The Earth's Energy budget: Balance and Imbalances, Knowns and Unknowns

Lazaros Oreopoulos, Climate and Radiation Lab (613)

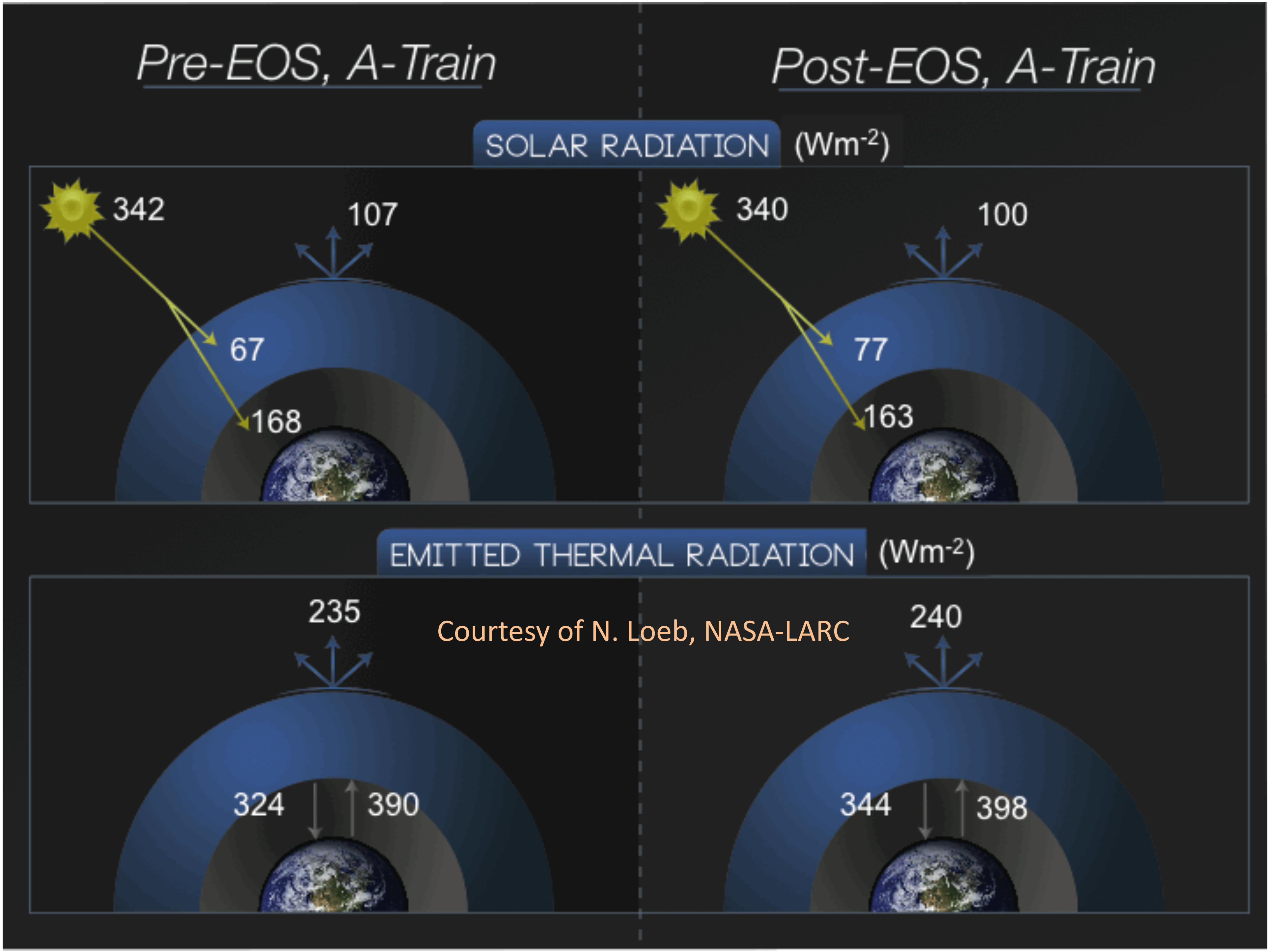
- ✓Our understanding of the Earth's energy budget in the last ~15 years
- ✓The major balances and imbalances
- ✓The relative radiative importance of atmospheric gases
- ✓The role of clouds

The big picture

The level of detail we need to know!

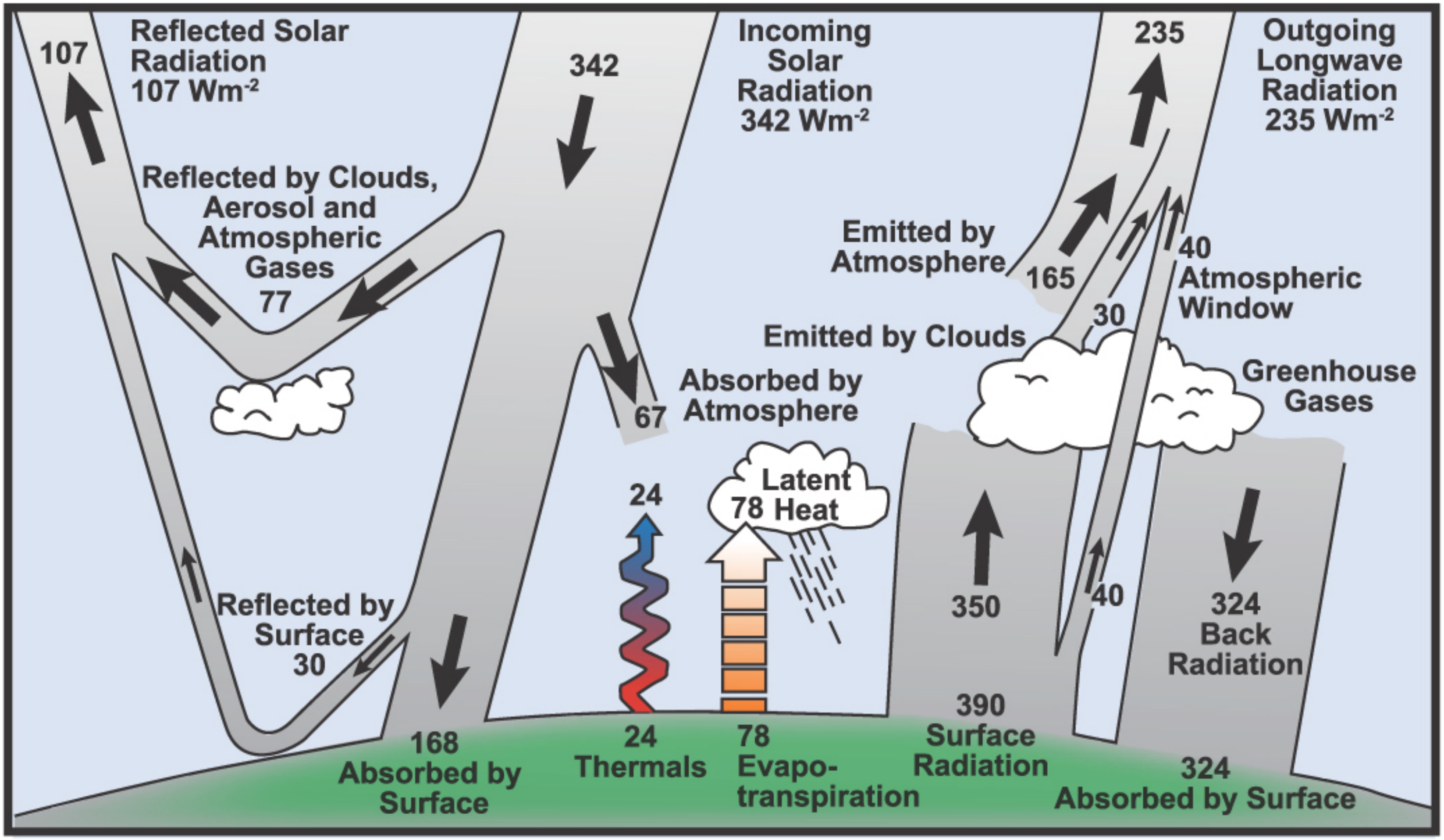
Table 9. Global Average Monthly Means for the Four Seasonal Months (January, April, July, and October), (Pseudo) Annual Mean Based on the Four Seasonal Months From April 1985 to January 1989, and Annual Mean Based on 12 Months for 5 Years (1985–1989)

	1986–1989 Jan.	1985–1988 April	1985–1988 July	1985–1988 Oct.	Pseudo ANN[a]	5-Year, 12-Month ANN
$S\downarrow_t$	352.97	339.28	330.96	344.03	341.81	341.82
$S\uparrow_t$	112.07	104.55	99.80	105.87	105.57	105.71
$S\downarrow_s$	195.50	190.84	179.96	191.42	189.43	189.21
$S\uparrow_s$	26.08	26.16	20.03	23.79	24.01	24.02
$L\downarrow_t$	0.00	0.00	0.00	0.00	0.00	0.00
$L\uparrow_t$	231.33	231.86	236.04	233.29	233.13	233.29
$L\downarrow_s$	337.47	342.97	353.13	344.58	344.54	344.65
$L\uparrow_s$	386.95	397.91	402.28	395.56	395.67	395.58
CLR-$S\downarrow_t$	352.97	339.28	330.96	344.03	341.81	341.82
CLR-$S\uparrow_t$	56.48	57.62	52.12	54.59	55.20	55.36
CLR-$S\downarrow_s$	260.32	246.81	235.28	251.06	248.37	248.26
CLR-$S\uparrow_s$	32.01	32.60	25.12	29.03	29.69	29.82
CLR-$L\downarrow_t$	.00	.00	.00	.00	.00	.00
CLR-$L\uparrow_t$	257.31	259.42	261.79	258.87	259.35	259.48
CLR-$L\downarrow_s$	304.62	312.70	323.96	313.76	313.76	313.54
CLR-$L\uparrow_s$	385.35	396.44	400.88	394.08	394.19	394.08
CLD-$S\downarrow_t$	352.97	339.28	330.96	344.03	341.81	341.82
CLD-$S\uparrow_t$	126.68	117.35	113.84	119.47	119.33	119.52
CLD-$S\downarrow_s$	176.71	174.52	163.02	175.01	172.32	172.01
CLD-$S\uparrow_s$	23.33	23.79	18.20	22.13	21.86	21.84
CLD-$L\downarrow_t$	0.00	0.00	0.00	0.00	0.00	0.00
CLD-$L\uparrow_t$	225.34	224.98	229.23	226.88	226.61	226.80
CLD-$L\downarrow_s$	352.53	356.62	367.31	358.53	358.75	358.97
CLD-$L\uparrow_s$	387.67	398.57	402.96	396.23	396.36	396.27
CFC-$S\downarrow_t$	0.00	0.00	0.00	0.00	0.00	0.00
CFC-$S\uparrow_t$	55.59	46.93	47.68	51.27	50.37	50.34
CFC-$S\downarrow_s$	−64.82	−55.98	−55.32	−59.64	−58.94	−59.05
CFC-$S\uparrow_s$	−5.92	−6.44	−5.09	−5.24	−5.68	−5.80
CFC-$L\downarrow_t$	0.00	0.00	0.00	0.00	0.00	0.00
CFC-$L\uparrow_t$	−25.97	−27.56	−25.75	−25.58	−26.22	−26.19
CFC-$L\downarrow_s$	32.84	30.27	29.17	30.82	30.78	31.11
CFC-$L\uparrow_s$	1.60	1.47	1.40	1.48	1.49	1.50



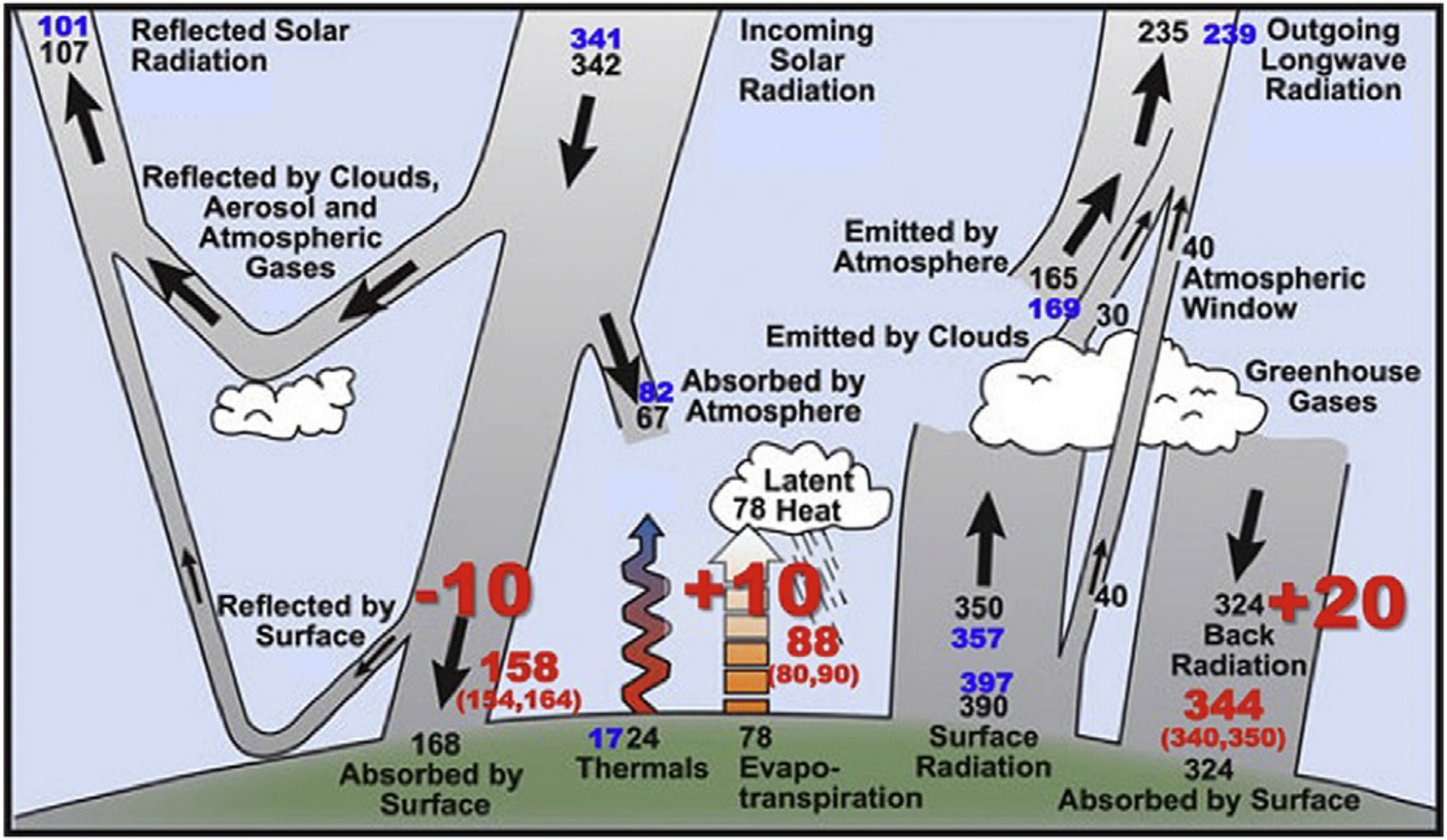
Pre-EOS, A-Train
Post-EOS, A-Train
SOLAR RADIATION (Wm-2)
342
107
67
168
340
100
77
163
EMITTED THERMAL RADIATION (Wm-2)
235
324
390
240
344
398
Courtesy of N. Loeb, NASA-LARC

The outdated picture (but still in the 2007 4AR IPCC report)



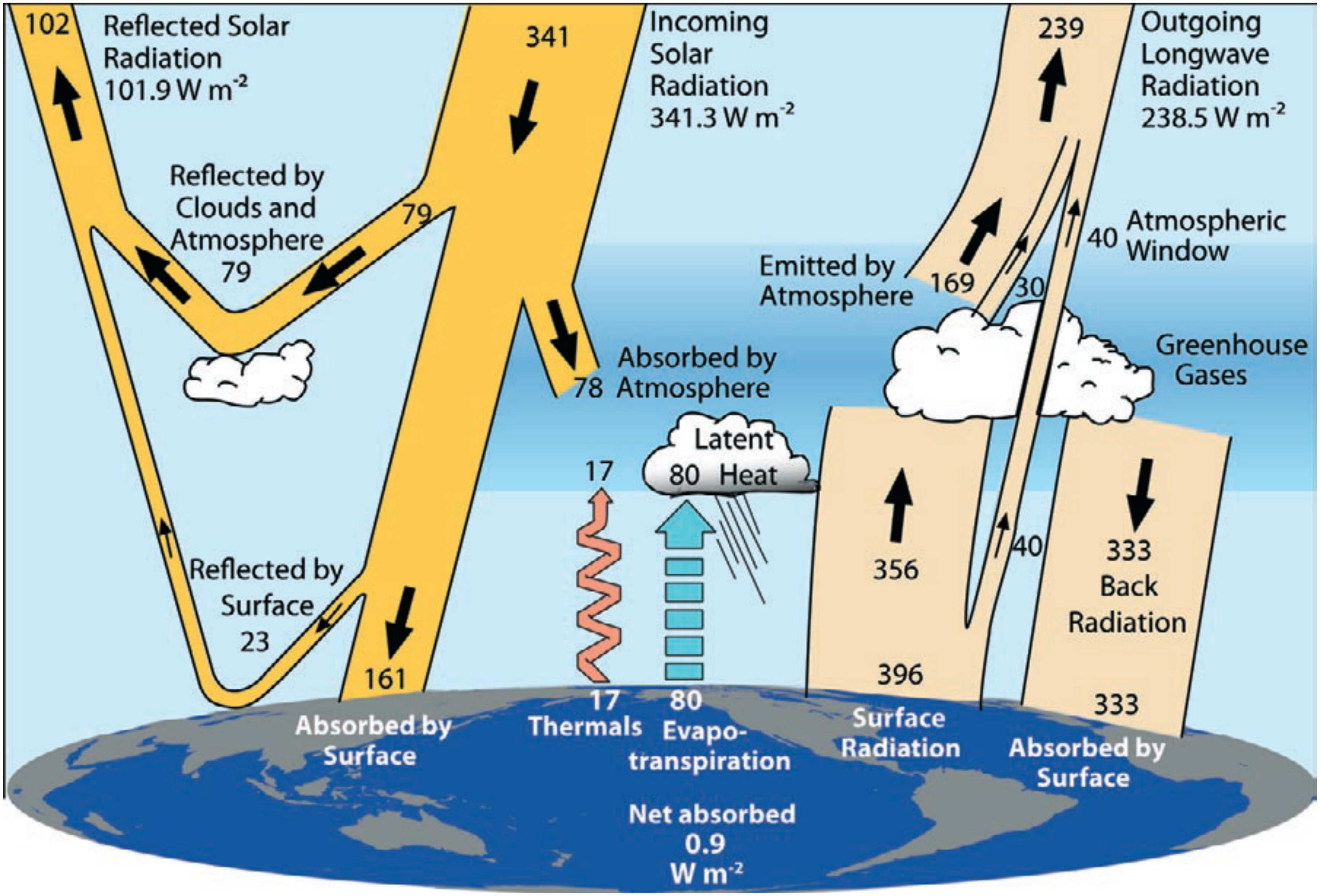
From Kiehl and Trenberth (1997)

Revisions to the 15 yr old picture (1)



From Wild (2012) (A **facelift** for the picture of the global energy balance)

Revisions to the 15 yr old picture (2)

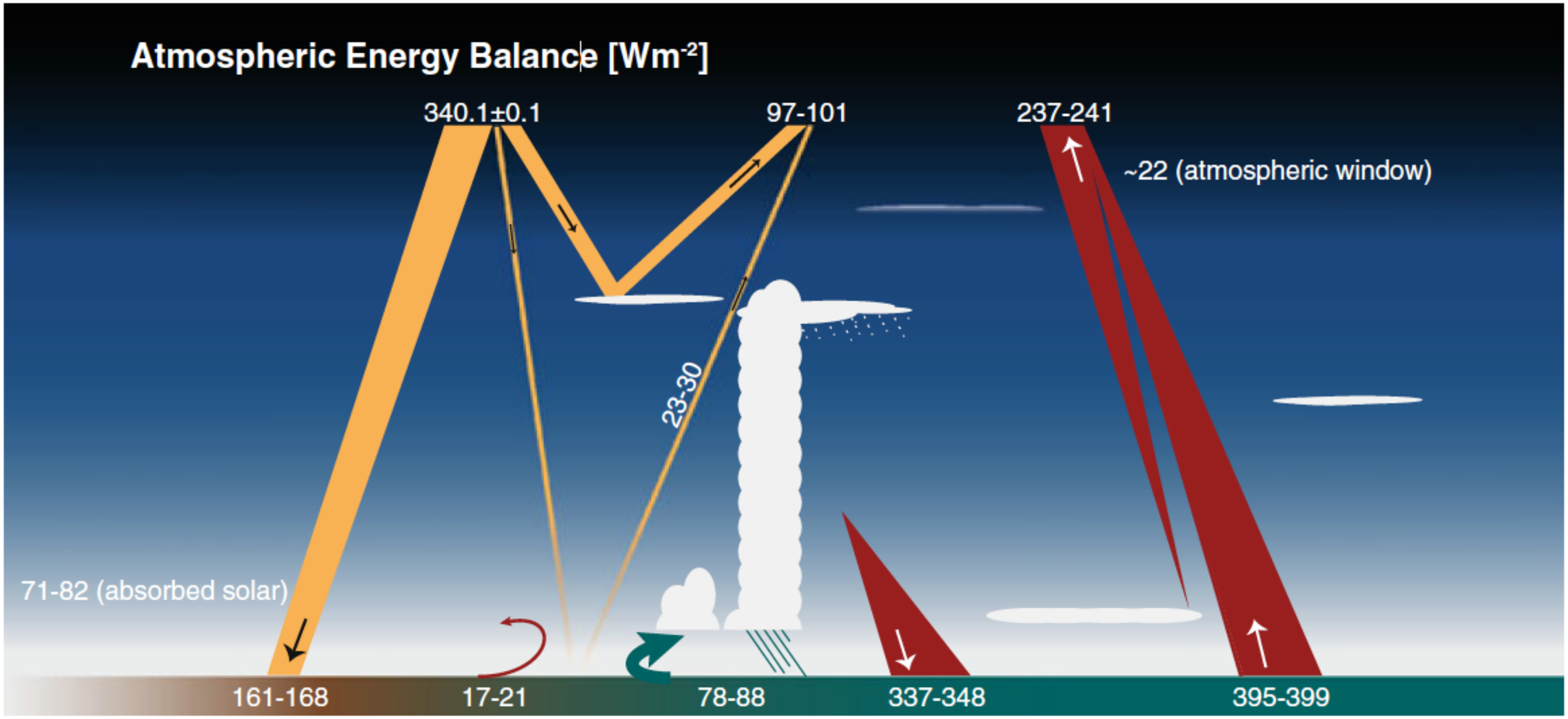


Trenberth et al. (2009)

Energy imbalances

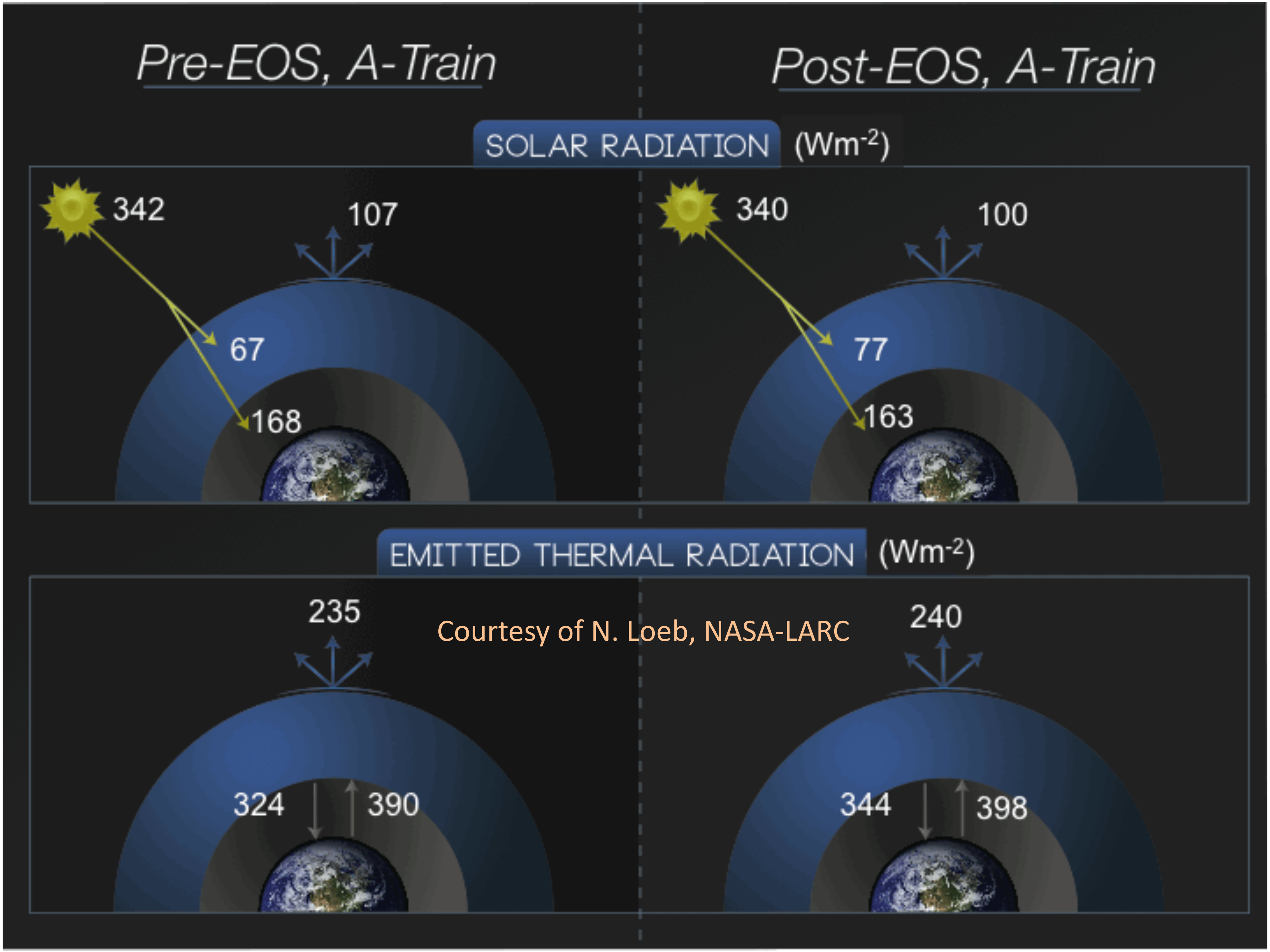
Surface and atmosphere radiative imbalances

From Stevens and Schwartz (2012)



Surface (SFC) gains: 163+344-398=109
Atmosphere (ATM) loses: 77+(398-240)-344=-109

From SFC to ATM: 88+21=109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EMITTED THERMAL RADIATION (Wm-2)
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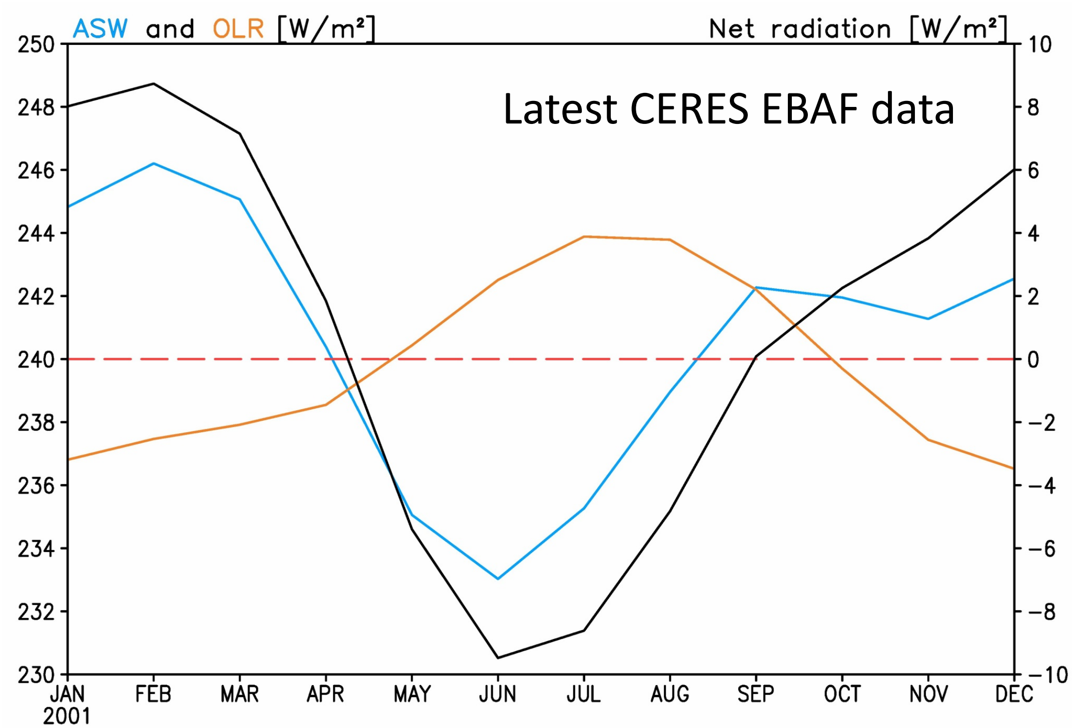
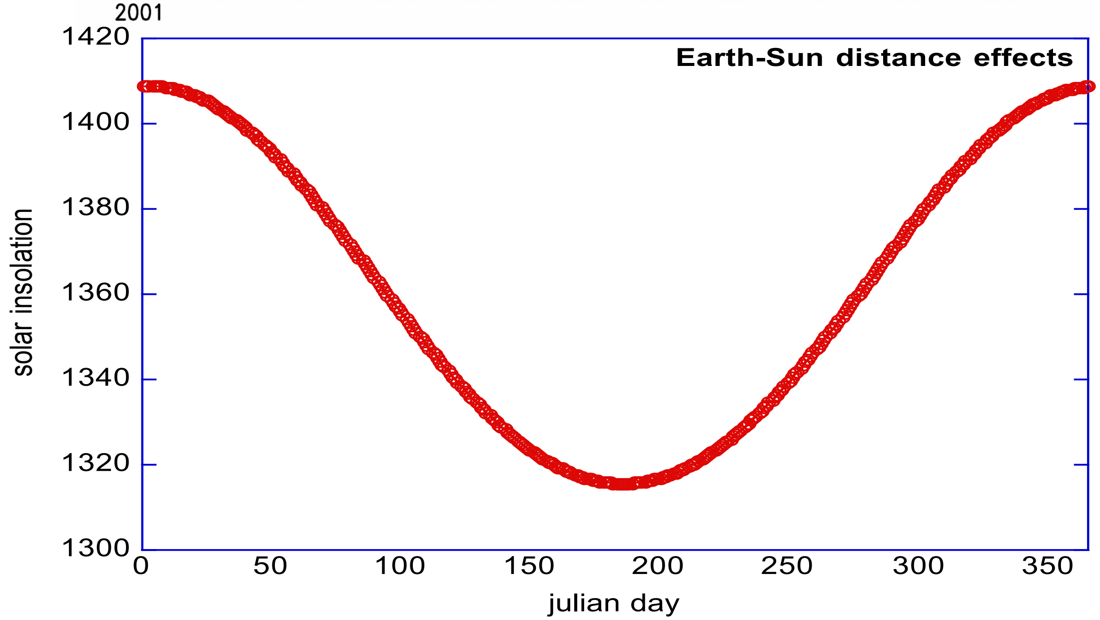
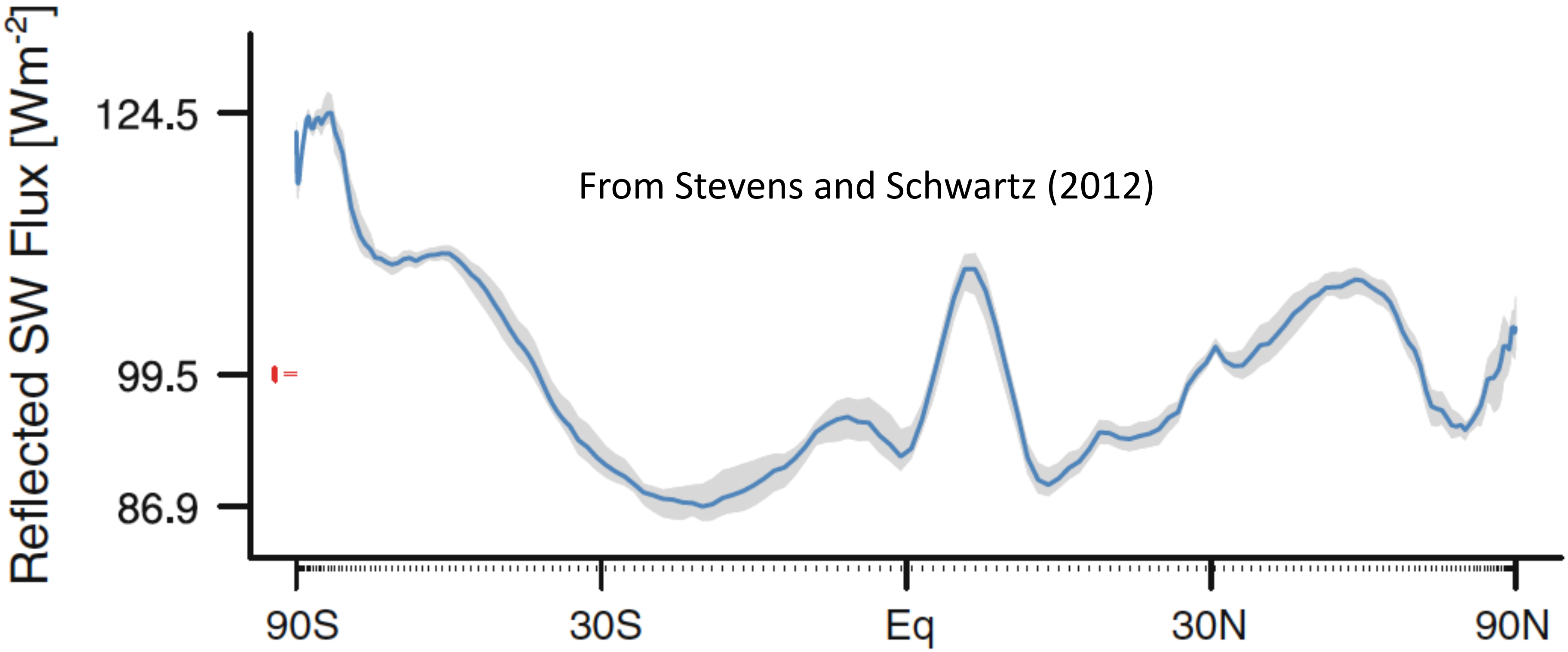
Courtesy of N. Loeb, NASA-LARC

Seasonal cycle imbalance



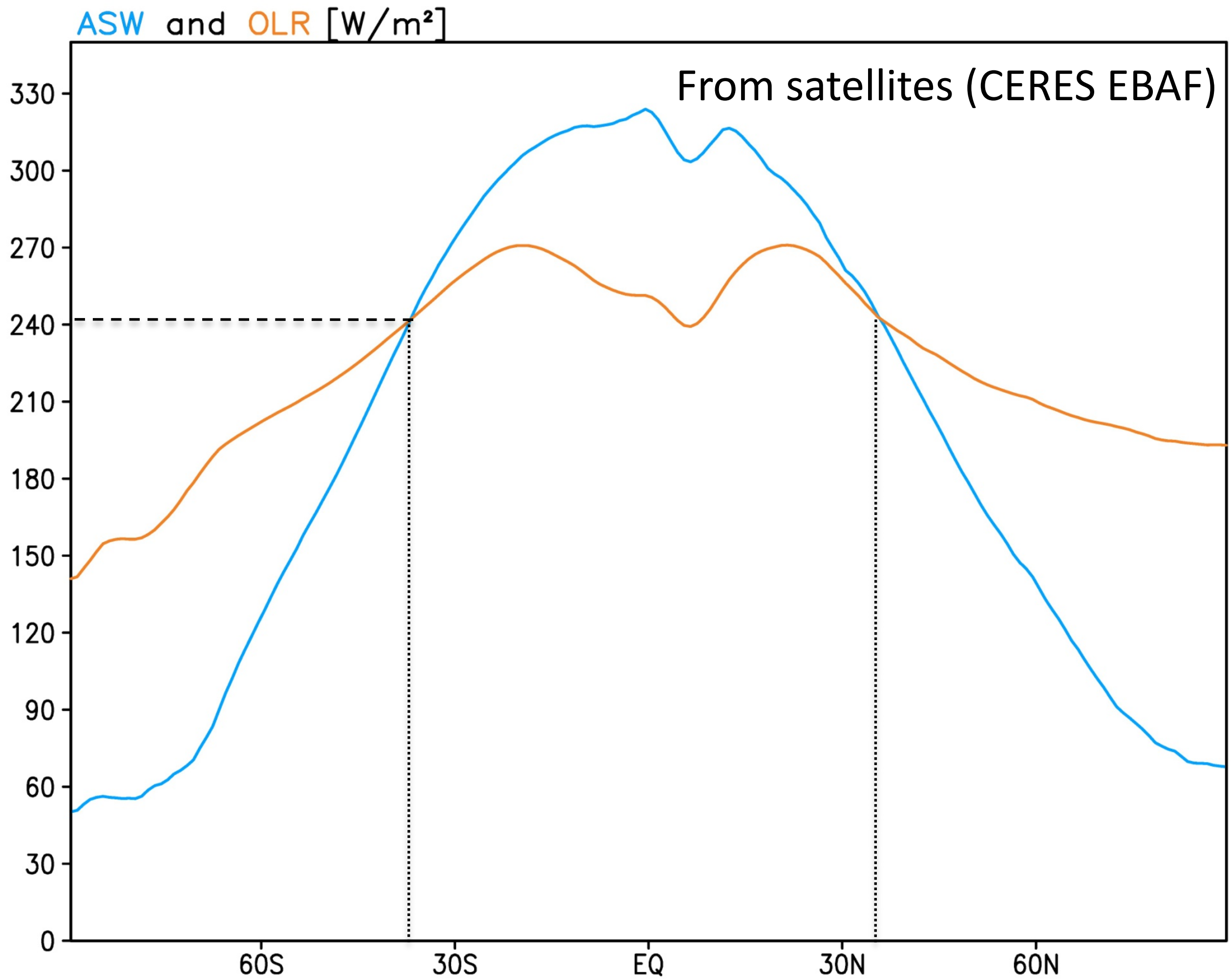


Stability of the Earth's albedo

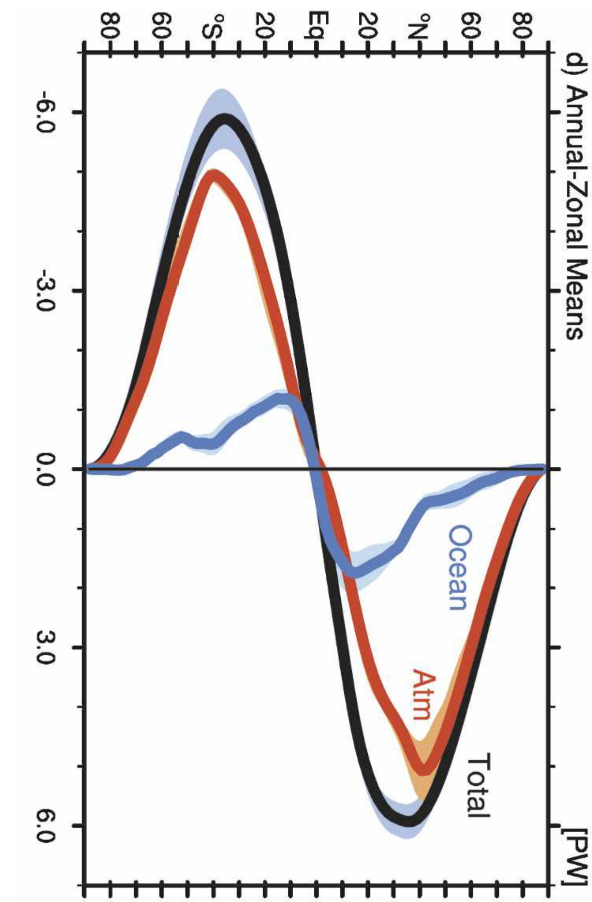


10-yr CERES EBAF. Blue curve is 10-yr mean. Gray shading indicates range

Annual Zonal radiative imbalance

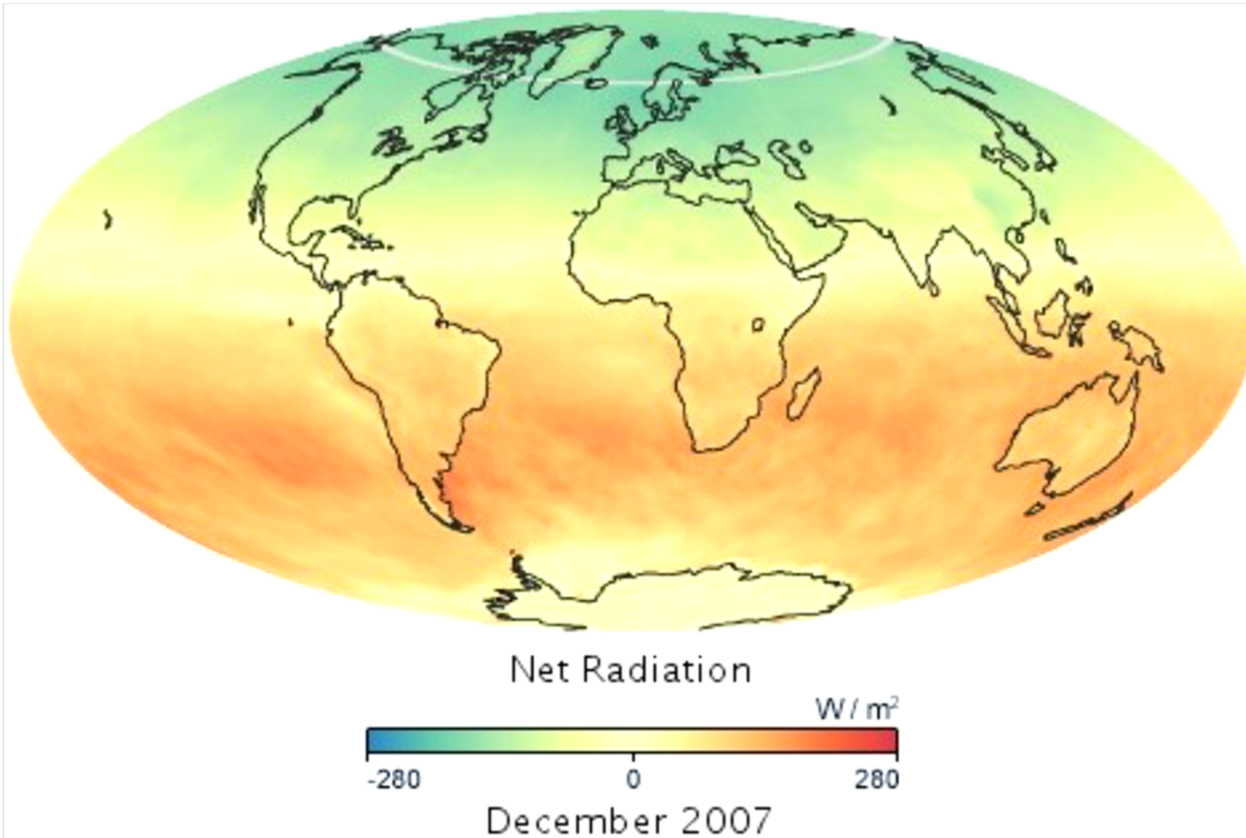


Fasullo and Trenberth (2008)



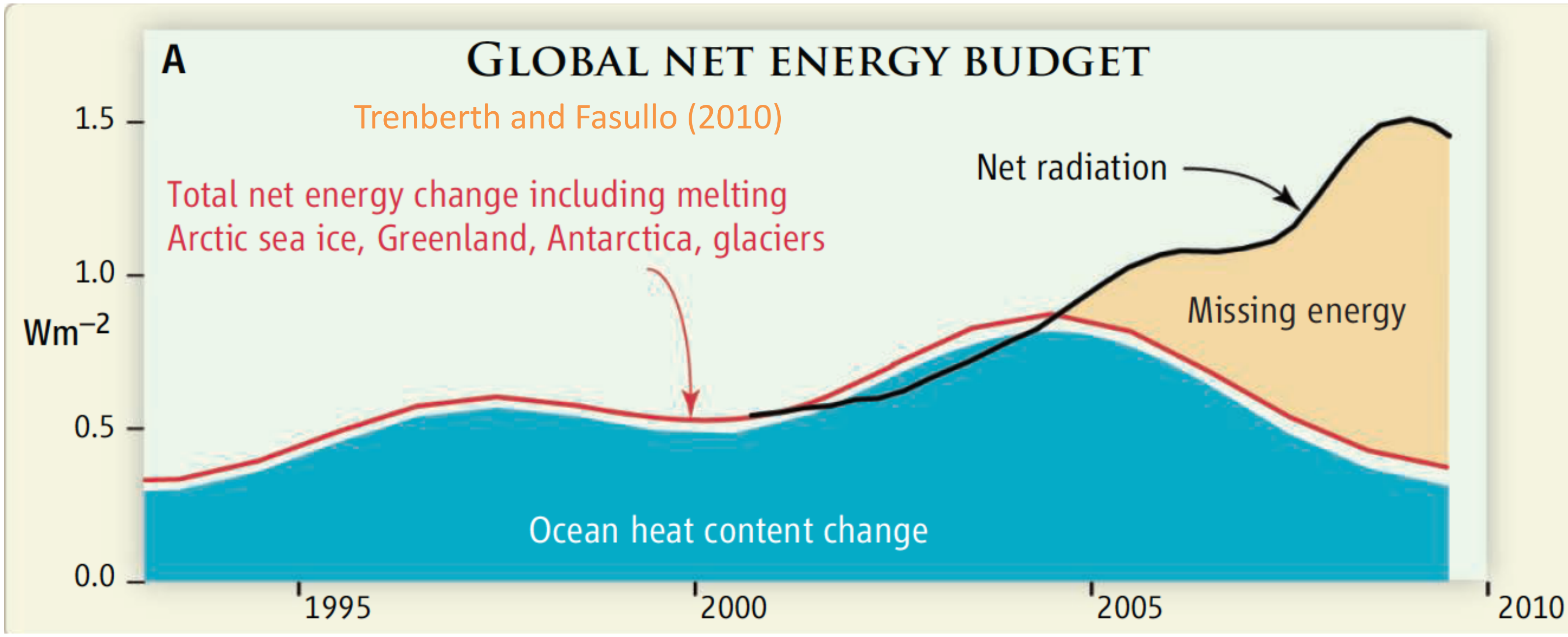
Meridional transport

TOA net radiation loop (from CERES data)



from http://earthobservatory.nasa.gov

Planetary scale imbalance



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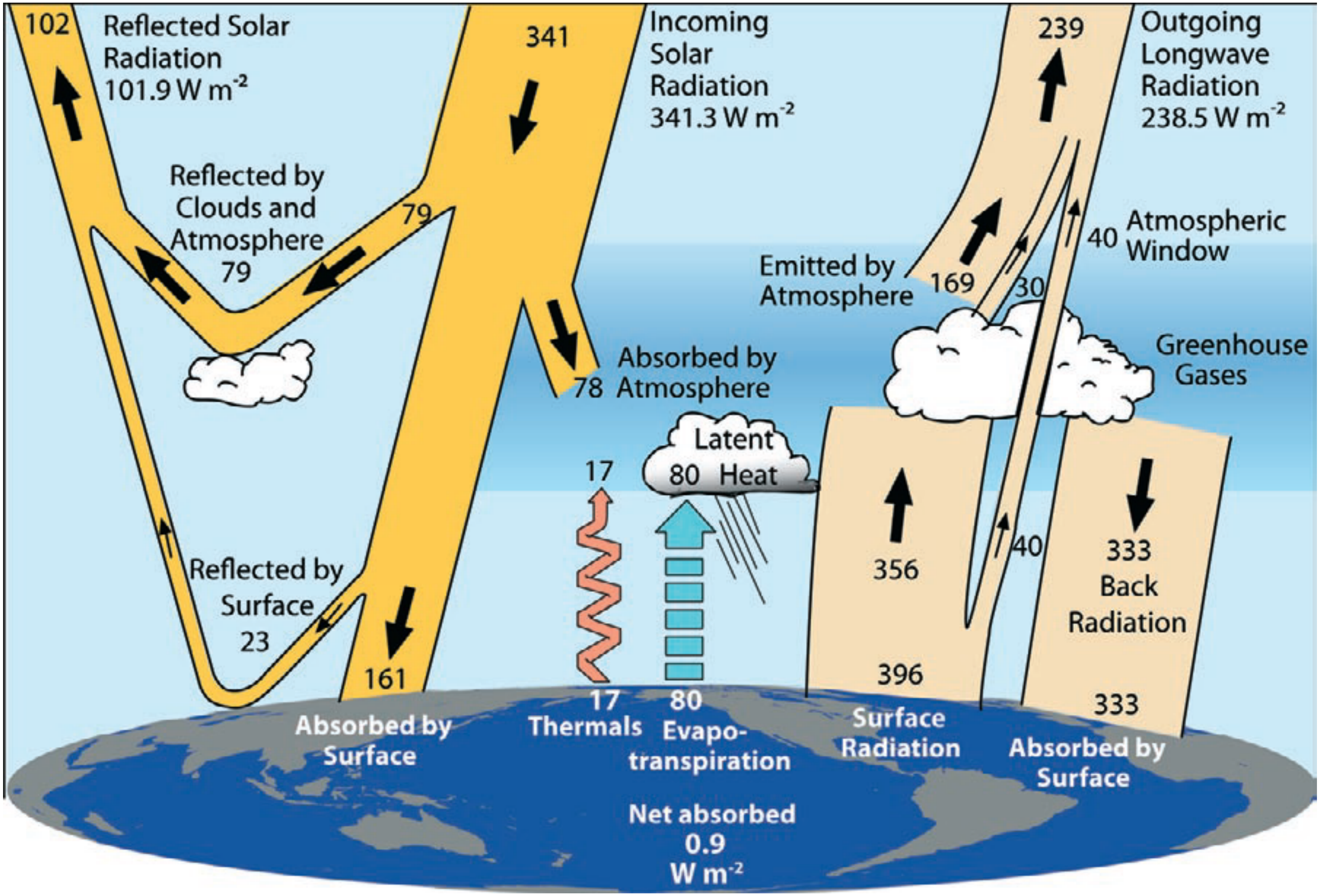
Observed changes in top-of-the-atmosphere radiation and upper-ocean heating consistent within uncertainty

Norman G. Loeb[1]*, John M. Lyman[2,3], Gregory C. Johnson[3], Richard P. Allan[4], David R. Doelling[1], Takmeng Wong[1], Brian J. Soden[5] and Graeme L. Stephens[6]

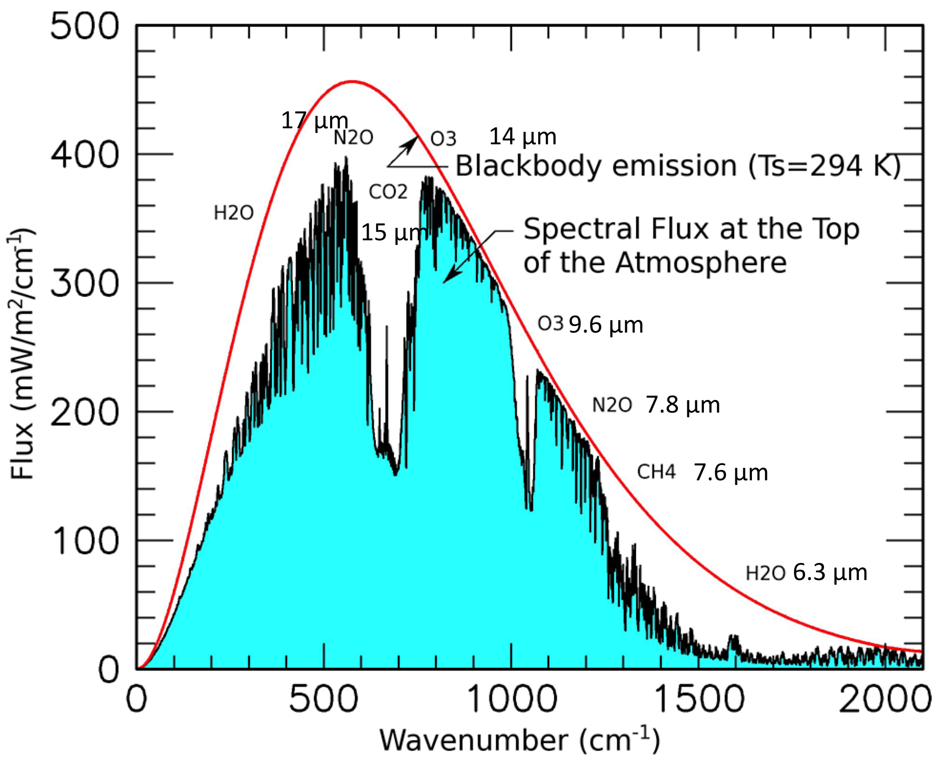
Revisions to the 15 yr old picture (2)



Trenberth et al. (2009)

The role of atmos. gases

Attribution of greenhouse effect



From Schmidt et al. (2010)

Table 1. Effect of Each Absorber on the Percentage Net LW Absorbed by the Circa 1980 Atmosphere for Each Absorber Being Removed (Minimum Effect) and for That Absorber Acting Alone (Maximum Effect)[a]

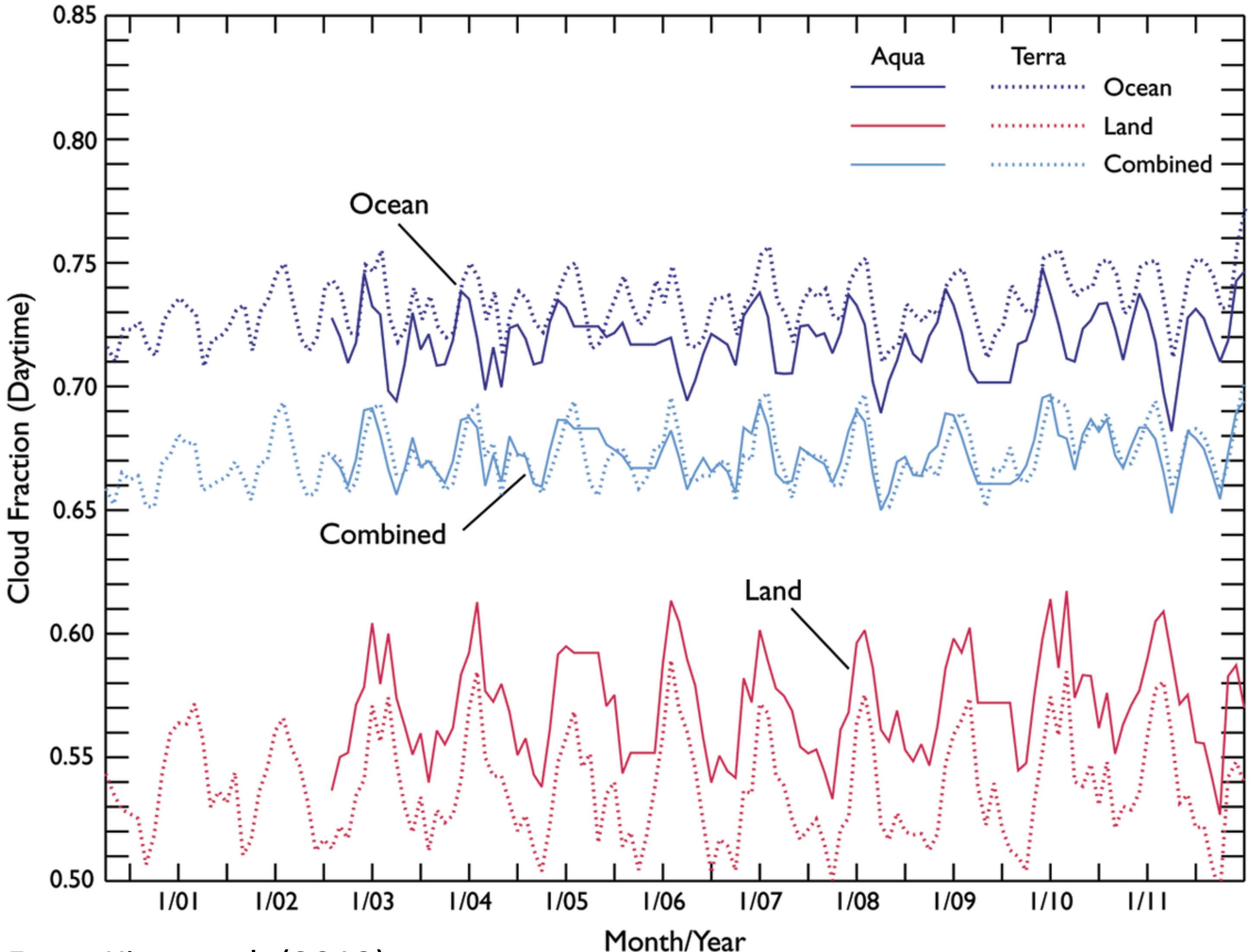
Absorber	Minimum effect: Single Factor Removal (% of Total *G*)	Maximum effect: Single Factor Addition (% of Total *G*)	Attribution (Including Overlaps): All Sky	Attribution (Including Overlaps): Clear Sky
H_2O (Vapor)	39.0	61.9	50	67
CO_2	14.0	24.6	19	24
Clouds	14.5	36.3	25	
All Others	4.9	9.2	7	9
N_2O	1.0	1.6		
Ozone	2.7	5.7		
CH_4	0.7	1.6		
CFCs	0.1	0.5		
Aerosols	0.3	1.8		
All GHGs	18.8	32.0		
H_2O + Clouds	66.9	80.9		
H_2O + CO_2	57.6	79.1		
H_2O + Clouds + CO_2	90.8	95.1		
All Others + CO_2	19.1	33.1		
All Others + Clouds	20.9	42.4		

[a]"All GHGs" encompasses CO_2, CH_4, N_2O, CFCs, and O_3. "All Others" refers to all absorbers other than H_2O, CO_2, and clouds. The attribution columns account for overlaps for "all-sky" and "clear-sky" conditions. Multiply all percentages by 155 W/m^2 to get the equivalent change in radiative flux units.

The role of clouds

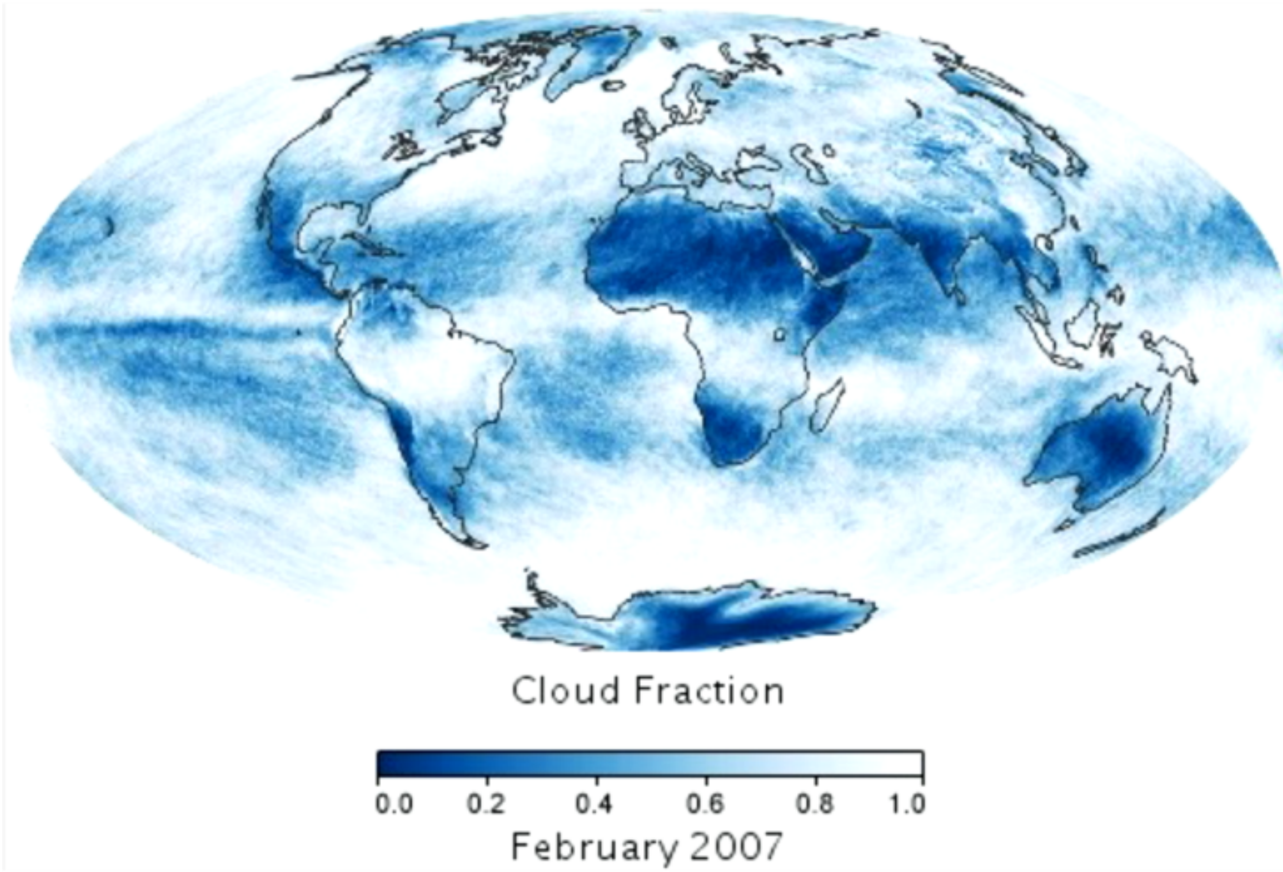
Time Series of Cloud Fraction during the Daytime

(March 2000-December 2011)



From King et al. (2012)

Cloud fraction loop (from MODIS data)



from http://earthobservatory.nasa.gov

Cloud LW effect (1)

CERES EBAF

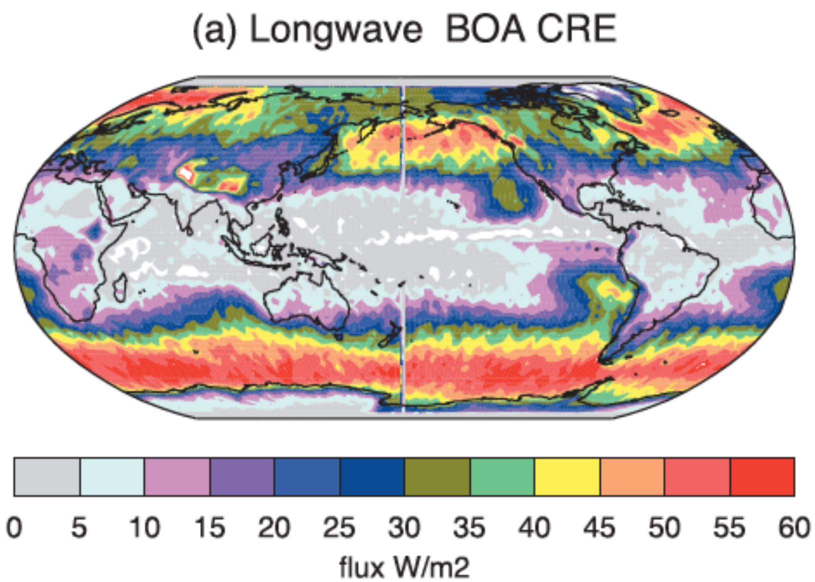
Level	Clear			Cloudy		
Wm-2	DOWN	UP	NET	DOWN	UP	NET
TOA	0	266	266	0	240	240
SFC	314	398	84	344	398	54

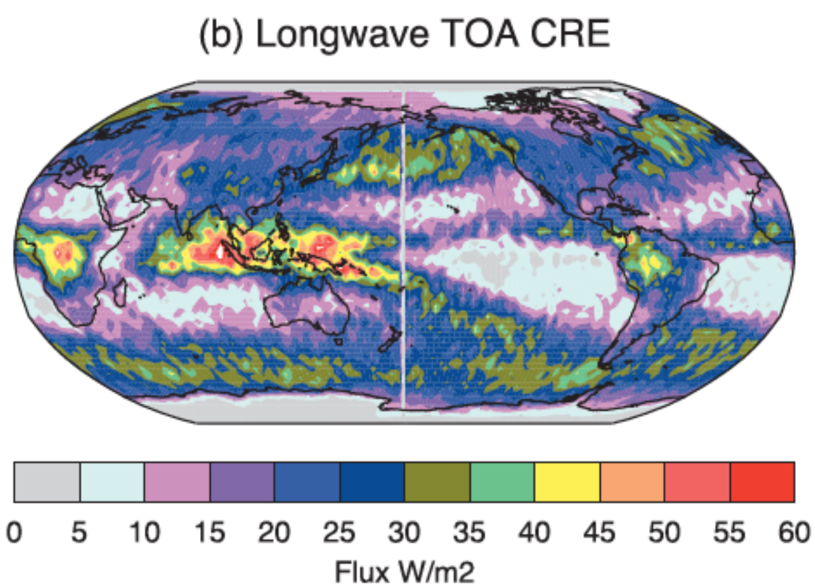
TOA effects of clouds: ~ 26 Wm^{-2} (~11%), SFC effect ~30 Wm^{-2} (~9%)

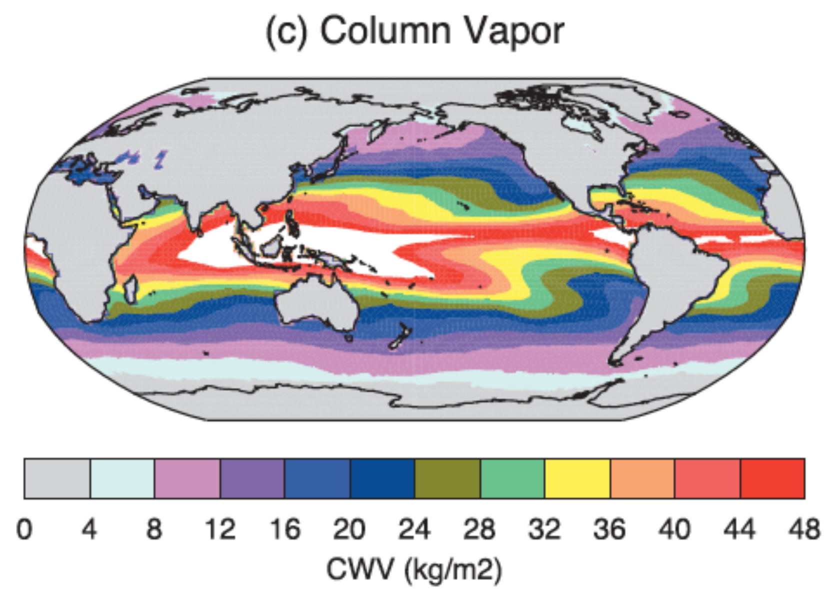
Kiehl and Treberth (1997)

Level	Clear			Cloudy		
$W\ m^{-2}$	F_d	F_u	Net	F_d	F_u	Net
TOA	0	265	265	0	235	235
SRF	278	390	112	324	390	66

Cloud LW effect (2)







From Stephens et al. (2012)

Cloud SW and net effect

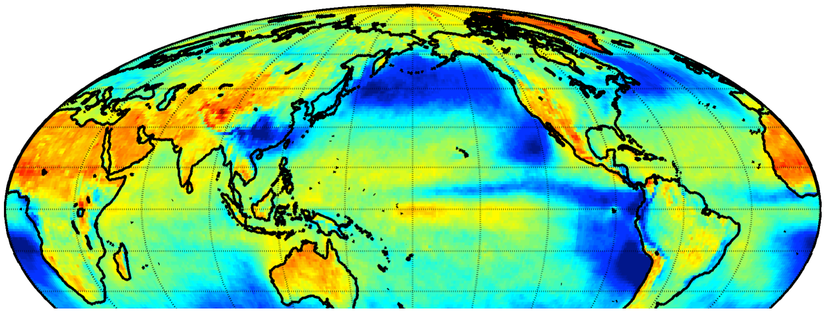
CERES EBAF

Level	Clear			Cloudy		
Wm-2	DOWN	UP	NET	DOWN	UP	NET
TOA	340	52	288	340	99	241
SFC	244	30	214	187	24	163

TOA effects of clouds: ~ -47 Wm^{-2}, SFC effect ~-51 Wm^{-2}

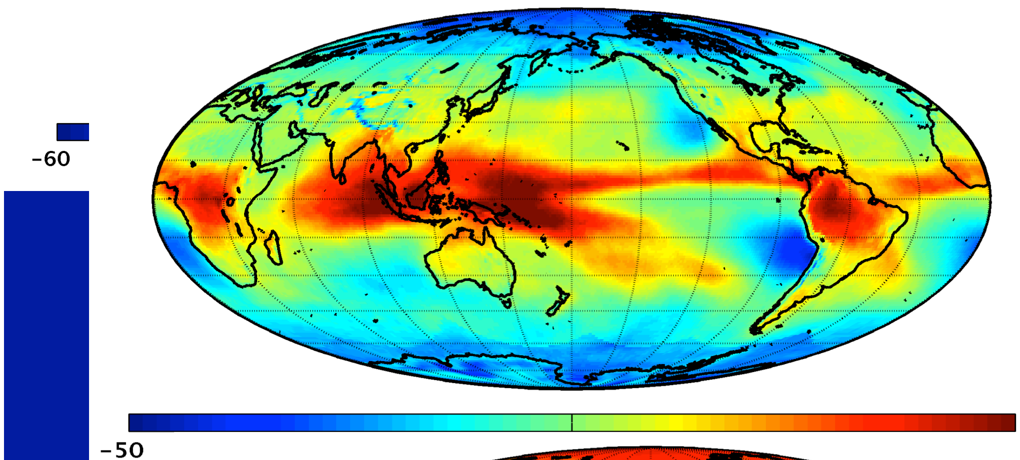
Net TOA: -47(SW)+26 (LW) = -21 Wm^{-2}
Net SFC: -51(SW) + 30(LW) = -21 Wm^{-2}
Net ATM = -21(SW)-(-21)(LW)=0 Wm^{-2}

CERES Data Fusion: Net Radiative Effects of Clouds on Earth's Radiation Budget



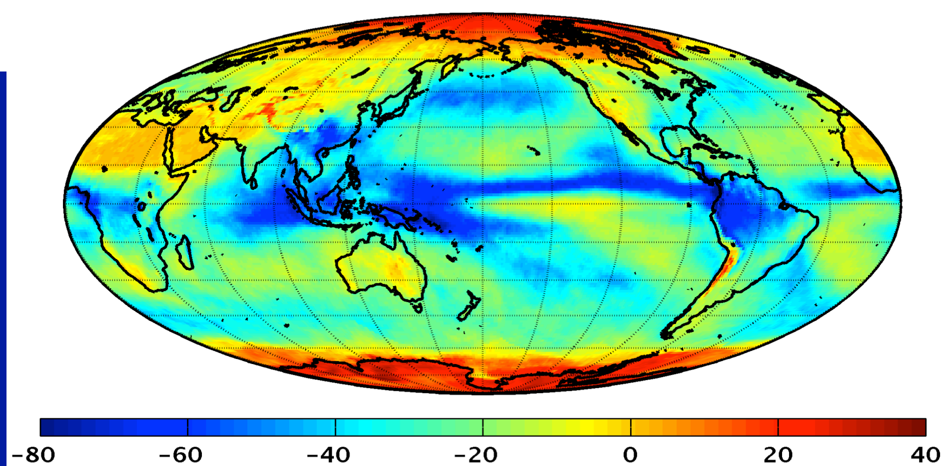
Top-of-Atmosphere (-20.9 Wm^{-2})

- SORCE-TIM: Solar Irradiance
- CERES: Reflected Solar, Emitted Thermal Flux
- MODIS: Cloud Detection & Properties
- 5 Geo Satellites: Diurnal Cycle



Within-Atmosphere (0.4 Wm^{-2})

- AIRS: Temperature/Humidity Profile
- MODIS: Aerosol & Cloud Properties
- CALIPSO: Cloud & Aerosol Profiles
- Cloudsat: Cloud Profile
- GMAO Reanalysis: Atmospheric State
- Aerosol Assimilation



Surface (-21.3 Wm^{-2})

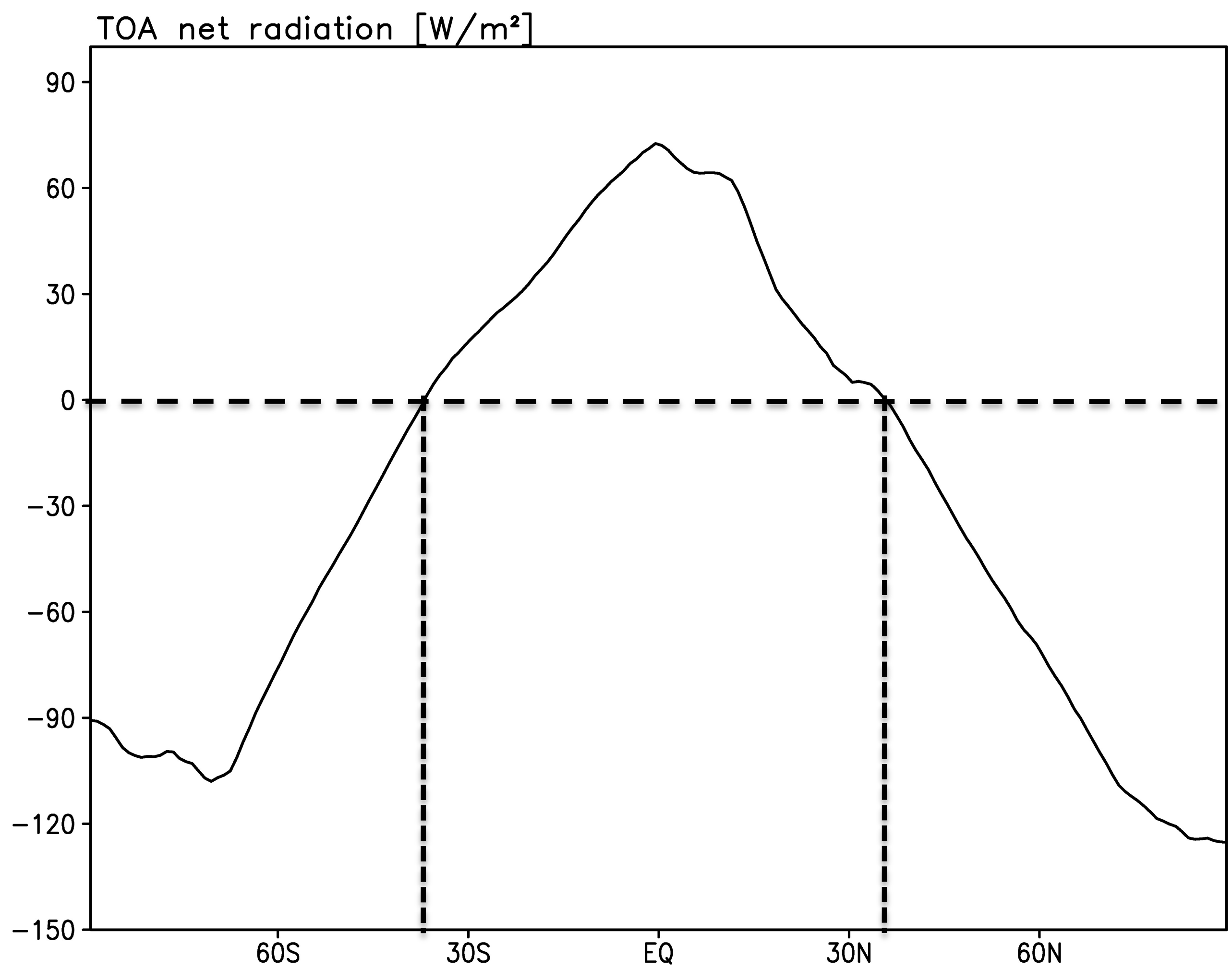
- MODIS: Surface albedo, emissivity & temperature
- NSIDC: Snow, sea-ice coverage

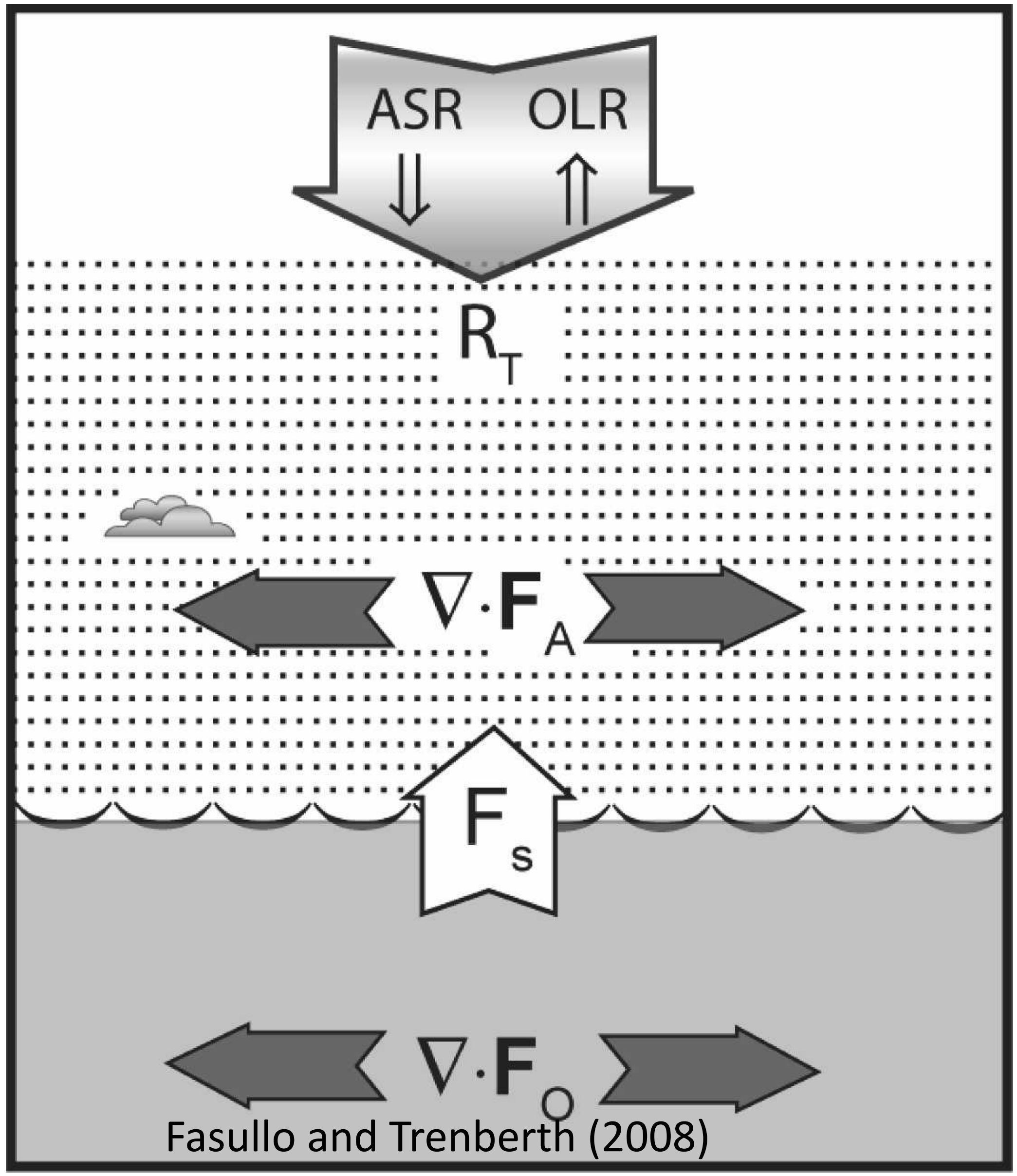
Take home points

- We have made significant progress quantifying Earth's main energy flow components
- This is because of advances in both satellite observations and modeling
- Because of satellites we know the radiative fluxes better at TOA than at SFC
- Surface gains radiative energy, atmosphere loses
- Low latitudes (35°S to 35°N) gain radiative energy, rest of the planet loses
- Current data suggest that the planet emits less LW than absorbs SW, extra energy stored in the ocean
- Greenhouse agents in order of importance: water vapor, clouds, carbon dioxide
- Clouds are very important: increase SW reflectance to space, reduce SW flux transmitted to surface, reduce LW emission to space, increase LW emission to surface
- Overall clouds cool the planet. Almost all of this is realized at the surface
- Predicting how energy flow components will change in the future is challenging, but is critical for understanding climate change.

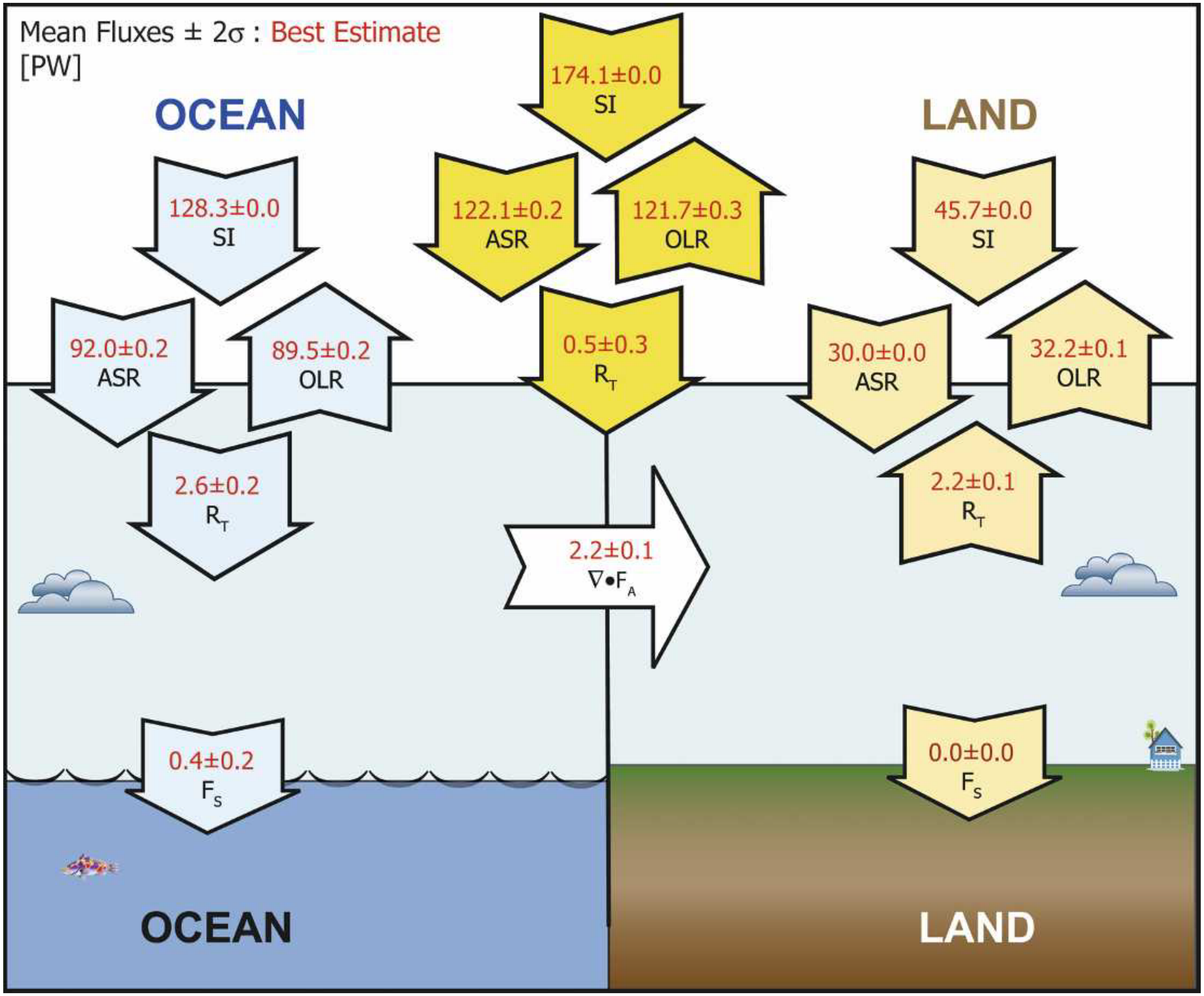
Extra slides

Annual net radiation at TOA
low latitudes gain, high latitudes lose

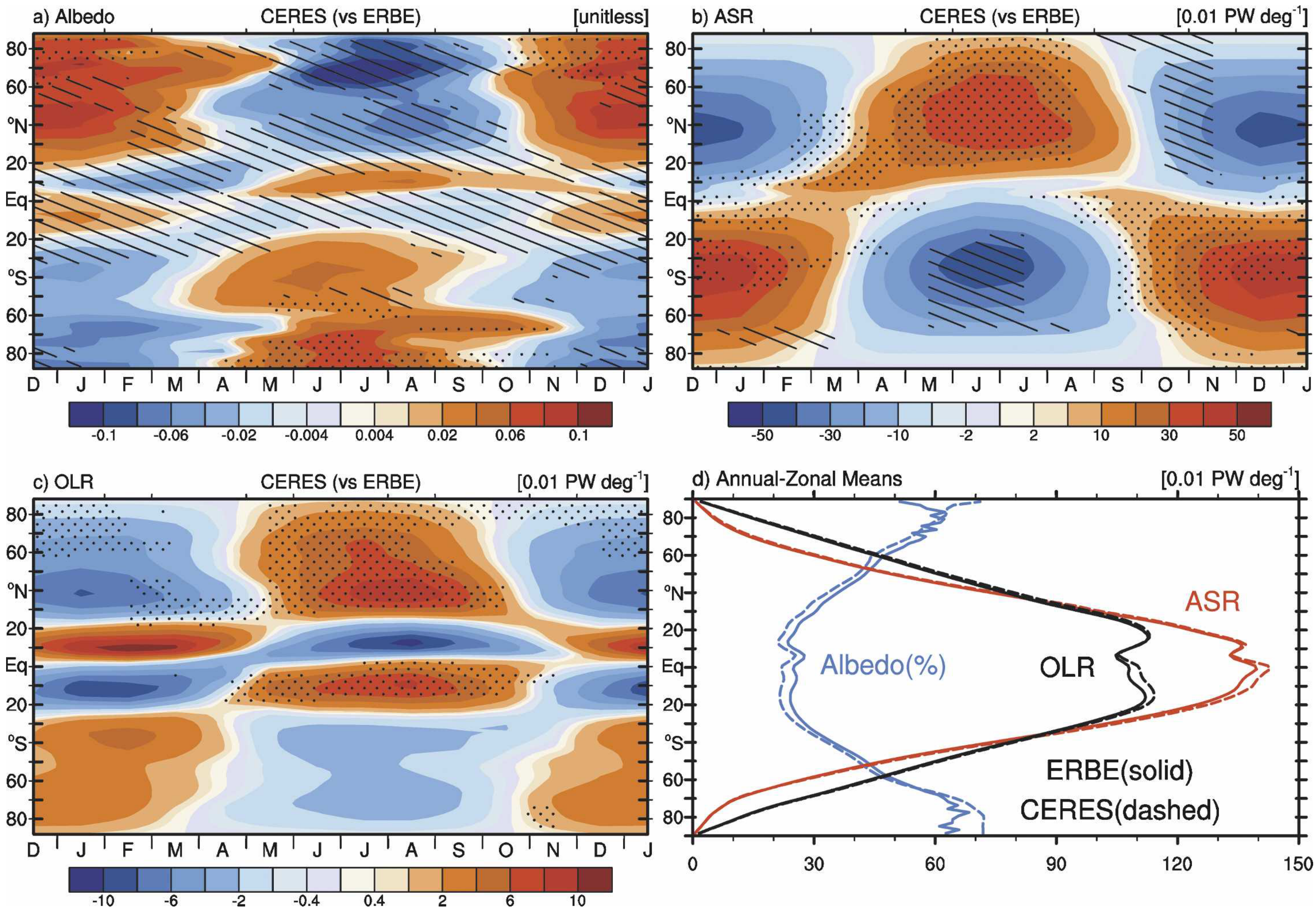




Fasullo and Trenberth (2008)

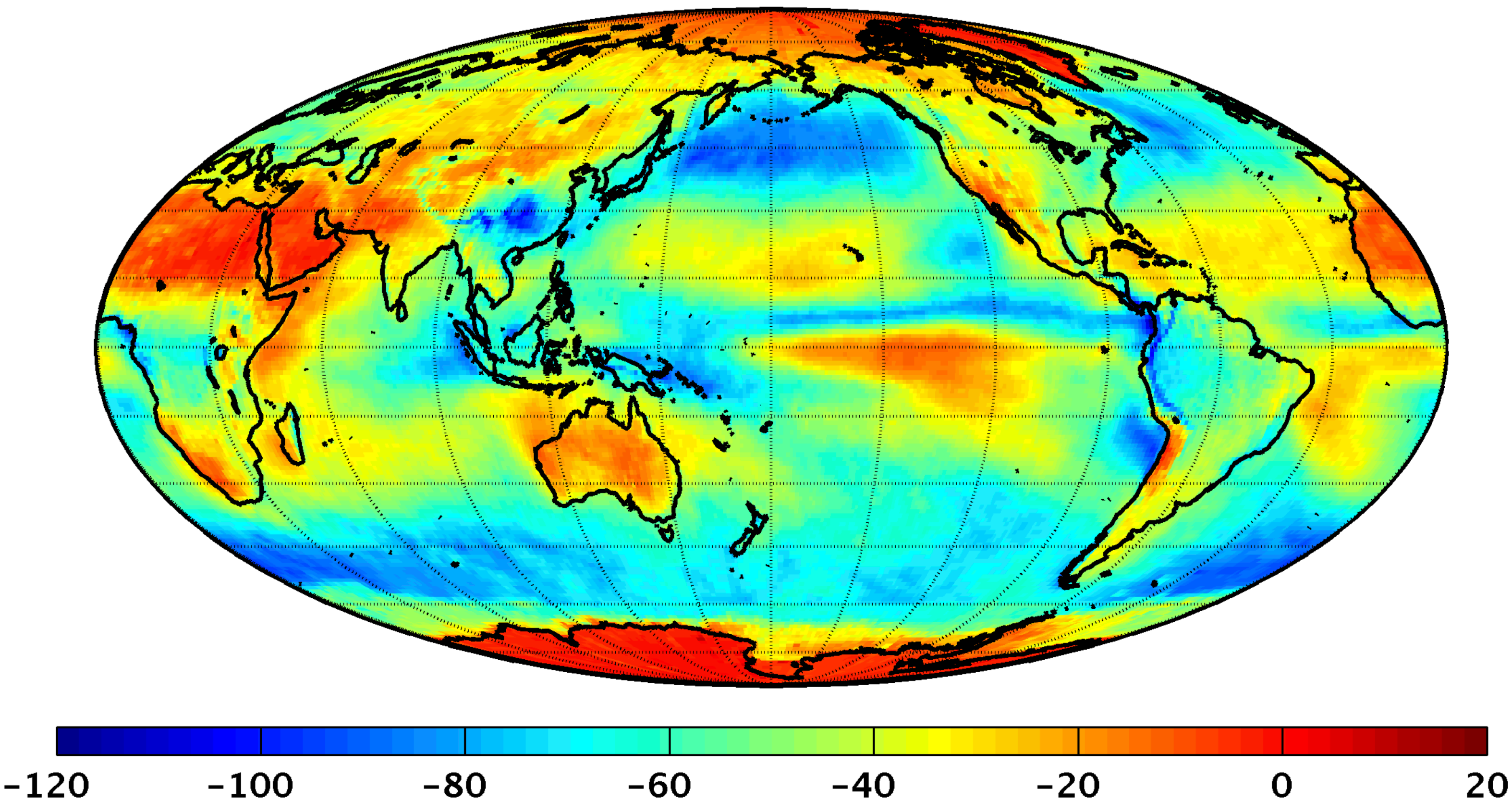


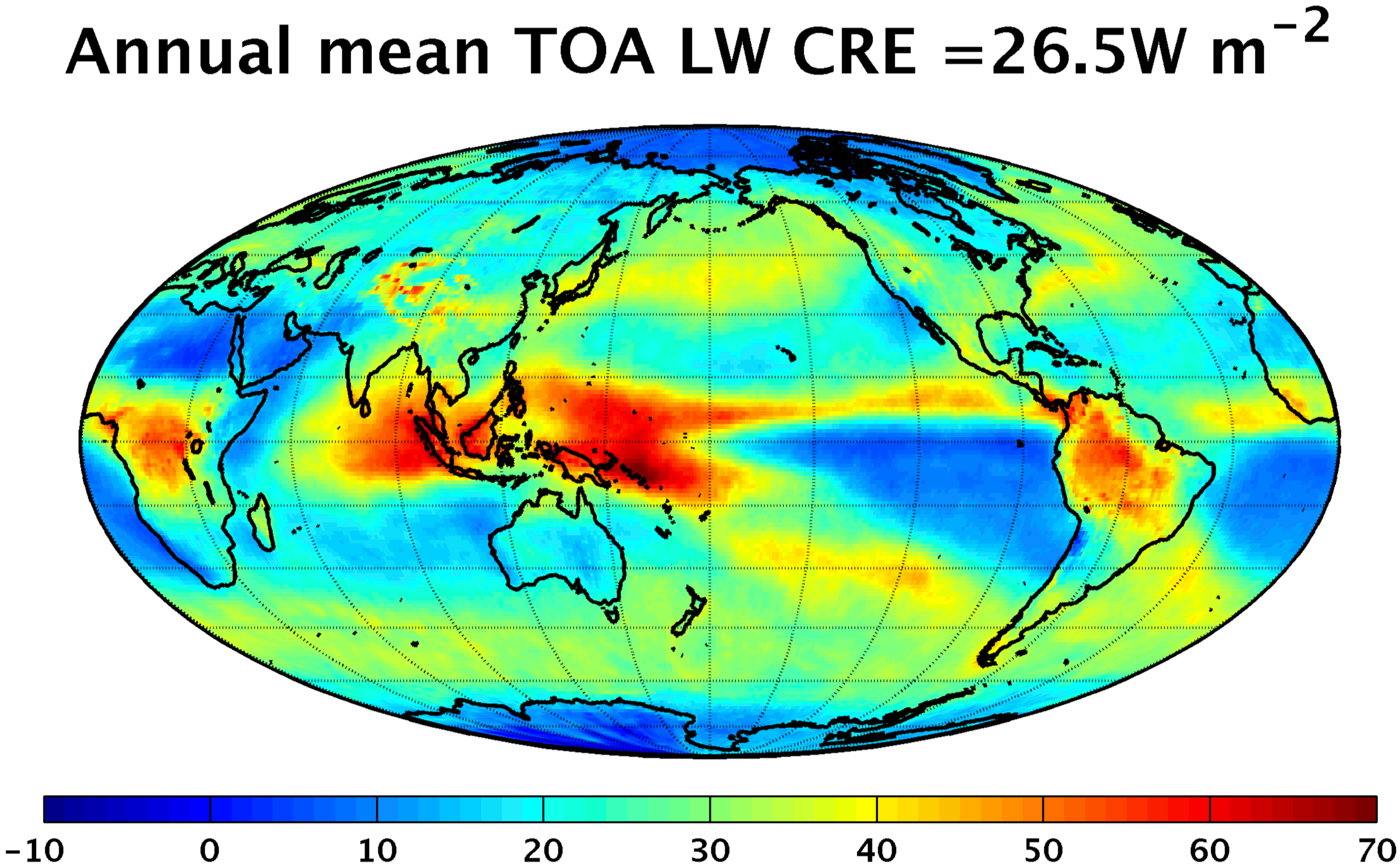
Mean Fluxes ± 2σ : Best Estimate
[PW]
OCEAN
LAND
174.1±0.0
SI
128.3±0.0
SI
122.1±0.2
ASR
121.7±0.3
OLR
45.7±0.0
SI
92.0±0.2
ASR
89.5±0.2
OLR
0.5±0.3
R_T
30.0±0.0
ASR
32.2±0.1
OLR
2.6±0.2
R_T
2.2±0.1
R_T
2.2±0.1
∇•F_A
0.4±0.2
F_S
0.0±0.0
F_S
OCEAN
LAND

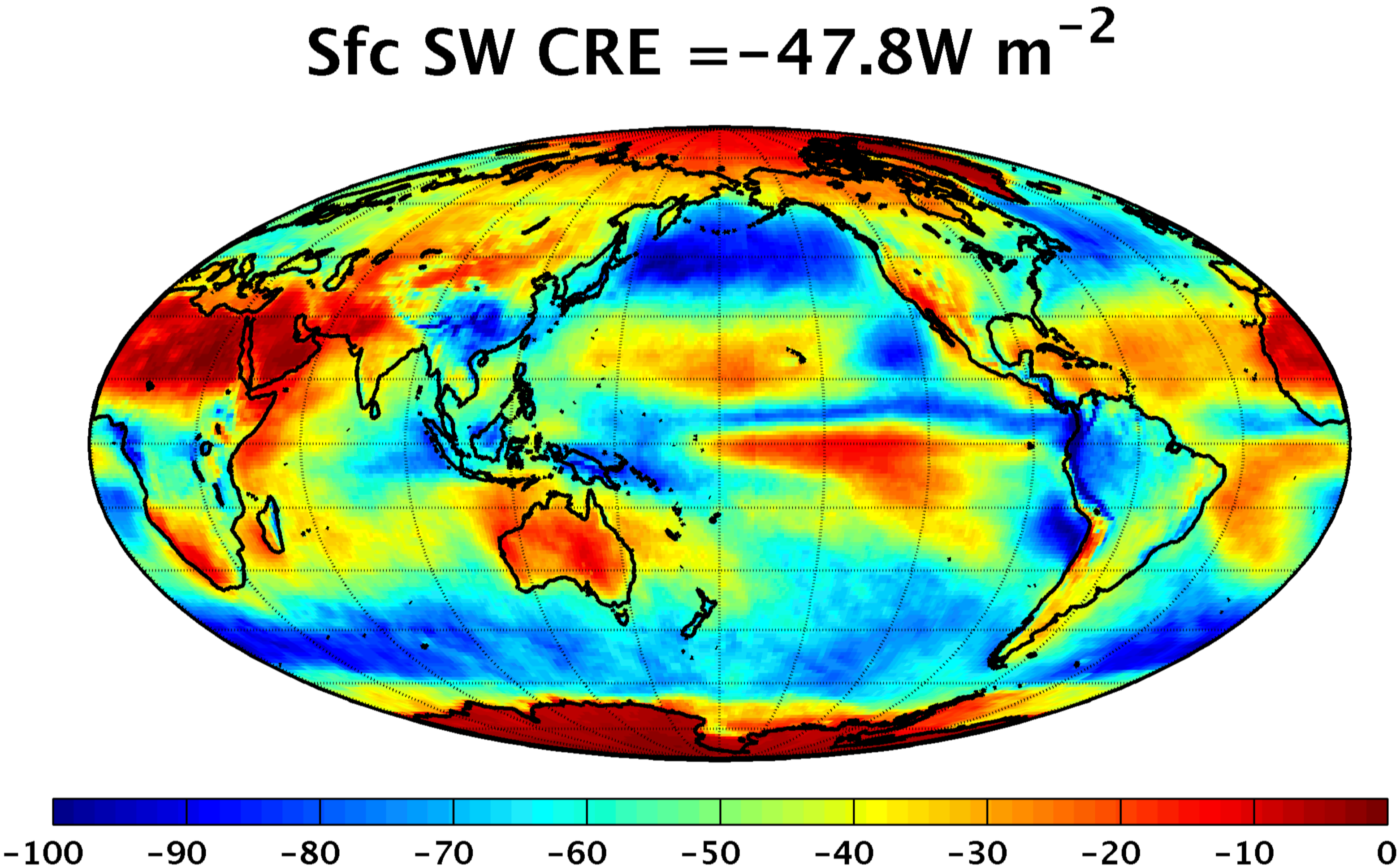


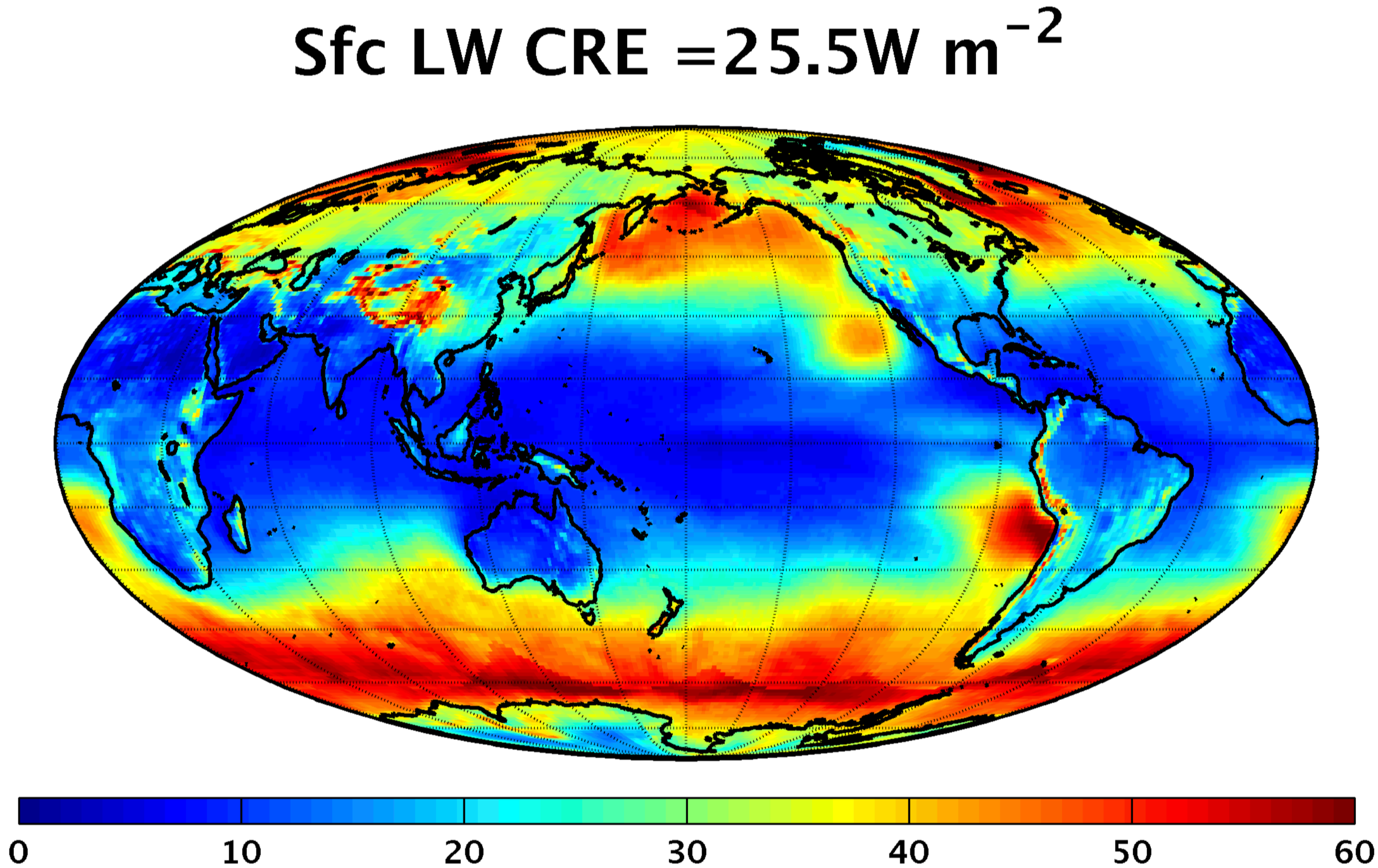
a) Albedo
CERES (vs ERBE)
[unitless]
b) ASR
CERES (vs ERBE)
[0.01 PW deg^{-1}]
c) OLR
CERES (vs ERBE)
[0.01 PW deg^{-1}]
d) Annual-Zonal Means
[0.01 PW deg^{-1}]
80
60
°N
20
Eq
20
°S
60
80
D J F M A M J J A S O N D J
-0.1 -0.06 -0.02 -0.004 0.004 0.02 0.06 0.1
-50 -30 -10 -2 2 10 30 50
-10 -6 -2 -0.4 0.4 2 6 10
ASR
Albedo(%)
OLR
ERBE(solid)
CERES(dashed)
0 30 60 90 120 150

Annual mean TOA SW CRE =−47.1W m^{-2}

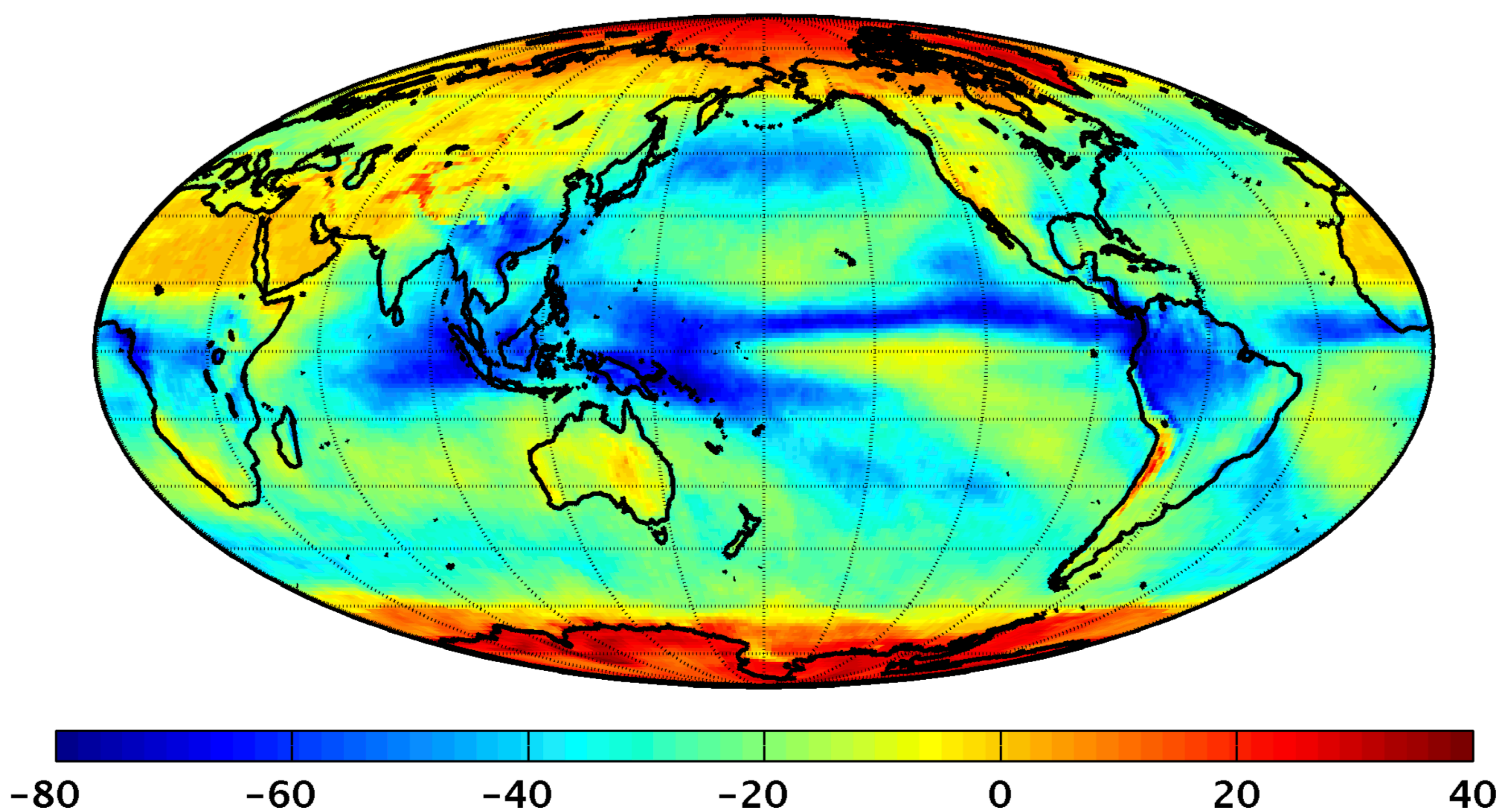


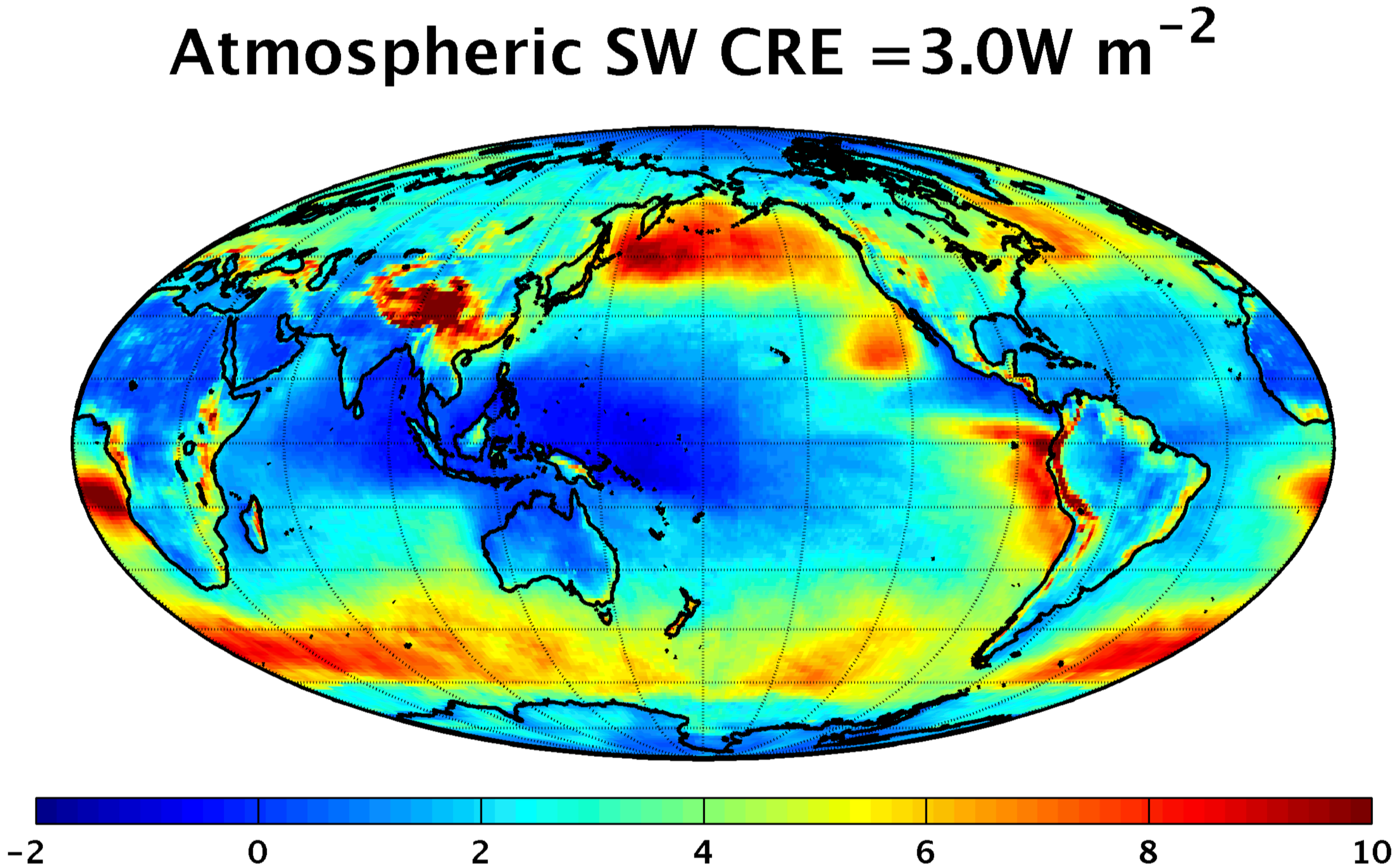

Annual mean TOA LW CRE =26.5W m^-2
-10
0
10
20
30
40
50
60
70

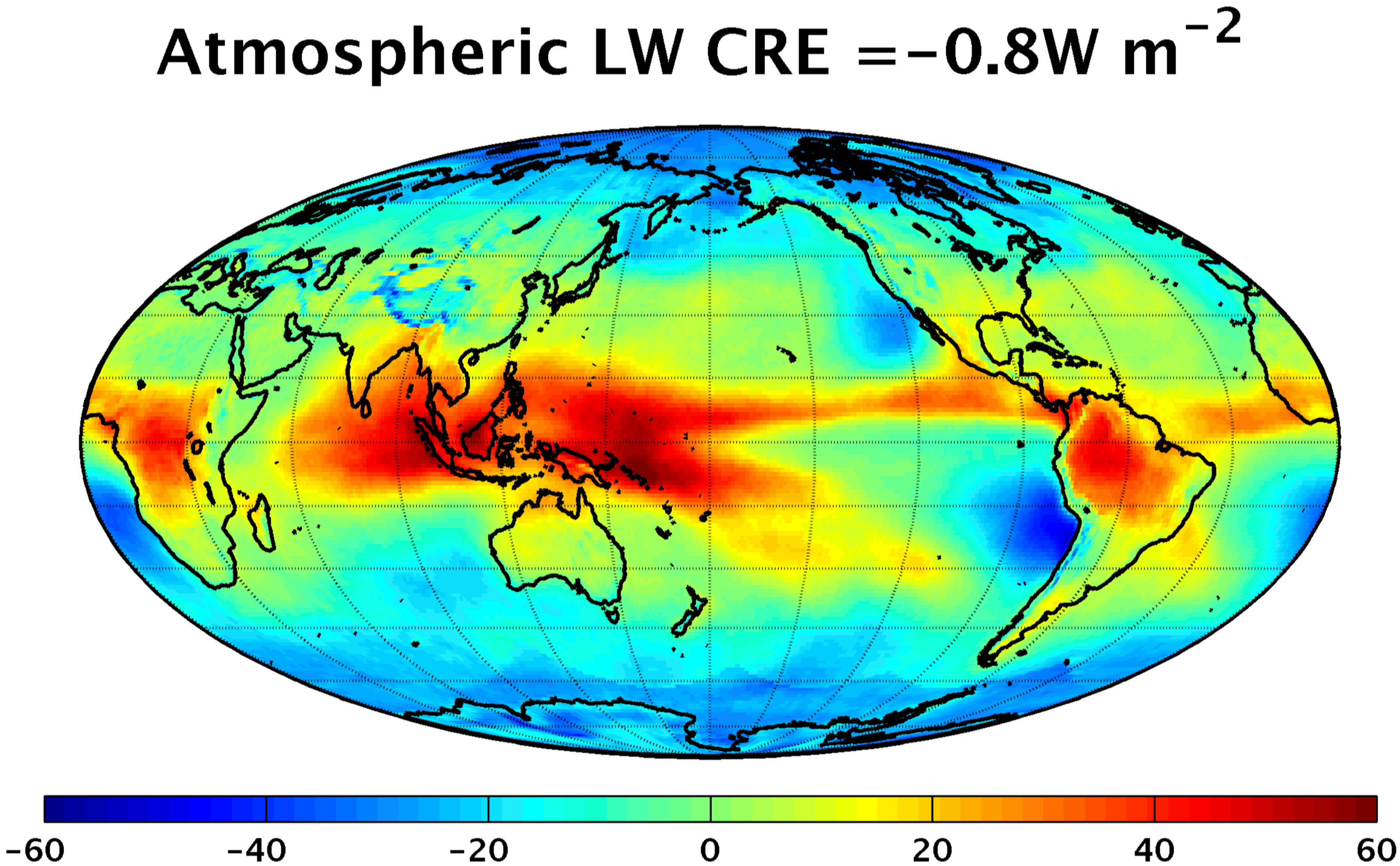

Sfc SW CRE =−47.8W m^{-2}
−100
−90
−80
−70
−60
−50
−40
−30
−20
−10
0


Sfc LW CRE =25.5W m^{-2}
0
10
20
30
40
50
60

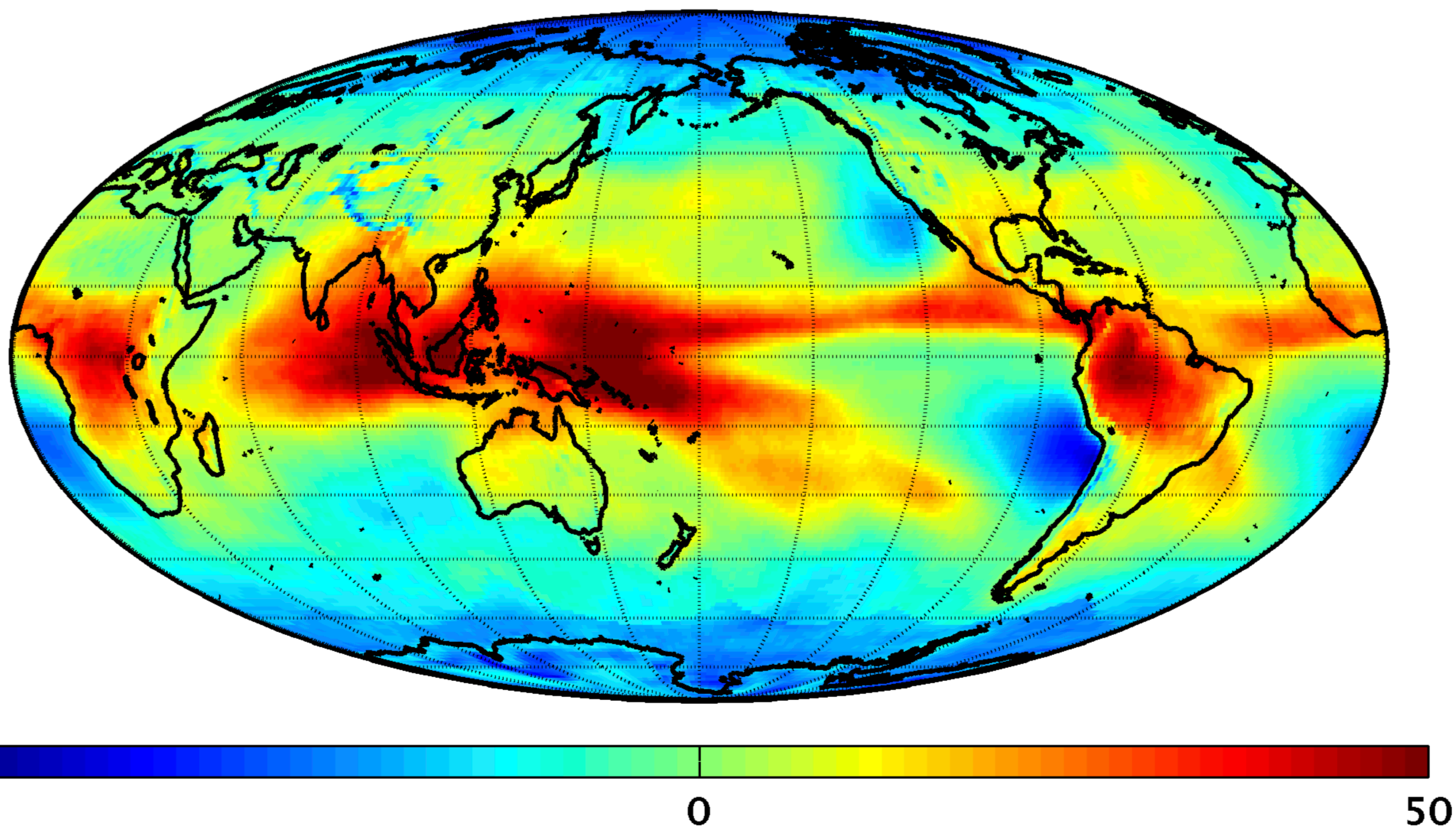
Net surface CRE =−22.3W m^{-2}

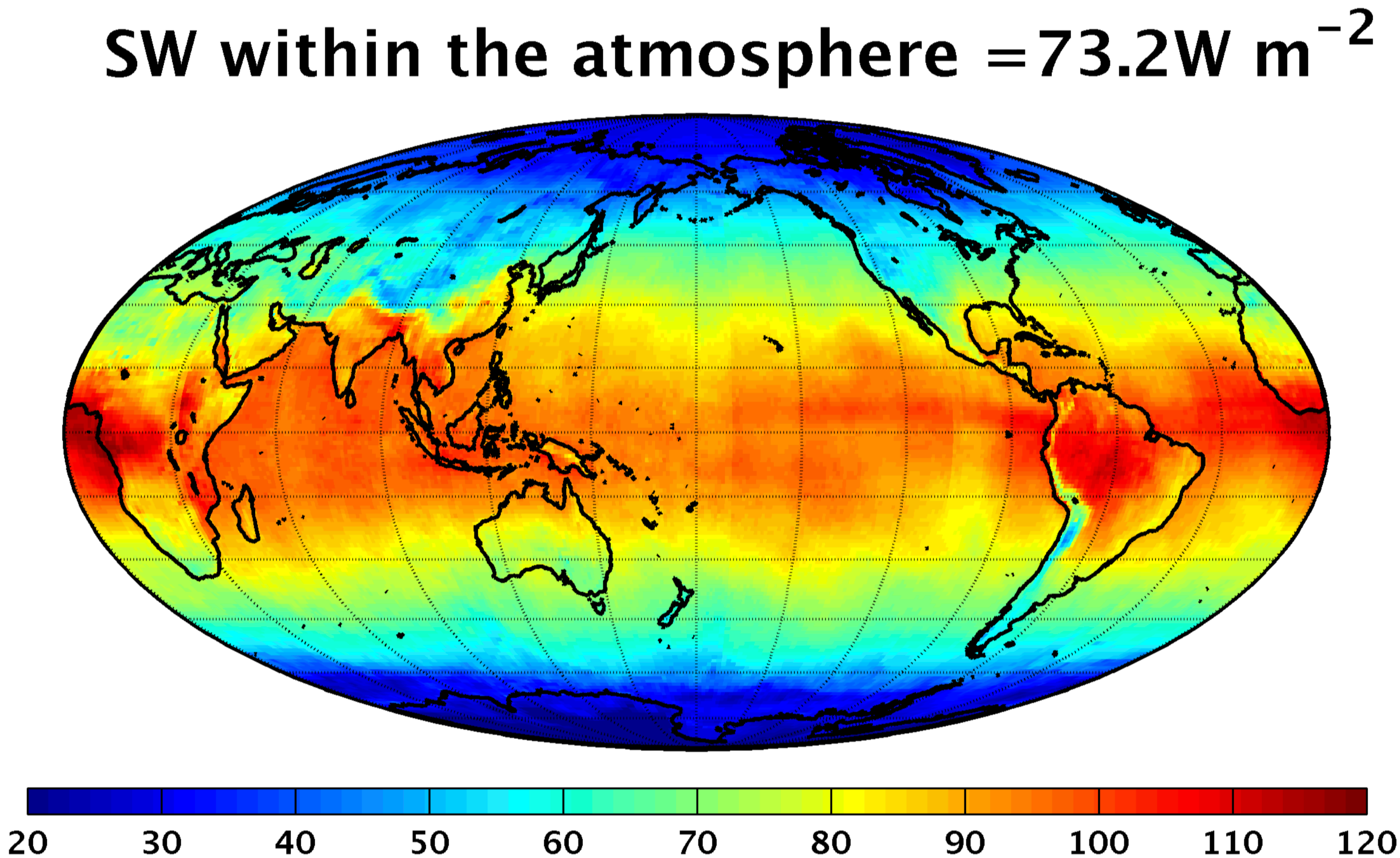


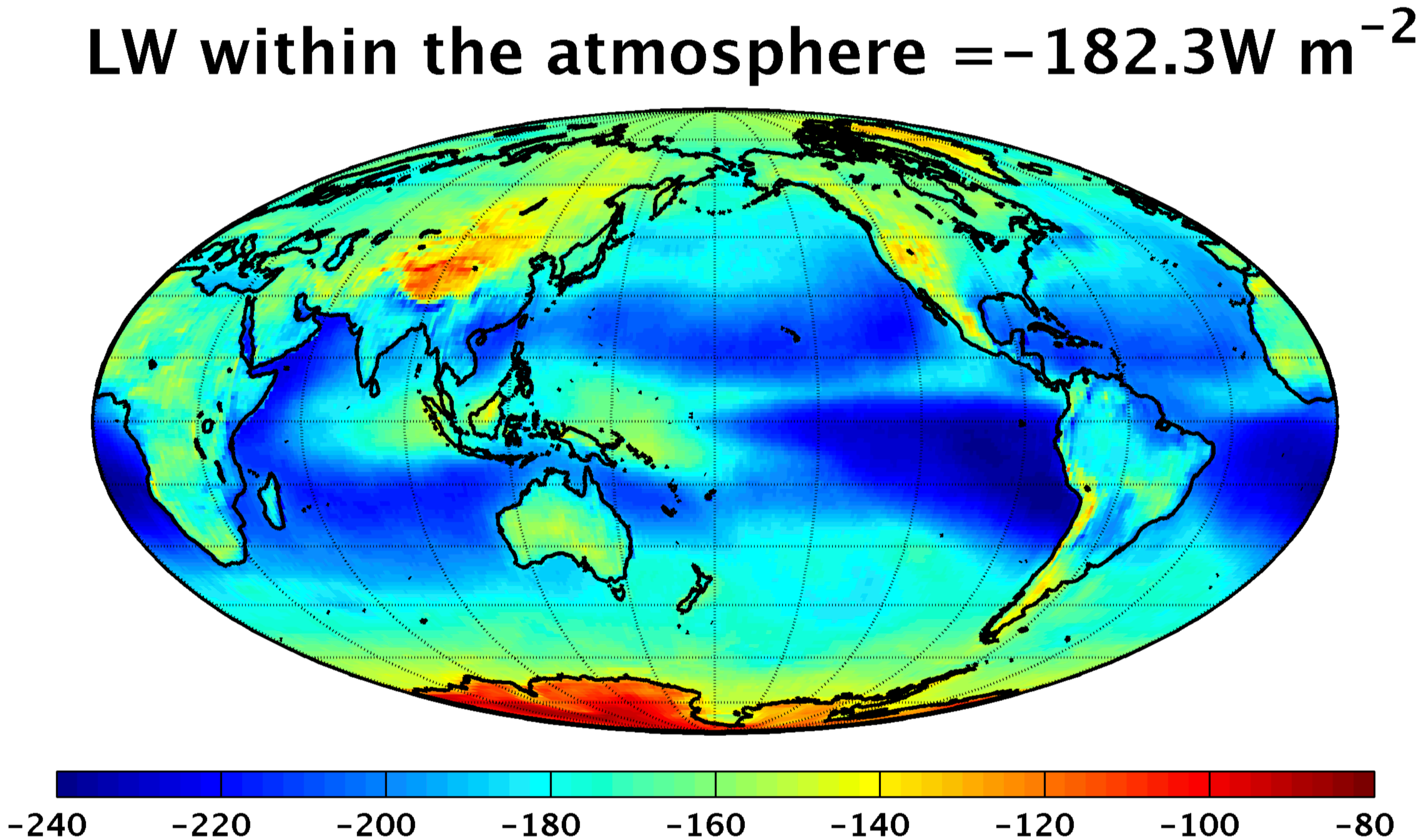

Atmospheric SW CRE =3.0W m^{-2}
-2
0
2
4
6
8
10


Atmospheric LW CRE =−0.8W m^{-2}
−60
−40
−20
0
20
40
60

Atmospheric Net CRE =2.2W m^{-2}




SW within the atmosphere =73.2W m^{-2}
20
30
40
50
60
70
80
90
100
110
120


LW within the atmosphere =−182.3W m−2
−240
−220
−200
−180
−160
−140
−120
−100
−80

Net Flux within Atmospheric =-109.1W m^{-2}

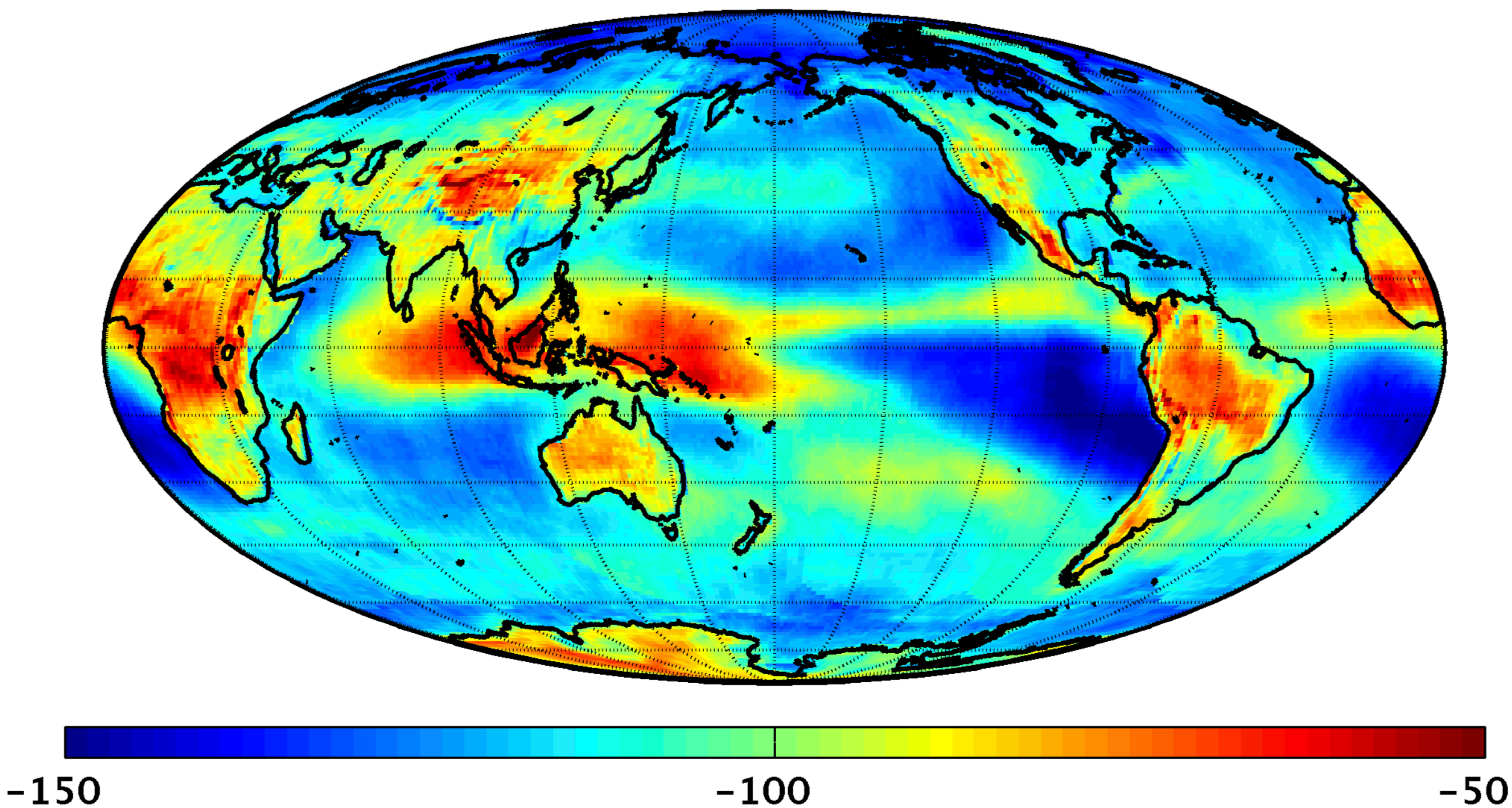


Table 10. Global Average Monthly Means for the Four Seasonal Months (January, April, July, and October), (Pseudo) Annual Mean Based on the Four Seasonal Months from April 1985 to January 1989, and Annual Mean Based on 12 Months for 5 Years (1985–1989)

	1986–1989 Jan.	1985–1988 April	1985–1988 July	1985–1988 Oct.	Pseudo ANN[a]	5-Year, 12-Month ANN
NS_t	240.90	234.73	231.16	238.16	236.24	236.11
NS_s	169.42	164.67	159.94	167.63	165.42	165.19
NS_a	71.48	70.05	71.22	70.53	70.82	70.92
NL_t	−231.33	−231.86	−236.04	−233.29	−233.13	−233.29
NL_s	−49.48	−54.94	−49.15	−50.97	−51.14	−50.93
NL_a	−181.85	−176.92	−186.89	−182.32	−181.99	−182.36
N_t	9.57	2.87	−4.88	4.87	3.11	2.82
N_s	119.94	109.73	110.79	116.66	114.28	114.25
N_a	−110.37	−106.87	−115.67	−111.79	−111.17	−111.44
CLR-NS_t	296.49	281.66	278.84	289.44	286.61	286.46
CLR-NS_s	228.31	214.21	210.16	222.03	218.68	218.44
CLR-NS_a	68.18	67.45	68.68	67.40	67.93	68.01
CLR-NL_t	−257.31	−259.42	−261.79	−258.87	−259.35	−259.48
CLR-NL_s	−80.72	−83.74	−76.92	−80.32	−80.42	−80.54
CLR-NL_a	−176.58	−175.68	−184.88	−178.55	−178.92	−178.94
CLR-N_t	39.19	22.24	17.05	30.57	27.26	26.98
CLR-N_s	147.59	130.47	133.24	141.71	138.25	137.90
CLR-N_a	−108.40	−108.23	−116.20	−111.15	−110.99	−110.93
CLD-NS_t	226.30	221.93	217.12	224.56	222.48	222.30
CLD-NS_s	153.38	150.73	144.83	152.87	150.45	150.16
CLD-NS_a	72.92	71.20	72.29	71.68	72.02	72.14
CLD-NL_t	−225.34	−224.98	−229.23	−226.88	−226.61	−226.80
CLD-NL_s	−35.14	−41.95	−35.65	−37.69	−37.61	−37.31
CLD-NL_a	−190.20	−183.03	−193.58	−189.19	−189.00	−189.49
CLD-N_t	.96	−3.06	−12.10	−2.33	−4.13	−4.50
CLD-N_s	118.24	108.78	109.18	115.18	112.84	112.86
CLD-N_a	−117.28	−111.83	−121.28	−117.51	−116.98	−117.36
CFC-NS_t	−55.59	−46.93	−47.68	−51.27	−50.37	−50.34
CFC-NS_s	−58.89	−49.54	−50.22	−54.40	−53.26	−53.25
CFC-NS_a	3.30	2.60	2.54	3.13	2.89	2.91
CFC-NL_t	25.97	27.56	25.75	25.58	26.22	26.19
CFC-NL_s	31.24	28.80	27.77	29.35	29.29	29.61
CFC-NL_a	−5.27	−1.24	−2.01	−3.77	−3.07	−3.42
CFC-N_t	−29.62	−19.37	−21.93	−25.70	−24.15	−24.16
CFC-N_s	−27.65	−20.74	−22.46	−25.05	−23.97	−23.65
CFC-N_a	−1.97	1.36	.53	−.64	−.18	−.51