Clear-sky, Cloudy-sky and All-sky Global Mean Energy Budgets as the Solution of Classic Theoretical Radiative Transfer Constraint Equations

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Abstract

The clear-sky and all-sky global mean energy flow system of the Earth as the solution of four radiative transfer constraint equations were presented in Zagoni (CERES STM 2020). These equations have their theoretical origin in the concept of radiative equilibrium for stratified atmospheres (Schwarzschild 1906, Eq. 11; Milne 1930, Eq. 93-95; Goody 1964, Chamberlain 1978, Eq. 1.2.29-1.2.30; Eq. 2.115; Goody and Yung 1989, Eq. 2.146 and Eq. 9.5; Houghton 2002, Eq. 2.13; Andrews 2010, Eq. 3.50-3.51; Pierrehumbert 2010, Eq. 4.44-4.45, etc.). We showed that each of the equations is justified by 19 years of CERES data within ± 3 Wm-2 and the all-sky equations by the IPCC-AR5 (2013) Fig. 2.11 global energy budget estimate within ± 2 Wm-2. The individual flux components, both for clear-sky and all-sky are valid within $\pm$ 1 Wm-2 at the TOA and within $\pm$ 4 Wm-2 at the surface. A fifth equation was introduced in Zagoni (EGU 2020) showing the place of a non-observable flux component (atmospheric window radiation) in the theoretical system; and a sixth equation allowed to extend the arithmetic structure to total solar irradiance. The set of these equations has a solution for LWCRE = 1 as unit flux, and the whole system of the global mean atmospheric energy flows can be described by small integers, in their own units, separately for the clear-sky, the cloudy sky and (as their weighted sum) for the all-sky case. OLR(all) = 9, OLR(clear) = 10, ULW = 15, G(all) = 6, G(clear) = 5 units = 133.40 Wm-2 with TSI = 51 units = 1360.68 Wm-2. Here we introduce the cloudy versions of the examined classic radiative transfer constraint equations and present the all-sky global mean energy budget as the weighted sum of the clear-sky and cloudy-sky energy flow system. "Clouds" are regarded as a single IR-opaque layer, represented by an effective cloud area fraction. Essential characteristics of the climate (like the clear-cloudy energy exchange; the surface, TOA, in-atmosphere and net CREs; and the greenhouse effect) are explained as the cooperation of the clear-sky and cloudy-sky geometric arrangements expressed in the transfer equations. This way, the theoretical description of the Earth's global mean energy budget is complete.

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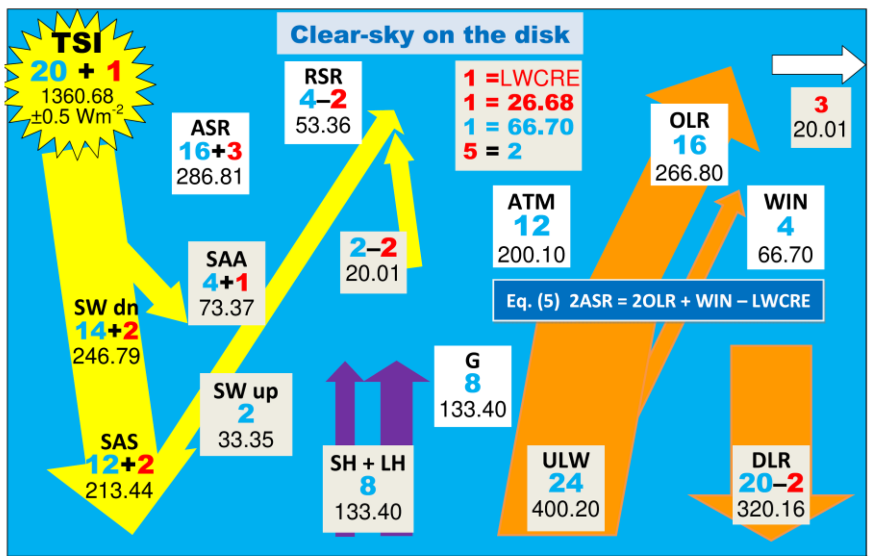
Equation:			Accuracy in CERES EBAF Ed4.1 19 years of data, Wm^{-2}
Eq. (1) (clear-sky, net)	Surface SW net (clear) + LW net (clear)	= OLR(clear-sky) / 2	–2.25
Eq. (2) (all-sky, net)	Surface SW net (all) + LW net (all)	= (OLR(all-sky) – LWCRE) / 2	+2.84
Eq. (3) (clear-sky, gross)	Surface SW net (clear) + LW down (clear)	= 2OLR(clear-sky)	–2.80
Eq. (4) (all-sky, gross)	Surface SW net (all) + LW down (all)	= 2OLR(all-sky) + LWCRE	+2.50

Solution:

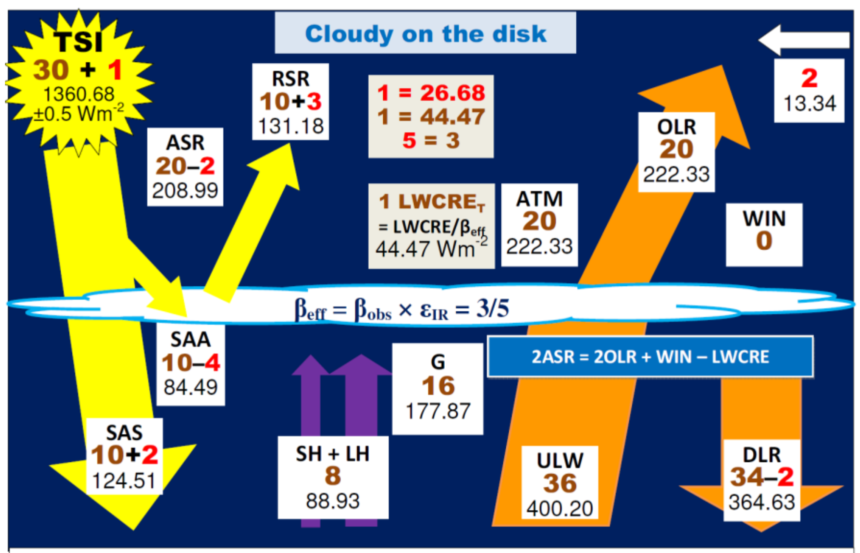
Surface LW up, all-sky	= 15	Surface LW up, clear-sky	= 15
Surface SW net, all-sky	= 6	Surface SW net, clear-sky	= 8
Surface LW net, all-sky	= –2	Surface LW net, clear-sky	= –3
Surface SW+LW net, all-sky	= 4	Surface SW+LW net, clear-sky	= 5
Surface SW+LW gross, all	= 19	Surface SW+LW gross, clear	= 20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

Clear-sky ratios: SFC (SW net + LW down) : ULW : OLR : ATM : G : WIN = 8 : 6 : 4 : 3 : 2 : 1; TSI = 20 + 1 = 50 + 1

Disk: TSI = 51, Clear-sky: RSR = 8, ASR = 43, OLR = 40, IMB = 3. All-sky: RSR = 15, ASR = 36, OLR = 36; albedo = 15/51 = 5/17.



TSI = 20 + 1 : 4 – 2 reflected, 16 + 3 absorbed, 16 emitted, 3 exported (on the disk). (Values after spherical weighting in Wm^{-2})



TSI = 30 + 1 : 10 + 3 reflected, 20 – 2 absorbed, 20 emitted, 2 imported (on the disk). (Values after spherical weighting in Wm^{-2})

Equations

SFC net, clear = OLR/2

SFC net, all = (OLR–LWCRE)/2

SFC gross, clear = 2OLR

SFC gross, all = 2OLR + LWCRE

SFC net, cloudy = $(OLR–LWCRE_T)/2$

SFC gross, cloudy = 2OLR + $LWCRE_T$

2ASR = 2OLR + WIN – LWCRE

TSI = 20 + 1 = 30 + 1 = 50 + 1

LWCRE = All-sky unit = 1

$LWCRE_{True}$ = Cloudy unit = 1

WIN(clear) = Clear-sky unit = 1

1 = 26. 68 Wm^{-2}

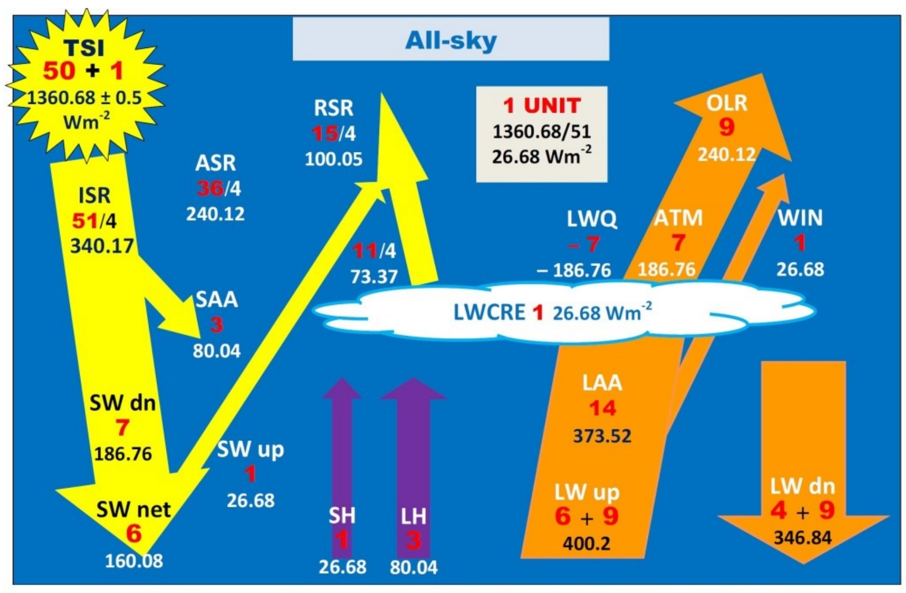
1 = 44.47 Wm^{-2}

1 = 66.70 Wm^{-2}

2 = 4/2, 5 = 10/2; 8 = 4 × 2; 20 = 10 × 2

2 = (5 – 1)/2; 2 + 9 = 11 = 5 × 2 + 1

4 = (9 – 1)/2: 4 + 15 = 19 = 9 × 2 + 1



Eq. (2) Surface net radiation = SFC (SW + LW) net = SH + LH = (OLR – LWCRE)/2 (4)

Eq. (4) Surface gross radiation = SFC (SW net + LW down) = SFC LW up + SH + LH = 2OLR + LWCRE (19)

Essential flux ratios

(from the solution of Eqs. 1 — 4)

ULW clear, cloudy, all = (6, 9, 15)

OLR clear, cloudy, all = (4, 5, 9)

G clear, cloudy, all = (2, 4, 6)

OLR clear = 4 = 6 = 10

G clear = 2 = 3 = 5

g (all) = (15 – 9) / 15 = 0.4

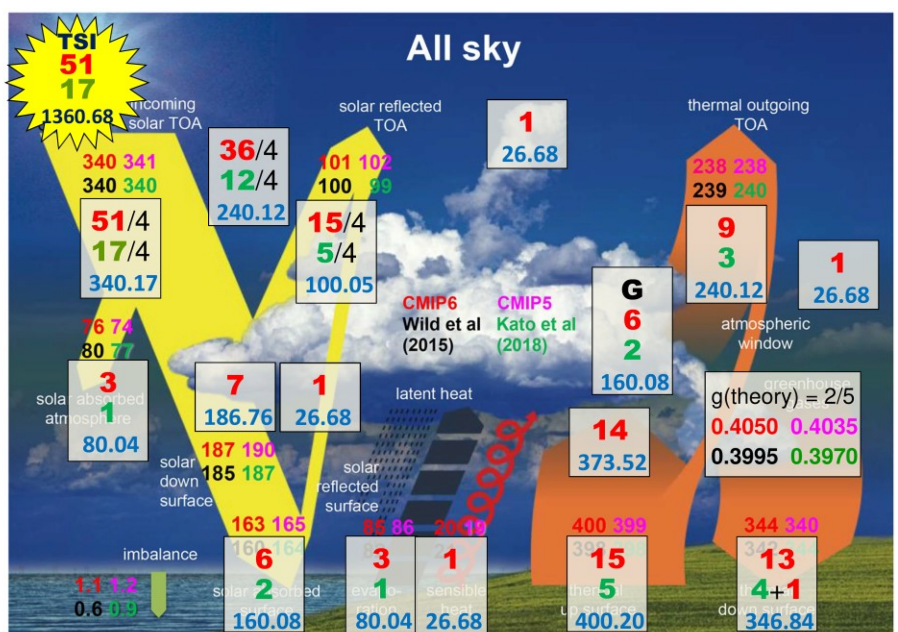
g(clear) = (15 – 10) /15 = = (9 – 6) / 9 = = (6 – 4) / 6 = 1/3

g (cloudy) = (9 – 5) / 9 = 4/9

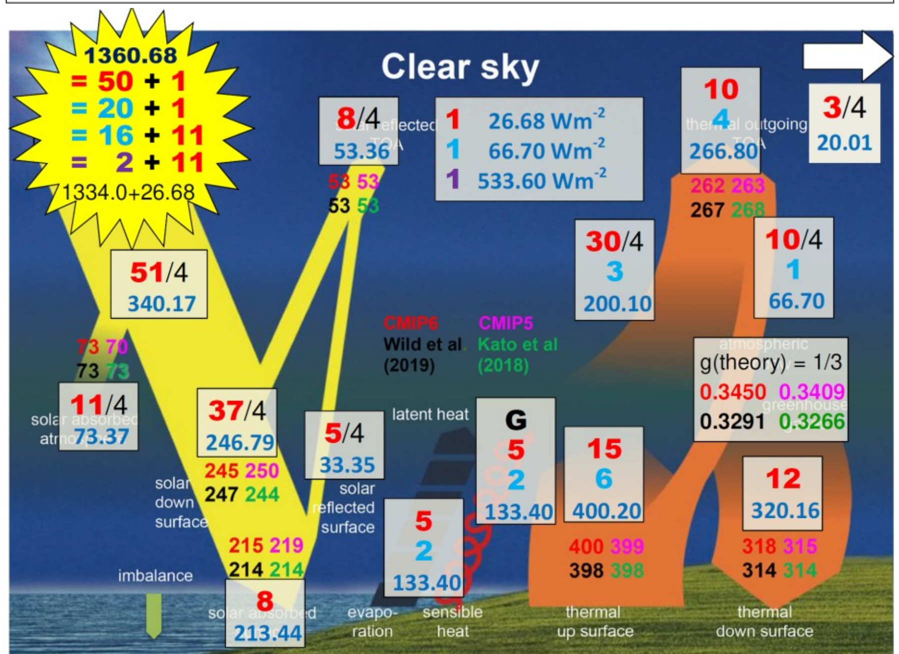
The global energy balance as represented in CMIP6 climate models *Wild (2020)*

Table 1 Global annual mean estimates of the magnitudes of various energy balance cc TOA, within the atmosphere and at the surface, representative for present-day climate

Energy balance component	Reference Estimates Wm^{-2}	# CMIP6 models N	Wm^{-2}	CMIP6 mean Wm^{-2}
TOA				
SW down TOA	340^a, 340^b, 340^c	51/4	340.17	**340.2**
SW up all-sky TOA	$–99^a$ – 100^b, – 102^c	15/4	100.05	**–100.6**
SW absorbed all-sky TOA	241^a 240^b, 238^c	9	240.12	239.5
SW up clear-sky TOA	$–53^a$, $–53^b$	2	53.36	–53.0
SW absorbed clear-sky TOA	287^a, 287^b	43/4	286.81	**287.3**
SW CRE TOA	$–46^a$, $–47^b$	7/4	46.69	–47.8
LW up (OLR) all-sky TOA	$–240^a$, $–239^b$, $–238^c$	9	240.12	–238.3
LW up (OLR) clear-sky TOA	$–268^a$, $–267^b$	10	266.80	–262.4
LW CRE TOA	28^a, 28^b	1	26.68	24.1
Net CRE TOA	$–18^a$, $–19^b$	3/4	20.01	–23.6
Imbalance TOA	0.7^a			1.1
Atmosphere				
SW absorbed all-sky atmos.	80^b. 74^c, 77^d	3	80.04	**76.0**
SW absorbed clear-sky atmos.	73^b, 73^d	11/4	73.37	**72.8**
SW CRE atmos.	7^b, 4^d	1/4	6.67	**3.2**
LW net all-sky atmos.	$–183^b$, $–180^c$, $–187^d$	7	186.76	**–182.1**
LW net clear-sky atmos.	$–183^b$ – 184^d	7	186.76	**–180.9**
LW CRE atmos.	0^b, $–3^d$			–1.3
Net CRE atmos.	7^b, 1^d	1/4	6.67	**1.9**
Surface				
SW down all-sky surface	185^b, 186^c, 187^d	7	186.76	**187.4**
SW up all-sky surface	$–25^b$, $–22^c$, $–23^d$	1	26.68	–23.9
SW absorbed all-sky surface	160^b, 164^c, 164^d	6	160.08	**163.4**
SW down clear-sky surface	247^b, 244^d	37/4	246.79	**244.8**
SW up clear-sky surface	33^b, 30^d	5/4	33.35	30.2
SW absorbed clear-sky surface	214^b, 214^d	8	213.44	**214.6**
SW CRE surface	$–54^b$, $–50^d$	2	53.36	**–51.2**
LW down all-sky surface	342^b, 341^c, 344^d	13	346.84	**343.8**
LW up all-/clear-sky surface	398^b, 399^c, 398^d	15	400.20	–399.9
LW net all-sky surface	$–56^b$, $–58^c$, $–54^d$	2	53.36	**–56.2**
LW down clear-sky surface	314^b, 314^d	12	320.16	**318.0**
LW net clear-sky surface	$–84^b$, $–84^d$	3	80.04	**–81.7**
LW CRE surface	28^b, 30^d	1	26.68	25.5
Net CRE surface	$–26^b$, $–20^d$	1	26.68	**–25.4**
Net radiation surface	104^b, 106^c, 110^d	4	106.72	107.2
Latent heat flux	$–82^b$, $–81^c$	3	80.04	–85.3
Sensible heat flux	$–21^b$, $–25^c$	1	26.68	**–20.1**
Surface Imbalance	0.6^b, 0.5^c			1.5



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



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