# Surface Radiation budget from CERES and A-train

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# Outline

- CERES surface irradiance products
- Evaluation of surface irradiance
- Surface irradiance uncertainty
- Surface and atmospheric net irradiance uncertainty
- Thoughts on the discrepancy

# Surface irradiance products produced by the CERES project

- CRS (Level 2)
- SYN1deg-Month (Level 3)
- EBAF-surface (Level 3B)

# SYN1deg-month

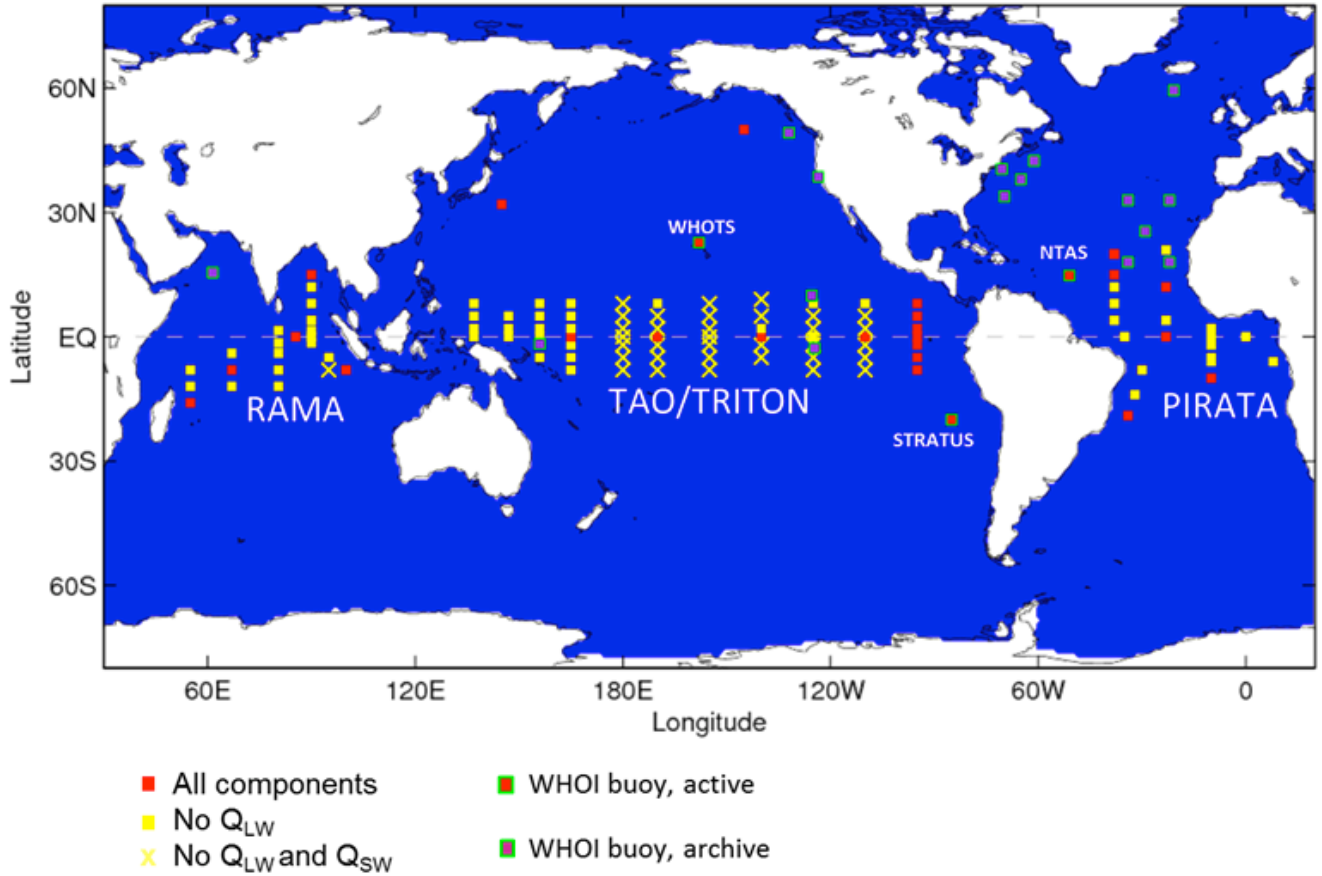
- MODIS derives clouds
- MODIS and MATCH derive aerosols
- GEOS-4 and -5 provide temperature and humidity profiles
- Daily snow and ice map (used in producing SYN)
- Surface albedo map derived from clear-sky CERES scenes

# EBAF-surface

- Surface irradiances produced by constraining TOA irradiance by CERES observations (i.e. computed TOA irradiances agree with CERES-derived irradiances).
- Correction of MODIS and GEO derived cloud properties by CALIPSO and CloudSat derived cloud properties
- Correction of GEOS-4 and 5 temperature and humidity by AIRS derived temperature and humidity profiles (upper troposphere) and by GEOS-5.4.1 (60°N to 60°S boundary layer)

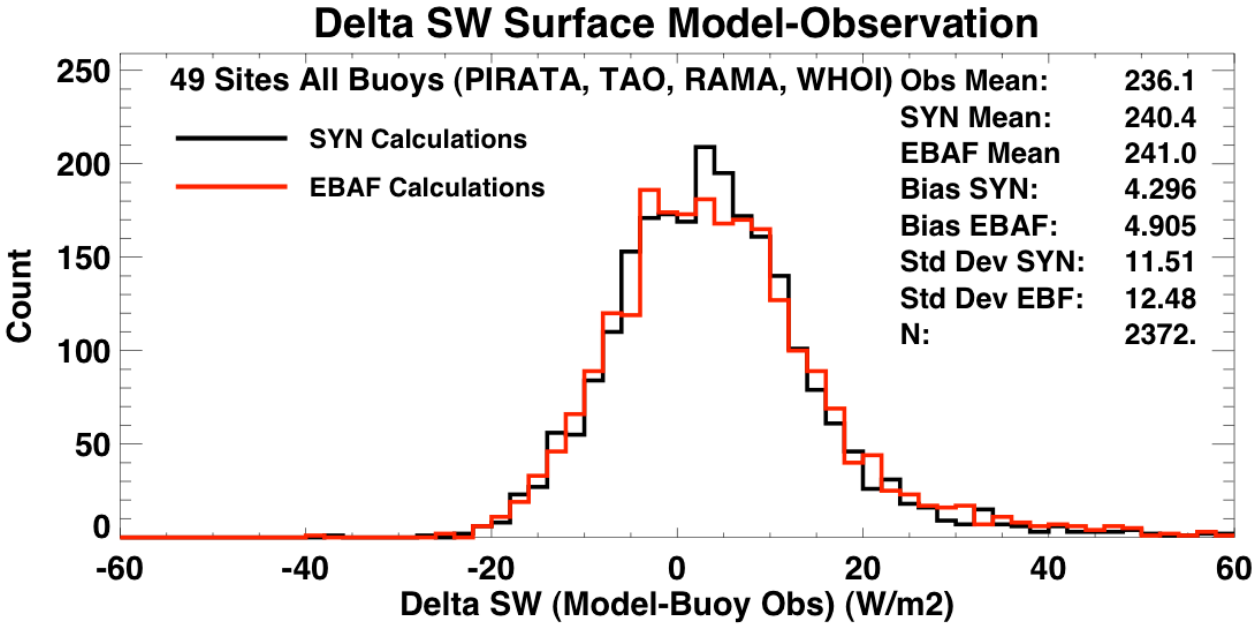
# Evaluation by surface observations

# Evaluation with surface observations (Ocean)



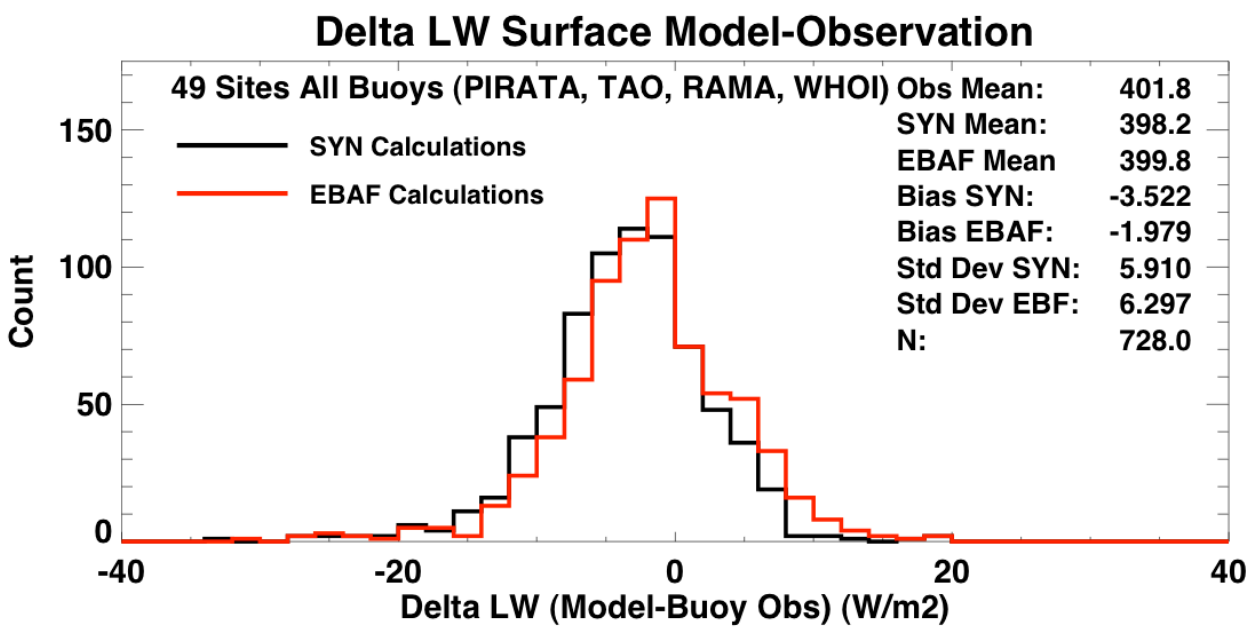

Use 71 buoys for shortwave comparison
Use 23 buoys for longwave comparison

# Evaluation with surface observations (Ocean)




Monthly mean Comparison

Result depends on how bad surface observations are screened




Measurement uncertainty in

Daily or annual mean

Downward shortwave

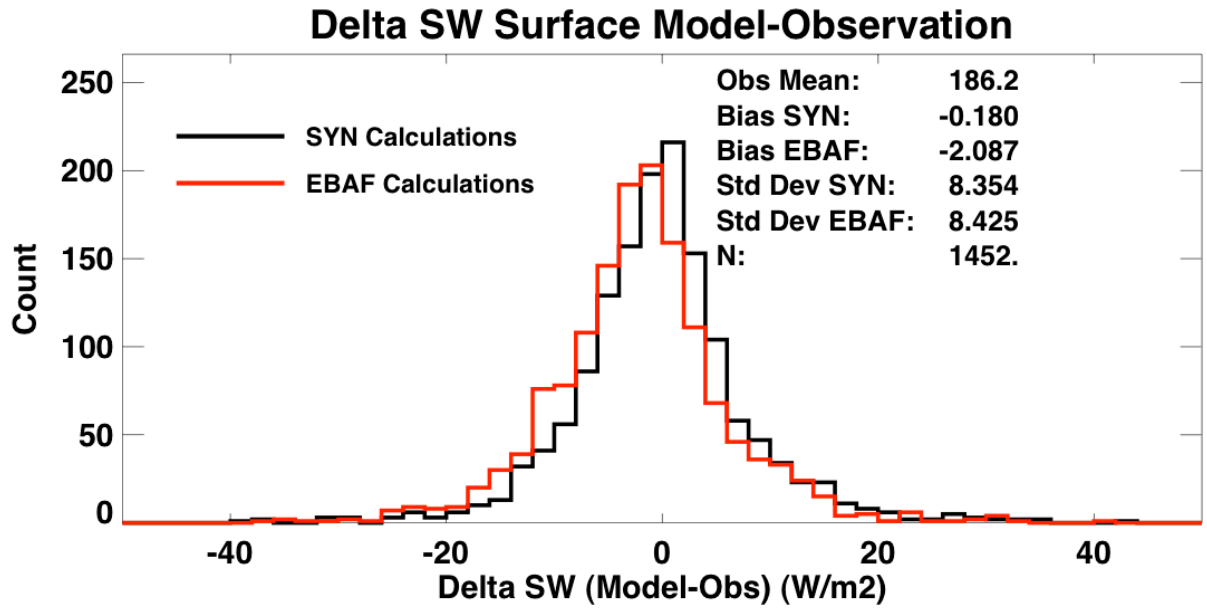
**5 to 6 $Wm^{-2}$**

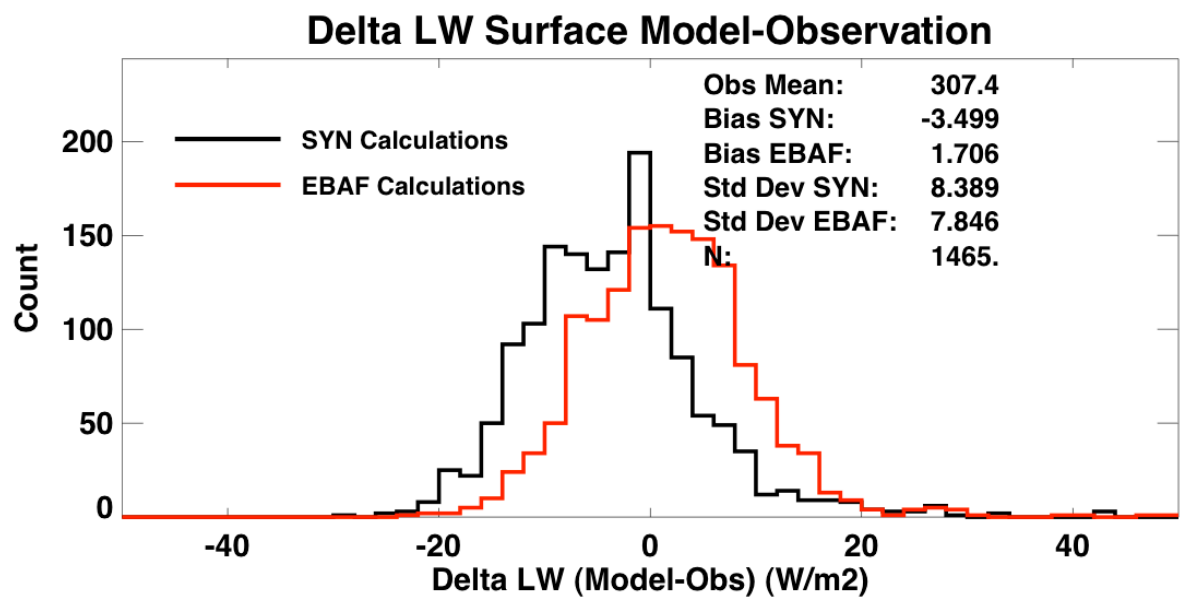
Downward longwave

**4 $Wm^{-2}$**

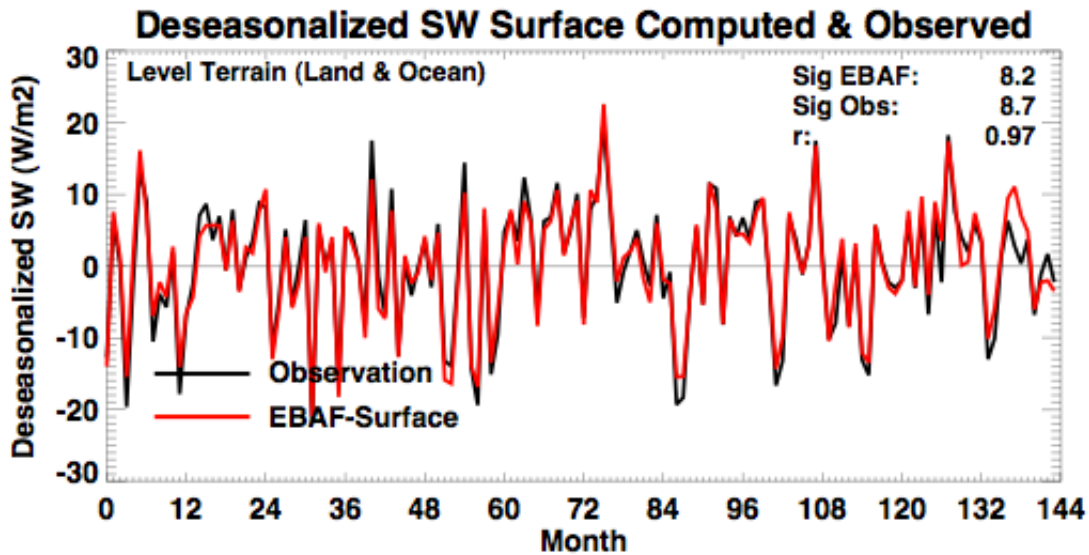
(Colbo and Weller 2009)

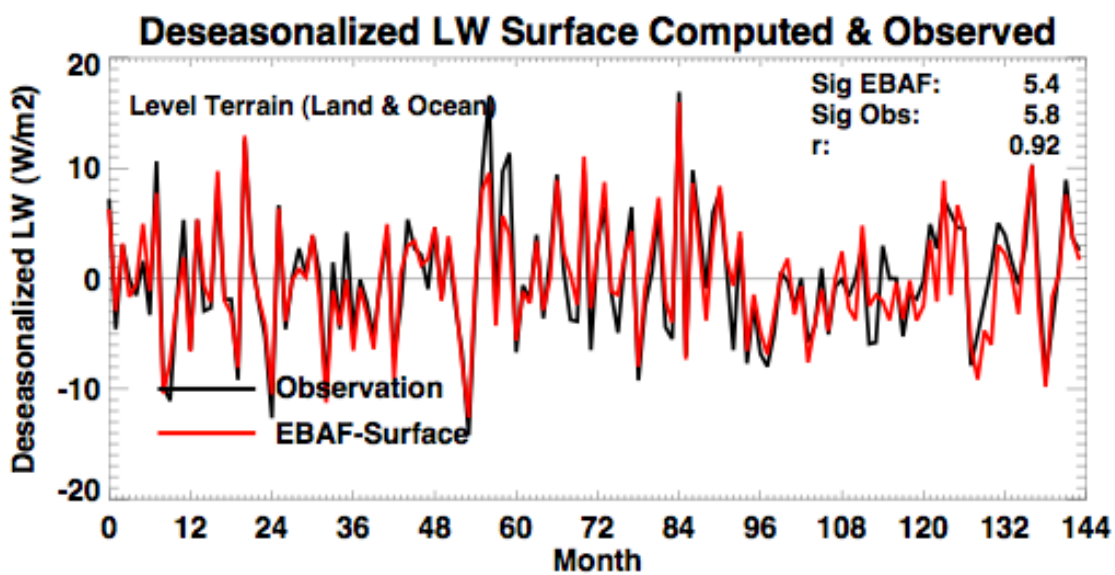
# Evaluation with surface observations (Land)



# Evaluation with surface observations (land and ocean) from March 2000 through Feb. 2012



# Uncertainty

- Temperature and humidity profile
- Cloud properties
- Land surface albedo and emissivity
  - Small uncertainty in ocean albedo and emissivity
- Diurnal cycle
- Aerosols
- 1D model

# Error budget (global annual mean)

TABLE 6. Surface irradiance uncertainty estimate (after Kato et al. 2012).

| | Bias error with known sign | Uncertainty | References |
|---|---|---|---|
| **Surface downward longwave irradiance** | | | |
| Cloud-base height | −3.6* | | Kato et al. (2011a) |
| Temporal interpolation | −2.6 | | Kato et al. (2011a) |
| Surface temperature | | 4.5 | Kato et al. (2011a) |
| Precipitable water | | 5.2 | Zhang et al. (2006), Kato et al. (2011a) |
| Interannual variability | | 0.8 | Kato et al. (2011a) |
| Overall uncertainty | | 6.9 | |
| **Surface upward longwave irradiance** | | | |
| Surface skin temperature | | 3.2 | Kato et al. (2012) |
| Surface emissivity (land only) | | 0.5 | This study |
| Interannual variability | | 0.4 | Kato et al. (2012) |
| Uncertainty due to TOA longwave irradiance | | | |
| Overall uncertainty | | 3.3 | |
| **Surface downward shortwave irradiance** | | | |
| Clouds | | 2.8 | Kato et al. (2012) |
| Aerosol optical thickness** | | 1.7 | Kim and Ramanathan (2008) |
| Aerosol single scattering albedo** | | 1.7 | Kim and Ramanathan (2008) |
| Precipitable water** | | 1.5 | Kim and Ramanathan (2008) |
| Ozone** | | 0.5 | Kim and Ramanathan (2008) |
| Interannual variability | | 0.3 | Kato et al. (2012) |
| Uncertainty due to TOA shortwave irradiance | | | |
| Overall uncertainty | | 4.0 | |
| **Surface upward shortwave irradiance** | | | |
| Albedo | | 3.4 | Kato et al. (2012) |
| Interannual variability | | 0.1 | Kato et al. (2012) |
| Uncertainty due to TOA shortwave irradiance | | | |
| Overall uncertainty | | 3.4 | |

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# Estimated surface irradiance uncertainty

TABLE 5. Summary of uncertainties in the irradiance computed with satellite-derived cloud and aerosol properties in W $m^{-2}$ (after Kato et al. 2012).

| | | | Estimated uncertainty | | | |
|---|---|---|---|---|---|---|
| | | Mean value | Monthly gridded | Monthly zonal | Monthly global | Annual global |
| Downward longwave | Ocean+land | 345 | 14 | 11 | 7 | 7 |
| | Ocean | 354 | 12 | 10 | 7 | 7 |
| | Land | 329 | 17 | 15 | 8 | 7 |
| Upward longwave | Ocean+land | 398 | 15 | 8 | 3 | 3 |
| | Ocean | 402 | 13 | 9 | 5 | 5 |
| | Land | 394 | 19 | 15 | 5 | 4 |
| Downward shortwave | Ocean+land | 192 | 11 | 10 | 6 | 5 |
| | Ocean | 190 | 11 | 10 | 6 | 5 |
| | Land | 203 | 12 | 10 | 7 | 5 |
| Upward shortwave | Ocean+land | 23 | 11 | 3 | 3 | 3 |
| | Ocean | 12 | 11 | 3 | 3 | 3 |
| | Land | 53 | 12 | 8 | 6 | 6 |

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Monthly mean RMS difference between computed and observed irradiance (less than or equal to monthly gridded uncertainty)

| | Ocean | Land |
|---|---|---|
| LW down RMS | 6.0 | 8.3 |
| SW down RMS | 10.9 | 8.9 |

# Comparison with other estimates (shortwave)

| | SW down | SW up | SW NET | TOA insolation | transmittance | Surface absorptance |
|---|---|---|---|---|---|---|
| Gupta et al. (1999) | 185 | 24 | 161 | 341 | 0.542 (184) | 0.472 (160) |
| Zhang et al. (2004) | 189 | 24 | 165 | 342 | 0.553 (189) | 0.483 (164) |
| Hatzianastassiou et al. (2005) | 172 | 23 | 149 | 342 | 0.503 (172) | 0.436 (148) |
| Kim and Ramanathan (2008) | | | 164 | 348 | | 0.471 (160) |
| L'Ecuyer et al. (2008) | 218 | 25 | 193 | 352 | 0.619 (211) | 0.548 (186) |
| Wang and Pinker (2009) | 184 | | 168 | 342 | 0.539 (184) | 0.492 (167) |
| Kato et al. (2011) | 192 | 23 | 169 | 341 | 0.563 (192) | 0.495 (168) |
| EBAF-surface 2.7 | 187 | 24 | 163 | 340 | 0.549 (187) | 0.478 (163) |

6 out of 8 downward surface irradiance estimates are within 4 $Wm^{-2}$
6 out of 8 absorbed surface irradiance estimates are within ±4.5 $Wm^{-2}$
Using solar constant of 340 Wm-2

# Comparison with other estimates (longwave)

TABLE 1. All-sky and clear-sky global, annual mean downward longwave fluxes in W m$^{-2}$. Uncertainties given as ± are determined from surface measurement validation (for surface radiation budget SRB) and from global average sensitivity studies. Asterisks indicate an incomplete estimate of error that accounts only for instrument error.

| | All sky | | | Clear sky | | |
|---|---|---|---|---|---|---|
| | LW up | LW down | LW net | LW up | LW down | LW net |
| Trenberth et al (2009), 2000–2004 | 396 | 333 | −63 | | | |
| Wild et al. 1998 | 397 | 345±>5* | −52 | 397 | 321.5±5 | −75.5 |
| Reanalysis | | | | | | |
| NRA | | | | | | |
| ERBE period (1985–1989) | 395.5 | 334.1 | −61.4 | | 312.7 | −84.7 |
| CERES period (2000–04) | 396.9 | 336.5 | −60.4 | | | |
| ERA-40 | | | | | | |
| ERBE | 394.2 | 340.2 | −54.2 | | 314.1 | −82.1 |
| JRA | | | | | | |
| ERBE | 395.6 | 324.3 | −71.3 | | | |
| CERES | 396.9 | 324.1 | −72.8 | | | |
| GEWEX SRB | | | | | | |
| January 1984–December 2007) | | | | | | |
| Primary | 396.5 | 343.9±11 | −52.6 | 395.9 | 310.4±11 | −85.5 |
| QC | 398.7 | 347.5±13 | −51.2 | | 313.2±13 | −85.5 |
| ERBE | | | | | | |
| February 1985–April 1989) | | | | | | |
| Primary | 395.9 | 343.7±11 | −52.2 | 395.4 | 309.2 | −86.2 |
| QC | 398.0 | 347.5±13 | −50.4 | | 312.0 | −85.9 |
| CERES | | | | | | |
| March 2000–May 2004) | | | | | | |
| Primary | 397.2 | 343.7±11 | −53.5 | 396.7 | 310.7 | −86.0 |
| QC | 399.1 | 346.7±13 | −52.3 | | 313.3 | −85.8 |
| ISCCP–FD 1985–1989 | 395.6 | 344.7±10/15 | −50.9 | 394.1 | 313.5±10/15 | −80.6 |
| CERES (Ed2 AVG) 2000–05 | 398.0 | 342.0 | −56.0 | 397.3 | 315.2 | −82.1 |
| A-Train | | | | | | |
| 2006–09 | | | | | | |
| Radar (only) | 398 | 334 | −64 | | | |
| Radar + lidar (*H*) | 398±9 | 350±9 | −48±9 | | 326 | −72 |
| Radar + lidar [CERES, CALIPSO, *CloudSat*, and MODIS (CCCM)] | 398±5 | 347.2±7 | −51±9 | 396 | 313 | −83 |

Satellite based LW down estimates are all within ±3 Wm$^{-2}$

Satellite based NET estimates are within within ±2.5 Wm$^{-2}$ (excluding radar only)

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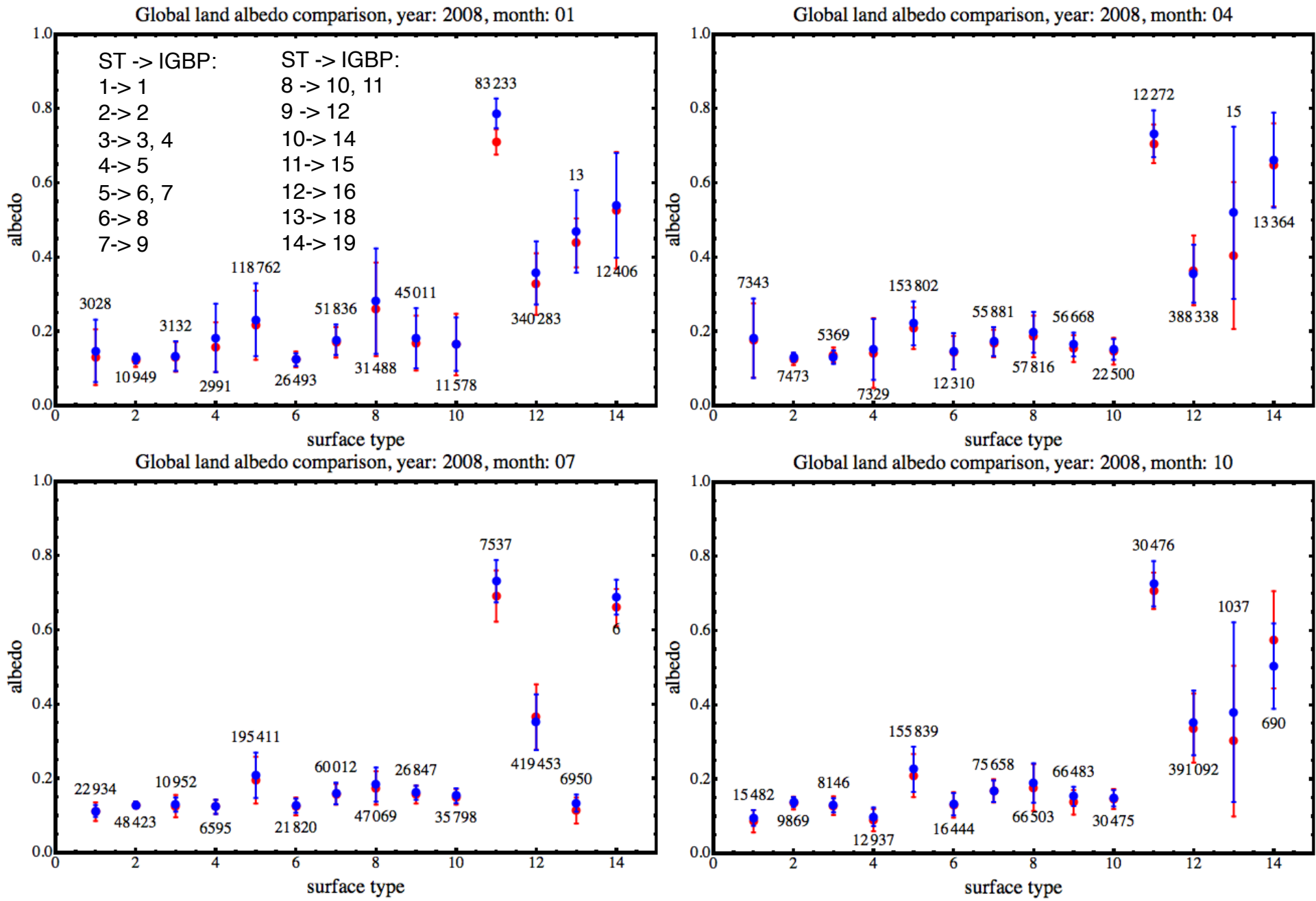
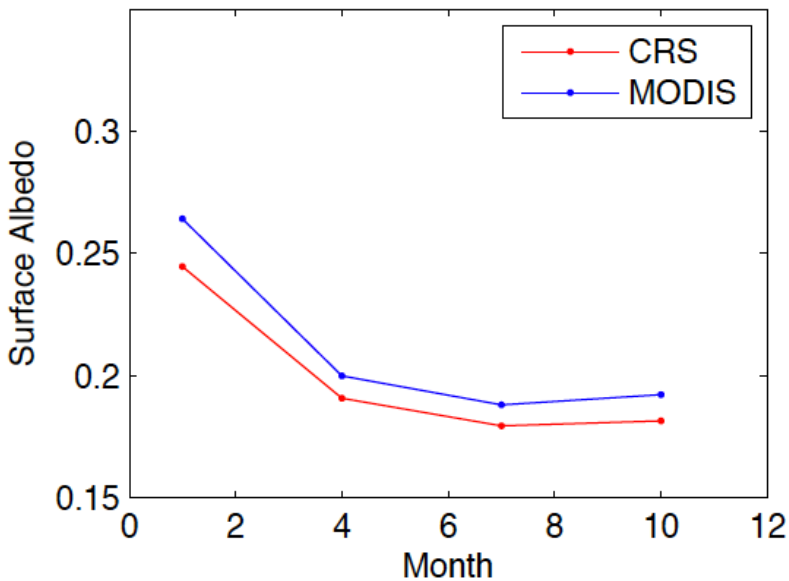
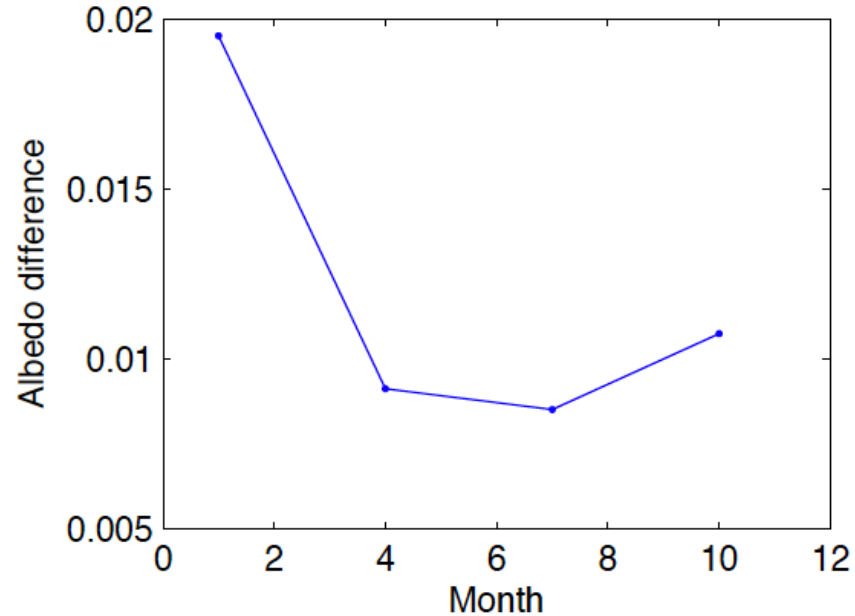
# Land surface albedo and surface emissivity

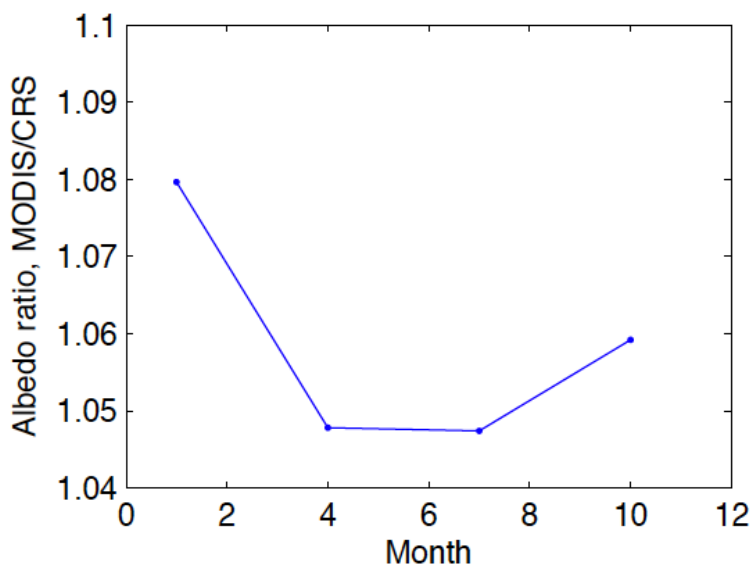
# CERES vs MODIS albedo comparison



# Land surface albedo uncertainty




Δalbedo Fsw_dn = 0.012 × 203
= 2.4 $Wm^{-2}$

Estimated annual global uncertainty of SW up over land: 6 $Wm^{-2}$

# Surface emissivity

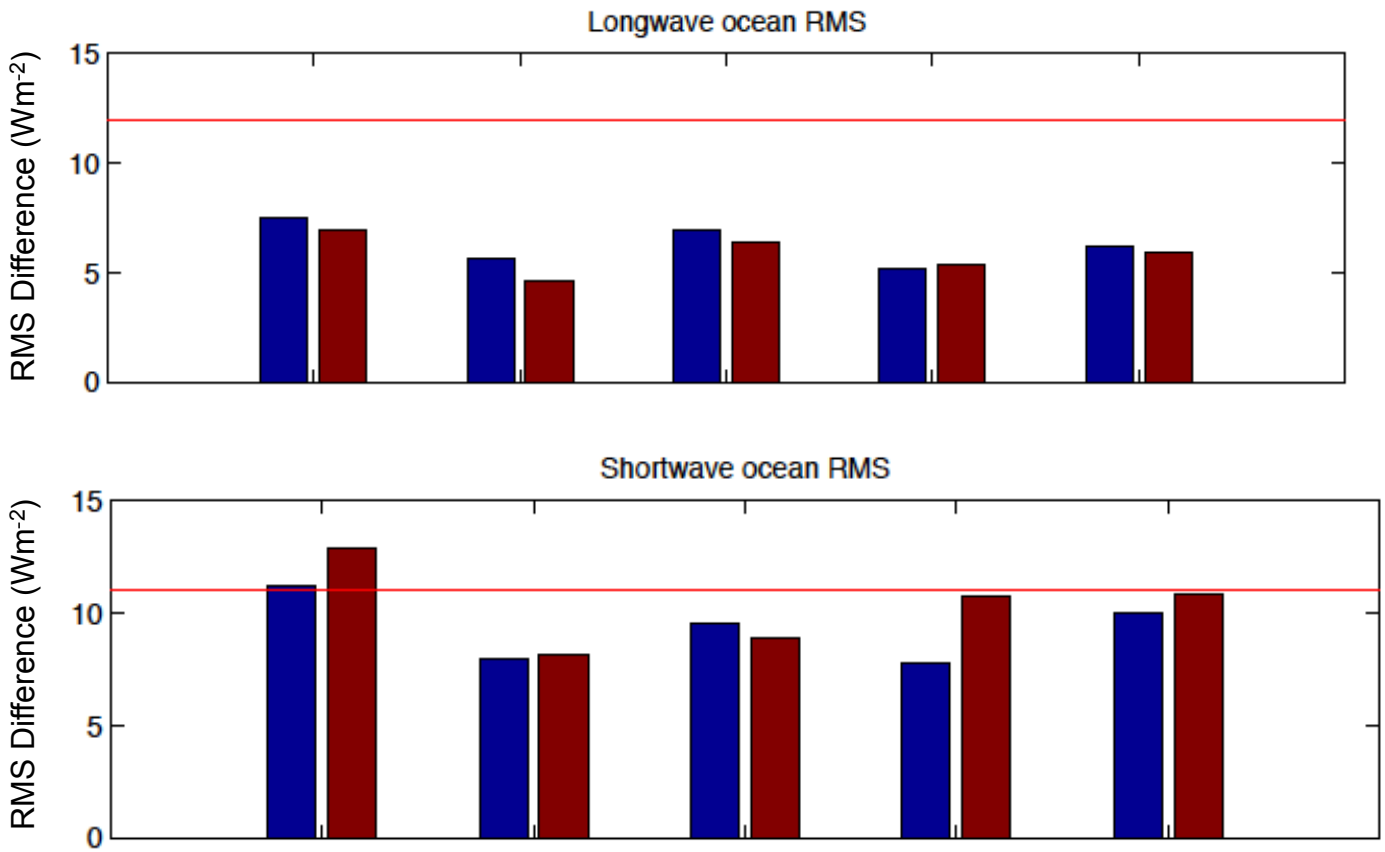
- A 1% surface emissivity perturbation changes the surface upward longwave irradiance by approximately 0.5 $Wm^{-2}$ when the surface temperature is 294K.
- Land surface emissivity uncertainty of 3% based on the difference of two data sets given by Zhang et al. (2006) [ISCCP-FD and Wilber et al. 1999]
- We estimate the global annual mean uncertainty of 0.5 $Wm^{-2}$ (1.5 $Wm^{-2}$ times 0.3, 30% global land cover) due to the surface emissivity uncertainty
- Ocean surface emissivity depends on wind speed and temperature. The range of the emissivity change caused by a realistic range of wind speed (Wu and Smith 1997; Hanafin and Minnett 2005) and temperature (Newman et al. 2005) is, however, well less than 1%.

# Aerosols radiative effects

| | | SYN (Su et al. JGR Jan 2013 Table 2 &3) | Kim and Ramanathan (2008) | CCCM (CALIPSO + CloudSat + MODIS) |
|---|---|---|---|---|
| Clear-sky | TOA ($Wm^{-2}$) | -5.8 | -5.9 | -3.3 |
| | ATM ($Wm^{-2}$) | 3.4 | 4.8 | |
| | SFC ($Wm^{-2}$) | -9.1 | -10.7 | |
| All-sky | TOA ($Wm^{-2}$) | -3.1 | -3.0 | -2.3 |
| | ATM ($Wm^{-2}$) | 3.3 | 4.4 | |
| | SFC ($Wm^{-2}$) | -6.3 | -7.4 | |

- Aerosol radiative effects have large uncertainty but the contribution to global mean radiation budget is small.
- Small particles can absorb more but high concentrations of small particles do not exist for very long time

# RMS compared with buoy observations




Atlantic Ocean 17 sites

Indian Ocean 10 sites

Pacific Ocean 19 sites

Woods Hole Buoys 3 sites

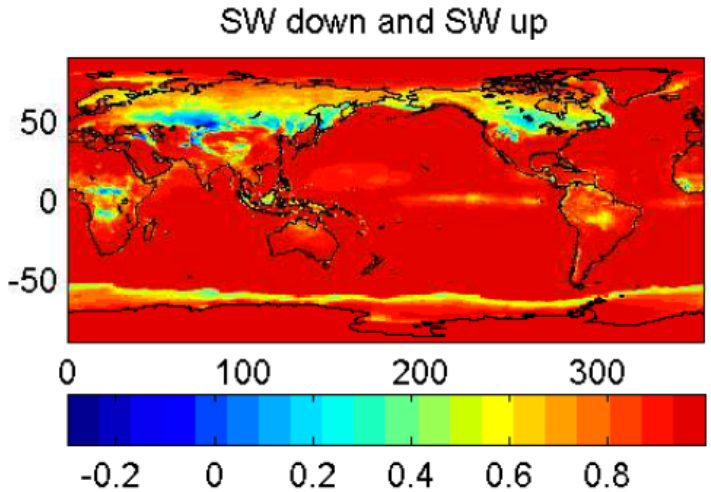
All 49 sites

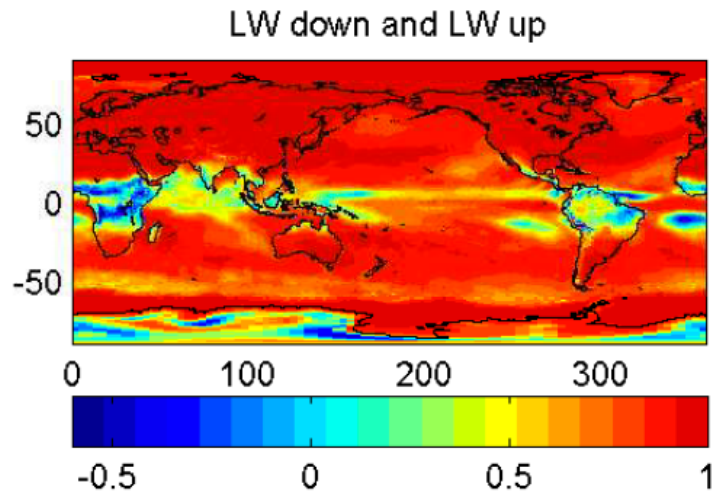
Red: SYN

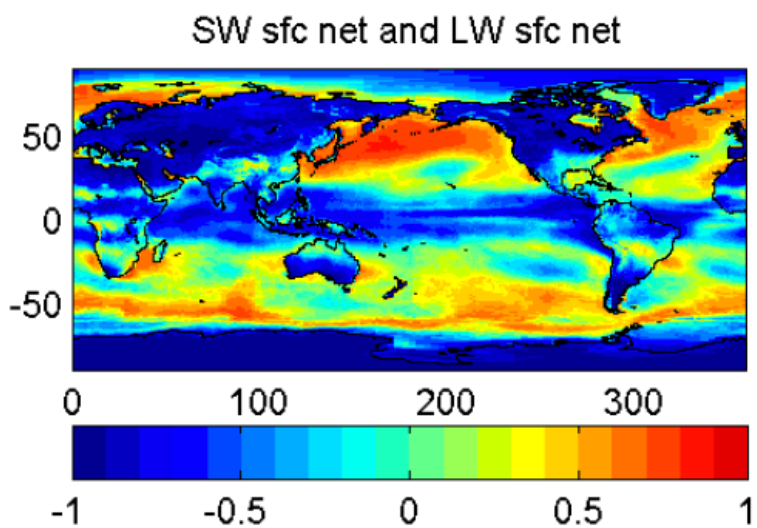
Blue: EBAF-surface

Red line: Monthly mean gridded uncertainty

# Uncertainty estimate of surface and atmospheric net irradiance




$$\sigma^2 = \sigma_x^2 + \sigma_y^2 + 2r_{xy}\sigma_x\sigma_y$$

x = up, y = down
x = SW net, y = LW net

# Surface and atmospheric net irradiance uncertainty (1σ)

| | | Mean value ($Wm^{-2}$) | Monthly gridded ($Wm^{-2}$) | Monthly zonal ($Wm^{-2}$) | Monthly global ($Wm^{-2}$) | Annual global ($Wm^{-2}$) |
|---|---|---|---|---|---|---|
| Surface LW net | Ocean+land | -53 | 27 | 18 | 9 | 9 |
| | Ocean | -48 | 23 | 18 | 11 | 10 |
| | land | -65 | 34 | 28 | 13 | 9 |
| Surface SW net | Ocean+land | 169 | 21 | 13 | 9 | 6 |
| | Ocean | 178 | 21 | 13 | 9 | 6 |
| | land | 150 | 24 | 28 | 12 | 10 |
| Surface SW +LW net | Ocean+land | 116 | 32 | 20 | 6 | 9 |
| | Ocean | 130 | 28 | 20 | 8 | 11 |
| | land | 85 | 41 | 33 | 4 | 15 |
| ATM SW +LW net | Ocean+land | -116 | 36 | 24 | 10 | 10 |
| | Ocean | -119 | 32 | 24 | 12 | 11 |
| | land | -103 | 45 | 37 | 8 | 19 |

# Temperature and humdity

Simple model for clear sky downward longwave irradiance
Dilley and O' Brien (1998), Stephens et al. (2012)

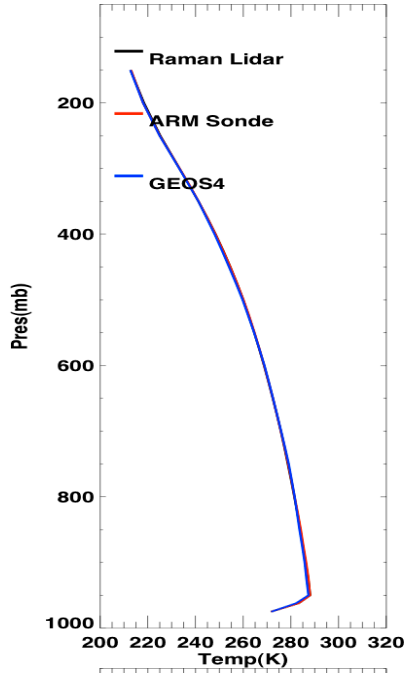
$$\Delta \mathrm{DLR} = 6\beta\left(\frac{T}{T_*}\right)^5 \frac{\Delta T}{T_*} + \frac{1}{2}\gamma\left(\frac{w}{w_*}\right)^{-1/2} \frac{\Delta w}{w_*}. \qquad (2)$$

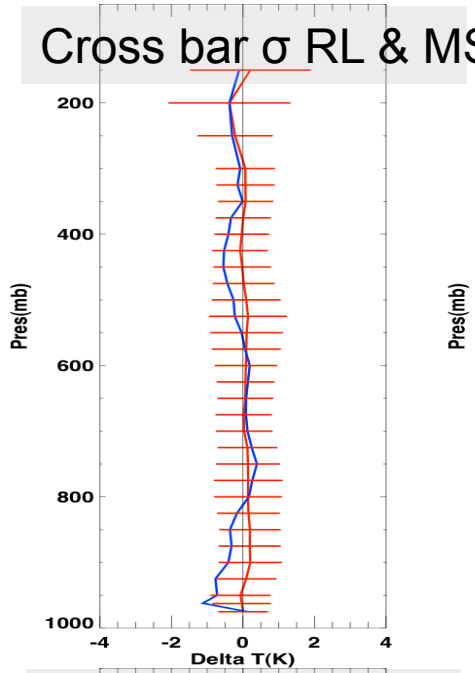
$$\Delta DLR \approx x\Delta T + y\Delta w$$

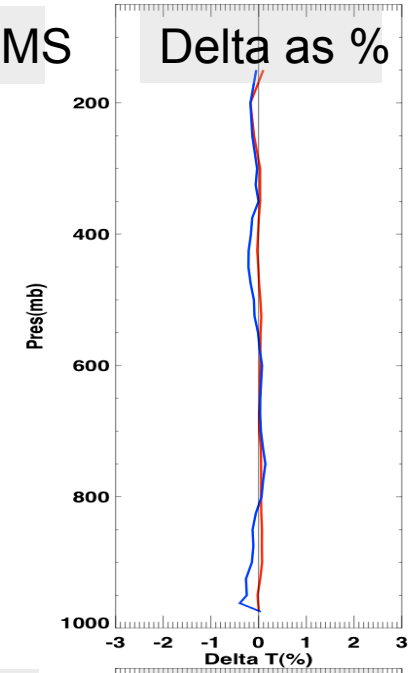
Monthly gridded downward longwave uncertainty over land
17 $Wm^{-2}$

# Temperature Comparison (°K)

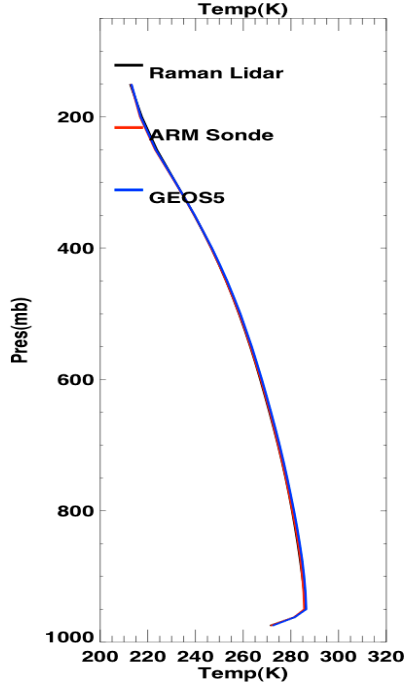
**GEOS 4**

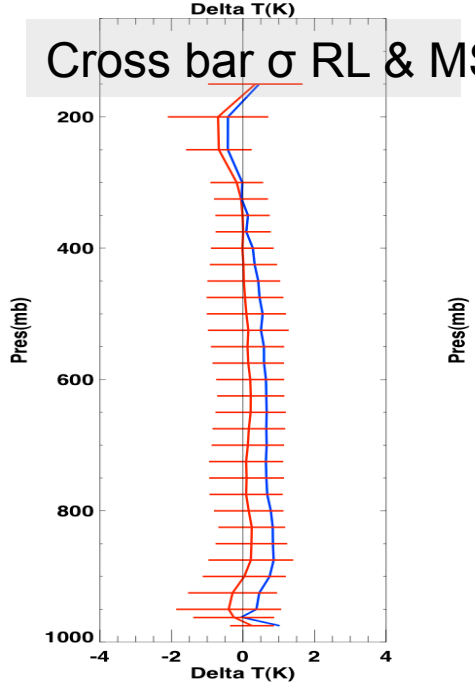


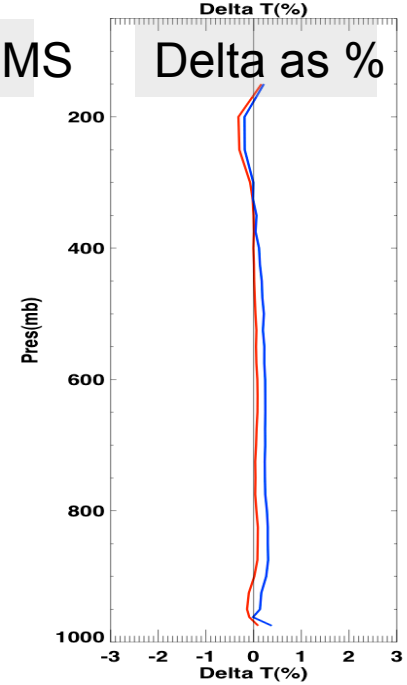




**GEOS 5**

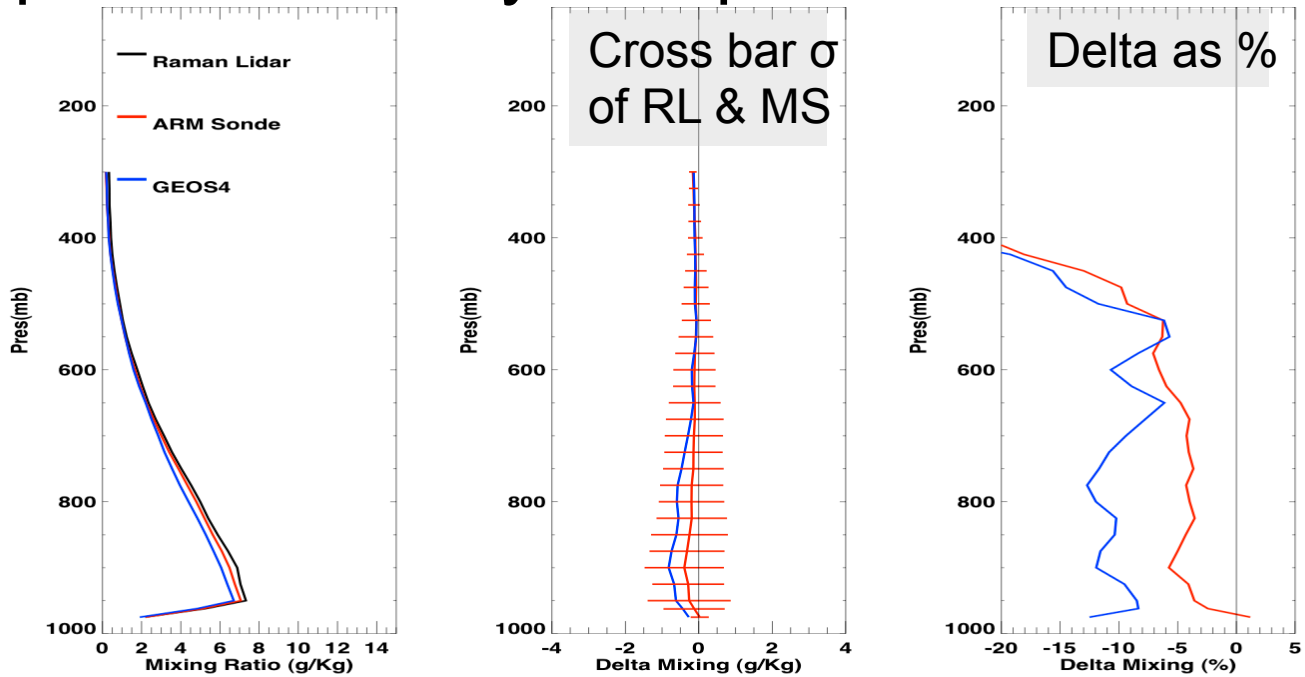


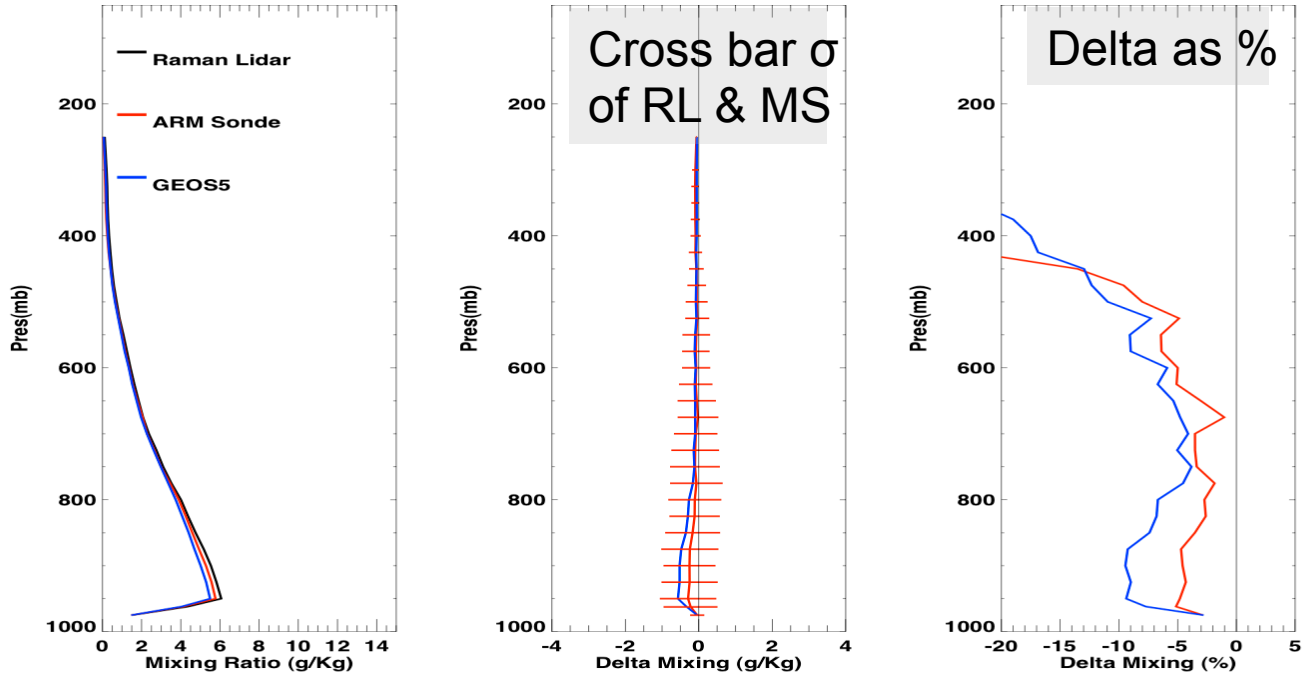



# Specific Humidity Comparison Difference

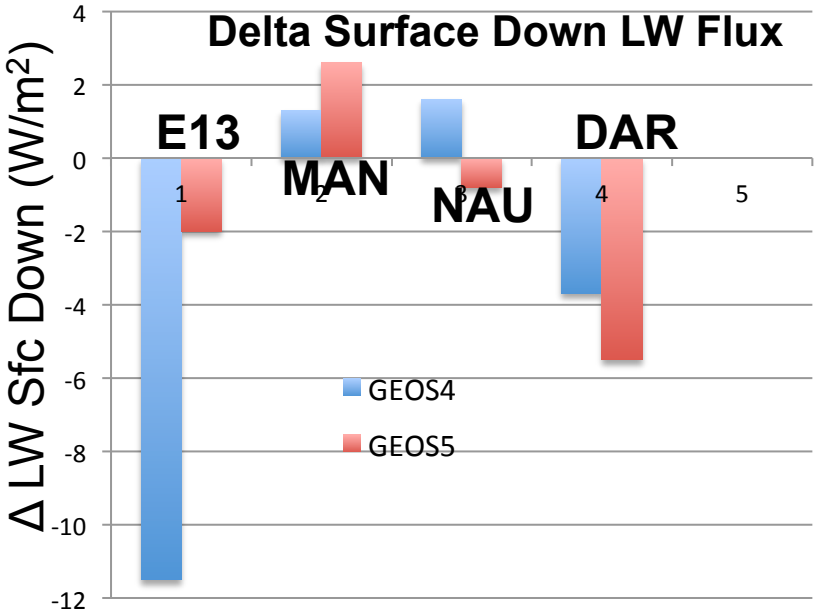
**GEOS 4**

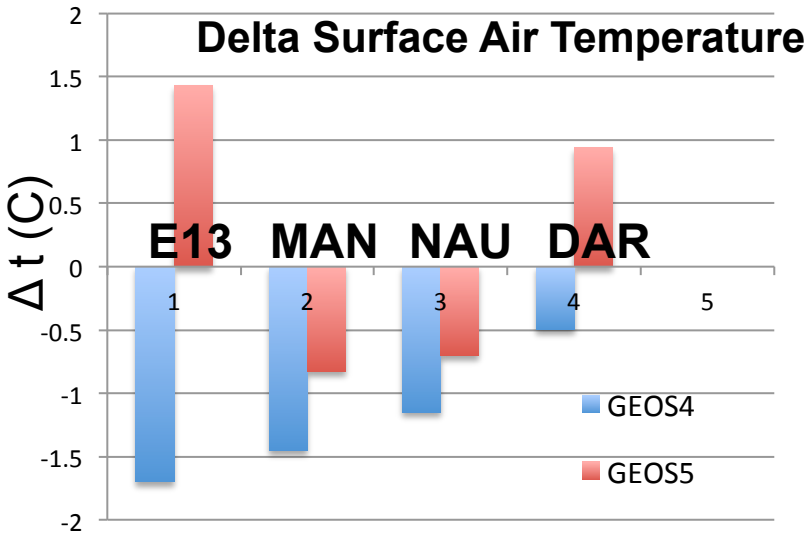


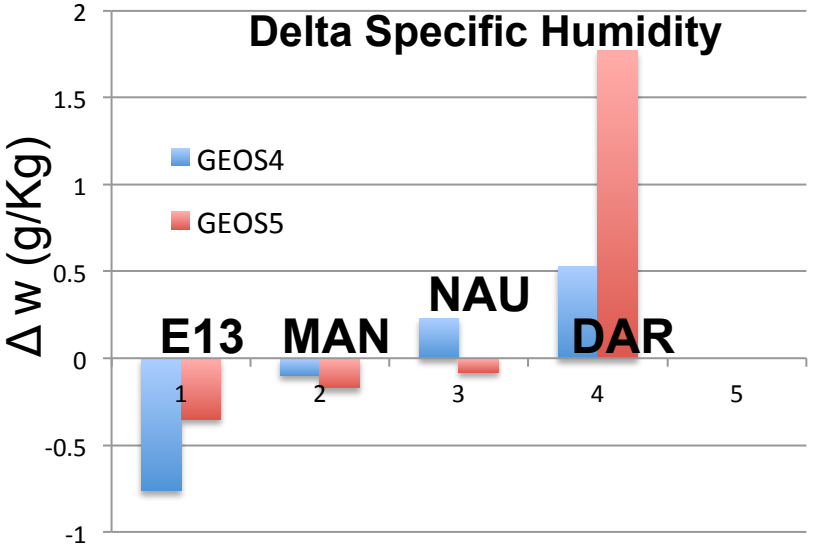

**GEOS 5**



# Clear Sky - Mean Difference in Surface Air Temperature, Specific Humidity & Surface Flux (Model-Obs) GEOS 4 & GEOS 5

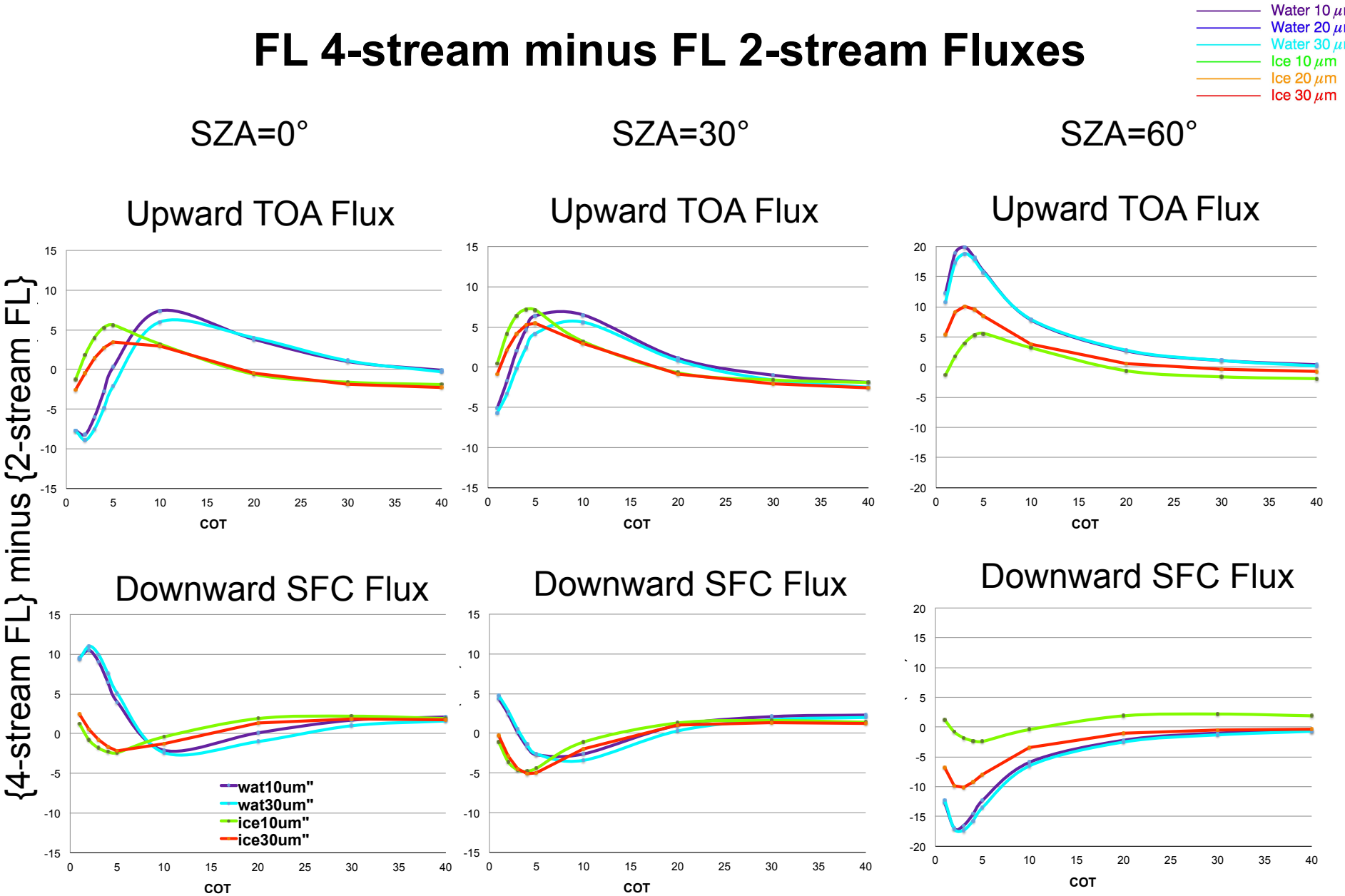


# 1D model

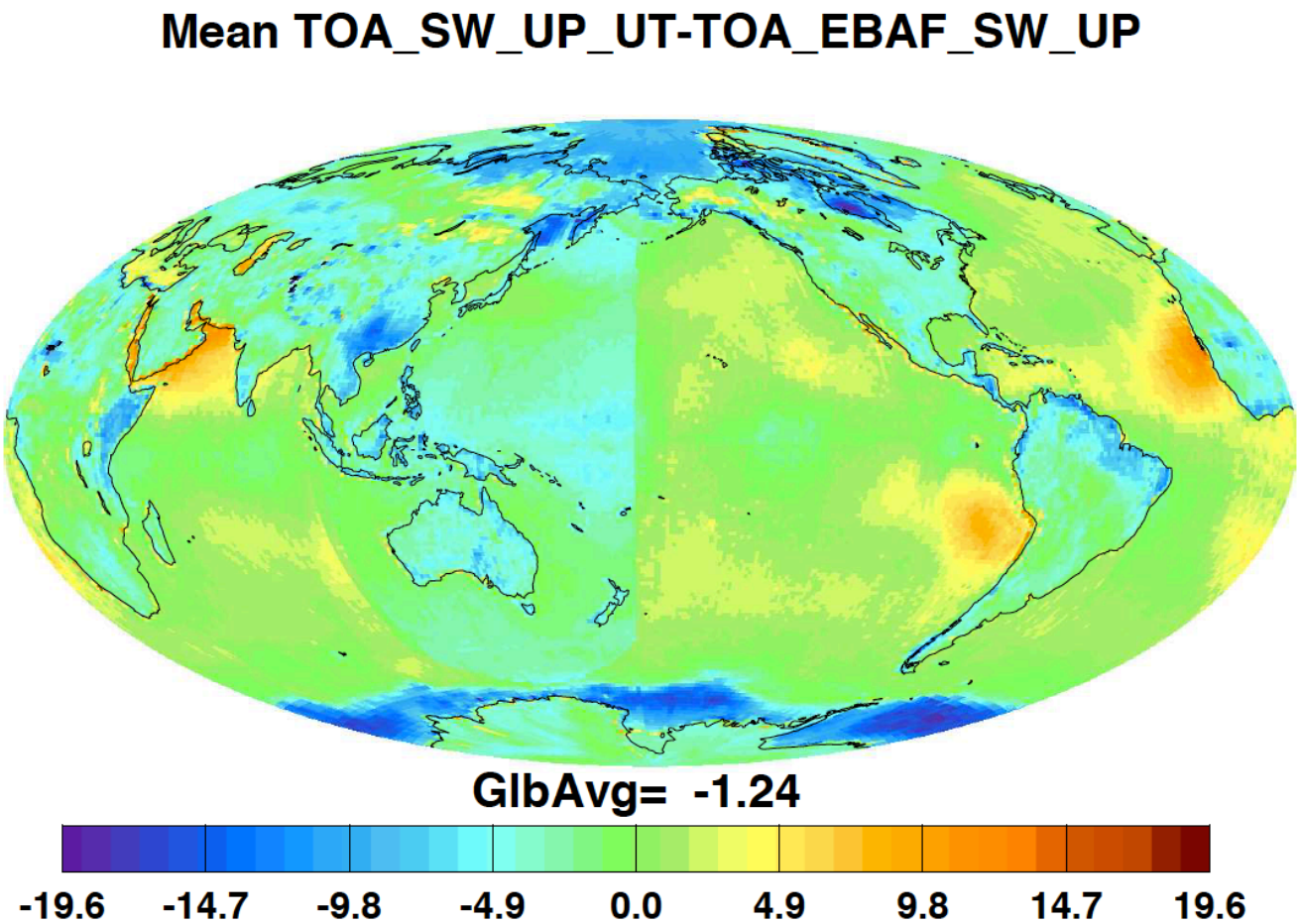
# FL 4-stream minus FL 2-stream Fluxes




Difference = {4-stream Fu-Liou} minus {2-stream Fu-Liou}

2-stream model has smaller TOA and larger surface irradiances

Units: $Wm^{-2}$



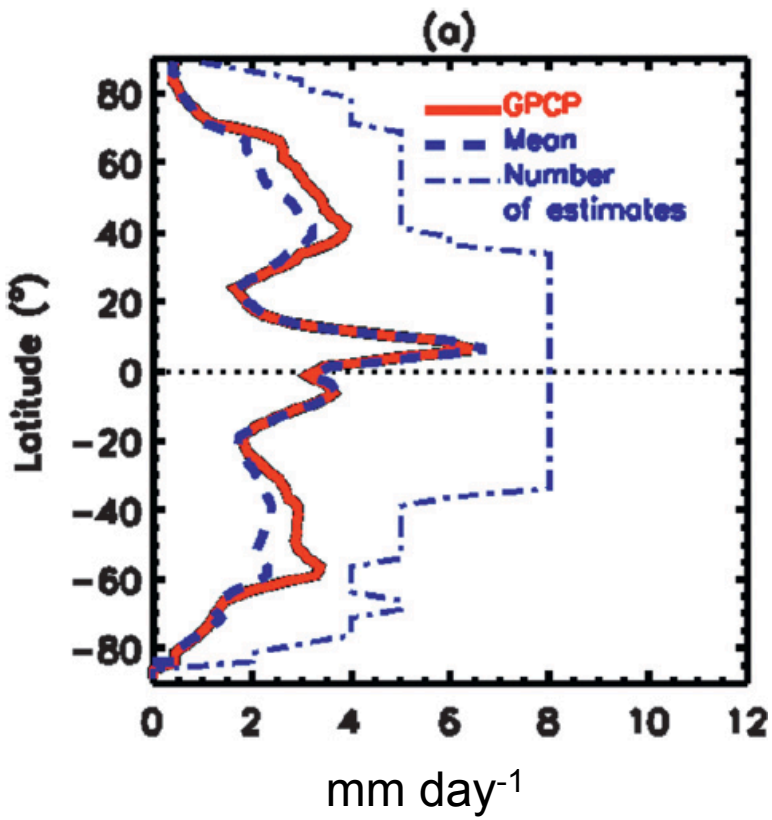

A 2-stream model tends to underestimate the reflected TOA shortwave irradiance compared to a model with higher streams especially for water clouds but there is no Indication that it is causing a large bias

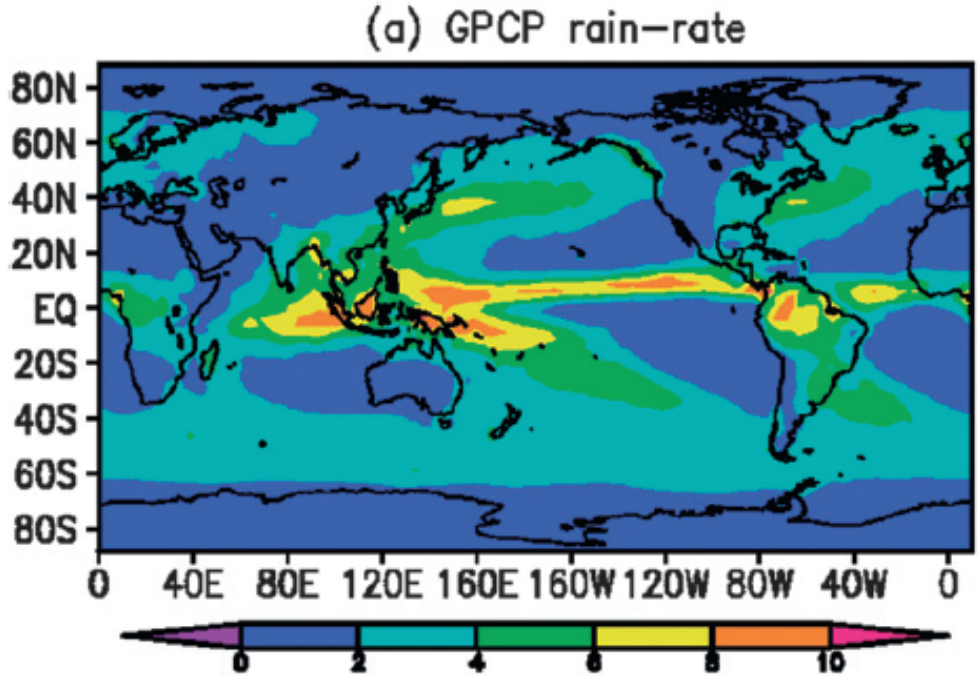
# Summary (radiation)

- Net atmospheric irradiance estimated by CERES project 109 ± 10 $Wm^{-2}$ while sensible heat + latent heat fluxes is ~94 $Wm^{-2}$.
- Surface irradiances over NH. Midlatitude land and tropical ocean are evaluated and agree with observations to within their uncertainty.
- No major missing components (magnitude of missing components is known)
- Need surface observations over SH oceans and storm track regions for evaluation of our surface irradiances

# Zonal mean precipitation

Ocean



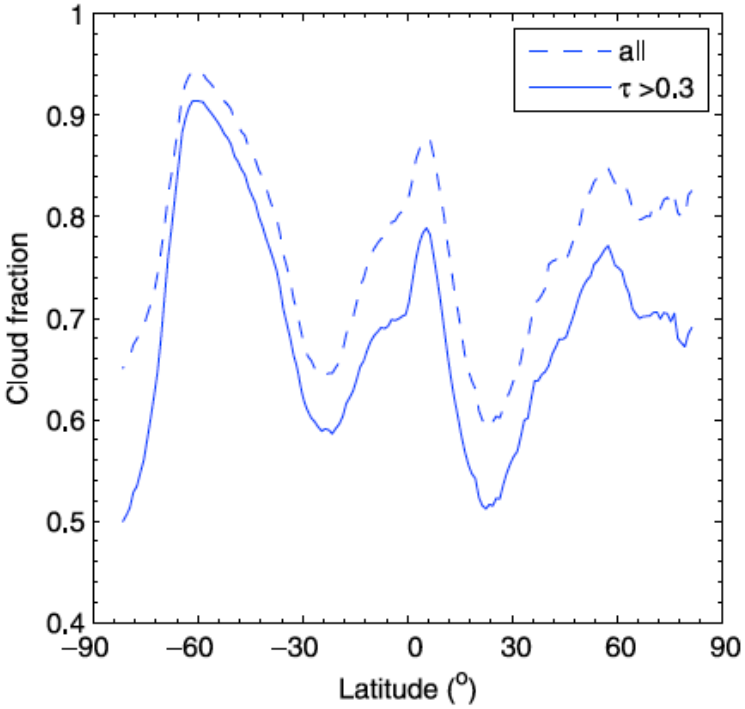



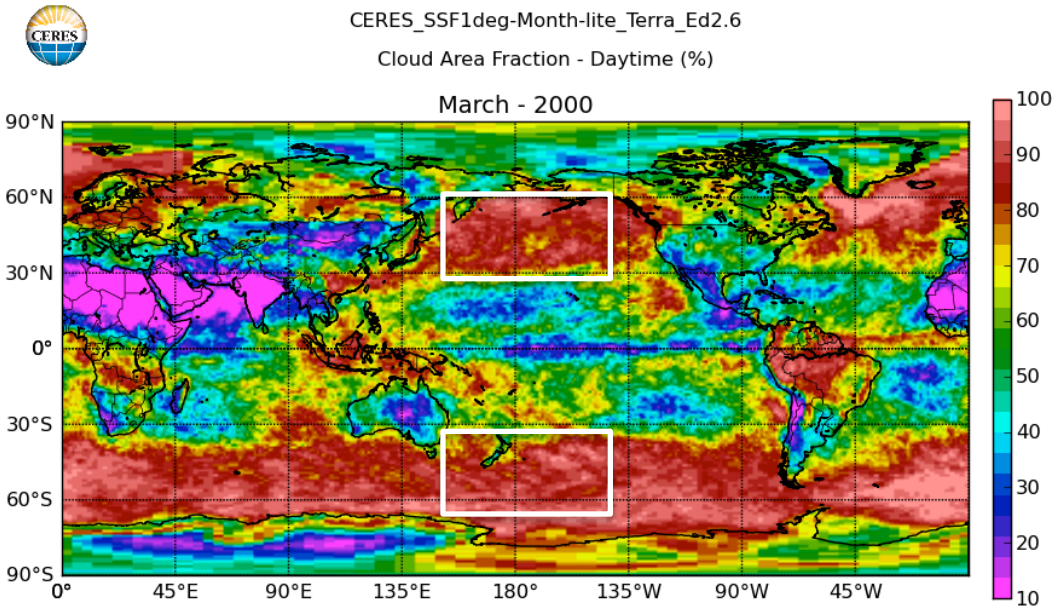

Between 30° to 60° latitude, NH rain rates is larger than SH rain rates

Adler et al. 2012

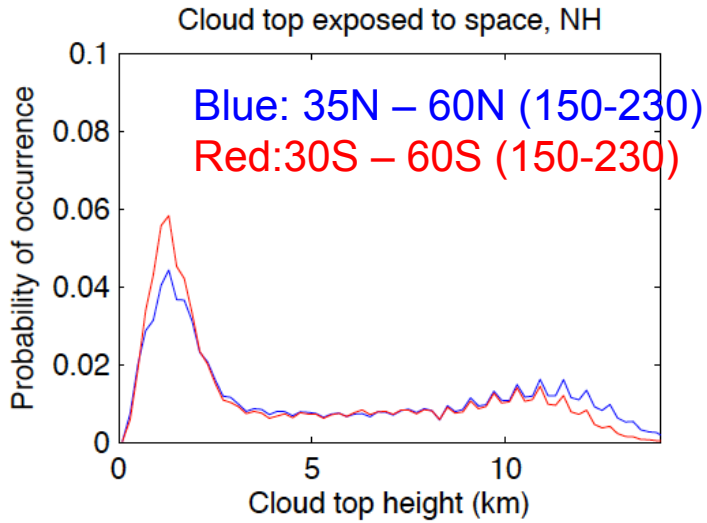
# Clouds over mid-latitude ocean

Cloud fraction derived from CALIPSO and CloudSat (annual mean)

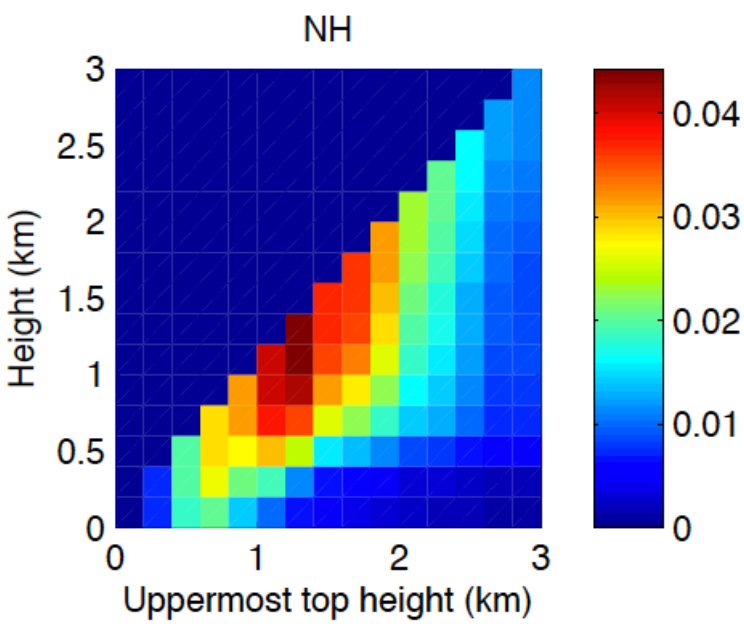


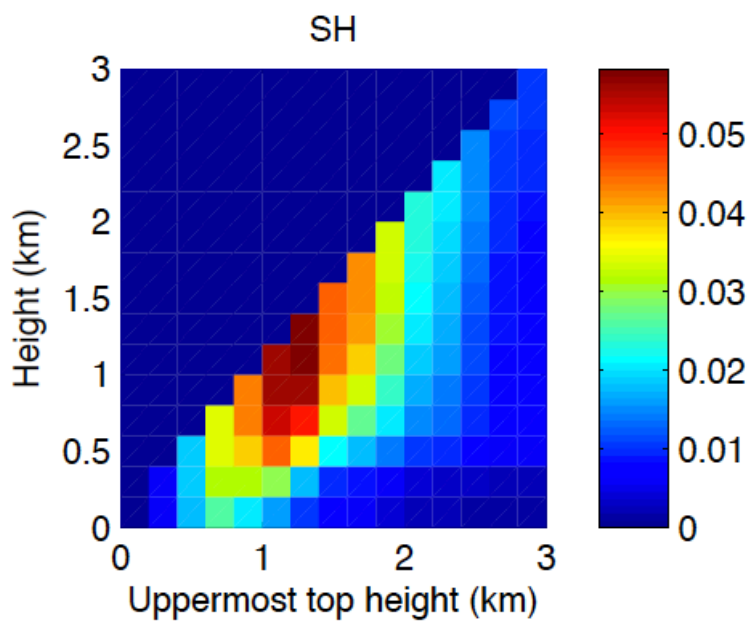



# Cloud height derived from CALIPSO and CloudSat (derived from 1 year of data 2008)




- Cloud top and base heights are similar
- More cloud fraction over SH indicates SH storms do not precipitate as much as NH storms?
- Aerosol loadings are less in SH
- Contribution to the global mean might be small



# Summary

- Net atmospheric irradiance estimated by CERES project 109 ± 10 $Wm^{-2}$ while sensible heat + latent heat fluxes is ~94 $Wm^{-2}$.
- Need to investigate the difference between NH and SH mid-latitude clouds over ocean
- Investigating the difference of cloud properties over land and ocean might provide some information too.

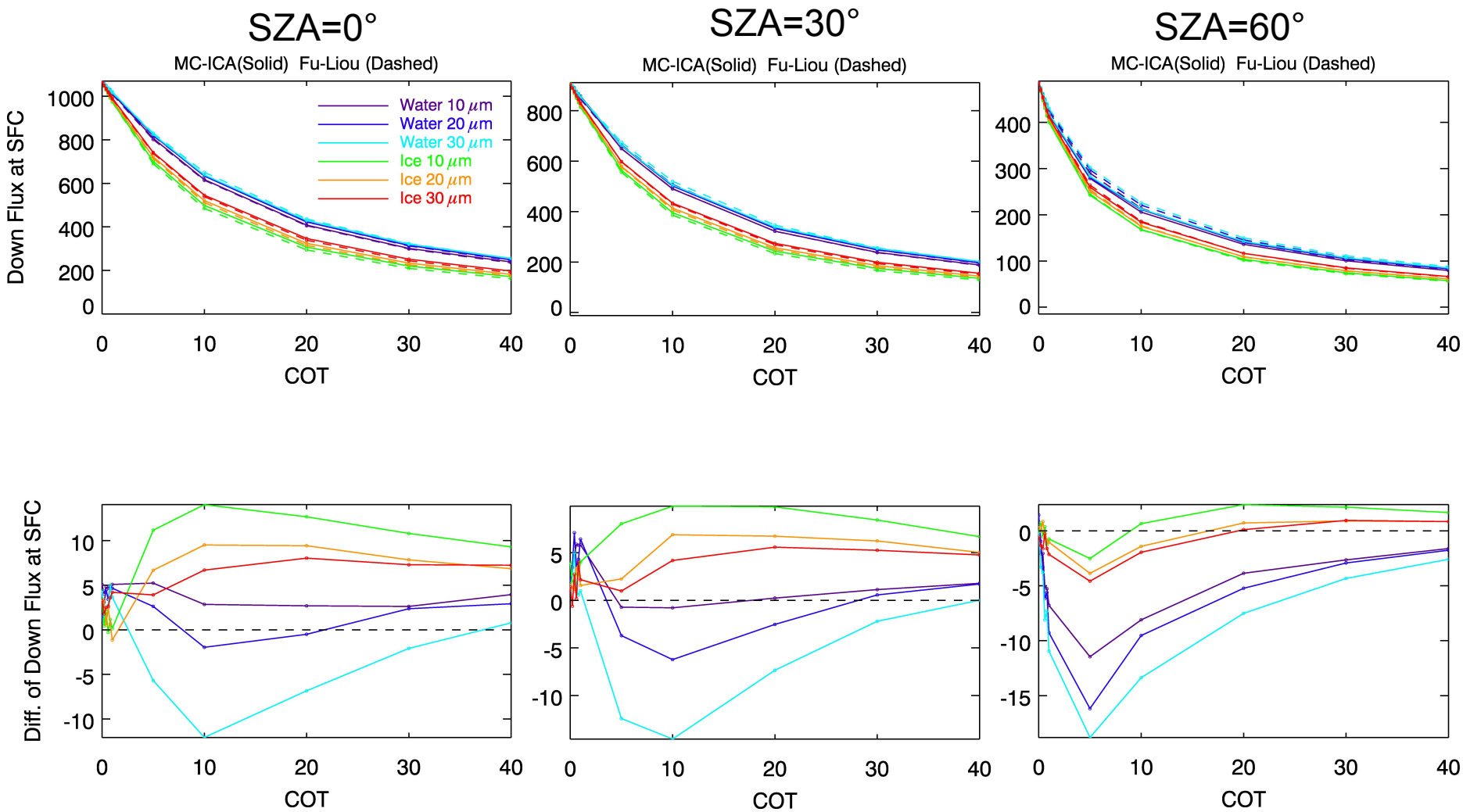
# Summary of evaluation of diurnal cycle with surface observations

| Surface Longwave Irradiance (Observed Mean 331Wm$^{-2}$) | | | | |
|---|---|---|---|---|
| Model | Monthly Mean Bias Wm$^{-2}$(%) | Standard Deviation Wm$^{-2}$(%) | | |
| | | 3-hr | Day | Month |
| SYN | -4.2 (-1.3) | 20.9 (6.3) | 15.6 (4.7) | 9.7 (2.9) |
| ISCCP | 8.4 (2.5) | 35.5 (10.7) | 29.7 (9.0) | 19.0 (5.7) |
| MERRA | -17.8 (-5.4) | 22.5 (6.8) | 16.9 (5.1) | 11.0 (3.3) |
| SRB | 0.0 (0.0) | 30.4 (9.2) | 20.9 (6.3) | 10.8 (3.3) |
| ERA-interim | -6.3 (-1.9) | | | 10.1 (3.1) |
| EBAF | 0.7 (0.0) | | | 9.8 (3.0) |

| Surface Shortwave Irradiance (Observed Mean 185Wm$^{-2}$) | | | | |
|---|---|---|---|---|
| Model | Monthly Mean Bias Wm$^{-2}$(%) | Standard Deviation Wm$^{-2}$(%) | | |
| | | 3-hr | Day | Month |
| SYN | 2.2 (1.2) | 53.2 (28.9) | 30.0 (16.3) | 11.5 (6.1) |
| ISCCP | -10.0 (-5.3) | 79.4 (43.1) | 39.9 (21.7) | 19.0 (10.1) |
| MERRA | 14.0 (7.4) | 84.5 (45.9) | 45.6 (24.8) | 19.5 (10.4) |
| SRB | -10.9 (5.8) | 80.0 (43.4) | 39.2 (21.3) | 20.6 (10.9) |
| ERA-interim | 9.7 (5.2) | | | 15.6 (8.3) |
| EBAF | -0.1 (0.1) | | | 11.8 (6.3) |

March 2000 to Dec 2007 (35 locations)

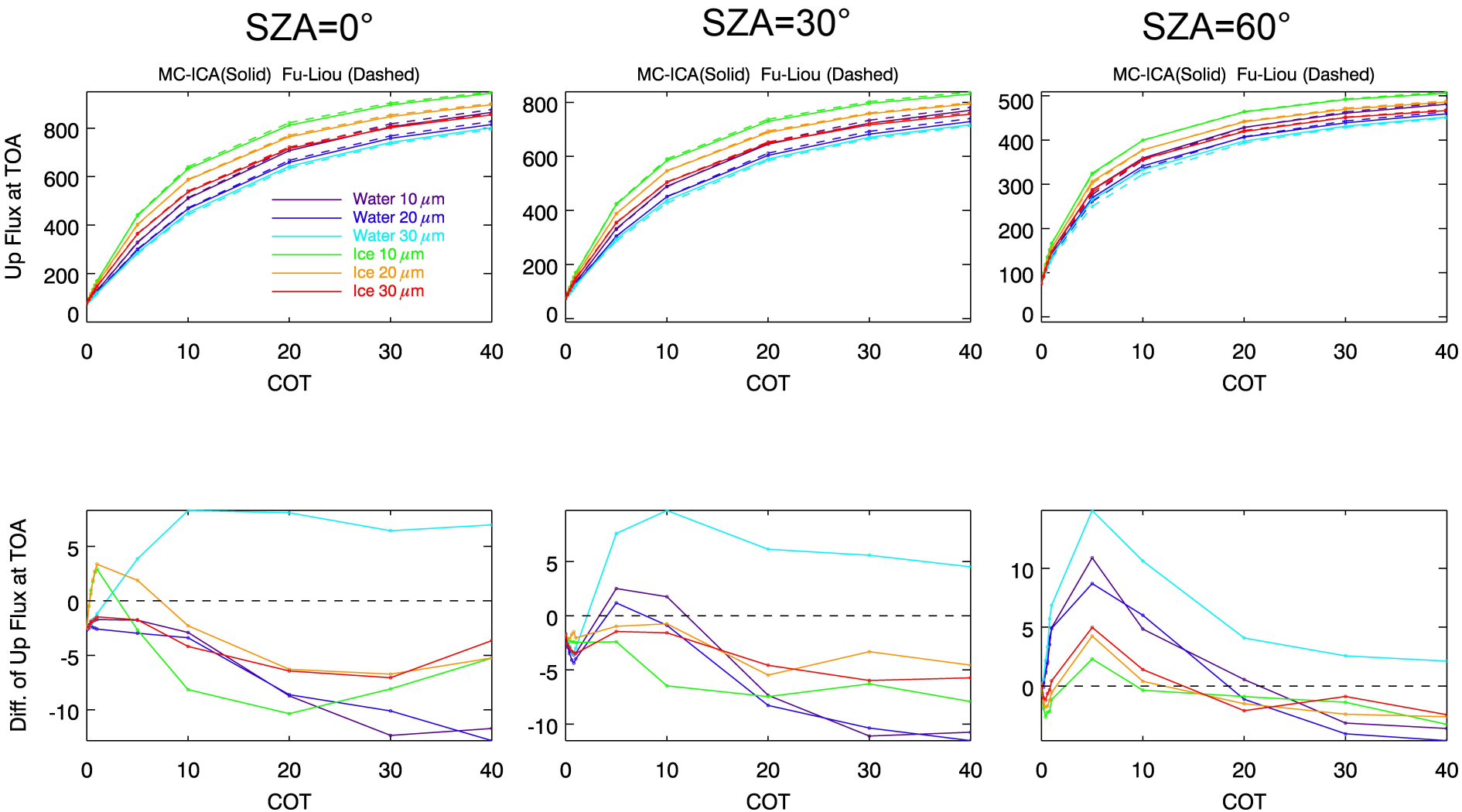
# MC-ICA vs. FL Downward Flux at SFC




Difference = MC-ICA minus FL

Unit: $Wm^{-2}$

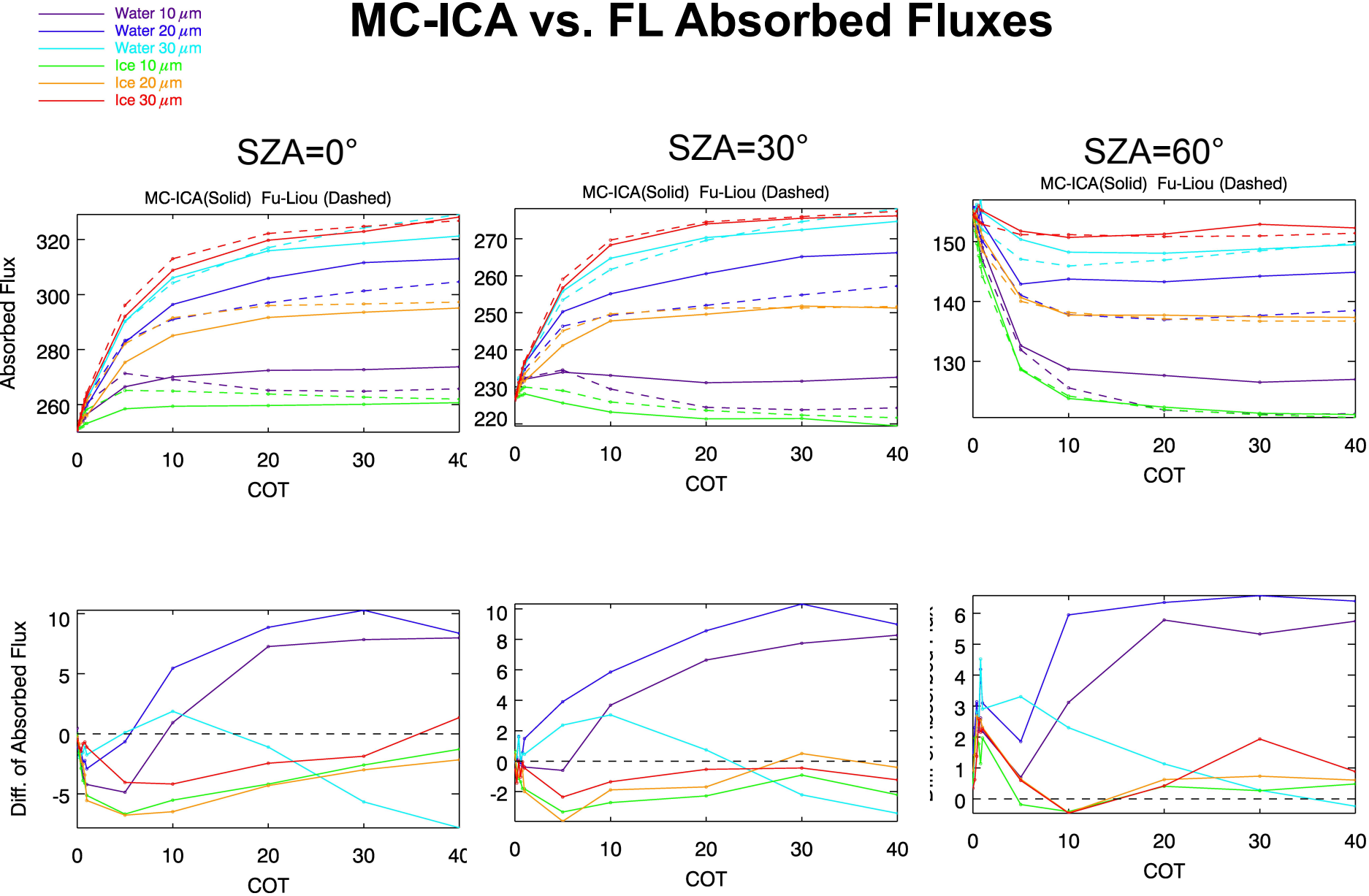
# MC-ICA vs. FL Upward at TOA




Difference = MC-ICA minus FL

Unit: $Wm^{-2}$

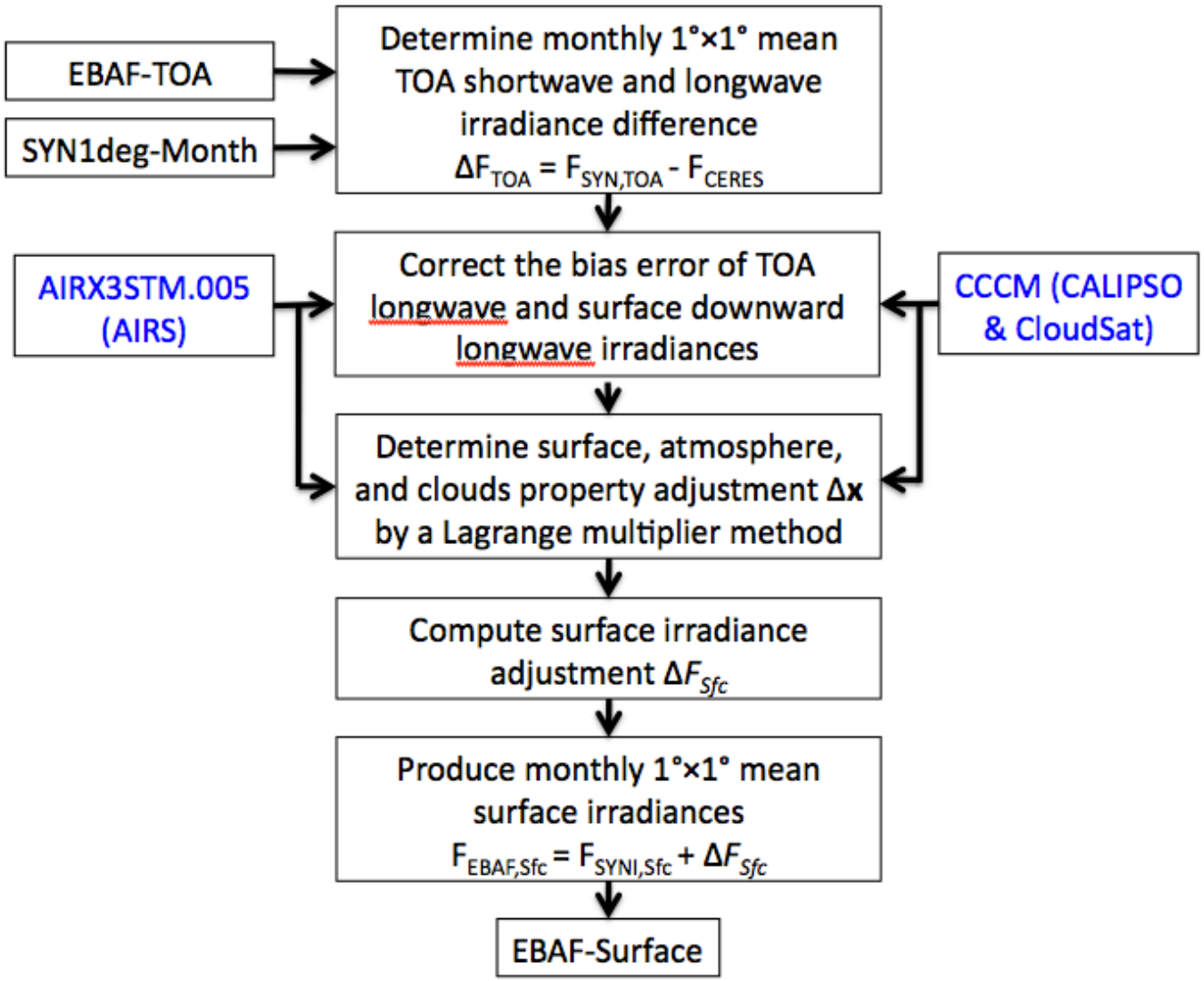
# MC-ICA vs. FL Absorbed Fluxes



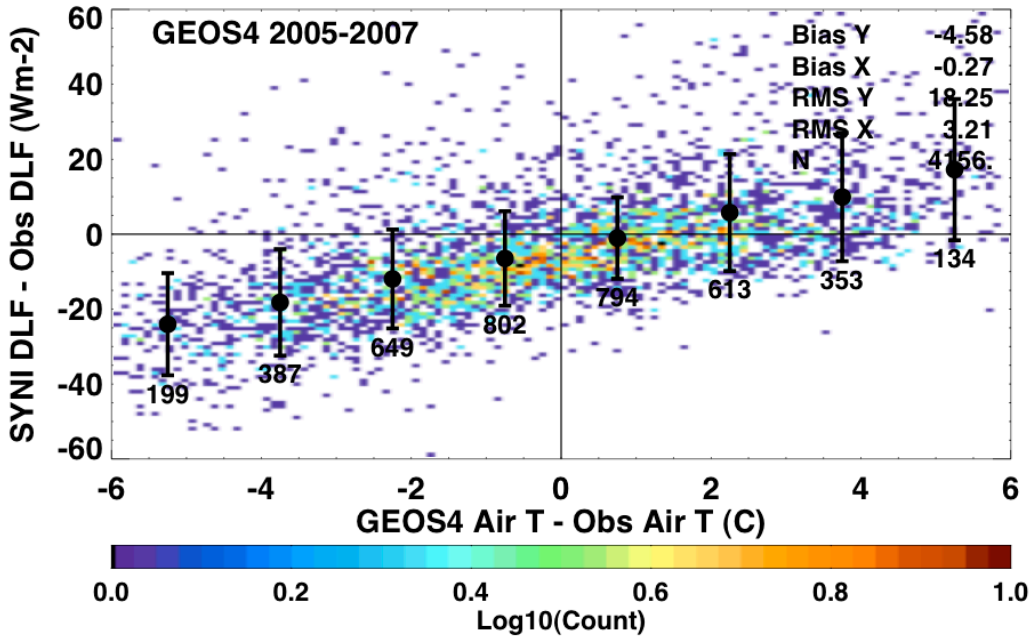

Unit: $Wm^{-2}$

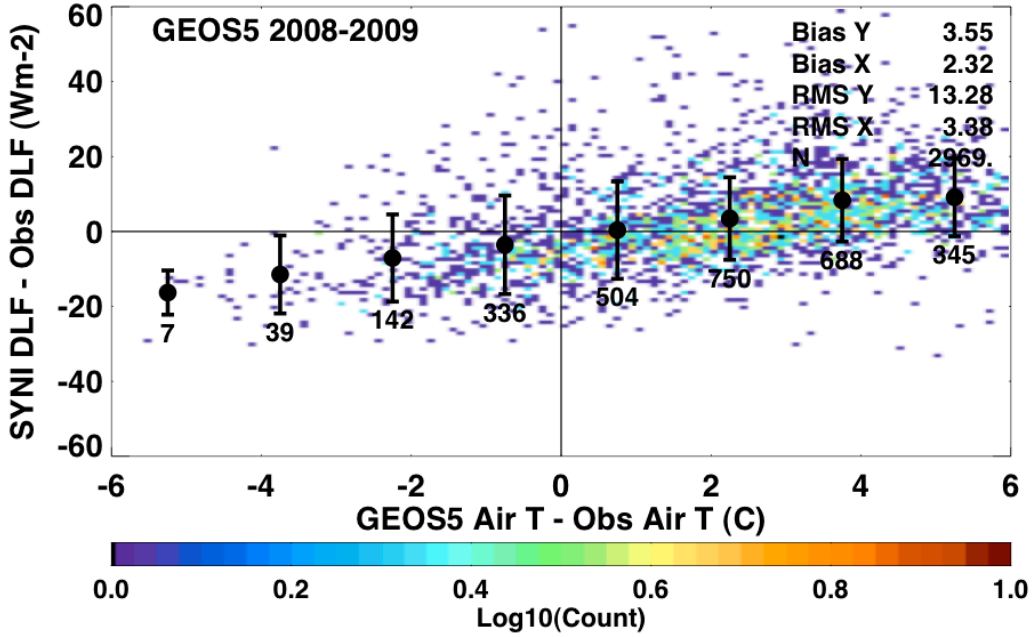
Difference = MC-ICA minus FL

# EBAF-surface production flow diagram

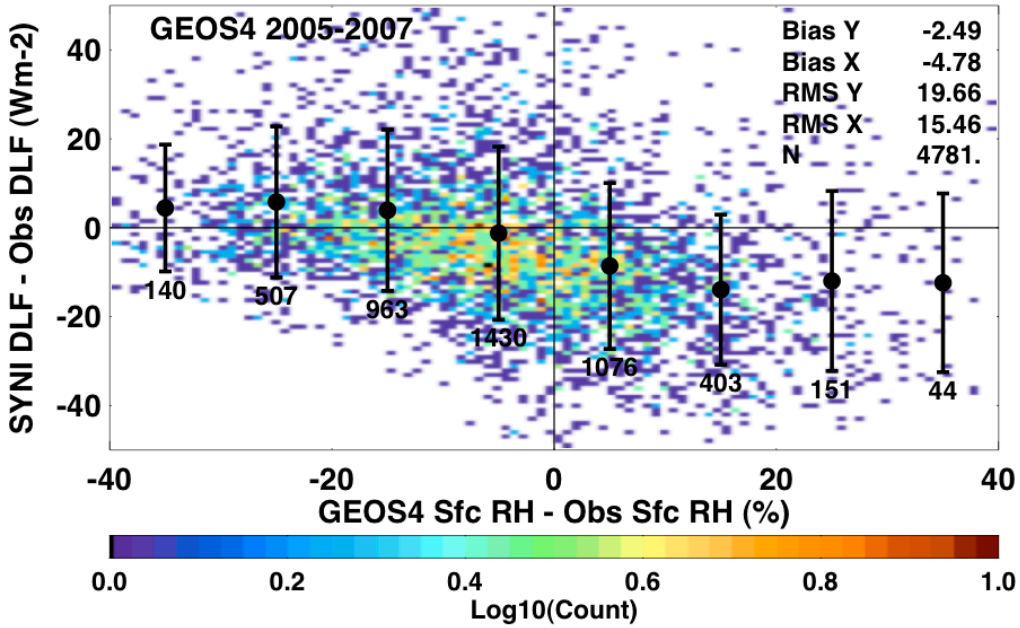


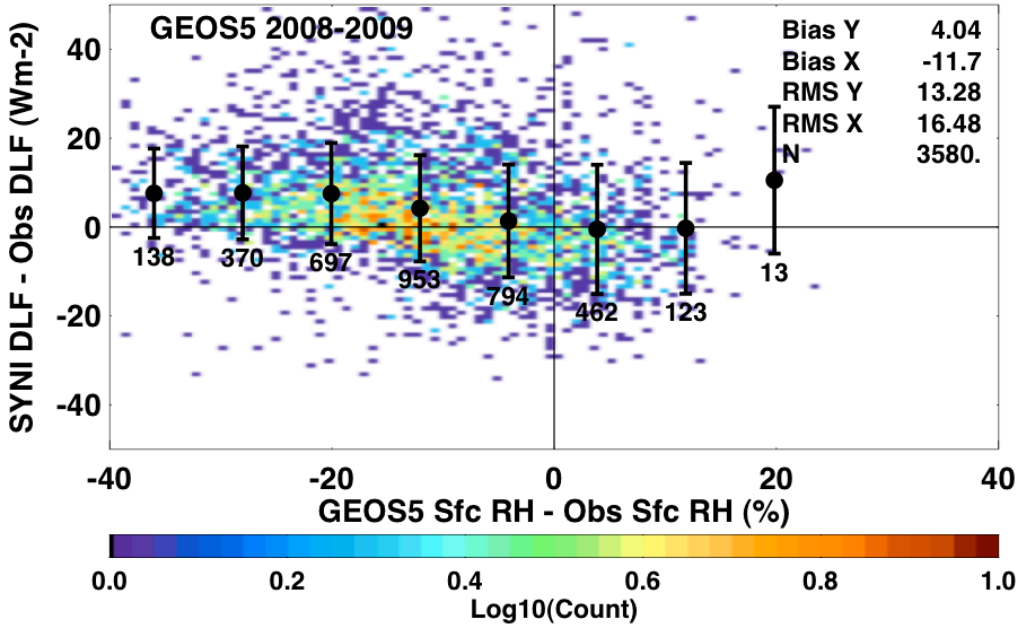
## Clear Sky: Delta LW Sfc Down vs. Delta Sfc Temp (GEOS - Obs)



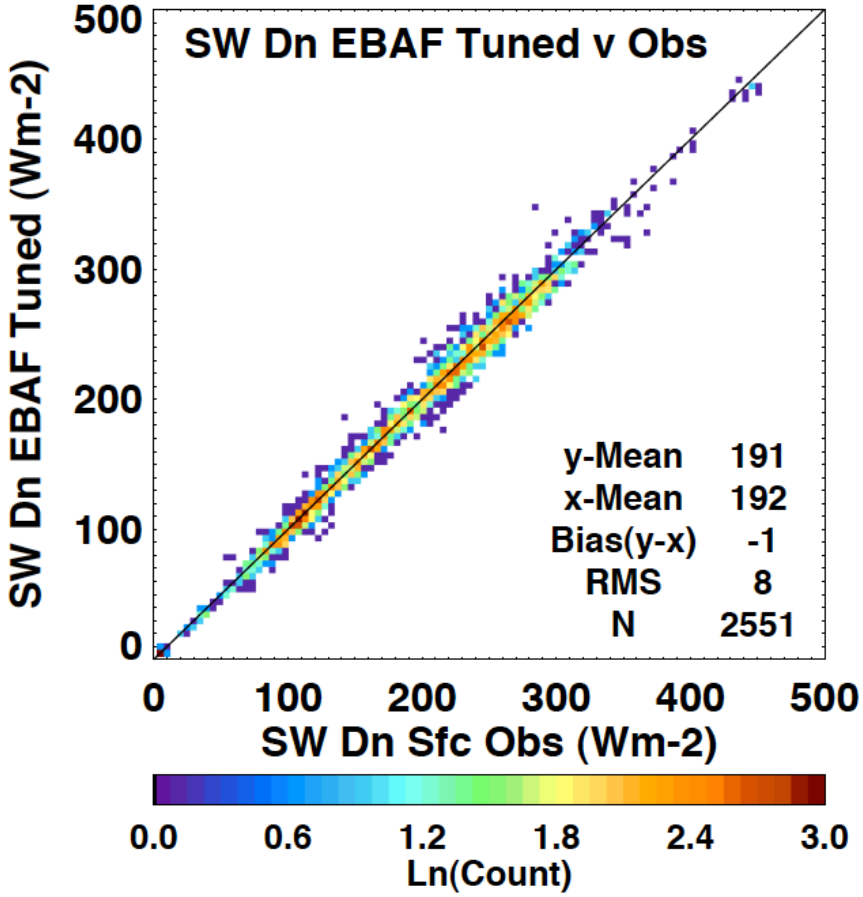



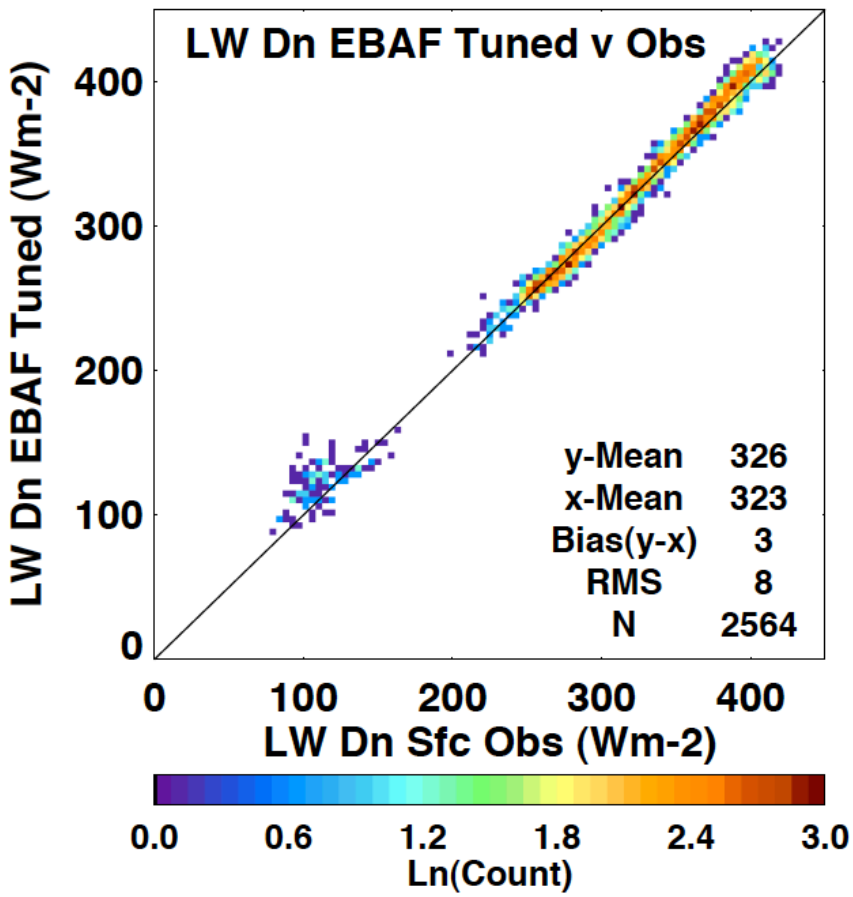
## Clear Sky: Delta LW Sfc Down vs. Delta Sfc Rel Humidity (GEOS - Obs)



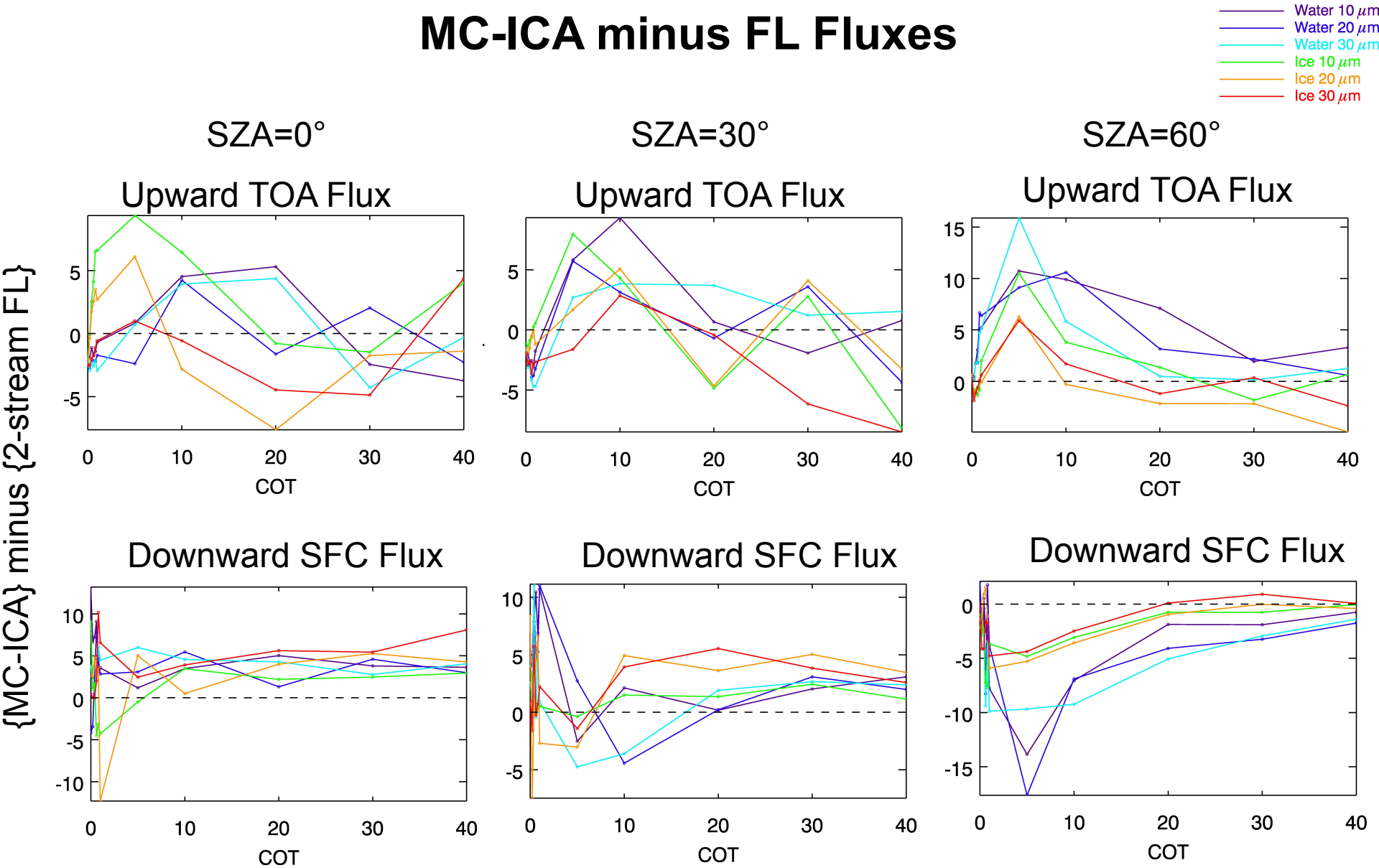



# RMS over land sites



# MC-ICA minus FL Fluxes




Difference = {Monte Carlo ICA} minus {2-stream Fu-Liou}

Units: $Wm^{-2}$

# Surface radiation budget

- Global annual surface net irradiance balances with the sum of latent and sensible heat fluxes and ocean heating
- Understanding the change of the atmospheric energy budget is a key element in understanding cloud feedback (Wielicki et al. 1995; Stephens 2005).
- The change of the atmospheric energy budget is the driver of global mean hydrological cycle change (Stephens 2005; Mitchell et al 1987; Allen and Ingram 2002; Stephens and Ellis 2008).

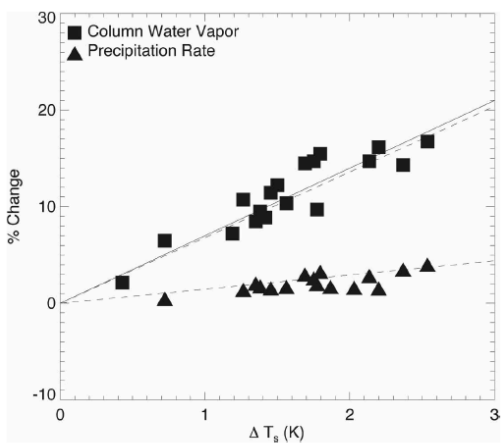



FIG. 3. The relative changes in column water vapor amount and precipitation rate, expressed as percentage changes, as functions of global temperature change derived from the AR4 models. The

Stephens and Ellis (J. Climate 2008)