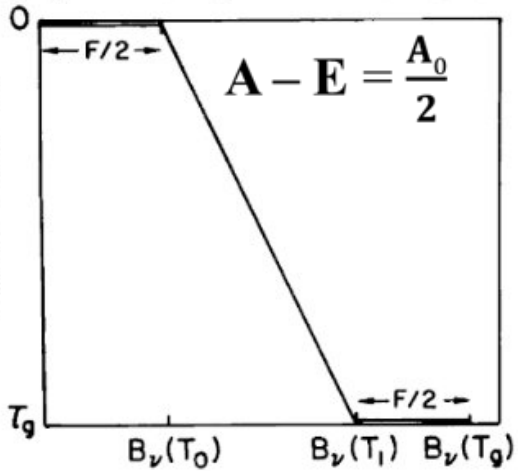
$$\mathbf{A = 2A_0}$$



Chamberlain (1978)
Theory of Planetary Atmospheres

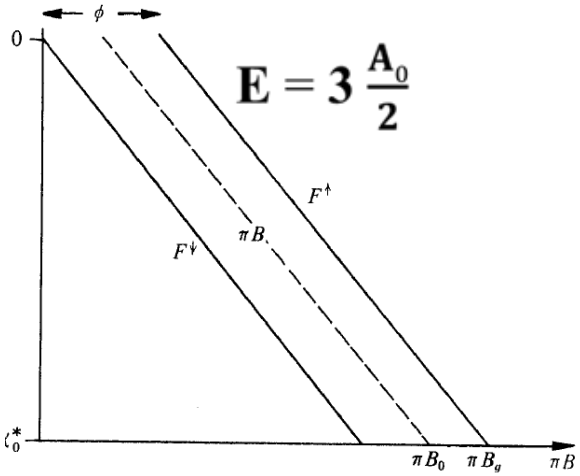
$$I_g^+ \equiv B_\nu(T_g) = B_\nu(T_1) + \tfrac{1}{2}F_\nu$$

$$\mathbf{A - E = \frac{A_0}{2}}$$

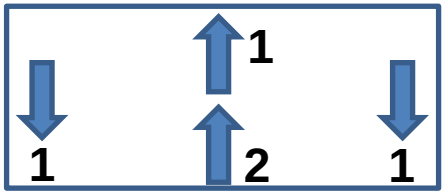


Houghton (1977)
The Physics of Atmospheres

$$\mathbf{E = 3\,\frac{A_0}{2}}$$



Single-slab => Continuous atmosphere in radiative-convective equilibrium



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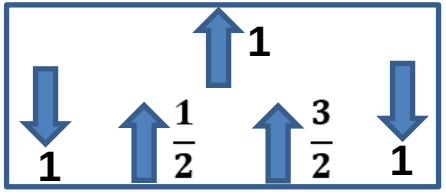

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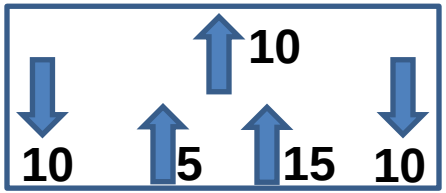
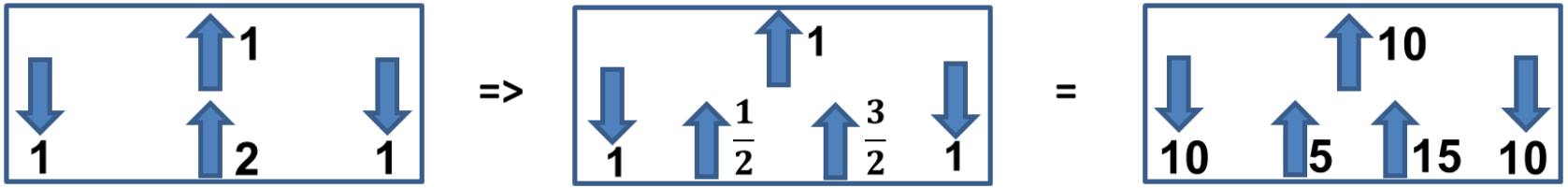
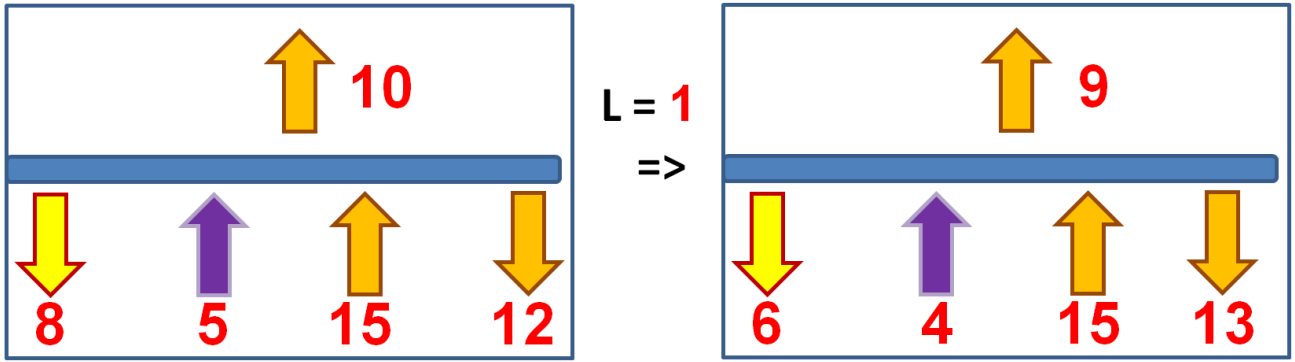




Single-slab

Continuous



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

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

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

Eq (2) $A = 2A_0$

Clear-sky

Eq (3) $A - E = (A_0 - L)/2$

Eq (4) $A = 2A_0 + L$

All-sky

Theory: The four equations

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

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

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

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

Data: CERES EBAF Ed4.1 (July2000-June2021)

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

240.86 – 29.08 + 317.41 = 2 × 266.01

(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

(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

Data: CERES EBAF Ed4.1 (July2000-June2021)

(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

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

240.86 – 29.08 + 317.41 = 2 × 266.01 -2.83

(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

(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

Data: CERES EBAF Ed4.1 (July2000-June2021)

(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
(2)	SFC (SW down – SW up) + LW down	(clear)	= 2 × TOA LW (clear)	
	240.86 – 29.08 + 317.41		= 2 × 266.01	-2.83
(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
(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		=	0.00

232	240.5806	265.8775	25.29678	190.1384	243.4592	23.03392	28.72066	345.35	317.4313	400.5147	400.0983	167.1045	214.7385	111.9398
233	238.2849	264.0271	25.7421	192.9237	250.0362	26.72641	32.72525	339.7899	311.1432	394.8521	394.3174	166.1973	217.3109	111.1351
234	238.3419	263.5357	25.19379	194.3816	252.9231	26.86485	32.78951	336.5753	308.589	392.0921	391.7437	167.5167	220.1335	111.9999
235	237.5992	262.9002	25.30084	192.0221	250.5116	24.52932	30.47829	336.7932	309.2402	390.9003	390.9109	167.4928	220.0333	113.3857
236	238.9387	264.0995	25.16078	191.8326	247.3356	22.81421	28.89151	338.4839	311.1572	392.763	392.9263	169.0184	218.4441	114.7392
237	238.9434	264.5448	25.60145	191.6538	243.393	22.94277	28.70653	340.0641	313.9244	395.9742	396.0075	168.711	214.6864	112.8009
238	239.6854	265.3033	25.61782	190.7455	239.0618	24.85472	30.17659	343.153	317.4505	400.7692	400.4102	165.8907	208.8851	108.2745
239	241.783	267.4445	25.66154	186.328	235.2378	24.87255	31.08537	347.4242	321.4639	405.1031	404.0949	161.4555	204.1523	103.7766
240	243.6528	268.8424	25.18955	179.9609	230.3688	21.66054	27.82054	351.8811	326.0796	408.1327	407.2986	158.3004	202.5483	102.0488
241	244.3724	269.916	25.5436	177.5758	228.6707	18.93763	24.55068	354.2381	328.4349	408.9658	408.5872	158.6382	204.1201	103.9105
242	244.7962	270.265	25.46881	180.8253	230.9673	18.07014	23.49308	353.5978	327.5986	408.2481	407.7277	162.7552	207.4742	108.1048
243	243.4063	268.3419	24.93558	184.3788	235.0425	19.45713	24.76397	349.9691	323.2565	405.3765	405.008	164.9217	210.2785	109.5143
244	240.6661	266.1968	25.53067	188.506	243.9077	23.29836	28.98416	344.4411	316.2766	399.9942	399.627	165.2076	214.9235	109.6545
245	239.3283	264.3495	25.02112	193.2095	251.2145	27.12736	33.31856	339.3771	310.8441	395.0079	394.4384	166.0821	217.896	110.4514
246	237.7579	262.951	25.19302	193.3444	253.8828	27.05768	33.15158	335.3092	307.3889	390.6691	390.4489	166.2868	220.7313	110.9268
247	237.4482	263.2164	25.7681	193.3754	252.863	24.7855	30.6412	333.2545	306.3332	389.5119	389.4991	168.59	222.2217	112.3326
248	238.5508	263.5722	25.02149	193.1669	249.1837	23.02699	29.04887	334.5251	308.0375	390.5228	390.8333	170.1399	220.1349	114.1422
249	238.3273	263.7777	25.45029	192.2169	244.1768	23.10015	28.77468	337.431	311.2424	394.1427	394.4612	169.1167	215.4021	112.405
250	238.5779	264.3643	25.7864	190.5441	239.7446	24.84071	30.36777	341.3257	315.4144	399.2494	399.0524	165.7034	209.3769	107.7797
251	240.4926	266.7023	26.20981	185.1975	235.3919	24.63445	31.1239	346.8448	320.1824	404.3804	403.388	160.5631	204.268	103.0275
252	242.4631	268.0773	25.61423	180.3911	230.664	21.67765	27.87111	351.2243	325.2448	407.6398	406.7827	158.7135	202.7929	102.2979
253	toa_lw_all	toa_lw_clr	toa_cre_lw	sw_dn_all	sw_dn_clr	sw_up_all	sw_up_clr	lw_dn_all	lw_dn_clr	lw_up_all	lw_up_clr	net_sw_all	net_sw_clr	net_tot_all
254	**240.24**	**266.01**	**25.77**	**186.83**	**240.86**	**23.17**	**29.08**	**345.04**	**317.41**	**398.73**	**398.51**	**163.66**	**211.78**	**109.97**
255														
256						ΔEq1 = **-2.3208**				ΔEq3 = **2.7308**				
257						ΔEq2 = **-2.8338**				ΔEq4 = **2.4425**				
258							mean = **0.0047**							

Integer solution 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**
ATM LW Cooling		=	**–7**	ATM LW Cooling		=	**–7**
SWCRE (surface)		=	**–2**	LWCRE (surface, TOA)		=	**1**

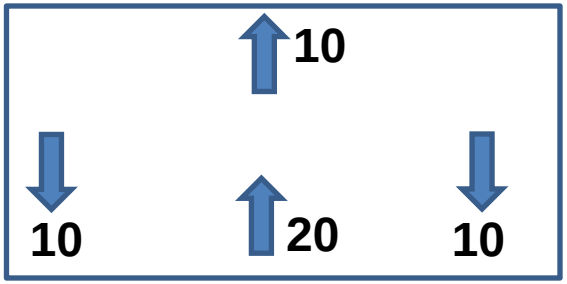
CERES EBAF Ed4.1, 252 months, July 2000 — June 2021 data, best fit:

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

Theory versus data

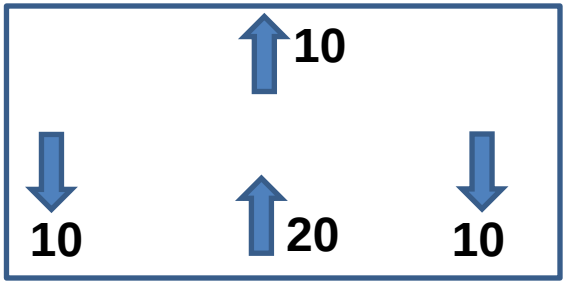
Clear-sky	N	N × Unit	July 2000 – June 2021	Difference
TOA LW up	10	266.80	266.01	-0.79
SFC SW net	8	213.44	211.78	-1.66
SFC LW down	12	320.16	317.41	-2.75
SFC LW up	15	400.20	398.51	-1.69
All-sky				
TOA LW up	9	240.12	240.24	0.12
SFC SW net	6	160.08	163.66	3.58
SFC LW down	13	346.84	345.04	-1.80
SFC LW up	15	400.20	398.73	-1.47
			Mean difference	**-0.81**

Summary

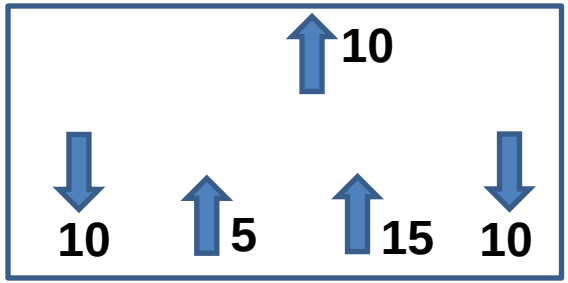


Single-slab

Summary

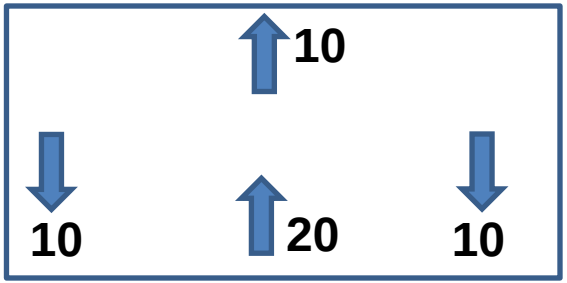


Single-slab

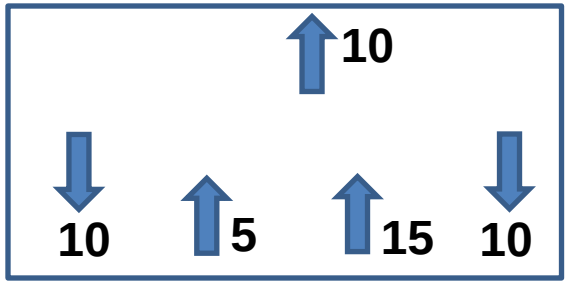


Continuous

Summary



Single-slab



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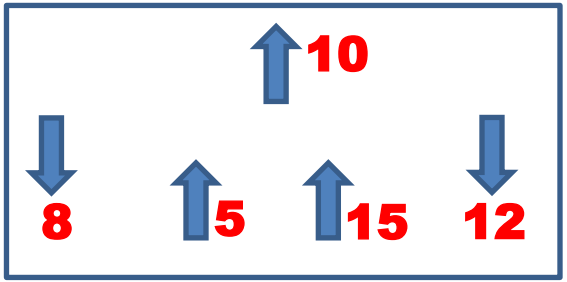
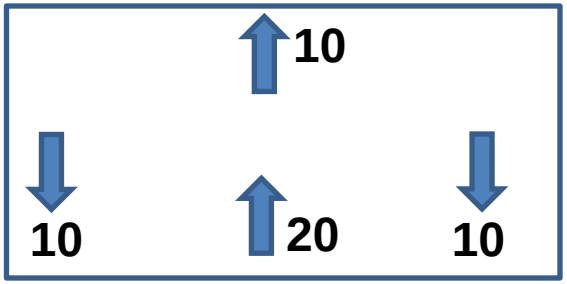
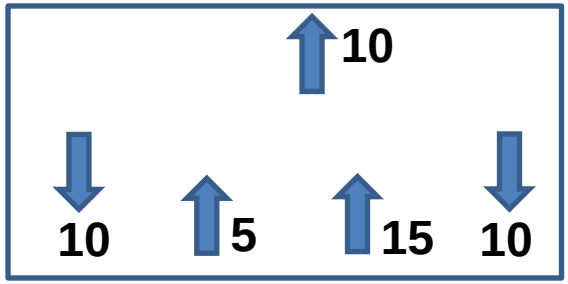


Clear-sky

Summary



Single-slab



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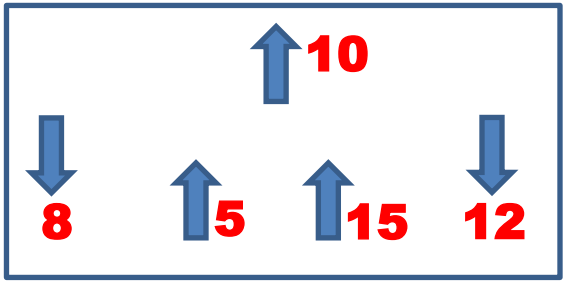
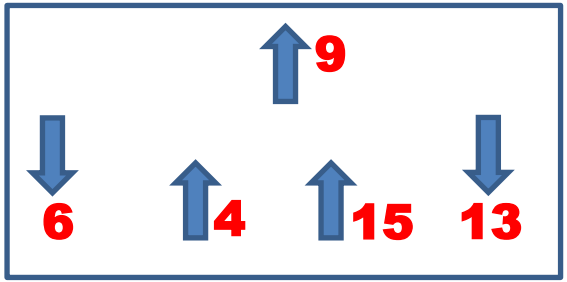
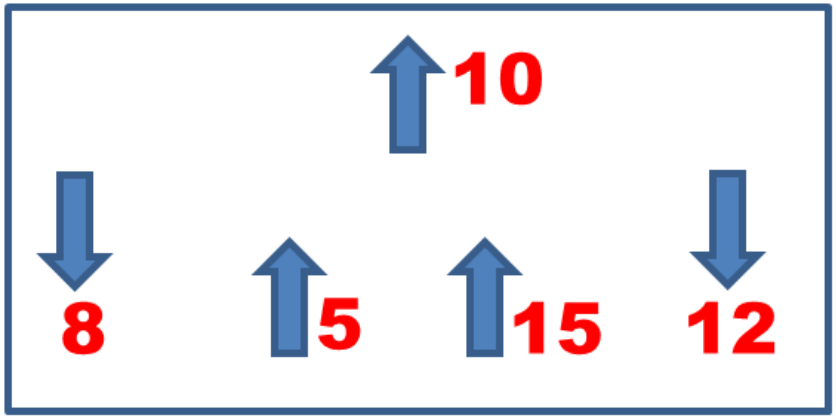


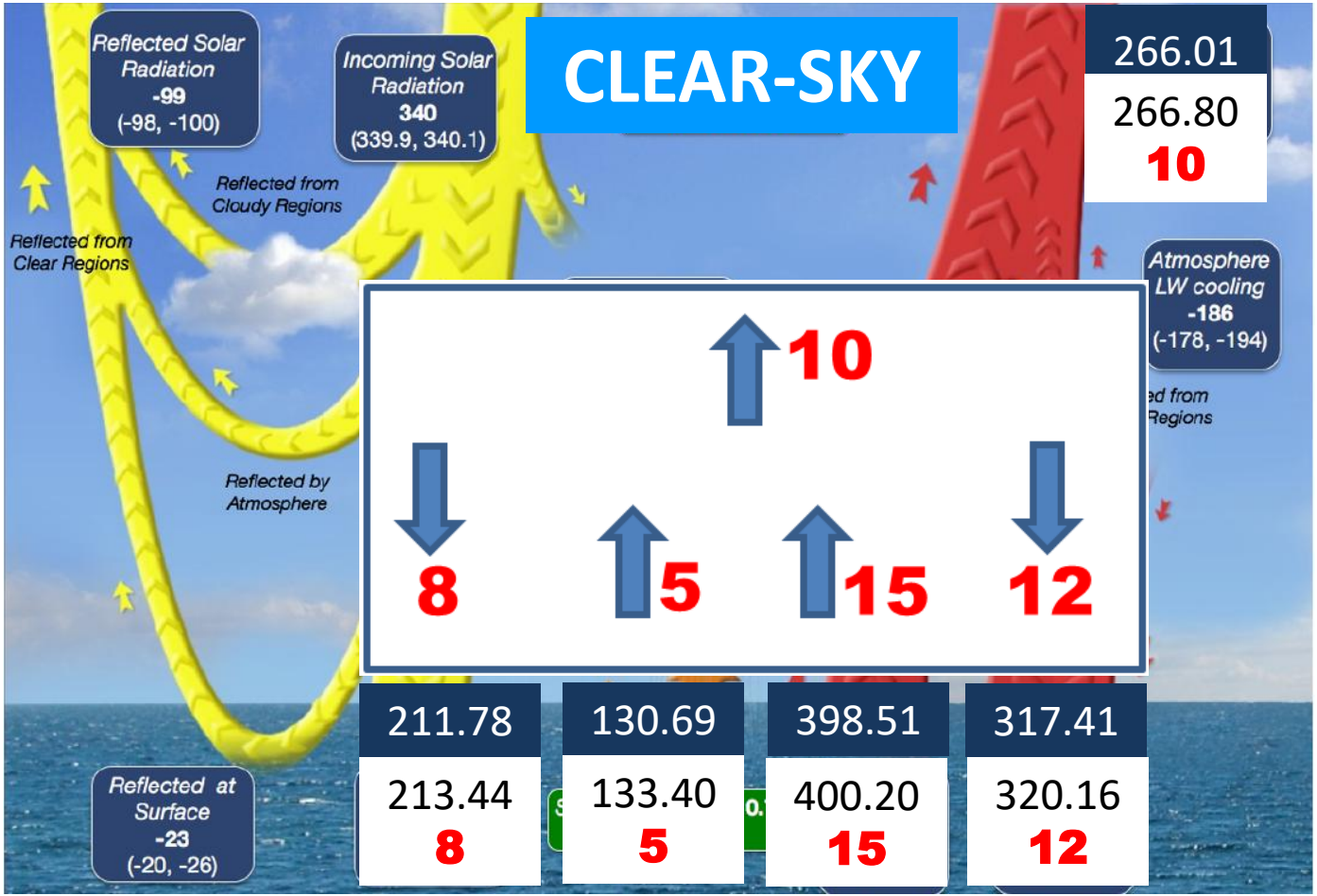
Clear-sky



All-sky


10
8
5
15
12

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



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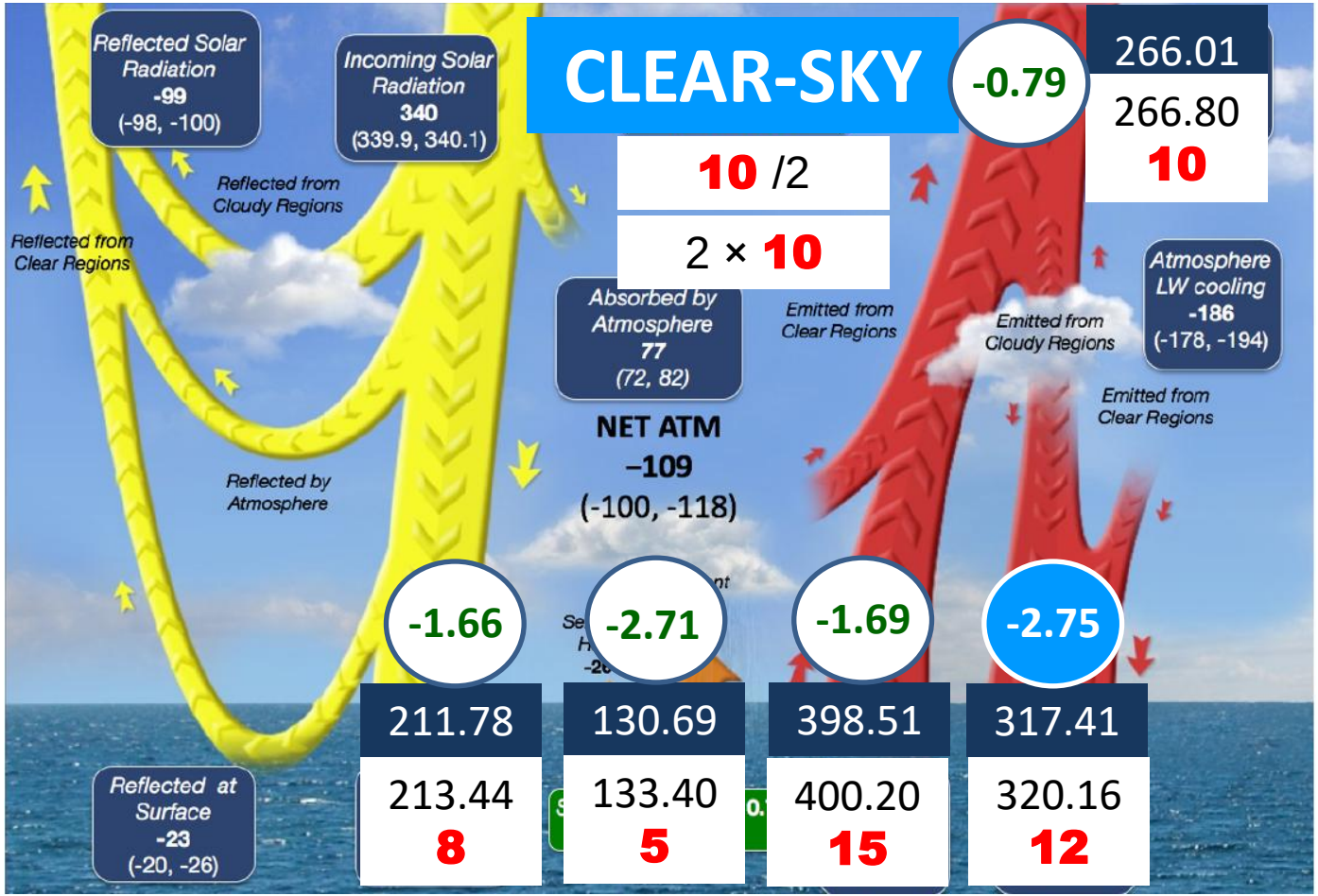
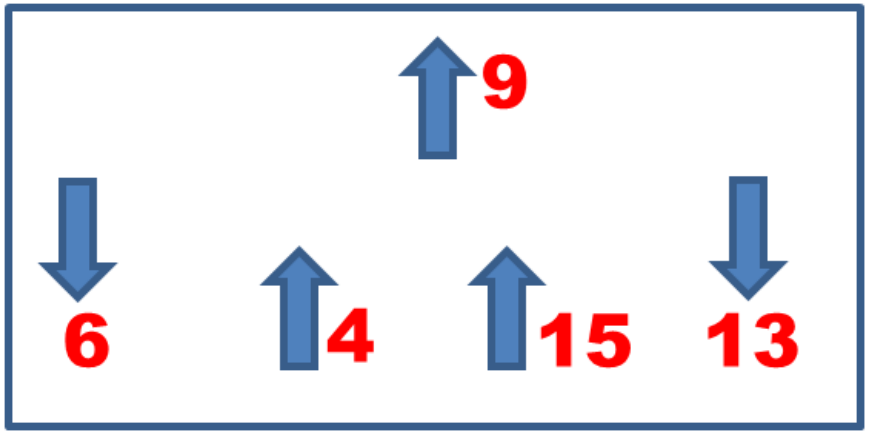
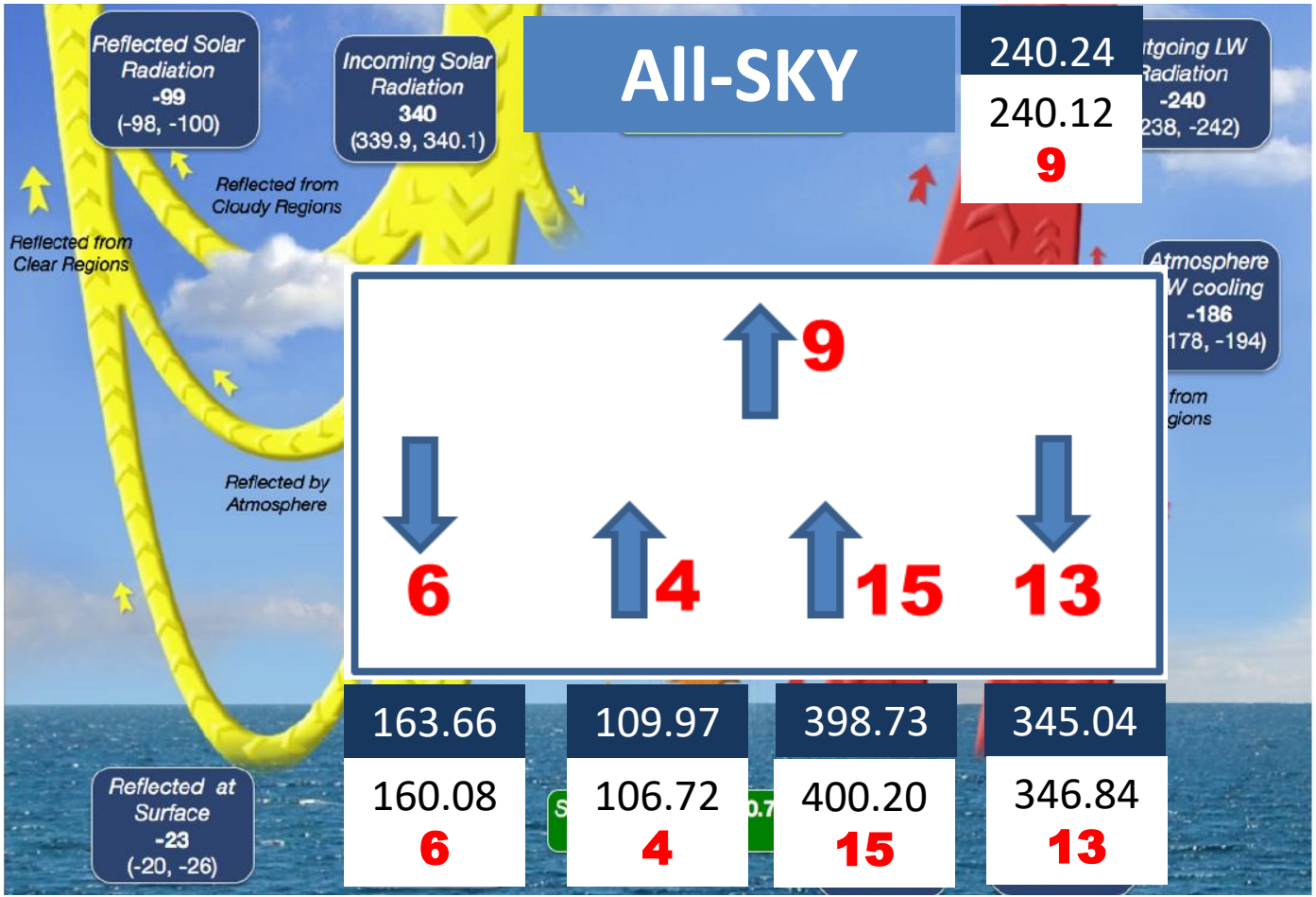



9
6
4
15
13

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



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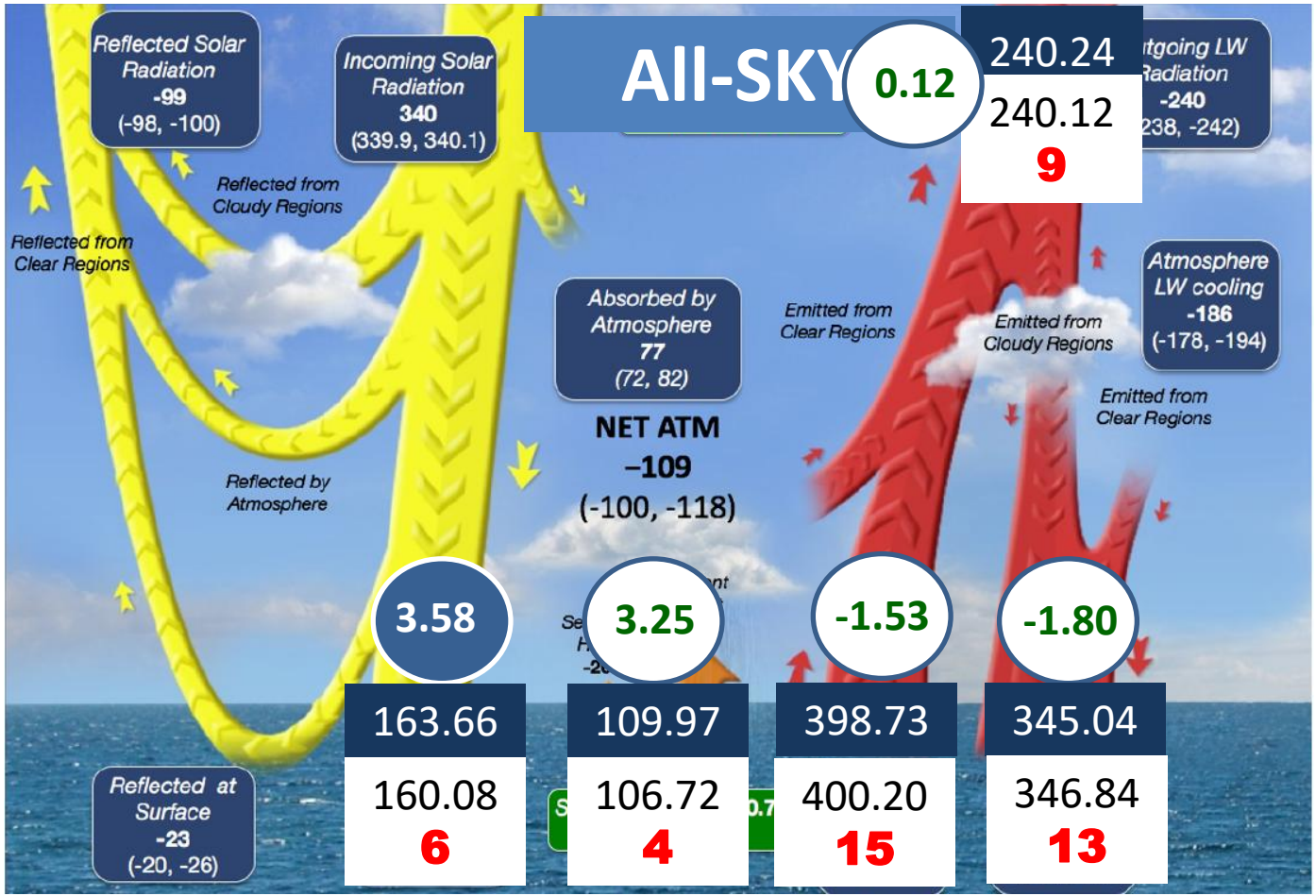

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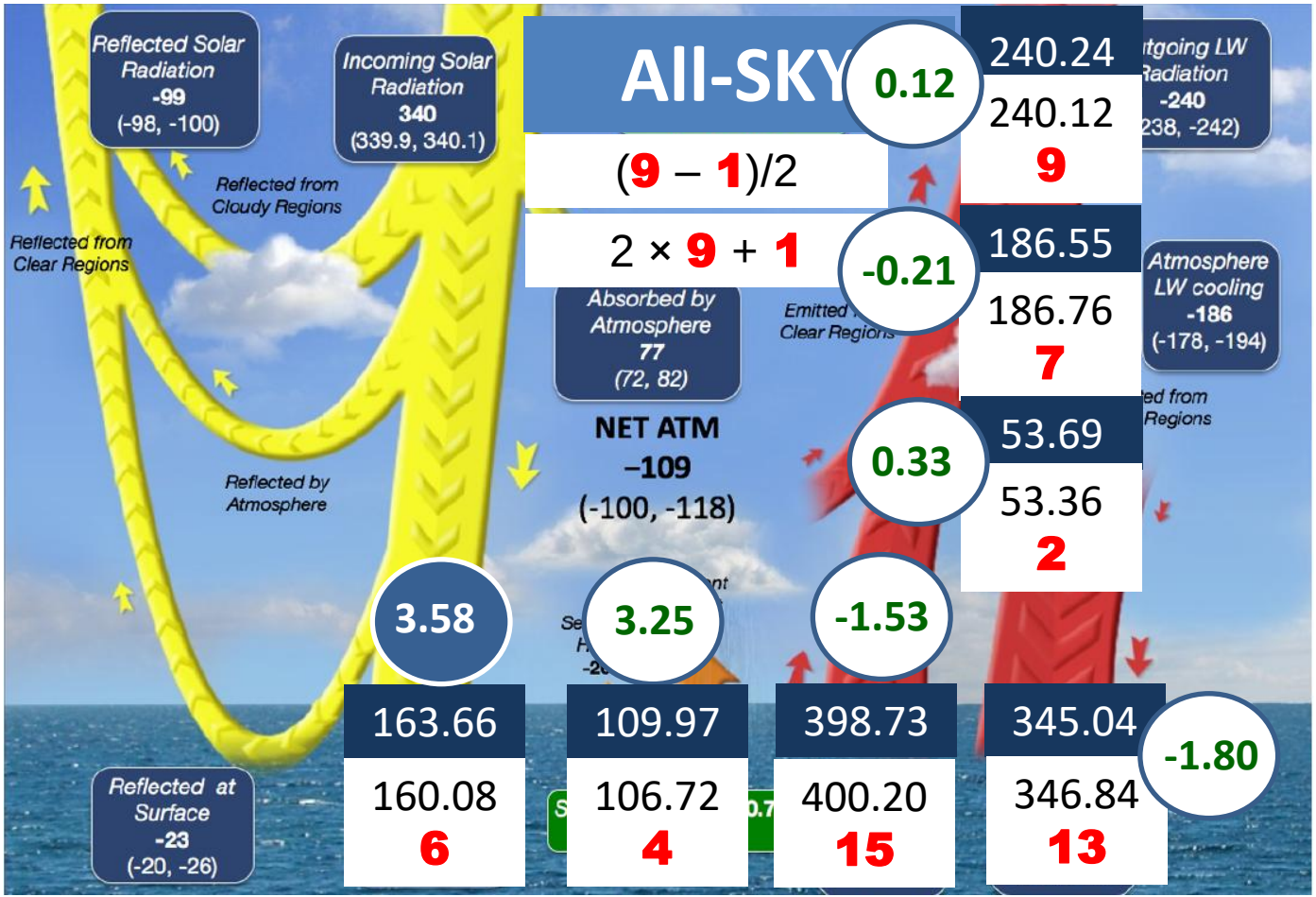


Part II.

Empirical extension

Surface SW Down $\in \mathbb{N}$

Surface SW Net = Surface (SW Down – SW Up)

- Not resolved into its downward and upward components
- CERES EBAF Ed4.1 (July 2000 – June 2021):

- **SFC SW Down (all-sky)** = 186.83 Wm^{-2}
- Integer position = 186.76 = **7** (diff = 0.07 Wm^{-2})

- **SFC SW Down (clear-sky)** = 240.86 Wm^{-2}
- Integer position = 240.12 = **9** (diff = 0.74 Wm^{-2})

TOA SW Up $\in \mathbb{N}$

TOA SW up (TSI, albedo and TOA Net CRE)

- **CERES TOA SW up (all) = 98.98 Wm^{-2}**
- Integer position = 100.05 = **15**/4 (diff = -1.07 Wm^{-2})
- **CERES TOA SW up (clear) = 53.72 Wm^{-2}**
- Integer position = 53.36 = **8**/4 = **2** (diff = 0.36 Wm^{-2}) =>
- **TSI SORCE 17 years = 1360.883 ± 0.5 Wm^{-2}** => 1360.68 = **51**

=> LWCRE = **1** = 26.68 ± 0.01 Wm^{-2}

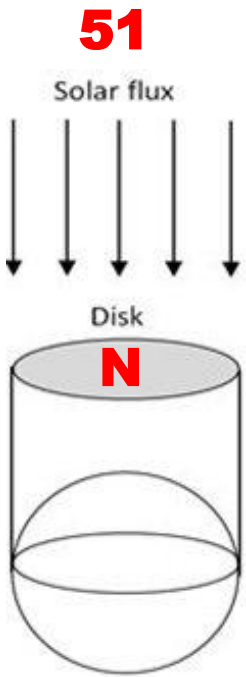
=> α_P (all-sky) = **15**/**51** = 0.294

RSR(all) = **15**/4, ASR(all) = **36**/4, OLR(all) = **36**/4; IMB(all) = 0

RSR(clr) = **8**/4, ASR(clr) = **43**/4, OLR(clr) = **40**/4; IMB(clr) = **3**/4:

ASR(clr) = 286.81 Wm^{-2}, OLR(clr) = 266.80 Wm^{-2}; IMB(clr) = 20.01 Wm^{-2}

=> TOA Net Imbalance (clear) = – TOA Net CRE = – 20.01 Wm^{-2}.



Sensible Heat & Latent Heat $\in \mathbb{N}$

Surface SW+LW net = SH + LH

- CERES EBAF Ed4.1, all, 21-yr = **109.98 Wm^{-2}**
- L'Ecuyer et al. (2015) NEWS = **106 Wm^{-2}**

  Sensible Heat = 25 Wm^{-2}

  Latent Heat = 81 Wm^{-2}
- Integer position (all-sky)

  Sensibe Heat = 26.68 = 1 (diff = **-1.68** Wm^{-2})

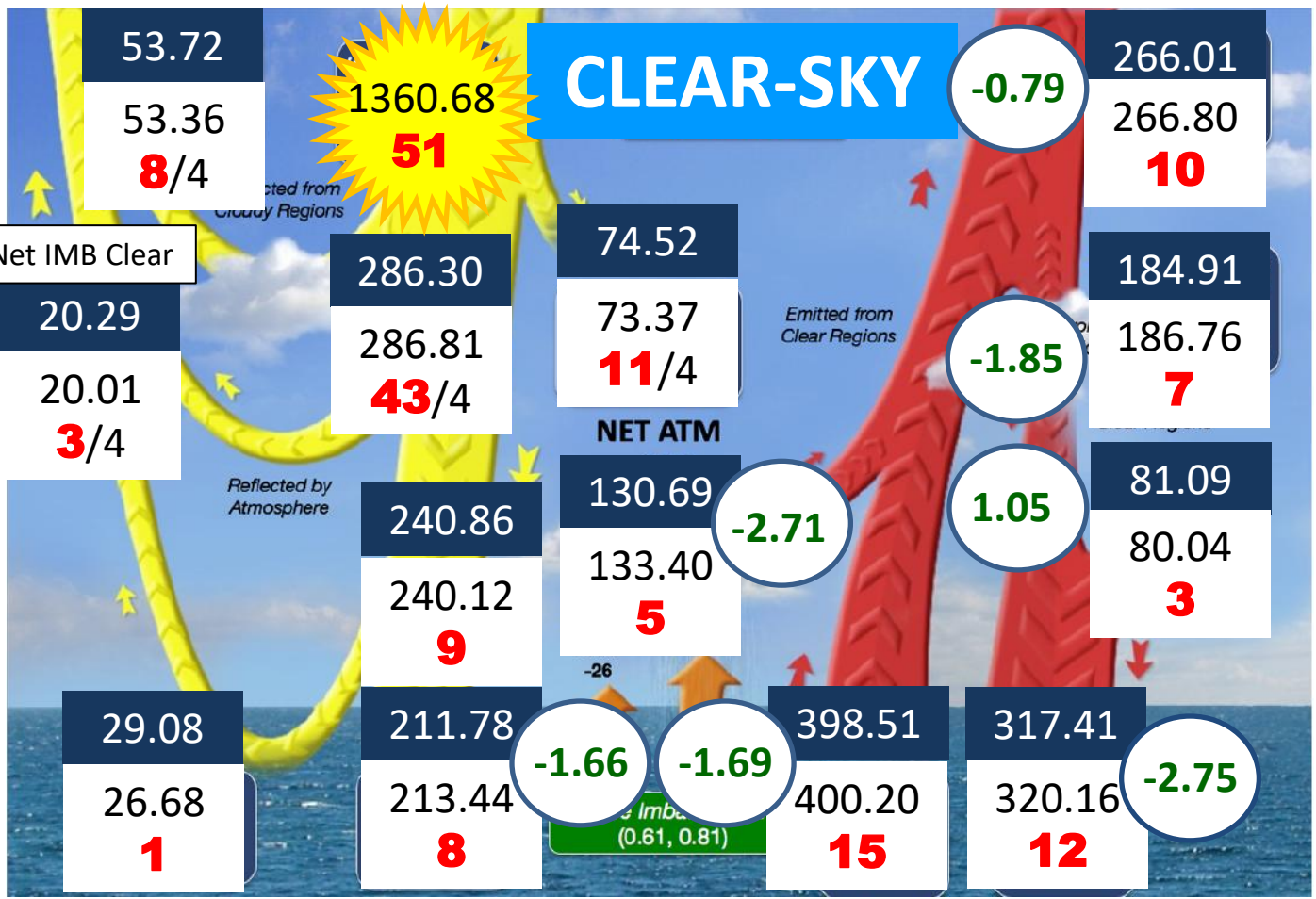
  Latent Heat = 80.04 = 3 (diff = **0.96** Wm^{-2})

  SFC SW+LW Net = 106.72 = 4 (diff = **0.72** Wm^{-2})

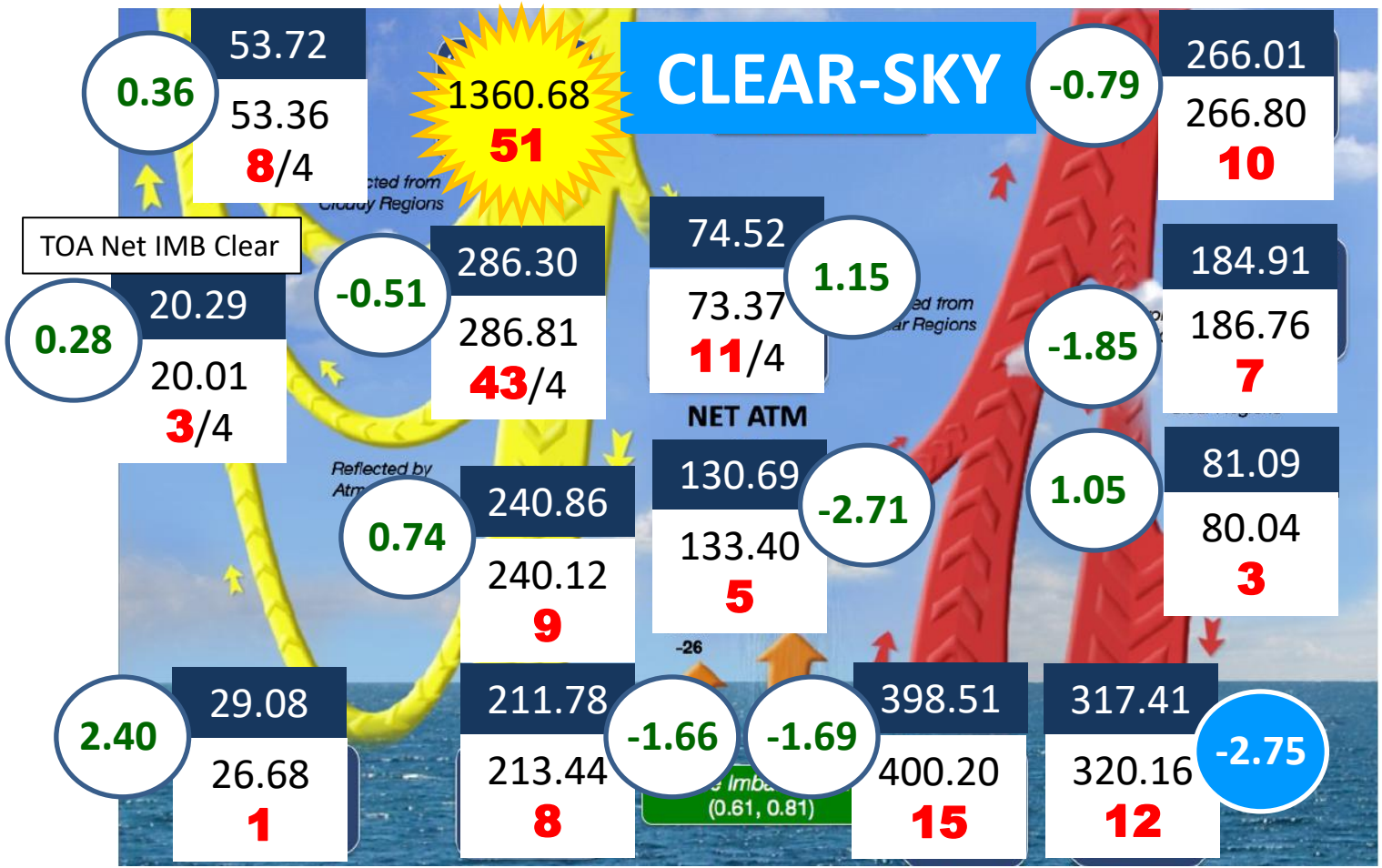
Global means (July2000 – June 2021)

Clear-sky	TSI = 51	N × Unit	EBAF Ed4.1, 252 months	Difference
TOA SW up	2	53.36	53.72	0.36
TOA LW up	10	266.80	266.01	-0.79
SFC SW down	9	240.12	240.86	0.74
SFC SW up	1	26.68	29.08	2.40
SFC LW down	12	320.16	317.41	-2.75
SFC LW up	15	400.20	398.51	-1.69
All-sky	**TSI = 51**			
TOA SW up	15/4	100.05	98.98	-1.07
TOA LW up	9	240.12	240.24	0.12
SFC SW down	7	186.76	186.83	0.07
SFC SW up	1	26.68	23.17	-3.51
SFC LW down	13	346.84	345.04	-1.80
SFC LW up	15	400.20	398.73	-1.47
			Mean difference	**-0.78**

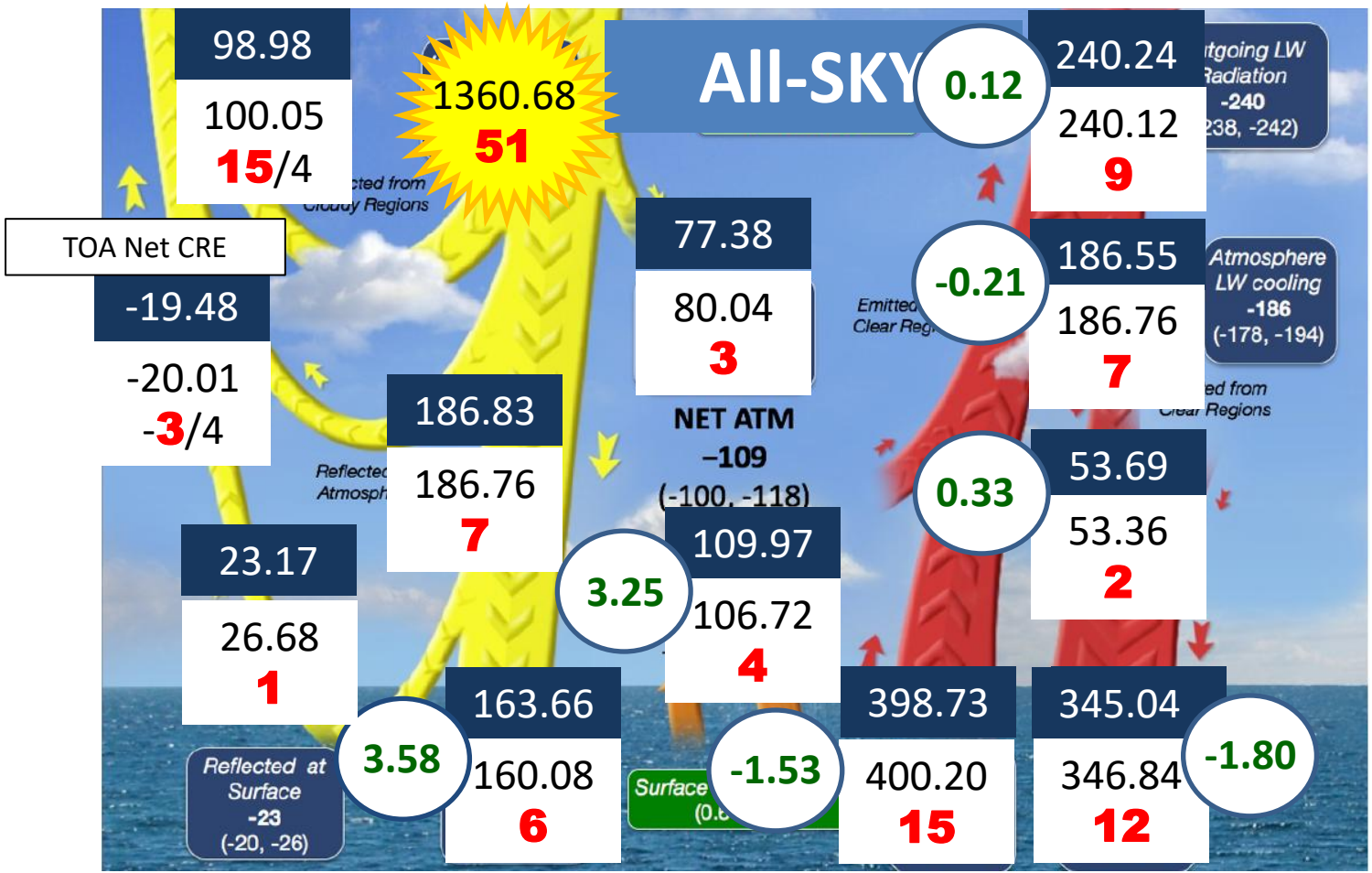
CERES EBAF Ed4.1 (July 2000 – June 2021)



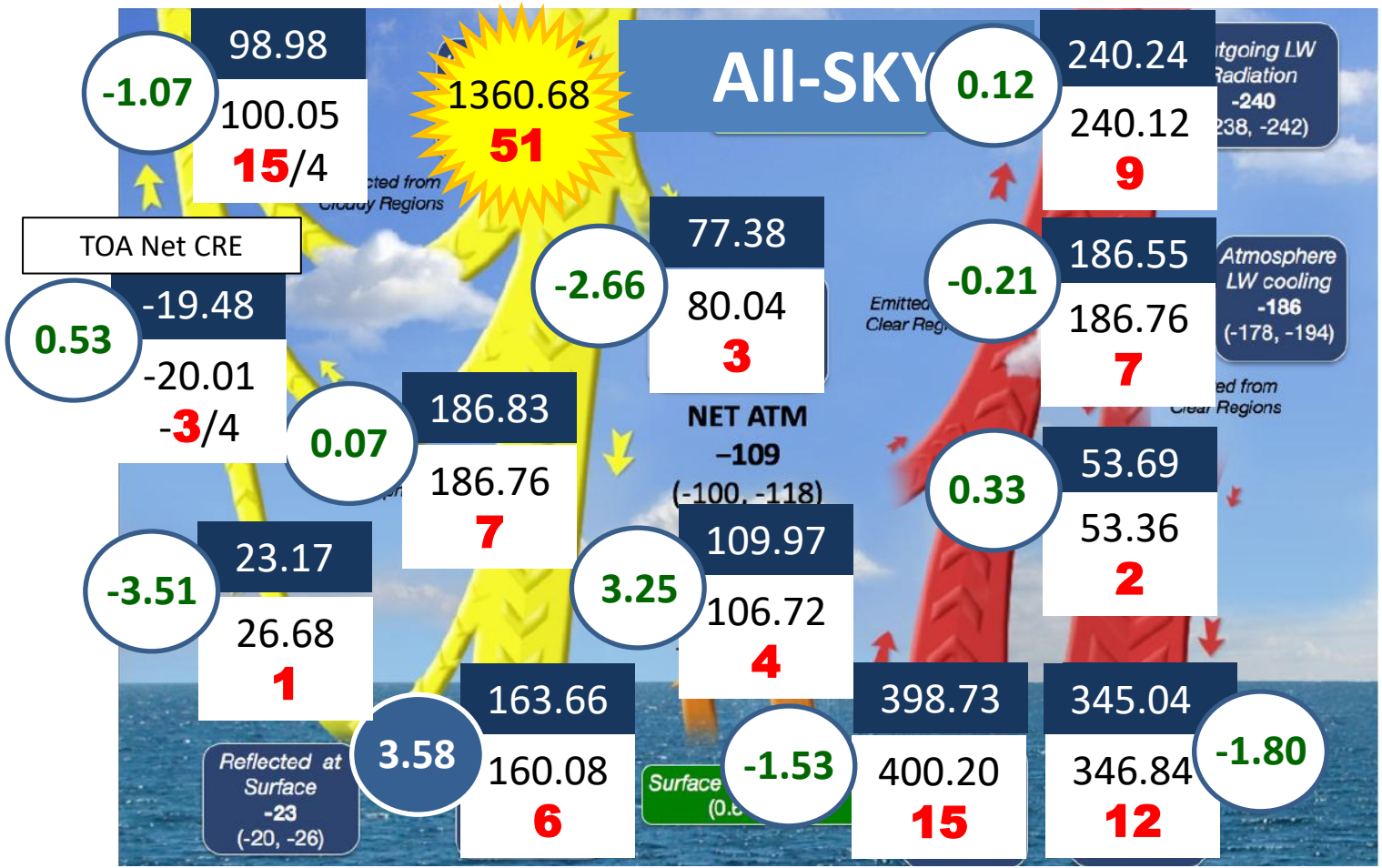
CERES EBAF Ed4.1 (July 2000 – June 2021)



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



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



Clear-Sky Greenhouse Effect at GFDL

LWCRE = **1** = 26.68 ± 0.5 Wm^{-2}

G (theory) = **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

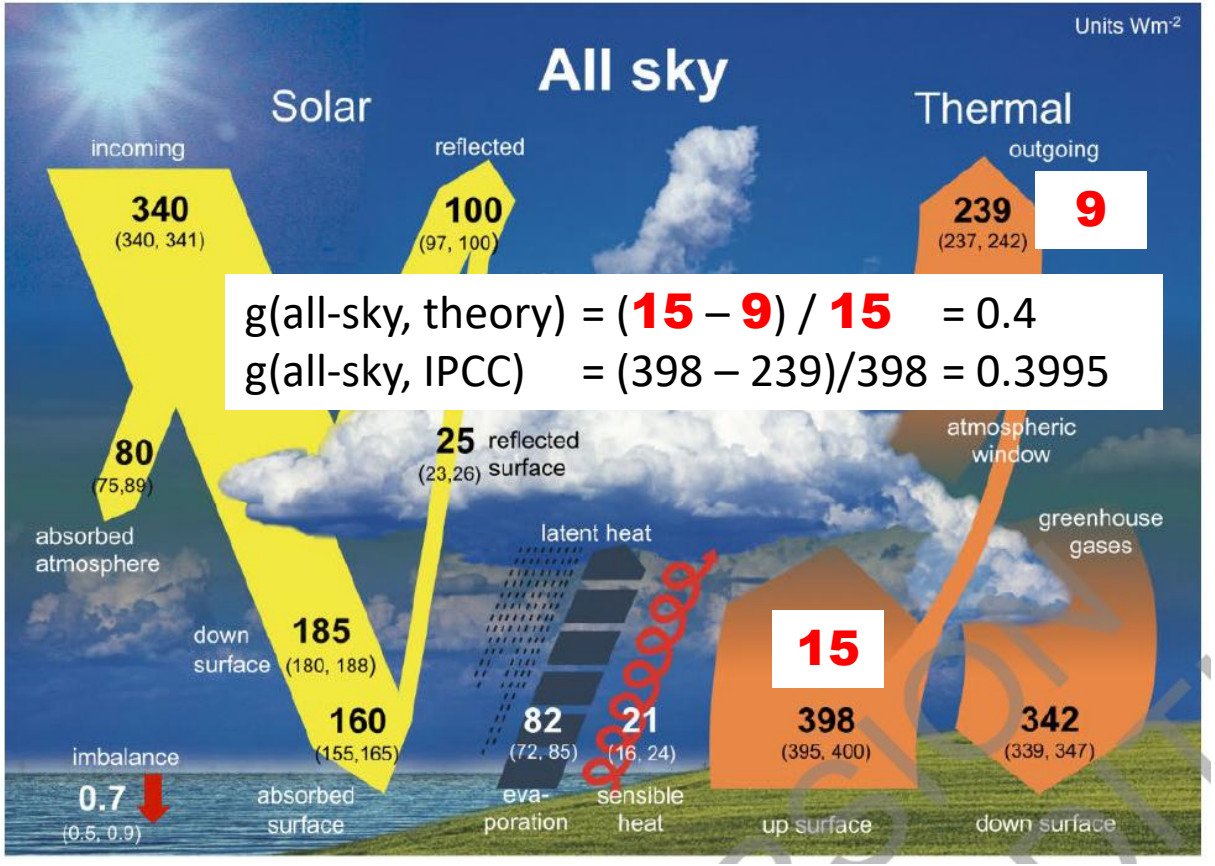
Shiv Priyam Raghuraman, David Paynter, V. Ramaswamy (JGR 2019)

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

All-sky Greenhouse Effect at IPCC



"climate conditions at the beginning of the 21st century"

Summary

- g (clear-sky, theory) = (**15** – **10**)/**15** = 1/3
- g (clear-sky, CERES) = 0.3325

- g (all-sky, theory) = (**15** – **9**)/**15** = 0.4
- g (all-sky, CERES) = 0.3975