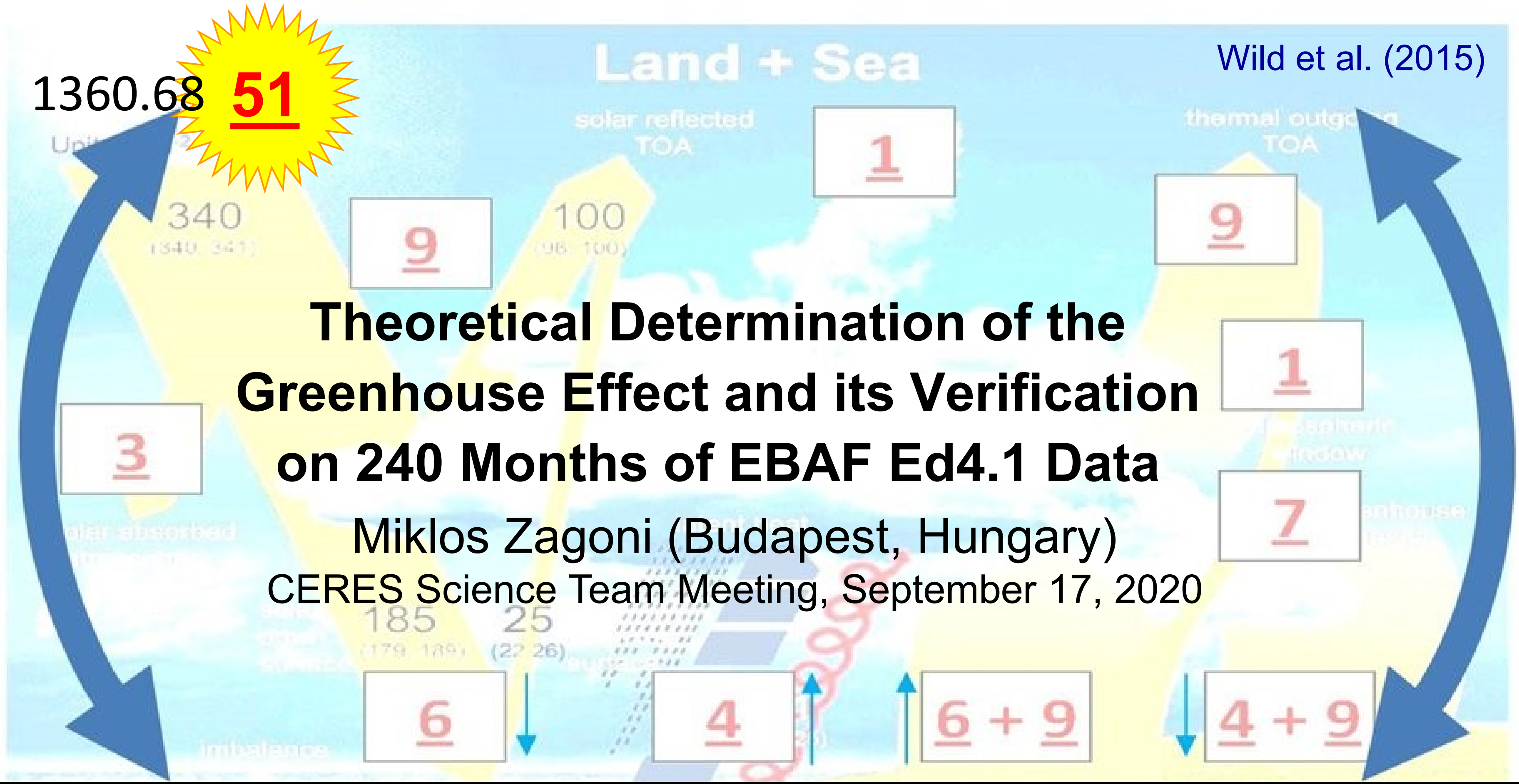
Celebrating 20 Years of CERES Observations



Theoretical Determination of the Greenhouse Effect and its Verification on 240 Months of EBAF Ed4.1 Data

Miklos Zagoni (Budapest, Hungary)

CERES Science Team Meeting, September 17, 2020

*“Denn in **der steten Wechselwirkung zwischen experimenteller und theoretischer Forschung**, die immer zugleich Antrieb und Kontrolle ist, wird auch in Zukunft die sicherste, die einzige Gewähr liegen für den gedeihlichen Fortschritt der physikalischen Wissenschaft .”* — Max Planck

*„Because **the constant interaction between experimental and theoretical research**, which is always inspiration and control, is the safest, the only guarantee of the prosperous progress of physical science.”* — Max Planck

KÖNIGLICH PREUSSISCHEN
AKADEMIE DER WISSENSCHAFTEN.
Vorsitzender Secretar: Hr. PLANCK.

Über Diffusion und Absorption in der Sonnenatmosphäre.

Von K. SCHWARZSCHILD.

(Vorgelegt von Hrn. EINSTEIN am 5. November 1914 [s. oben S. 979].)

Diffusion and Absorption in the Sun's Atmosphere

by K. Schwarzschild

(read by Mr. Einstein at the meeting of the Berlin Academy of Sciences on November 5, 1914)

Einstein read a paper at the meeting of the Berlin Academy of Sciences on November 5, 1914 (chair: Max Planck) in the absence of the author, Karl Schwarzschild, who served as a soldier in World War I. The paper introduced the equation of radiation transfer:

Schw (1914, Eq. 3)

in Liou (1980) An Introduction to Atmospheric Radiation:

1.4.3 Schwarzschild's Equation and Its Solution

Hence, the equation of transfer may be written as

$$\frac{dI_\lambda}{k_\lambda \rho\, ds} = -I_\lambda + B_\lambda(T). \tag{1.55}$$

This equation is called Schwarzschild's equation. The first term in the right-hand side of Eq. (1.55) denotes the reduction of the radiant intensity due to absorption, whereas the second term represents the increase of the radiant intensity arising from blackbody emission of the material. To seek a solution

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in Goody and Yung (1989) Atmospheric Radiation:

$$-\frac{1}{e_{\nu,\nu}}\frac{dI_\nu(P, \mathbf{s})}{ds} = I_\nu(P, \mathbf{s}) - J_\nu(P, \mathbf{s}). \tag{2.17}$$

Equation (2.17) is known as the *equation of transfer*, and was first given in this form by Schwarzschild.

Schwarzschild (1906, Eq. 11):
Two-stream approximation to the same problem

Ueber das Gleichgewicht der Sonnenatmosphäre

Von

K. Schwarzschild.

Vorgelegt in der Sitzung vom 13. Januar 1906.

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

$A - E = A_0/2$ constant net flux independent of m.

On Earth, in radiative-convective equilibrium: surface net radiation (non-radiative fluxes: latent + sensible) constrained to OLR/2.

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

Houghton (2002, Eq. 2.13)
The Physics of Atmospheres, Cambridge University Press

m optische Masse, τ

Houghton (2002)

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

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

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

Eq.(1) $B_g - B_0 = B_{eff}/2$

given in every RT textbook

2.5 The greenhouse effect

Combining (2.12) and (2.13) we find that for the radiative equilibrium atmosphere:

$$B_g = \frac{\phi}{2\pi}(\chi_0^* + 2) \quad (2.15)$$

In the specific case of optical depth $\chi^*_0 = 2$,

My Eq.(3) Surface gross (total) absorption: $B_g = 2B_{eff}$

But why optical depth $\chi^*_0 = 2$? Can it be real? A first check:

Rose et al (2017) Global Means(Mar2000-Feb2016) *CERES 27th STM*

All Sky	**Ed4**	**Ed2.8**	**Ed4 –Ed2.8**
TOA SW Insolation	340.04	339.87	0.17
TOA SW Up	*99.23*	*99.62*	*-0.39*
TOA LW Up	*240.14*	*239.60*	*0.54*
SFC SW Down	187.04	186.47	0.57
SFC SW Up	23.37	24.13	-0.76 (3.1%)
SFC LW Down	344.97	345.15	-0.18
SFC LW Up	398.34	398.27	0.07

Clear Sky	**Ed4**	**Ed2.8**	**Ed4 –Ed2.8**
TOA SW Insolation	340.04	339.87	0.17
TOA SW Up	*53.41*	*52.50*	*0.91 (1.73%)*
TOA LW Up	*268.13*	*265.59*	*2.54*
SFC SW Down	243.72	244.06	-0.33
SFC SW Up	29.81	29.74	0.07
SFC LW Down	314.07	316.27	-2.20
SFC LW Up	397.59	398.40	-0.81

Data from Rose et al (2017, Ed2.8)

- TOA LW up (clear) = 265.59
- SFC SW down (clear) = 244.06
- SFC SW up (clear) = 29.74
- SFC SW net (clear) = 214.32
- SFC LW down (clear) = 316.27
- SFC LW up (clear) = 398.40

ΔEq.(1) = –0.60

ΔEq.(3) = –0.59

Eq.(3) Surface gross (total) absorption = 2OLR

SFC SW net + LW down = 214.32 + 316.27 = 2 × 265.59 – **0.59** Wm^{-2}

Loeb et al. (2013):

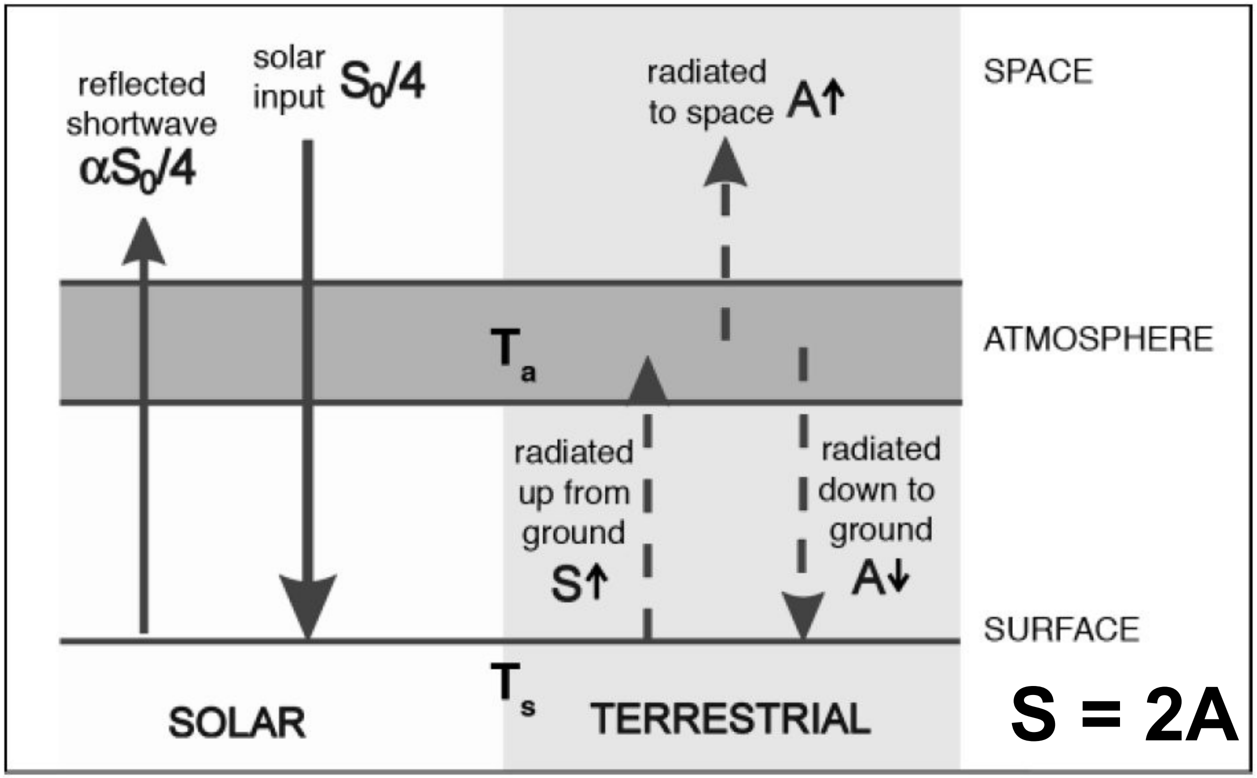
=> Net planetary imbalance for July 2005-June 2010: 0.58±0.43 Wm^{-2}

What does Eq. (3) mean ?

(A theory / explanation / interpretation)

The simplest greenhouse model

Marshall and Plumb (2008)



S = 2A (Eq3)

FIGURE 2.7. The simplest greenhouse model, comprising a surface at temperature T_s, and an atmospheric layer at temperature T_a, subject to incoming solar radiation $S_0/4$. The terrestrial radiation upwelling from the ground is assumed to be completely absorbed by the atmospheric layer.

Further, $G = S - A = A = S_0(1 - \alpha)/4$, solar absorbed surface

Hartmann (1994, Fig. 2.3)

Global Physical Climatology

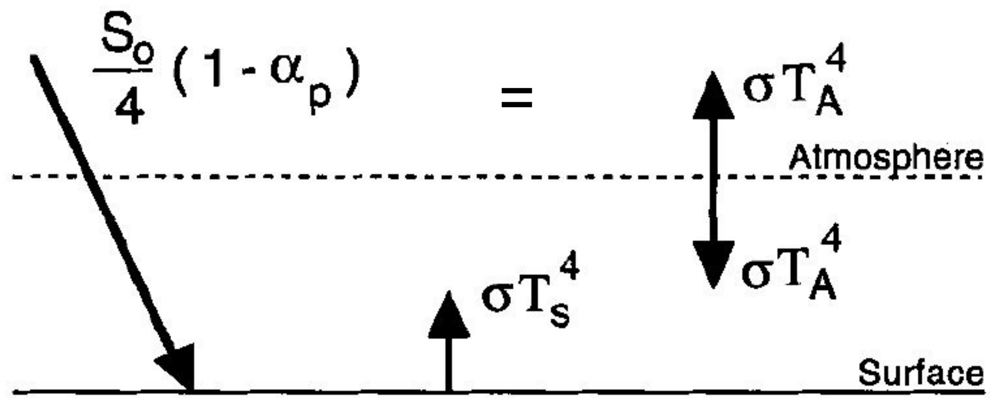


Fig. 2.3 Diagram of the energy fluxes for a planet with an atmosphere that is transparent for solar radiation but opaque to terrestrial radiation.

$$\sigma T^4_S = 2\sigma T^4_A \quad \text{(Eq3)}$$

and, of course,

$$G = \sigma(T_S{}^4 - T_A{}^4) = \sigma T_A{}^4 = S_0(1 - \alpha_p)/4 \text{ solar absorbed surface}$$

Liou (1980)

$$Q(1-\bar{r}) - \bar{\varepsilon}\sigma T_a^4 - (1-\bar{\varepsilon})\sigma T^4 = 0, \qquad \text{TOA} \qquad (8.31)$$

$$Q(1-\bar{r}-\bar{A}) + \bar{\varepsilon}\sigma T_a^4 - \sigma T^4 = 0, \qquad \text{SFC} \qquad (8.32)$$

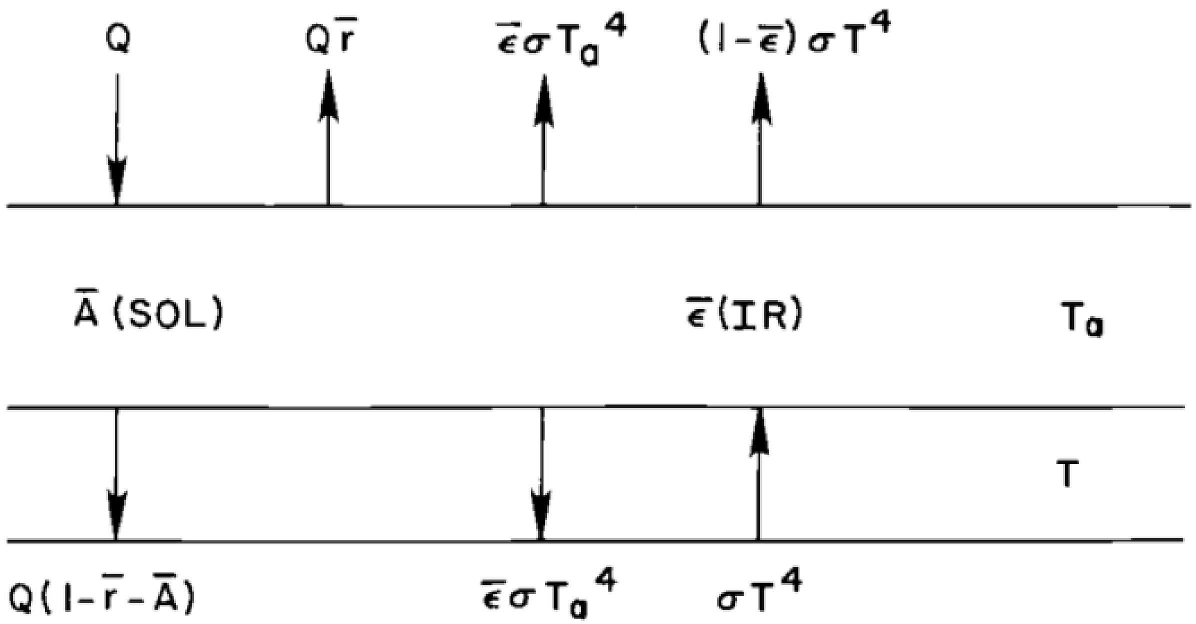


Fig. 8.20 Two-layer global radiative budget model.

In the case of $A = 0$ and $\varepsilon = 1$, it follows that $\boldsymbol{\sigma T^4 = 2\sigma T_a^4}$, and

$\mathbf{G = \sigma T^4 - (\varepsilon\sigma T_a^4 + (1 - \varepsilon)\sigma T^4) = Q(1 - r - A)}$ even if $\mathbf{A \neq 0}$

But wait … $\bar{\varepsilon} \neq 1$

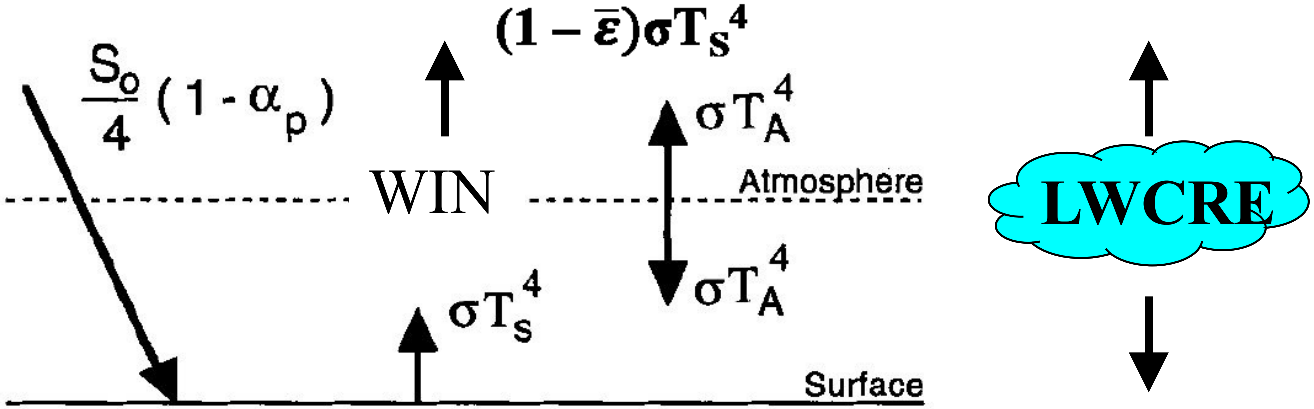


Fig. 2.3 Diagram of the energy fluxes for a planet with an atmosphere that is transparent for solar radiation but opaque to terrestrial radiation.

If (hypothesis) on Earth we have **LWCRE ≈ WIN(all)**, **clouds might compensate for the lost energy.**

K. Shine (2012): WIN (clear) = 66 Wm^{-2}

Their computed WIN(all) = 22 Wm^{-2} with $\beta_{obs} = 0.67$ and IR-opaque clouds

WIN(all) = WIN(clear) × $(1 - \beta_{eff})$ = 26.4 Wm^{-2} with $\beta_{eff} = 0.6$

At least, not impossible.

Further details in Zagoni EGU 2020 and forthcoming AGU2020.

What does it follow from Eq. (1) and Eq. (3)?

Theory: clear-sky, net and gross

Eq. (1) $B_g - B_0 = B_{eff}/2$

Eq. (3) $B_g = 2B_{eff}$

=> $B_g : B_0 : B_{eff} : B_{Green}$ = **4 : 3 : 2 : 1**

where $B_{Green} = B_0 - B_{eff}$ (G = ULW – OLR)

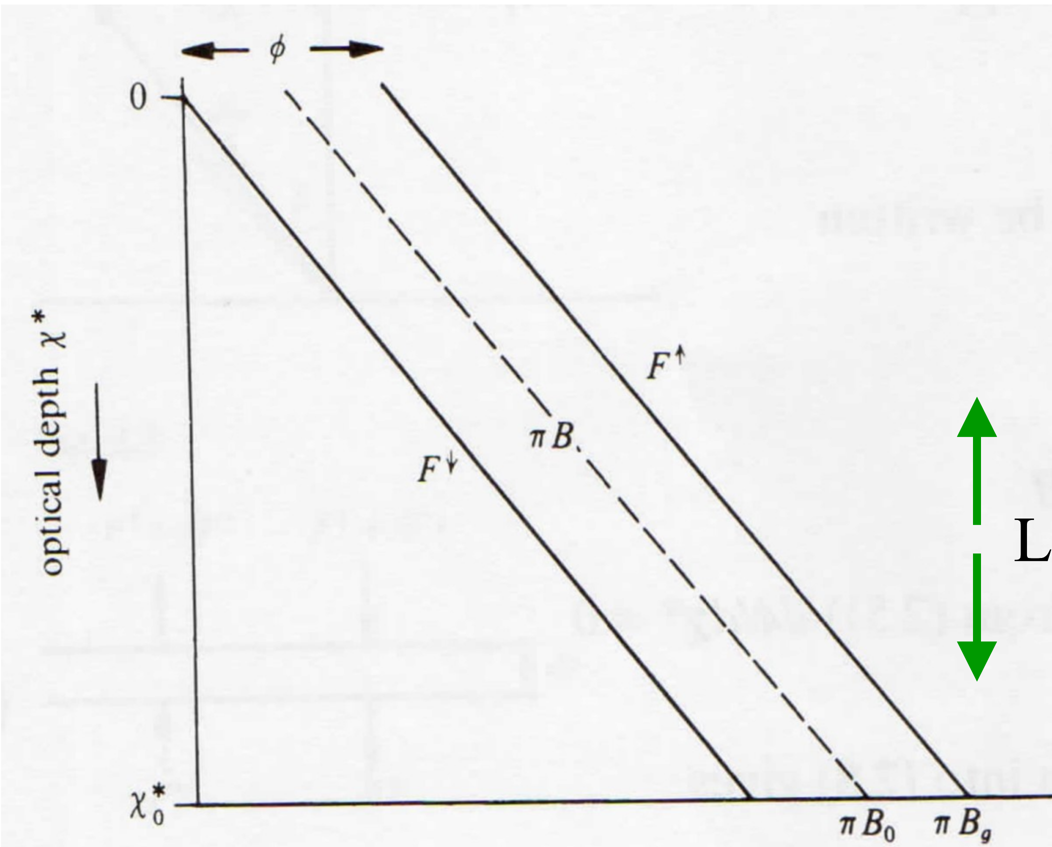
=> **4 : 3 : 2 : 1** = **20 : 15 : 10 : 5**, "all-sky units"

Theory:

=> **g normalized greenhouse effect (greenhouse factor) =**

= B_{Green} / B_0 = (ULW – OLR) / ULW = 5/15 = 1/3.

Creating the all-sky version (Eq2) from Eq1
Houghton (2002, Fig. 2.4)



Eq1 (clear-sky)
$$B_g - B_0 = B_{eff} / 2$$

My Eq2 (all-sky)
$$B_g - B_0 = (B_{eff} - L)2$$

Separating atmospheric radiation from longwave cloud effect (L):

Eq2 $$B_g - B_0 = (B_{eff} - L)/2$$ **(surface net, all-sky)**

Creating the all-sky version (Eq4) from Eq3

Hartmann (1994, Fig. 2.3)

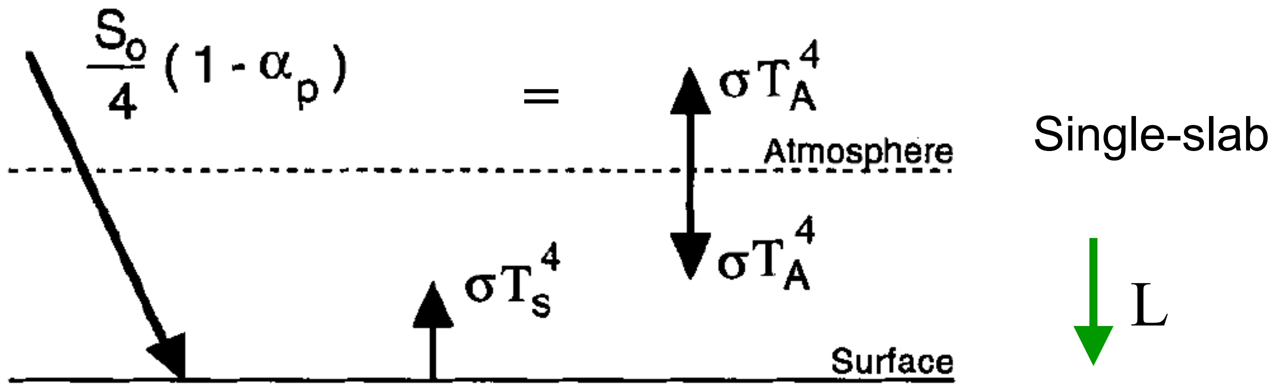


Fig. 2.3 Diagram of the energy fluxes for a planet with an atmosphere that is transparent for solar radiation but opaque to terrestrial radiation.

atmosphere and the surface. The atmospheric energy balance gives

$$\sigma T_s^4 = 2\sigma T_A^4 \quad \Rightarrow \quad \sigma T_s^4 = 2\sigma T_e^4 \qquad (2.12)$$

and the surface energy balance is consistent:

$$\frac{S_0}{4}\left(1-\alpha_p\right)+\sigma T_A^4 = \sigma T_s^4 \quad \Rightarrow \quad \sigma T_s^4 = 2\sigma T_e^4 \qquad (2.13)$$

Eq3 Surface total (gross) SW + LW energy income: $B_g = 2B_{eff}$

Eq4 Adding cloud effect, the surface absorption is: $B_g = 2B_{eff} + L$

The equations and their integer solution

Global mean $F = F_0 + \Delta F$, where F_0 = N × UNIT; UNIT = 1 = LWCRE

ΔF = observation uncertainty + natural fluctuation + systematic deviation

Eq. (1) Surface SW net + LW net (clear) = TOA LW(clear) /2

Eq. (2) Surface SW net + LW net (all) = (TOA LW(all) – **LWCRE**) /2

Eq. (3) Surface SW net + LW down (clear) = 2TOA LW(clear)

Eq. (4) Surface SW net + LW down (all) = 2TOA LW(all) + **LWCRE**

Surface LW up, clear-sky	= **15**	Surface LW up, all-sky	= **15**
Surface SW net, clear-sky	= **8**	Surface SW net, all-sky	= **6**
Surface LW net, clear-sky	= **–3**	Surface LW net, all-sky	= **–2**
Surface SW+LW net, clr-sky	= **5**	Surface SW+LW net, all-sky	= **4**
Surface SW+LW gross, clear	= **20**	Surface SW+LW gross, all	= **19**
Surface LW down, clear-sky	= **12**	Surface LW down, all-sky	= **13**
OLR clear-sky	= **10**	OLR all-sky	= **9**
G greenhouse effect, clear-sky	= **5**	G greenhouse effect, all-sky	= **6**
SWCRE (surface)	= **–2**	LWCRE (surface, TOA)	= **1**
g(clear-sky) = **5/15**	= 1/3	g(all-sky) = **6/15**	= **0.4**.

Best fit 1 = 26.68 Wm^{-2}

So much about theory. And now, the experimental research.

Data from Rose et al (2017, Ed2.8)

- TOA LW up(clear) = 265.59 Wm^{-2}
- SFC LW up(clear) = 398.40 Wm^{-2}
- G (clear) = 132.81 Wm^{-2}

- g(clear) = G(clear) / SFC LW up =
  = 132.81 / 398.40
  = 0.3333
- g(clear, theory) = 1/3.


20
CERES

Celebrating 20 years of CERES Data
EBAF Ed4.1, April 2000 — March 2020

Eq. (1) SFC SW+LW net (clear-sky) = OLR(clear-sky)/2

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

CERES 20-yr	F	N × UNIT	F_0	ΔF
SFC SW net	211.73	**8** × 26.68	**213.44**	**−1.71**
SFC LW down	317.44	**12** × 26.68	**320.16**	**−2.72**
SFC LW up	398.44	**15** × 26.68	**400.20**	**−1.76**
TOA LW up	266.02	**10** × 26.68	**266.80**	**−0.78**
SW+LW net	130.73	**5** × 26.68	**133.40**	**−2.67**
G	132.42	**5** × 26.68	**133.40**	**−0.98**

Eq. (1) 8 + 12 – 15 = 5 = 10/2 **– 2.28**

g(clear-sky, theory) = 5/15 = 1/3.

g(clear-sky) = 132.43/398.44 = 0.3323

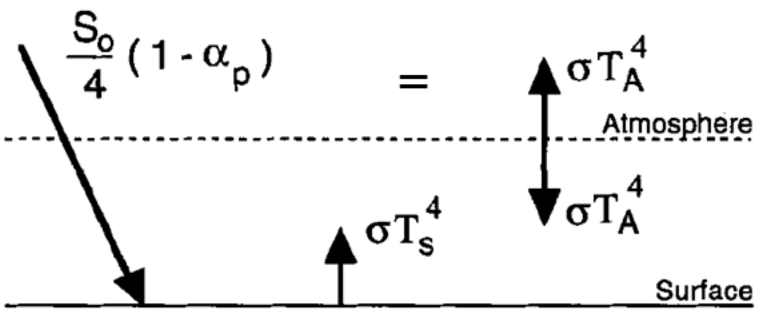
Eq. (2) SFC SW+LW net = (OLR – LWCRE)/2, all-sky

CERES 20-yr	F	N × UNIT	F_0	ΔF
SFC SW net	163.57	6 × 26.68	**160.08**	**3.49**
SFC LW down	345.13	13 × 26.68	**346.84**	**–1.71**
SFC LW up	398.66	15 × 26.68	**400.20**	**–1.54**
TOA LW up	240.21	9 × 26.68	**240.12**	**0.09**
LWCRE	25.81	1 × 26.68	**26.68**	**-0.87**
SW+LW net	110.04	4 × 26.68	**106.72**	**3.32**
(OLR – LWCRE)/2	107.20	4 × 26.68	**106.72**	**0.48**
G	158.45	6 × 26.68	**160.08**	**–1.63**

Eq. (2) 6 + 13 – 15 = 4 = (9 – 1)/2 **2.84**
g(all-sky, theory) = 6/15 = 0.4.
g(all-sky) = (398.66 – 240.21)/398.66 = 0.3975

ΔSFC SW net = 3.49 Wm^{-2} the largest individual bias on the whole data set

Eq. (3) SFC SW net + LW down (clear) = 2OLR(clear)



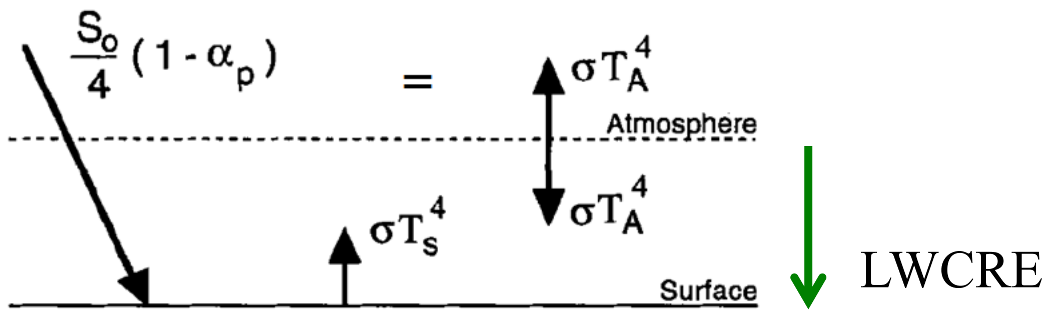
$$\sigma T^4{}_S = 2\sigma T^4{}_A$$

CERES 20-yr	F	N × UNIT	F_0	ΔF
SFC SW net	211.73	8 × 26.68	**213.44**	–1.71
SFC LW down	317.44	12 × 26.68	**320.16**	–2.72
SW net + LW down	529.17	20 × 26.68	**533.60**	–4.43
TOA LW up	266.02	10 × 26.68	**266.80**	–0.72

Eq. (3) 8 + 12 = 20 = 2 × 10 **–2.88**

ΔSFC SW net + LW down = –4.43 Wm^{-2} the largest composite bias on the whole data set

Eq. (4) SFC SW net + LW down (all) = 2OLR(all) + LWCRE



CERES 20-yr	F	N × UNIT	F_0	ΔF
SFC SW net	163.57	6 × 26.68	**160.08**	3.49
SFC LW down	345.13	13 × 26.68	**346.84**	–1.71
TOA LW up	240.21	9 × 26.68	**240.12**	0.09
LWCRE	25.81	1 × 26.68	**26.68**	-0.87
SW net + LW down	508.70	19 × 26.68	**506.92**	1.78
2OLR + LWCRE	506.23	19 × 26.68	**506.92**	–0.69

Eq. (4) 6 + 13 = 19 = 2 × 9 + 1 2.46

Mean bias of the four equations

$$\left.\begin{array}{ll}\bullet\ \text{Net (clear-sky)} & \Delta Eq1 = -2.28\\ \bullet\ \text{Net (all-sky)} & \Delta Eq2 = 2.84\end{array}\right\}\ 0.28$$

$$\left.\begin{array}{ll}\bullet\ \text{Gross (clear-sky)} & \Delta Eq3 = -2.88\\ \bullet\ \text{Gross (all-sky)} & \Delta Eq4 = 2.46\end{array}\right\}\ -0.21$$

mean = **0.035 Wm^{-2}**

$$\left.\begin{array}{ll}\bullet\ \text{Clear-sky (net)} & \Delta Eq1 = -2.28\\ \bullet\ \text{Clear-sky (gross)} & \Delta Eq3 = -2.88\end{array}\right\}\ -2.58$$

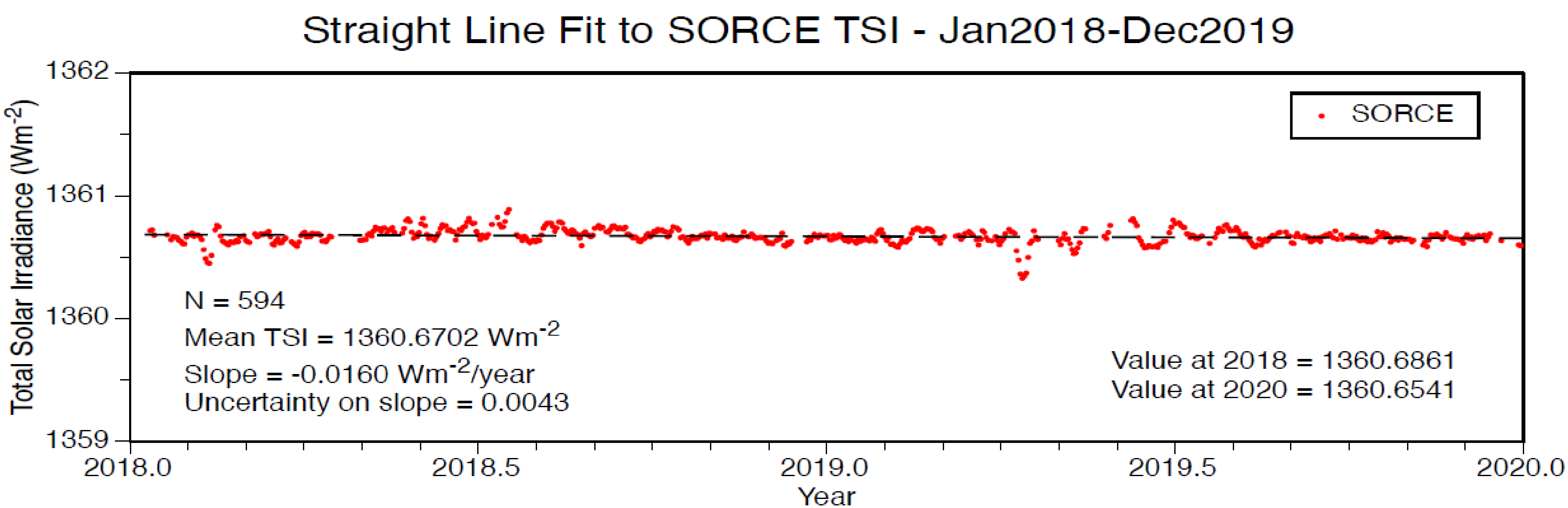
$$\left.\begin{array}{ll}\bullet\ \text{All-sky (net)} & \Delta Eq2 = 2.84\\ \bullet\ \text{All-sky (gross)} & \Delta Eq4 = 2.46\end{array}\right\}\ 2.65$$

mean = **0.035 Wm^{-2}**

Extension to Total Solar Irradiance

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



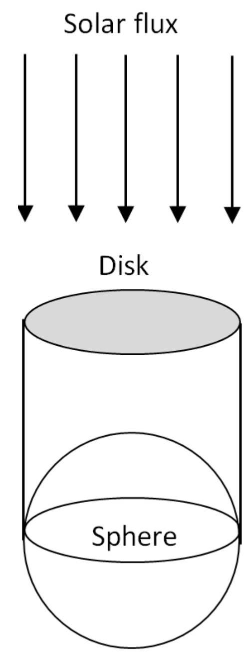
TSI = 1360.670 Wm^{-2}, value at 2018 = 1360.686 Wm^{-2}

Accuracy of TOA Fluxes

clear-sky for total area, EBAF Ed4.1, 04/2000 – 03/2020

Flux name, F	N	$F = F_0 + \Delta F$	F_0 = N × UNIT	ΔF
SW clear-sky	**8** / 4	53.76	53.36	**0.40**
LW clear-sky	**40** / 4	266.02	266.80	**-0.78**
SW all-sky	**15** / 4	99.04	100.05	**-1.01**
LW all-sky	**36** / 4	240.21	240.12	**0.09**
TOA LW CRE	**4** / 4	25.81	26.68	**-0.87**
TOA SW CRE	**-7** / 4	-45.28	-46.69	**1.41**
TOA Net CRE	**-3** / 4	-19.47	-20.01	**0.54**
Albedo, clear	**8** / **51**	0.158	0.157	**0.001**
Albedo, all	**15** / **51**	0.291	0.294	**-0.003**

1360.68 ± 0.5 Wm^{-2}



Each flux is an integer on the intercepting cross-section disk

Mean TSI = **51** = 1360.68 ± 0.5 Wm^{-2} => UNIT = **1** = 26.68 ± 0.01 Wm^{-2}

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

All-sky: SW up = **15** SW in = **36** LW up = **36**

The Clear-Sky Greenhouse Effect at GFDL

SORCE TSI = **51** = 1360.68 ± 0.5 Wm^{-2}

=> G(clear-sky) = **5** = 133.40 ± 0.05 Wm^{-2}

G(GFDL AM4) = 133.4 ± 0.6 Wm^{-2} **ΔF = 0.0**

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

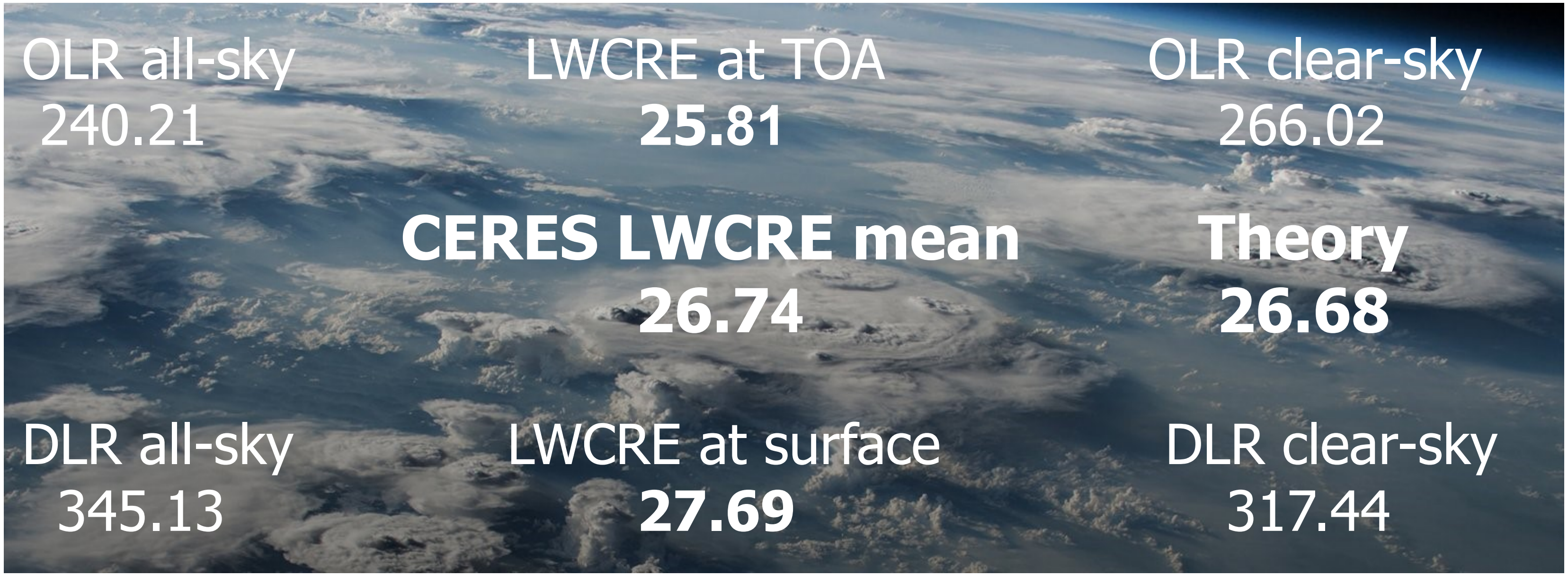
Shiv Priyam Raghuraman[1], David Paynter[2], and V. Ramaswamy[2] (2019)

[1]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA, [2]Geophysical Fluid Dynamics Laboratory, NOAA, Princeton, NJ, USA

Table 2
Global Mean and Time Mean G Comparison Between Observational, Reanalysis, and Modeling Data Sets Over March 2000 to August 2016

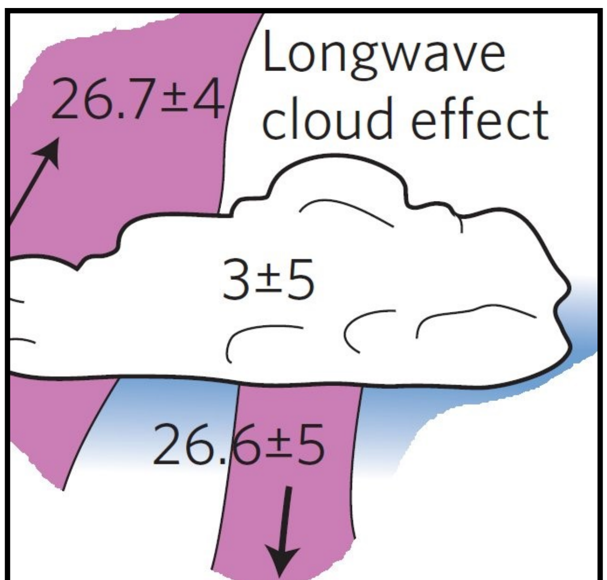
Quantity	ERBE	CE 4.1 "c"	CE 4.1 "t"	ERA-Interim	GFDL AM4
G_{Oceans}	146 ± 7	131.3 ± 0.5	134.1 ± 0.5	134.8 ± 0.6	135.0 ± 0.5
G	–	129.7 ± 0.6	132.4 ± 0.6	133.1 ± 0.7	133.4 ± 0.6

The Greenhouse Effect of Clouds, ΔF(CERES) = 0.06 Wm^{-2}



Stephens et al. (2012) LWCRE mean = 26.65 Wm^{-2}

ΔF(Stephens) = -0.03 Wm^{-2}



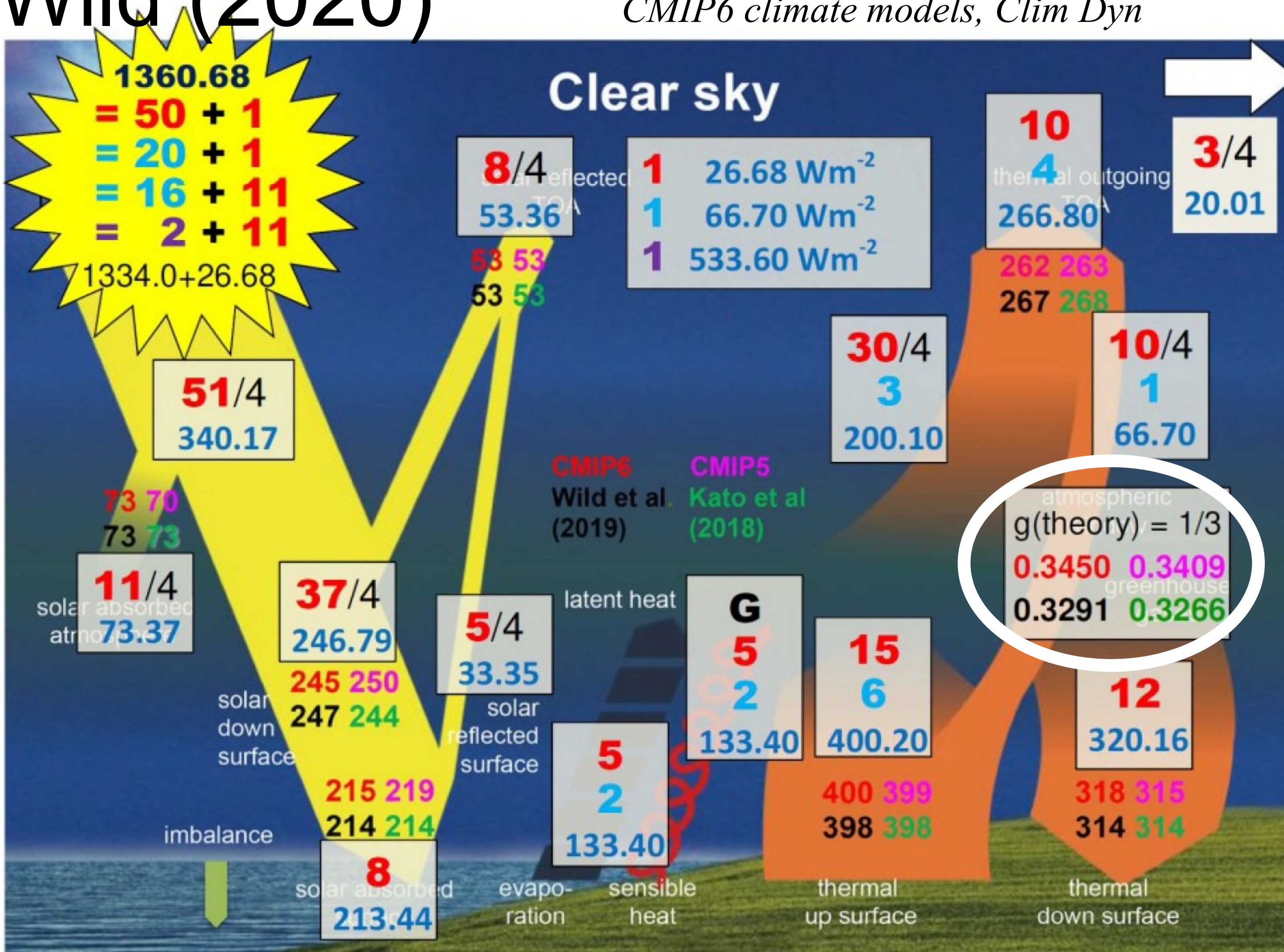
LWCRE Theory

1 = TSI/51
= 1360.68/51
= 26.68 Wm^{-2}

CERES – Theory:
0.06 Wm^{-2}

Wild (2020)

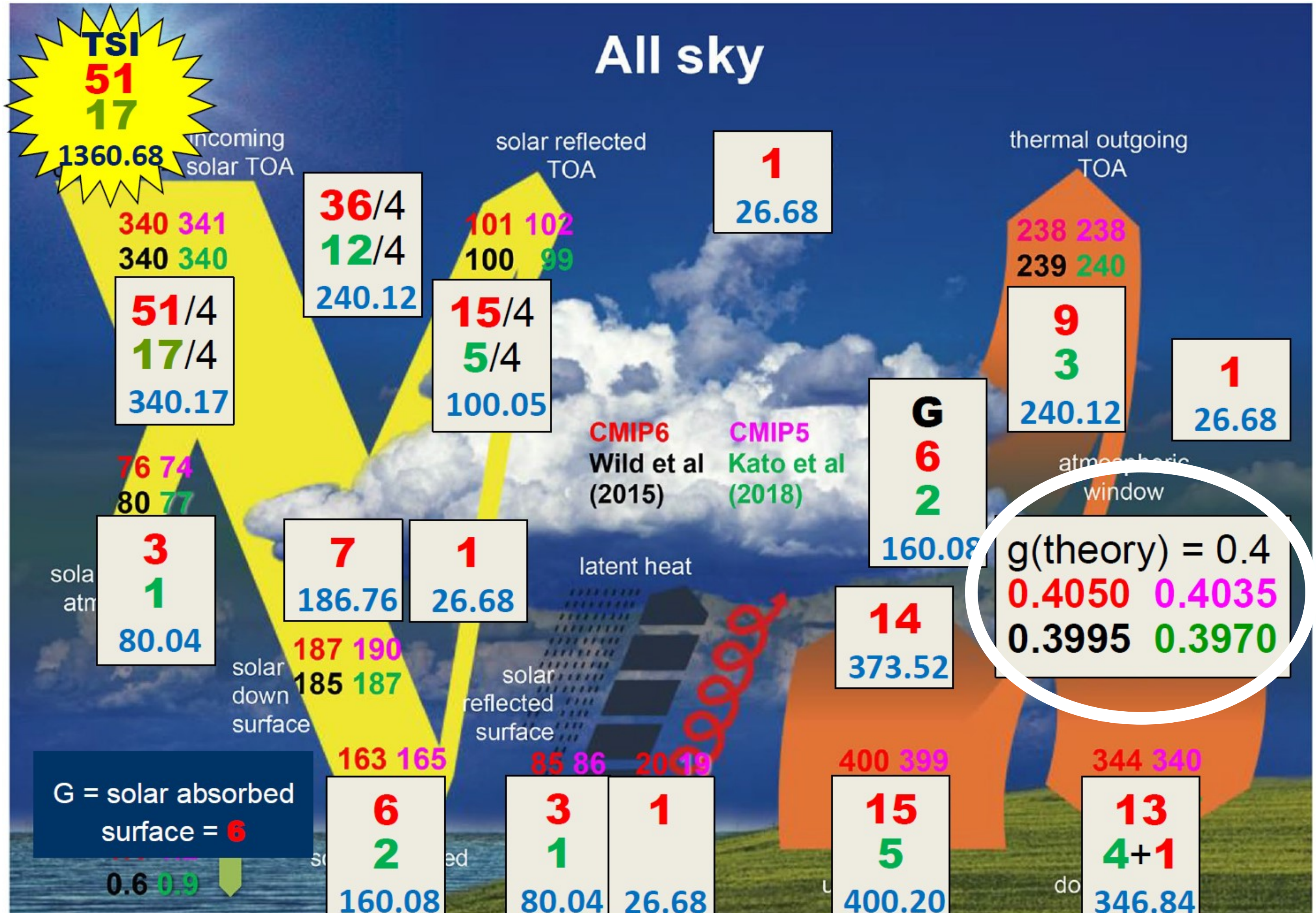
The global energy balance as represented in CMIP6 climate models, Clim Dyn



$\Delta B_g = B_{eff}/2$ (**5**, **2**) = G; $B_0 = 3/2\ B_{eff}$ (**15**, **6**); $B_g = 2B_{eff}$ (**20**; **8**; **1**)

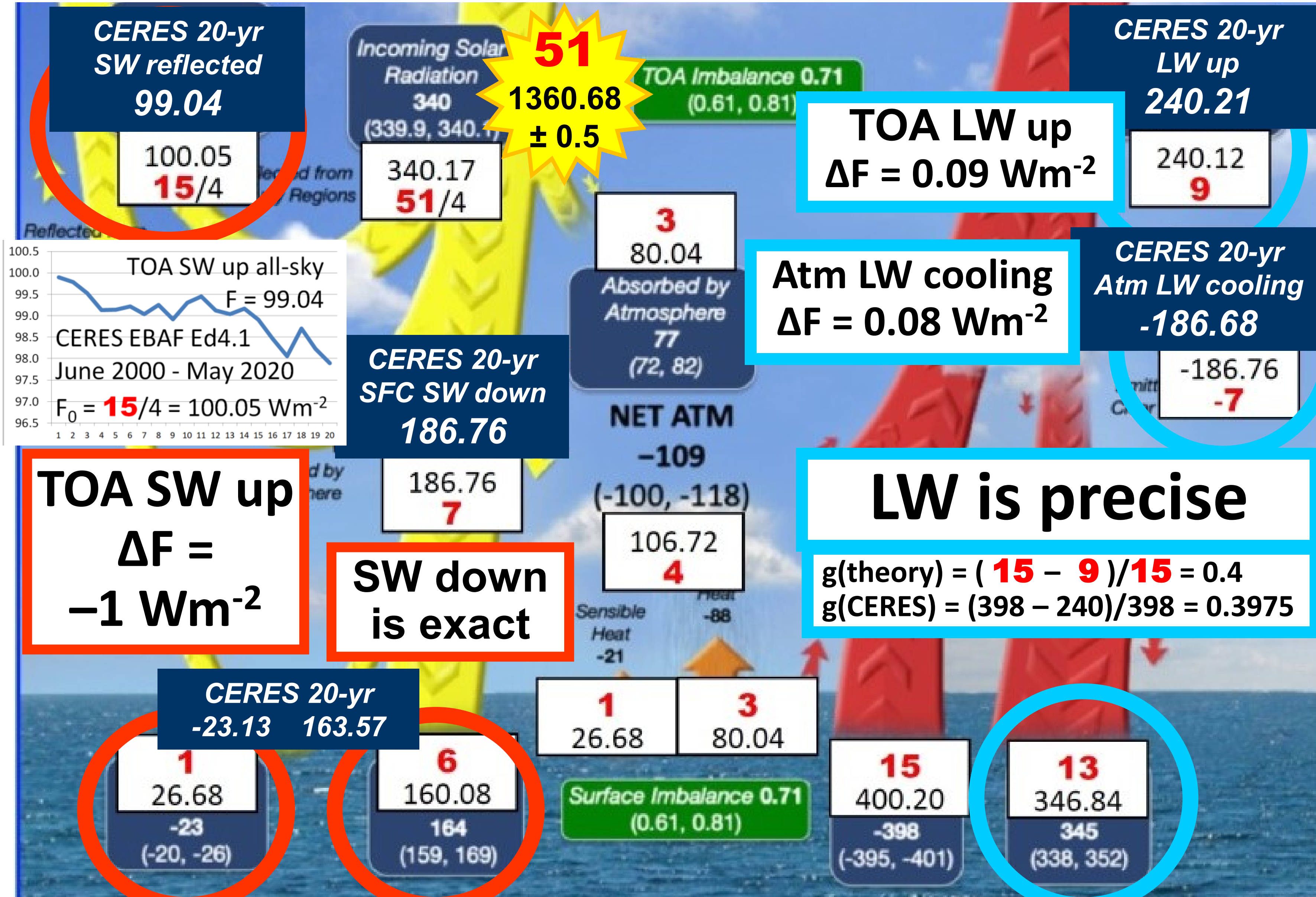
Wild (2020)

The global energy balance as represented in CMIP6 climate models, Clim Dyn



SFC SW net + LW net = (OLR – LWCRE)/2 (4; 1+1); SFC SW net + LW down = 2OLR + LWCRE (19; 6+1)

Your recent approach to imbalance: EEI = *f*(GHG, LW)



SFC SW up ΔF = –3.55 Wm^{-2}

I propose to consider EEI = *f*(SW)

Understanding 20 Years of CERES Data

Clear-sky

Flux	ISR	TOA SW up	TOA LW up	Net CRE	SFC SWnet	SFC LW dn	SFC LW up	g clear	albedo clear
F	**340.02**	**53.76**	**266.02**	**-19.47**	**211.73**	**317.44**	**398.44**	**0.3323**	**0.158**
F_0	340.17	53.36	266.80	-20.01	213.44	320.16	400.20	1/3	0.157
ΔF	**-0.15**	**0.40**	**-0.78**	**0.54**	**-1.71**	**-2.72**	**-1.76**	**-0.001**	**0.001**
N	**51**/4	**8**/4	**40**/4	**3**/4	**8**	**12**	**15**	**5**/**15**	**8**/**51**

ΔEq1 (clear, net) = **-2.28**

ΔEq3 (clear, gross) **= -2.88**

All-sky

Flux	TOA SW up	TOA LW up	SFC SW dn	SFC SWnet	SFC LW dn	SFC LW up	ATM LW cooling	g all-sky	albedo all-sky
F	**99.04**	**240.21**	**186.76**	**163.57**	**345.13**	**398.66**	**-186.68**	**0.3974**	**0.291**
F_0	100.05	240.12	186.76	160.08	346.84	400.20	-186.76	0.4	0.294
ΔF	**-1.01**	**0.09**	**0.00**	**3.49**	**-1.71**	**-1.54**	**0.08**	**-0.003**	**-0.003**
N	**15**/4	**36**/4	**7**	**6**	**13**	**15**	**-7**	**6**/**15**	**15**/**51**

ΔEq2 (all, net) = **2.84**

ΔEq4 (all, gross) = **2.46**

Conclusions / 1

- **Eq1** is a standard textbook formula; it may be derived from first principles; its validity was expected, and proved by CERES within 2.3 Wm^{-2}. It constrains the global hydrological cycle to OLR/2.
- Yet it is missing from the Charney Report's "principal premises". It is missing from the climate models, sensitivity studies, forcing and feedback estimates, imbalance computations and climate change assessments.
- **Eq2** is its evident all-sky extension, valid within the same range of uncertainty.
- **Eq3** and **Eq4** describe a particular state with specific determinations, justified within the same difference.
- The **g** greenhouse factors come from the equations without reference to the atmospheric trace-gas composition. They do not show any enhancement or deviation from their theoretical position during these 20 years.
- The extension of the **N** system to TSI is unexpected but extremely accurate, providing us with the correct albedos. Identifying the all-sky unit as the greenhouse effect of clouds gives **1** = LWCRE, with a best fit of 26.68 Wm^{-2}
- We can see variations in the F values during these two decades, but they might be fluctuations around, rather than permanent deviations from the F_0 positions, where for each flux ΔF is within the known observation uncertainty.
- I expect $\Delta LW < \pm 3$ Wm^{-2} for the next decades as well.

Conclusions / 2

As the last speaker of this conference, I took the liberty of concluding from my point of view.

I wish to say thank you to the CERES Science Team for their endless effort for better and better accuracy.

Without that high level of data quality, my theoretical considerations would not have been possible.

I hope my theory justified your data and your data verified my theory, for the benefit of both of us.