Understanding Global Cloud Radiative Impacts

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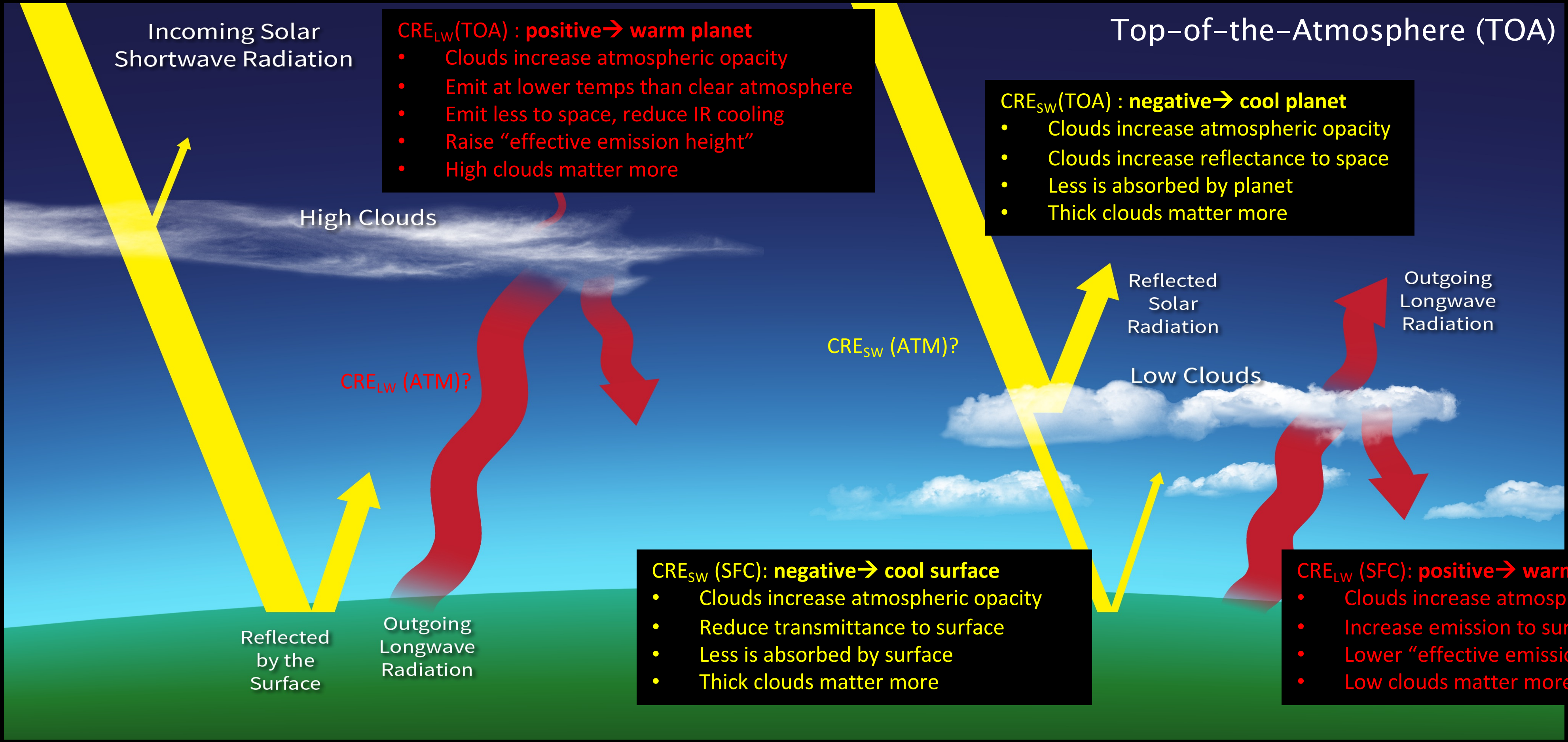
How clouds affect the radiation budget: Fundamentals

Solar (SW): Scatter (reflect up) and absorb (remaining is transmitted)
Thermal IR (LW): Absorb and emit (up and down) thermal (scattering is small)



A standard measure of cloud impact:

Cloud Radiative ~~Forcing~~ Effect (CRE)= (All-Sky Net Flux) – (Clear-Sky Net Flux)

Net Flux = Down Flux – Up Flux

$CRE_{TOT}=CRE_{SW}+CRE_{LW}$

$CRE(TOA)=CRE(SFC)+CRE(ATM)$

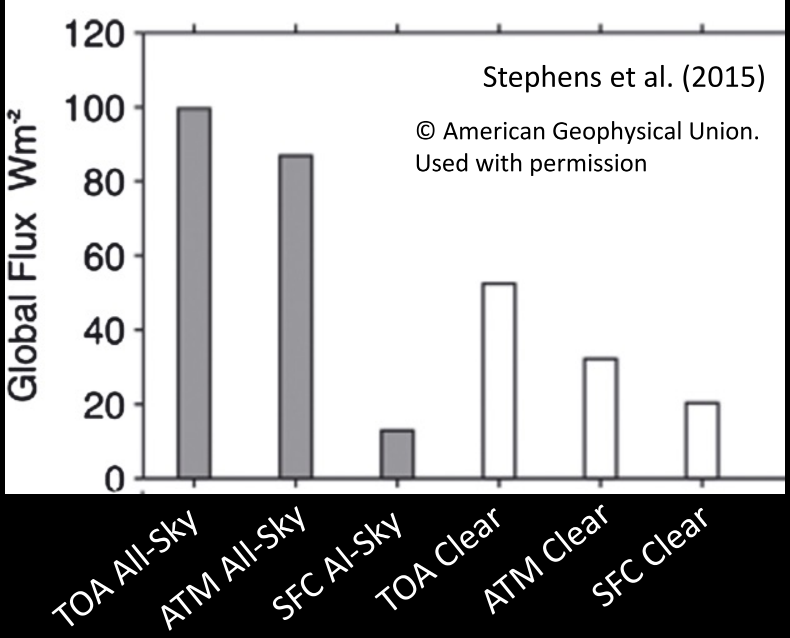
Q1: How much brighter is the Earth because of clouds? (space/TOA perspective)

Increase in albedo ~ 81% : *0.29 vs 0.16*

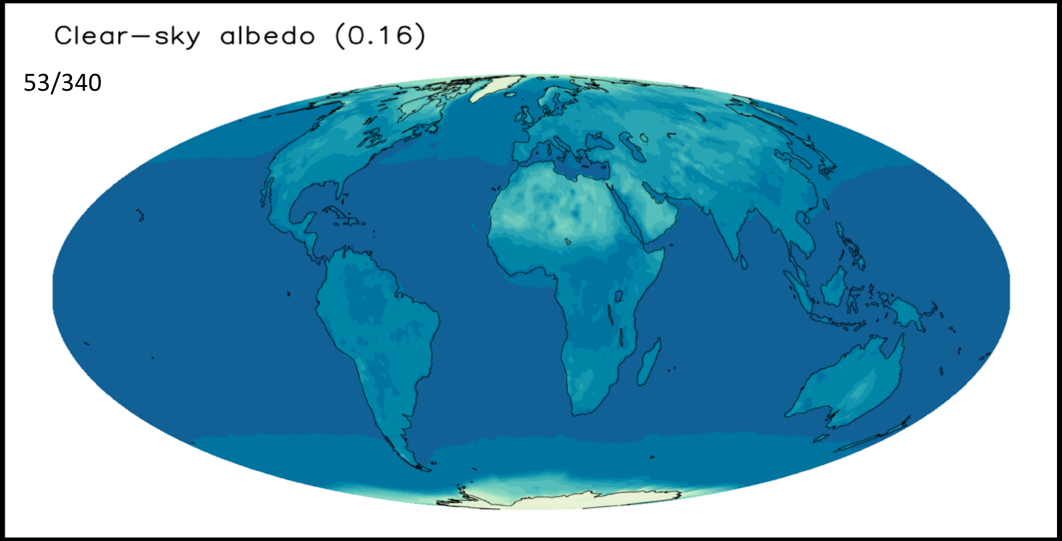
- Even for clear skies atmosphere contributes more than surface (see below).

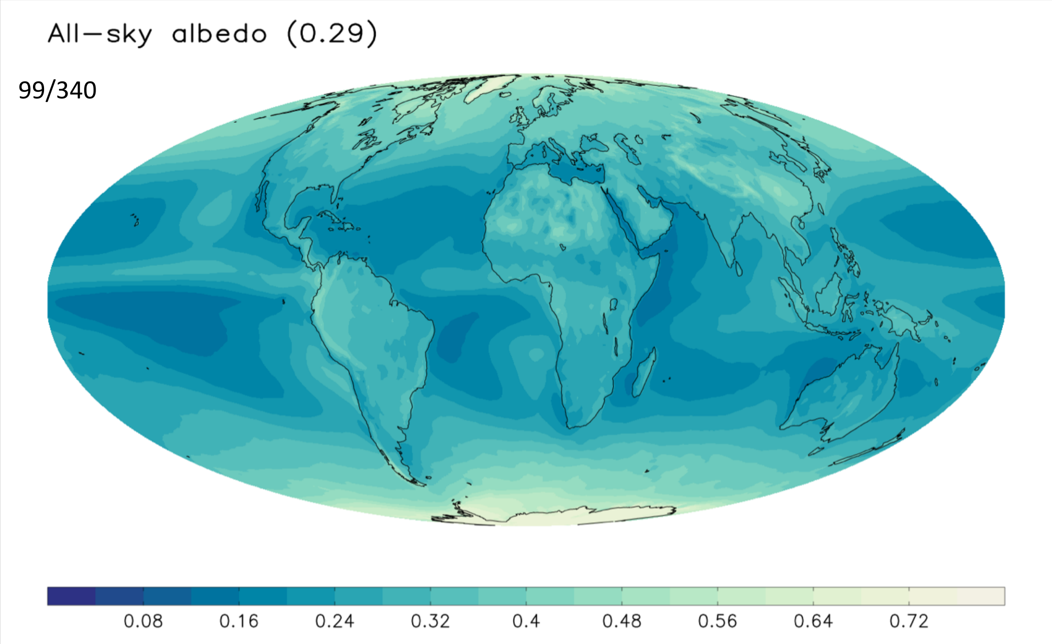
In energy units:

- CRE_{SW}(TOA)= (All-Sky Flux) – (Clear-sky Flux) ≈ **−46 Wm^{-2} more reflected to space (less absorbed by the planet)**

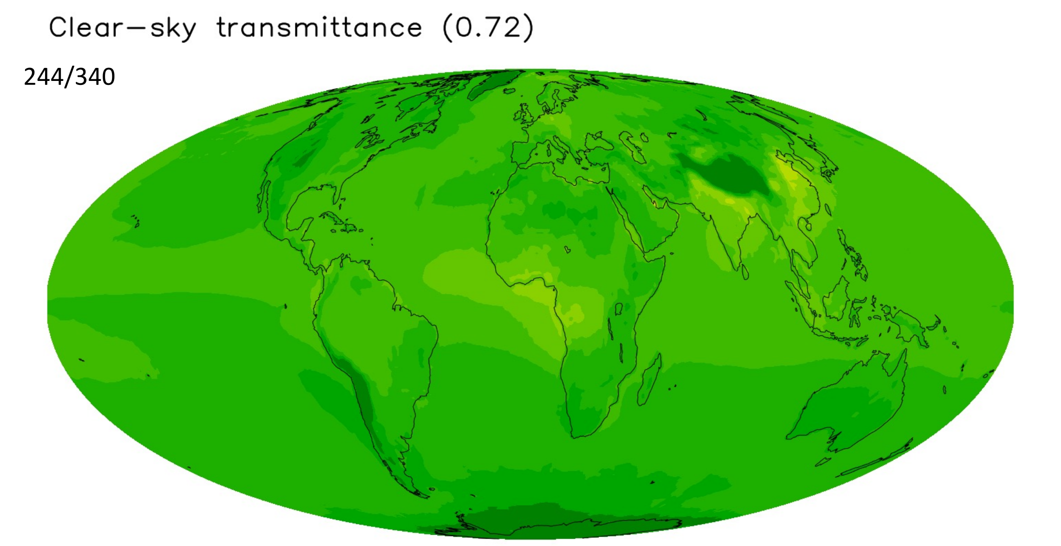


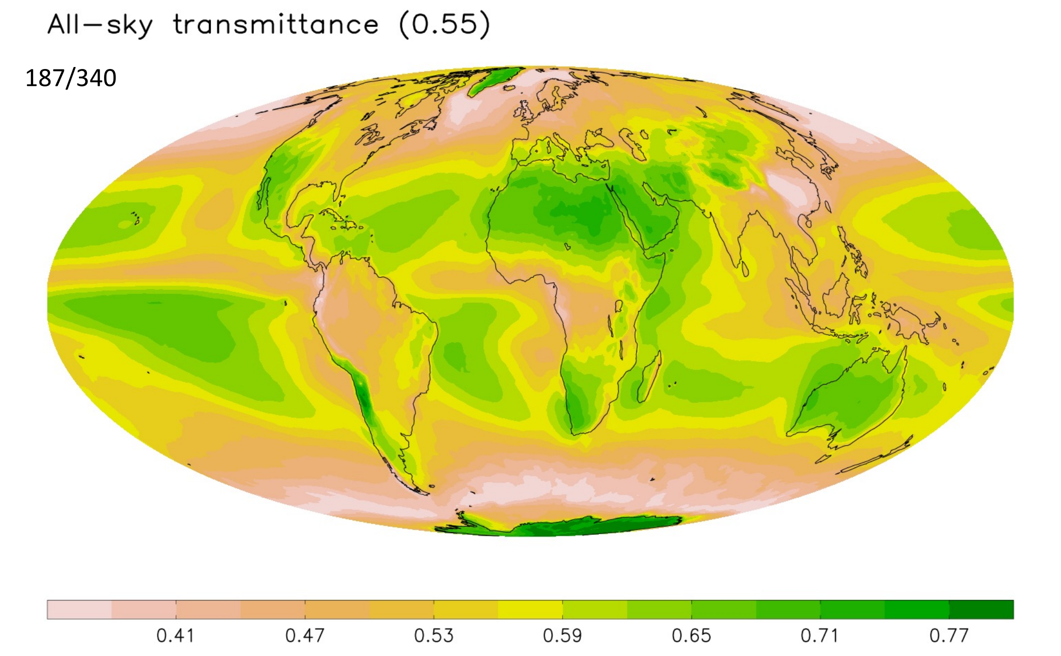
Flux=Down-Up
46/340≈0.13; 53/340≈0.16





Q2: How much dimmer is the Earth's surface because of clouds? (SFC perspective)





Clouds decrease solar reaching (and absorbed by) the surface by ~23%: *0.55 vs 0.72 (0.48 vs 0.63)*

In energy units: CRE_{SW}(SFC)= (All-Sky Flux absorbed@SFC)-(Clear-sky Flux absorbed@SFC) ≈164-214= **–50 Wm^{-2} less absorbed by the surface**

CRE_{SW}(ATM)=–46-(–50)≈ **4 Wm^{-2}, i.e, ~5% additional atmospheric absorption due to clouds** (77 Wm^{-2} vs 73 Wm^{-2})

Q3: How much less thermal radiation escapes to space because of clouds? (TOA perspective)

Greenhouse factor: $\frac{F_{up}^{TOA}}{F_{up}^{SFC}}$; compare $\frac{F_{up}^{TOA}(all\_sky)}{F_{up}^{SFC}(all\_sky)}$ to $\frac{F_{up}^{TOA}(clear)}{F_{up}^{SFC}(clear)}$

0.60/0.67≈0.89, i.e, **~11 % less escapes to space → ~11% stronger greenhouse with clouds**

Much simpler: $\frac{F_{up}^{TOA}(all\_sky)}{F_{up}^{TOA}(clear)} \approx \frac{240}{268} \approx 0.89$

also 11% reduction (surface upwelling is on average same under clear and cloudy conditions)

In energy units:

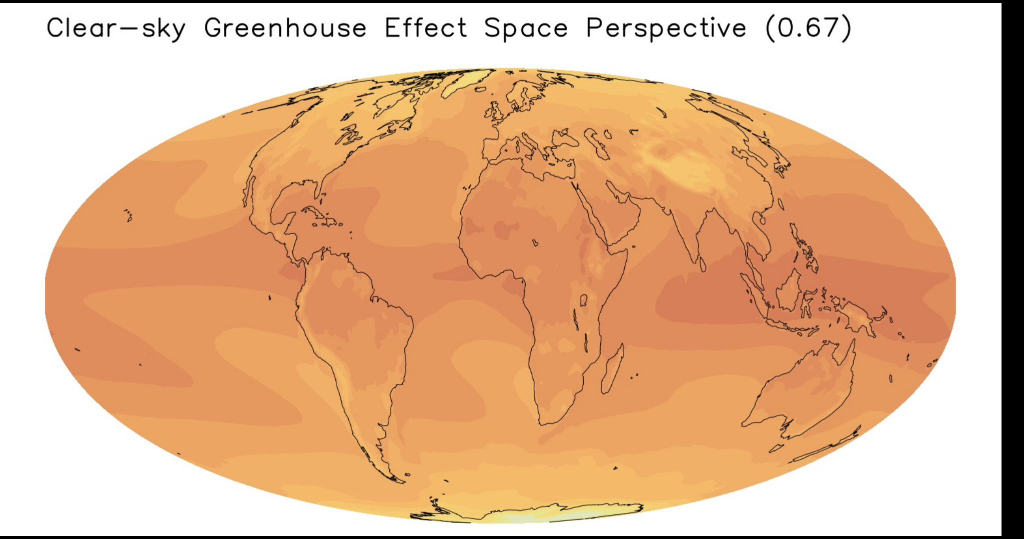
CRE_{LW}= (All-Sky Flux) – (Clear-sky Flux) ≈ **28 Wm^{-2} less emitted to space**

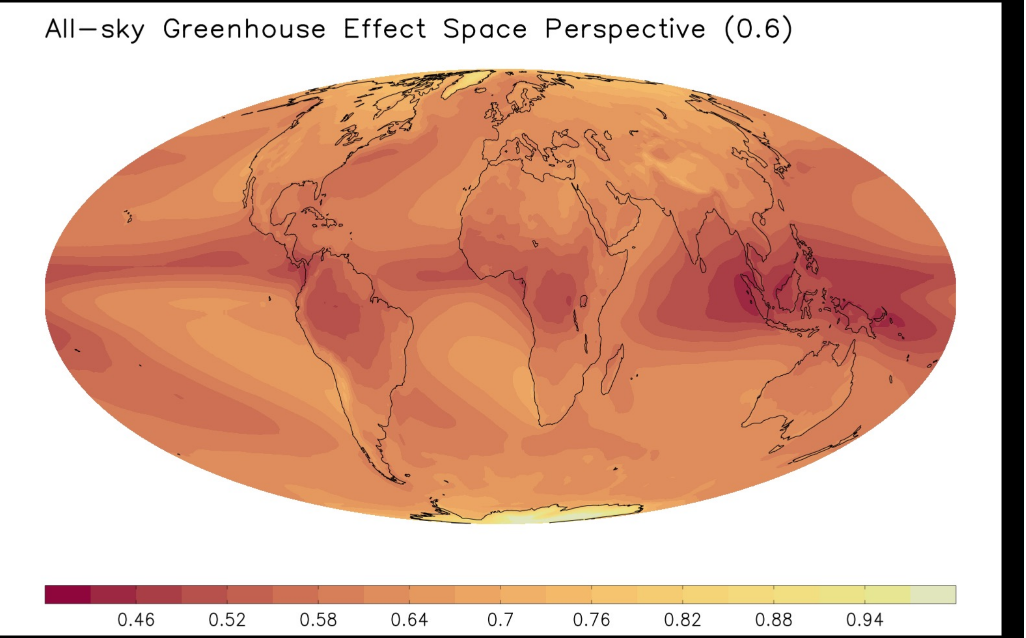
Flux=Down-Up

How much colder does the Earth appear from space because of clouds? (TOA perspective)

$$T_{eff}^{all\_sky,TOA} = \left(\frac{F_{up}^{TOA}(all\_sky)}{\sigma}\right)^{1/4} \approx 255\ \mathrm{K} \qquad T_{eff}^{clear,TOA} = \left(\frac{F_{up}^{TOA}(clear)}{\sigma}\right)^{1/4} \approx 262\ \mathrm{K}$$

(if Earth is assumed a blackbody)





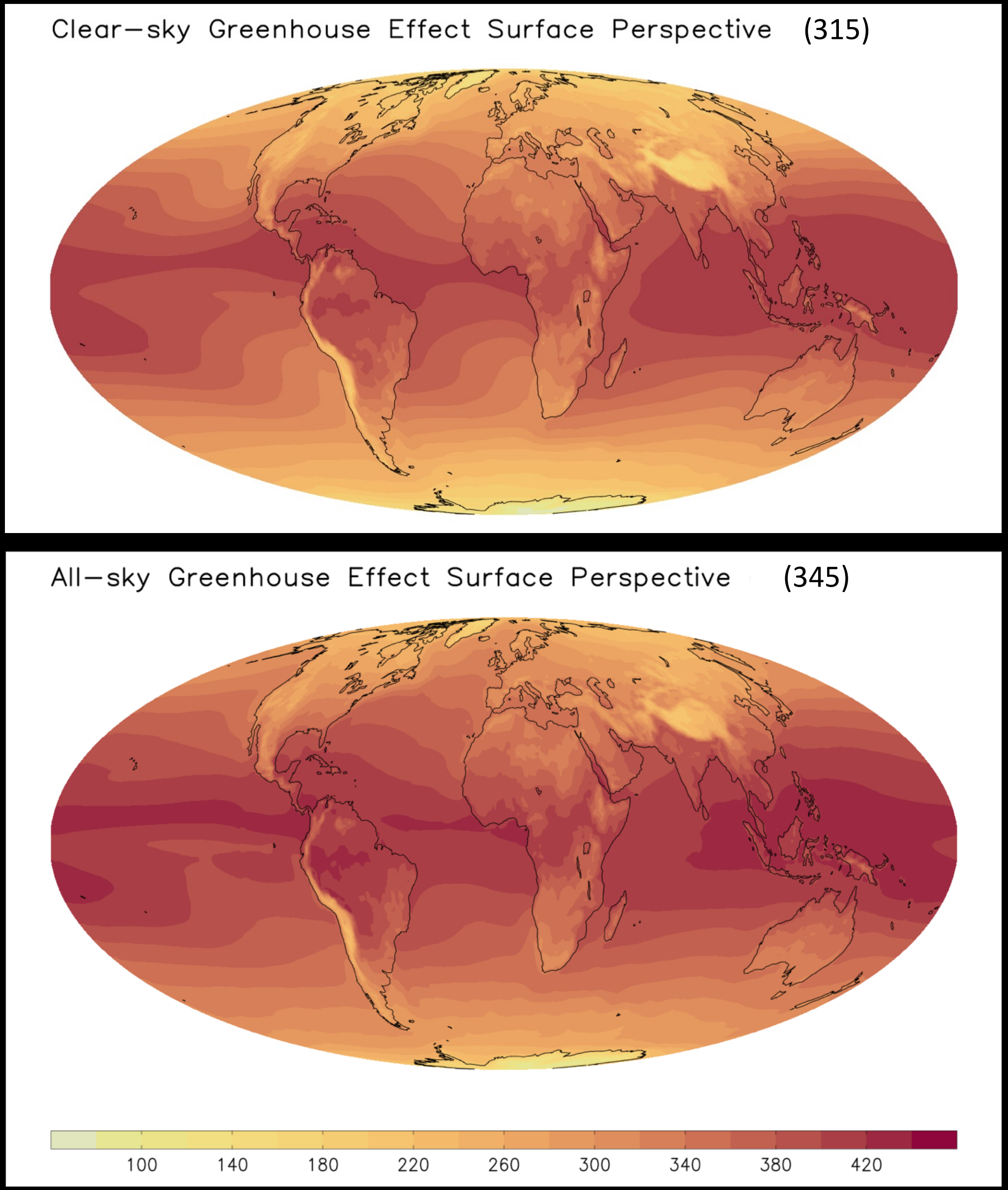
Q4: How much more downwelling does the Earth's Surface receive because of clouds? (SFC perspective)

- 345/315, ~**10% more to surface, due to clouds**
- CRE_{LW}(SFC)= (All-Sky Flux) - (Clear-sky Flux) ≈ **30 Wm^{-2} more to surface**
- CRE_{LW}(ATM)=28-30≈ **-2 Wm^{-2}, very small global decrease in atmospheric LW absorption due to clouds, but with substantial uncertainty**

How much warmer does the atmosphere appear from the surface because of clouds? (SFC perspective)

$$T_{eff}^{all\_sky,SFC} = \left(\frac{F_{down}^{SFC}(all\_sky)}{\sigma}\right)^{1/4} \approx 279\text{ K} \qquad T_{eff}^{clear,SFC} = \left(\frac{F_{down}^{SFC}(clear)}{\sigma}\right)^{1/4} \approx 273\text{ K}$$

(if atmosphere is assumed a blackbody)



Summary of global annual Cloud Radiative Effects

(annual, according to CERES EBAF Ed4.0)

Can be positive in the winter hemisphere

"Isolated" low clouds (L, liquid, CR7-CR11) biggest contributor

Very few clouds have warming effect on annual basis

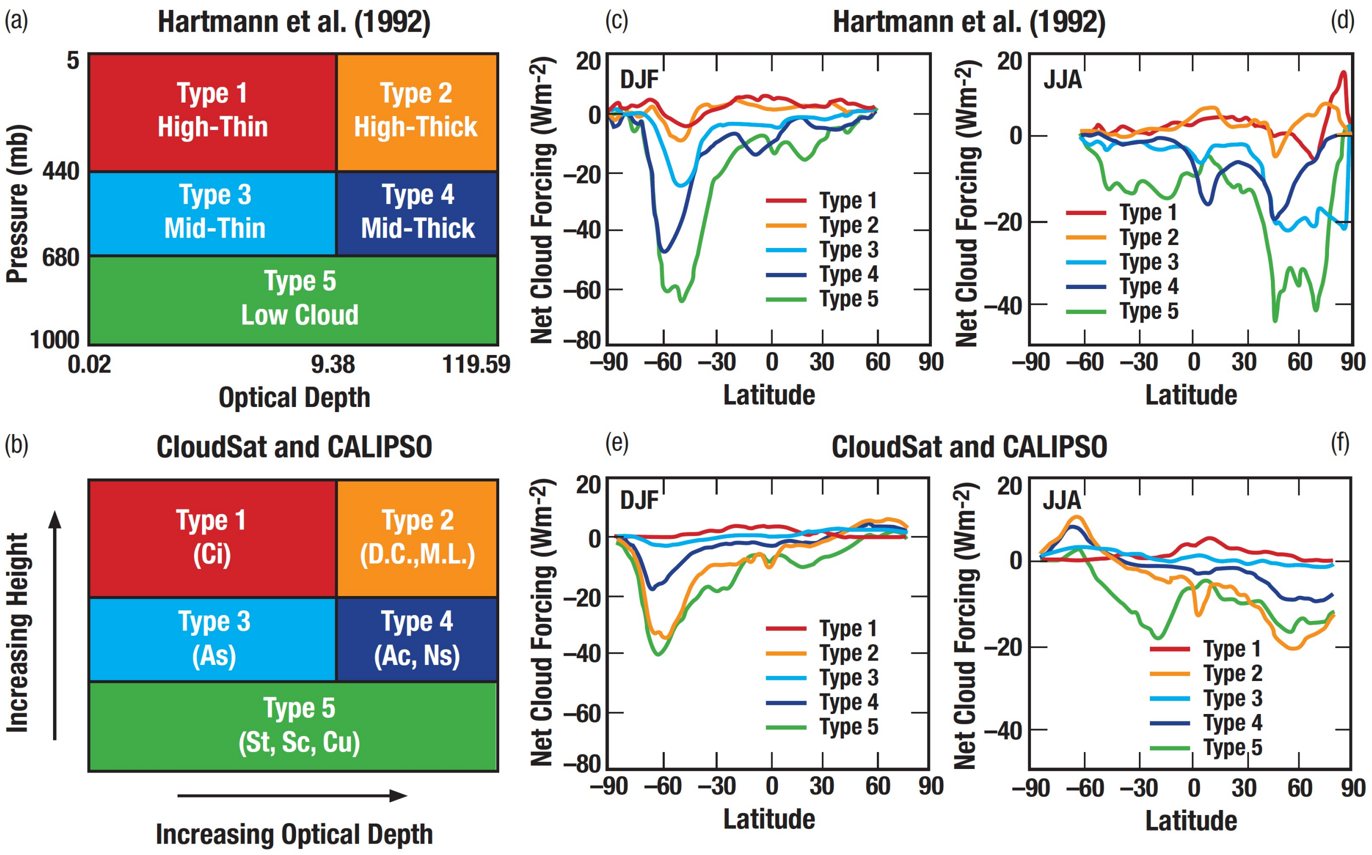
Perspective	LW	SW	Total	Impact
TOA ("Planet", "Climate")	+28	−46	−18	Cooling
Surface (SFC, BOA)	+30	−50	−20	Cooling
Atmosphere (ATM)	−2	+4	+2	Slight Warming

substantial uncertainty

Outcome of many cancellations, and large uncertainty: high clouds warm, low clouds cool

Virtually no clouds have warming effect on annual basis

CRE by cloud type



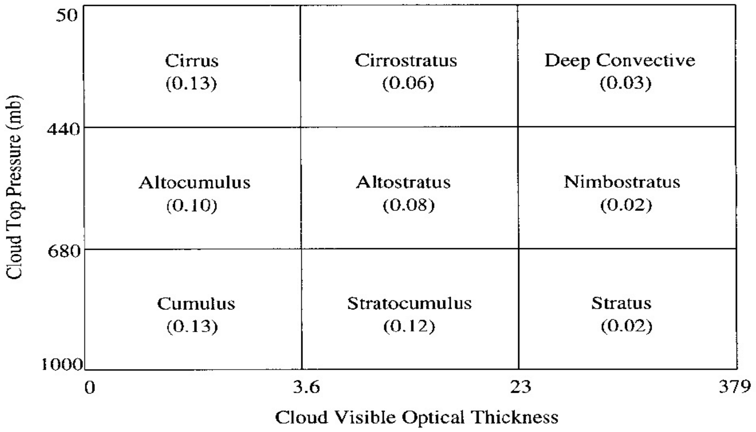
ERBE-ISCCP

CloudSat-CALIPSO

Stephens et al. (2018)

Current climate: $CRE_{TOT} < 0$
Relevant for future: CRE anomaly

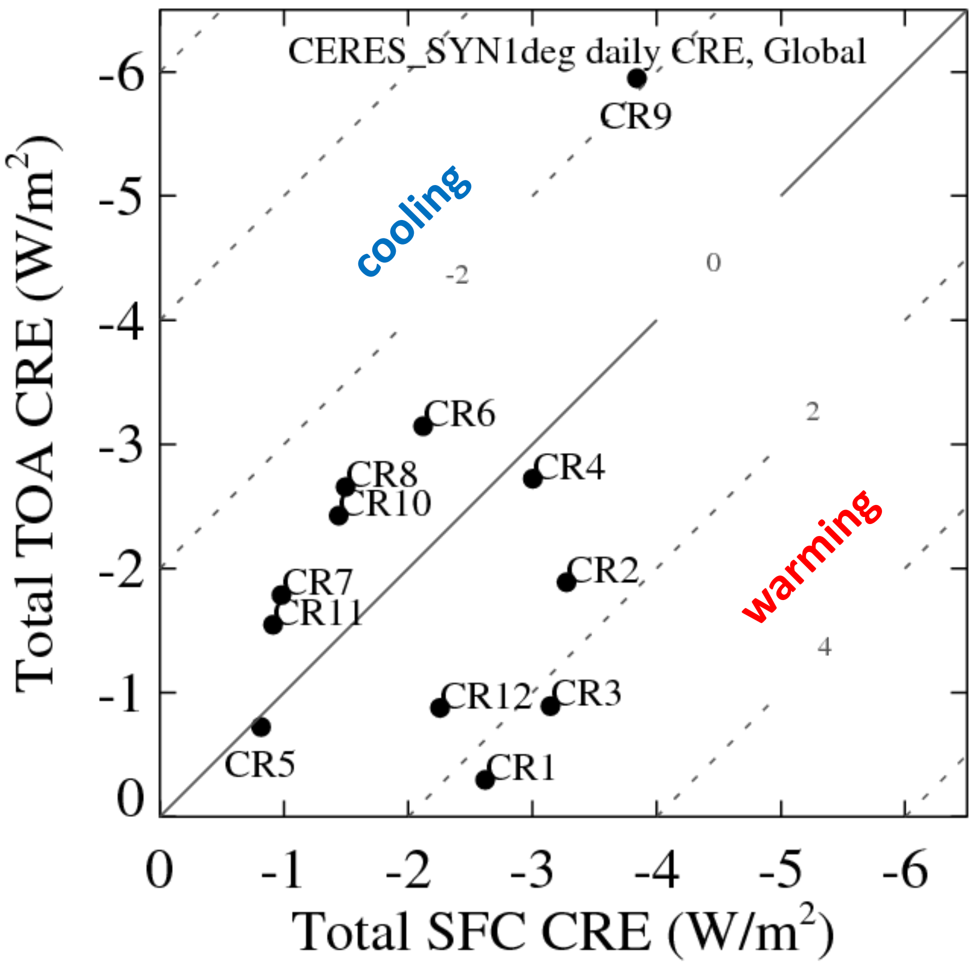
ISCCP

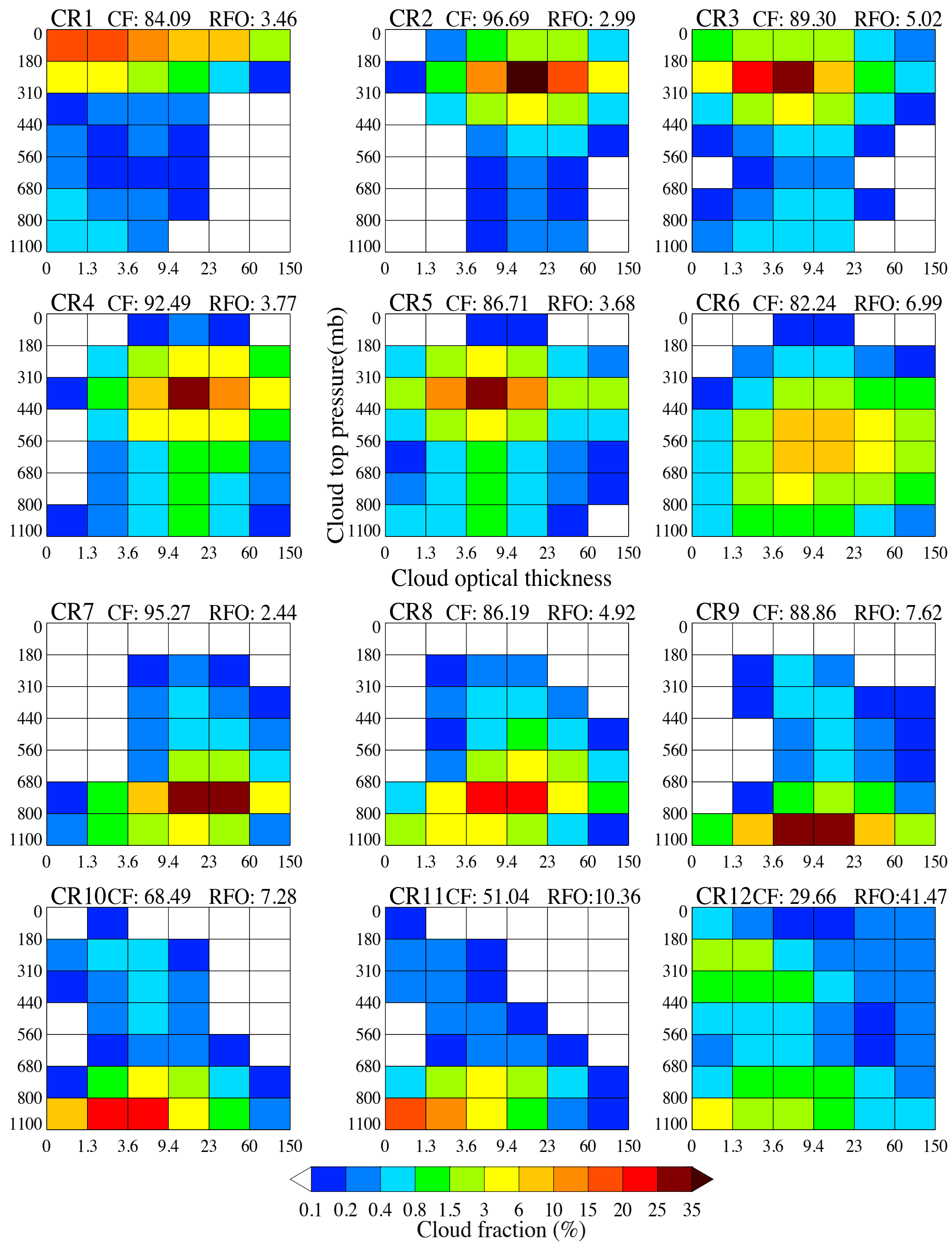


	TOA		
Cloud type	SW	LW	TL
Cirrus	−4.2	5.5	1.3
Cirrostratus	−7.9	5.5	−2.4
Deep convective	−6.2	2.9	−3.3
Altocumulus	−3.2	1.5	−1.7
Altostratus	−8.3	2.0	−6.3
Nimbostratus	−3.4	0.7	−2.7
Cumulus	−5.2	0.6	−4.6
Stratocumulus	−12.7	1.2	−11.5
Stratus	−2.4	0.2	−2.2
Sum (true)	−53.5	20.1	−33.4

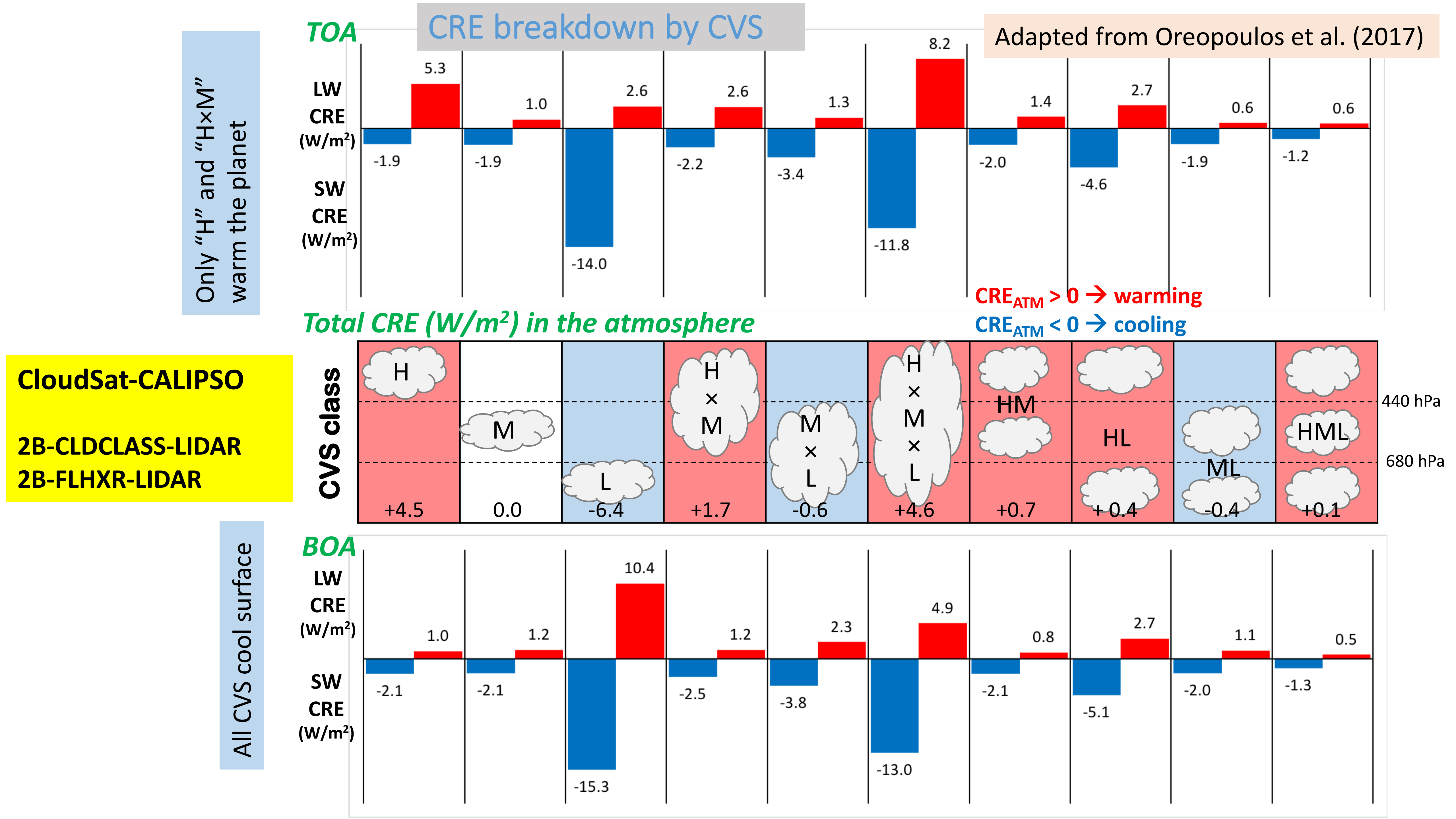
Chen et al. 2000

CRE breakdown by MODIS Cloud Regimes

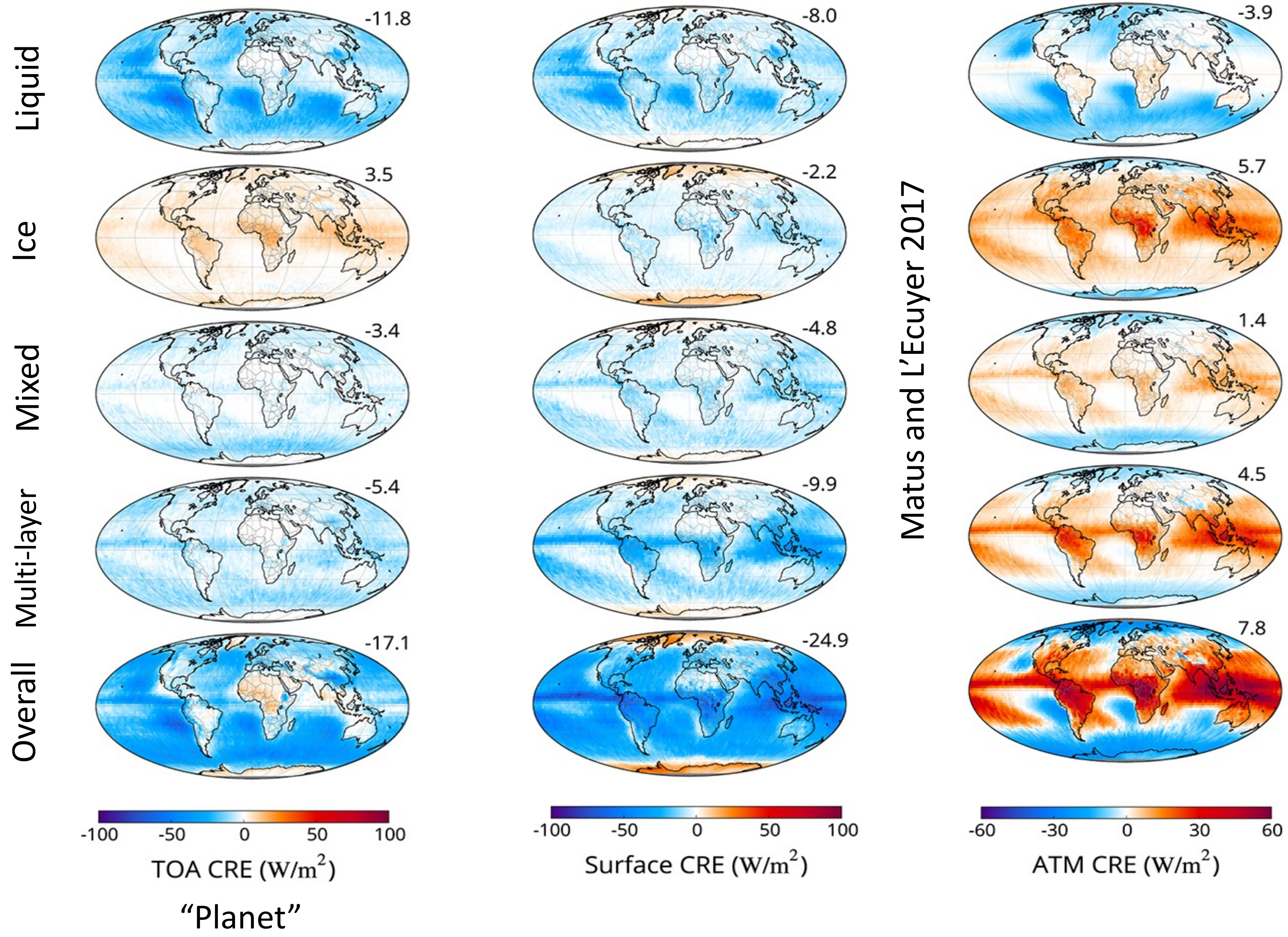




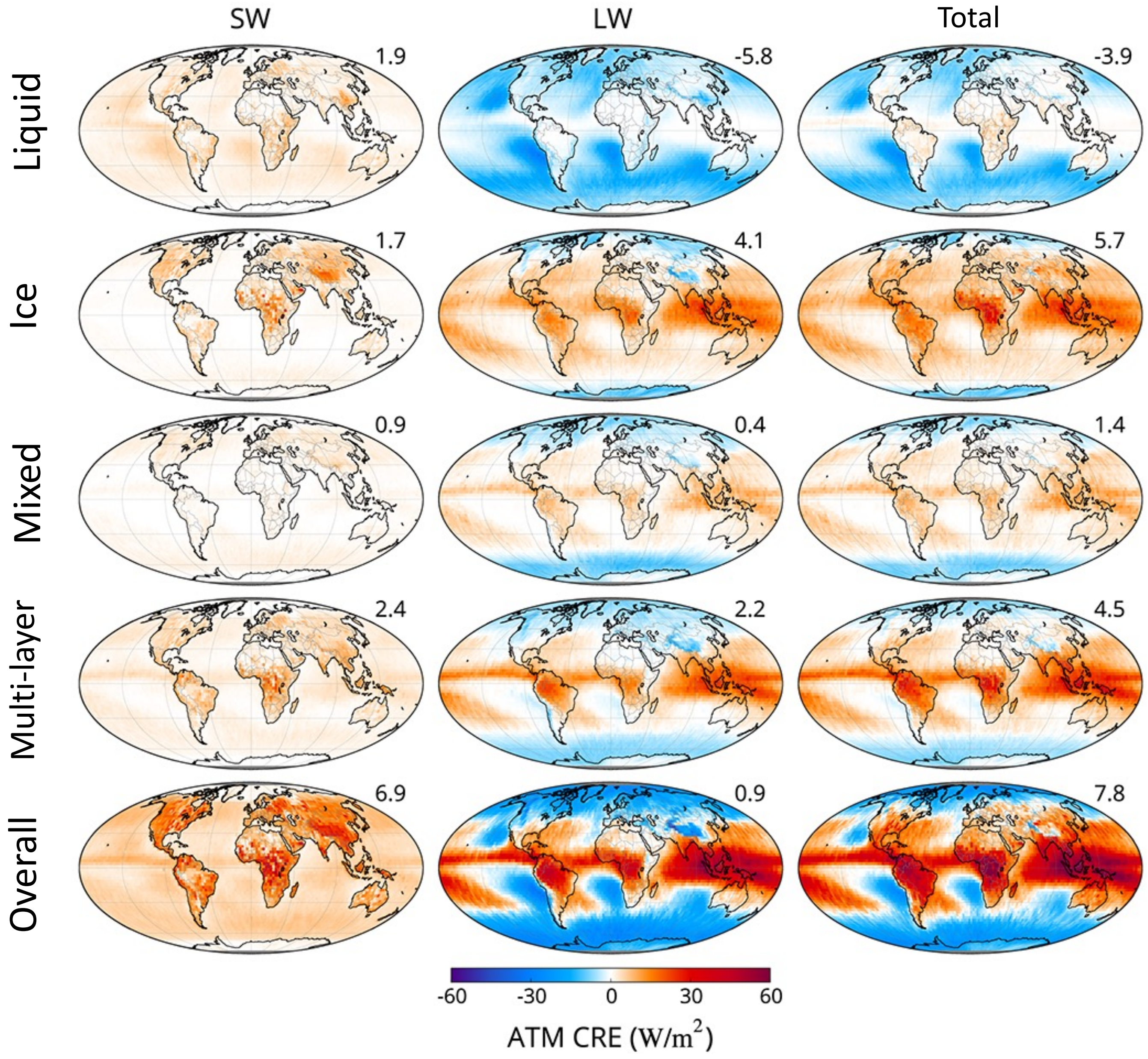
Adapted from Oreopoulos et al. (2016)


CRE breakdown by CVS
Adapted from Oreopoulos et al. (2017)
Only “H” and “H×M” warm the planet
TOA
LW CRE (W/m²)
SW CRE (W/m²)
5.3
1.0
2.6
2.6
1.3
8.2
1.4
2.7
0.6
0.6
-1.9
-1.9
-14.0
-2.2
-3.4
-11.8
-2.0
-4.6
-1.9
-1.2
CRE_ATM > 0 → warming
CRE_ATM < 0 → cooling
Total CRE (W/m²) in the atmosphere
CloudSat-CALIPSO
2B-CLDCLASS-LIDAR
2B-FLHXR-LIDAR
CVS class
H
M
L
H × M
M × L
H × M × L
HM
HL
ML
HML
440 hPa
680 hPa
+4.5
0.0
-6.4
+1.7
-0.6
+4.6
+0.7
+0.4
-0.4
+0.1
All CVS cool surface
BOA
LW CRE (W/m²)
SW CRE (W/m²)
1.0
1.2
10.4
1.2
2.3
4.9
0.8
2.7
1.1
0.5
-2.1
-2.1
-15.3
-2.5
-3.8
-13.0
-2.1
-5.1
-2.0
-1.3

Breakdown of total planetary cloud radiative effect by phase



Breakdown of atmospheric cloud radiative effect by phase



Matus and L'Ecuyer 2017

Summary of Global Cloud Radiative Impacts

- Overall, current clouds radiatively cool the planet and (a bit more) the surface; radiative impact on atmosphere is much smaller (slight warming, from SW, within uncertainties)
  - Atmospheric effect is result of lots of cooling/warming cancellation in LW
- Clouds can have extensive warming TOA/SFC effect in the winter hemisphere
- Thanks to modern satellite observations and radiative transfer modeling, the radiative impact of clouds can be decomposed by cloud class:
  - Cloud classes with low/liquid clouds cool the surface and atmosphere
  - Cloud classes with high clouds still cool the surface, but warm the atmosphere
- Of climate change relevance (cloud feedback):
  - Positive feedback: Fewer clouds that cool and/or more that warm planet
  - Negative feedback: More clouds that cool and/or fewer that warm planet