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Article

Deducing Earth's Global Energy Flows from a Simple Greenhouse Model

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Abstract: Earth atmosphere is almost opaque in the infrared: about 374 W/m² is absorbed by the atmosphere out of 396 W/m² surface upward longwave radiation, and only about 22 W/m² leaves the system unabsorbed in the atmospheric window. This makes rise to the idea to approximate the annual global mean energy flow system from a simple idealized greenhouse model, where the surface is surrounded by a single-layer shortwave (SW) transparent, longwave (LW) opaque, non-turbulent atmosphere. The energy flows in this geometry can be described by elementary arithmetic relationships. Starting from this model, the realistic Earth's atmosphere can be achieved by introducing partial atmospheric SW opacity, partial atmospheric LW transparency and turbulent fluxes during the course of the deduction. The resulted global mean energy flow system is then compared to several data sets such as satellite observations from the CERES mission; estimates using direct surface observations and climate models; global energy and water cycle assessments; and independent detailed clear-sky radiative transfer computations. We find that the deduction from this idealized model approximates the real values in Earth energy budget with reasonable accuracy: the deduced fluxes and the observed ones are consistent within the acknowledged error of observations; while fundamental features of the initial geometry like special ratios and definite relationships between the fluxes are preserved.

Keywords: global energy budget; simple greenhouse model; infrared-opaque limit

1. Introduction

Satellite observation of radiation in the spectral range of the mid-infrared atmospheric window (8-12 μm) does not produce realistic value for the real magnitude of the terrestrial radiation that goes through the atmosphere unattended: there is also some upward longwave emission from the atmosphere in that spectral range, and there is also non-absorbed surface radiation outside this range. The accurate value of the so-called surface transmitted irradiance (STI) can only be computed. A detailed radiative transfer computation [1] resulted in a value about 1/6 for the clear-sky atmospheric LW transmittance: 65 W/m² of upward LW radiation from the surface leaves the system without being absorbed out of 386 W/m² terrestrial blackbody emission of that model. Introducing an infrared (IR) opaque cloud layer; this value is reduced to about 1/15 in the all-sky. Recent global energy budget estimates [2], [3] accept this result and a value of STI(all-sky) = 22 W/m² and 20 ± 4 W/m² is included in their distributions. This quasi-opaque character of our atmosphere allows us to try to approximate Earth's energy flow system starting from an idealistic model that assumes a complete LW-opacity for the atmosphere and introduces small partial LW-transparency in the course of the deduction.

The simplest greenhouse model comprises a surface surrounded by a thin atmospheric layer which is assumed to be completely transparent to the incoming solar radiation (that is, all the incident solar radiation hits the ground), and completely opaque to longwave radiation (that is, absorbs all the LW upward radiation from the ground). Further, in this initial model it is assumed that there is no other energetic connection between the surface and the atmospheric layer than radiative (*i.e.*, no

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sensible heat and latent heat fluxes are allowed). We will refer to this model as the "glass-shell" atmosphere; see Figure 1.

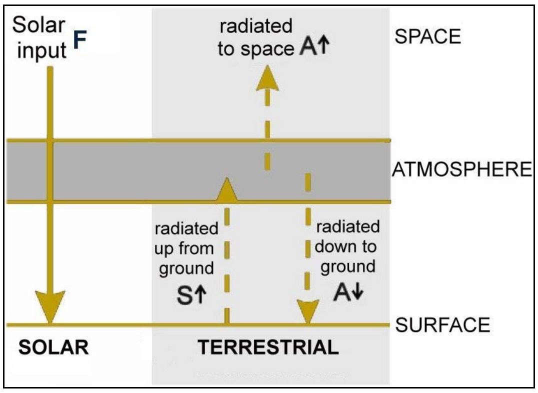

Figure 1. A shortwave-transparent, longwave-opaque, non-turbulent atmospheric model. F solar radiation from space reaches the ground; it is equilibrated by outgoing longwave radiation A. The atmospheric layer absorbs all the upwelling terrestrial radiation from the ground and emits it upward and downward equally. After Fig 2.7 of [4].

The fundamental characteristics of this model are:

(a) There is no solar energy absorbed by the atmosphere; all the incoming solar radiation F is absorbed by the surface.

(b) The solar energy absorbed by the system is radiated out as longwave radiation: the outgoing longwave radiation A equals to the surface solar absorption, A = F.

(c) The atmospheric layer emits upward and downward equally, hence the downward longwave radiation to the surface (A) equals to the outgoing longwave radiation (A).

(d) The surface absorbs F solar radiation and A downward radiation; its upward longwave emission in equilibrium is S = F + A = 2A.

(e) The greenhouse effect of this system is G = S – A, and equals to the outgoing LW radiation: G=A.

(f) Since A = F, the greenhouse effect in this model equals to the solar energy absorbed by the surface: G = F.

The basic ratios in (a)-(f) can be shown in the following schematics (see Figure 2.)

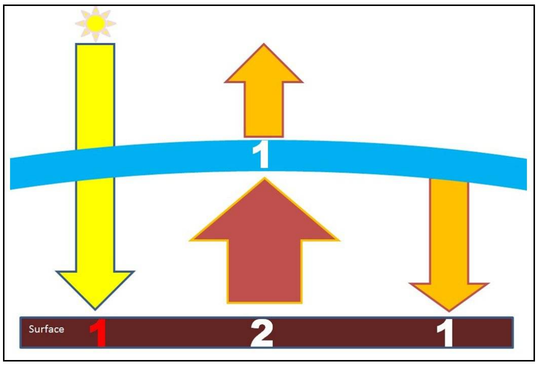

Figure 2. The values in Fig. 1 are indicated as F = 1, A = 1, and S = 2.

We will use this diagram as a starting point for deducing the realistic Earth fluxes. We will introduce partial atmospheric SW absorption, partial LW transparency, clouds, and the supplying

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turbulent fluxes (sensible heat and latent heat) in the course of deduction. Our basic condition is to preserve the basic 1/2 ratios from the initial geometry.

2. Deduction

As a first step, let us introduce partial shortwave opacity for the atmosphere (that is, allow some incoming solar radiation to be absorbed by the atmosphere). As we would like to maintain the basic 1/2 ratios of the initial model, let us first make a unit change from 1 to 3 (see Figure 3):

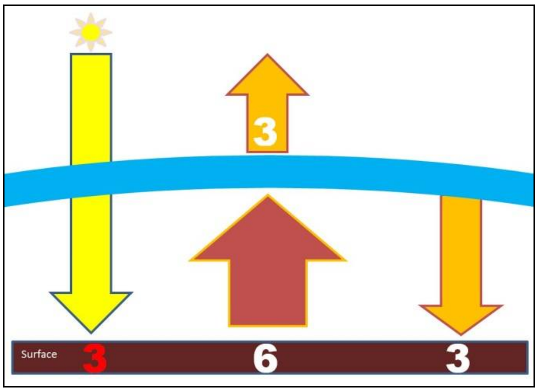

Figure 3. The unit was changed from 1 to 3; everything else remained the same.

Step 2: Now we can introduce partial atmospheric SW absorption as 1 unit; this allows 2 units to be absorbed by the ground (see Figure 4):

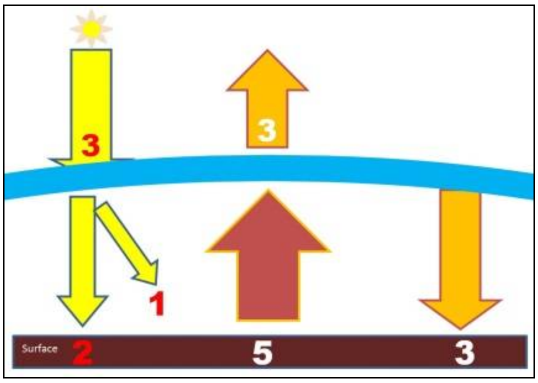

Figure 4. Introducing 1 unit for atmospheric SW absorption allows 2 units to be absorbed by the surface. Notice that property (f) of the glass-shell model: the equality of the G greenhouse effect (G=5–3=2) with the magnitude of the energy in surface solar absorption (2) is preserved.

The surface energy balance has been modified here: from now, the total SW + LW surface absorption becomes 2+3, hence the LW emission from the ground has to be 5 units. One unit of atmospheric SW absorption plus five units from surface LW emission go to the three units of outgoing and three units of down-welling LW flux radiated by the shell.

Step 3: For the same reason as above (maintaining the 1/2 ratio), introduce another unit change of 1 => 3 again (Figure 5):

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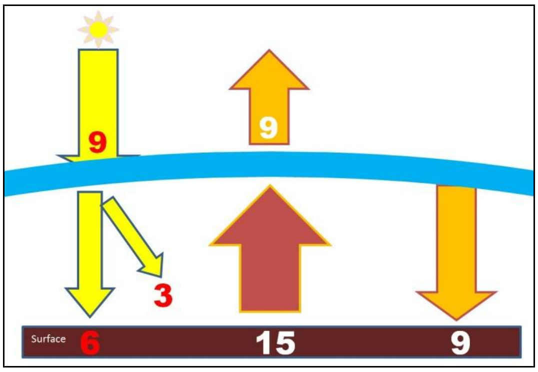

Figure 5. The unit was changed from 3 to 9; everything else remained the same.

Step 4: Now we are able to introduce one unit for surface transmitted irradiance (Figure 6):

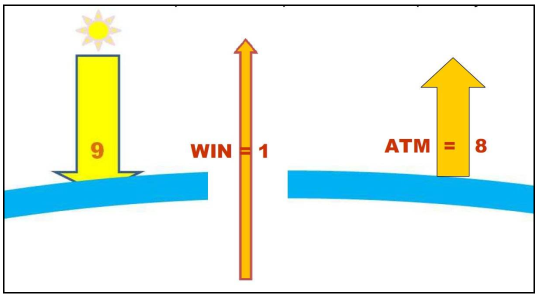

Figure 6. Introduce 1 unit for surface transmitted irradiance (LW radiation in the "window")

Having one unit for the window radiation, this allows eight units for the atmospheric upward emission to maintain OLR = 9.

Step 5: Now let us introduce clouds through the longwave cloud radiative effect (LWCRE). (The shortwave cloud effect is assumed to be already accounted in the absorbed solar radiation). We are going to define LWCRE = one unit (see Figure 7).

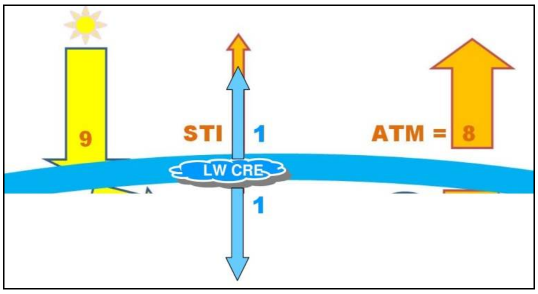

Figure 7. Clouds are introduced into the model through altogether two units for longwave cloud radiative effect: one at the TOA, one at the surface.

This way, we allowed two units for LW cloud effect: one unit for TOA LWCRE and one unit for the surface. To compensate and close the balance, our final step will be to have four units for turbulent fluxes (sensible heat plus latent heat). Figure 8 shows the complete structure of the resulted energy flow system: we have finally 6 units SW and 4+9=13 units LW absorbed by the surface; this is balanced out by 6+9=15 units of upward LW radiation by the surface and 4 units in form of non-radiative heat flows. The gross energy absorbed (and re-emitted) by the surface is than 19 units. The atmospheric energy budget has two more units (up and down LWCRE), processing altogether 21 units of energy.

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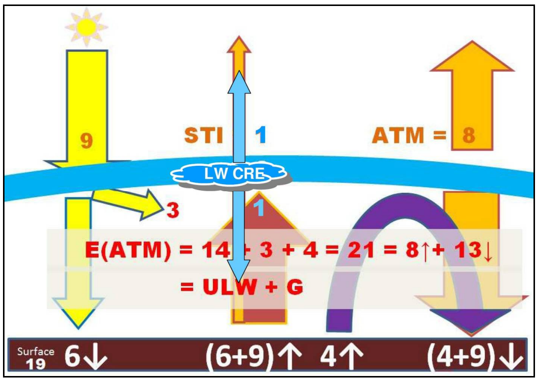

Figure 8. Four units are introduced for turbulence as a counterpart of two units for the longwave cloud effects. The atmospheric energy balance equation is indicated.

The resulted energy flow system can be compared to observations if 9 units of absorbed solar radiation are equated to its observed quantity of 240 W/m² [5]. Hence we get a distribution shown in Table 1. The clear-sky OLR and DLR come from the all-sky values adding and subtracting one LWCRE; while the clear-sky surface solar absorption defines SW CRE as two units.

Table 1. Global mean flux values as integer ratios deduced from the initial model. The corresponding values are scaled with the observed Absorbed Solar Radiation (ASR).

Flux name (all-sky)		**UNITS**	**W/m²**
Absorbed Solar Radiation	ASR	9	240
Solar Absorbed Atmosphere	SAA	3	80
Solar Absorbed Surface	SAS	6	160
Upward Longwave Surface	ULW	15	400
Downward Longwave Radiation	DLR	13	347
Sensible Heat and Latent Heat	SH+LH	4	107
Greenhouse Effect	G	6	160
Atmosphere LW net	LW net	-7	-187
Gross SW + LW Surface	SAS+DLR	19	507
Longwave Cloud Radiative Effect	LWCRE	1	26.67
Flux name (clear-sky)			
Outgoing Longwave Radiation	OLR	10	266.7
Downward Longwave Radiation	DLR	12	320
Solar Absorbed Surface	SAS	8	213
Upward Longwave Surface	ULW	15	400
Sensible Heat and Latent Heat	SH+LH	5	133
Gross SW + LW Surface	SAS+DLR	20	533
Greenhouse Effect	G	5	133

Let us project these values on the global energy balance diagram updated from the IPCC AR5 (see Figure 9), and a recent clear-sky global energy budget assessment (Figure 10 and Figure 11 with the CRE fluxes), and note that further flux elements of the system (surface downward and reflected shortwave in the all-sky; and TOA SW reflection in clear-sky) accommodate themselves into the integer structure though these values were not involved in the deduction:

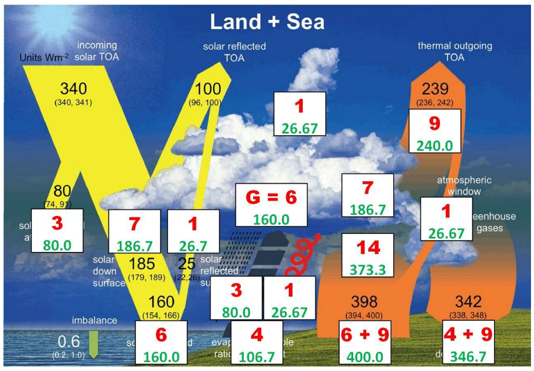

Figure 9. Diagram of the global mean energy flows in the climate system under all-sky conditions, with our additions in white text boxes. Red numbers: integers (dimensionless); green numbers in W/m². Original: [6].

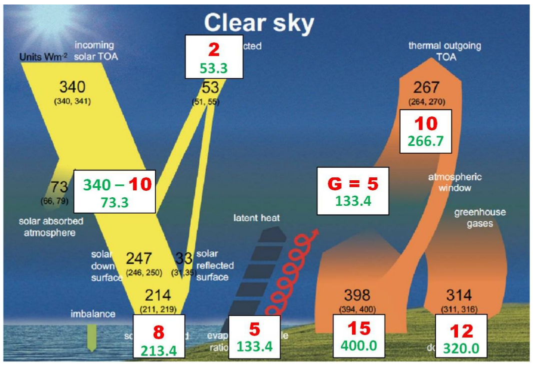

Figure 10. Diagram of the global mean energy flows in the climate system under clear-sky conditions, with our additions in white text boxes. Red numbers: integers (dimensionless); green numbers in W/m². Original: [7].

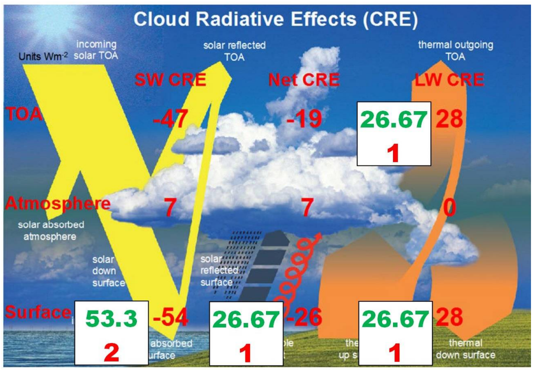

Figure 11. Cloud Radiative Effects (CRE) in the climate system. Our additions are in white text boxes where the red numbers are dimensionless integers and the green numbers are in W/m². Original: [7].

3. Results and Discussion

The following fundamental characteristics of the deduced global mean energy flow system can be recognized.

3.1 There is an integer set for all-sky, clear-sky and the CRE fluxes. Comparison with the CERES EBAF Surface Edition 4.0 data product is given in Table 2; an early appearance of the integer structure is shown in Table 3.

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Table 2. All-sky and clear-sky CERES EBAF Ed4.0 data (July 2005-June 2015), as published in [9]. ONE UNIT ≡ TOA LW up / 9 = 240.0/9 = 26.67 W/m². The largest difference in the all-sky individual fluxes is Δ_{max} = 3.4 W/m² (SW up). Our values are presented as EdMZ = N x UNIT.

Flux name All-sky	**Ed4.0 (W/m²)**	**N (integer)**	**EdMZ (W/m²)**	**Ed4.0 – EdMZ (W/m²)**
TOA SW insolation	340.0			
TOA SW up	99.1			
TOA LW up	240.0	9	240.0	0.0
SW down	187.1	7	186.7	0.4
SW up	23.3	1	26.67	-3.4
SW net	163.8	6	160.0	3.8
LW down	344.7	13	346.7	-2.0
LW up	398.3	15	400.0	-1.7
LW net	-53.6	2	-53.3	-0.3
SW + LW net	110.2	4	106.7	3.5
Atm SW net	77.1	3	80.0	-2.9
Atm LW net	-186.5	7	-186.7	0.2
Atm SW + LW net	-109.4	4	-106.7	-2.7
Greenhouse effect	158.3	6	160.0	-1.7
SFC SW + LW in	508.5	19	506.7	1.8
2OLR + LWCRE	510.7	19	506.7	4.0
Flux name Clear-sky				
TOA SW insolation	340.0			
TOA SW up	53.1	2	53.3	-0.2
TOA LW up	267.9	10	266.7	1.2
SW down	243.8	9	240.0	3.8
SW up	29.8	1	26.67	3.1
SW net	214.0	8	213.4	0.6
LW down	314.0	12	320.0	-6.0
LW up	397.6	15	400.0	-2.4
LW net	-83.6	3	-80.0	-3.6
SW + LW net	130.4	5	133.3	-2.9
Atm SW net	73.0	340.0 – 10	73.3	-0.3
Atm LW net	-184.3	7	-186.7	2.4
Atm SW + LW net	-111.4	4	-106.7	-4.7
Greenhouse effect	129.7	5	133.3	-3.6
SFC SW + LW in	528.0	20	533.4	-5.4
2OLR	535.8	20	533.4	2.4

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Table 3. Data from different independent studies in Surveys in Geophysics (2012) Special Issue on Observing and Modeling Earth Energy Flows [2], [9], [10].

Flux name All-sky	Source	Value W/m²	N	N × UNIT W/m²	Diff W/m²
SFC LW Up	Kato et al. [9]	398 ± 3	15	397.5	0.5
SFC LW Dn	Kato et al. [9]	345 ± 7	13	344.5	0.5
SFC Net	Kato et al. [9]	106 ± 12	4	106.0	0.0
TOA LW Up	Trenberth and Fasullo [2]	238.5	9	238.5	0.0
Solar Abs Atm	Trenberth and Fasullo [2]	78	3	79.5	-1.5
Solar Abs SFC	Trenberth and Fasullo [2]	161	6	159.0	2.0
LW CRE	Stevens and Schwartz [10]	26.5	1	26.5	0.0
ATM LW net	Kato [9], Trenberth [2]	185.5	7	185.5	0.0
G greenhouse effect	Kato [9], Trenberth [2]	159.5	6	159.0	0.5

3.2. The total shortwave and longwave energy income of the surface equals twice the OLR in the clear-sky and twice the OLR plus one LWCRE in the all-sky (see the two bottom rows of Table 2):

$$\text{SW + LW absorbed by surface, clear-sky} = 2 \times \text{OLR(clear-sky)} \qquad (1)$$

$$\text{SW + LW absorbed by surface, all-sky} = 2 \times \text{OLR(all-sky)} + \text{LWCRE} \qquad (2)$$

The most accurate appearance of Eq. (2) is in [8], see Figure 12:

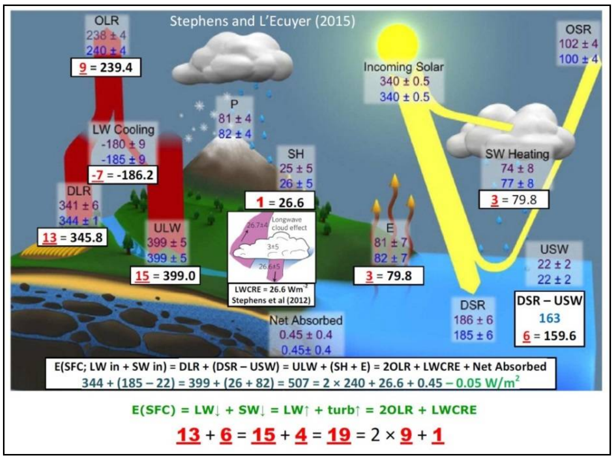

Figure 12. The accuracy of Eq. (2) in the energy balance estimate [8] is 0.05 W/m². As clear-sky OLR is not indicated in that study, we take LWCRE from an earlier publication of the same authors [3].

Another version, with an atmospheric form of the Eq. (2) is in [3], see Figure 13:

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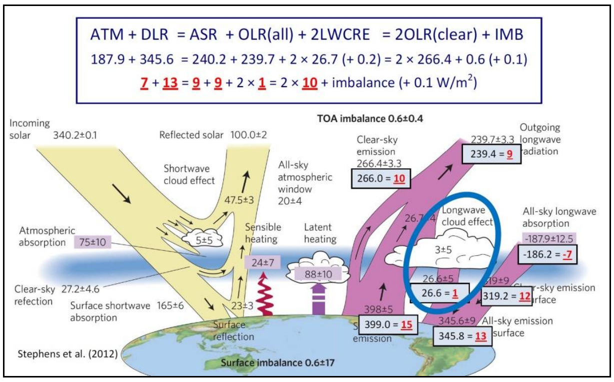

Figure 13. Integer ratios in white textboxes are projected on a recent energy balance diagram [3]. A revealed atmosphere/TOA constraint relationship, valid with 0.1 W/m², is also indicated.

3.3 Compared to the CERES EBAF Surface data set (Table 2), the largest individual flux difference in the all-sky is 3.4 W/m² (SW up), while the best fit is in the composite flux of Atmospheric LW Net, where the accuracy is 0.2 W/m². This essential energy flow component comprises the SW, LW and non-radiative fluxes as well; the close equality of the deduced value (186.7 W/m² = 7 units) with the observed one (186.5 W/m²) is an indicator of the robustness of the integer structure.

3.4 The similarity of the longwave greenhouse effect with the magnitude of energy in the solar surface absorption (characteristic (f) in the initial model) is formally preserved during the steps of the deduction. It is valid in the all-sky case with 5 W/m² in CERES EBAF Ed4.0, (158.3 W/m² and 163.3 W/m²), see Table 2.

$$G(\text{all-sky}) = SAS(\text{all-sky}) \tag{3}$$

In the clear-sky case, the longwave energy in the greenhouse effect is balanced out by the non-radiative fluxes:

$$G(\text{clear-sky}) = (SW + LW)\ \text{net}\ (\text{clear-sky}) \tag{4}$$

This feature is shown with 0.7 W/m² difference (129.7 W/m² and 130.4 W/m²) in the CERES data set.

3.5 Using the values from NASA NEWS global energy and water cycle assessment (see Fig. 12), it should be recognized that the non-radiative flux element of the system can be further separated into sensible heat (SH) and latent heat (LH) in the integer structure, with values of SH = 26 ± 5 W/m² (1 unit = 26.6 W/m²) and LH = 82 ± 7 W/m² (3 units = 79.8 W/m²).

3.6 The computed fundamental clear-sky values of atmospheric window radiation and atmospheric upward LW emission satisfy their own internal integer ratios, see the computation of [1], Table 4:

Table 4. Clear-sky fluxes from detailed radiative transfer computations [1], and their integer ratios

Costa and Shine (2012) Clear-sky	Value W/m²	N integer	N × UNIT W/m²	Diff W/m²
STI (WIN) (clear-sky)	65	1	65	0
G greenhouse effect	127	2	130	3
ATM LW up	194	3	195	1
TOA LW up	259	4	260	1
Surface LW up	386	6	390	4
2 × TOA LW up	518	8	520	2

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3.7 In Steps 5 and 6, when introducing the triplet of one unit for window radiation, one unit for upward and one unit for downward LW cloud effect, the numerical values of the literature are the followings: all-sky window radiation is computed to be 22 ± 4 W/m² [1], while the value of the LW cloud effects is estimated to be around 27 W/m². This 5 W/m² difference is still within the acknowledged modeling error. Let us take the equality as an assumption; this would allow us to propose a possible explanation of why the Earth's atmosphere (which in reality is not perfectly opaque in the IR) still "mimics" the IR-opaque limit. The working hypothesis might be this: the WIN = LWCRE equality means that the energetic role of the clouds in the Earth's atmosphere is to close the open atmospheric window. In that case, the radiative energy being lost to space in the window is gained back to the surface by the greenhouse effect of clouds; and the surface sees an IR-closed ceiling above itself. This assumption might help to explain the curious fact that the realistic Earth's system is able to follow the glass-shell model. But it should be emphasized that the validity of the revealed arithmetic relationships does not depend on the validity of the proposed interpretation.

4. Conclusions

We deduced the annual global mean energy flow structure in Earth's atmosphere from a very simple greenhouse model through reasonable physical steps, and presented several features in the observational data sets that can be understood as a legacy from the initial geometry. Both the small integer ratios and the direct top-of-atmosphere/surface energetic constraint relationships are characteristics of the original model. We showed that the resulted energy flow system and the independent satellite- and surface-based observations of the global mean fluxes are consistent within the acknowledged measurement and modeling uncertainty.

If the observed integer ratios and the revealed relationships are not special features of the examined two decades of accurate satellite data only (which would be very unlikely) but represent permanent characteristics of the Earth's physical reality, we should expect them to be valid in the future as well. Based on the determination of DLR and ULW (downward and upward longwave surface radiations) as connected to the change in OLR, a prediction can be made on the evolution of DLR and ULW, compared to projections for DLR in 10 CMIP5 models [11], see Figure 14:

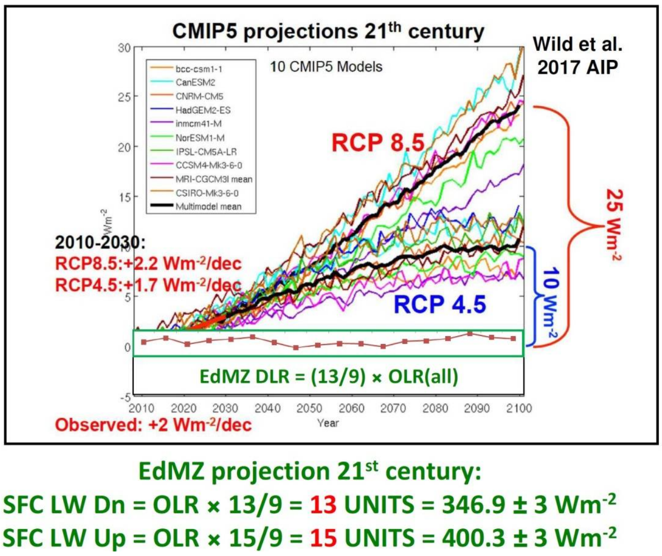

Figure 14. Data projection for DLR and ULW from the integer tables. Both surface downward and upward longwave radiations are expected to go with the evolution of OLR.

Conflicts of Interest: We declare no conflict of interest.

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