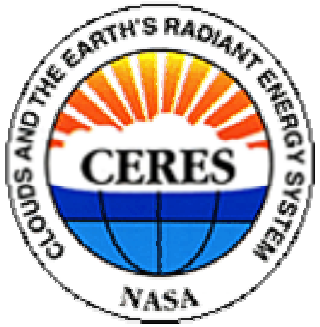
TOA Radiative Flux Estimation From CERES/Terra Angular Distribution Models

Norman G. Loeb

Hampton University/NASA Langley Research Center

Hampton, VA



Contributors: S. Kato, K. Loukachine, N. M. Smith

April 1, 2004, NCAR

Outline

1. Introduction

2. CERES/Terra Shortwave ADMs

3. CERES/Terra Longwave ADMs

4. Comparisons with CERES ERBE-Like

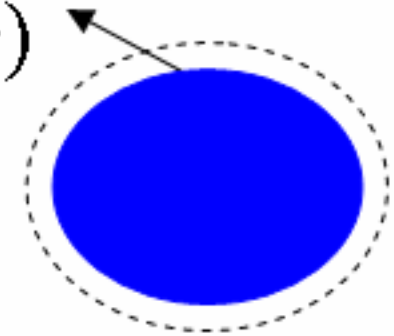
5. Validation: Accuracy of regional means

6. Validation: Accuracy of Instantaneous TOA fluxes

Instantaneous Fluxes at TOA and Angular Distribution Models

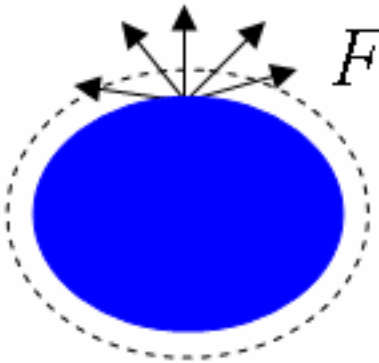
CERES Radiance Measurement

$L(\theta_o, \theta, \phi)$



$\Rightarrow$

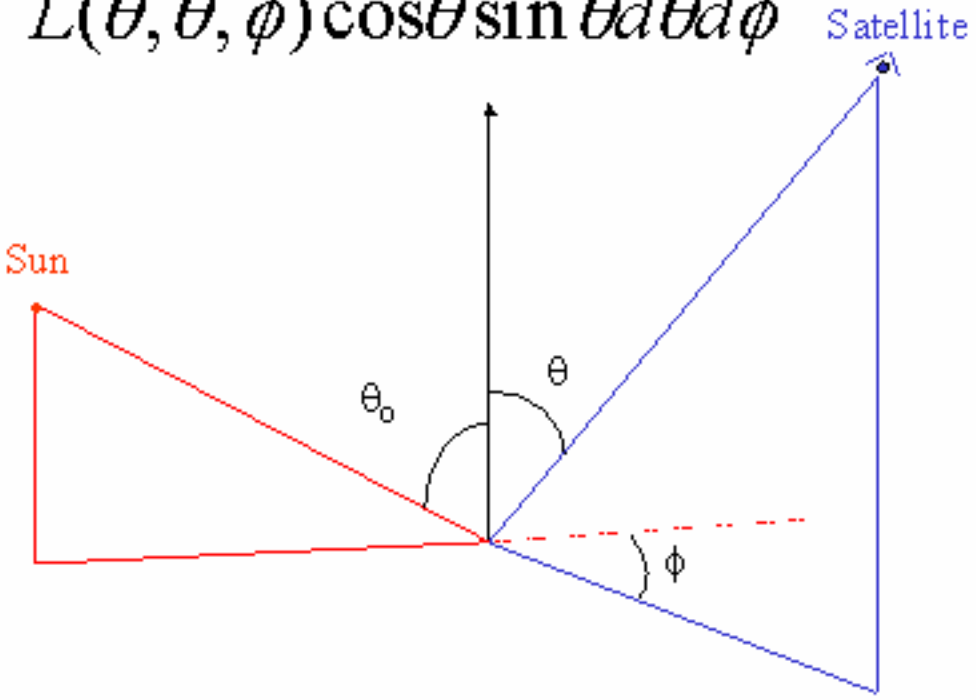
TOA Flux Estimate



$F(\theta_o)$

SW
LW
WN

$$F(\theta_o) = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} L(\theta, \theta, \phi) \cos\theta \sin\theta d\theta d\phi$$



TOA flux estimate from CERES radiance:

$$\hat{F}(\theta_o, \theta, \phi) = \frac{\pi L(\theta_o, \theta, \phi)}{R_j(\theta_o, \theta, \phi)}$$

where,

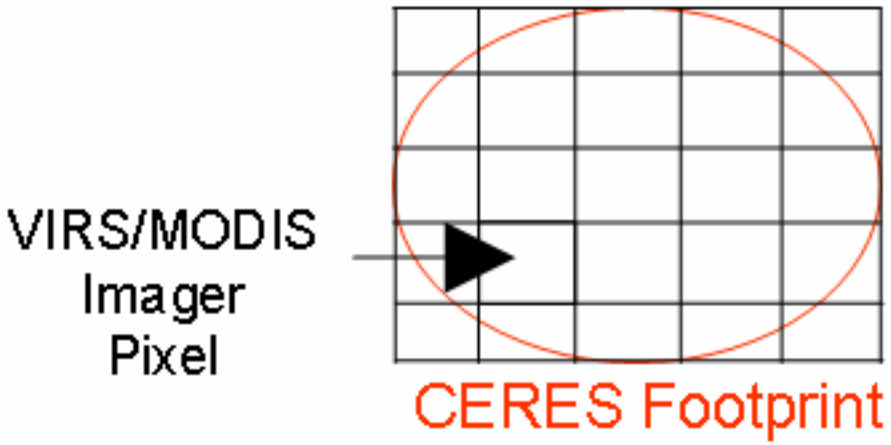
$$R_j(\theta_o, \theta, \phi) = \frac{\pi L_j(\theta_o, \theta, \phi)}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} L_j(\theta_o, \theta, \phi) \cos\theta \sin\theta \, d\theta d\phi}$$

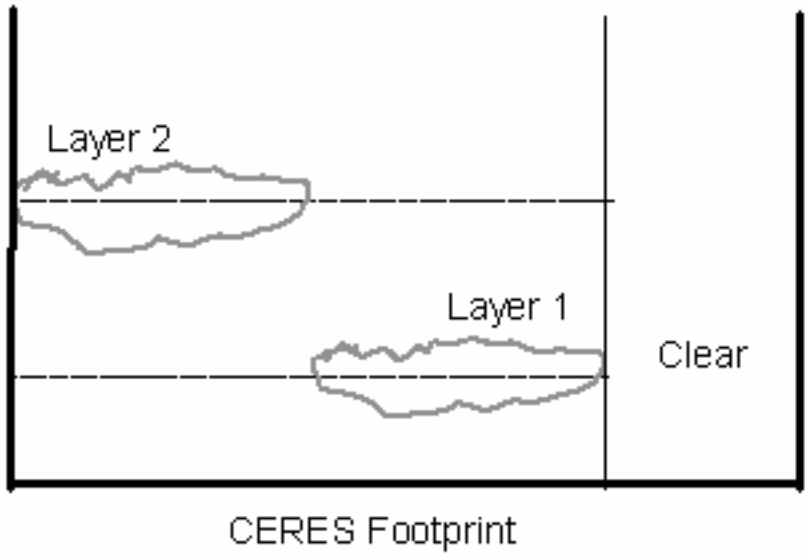
$R_j(\theta_o, \theta, \phi)$ is the Angular Distribution Model (ADM) for the "jth" scene type.

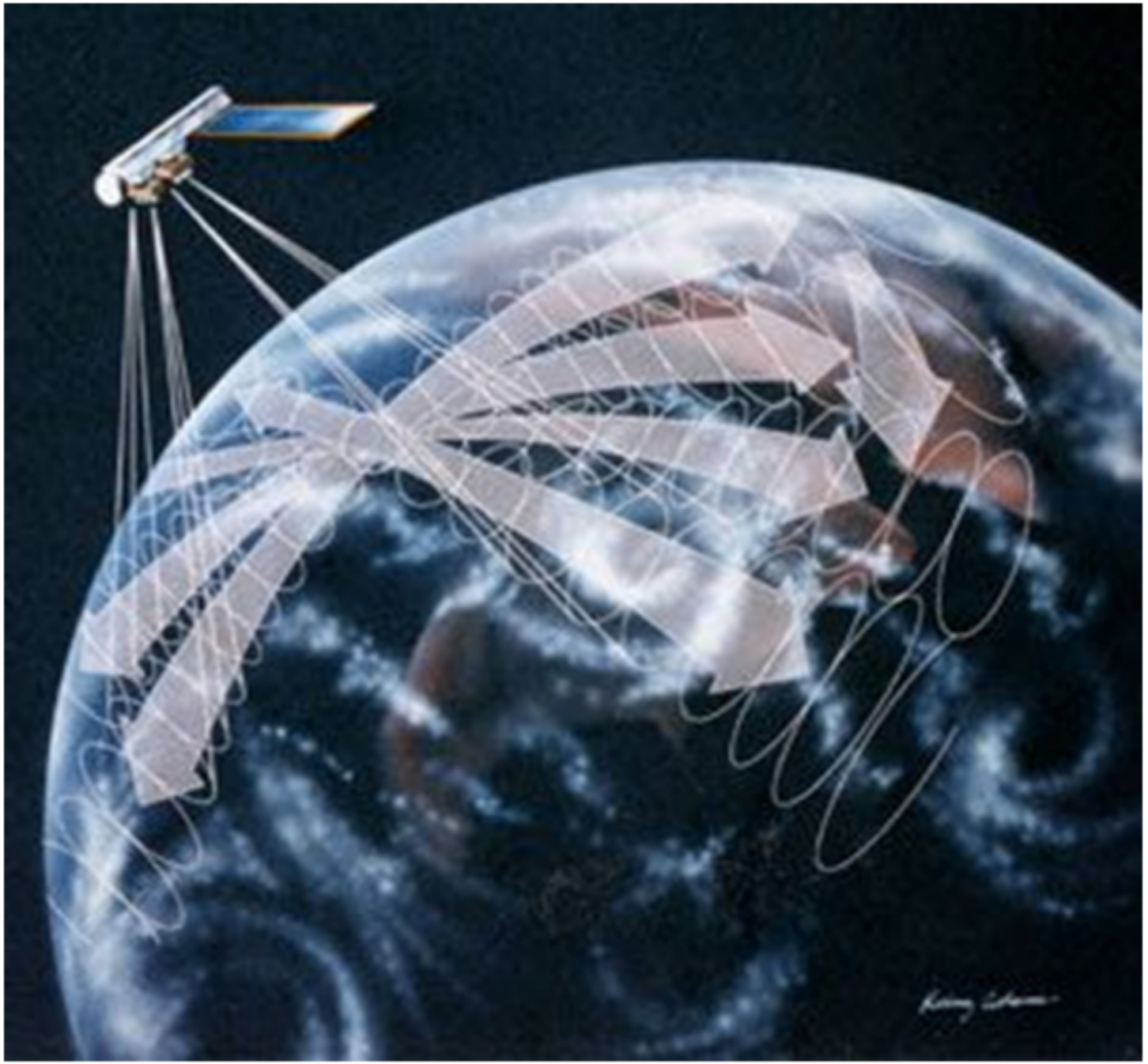
CERES Single Scanner Footprint (SSF) Product

- Coincident CERES radiances and imager-based cloud and aerosol properties.
- Use VIRS (TRMM) or MODIS (Terra, Aqua) to determine following parameters in up to 2 cloud layers over every CERES FOV:

Macrophysical: Fractional coverage, Height, Radiating Temperature, Pressure
Microphysical : Phase, Optical Depth, Particle Size, Water Path
Clear Area : Albedo, Skin Temperature, Aerosol optical depth, Emissivity





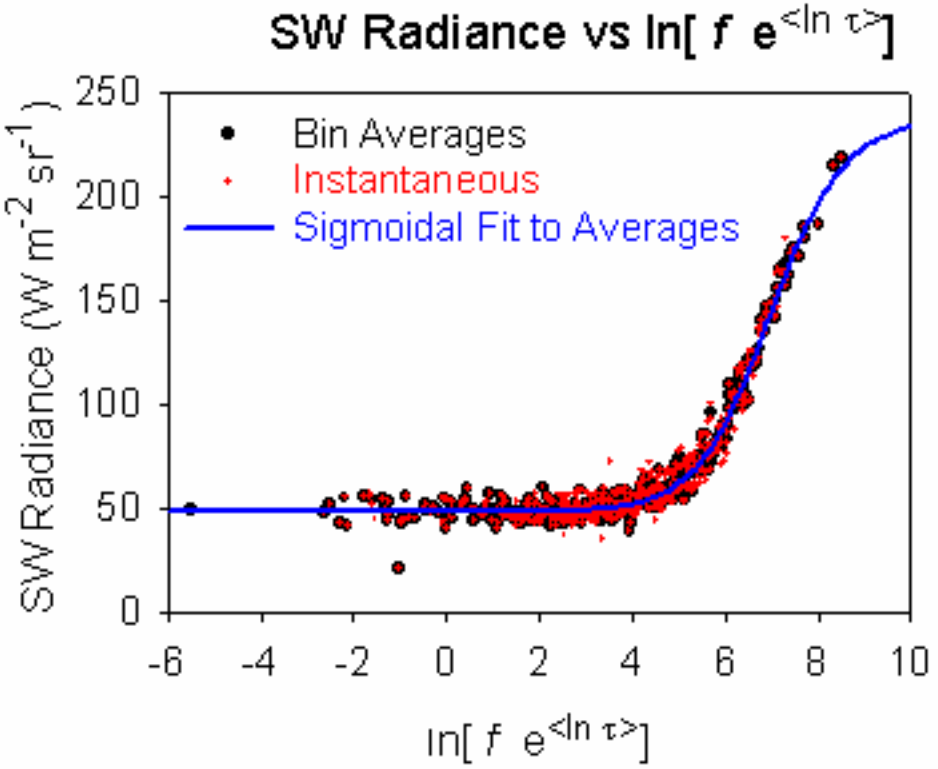


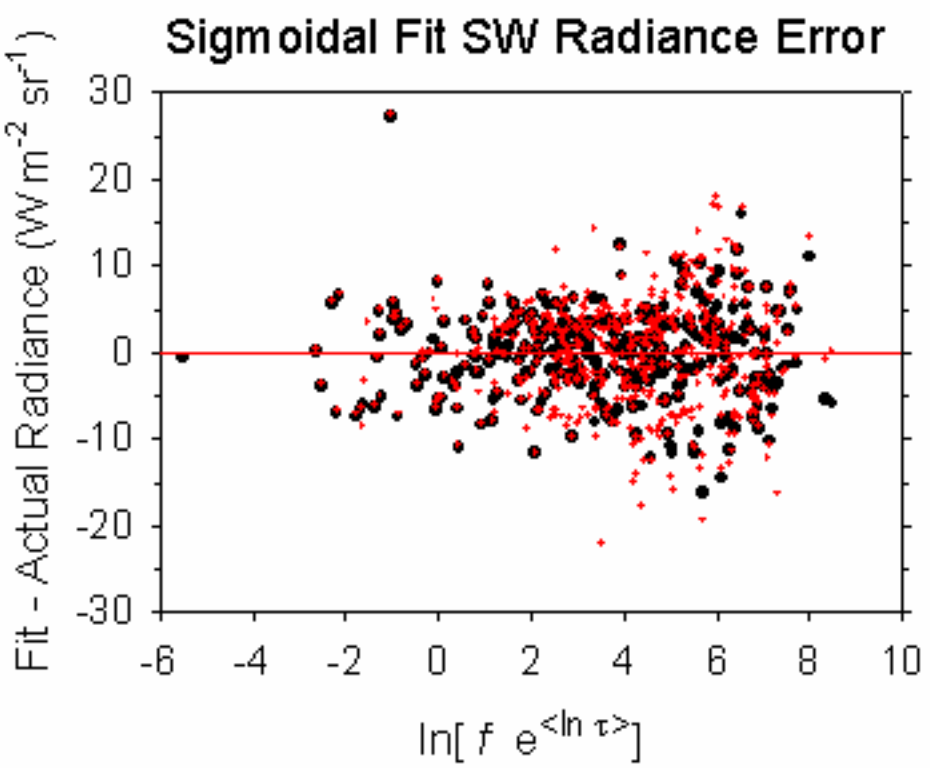
CERES/Terra Shortwave ADMs for Different Scene Types

Scene Type	Description
Clear Ocean	Function of wind speed; Correction for aerosol optical depth included.
Cloud Ocean	Function of cloud phase; Continuous function of cloud fraction and cloud optical depth (5-parameter sigmoid).
Land & Desert Clear	1° regional monthly ADMs using Analytical Function of TOA BRDF (Ahmad and Deering, 1992).
Land & Desert Cloud	Function of cloud phase; continuous function of cloud cover and cloud optical depth; uses 1°-regional clear-sky BRDFs to account for background albedo.
Permanent Snow	Cloud Fraction, Surface Brightness, cloud optical depth
Fresh Snow	Cloud Fraction, Surface Brightness, Snow Fraction, cloud optical depth
Sea-Ice	Cloud Fraction, Surface Brightness, Ice Fraction, cloud optical depth

Uncertainties in Sigmoidal SW Radiance Fits

(Liquid Water Clouds; θ_0=34°-36°; θ=50°-52°; ϕ=6°-8°; TRMM+Terra RAPS+Alongtrack)





Avg Rad	= 70.5	$W m^{-2} sr^{-1}$	
Bias	= 0.038	$W m^{-2} sr^{-1}$	(0.05%)
Stdev	= 5.26	$W m^{-2} sr^{-1}$	(7.5%)

Five Parameter Sigmoid

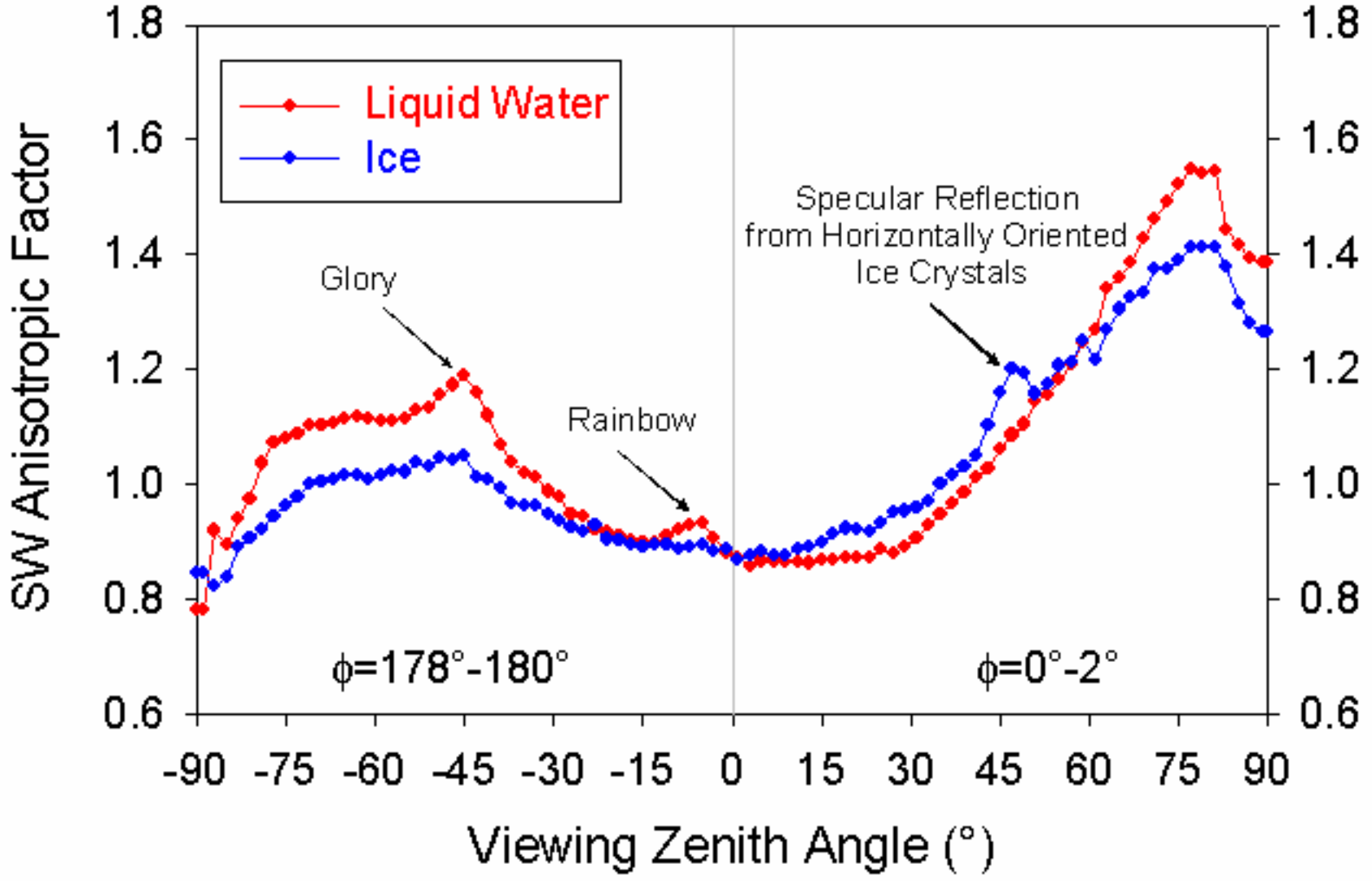
$$I = I_o + \frac{a}{\left[1 + e^{-\left(\frac{x - x_o}{b}\right)}\right]^c}$$

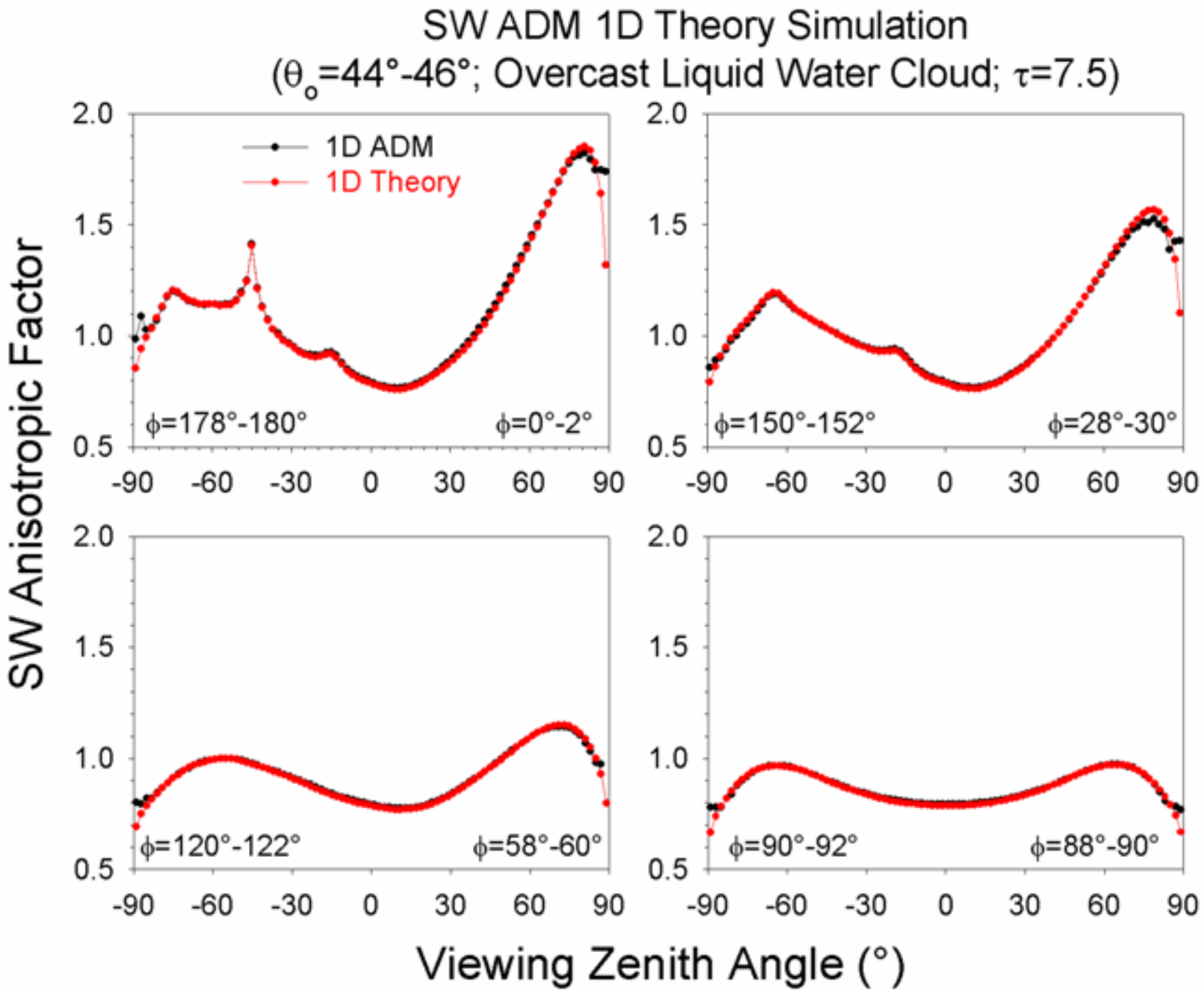
where, $x = \ln(f \times e^{<\ln \tau>})$

x_o, I_o, a, b, c = coefficients of fit

CERES/Terra ADM Anisotropic Factors in the Principal Plane

(θ_0=44°-46°; Ocean; $f\, e^{<\ln\tau>}$ = 7.5; November 2000 - August 2001)




SW ADM 1D Theory Simulation
(θo=44°-46°; Overcast Liquid Water Cloud; τ=7.5)
SW Anisotropic Factor
Viewing Zenith Angle (°)
1D ADM
1D Theory
ϕ=178°-180°
ϕ=0°-2°
ϕ=150°-152°
ϕ=28°-30°
ϕ=120°-122°
ϕ=58°-60°
ϕ=90°-92°
ϕ=88°-90°
2.0
1.5
1.0
0.5
-90
-60
-30
0
30
60
90

Clear Land & Desert

- Collect one month of clear land CERES reflectances over ≈1° equal-area regions. Stratify by solar zenith angle and TOA NDVI.
- If sampling over angle is sufficient, use an 8-parameter nonparametric fit (from Ahmad and Deering, 1992) to produce brdf and ADM for the ≈1° region.

$$r(\mu,\phi,\mu_o)=\frac{1}{4}\frac{\omega}{\mu+\mu_o}\left\{1-\exp\left[-\tau\left(\frac{1}{\mu}+\frac{1}{\mu_o}\right)\right]\right\}\cdot\left\{P(\alpha)\left[1+B(\alpha')\right]\right\}+\frac{1}{4}\frac{\omega}{\mu+\mu_o}$$

$$\cdot\left[H^{(0)}(\mu)H^{(0)}(\mu_o)(1-e(\mu+\mu_o)-b(1-\omega)\mu\mu_o+b(1-\mu^2)^{1/2}\cdot(1-\mu_o^2)^{1/2}H^{(1)}(\mu)H^{(1)}(\mu_o)\cos\phi\right]$$

$$-\frac{1}{4}\frac{\omega}{\mu+\mu_o}P'(\alpha)+\left(d_o+\frac{d_1}{\mu+\mu_o}\right)$$

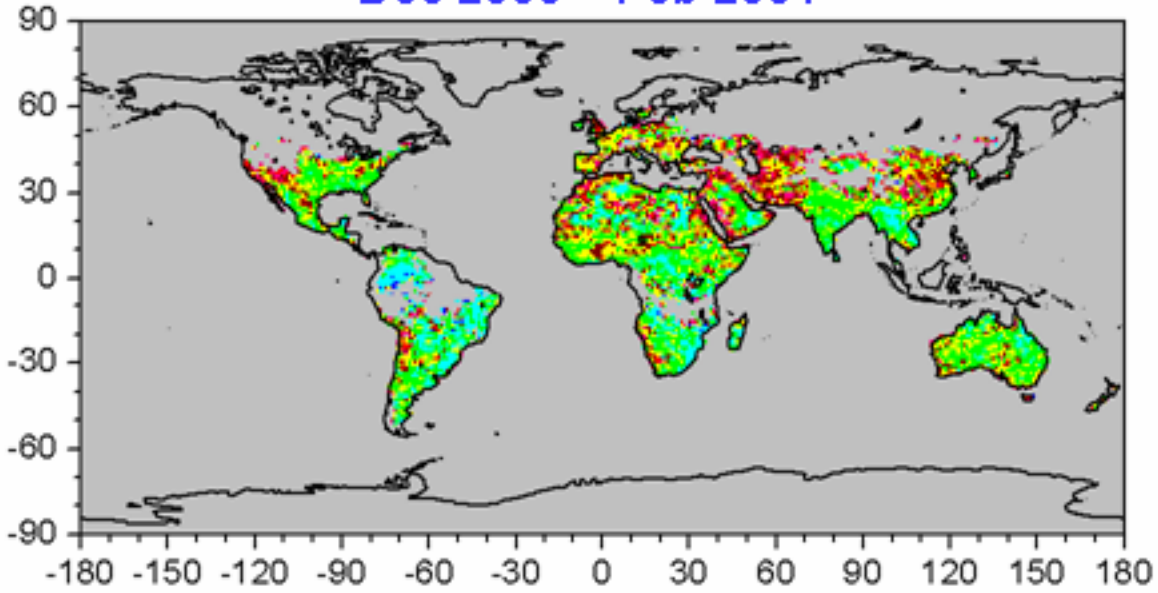
-Multiple scattering based on Chandrasekhar's RT solution for semi-infinite medium.

-"Hot-spot" modeled using empirical term (Hapke, 1986).

Relative RMS Error in Clear Land BRDF Fits (RAP+Crosstrack)

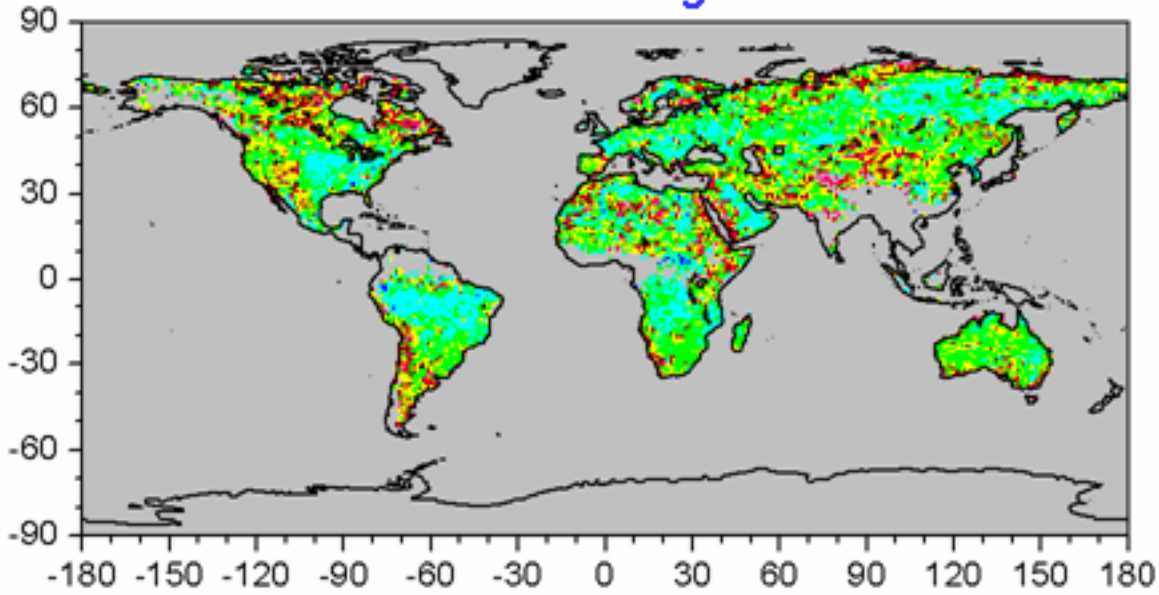
Dec 2000 – Feb 2001

Overall Error
6%

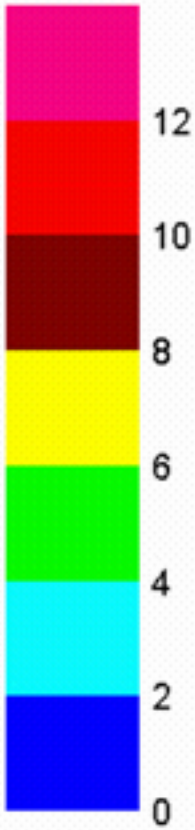


Jun 2000 – Aug 2000

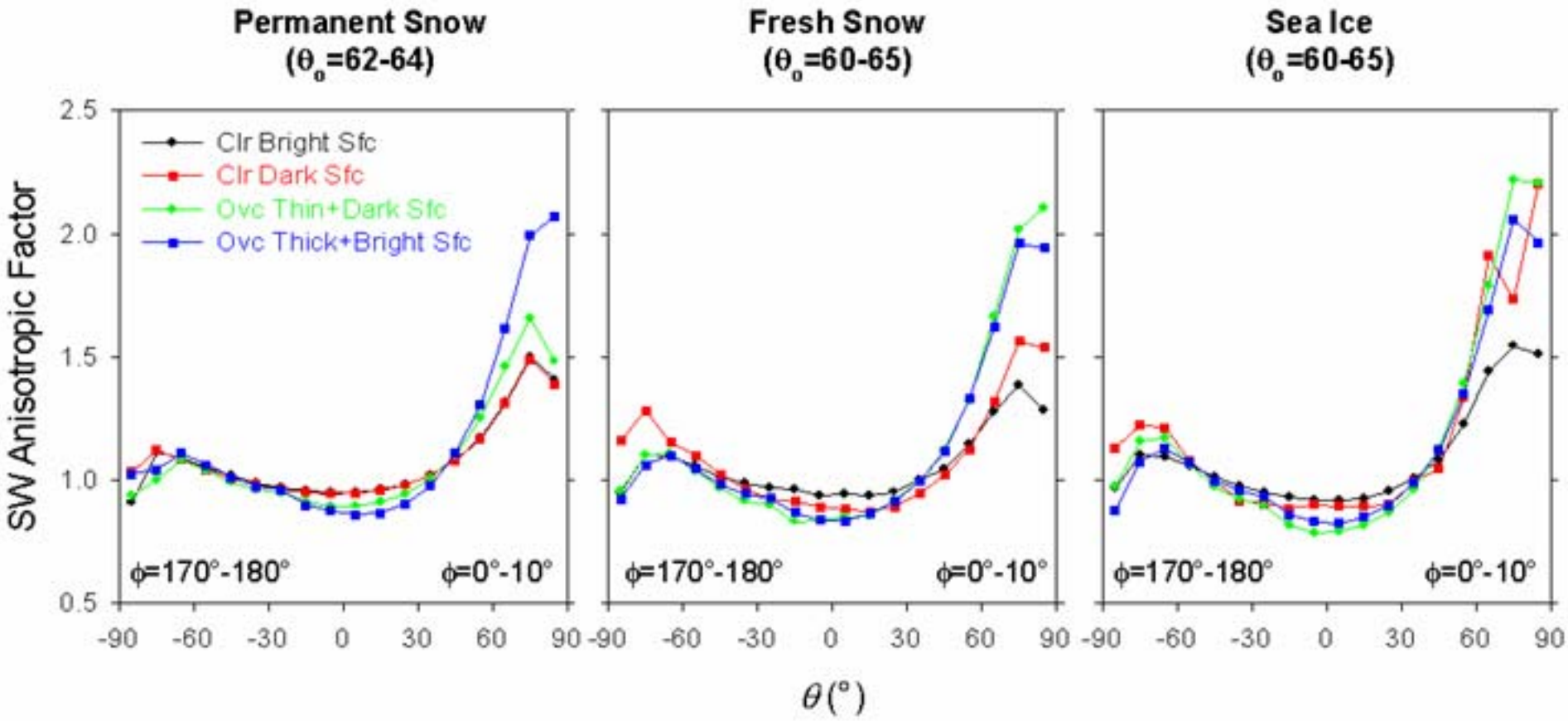
Overall Error
7%



Relative RMS Error
(%)



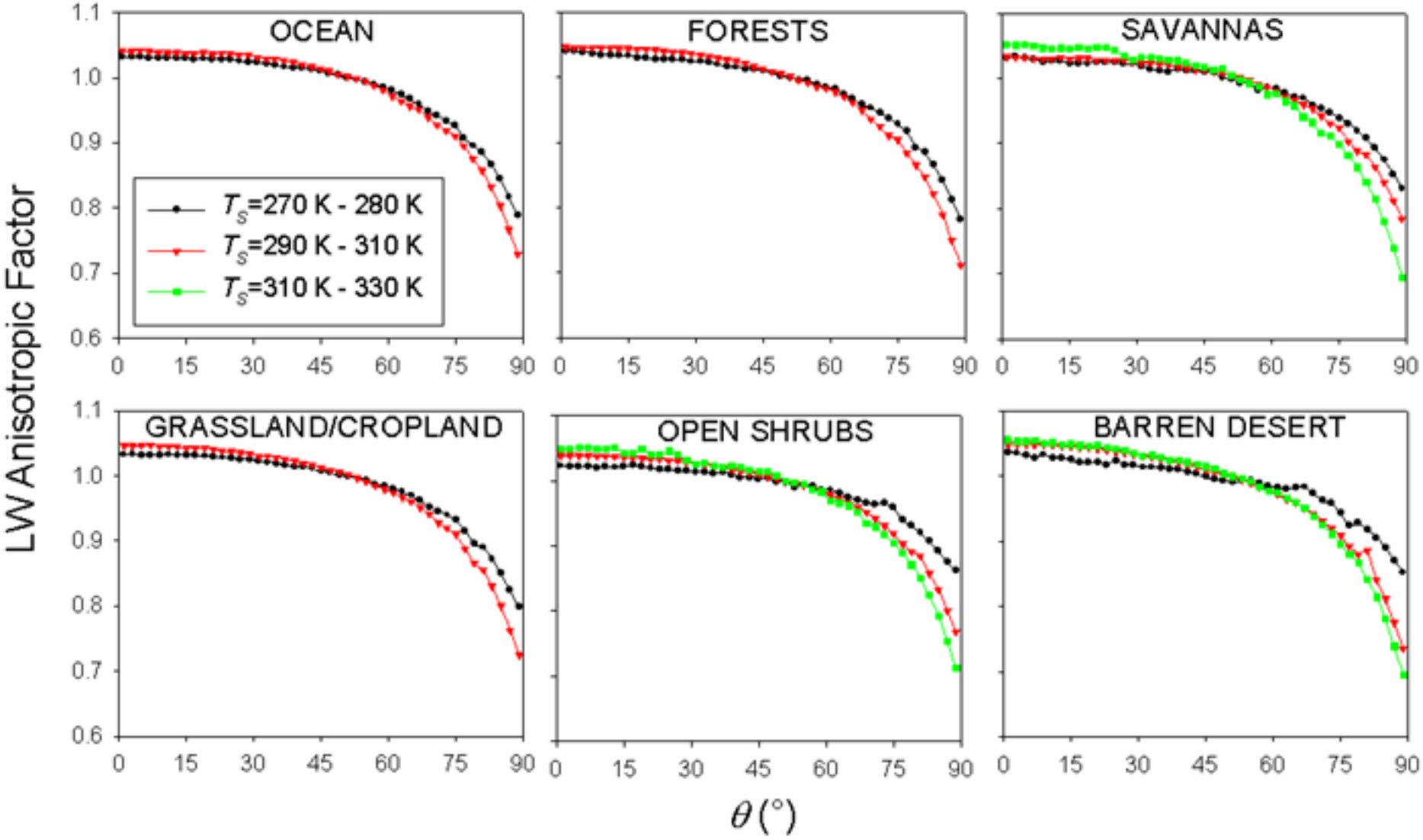
SW ADMs over Snow and Sea Ice



CERES/Terra Longwave & Window ADMs for Different Scene Types

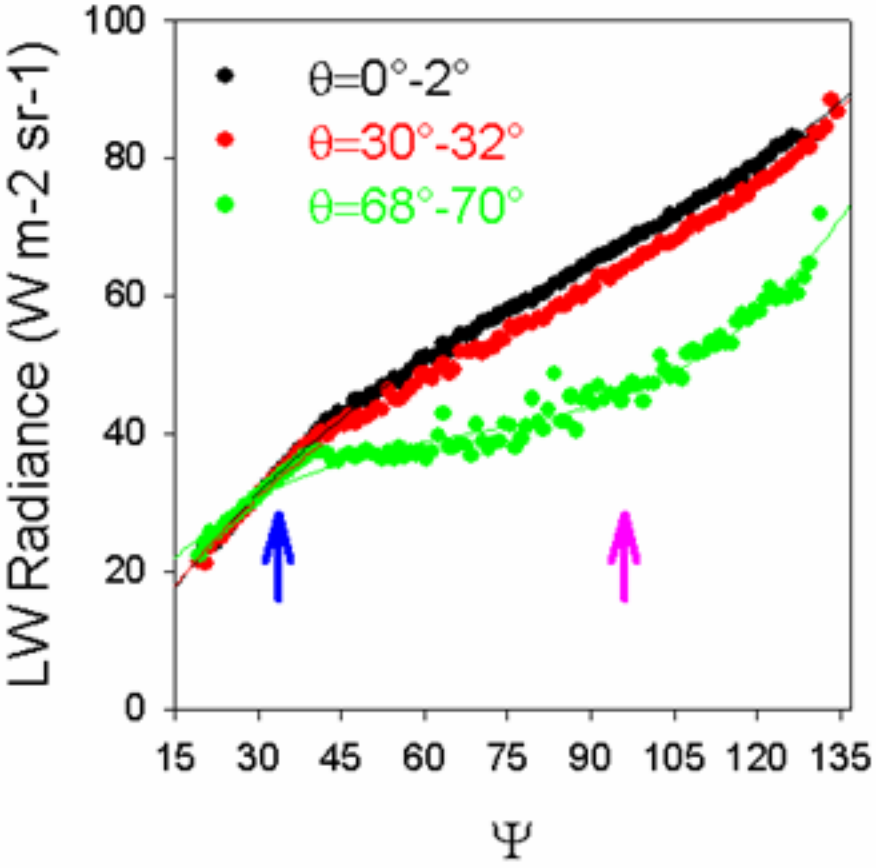
Scene Type	Description
Clear Ocean, Land, Desert	Ocean, Forest, Cropland/Grass, Savanna, Bright Desert, Dark Desert, precip. water, lapse rate, skin temperature
Clouds Over Ocean, Land, Desert	Function of precip. water, skin temp., sfc-cloud temp. diff; continuous function of parameterization involving cloud fraction, cloud and sfc emissivity, sfc and cloud temp.
Permanent Snow Fresh Snow Sea-Ice	Each a function of cloud fraction, sfc temp, sfc-cld temp diff

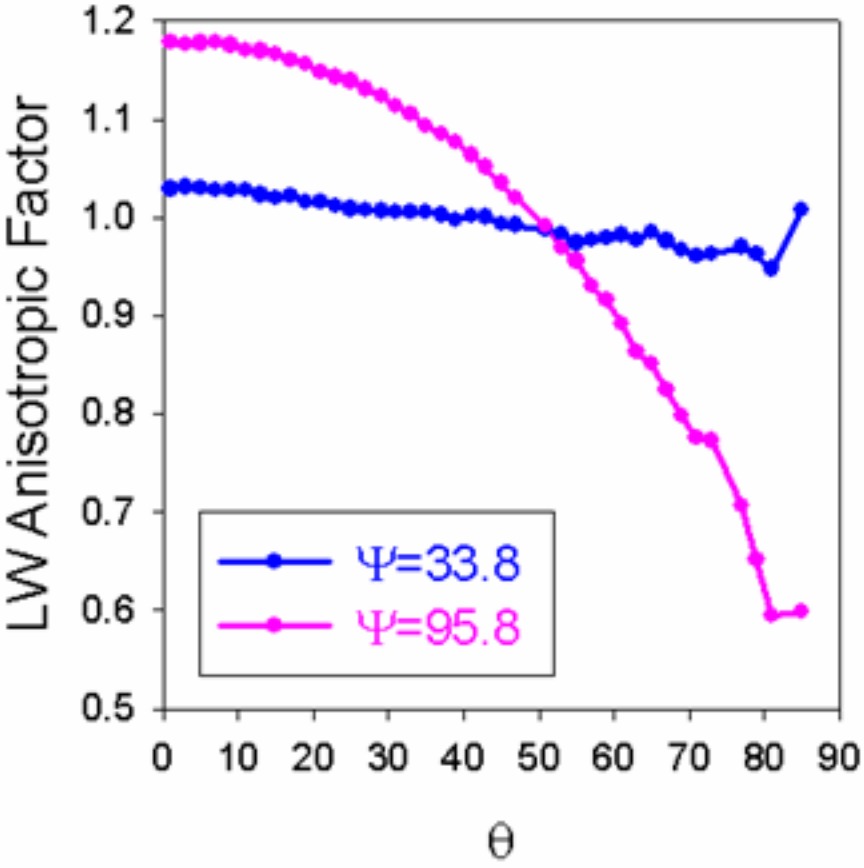
Clear Sky LW ADMs
(pw=0.0-1.0 cm; Lapse Rate = 15-30 °C)



LW ADMs over Ocean (Clouds)

(pw > 5 cm^{-1}; T_s=300°-305° K; T_s-T_c > 85° K; *f*=1.0)

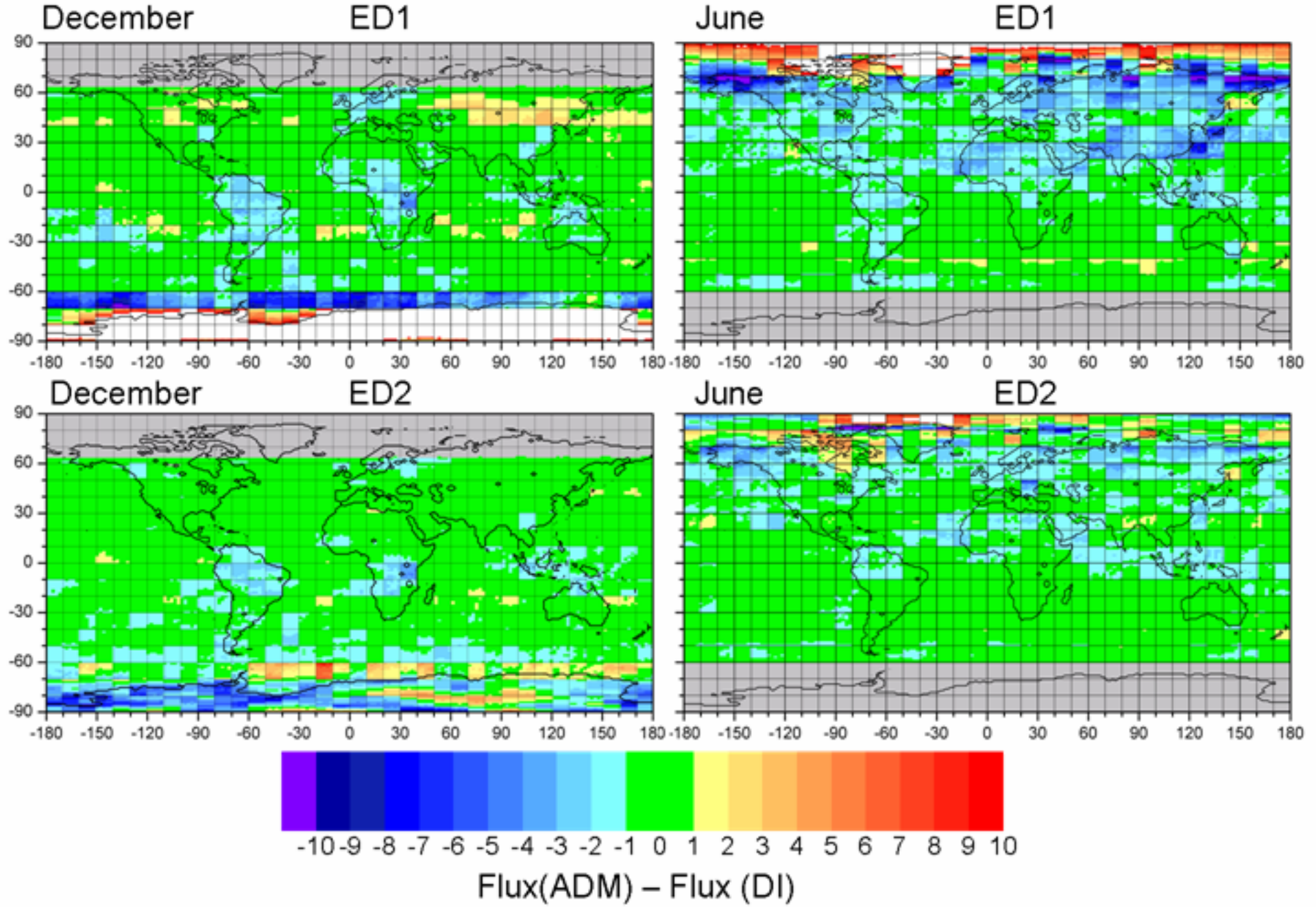




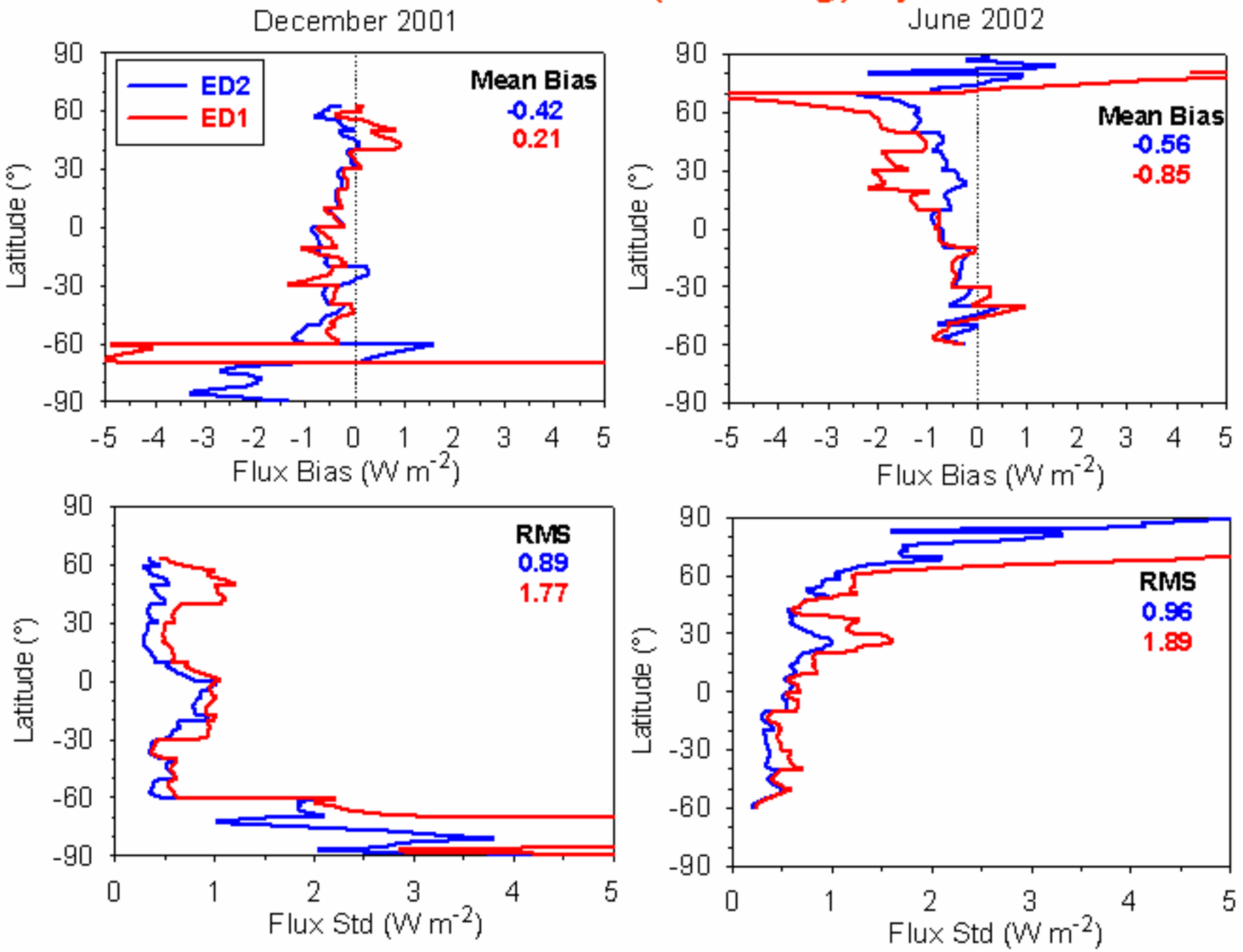
$$\psi(w,T_s,T_c,f,\varepsilon_s,\varepsilon_c) = (1-f)\varepsilon_s B(T_s) + \sum_{j=1}^{2}\left(\varepsilon_s B(T_s)(1-\varepsilon_{c_j}) + \varepsilon_{c_j} B(T_{c_j})\right) f_j$$

Uncertainty in Regional Mean TOA Flux Due to ADMs

SW Flux Direct Integration Test

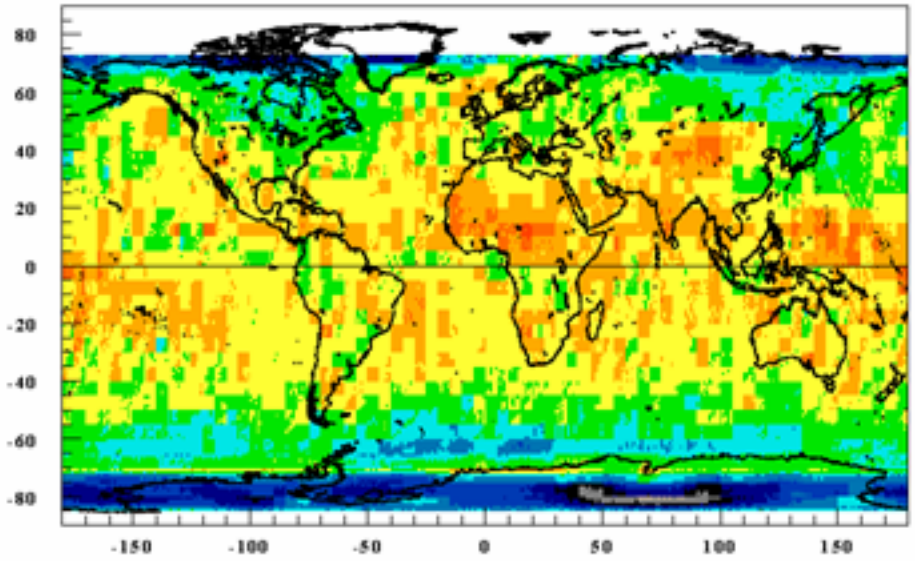


SW TOA Flux Errors (24-h avg) by Latitude

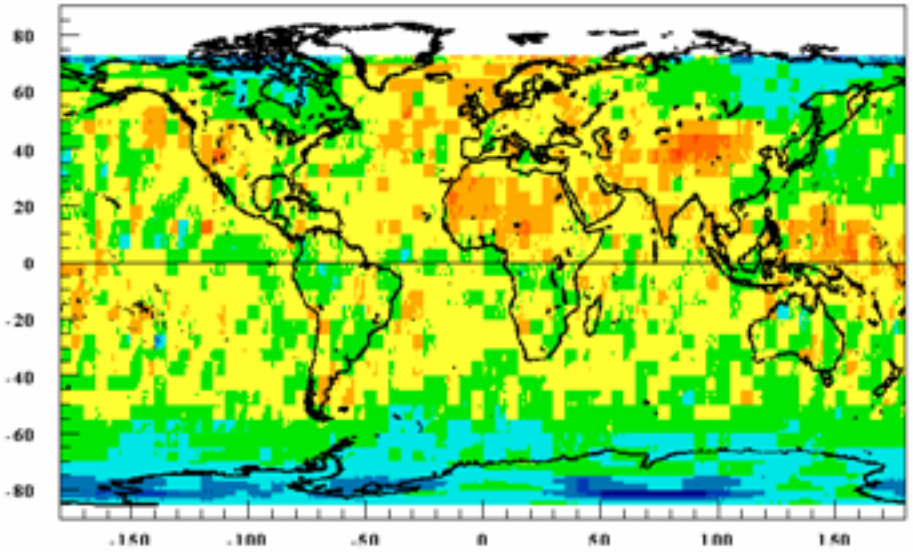


All-Sky **Daytime** Longwave Flux Direct Integration Tests (DJF)

TRMM ADMs
F(ADM) – F(DI)
MN DIFF
-0.13 W m^{-2}
RMS Diff
1.45 W m^{-2}



Terra ADMs
F(ADM) – F(DI)
MN DIFF
-0.04 W m^{-2}
RMS Diff
0.93 W m^{-2}



Flux Error
(W m^{-2})

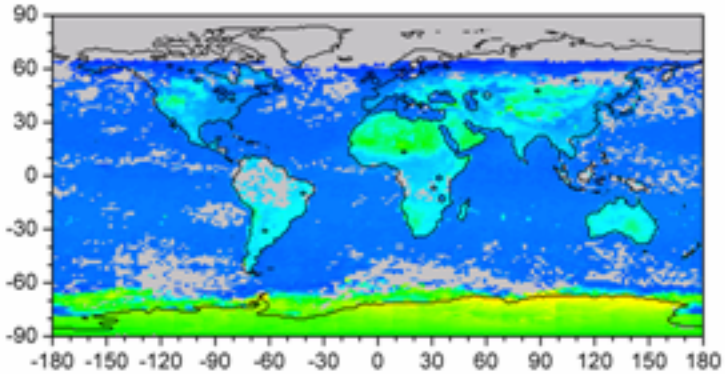
TOA Flux Differences Between CERES/Terra ES8, ED1 and ED2

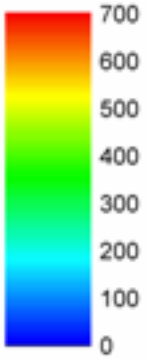
SW TOA Flux Comparisons

DECEMBER, 2001

CLEAR-SKY

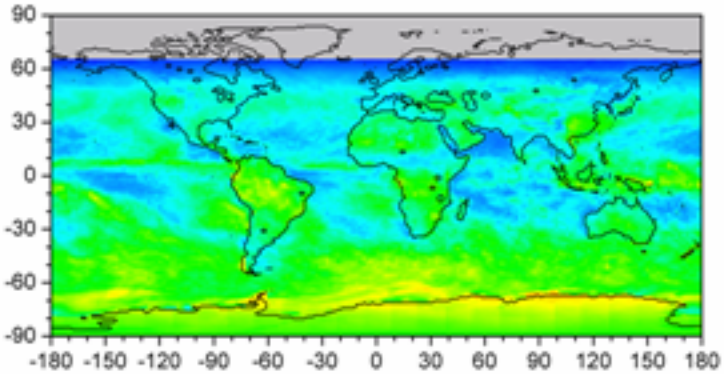
ED2



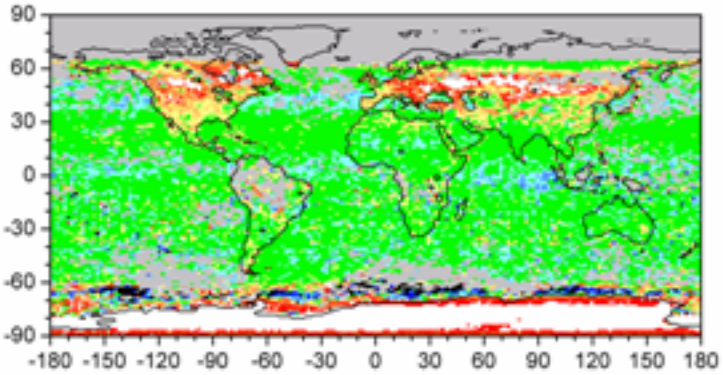


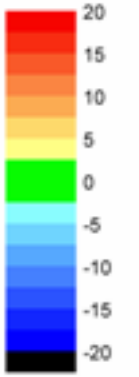
All-SKY

ED2

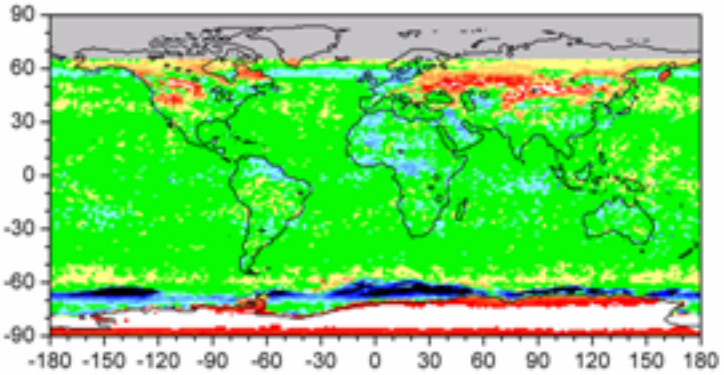


ED1 - ED2

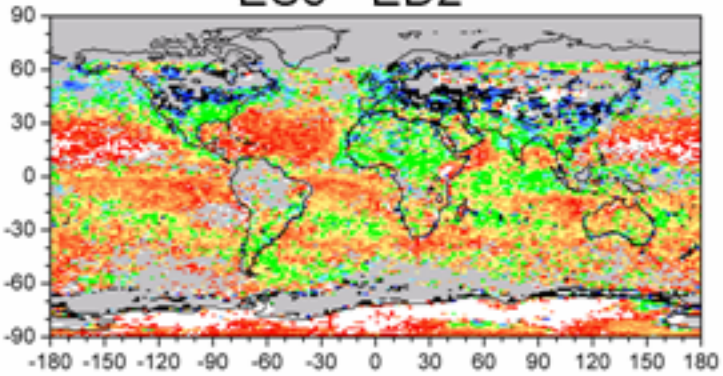


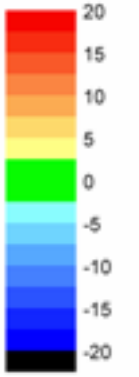


ED1 - ED2

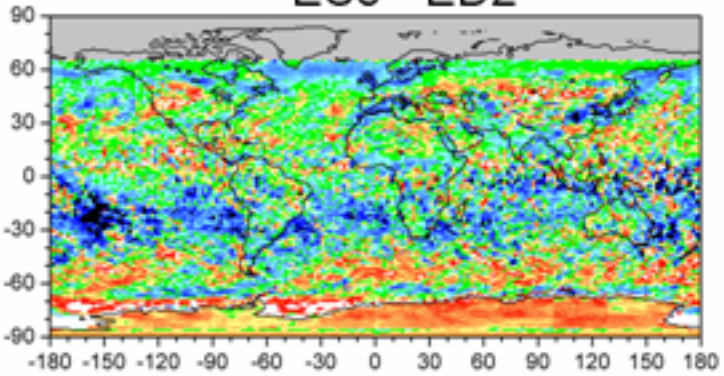


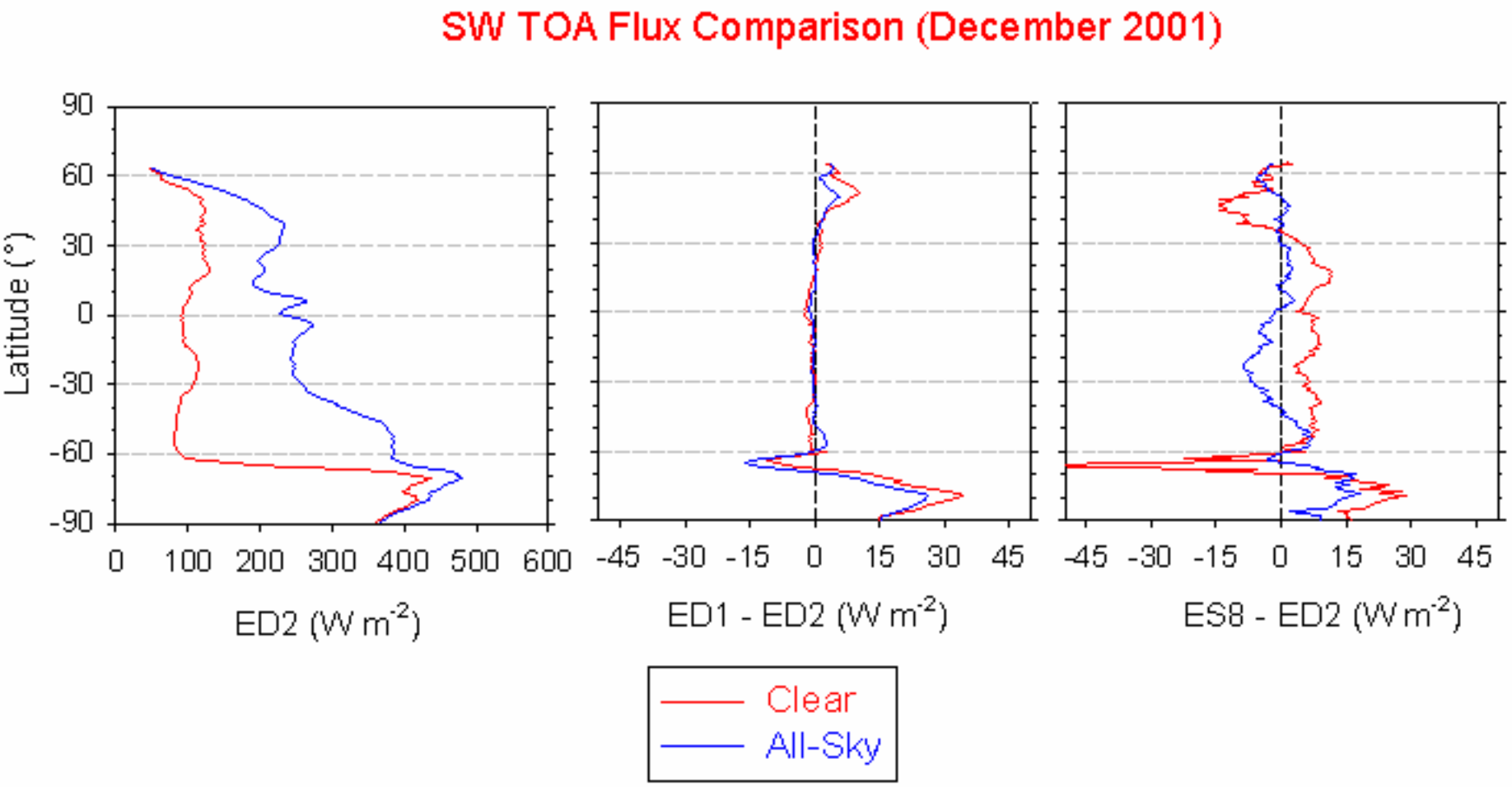
ES8 - ED2





ES8 - ED2




SW TOA Flux Comparison (December 2001)
Latitude (°)
90
60
30
0
-30
-60
-90
0 100 200 300 400 500 600
ED2 (W m-2)
-45 -30 -15 0 15 30 45
ED1 - ED2 (W m-2)
-45 -30 -15 0 15 30 45
ES8 - ED2 (W m-2)
Clear
All-Sky

SW TOA Flux Differences: ES8 & ED1 vs ED2 (December 2001)

	Avg	Avg Diff		RMS Diff		
				1°-Regional		FOV
	ED2	ES8 vs ED2	ED1 vs ED2	ES8 vs ED2	ED1 vs ED2	ED1 vs ED2
Clear (30°S-30°N)	107.1	7.2	-0.6	12.1	3.3	5.0
All-Sky (30°S-30°N)	233.9	-2.0	-0.3	9.2	1.9	10.8
Clear (Global)	117.4	3.8	1.1	22.3	6.0	7.0
All-Sky (Global)	255.4	-0.6	0.7	9.0	3.9	11.9

Notes: i) Diff = SW Flux(ES8) – SW Flux(ED2) or SW Flux(ED1) – SW Flux(ED2)

ii) No diurnal Averaging

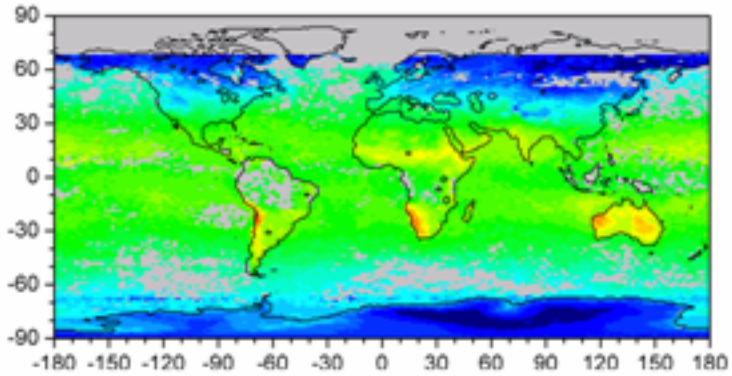
iii) All fluxes in W m^{-2}

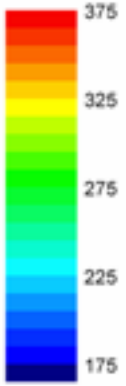
iv) 30°S-30°N insolation = 1121 W m^{-2}; Global = 956 W m^{-2}

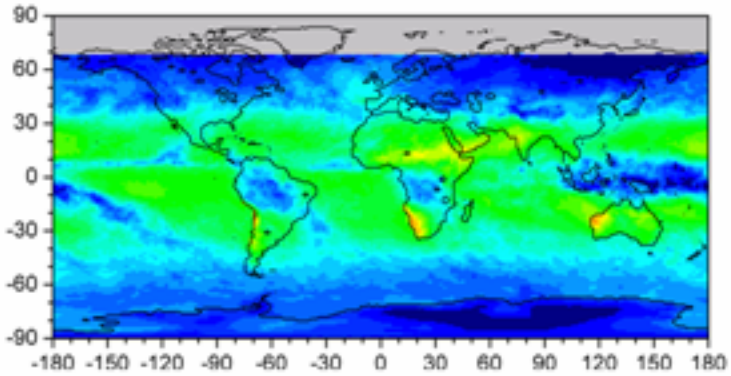
LW Daytime TOA Flux Comparisons

CLEAR-SKY DECEMBER, 2001 All-SKY

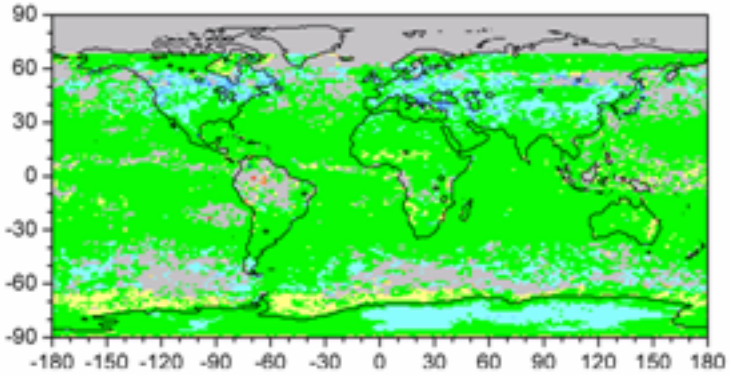
ED2

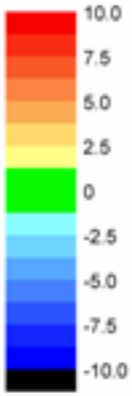


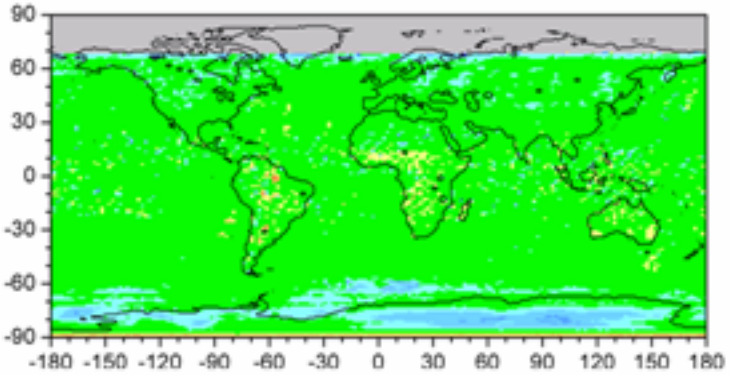




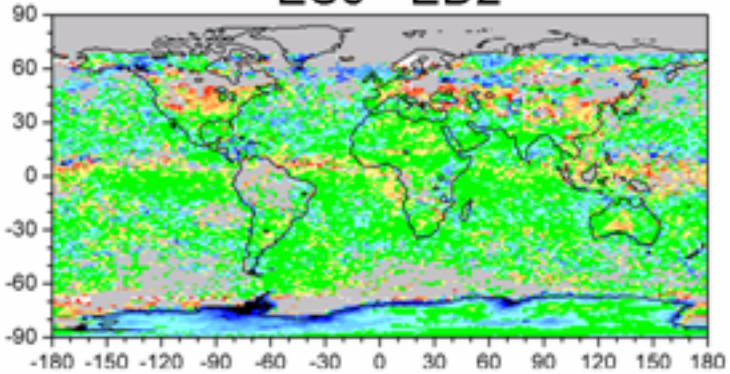
ED1 - ED2

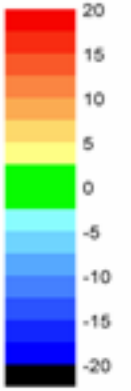


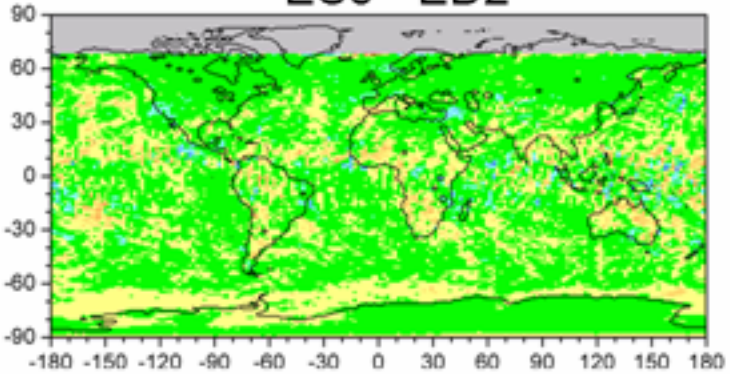




ES8 - ED2







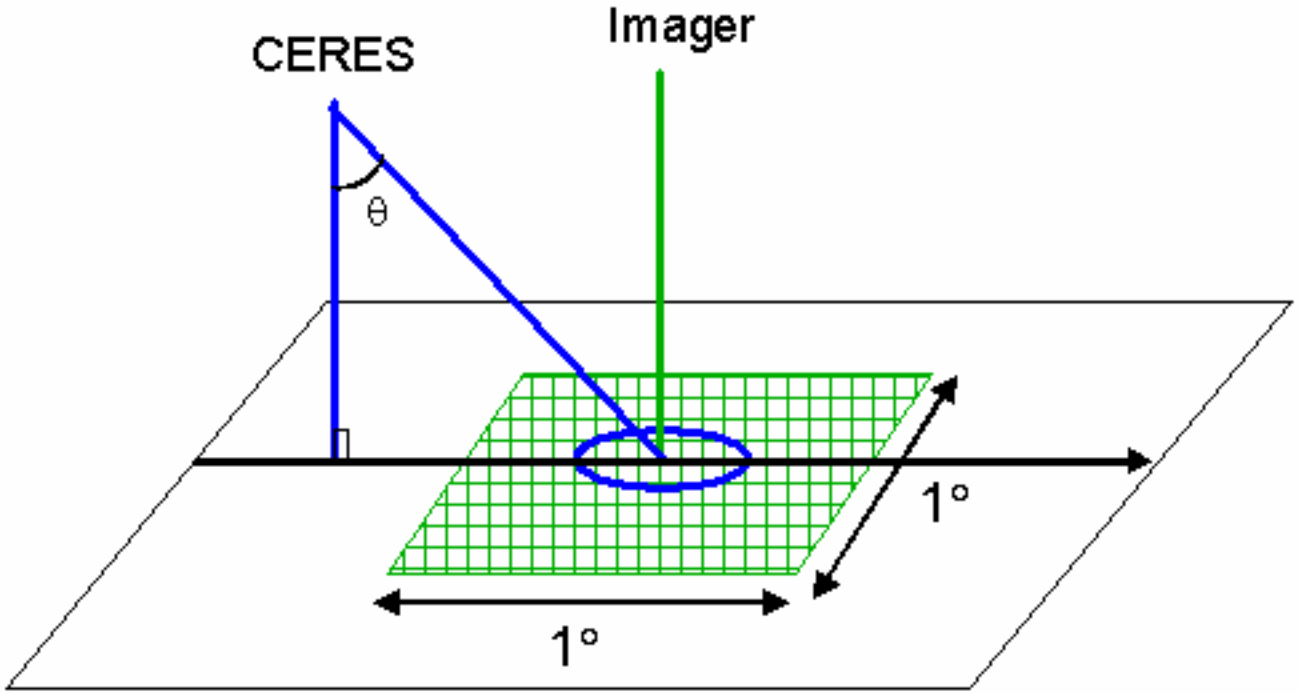
Daytime LW TOA Flux Differences: ES8 & ED1 vs ED2 (December 2001)

	Avg	Avg Diff		RMS Diff		
				1°-Regional		FOV
	ED2	ES8 vs ED2	ED1 vs ED2	ES8 vs ED2	ED1 vs ED2	ED1 vs ED2
Clear (30°S-30°N)	290.4	-0.2	0.3	4.2	0.6	0.9
All-Sky (30°S-30°N)	257.6	1.9	0.4	3.1	0.8	2.5
Clear (Global)	267.1	-0.3	-0.1	5.6	0.8	1.2
All-Sky (Global)	237.5	1.6	0.0	2.7	0.6	2.8

Notes: i) Diff = LW Flux(ES8) – LW Flux(ED2) or LW Flux(ED1) – LW Flux(ED2)
ii) All fluxes in W m^{-2}

TOA Flux Consistency Tests

Instantaneous TOA Flux Consistency Tests



- Convert imager nadir visible radiance to broadband flux
- Compare off-nadir CERES flux with nadir flux inferred from imager visible radiance
- 41 global alongtrack days over 2 years

Approach

- Convert imager nadir visible radiance to broadband flux:
  i) Narrow-to-broadband radiance regression developed using instantaneous nadir CERES and imager radiances over 1° regions.
  ii) Retain only cases where error in fit is < 3% (≈57% of popl'n)
  iii) Apply CERES ADMs to CERES off-nadir and imager nadir broadband radiances.

- Compare off-nadir and nadir instantaneous TOA fluxes by latitude, region, IGBP type, cloud type, etc.

Regional Stratification:

Tropics - Lat ≤ 30°, Ocean, Land, Desert
Midlatitudes - Lat > 30°, Ocean, Land, Desert
Polar - Global, FOV contains Snow or Sea Ice

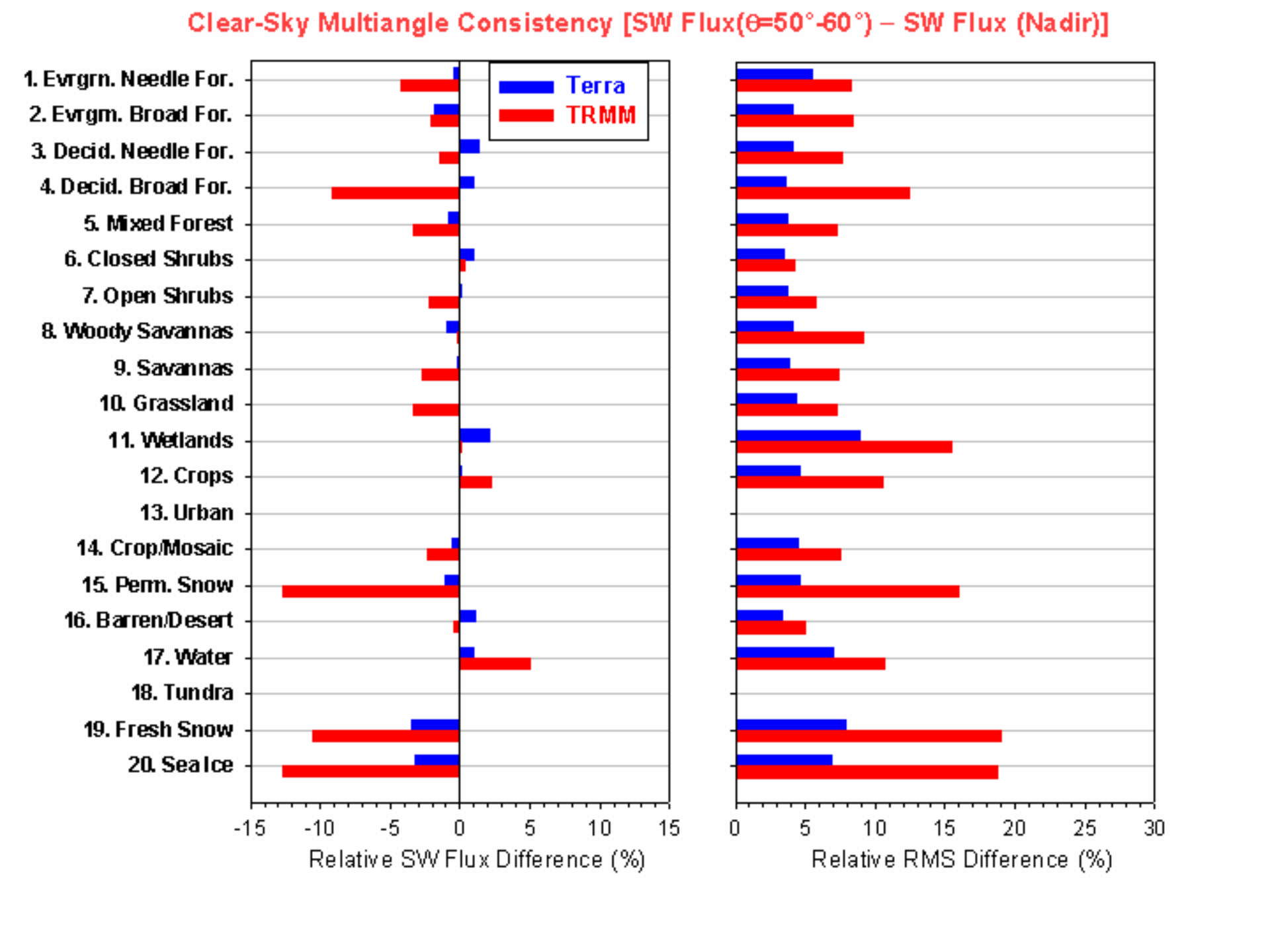
Clear-Sky Instantaneous SW TOA Flux Consistency
(F(θ=50°-60°) – F(Nadir))

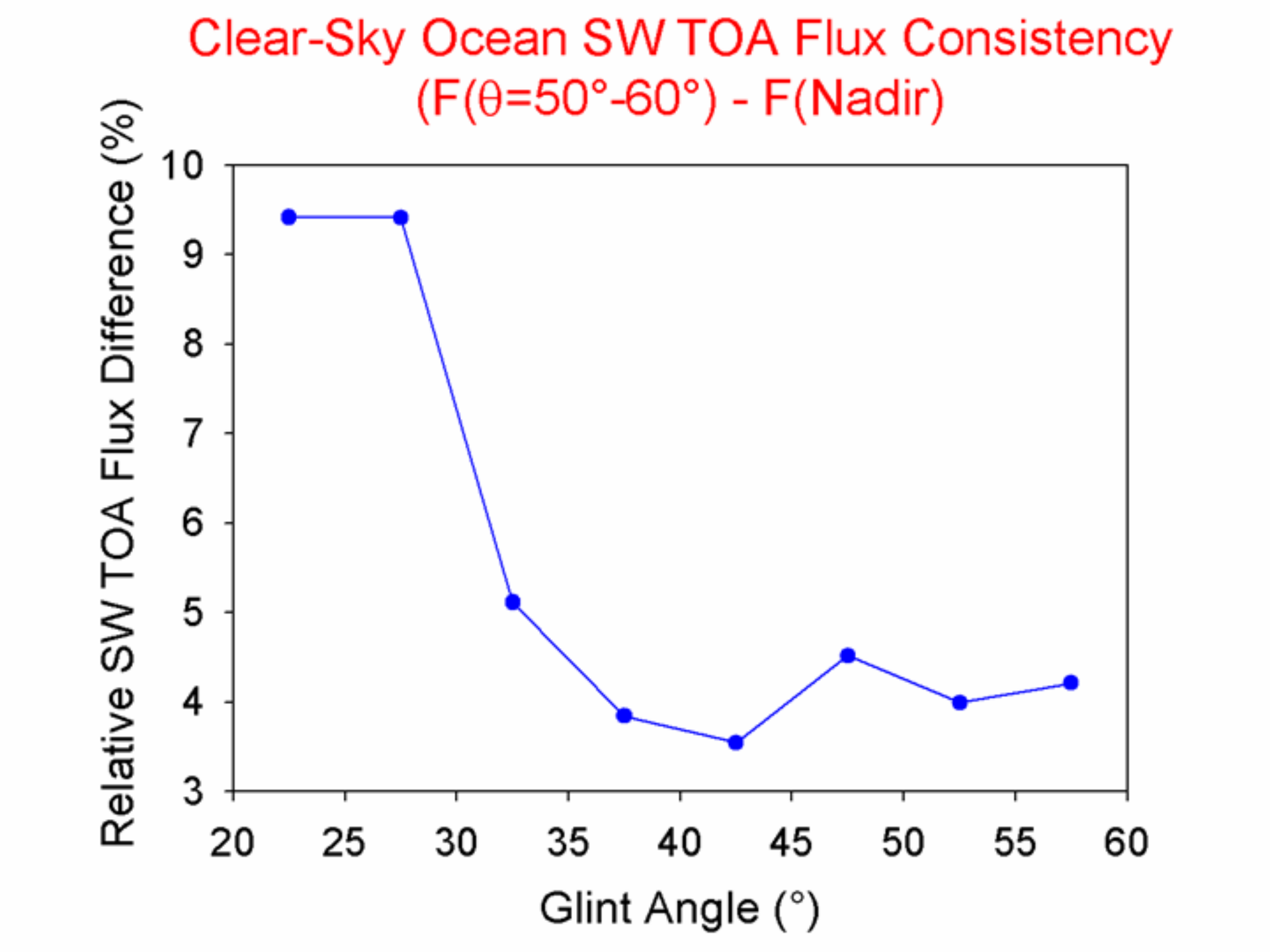
Terra ADMs

Region	Mean SW Flux ($W\ m^{-2}$)	Bias (%)	RMS (%)	No. FOVs
Tropics	223.3	0.6	3.7	32,352
Midlat	163.1	0.5	4.9	15,117
Polar	293.0	-2.0	6.5	19,105

TRMM ADMs

Region	Mean SW Flux ($W\ m^{-2}$)	Bias (%)	RMS (%)	No. FOVs
Tropics	212.5	-0.4	5.9	35,501
Midlat	155.4	-0.3	9.1	16, 914
Polar	312.6	-12.1	17.7	18,692


Clear-Sky Multiangle Consistency [SW Flux(θ=50°-60°) – SW Flux (Nadir)]
1. Evrgrn. Needle For.
2. Evrgm. Broad For.
3. Decid. Needle For.
4. Decid. Broad For.
5. Mixed Forest
6. Closed Shrubs
7. Open Shrubs
8. Woody Savannas
9. Savannas
10. Grassland
11. Wetlands
12. Crops
13. Urban
14. Crop/Mosaic
15. Perm. Snow
16. Barren/Desert
17. Water
18. Tundra
19. Fresh Snow
20. Sea Ice
Terra
TRMM
-15
-10
-5
0
5
10
15
Relative SW Flux Difference (%)
0
5
10
15
20
25
30
Relative RMS Difference (%)


Clear-Sky Ocean SW TOA Flux Consistency
(F(θ=50°-60°) - F(Nadir)
Relative SW TOA Flux Difference (%)
10
9
8
7
6
5
4
3
20
25
30
35
40
45
50
55
60
Glint Angle (°)

All-Sky Instantaneous SW TOA Flux Consistency
(F(θ=50°-60°) – F(Nadir))

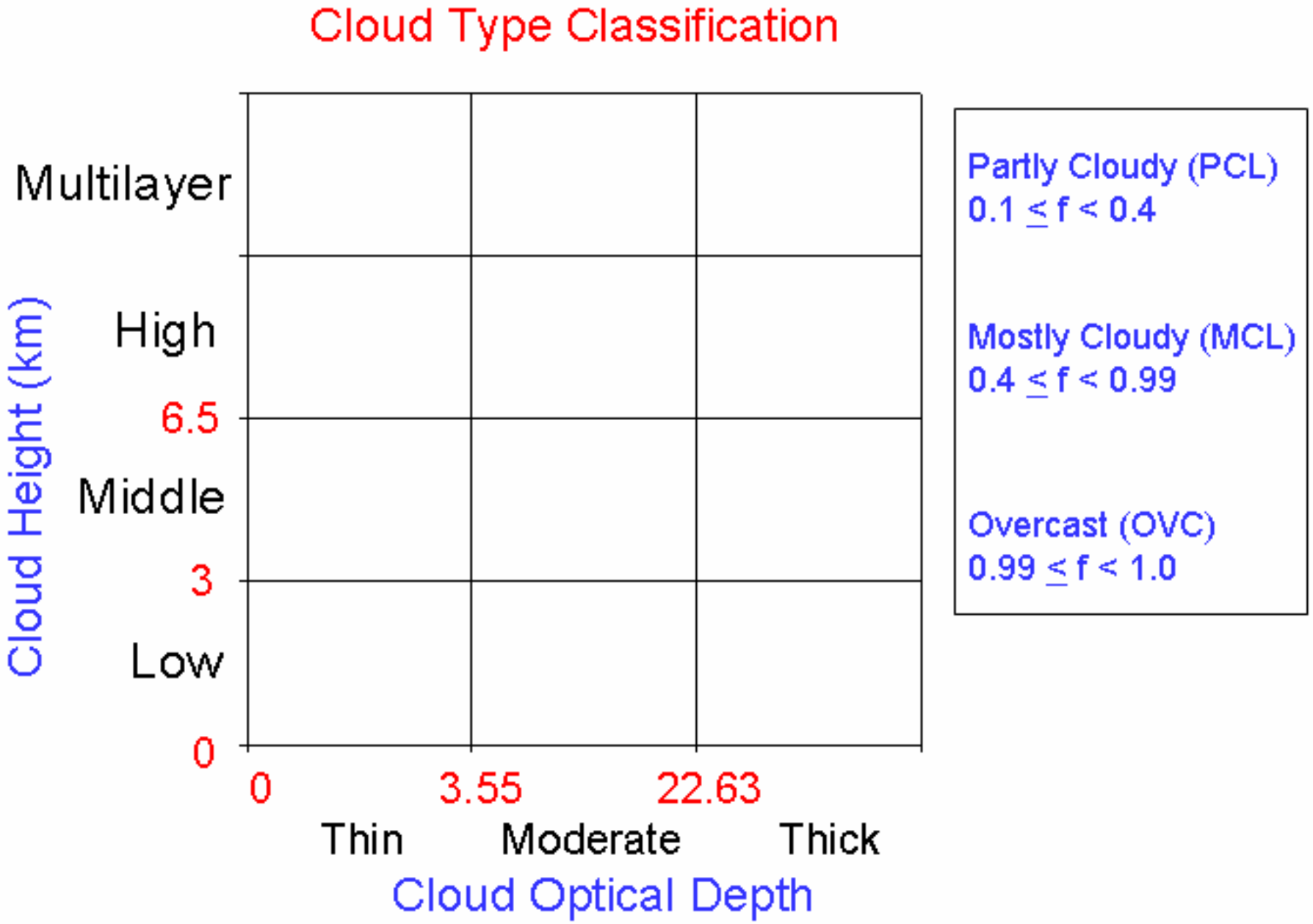
Terra ADMs

Region	Mean SW Flux ($W\ m^{-2}$)	Bias (%)	RMS (%)	No. FOVs
Tropics	282.6	0.8	8.6	202,639
Midlat	347.4	0.7	6.3	394,018
Polar	292.0	-1.9	9.0	172,998

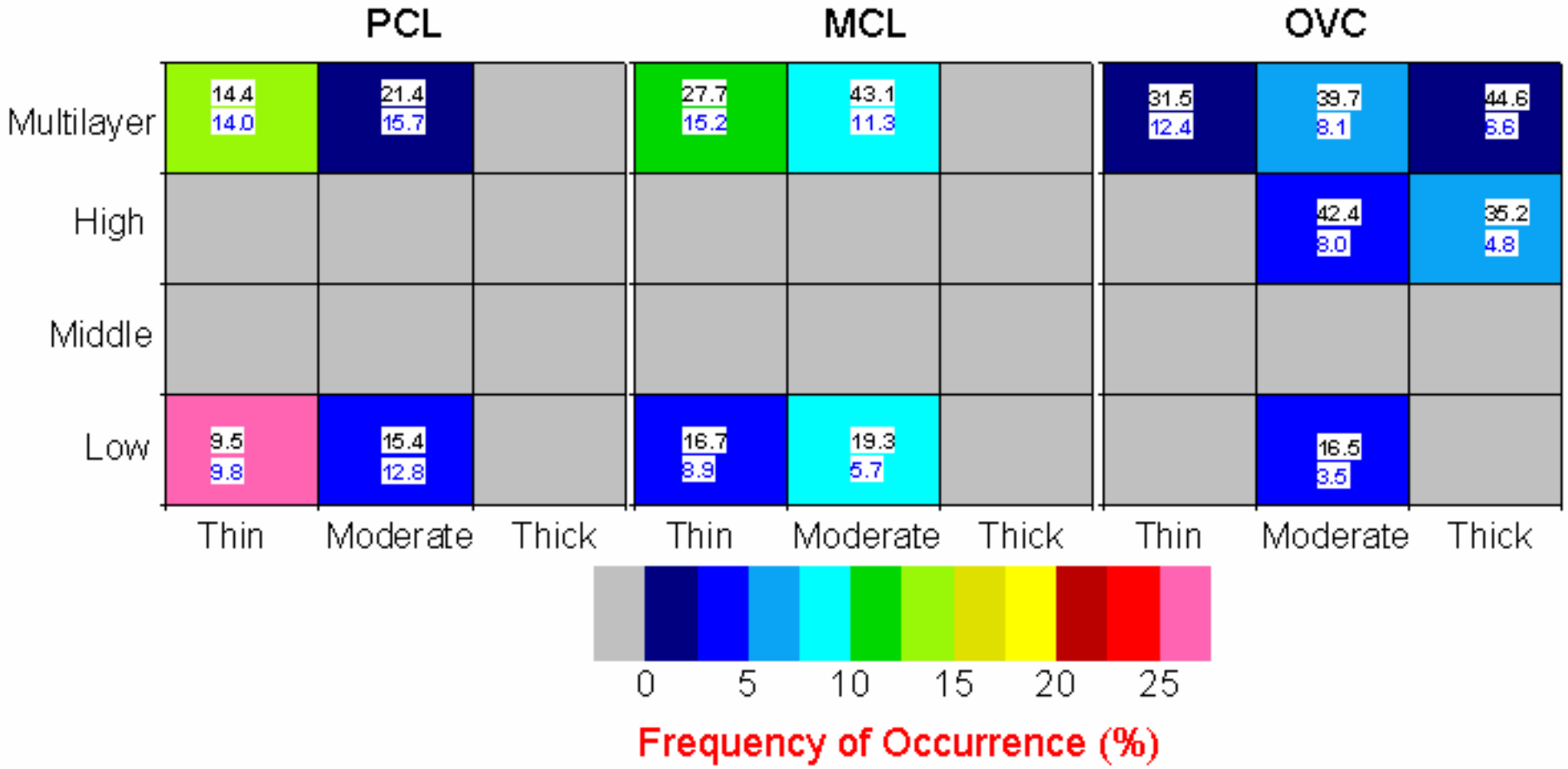
TRMM ADMs

Region	Mean SW Flux ($W\ m^{-2}$)	Bias (%)	RMS (%)	No. FOVs
Tropics	248.8	1.3	10.0	240,414
Midlat	338.3	1.0	6.5	402,846
Polar	298.9	-5.0	14.9	169,418

TOA Flux Consistency By Cloud Type


Cloud Type Classification
Multilayer
High
6.5
Middle
3
Low
0
Cloud Height (km)
0
3.55
22.63
Thin
Moderate
Thick
Cloud Optical Depth
Partly Cloudy (PCL)
0.1 ≤ f < 0.4
Mostly Cloudy (MCL)
0.4 ≤ f < 0.99
Overcast (OVC)
0.99 ≤ f < 1.0

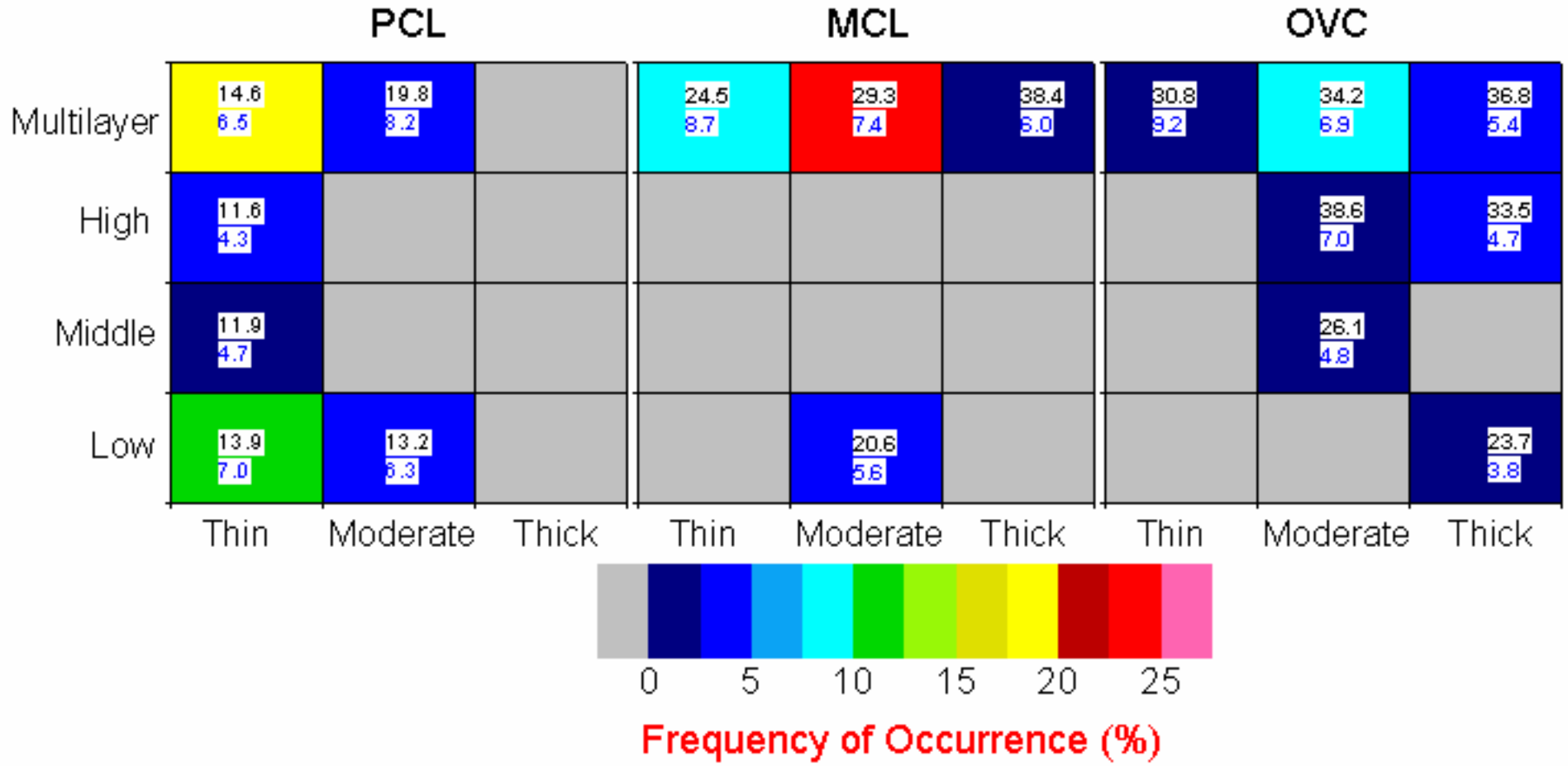
SW TOA Flux Consistency by Cloud Type (Tropical Ocean; S_o=1157 W m^{-2})



Numbers in Black = F(θ=50°)-F(Nadir) RMS Flux Difference (W m^{-2})

Numbers in Blue = F(θ=50°)-F(Nadir) Relative RMS Flux Difference (%)

SW TOA Flux Consistency by Cloud Type (Tropical Land; S_o=1156 W m^{-2})



Numbers in Black = F(θ=50°)-F(Nadir) RMS Flux Difference (W m^{-2})

Numbers in Blue = F(θ=50°)-F(Nadir) Relative RMS Flux Difference (%)

Instantaneous LW TOA Flux Consistency
(F(θ=50°-60°) – F(Nadir))

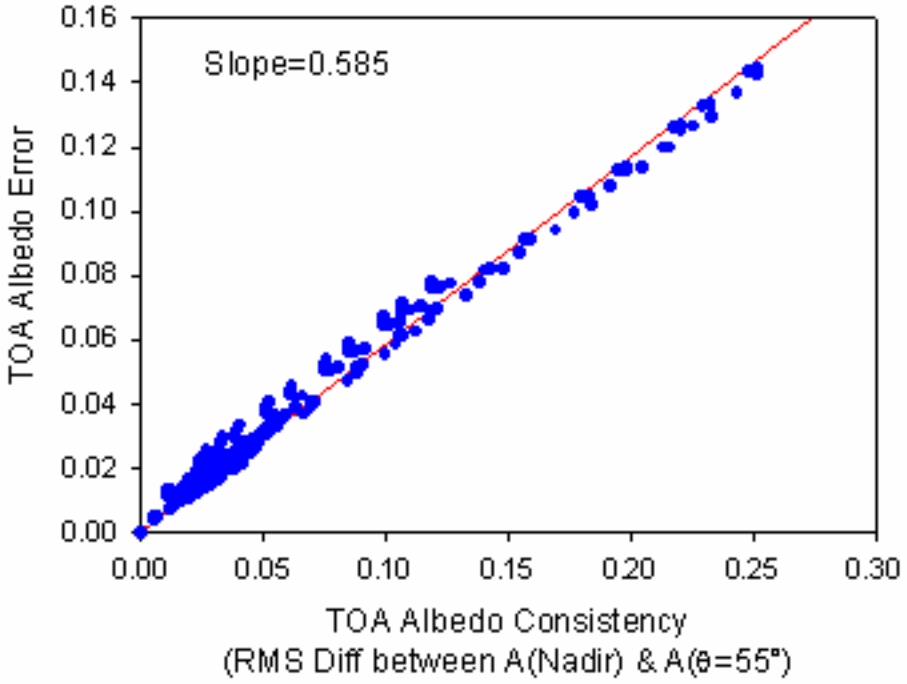
Clear-Sky

Region	Mean SW Flux ($W\ m^{-2}$)	Bias (%)	RMS (%)	No. FOVs
Tropics	307.3	-1.1	1.8	38,830
Midlat	285.5	-0.9	1.7	23,929
Polar	204.1	-0.8	2.7	17,520

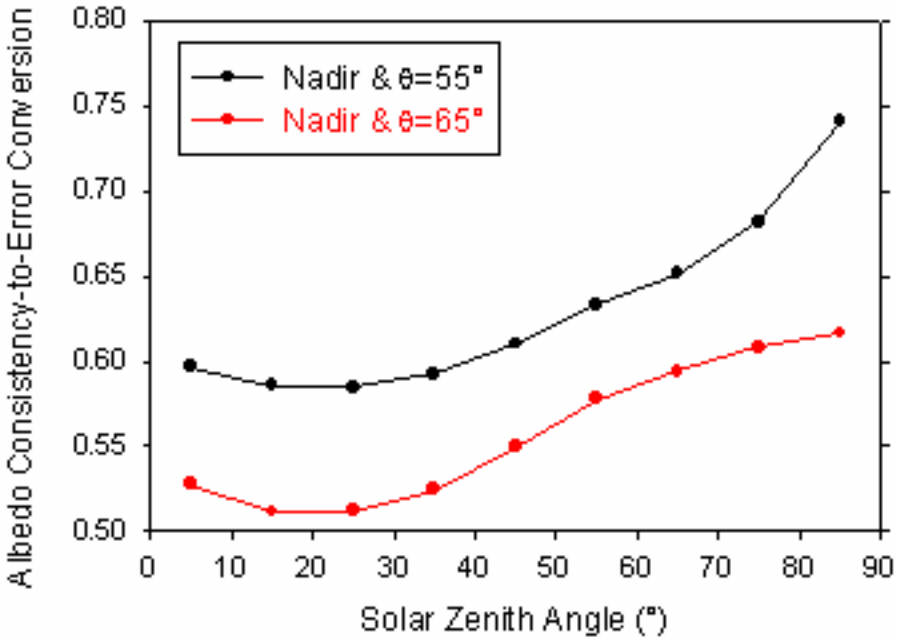
All-Sky

Region	Mean SW Flux ($W\ m^{-2}$)	Bias (%)	RMS (%)	No. FOVs
Tropics	282.2	-0.8	3.0	266,246
Midlat	234.3	-0.9	3.8	340,387
Polar	200.5	-0.6	3.3	147,239

TOA Albedo Error vs Albedo Consistency at Nadir and θ=55°
(3 ADMs Applied to 1D Cloud Popln; θ_0=20°-30°)



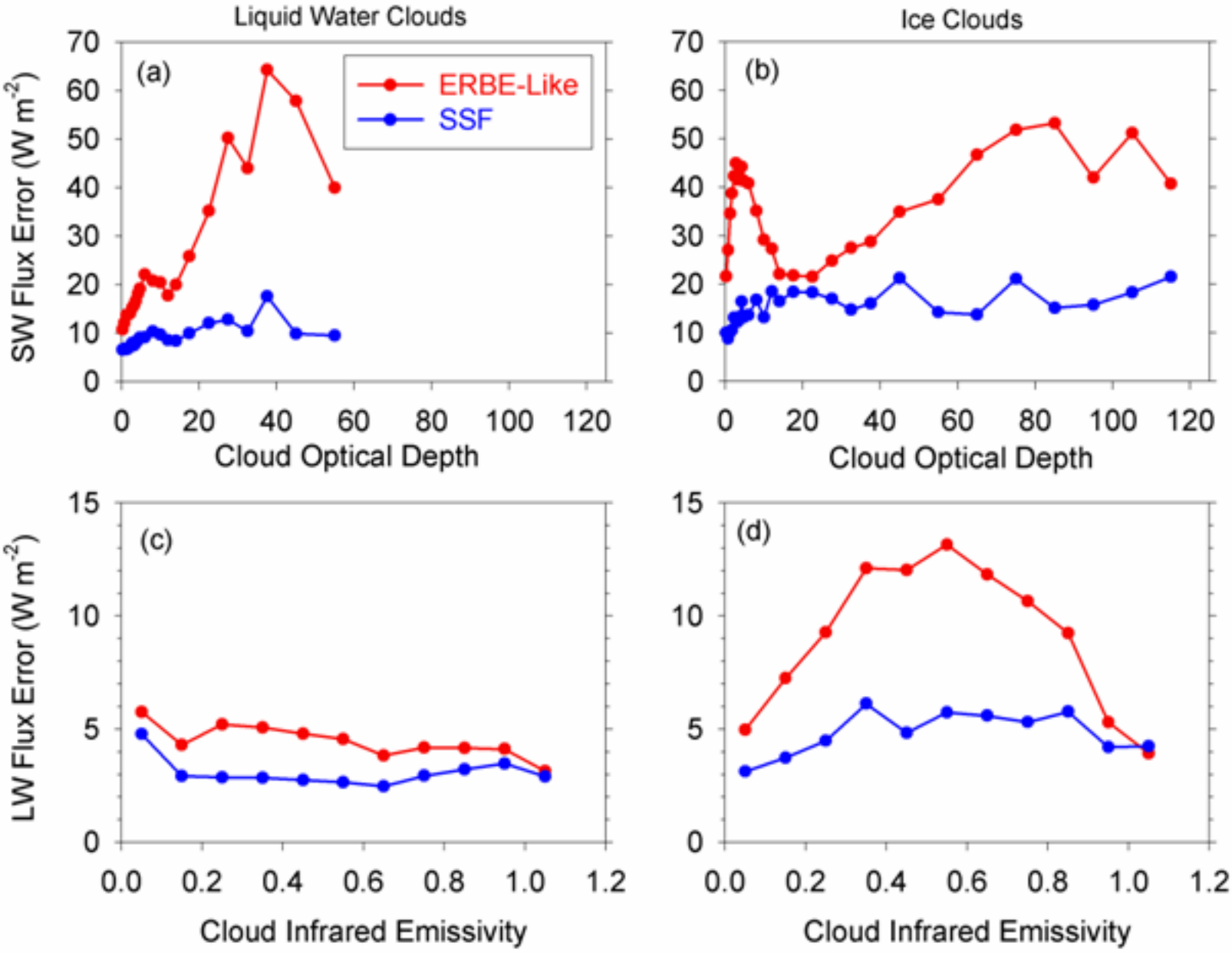
Albedo Consistency-to-Error Conversion vs θ_o



Estimated Instantaneous TOA Flux Error

Region	S_o (W m^{-2})	Terra ADMs W m^{-2} (%)		TRMM ADMs W m^{-2} (%)	
		Clear	All-sky	Clear	All-sky
Tropics	1150	5.2 (2.2)	14.3 (5.1)	7.7 (3.5)	14.3 (5.8)
Midlat	870	4.2 (3.0)	13.5 (3.9)	7.3 (5.6)	13.7 (4.1)
Polar	540	12.8 (4.3)	17.3 (5.9)	37.0 (11.7)	29.2 (9.8)

Instantaneous TOA Flux Error by Cloud Property



Conclusions

- New Terra ADMs show notable improvements in TOA flux accuracy relative to CERES/TRMM ADMs for:
  - Snow and sea-ice (SW and LW)
  - Clear and all-sky land (SW)

- Expect large differences between ES8 and SSF cloud radiative forcing:
  => large increase in SW CRF from SSF (~5 W m^{-2}); modest increase in LW CRF (~2 W m^{-2})

- Differences between ES8 and SSF scene id and ADMs alone do not explain the ~5 W m^{-2} imbalance in global annual net radiation.

- Instantaneous SW TOA flux accuracy best for low-level overcast conditions (< 5%); worst for thin and multi-layer clouds (~10-15%).

- Marked increase in SW TOA flux errors over clear ocean near sunglint.