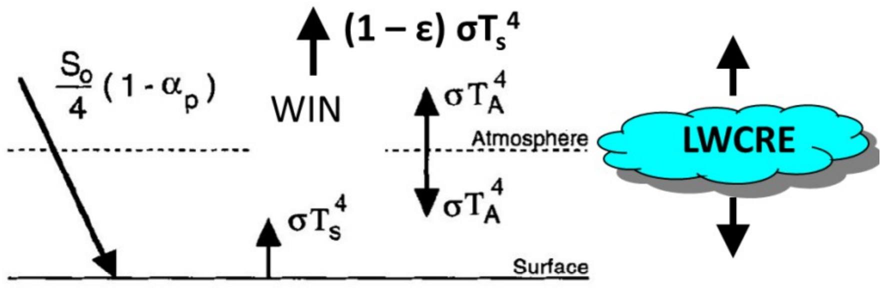
Section 4. Equation (5) and Clouds

- Our Eqs (1) and (3) were validated with high accuracy for clear-skies.
- The original equations of Schwarzschild were given for the Sun’s atmosphere, where “clear-sky” is evidently meaningless.
- The textbooks for planetary applications, like Goody, or Houghton, use Φ_S on the right-hand side, noting that it equals both the incoming solar and the outgoing terrestrial radiation.
- This latter in Earth’s conditions holds in the all-sky.
- But we used these equations for the clear-sky, where a large imbalance exists between the absorbed solar and the emitted thermal energy.
- It is not evident why the equations are valid with OLR, instead of ASR?

More about the single-slab

- In the single-slab model, ASR = OLR, and πB_g = 2ASR = 2OLR
- But since WIN is lost, and only LWCRE is gained back,
- Surface LW+SW gross absorption cannot be equal to 2ASR, but only **2ASR – WIN + LWCRE = 2OLR**



- That's why in the clear-sky gross equation we have πB_g = **2OLR**, instead of 2ASR.
- In the all-sky, the 'leak' is closed by LWCRE:
- ASR (all) = OLR (all) and WIN(all) = LWCRE.
- **But how much is WIN(clear) in theory**?

Eq. (5) 2ASR = 2OLR + WIN – LWCRE

- How much is WIN(clear)? As we have seen, Costa and Shine (2012) found WIN(clear) = 65 Wm^{-2} for their model-OLR = 259 Wm^{-2}.
- Assuming proportionality, for our OLR = 266.80 Wm^{-2} the corresponding WIN(clear) is 66.96 Wm^{-2}.
- The **N**-position in the integer system is 66.70 Wm^{-2}.
- That is, **WIN(clear) = OLR(clear)/4** = **10**/4 units.

Eq. (5) 2ASR = 2OLR + WIN – LWCRE

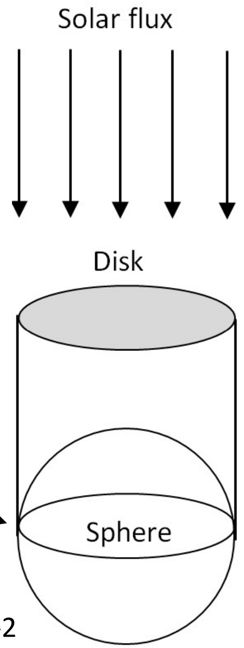
All-sky: ASR all = OLR all = **9**; WIN all = LWCRE = **1**

Clear-sky: OLR clear = **10**; WIN clear = **10**/4 = **2.5** =>

Clear-sky: ASR clear = **10.75**; **Clear-sky TOA net** = **3/4**

This was for the spherical surface of Earth.

For the intercepting cross-section disk (x4):



TSI = **51**, **Clear-sky**: ASR = **43**, OLR = **40**, WIN = **10**,

Reflected (RSR) = **8**, **Clear-sky TOA net** = **3**.

Substitute TSI = **51** = 1360.68 Wm^{-2} and divide by 4

RSR = **2** = 53.36 Wm^{-2}, ASR = **43**/4 = 286.81 Wm^{-2},

OLR = **10** = 266.80 Wm^{-2}; Clear-sky TOA net = 20.01 Wm^{-2}

All-sky: TSI = **51**, RSR = **15**/4, ASR = OLR = **36**/4 = 240.12 Wm^{-2}

It seems that the energetic role of clouds in the LW is to close the open atmospheric window. The radiative energy being lost in the window is gained back by the greenhouse effect of clouds. This interplay is expressed by Eq. (5).

Effective cloud area fraction

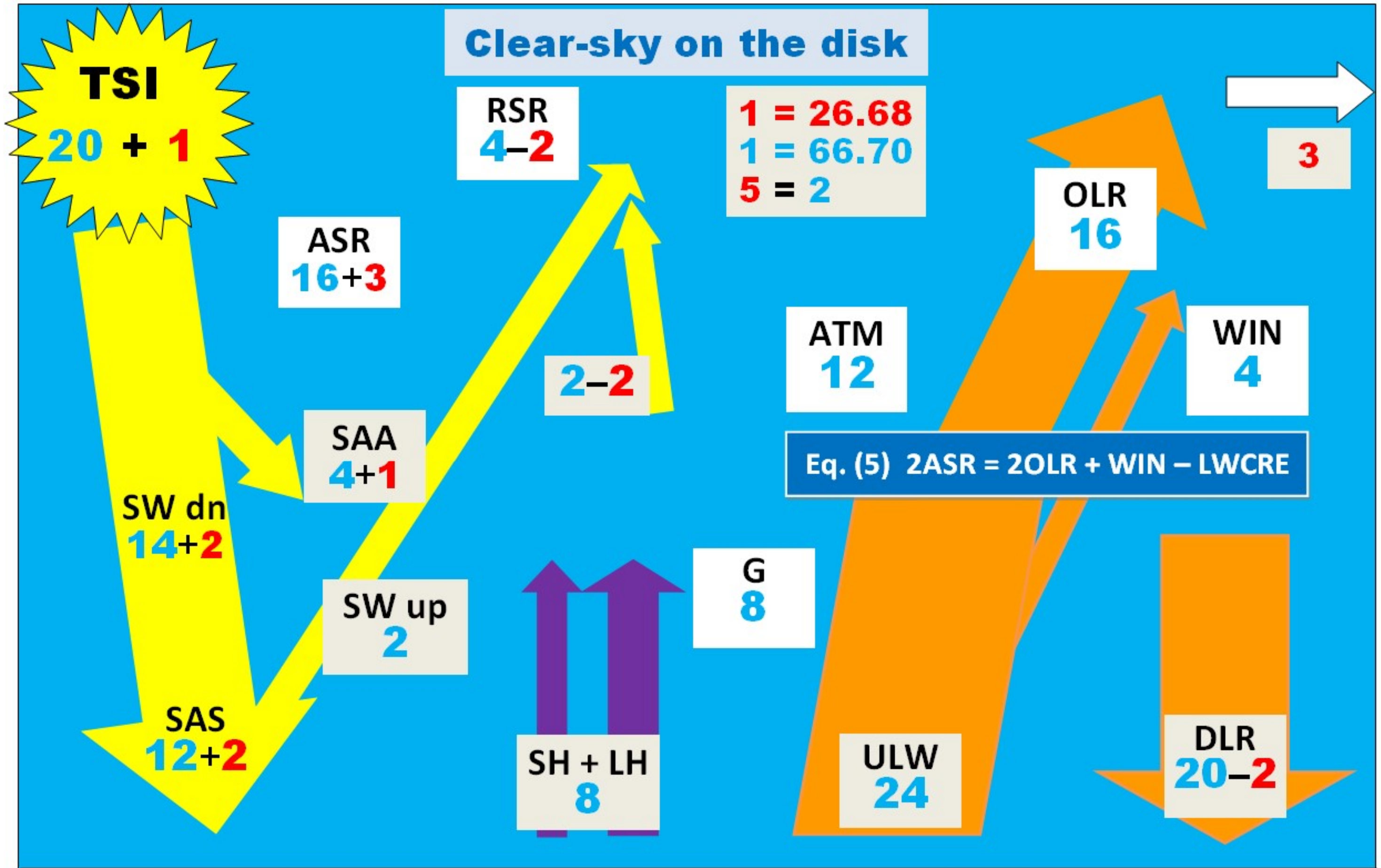
- As we know that WIN(all) = LWCRE = **1** and WIN(clear) = **10**/4, we can construct a single IR-opaue effective cloud area fraction:
- WIN (all) = $(1 - \beta_{eff}) \times$ WIN (clear) =>
- $\beta_{eff} = 3/5 = 0.60$.
- Not unrealistic, since $\beta_{obs} = 0.67$.

Total LWCRE

- This way, it is easy to define the “total” longwave cloud radiative effect as
- $LWCRE_T$ = LWCRE / β_{eff} = 26.68/0.6 = 44.466667 Wm^{-2}
- Evidently,
- $LWCRE_T$ = OLR(clear) – OLR(cloudy)
- Therefore OLR(cloudy) = 222.33 Wm^{-2}.
- Further, DLR(cloudy) = DLR(clear) + $LWCRE_T$ = 364.63 Wm^{-2}, and
- G(cloudy) = G(clear) + $LWCRE_T$ = ULW – OLR(cloudy) = 177.867 Wm^{-2}.
- Now we are ready to construct an idealized global mean cloudy energy flow system with β_{eff} = 0.6

Clouds: The real single-slab model

- The general weighting equation, connecting the fluxes is
- F(all) = β_{eff} × F(cloudy) + (1 – β_{eff}) × F(clear) .
- We know the all-sky and the clear-sky fluxes from the equations, we use them to constract the cloudy fluxes. *E.g.*,
- DLR(cloudy) = 364.63 Wm^{-2} = DLR(clear) + $LWCRE_T$, as ought.
- Since there is a **3**/4 unit = 20.01 Wm^{-2} surplus in the clear-sky part, this energy is transported to the cloudy area, weighted by the clear/cloudy area ratio of 2/3.
- That is, an energy of **1**/2 unit = 13.34 Wm^{-2} is to be added.



TSI = 20 + 1 : 4 – 2 (8) reflected, 16 + 3 (43) absorbed, 16 (40) emitted, 3 exported.

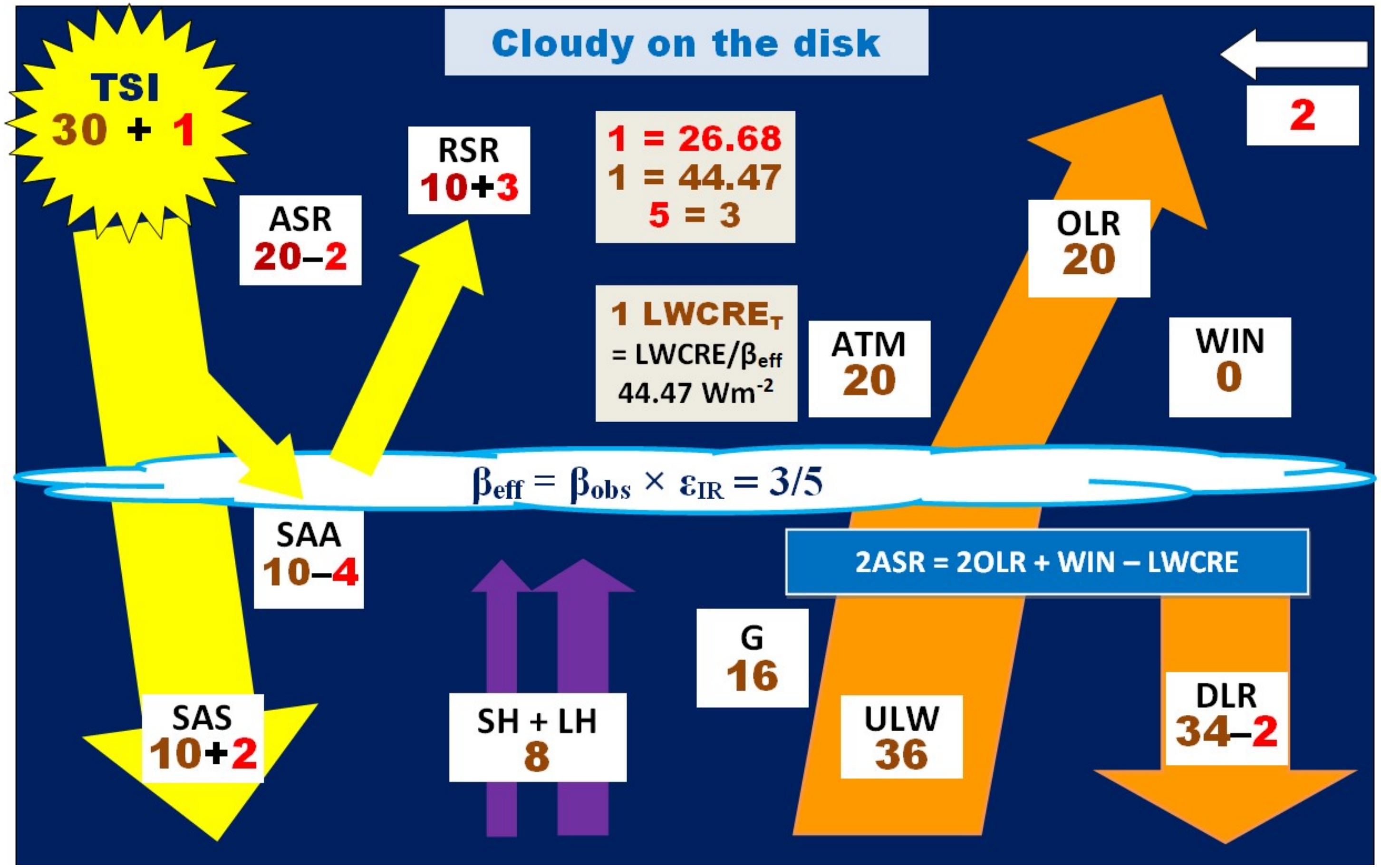
1 clear-sky unit =
WIN(clear) =
66.70 Wm-2

1 all-sky unit =
LWCRE =
26.68 Wm-2

TSI = 1360.68 Wm-2
20 + 1 = 50 + 1

OLR = 16 = 40
ULW = 24 = 60
G = 8 = 20
WIN = 4 = 10

On the sphere:
OLR = 4 = 10
ULW = 6 = 15
G = 2 = 5
WIN = 1 = 2.5



TSI = **30** + **1**; **10** + **3** reflected, **20** – **2** absorbed, **20** emitted, **2** imported.

1 cloudy unit =
LWCRE$_T$ =
44.466667 Wm-2

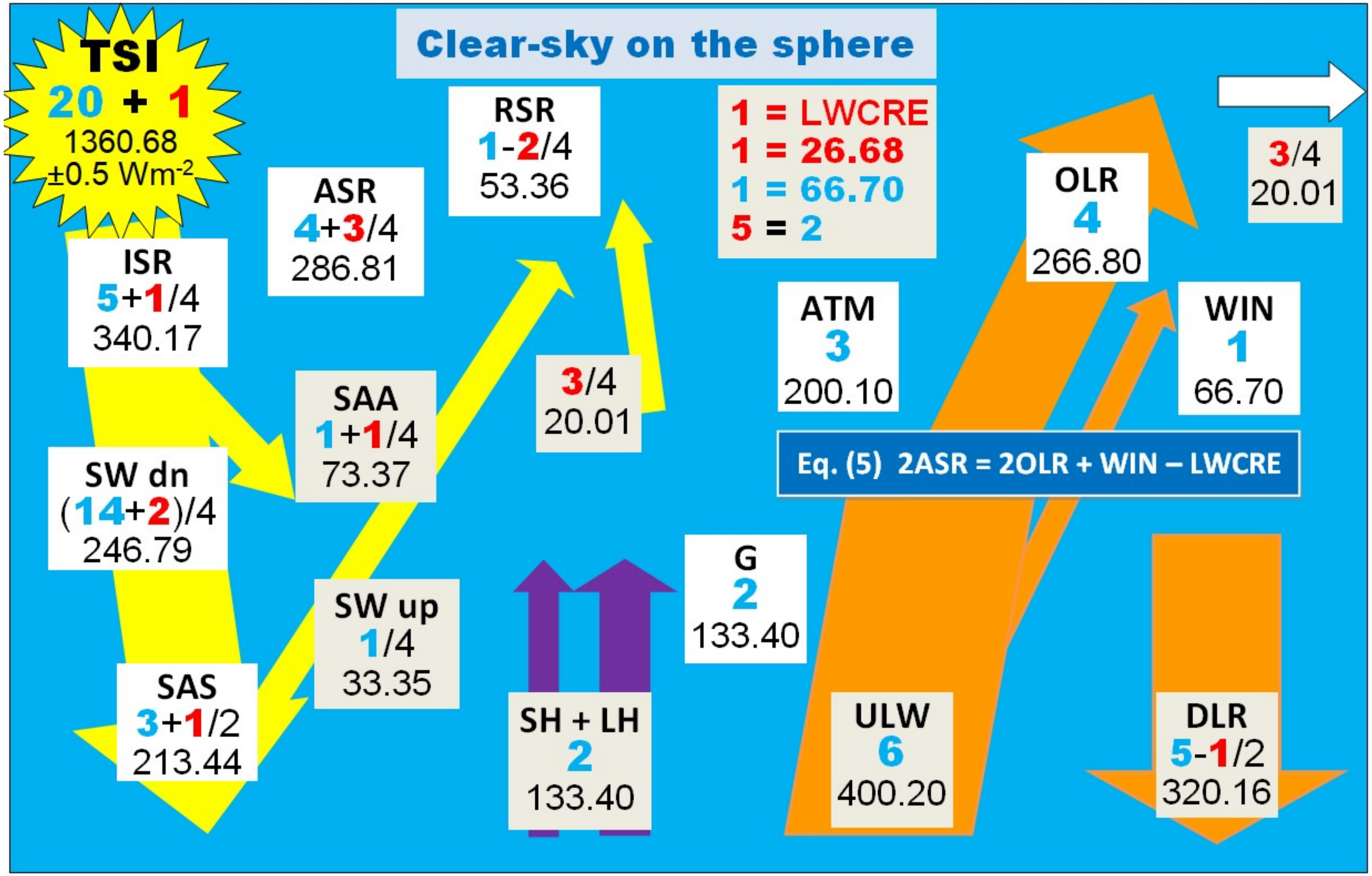
1 all-sky unit =
LWCRE =
26.68 Wm-2

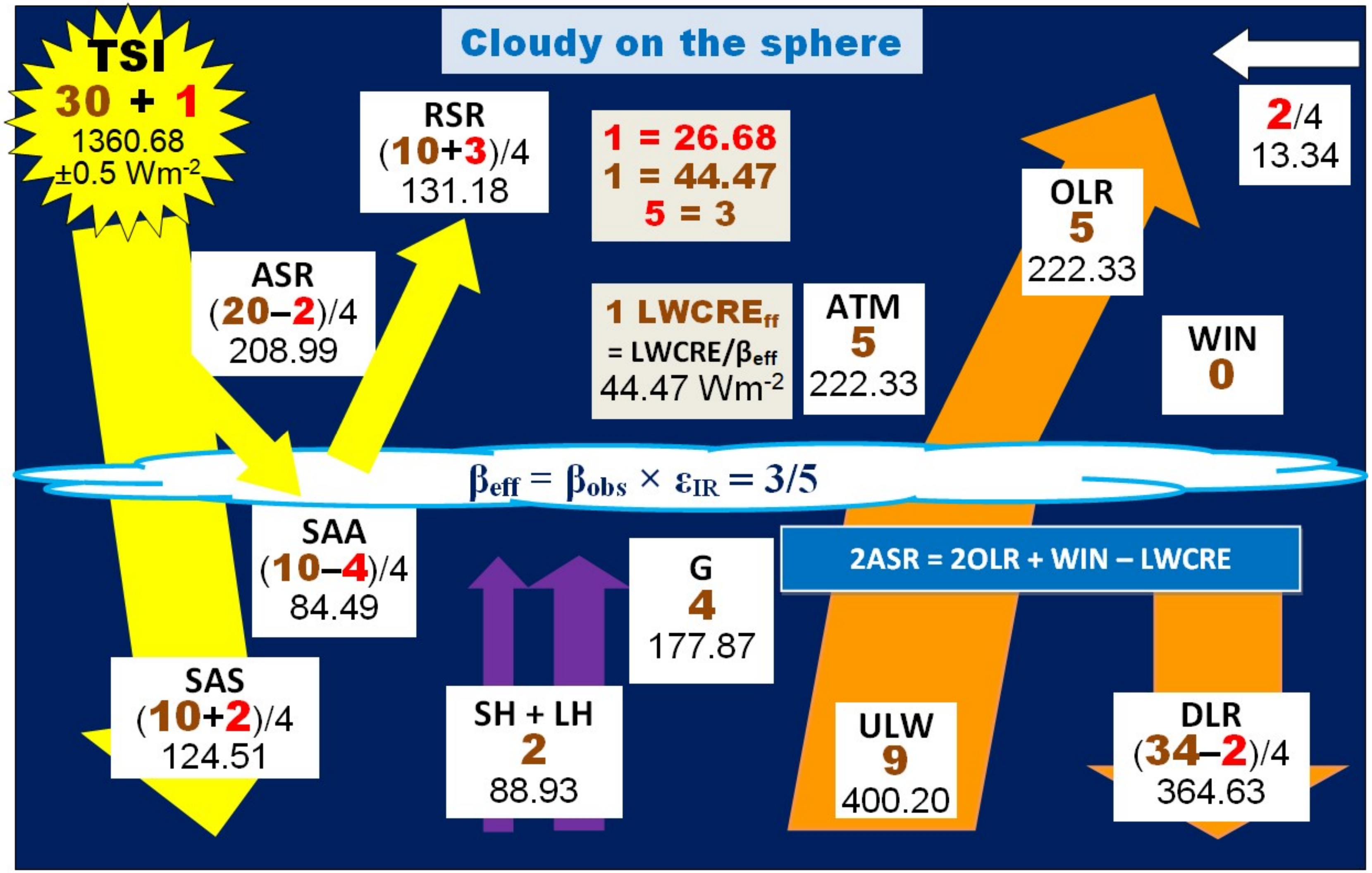
TSI = 1360.68 Wm-2
30 + **1** = **50** + **1**

Equations:

SFC net =
(OLR – LWCRE$_T$)/2

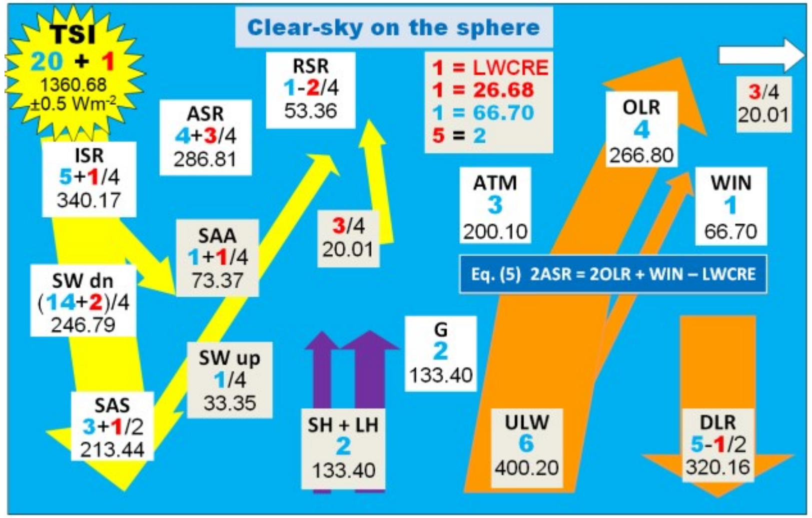
SFC gross =
2OLR + LWCRE$_T$

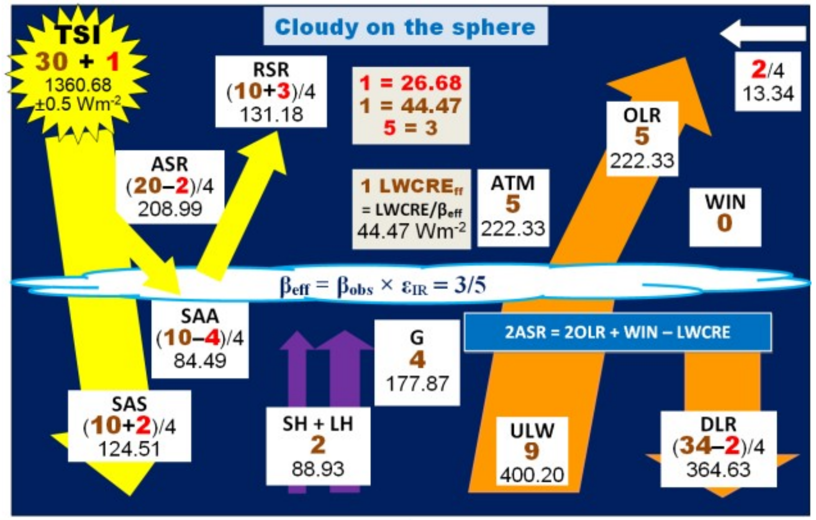

TSI
20 + 1
1360.68
±0.5 Wm-2
Clear-sky on the sphere
RSR
1-2/4
53.36
1 = LWCRE
1 = 26.68
1 = 66.70
5 = 2
ASR
4+3/4
286.81
ISR
5+1/4
340.17
OLR
4
266.80
3/4
20.01
SAA
1+1/4
73.37
3/4
20.01
ATM
3
200.10
WIN
1
66.70
Eq. (5) 2ASR = 2OLR + WIN – LWCRE
SW dn
(14+2)/4
246.79
G
2
133.40
SW up
1/4
33.35
SAS
3+1/2
213.44
SH + LH
2
133.40
ULW
6
400.20
DLR
5-1/2
320.16


Cloudy on the sphere
TSI
30 + 1
1360.68
±0.5 Wm-2
RSR
(10+3)/4
131.18
1 = 26.68
1 = 44.47
5 = 3
2/4
13.34
OLR
5
222.33
ASR
(20–2)/4
208.99
1 LWCREff
= LWCRE/βeff
44.47 Wm-2
ATM
5
222.33
WIN
0
βeff = βobs × εIR = 3/5
SAA
(10–4)/4
84.49
G
4
177.87
2ASR = 2OLR + WIN – LWCRE
SAS
(10+2)/4
124.51
SH + LH
2
88.93
ULW
9
400.20
DLR
(34–2)/4
364.63

Cloudy on the sphere

- The numbers in the cloudy equations look like this:
- SFC net = **2** = (OLR – $LWCRE_T$)/2 = (**5** – **1**)/2
- SFC gross = **9** + **2** = 2OLR + $LWCRE_T$ = 2 × **5** + **1**
- Their form is the "all-sky" form, including $LWCRE_T$ in the place of LWCRE.
- The all-sky system is now can be created as the weighted sum of the clear-sky and cloudy fluxes:





OLR(all) =

4 × 2/5 + **5** × 3/5 = **9**

ULW =

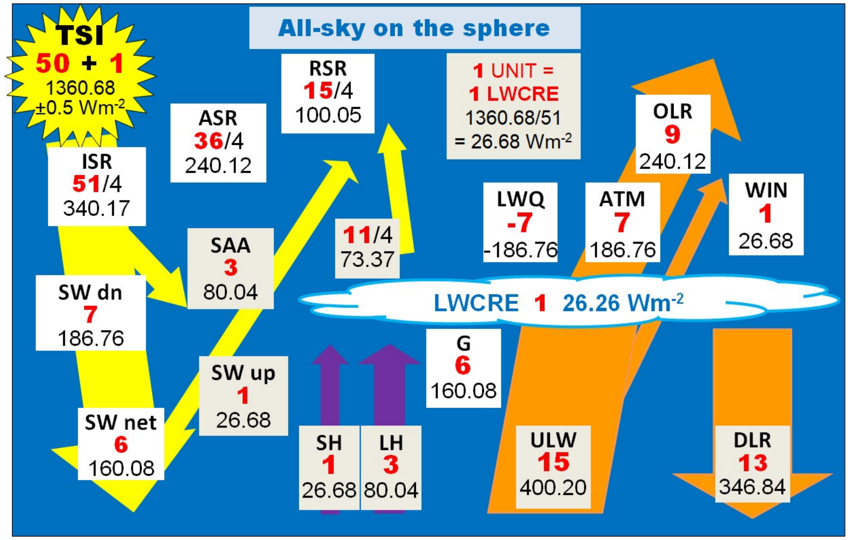
6 × 2/5 + **9** × 3/5 = **15**

SH+LH(all) =

2 × 2/5 + **2** × 3/5 = **4**

G(all) =

2 × 2/5 + **4** × 3/5 = **6**



TSI = 1360.68 Wm^{-2}

=

20 + **1**

=

30 + **1**

=

50 + **1**

Eq. (5) Cloudy numerical check

- 2ASR(cloudy) = 2OLR(cloudy) + WIN – LWCRE
- WIN = 0 => ASR(cloudy) = OLR(cloudy) – LWCRE/2 = 222.33 – 13.34 = 208.99 Wm^{-2}
- ASR(all) = β_{eff} × ASR(cloudy) + (1 – β_{eff}) × ASR(clear)
- 240.12 = 0.6 × 208.99 + 0.4 × 286.81
- TOA net IMB (clear) = ASR(clear) – OLR(clear) = 20.01 Wm^{-2}
- TOA net IMB (cloudy) = ASR(cloudy) – OLR(cloudy) = – 13.34 Wm^{-2}
- 20.01 × 0.4/0.6 = 13.34 Wm^{-2}

Equations

1. SFC net, clear = OLR/2
2. SFC net, all = (OLR–LWCRE)/2
3. SFC gross, clear = 2OLR
4. SFC gross, all = 2OLR + LWCRE

2 (cloudy) SFC net, cloudy = $(OLR–LWCRE_T)/2$

4 (cloudy) SFC gross, cloudy = $2OLR + LWCRE_T$

5. 2ASR = 2OLR + WIN – LWCRE

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

LWCRE = All-sky unit = **1**

$LWCRE_{Total}$ = 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; **3** = **6** / 2; **5** = **10** / 2;

8 = **4** × 2; **12** = **6** × 2; **20** = **10** × 2

2 = (**5** – **1**)/2; **2** + **9** = **11** = **5** × 2 + **1**

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

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

OLR(all-sky) = **9** = 240.12 Wm^{-2}

9/15

5 = 222.33 Wm^{-2} × 0.6 = **5** = 133.4 Wm^{-2}

β_{eff} = 0.6

OLR(all) = OLR(cloudy) × 0.6 + OLR(clear) × 0.4

WIN(cloudy) = 0 => ATM(cloudy) = OLR(cloudy)

OLR(cloudy) (**5**) × 0.6 – OLR(clear) (**4**) × 0.4 =

5 – **4** = 133.4 – 106.72 = LWCRE = **1** = 26.68 Wm^{-2}

ATM(all) = ATM(cloudy) × 0.6 + ATM(clear) × 0.4 =

0.6 × 222.33 (**5**) + 0.4 × 200.1 (**3**) = **8** = 213.44 Wm^{-2}

OLR(all) = ATM(all) + WIN = (ATM + LWCRE) + WIN

5/15

ATM = **3** =
240.12 × 1/3 =
80.04 Wm^{-2}

GHG

1/15

WIN =
1 =
400.2 ×
1/15 =
26.68
Wm^{-2}

266.8 × 0.4 = **4** × 0.4 = **4**
= **3** + **1** = 106.72 Wm^{-2}

4 = 266.8 = **3** + **1** =
200.1 + 66.7 Wm^{-2}

ULW = **15** = 400.2 Wm^{-2}