Observing and Modeling Earth's Energy Flows, Thirteen Years Later

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Abstract Observing and modeling energy flows in Earth's climate system was reviewed in an article in Surveys in Geophysics thirteen years ago as a concluding paper of a special collection with the same title. Analyzing their global mean energy budget estimate, a remarkable recognition can be made: there are specific small integer ratios among the flux components, as each of them are very close to an integer multiple of a unit flux, which is the longwave cloud radiative effect (LWCRE) with a value of 26.5 Wm^{-2}, as given in that study. Similar global energy budget estimates later by other authors, the IPCC and the NASA CERES science team show the same structure with convincing accuracy: typically, within the stated ranges of uncertainty. The physical science basis for the core flux components is identified in four radiative transfer constraint equations having their origin in the long-known two-stream approximation of Schwarzschild's equation; the fundamental integer ratios are solutions of the set of these four equations.

Keywords: global mean energy flow systems; integer relationships; radiative transfer equations

Introduction

A review article was published in Surveys in Geophysics thirteen years ago as a concluding study of a special collection with the same title (Stevens and Schwartz, 2012). Projecting longwave cloud radiative effect (LWCRE) on the energy flow distribution with the given CERES value of 26.5 Wm-2, it is easy to recognize that the flux components are integer multiples of that unit flux, close to the stated ranges of uncertainty; see Fig. 1.

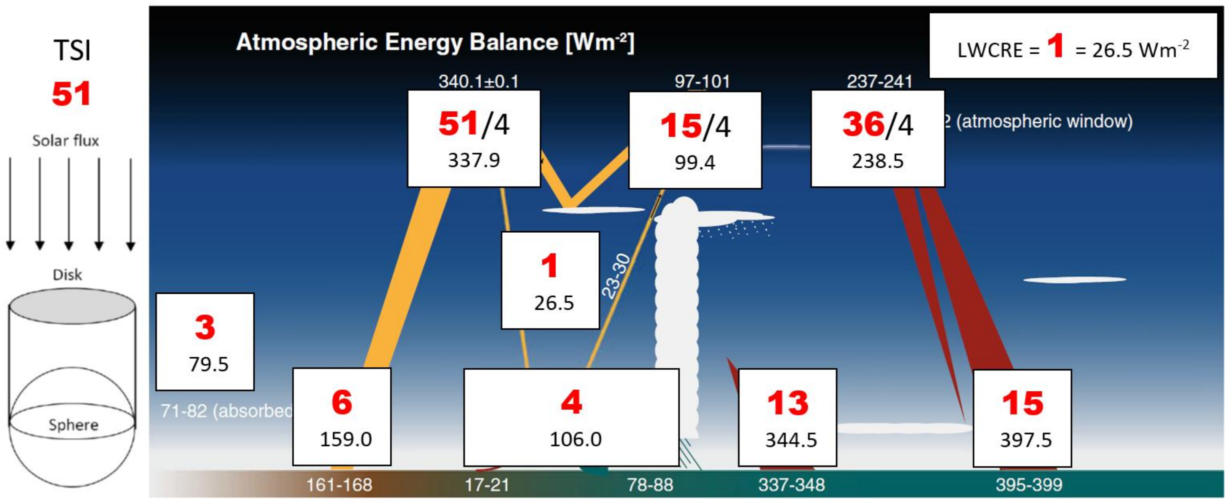

Fig. 1 Earth's global and annual mean energy flow system. Values are presented as a two-sigma range (Wm^{-2}). Original: Stevens and Schwartz (2012). We inserted LW CRE from their study, with their value from CERES EBAF. Numbers in red bold typeface are expressed in the unit of 26.5 Wm^{-2}. TOA fluxes are integers on the intercepting cross-section disk of incoming solar radiation.

At the top of the atmosphere (TOA), integer positions are quarters, that is, they are integers on the intercepting cross-section disk to incoming solar radiation, that is, before division by 4 for spherical weighting. Incoming solar radiation is smaller than the given lower limit by 2 Wm^{-2}. Atmospheric window is not part of the system. At the surface, integer position for absorbed solar radiation (6 units, with a value of 159.0 Wm^{-2}) falls out the indicated range of 161-168. Components of the convective flux (sensible heat and latent heat) do not fit separately into the integer system, but their sum (4 units = 106.0 Wm^{-2}) does. The position of total solar irradiance (TSI) is 51 units which, using the spherical factor, would be 1351.5 Wm^{-2}; with geodetic weighting (factor 4.0034, as in CERES EBAF), 1352.65 Wm^{-2}; still unacceptably low.

With these several exceptions, the appearance of the integer ratio system is interesting, but not convincing; without further indication, it may be regarded as a simple coincidence.

But later in that year, another update on global energy balance was published, based on the then-available best global observations (Stephens et al. 2012), where similar structures appear. First, the longwave cloud effect at TOA was upgraded to 26.7 (±4) Wm^{-2}, resulting in TSI = 51 units = 1361.7 Wm^{-2} (with the spherical multiplying factor of 4), or 1362.86 Wm^{-2} (with the geodetic formula of 4.0034). Since the then-accepted solar irradiance value was TSI = 1360.8 ± 0.5 Wm^{-2} (Kopp and Lean 2011), the latter would result in TSI/51 = 26.68 Wm^{-2} in the spherical case, and

26.66 Wm^{-2} in real-Earth geometry, supporting the fine-tuning in LWCRE. Integer positions for "Incoming solar" with the CERES geodetic factor of 4.0034 is 340.14 Wm^{-2}, and "Reflected solar" is 100.04 Wm^{-2} (340.2 and 100.0 are shown in the diagram).

Now with the value of 26.7 Wm^{-2}, given as the difference of "Clear-sky emission" (266.4) and "Outgoing longwave radiation" (all-sky emission, 239.7) in Fig. B1 of Stephens et al. (2012), these values themselves are integer multiples of this unit flux as 266.4 = 10 × 26.7 (and consequently 239.7 = 9 × 26.7) with a difference 0.6 Wm^{-2} only, which is far within the stated range of uncertainty (3.3), and equivalent to the indicated TOA imbalance. Similarly, at the surface, "Clear-sky emission to surface" (319) and "All-sky emission to surface" (345.6) differ by the longwave cloud effect at the surface (LWCRE SFC, 26.6), and these values are integer multiples of LWCRE SFC, as 319 = 12 × 26.6 with a difference of 0.2 Wm^{-2}, hence 345.6 = 13 × 26.6 (– 0.2 Wm^{-2}), compared to the stated ±9 Wm^{-2} uncertainty. Finally, "Surface emission" (398) also occupies an integer position, as 398 = 15 × 26.6, the difference is 1 Wm^{-2}, while the indicated uncertainty range is ±5 Wm^{-2}; the longwave part is shown in Fig. 2.

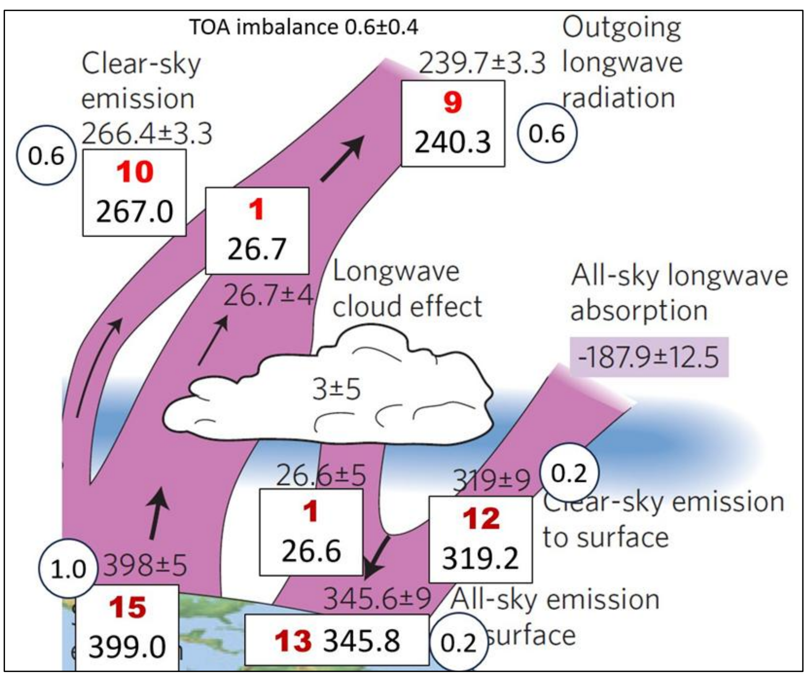

Figure 2 The longwave part of the global annual mean energy budget of Earth (Stephens et al. 2012, Fig.B1), with the integer system projected on it in textboxes. Red, bold typeface gives the integer values in units of one LWCRE at TOA (26.7 Wm^{-2}); purple values in units of one LWCRE at the surface (26.6 Wm^{-2}); the differences of the original values and the integer multiples are given in circles in Wm^{-2}.

Regarding the given uncertainty for LWCRE TOA as ± 4 Wm^{-2}, from now we will use one common unit flux for TOA and the surface.

Next year, another global mean energy budget distribution was presented (Wild et al. 2013), where the shortwave components were further updated, resulting in accurate positions in the integer system when using the same LWCRE TOA of 26.7 Wm^{-2} for unit flux as above. At TOA, incoming solar 340 occupies position of 51/4 (=340.4), where the division factor of four comes from spherical weighting; hence total solar irradiance TSI = 51 units = 1361.7 Wm^{-2}. Solar reflected (100) equals 15/4 = 100.1 with a difference of 0.1 Wm^{-2} only, resulting in an integer ratio for TOA albedo as 15/51, being arithmetically identical to the indicated 100/340. Absorbed solar and outgoing thermal radiation in equilibrium are equal with 9 units = 9 × 26.7 = 240.3 Wm^{-2}. Solar absorbed in the atmosphere is indicated as 79 Wm^{-2}; an integer position is 3 units = 80.1 Wm^{-2}, allowing solar down to the surface 185 Wm^{-2} in the diagram and 186.9 Wm^{-2} in the integer system as 7 units; with 161 Wm^{-2} solar absorbed at the surface in the diagram and 160.2 Wm^{-2} as 6 units in the integer system. The largest difference is in “Thermal down surface”, given as 342 Wm^{-2}, when 13 units = 347.1 Wm^{-2}, so the bias is 5.1 Wm^{-2}, still within the noted uncertainty; see Fig. 3.

Even this discrepancy disappeared next year, when Loeb (2014) published a global mean energy budget based on CERES EBAF data. Refining the unit flux from 26.7 Wm^{-2} to 26.67 Wm^{-2}, the flux component “thermal down surface” (called here “Absorbed at Surface”) in the integer ratio system is 346.7 Wm^{-2}; with a bias of 1.7 Wm^{-2} to the given value of 345 Wm^{-2}. The most peculiar feature here is that at the TOA, all three flux components (Incoming Solar, Reflected Solar and Outgoing LW Radiation) fit to their integer position with zero difference; see Fig. 4.

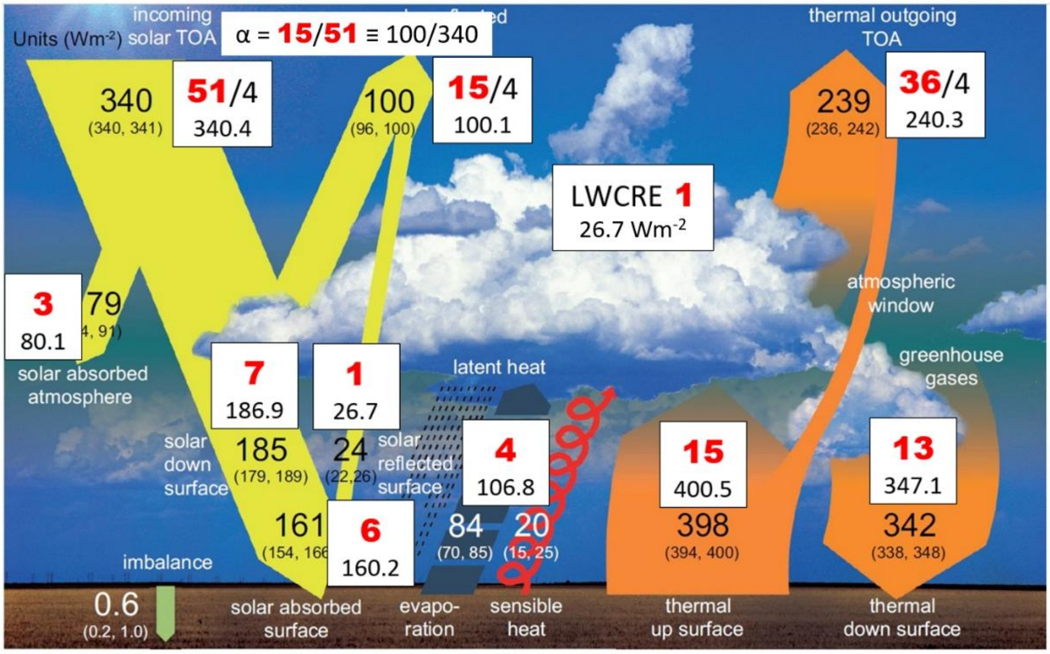

Figure 3 Integer structure projected a global energy balance from a surface perspective (Wild et al. 2013), using the same unit flux of 26.7 Wm^{-2} as above

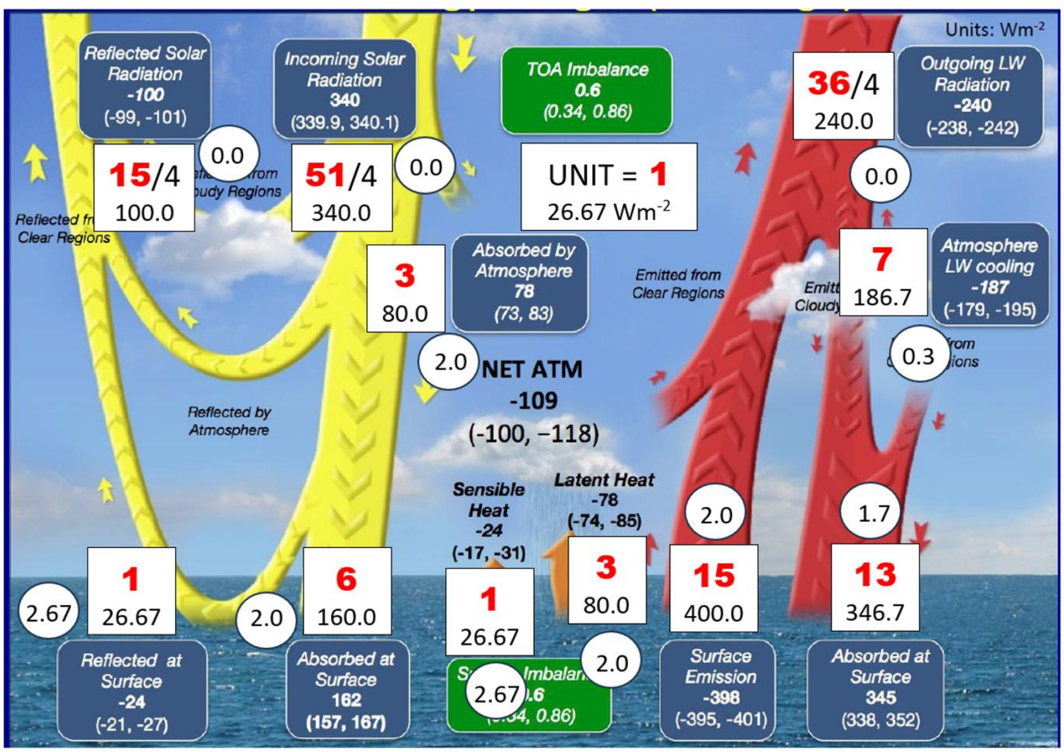

Figure 4 Integer structure projected a global mean energy budget from CERES EBAF data (Loeb 2014)

In the past decade, this higher value for the downward longwave radiation became widely accepted. In a current assessment of the global radiation budget from a surface perspective (Li, Li, Wild and Jones, 2024) based on 34 CMIP6 models, SW down radiation to the surface is 186±6, Reflect by surface = 24±3, convective flux (sensible heat + latent heat) = 106, Thermal down surface = 346±6, and Thermal up surface = 402±5 [Wm^{-2}]. The corresponding integer positions, with the same unit flux of 26.67 Wm^{-2} are as follows: 7 units = 186.69, 1 unit = 26.67, 4 units = 106.68, 13 units = 346.71, and 15 units = 400.05 [Wm^{-2}]; the differences are 0.69; 2.67; 0.68; 0.71, and 1.95 [Wm^{-2}], respectively — each of them far within the indicated uncertainty range.

At the top of the atmosphere, Stackhouse et al. (2024) provide a radiation budget from CERES satellite observations for 2001-2022. As shown in Table 1, with an upgraded unit flux of 26.68 Wm^{-2}, the difference of their climatological mean from the integer positions falls within, or close to (in the case of ASR), the interannual variability for the same period. Data taken from their Table 2.9.

Table 1 Global mean TOA radiative fluxes (Climatological Mean and Interannual Variability) from CERES, compared to the integer positions

Global	N	N × unit unit = 26.68 Wm^{-2}	Climatological Mean 2001-22 Wm^{-2}	Difference Wm^{-2}	Interannual Variability 2001-22, Wm^{-2}
OLR	36/4	240.12	240.35	0.23	±0.65
TSI	51/4	340.17	340.20	0.03	±0.15
RSW	15/4	100.05	99.00	1.05	±1.05
ASR	36/4	240.12	241.20	1.08	±1.05
Net	0	0	0.85	0.85	±0.85

The accuracy altogether is much better than expected from a simple coincidence, therefore an intense quest for a possible physical science basis was initiated. Four radiative transfer equations were identified and verified on published global energy flow distributions of CERES and GEWEX data, from which the integer ratios for the principal components arise as a solution.

Results

The first equation is a well-known constraint on the net radiation at the surface, coming directly from Schwarzschild's (1906, Eq. 11) two-stream radiative equilibrium relationships (*E* being the emission of the surface; *A* upward beam, *B* downward beam, A_0 the emerging flux at the top-of-atmosphere, and τ the optical depth):

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

reproduced in standard university textbooks like Goody (1964, Eq. 2.115); Houghton (1977, 1986, 2002, Eq. 2.13); Chamberlain (1978, 1987, Eq. 1.2.29 and Fig.1.4); Goody and Yung (1989, Eq.2.146); Hartmann (1994, 2016, Eqs. 3.48-3.54); Salby (1996, 2012, Eq. 8.67); Pierrehumbert (2008, Eq. 4.45); Ambaum (2021, Eq. 10.56), and in university lecture notes (Stephens 2003), for example as $\pi B_S - \pi B_0 = F_\infty/2$, see Fig.5.

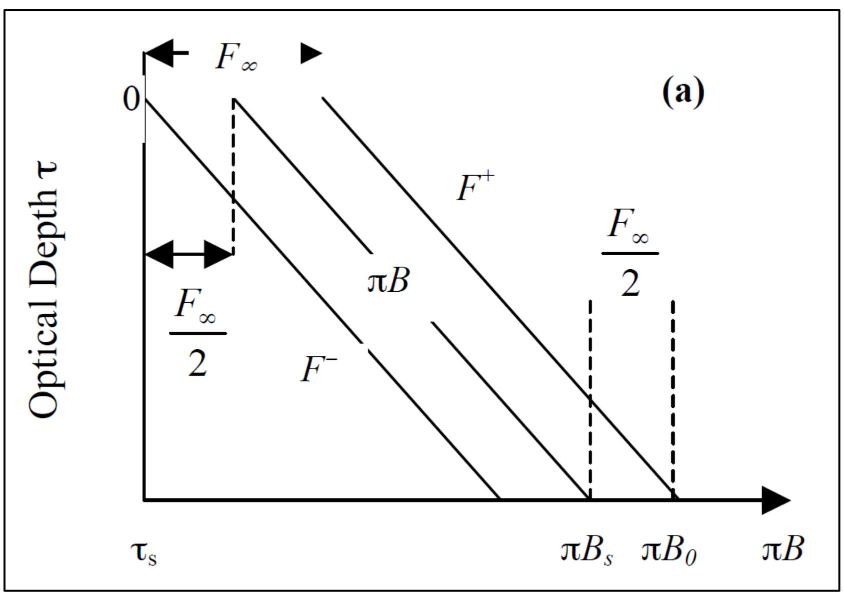

Figure 5 The flux profiles and blackbody function predicted by the simple gray body model as a function of optical depth (Stephens 2003)

The middle and third terms in Schwarzschild's (1906, Eq. 11) for the upward and downward beam were also reproduced in identical form in Stephens et al. (1994). The difference of the second and first terms in Schwarzschild (1906, Eq. 11) results the net radiation at the surface, representing a temperature discontinuity in radiative equilibrium, being "*greatly diminished by convection and heat conduction*", as noted by Emden (1903). Authors generally note that "*such a steep lapse rate is very unstable with respect to vertical motion, and will soon be destroyed by the process of convection*" (Houghton 1977), "*such discontinuities are usually are greatly suppressed in reality because of efficient heat transport by conduction and convection*" (Hartmann 1994), also "*This temperature discontinuity is unstable in practice and there will be turbulent heat exchange which will remove the temperature discontinuity*" (Ambaum 2021).

The equation states that the net radiation at the surface (R_N) in radiative equilibrium — and the corresponding convection in radiative-convective equilibrium — is independent of the optical depth and equals half of the outgoing longwave radiation (OLR) in the clear-sky:

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

As an initial justification, the equation was controlled on the then-available NASA CERES dataset, Energy Balanced and Filled (EBAF-Surface) Edition 2.8. Data were taken from the Data Quality Summary (2015).

Eq. (1) CERES_EBAF-Surface Ed2.8, Table 4.1

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

$$243.9 - 29.7 + 316.0 - 398.0 = 265.7/2 - 0.65$$

The equation is valid on that data product with a difference of 0.65 Wm^{-2}. [Note that Earth's heat uptake in that time was estimated as 0.58 ± 0.38 Wm^{-2} (Loeb et al. 2012).]

Since the first equation prescribes the convective flux (the sum of the sensible heat flux and latent heat flux) in a direct relationship to the outgoing longwave radiation (OLR) at TOA in the clear-sky, and convection changes almost linearly with sea surface temperature, a definite OLR-dependent convection assumes a definite, OLR-dependent surface upward longwave (ULW) thermal emission. Exploring possible formulas, as the optical depth (τ) of zero defines TOA, and $\tau = 1$ the level where OLR is initiated, Schwarzschild's formula for the surface (the middle term in Eq. 11) was tried at $\tau = 2$. Then the second equation gives the total SW + LW absorbed radiation (R_T) at the surface in the clear-sky:

Eq. (2) R_T (clear-sky) = (SW down – SW up + LW down) (clear-sky) = 2OLR(clear-sky).

CERES EBAF-Surface Ed2.8 Data Quality Summary (DQS) data [17]:

$243.9 - 29.7 + 316.0 = 2 \times 265.7 - 1.2$ Wm^{-2}.

This accuracy (compared to the estimated uncertainties in the EBAF-Surface data of 1σ between 3 and 7 Wm^{-2}, see Table 4.2 of [17]) was convincing enough to proceed further in this direction.

For all-sky, a third and fourth equations were created from the first pair, by separating atmospheric radiation transfer from the longwave effect of clouds (LWCRE) and using all-sky data on both sides:

Eq. (3) R_N (all-sky) = Surface SW net + LW net (all-sky) = [OLR(all-sky) – LWCRE]/2;

and

Eq. (4) R_T (all-sky) = Surface (SW + LW) absorbed (all-sky) = (SW down – SW up + LW down) (all-sky) = 2OLR (all-sky) + LWCRE.

Their accuracy on that data product was 2.65 Wm^{-2} for Eq. (3) and 2.10 Wm^{-2} for Eq. (4).

Controlled the four equations on EBAF Ed4.1_V3 and Ed4.2_V4 data products, we have the biases of the individual equations are within the range of ± 2.83 Wm^{-2}; and the mean bias of the four equations is 0.0007 Wm^{-2} (this justifies the use of four decimal places in the netCDF file), see Table 2, shown in green. EBAF Edition 4.2 is also controlled; with Version 4 data, first on the same period (April 2000-March 2022); the differences become as follows: -2.35, -2.70, 3.98, 3.46; the mean bias is 0.60 [Wm^{-2}] (red); then on the extended time period April2000-March 2024 (brown), and have -2.32, -2.50, 4.01, 3.67, with a mean of 0.715 [Wm^{-2}], still far within the absolute calibration uncertainty of the CERES instrument, and in the magnitude of the estimated Earth's Energy Imbalance.

Table 2 The four equations controlled on CERES EBAF Ed4.1 (April 2000 – March 2022) and Ed4.2 (April 2000 – March 2022, and April 2000 – March 2024) data

CERES EBAF Ed4.1 Version 3, 22 years (April 2000 – March 2022) (Wm^{-2})
CERES EBAF Ed4.2 Version 4, 22 years (April 2000 – March 2022) (Wm^{-2})
CERES EBAF Ed4.2 Version 4, 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
						Mean	0.0007
							0.5994
							0.7147

This unprecedented accuracy of the constraint equations raises a couple of questions. Do these four equations express an arithmetic identity? The answer is no; in the prevailing theory we are not aware of any relationship that would require these couplings between surface and TOA irradiances, without referring to any atmospheric gaseous composition or the optical depth. Or, are these four equations built in the CERES data production protocol? No again: the mean bias in the first five years vary between -0.5 and -0.2 [Wm^{-2}] and it approaches zero after including 17 years into the averaging; then it occupies the value of zero and remains there after only two decades.

Notice that the clear-sky equations prescribe the ratio

R_N : (TOA_LW_up) : (SFC_LW_up) : R_T = 1 : 2 : 3 : 4 ,

resulting in a clear-sky greenhouse factor of

g(clear-sky) = G(clear-sky) / (SFC_LW_up) = [(SFC_LW_up) –(TOA_LW_up)] / (SFC_LW_up) = 1/3.

With CERES EBAF Edition 4.2 V4 (24-yr) data (Table 1), g(clear-sky, CERES) = (398.7742 – 265.9748) / 398.7742 = 0.3330.

Recently, data were published from global energy and water cycle assessments on 30 years of the GEWEX mission (Stephens et al. 2023). Their data are for all-sky, therefore only equations (3) and (4) maybe controlled, with LWCRE taken from an earlier study of the same authors (Stephens et al. 2012) as 26.7 Wm^{-2}. According to Fig. 2 of the GEWEX study, net radiation at the surface (R) equals the sum of the convective fluxes: latent heat (evaporation) and sensible heat. Using data from Fig. SB3,

Eq. (3) R_N = LE + H = "Evaporation" + "Sensible heat" = (“Outgoing LW” –LWCRE)/2

81.1 + 25.4 = (239.5 – 26.7)/2 + 0.1 [Wm^{-2}]

Eq. (4) R_T = “Surface SW” – “Surface Reflection” + “All-sky emission” = 2 × “Outgoing LW” + LWCRE

184.0 – 23.3 + 345.1 = 2 × 239.5 + 26.7 + 0.1 [Wm^{-2}]

On GEWEX data, both the all-sky equations are valid within 0.1 Wm^{-2}; see Fig. 6.

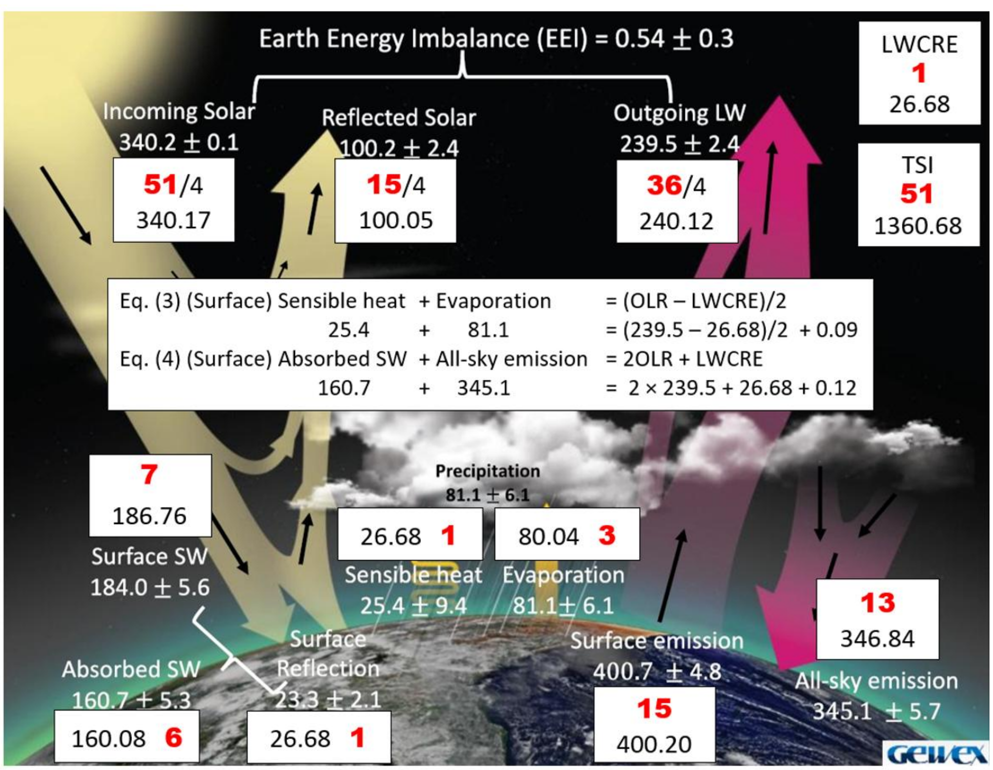

Figure 6 The all-sky (third and fourth) equations and the integer structure is projected on the GEWEX dataset, based on 30 years of data collection (Stephens et al. 2023). The unit flux of LWCRE is a refined value from 26.7 Wm^{-2} from Stephens et al. (2012) to 26.68 Wm^{-2} as the most accurate fit to TSI.

Discussion: The integer solution

As the equations are not direct functions of τ, a stationary (geometric) representation may be applied (Fig.7). Let's start with the second equation, stating the equality of the total energy absorbed (and emitted) by the surface to twice the OLR under clear-sky. This case is described by the simplest greenhouse model, see for example Hartmann (1994, Fig. 2.3), representing the flux ratios of $A = 2A_0$ [in Schwarzschild's (1906, Eq. 11) notation] as shown in the upper left panel; Equation (1) is represented in the upper middle panel as $\Delta A = A - E = A_0/2$ and $E = (3/2)A_0$ (for its simple derivation, see Hartmann 1994, Fig. 3.11 and Eq. 3.54). In the right panel of the upper row, the ratios are the same as in the middle, multiplied by 10 (since the unit is not specified yet). Then, introducing the red unit (for LWCRE), and keeping in mind that if Upward LW at TOA is 10 units (of LWCRE) in the clear-sky, then it must by 9 units in the all-sky; and if Downward LW is 12 units in the clear-sky, then it will be 13 units in the all-sky, with the constraint that Upward LW at the surface is the same in both cases, we have an integer ratio system, as shown in Fig.7.

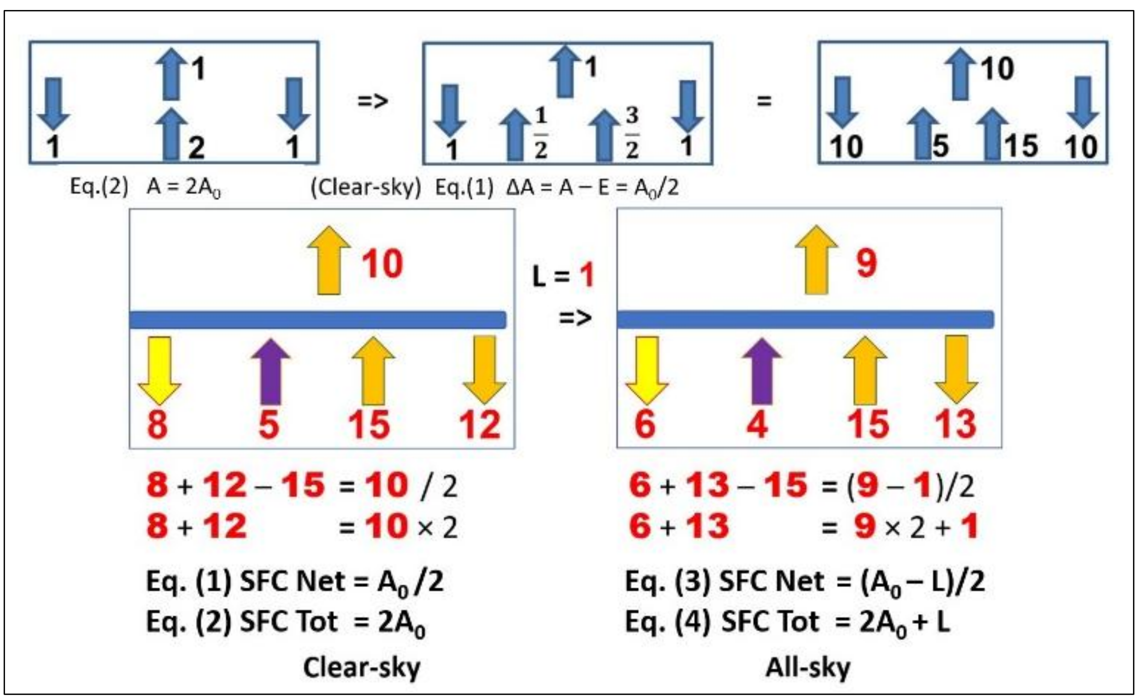

Figure 7 Stationary (geometric) representation of the four equations, with integer solution as multiples of the unit flux of L (representing LWCRE).

Validity of equations and the extended set of the integers on CERES data are given in Table 3. The fit of components not included in the equations (for example, TOA SW up both in clear-sky and all-sky) is remarkable. Notice also that the components of convection in the GEWEX study (based on the NEWS – NASA Energy and Water-cycle Study methodology (L'Ecuyer et al. 2015) occupy integer positions separately.

Table 3 The four equations and the integer positions for the clear-sky and all-sky global mean energy flow system, including TSI, using the unit flux of 26.68 Wm^{-2} as the best fit on CERES EBAF Ed4.2 data, and the differences. The greenhouse effect is also shown.

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

Eq. (1) $8 + 12 - 15 = 10/2$; Eq. (2) $8 + 12 = 10 \times 2$;

Eq. (3) $6 + 13 - 15 = (9 - 1)/2$; Eq. (4) $6 + 13 = 9 \times 2 + 1$ $1 = 26.68$ 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

Let us call here an independent estimate of the clear-sky greenhouse effect from the GFDL Atmospheric Model 4 (Raghuraman et al. 2019), showing its value as 133.4 ± 0.6 Wm^{-2}. Notice that the clear-sky greenhouse factor is g (clear-sky) = G / SFC LW up = 5/15 = 1/3 in the integer system and 132.63/398.58 = 0.333 with CERES data. The integer position for the all-sky greenhouse factor is g(all-sky) = 6/15 = 0.4, while CERES data gives 158.38/398.75 = 0.397.

References

Ambaum, M. H. P. *Thermal Physics of the Atmosphere.* Royal Meteorological Society (2021).

Andrews, D. *An Introduction to Atmospheric Physics*. Cambridge University Press (2010).

Chamberlain, J. *Theory of Planetary Atmospheres*. Academic Press (1978) (2nd edition: 1987).

Emden, R. (1913) Über Strahlungsgleichgewicht und atmosphärische Strahlung. Sitzungsberichte der mathematisch-physikalischen Klasse der Königlich Bayerischen Akademie der Wissenschaften zu München. English translation: Radiation equilibrium and atmospheric radiation, by H. Bateman. Monthly Weather Review (1916).

Goody, R. *Atmospheric Radiation: Theoretical Basis*. Oxford University Press (1964, 2nd edition with Y.L.Yung, 1989).

Hartmann, D. *Global Physical Climatology*. Academic Press. (1994). (2nd edition: 2016).

Houghton, J. *The Physics of Atmospheres*. Cambridge University Press (1977).

Kopp, G. and J. Lean, A new, lower value of total solar irradiance: Evidence and climate significance. *GRL* **38**, L01706 (2011), https://doi.org/10.1029/2010GL045777

L'Ecuyer, T. S., and Coauthors, The Observed State of the Energy Budget in the Early Twenty-First Century, *J. Climate*, **28**, 8319–8346 (2015) https://doi.org/10.1175/JCLI-D-14-00556.1.

Li, X., Q. Li, M. Wild, P. Jones (2024) An intensification of surface Earth's energy imbalance since the late 20th century. *Nature Comm. EE*, 30 Oct 2024.

Loeb, N., Lyman, J., Johnson, G. *et al.* Observed changes in top-of-the-atmosphere radiation and upper-ocean heating consistent within uncertainty. *Nature Geosci* **5**, 110–113 (2012). https://doi.org/10.1038/ngeo1375

NASA CERES CERES_EBAF-Surface_Ed2.8 Data Quality Summary (March 27, 2015).

NASA CERES EBAF Ed4.1_V3 and Ed4.2_V4.

Pierrehumbert, R., *Principles of Planetary Climate*. Cambridge University Press (2008).

Raghuraman, S. P., Paynter, D., & Ramaswamy, V. (2019). Quantifying the drivers of the clear sky greenhouse effect, 2000–2016. *Journal of Geophysical Research: Atmospheres*, 124, 11354–11371. https://doi.org/10.1029/2019JD031017,

Salby, M., *Fundamentals of Atmospheric Physics*. Academic Press (1996).

Salby, M., *Physics of the Atmosphere and Climate*. Cambridge University Press (2012).

Schwarzschild, K. (1906) Ueber das Gleichgewicht der Sonnenatmosphäre. Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen. Mathematisch-physikalische Klasse, pp. 41-53, Eq. 11. English translation: Menzel, D. H. (ed), *Selected Papers on the Transfer of Radiation* Dover Publ. (1966)

Stackhouse, P. et al. (2024) State of the Climate in 2023; *Bull. Am. Met. Soc.*, August 2024.

Stephens, G. (2003) Colorado State University AT622 Section 6, Eqs. (6.10a)-(6.10b), Example 6.3, Fig. 6.3a. https://reef.atmos.colostate.edu/~odell/AT622/stephens_notes/AT622_section06.pdf

Stephens, G., Li, J., Wild, M. *et al.* An update on Earth's energy balance in light of the latest global observations. *Nature Geosci* **5**, 691–696 (2012). https://doi.org/10.1038/ngeo1580

Stephens, G. L., Slingo, A., Webb, M. J., Minnett, P. J., Daum, P. H., Kleinman, L., ... & Randall, D. A. (1994). Observations of the Earth's Radiation Budget in relation to atmospheric hydrology: 4. Atmospheric column radiative cooling over the world's oceans. *Journal of Geophysical Research: Atmospheres*, *99*(D9), 18585-18604.

Stephens, G., and Coauthors, (1994) The First 30 Years of GEWEX. *Bull. Amer. Meteor. Soc.*, **104**, E126–E157, https://doi.org/10.1175/BAMS-D-22-0061.1.

Stevens, B., Schwartz, S. (2012) Observing and Modeling Earth Energy flows. *Surv Geophys* 33:779-816

Wild, M., Folini, D., Schär, C. *et al.* The global energy balance from a surface perspective. *Clim Dyn* **40**, 3107–3134 (2013). https://doi.org/10.1007/s00382-012-1569-8