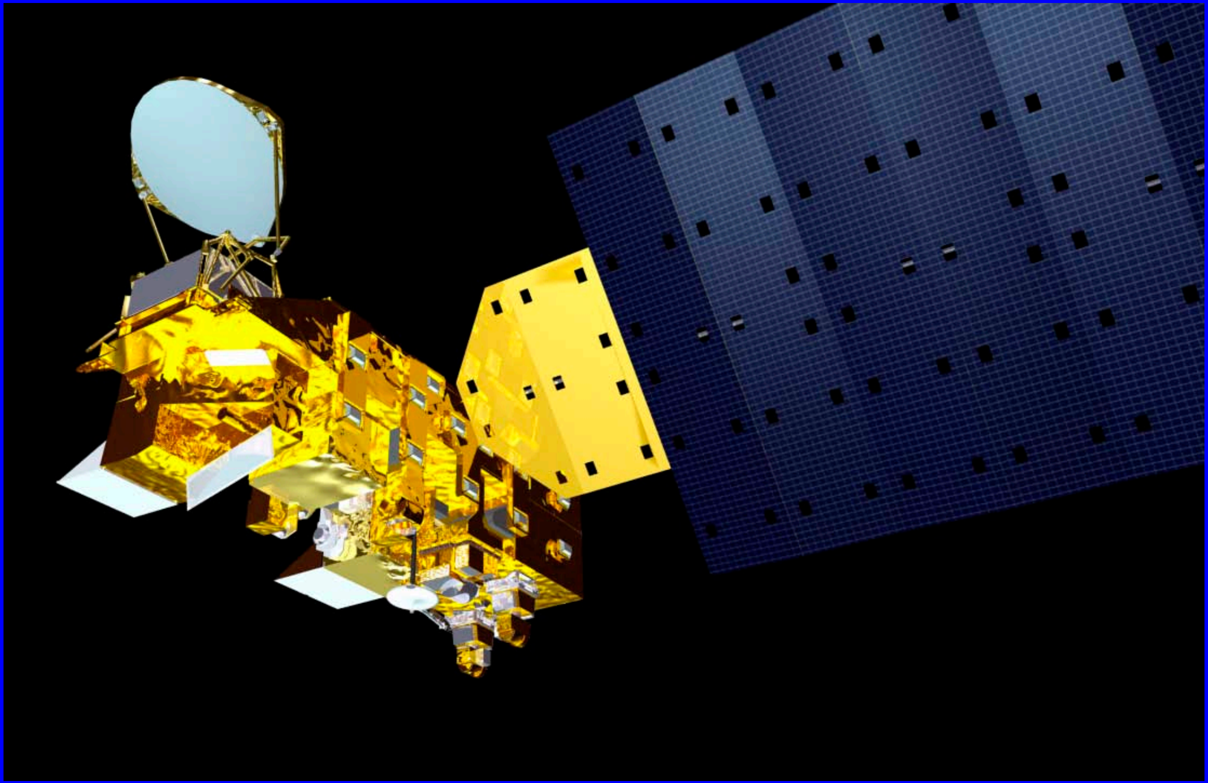
CERES Overview



Norman G. Loeb, NASA Langley Research Center, Hampton, VA

Contributions from: Tak Wong, Dave Doelling, Zack Eitzen, Jason Cole, Kuan-Man Xu, Bruce A. Wielicki

Community Climate System Model Workshop June 15-18, 2009, Breckenridge, CO

OUTLINE

- Motivation for Earth Radiation Budget Observations

- CERES Instruments and Data Products

- Closing the Earth’s Global Mean Radiation Budget

- Cloud-Radiation Variability

- Recent studies involving CERES for testing Climate Models

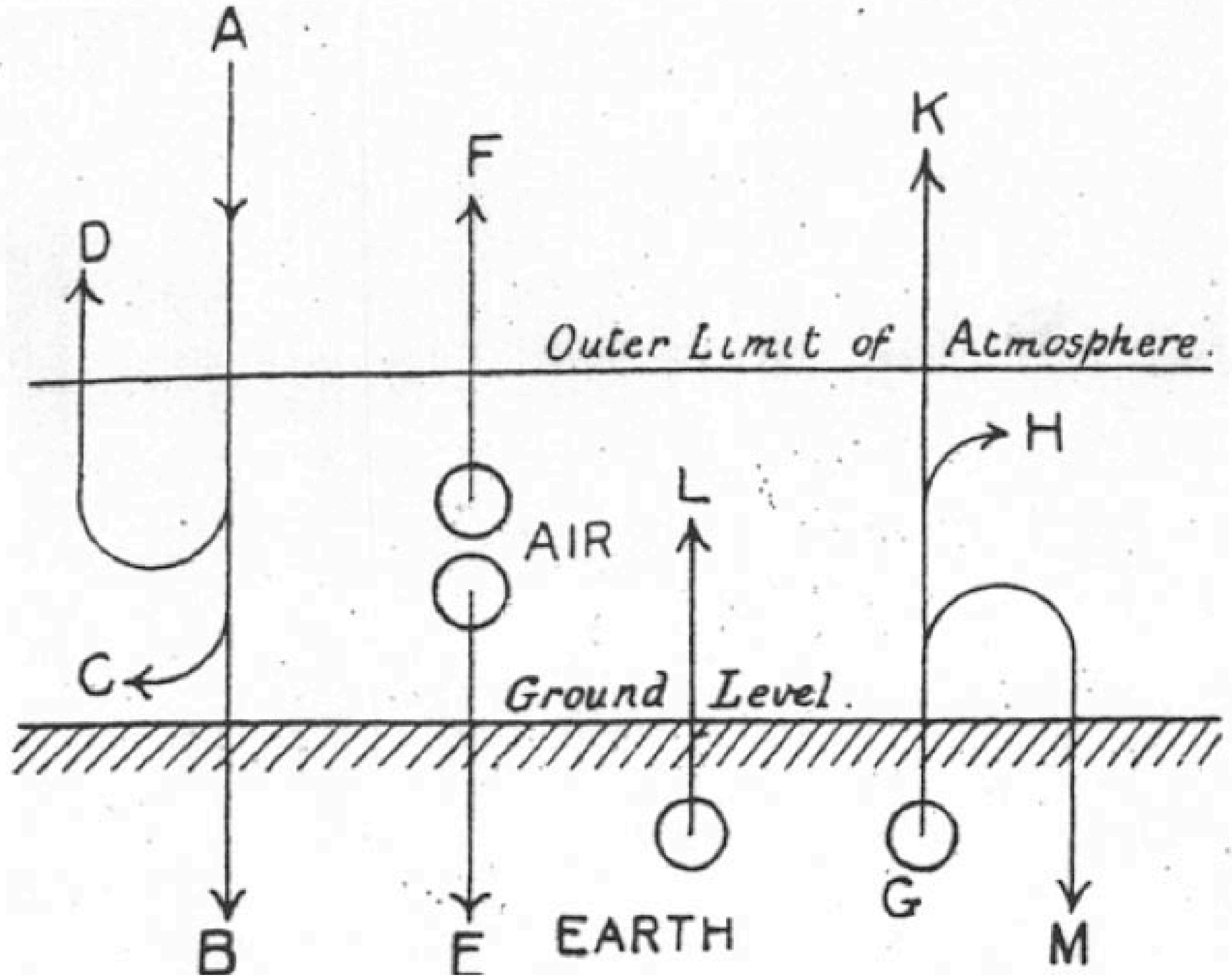
Clouds and the Earth’s Radiant Energy System (CERES)

- Changes in the Earth’s radiation budget can have profound impacts on the Earth’s climate (temperature, precipitation, sea-level, etc.).
- Capturing changes in the Earth’s Radiation Budget requires a long-term observing strategy.

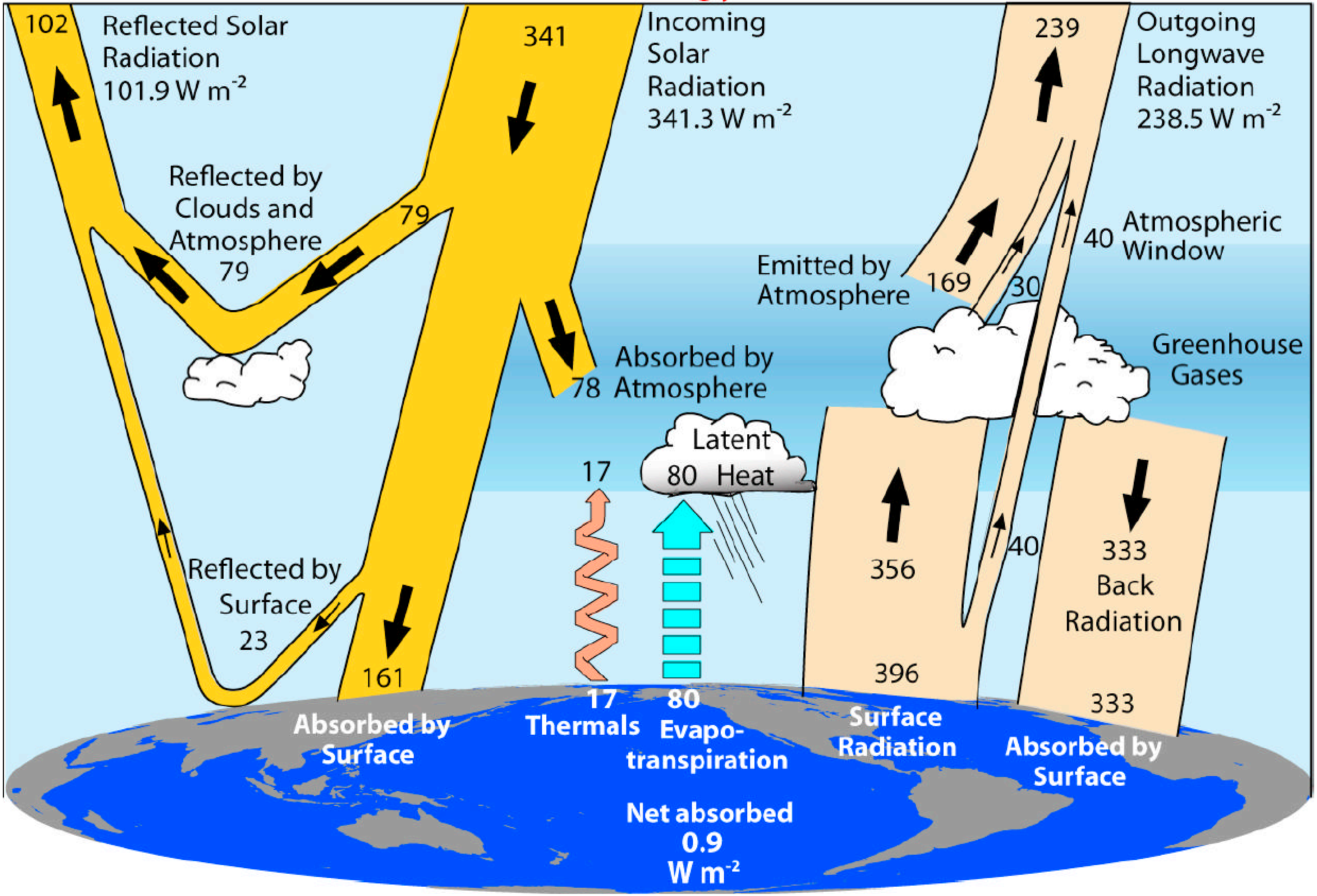
- Primary Goal of CERES:
  - Produce long-term climate data records of radiation budget at the top-of-atmosphere, within the atmosphere and at the surface with consistent cloud and aerosol properties at climate accuracy.

- Scope:
  - Integrated instrument-algorithm-validation science team that provides development of higher-level products (Levels 1-3) and investigations.
  - High level of data fusion: 11 instruments on 7 spacecraft all integrated to obtain climate accuracy in top to bottom radiative fluxes.
  - Total of 25 unique input data sources are used to produce 18 CERES data products. Over 90% of the CERES data product volume involves two or more instruments.
- Heritage: Earth Radiation Budget Experiment (ERBE)

“Heat balance of the Atmosphere” (Dines, 1917)

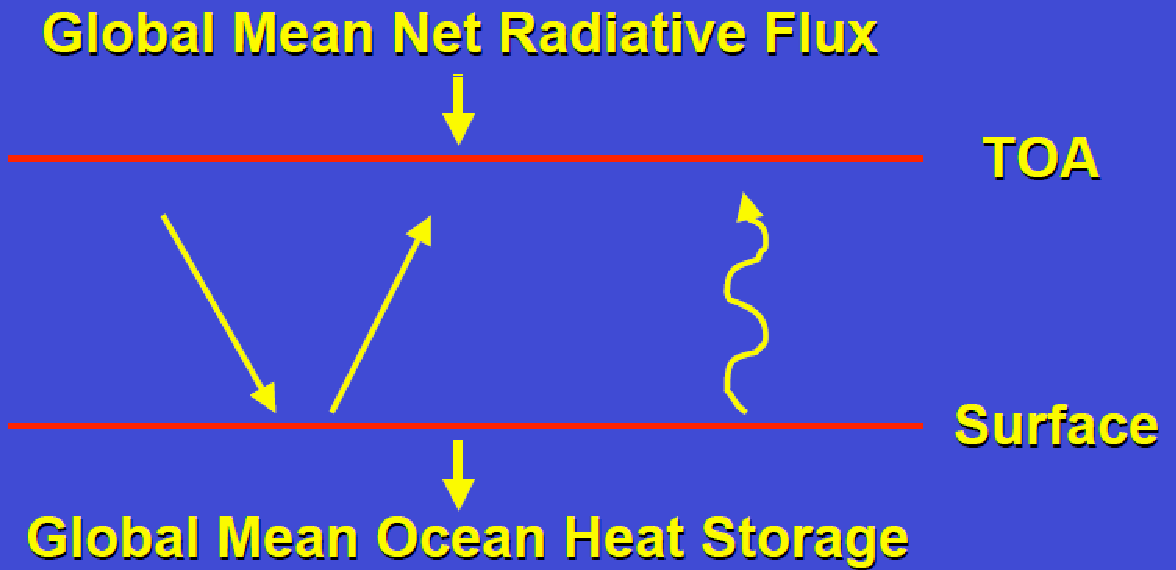


Global Energy Flows W m^{-2}



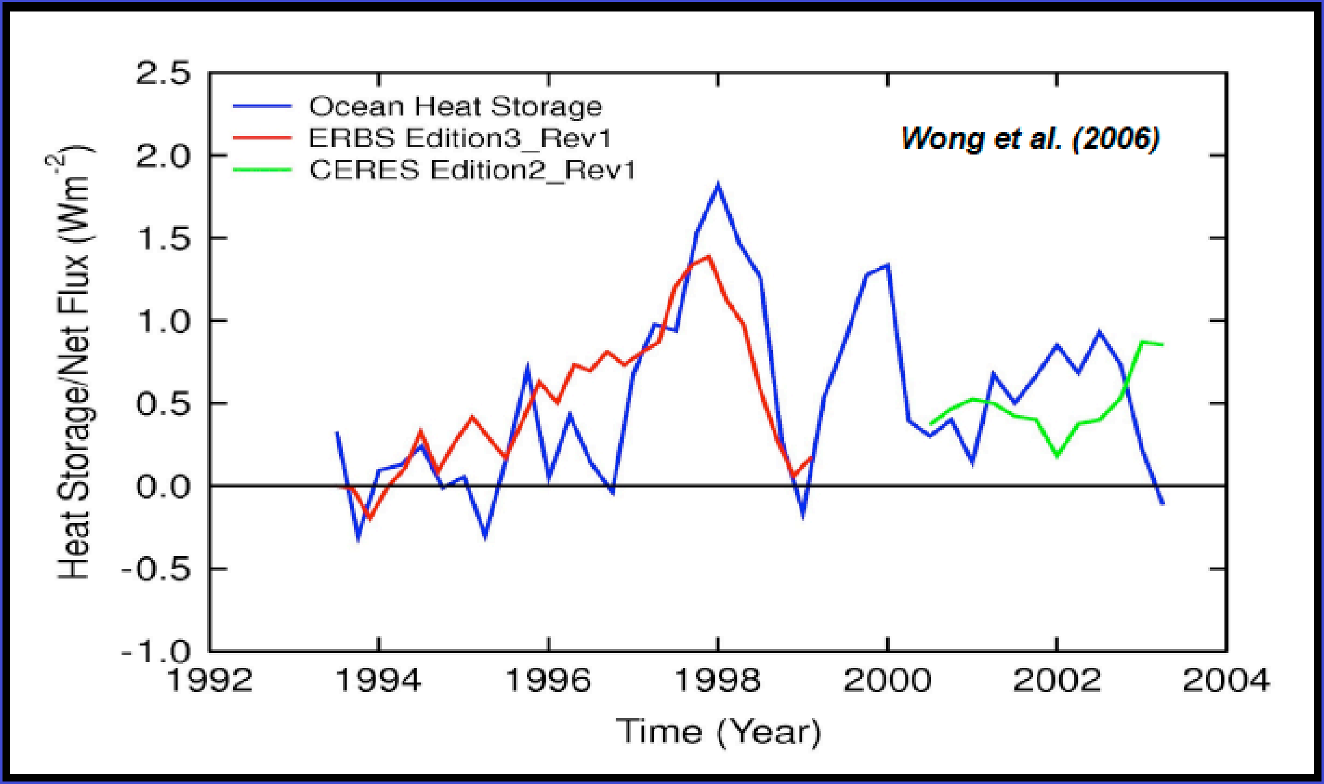
Trenberth et al., 2009

TOA Net Radiation and Ocean Heat Storage



- Over the long-time average (I.e., year and longer), the global Net radiation at TOA should be in phase with and of the similar magnitude to global ocean heat storage since other storage terms in the Earth climate system are factors of 10 or more smaller than ocean heat storage (Levitus, 2001)

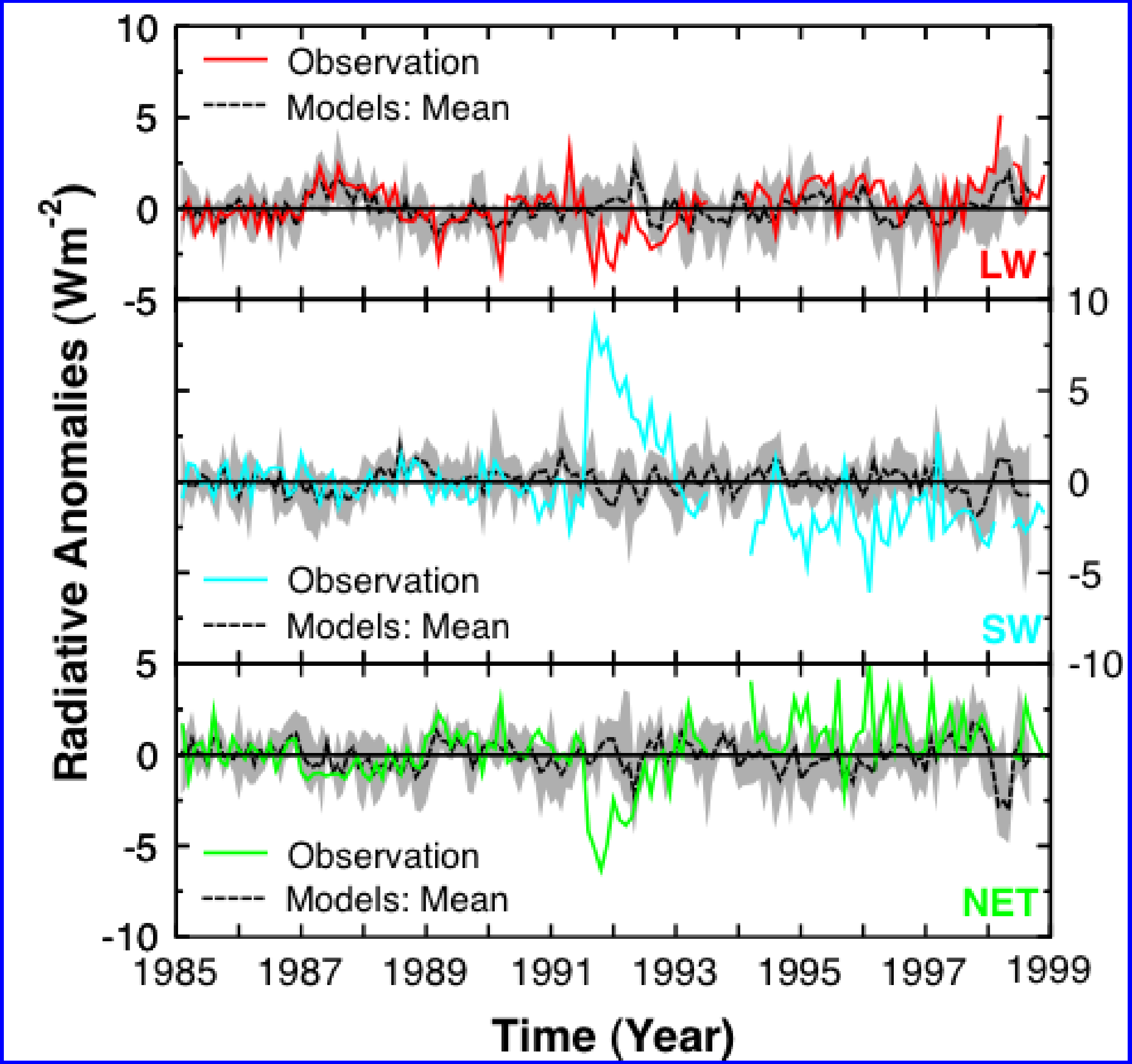
Global Net Radiation and Ocean Heat Energy



- Interannual net flux anomalies from ERBS and CERES agree within ocean heat storage sampling uncertainties (1 sigma of 0.4 Wm^{-2})
- The net flux anomalies within a single decade can be as large as 1.5 Wm^{-2} and are due, most likely, to changes in cloudiness

Wong et al., J. Climate, 2006

Tropical (20S - 20N) TOA Radiation Anomalies: Observations vs. Climate Models



Edition 3 ERBS

Decadal Changes (1980s to 1990s)

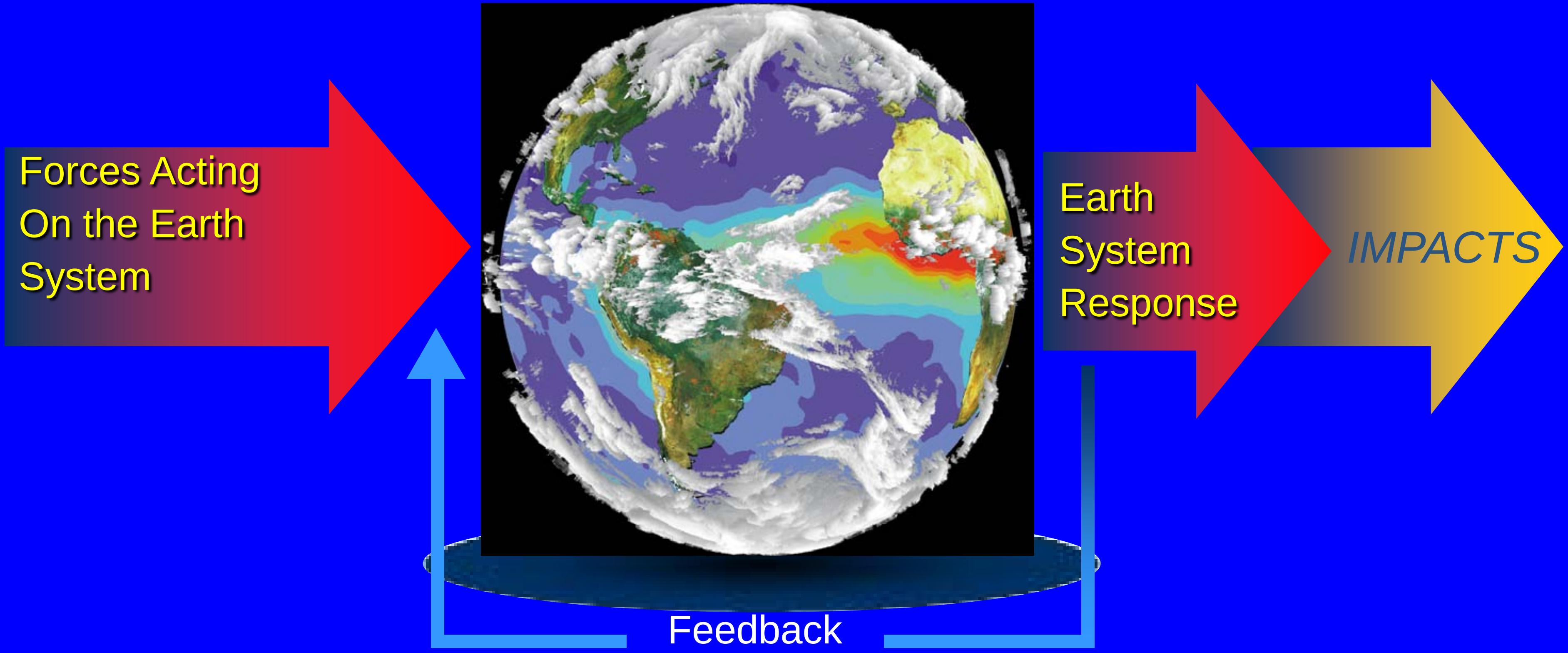
LW: 1.6 Wm^{-2}
SW: -3.1 Wm^{-2}
NET: 1.5 Wm^{-2}

Models less variable than the observations:

- ***missing feedbacks?***
- ***missing forcings?***
- ***clouds physics?***

Wong et al., J. Climate, 2006

How does the Earth Respond?



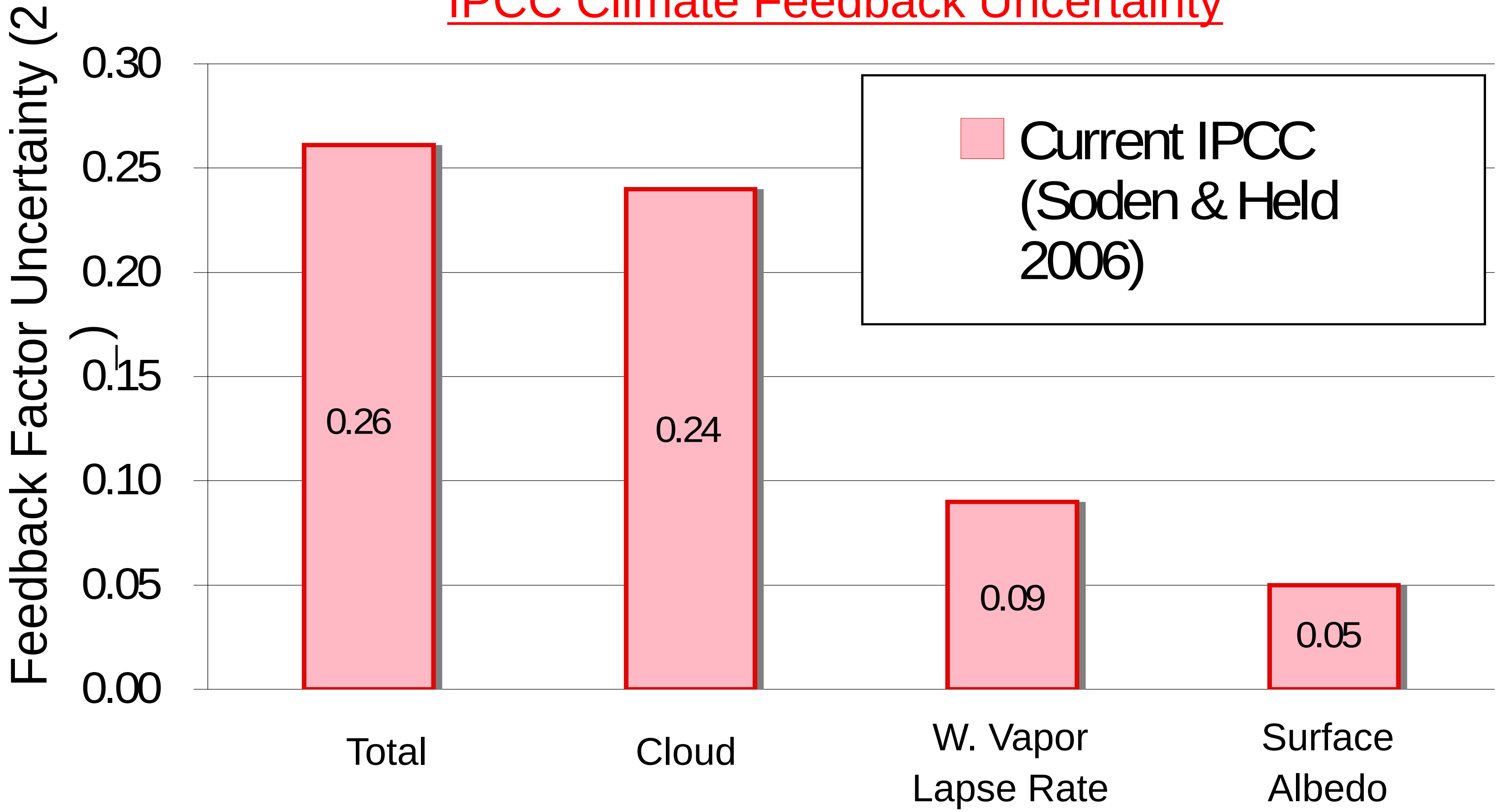
Forces Acting
On the Earth
System

Earth
System
Response

IMPACTS

Feedback

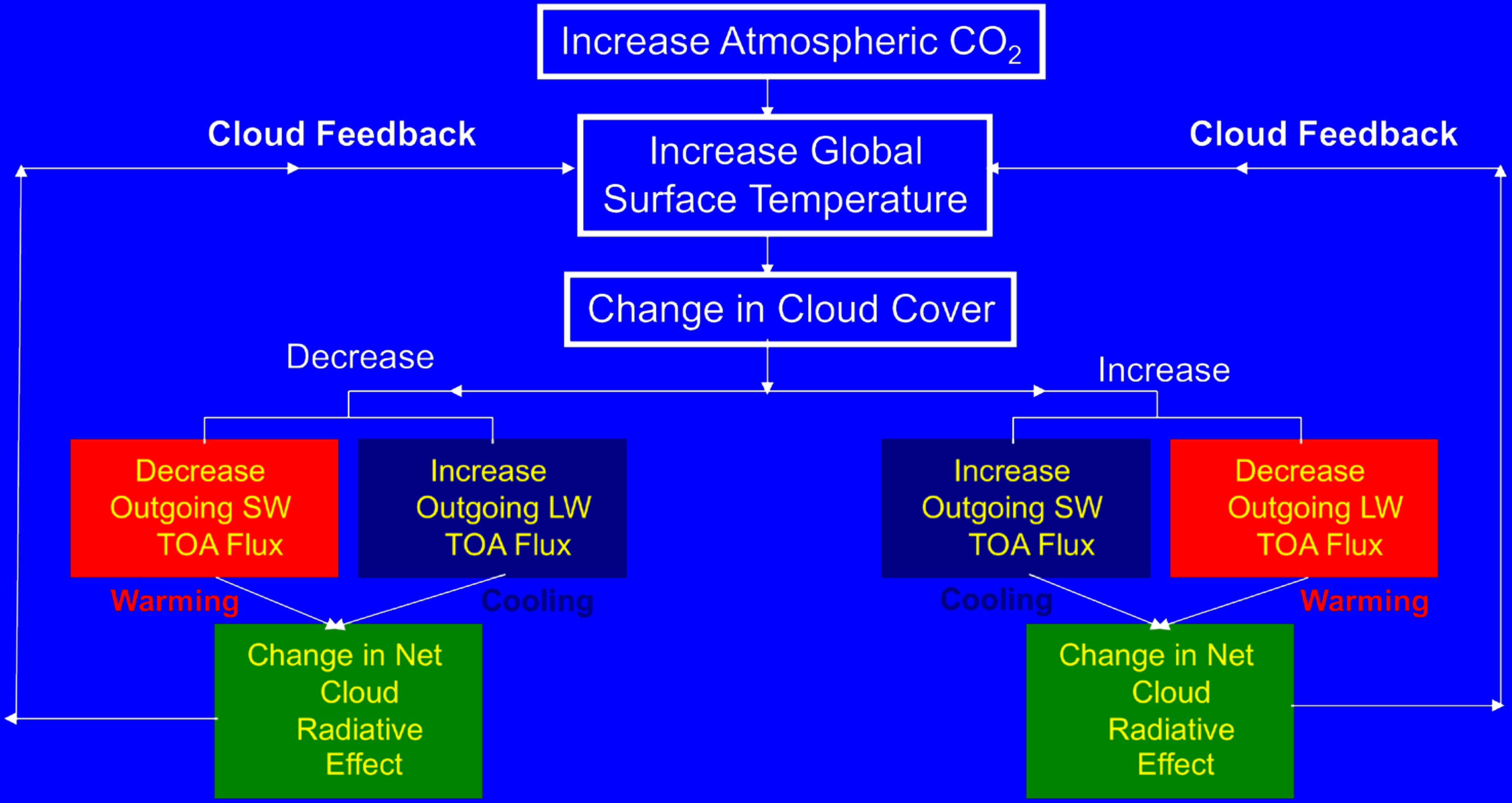
IPCC Climate Feedback Uncertainty



The uncertainty in climate feedback is driven by these three components. The feedback for the climate system is f = 0.62 ± 0.26 (2σ).

This corresponds to a 2ºC-10ºC range in equilibrium climate sensitivity in response to doubling CO_2*.*

Cloud Feedback



Increase Atmospheric CO_2

Increase Global Surface Temperature

Change in Cloud Cover

Cloud Feedback

Cloud Feedback

Decrease

Increase

Decrease Outgoing SW TOA Flux

Increase Outgoing LW TOA Flux

Increase Outgoing SW TOA Flux

Decrease Outgoing LW TOA Flux

Warming

Cooling

Cooling

Warming

Change in Net Cloud Radiative Effect

Change in Net Cloud Radiative Effect

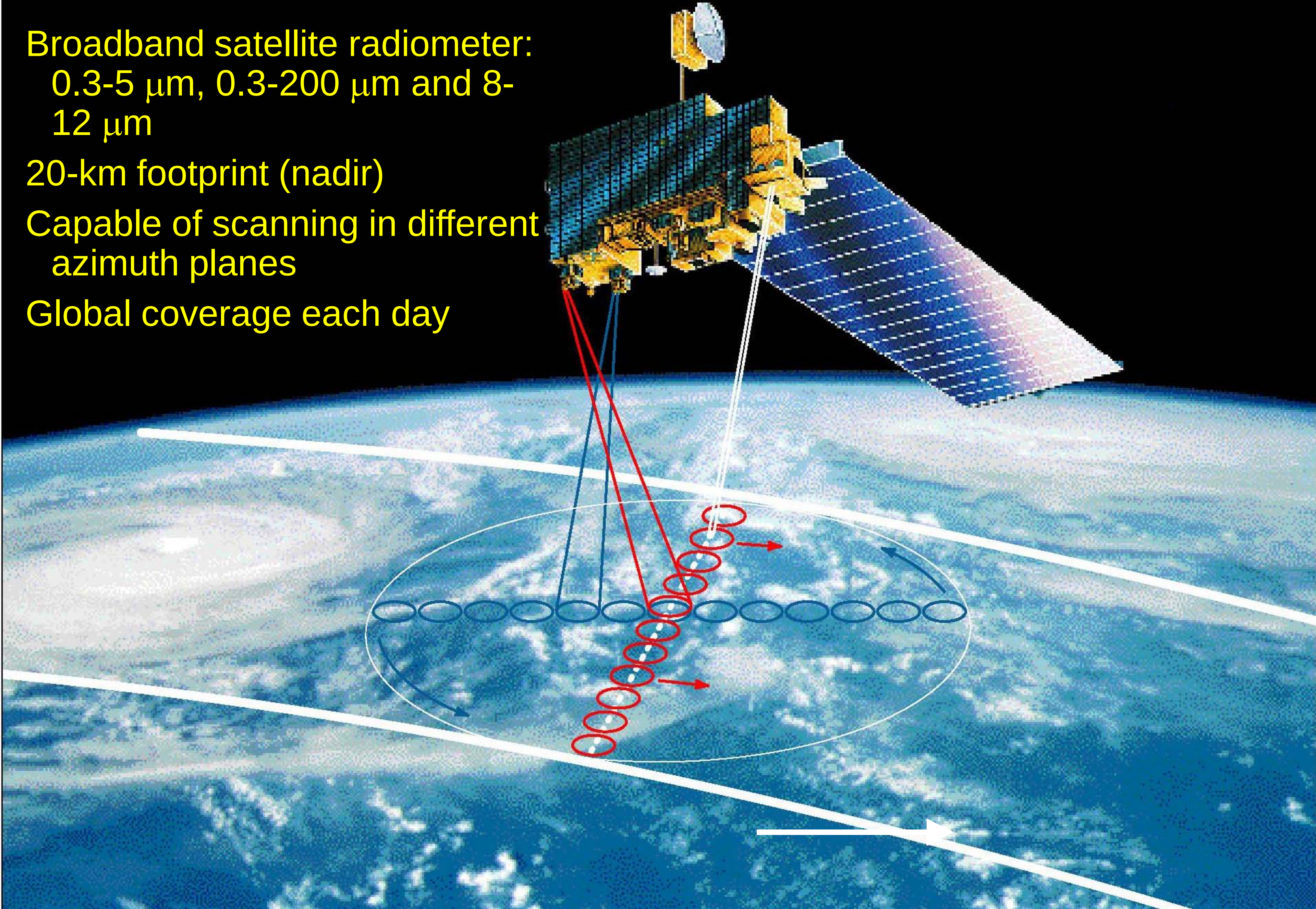
- ***CERES will observe decadal changes in net cloud radiative effect that will reduce the uncertainty in cloud feedback and therefore climate sensitivity.***

…and so does every tenth of a Wm^{-2} change in CERES TOA Radiation

CERES Instruments and Data Products

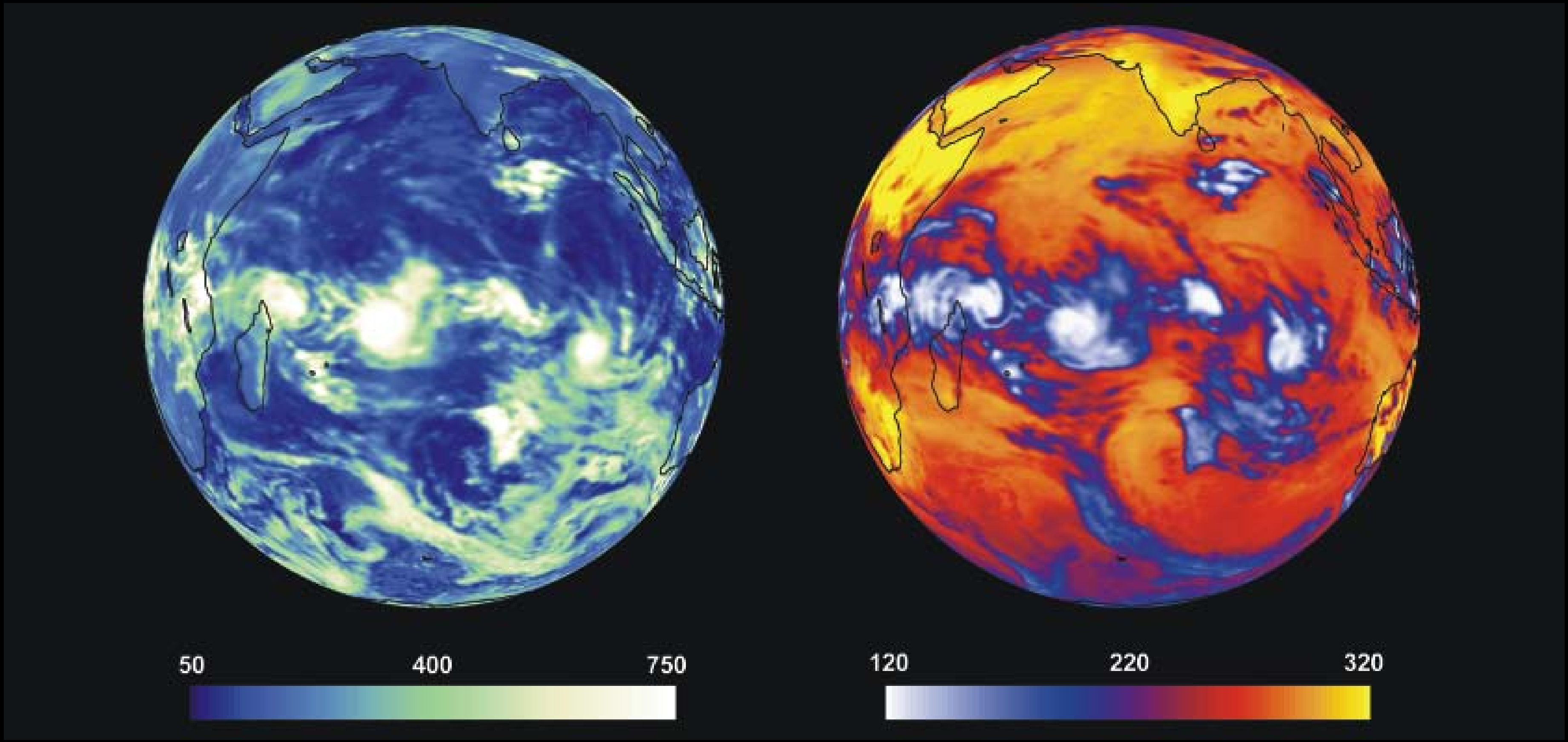
Clouds and the Earth's Radiant Energy System

- Broadband satellite radiometer: 0.3-5 μm, 0.3-200 μm and 8-12 μm
- 20-km footprint (nadir)
- Capable of scanning in different azimuth planes
- Global coverage each day



Cyclones over the Indian Ocean

(February 11th, 2003; CERES/Terra)



Reflected Solar Radiation (Wm^{-2})

Outgoing Longwave Radiation (Wm^{-2})

NASA Earth Science Enterprise (2004)

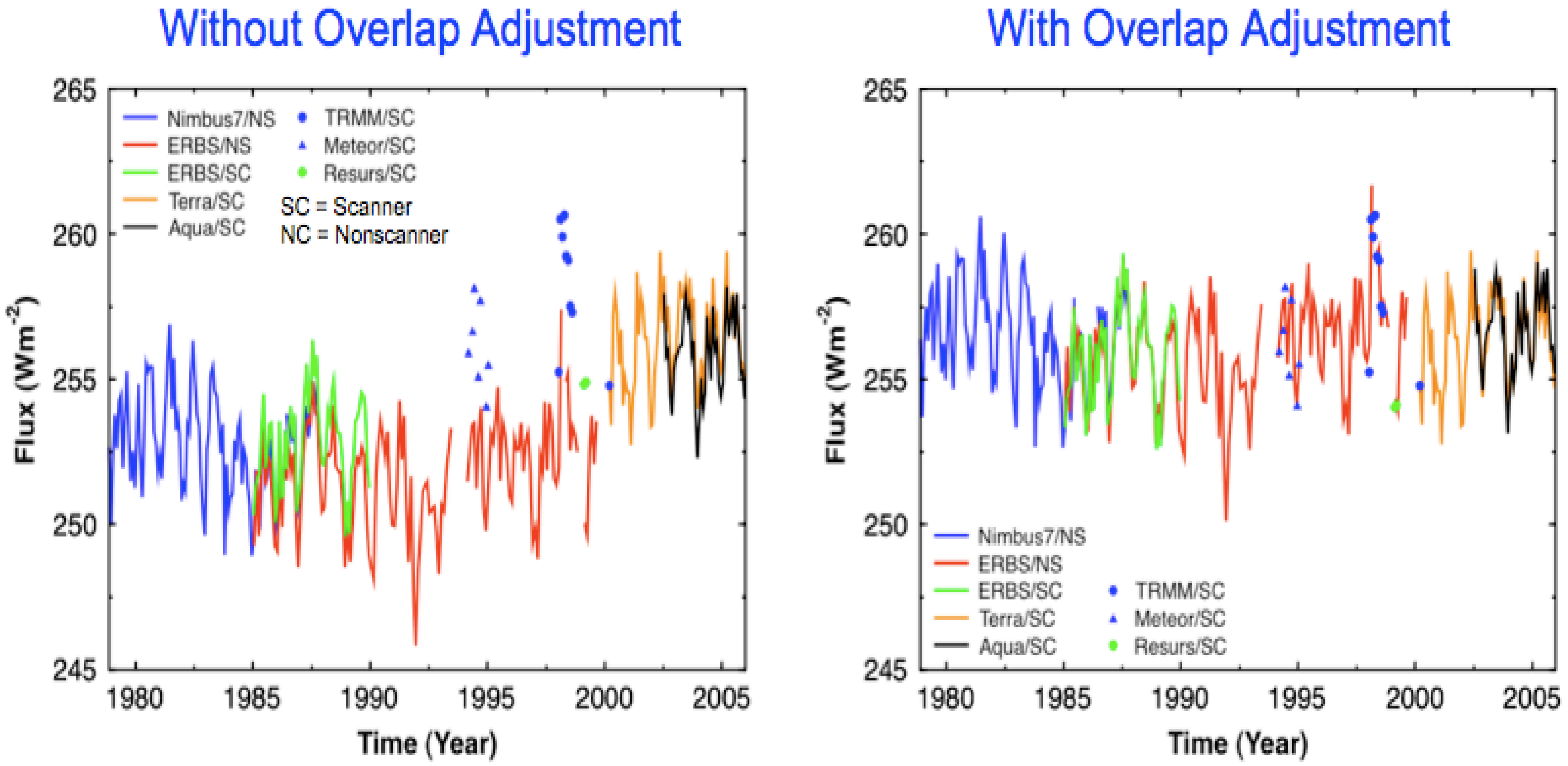
CERES Flight Schedule

Enabling Climate Data Record Continuity

Spacecraft	Instruments	Launch	Science Initiation	Collected Data (Months)
TRMM	PFM	11/97	1/98	9
Terra	FM1, FM2	12/99	3/00	100 +
Aqua	FM3, FM4	5/02	6/02	75 +
NPP	FM5	January 2011	-	-
NPOESS C1	*FM6*	*May 2014*	-	-
NPOESS C3	*CERES Follow-on*	*January 2018*	-	-

33 Instrument Years of Data

Tropical Mean (20°N to 20°S) Outgoing Longwave Radiation



Without Overlap Adjustment

With Overlap Adjustment

- ***Instrument-to-instrument absolute calibration differences are 1 to 4 Wm^{-2}.***

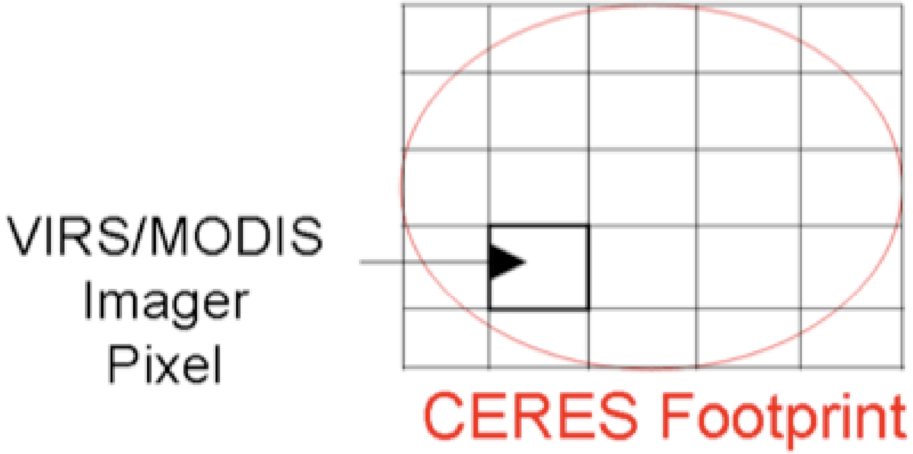
=>Absolute accuracy alone is insufficient to detect climate change at the 0.6 Wm^{-2} per decade level of anthropogenic radiative forcing by greenhouse gases.

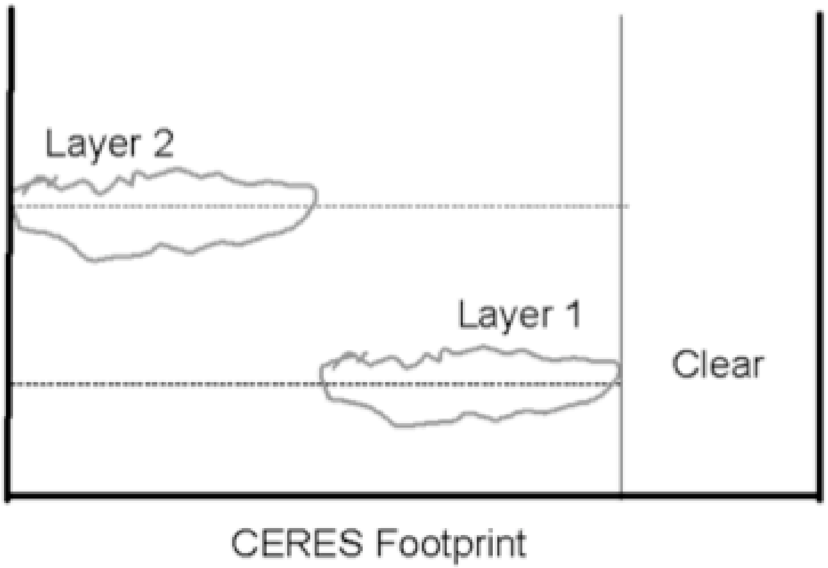
- ***Overlapping observations allows the use of instrument stability instead of absolute accuracy to constrain decadal climate change.***

Merging CERES and Imager Radiances, Cloud and Aerosol Properties

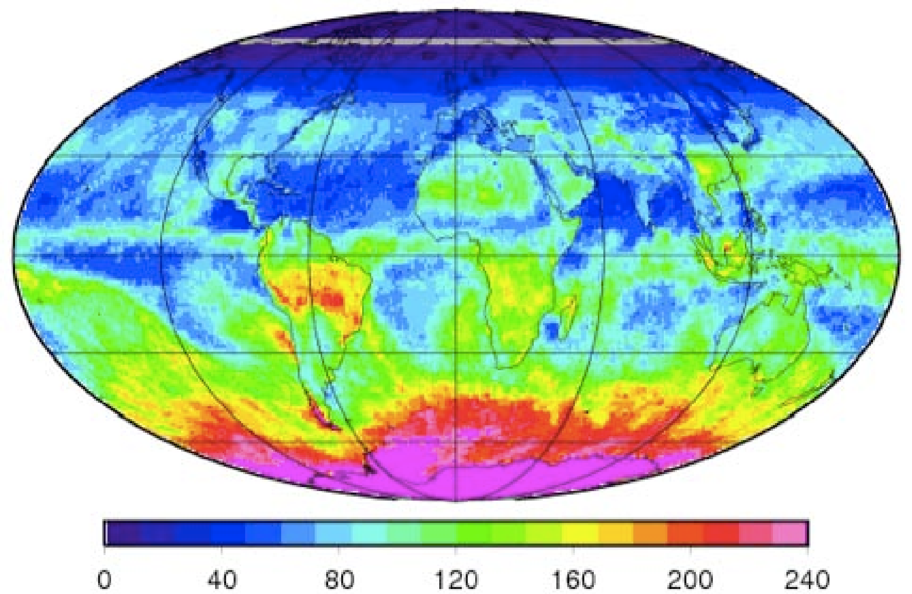
- Coincident CERES radiances and imager-based cloud and aerosol properties.
- Use VIRS (TRMM) or MODIS (Terra, Aqua) to determine following parameters in up to 2 cloud layers over every CERES FOV:

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

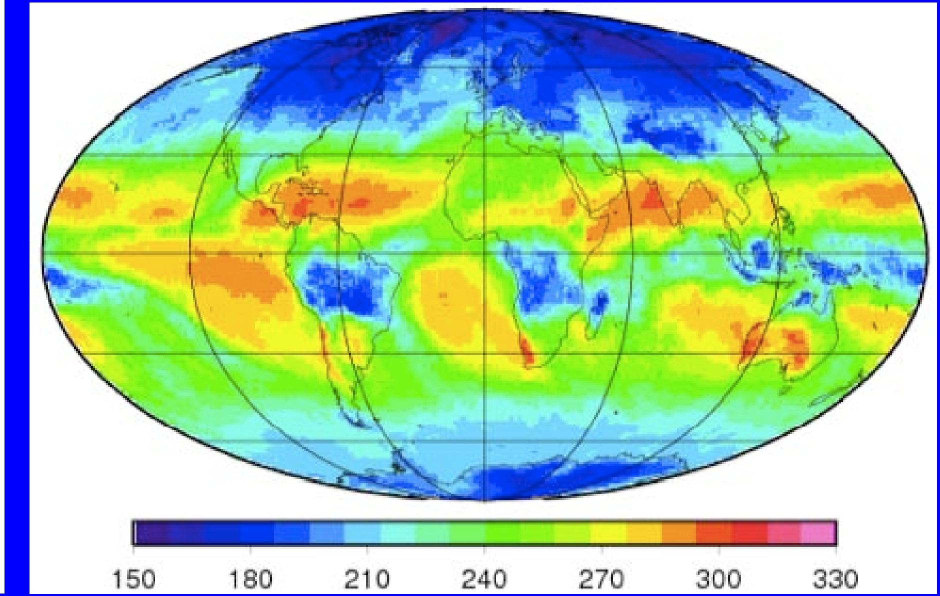




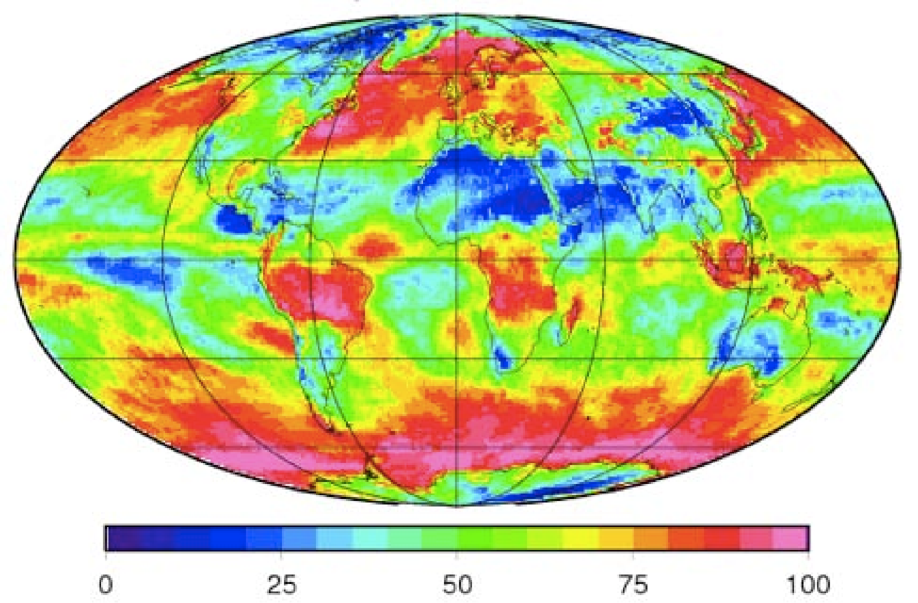
CERES+MODIS+GEO Cloud & Radiation Data (January 2004)



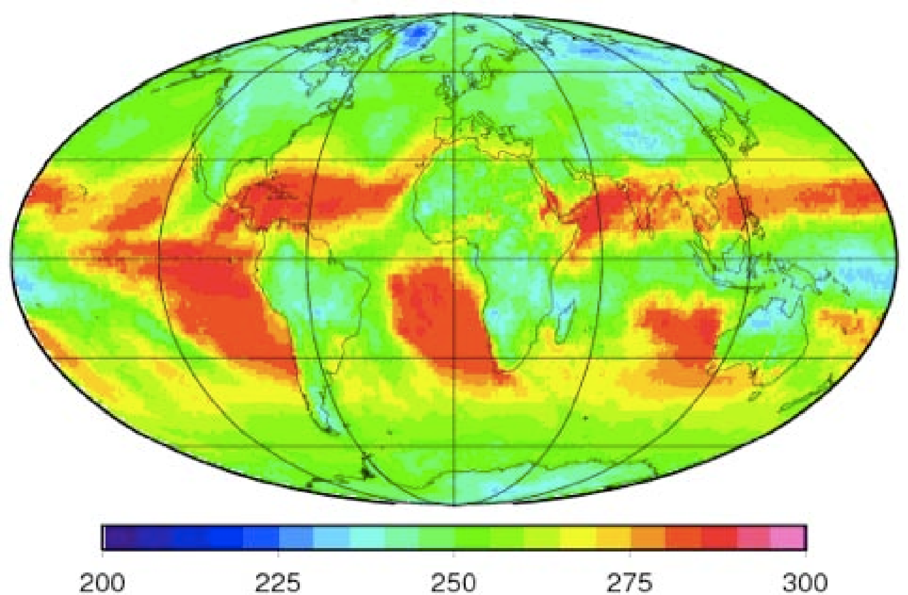
CERES SW TOA Flux (Wm^{-2})



CERES LW TOA Flux (Wm^{-2})

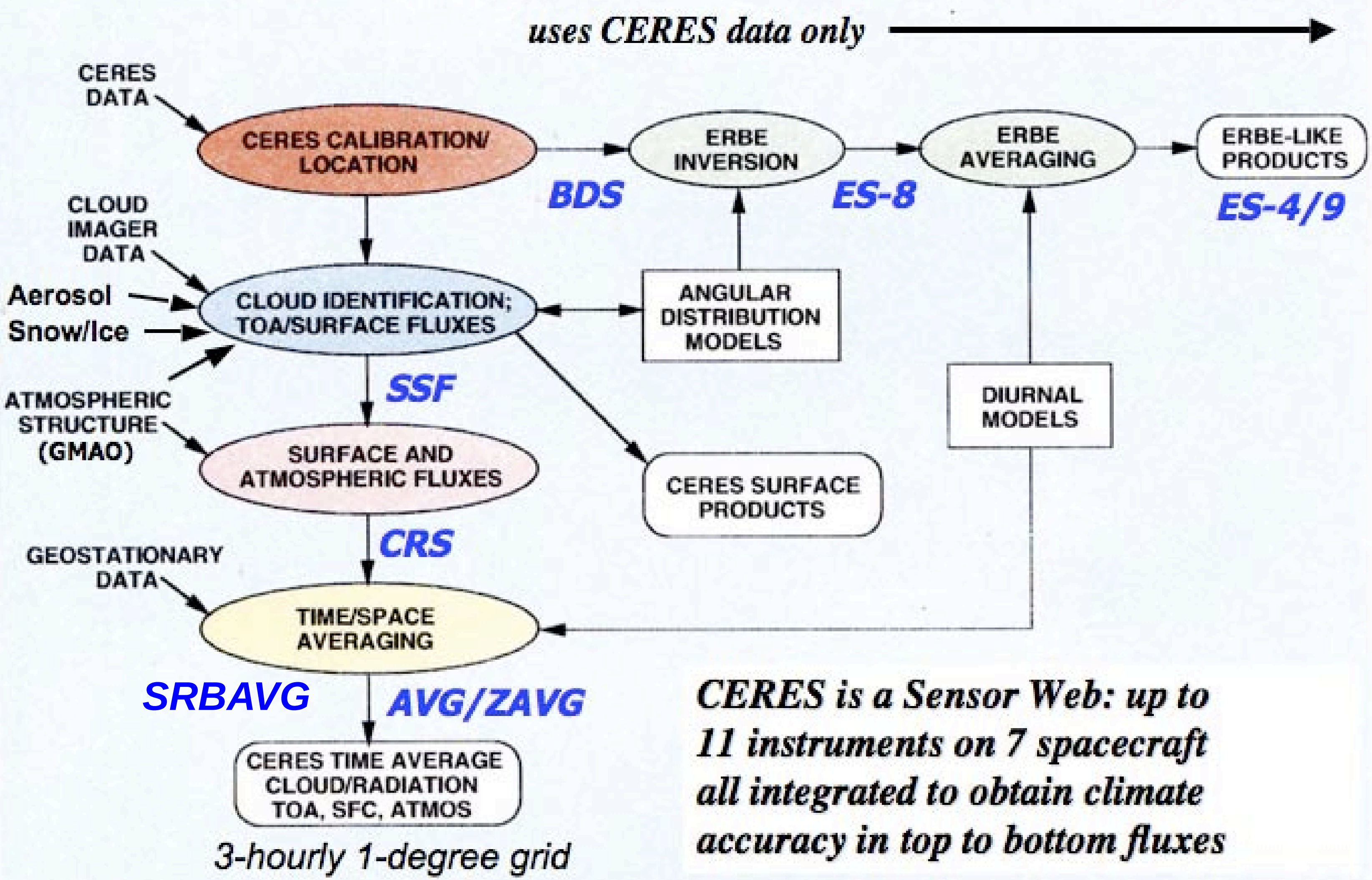


MODIS Cloud fraction (%)



MODIS Cloud-Top Temperature (K)

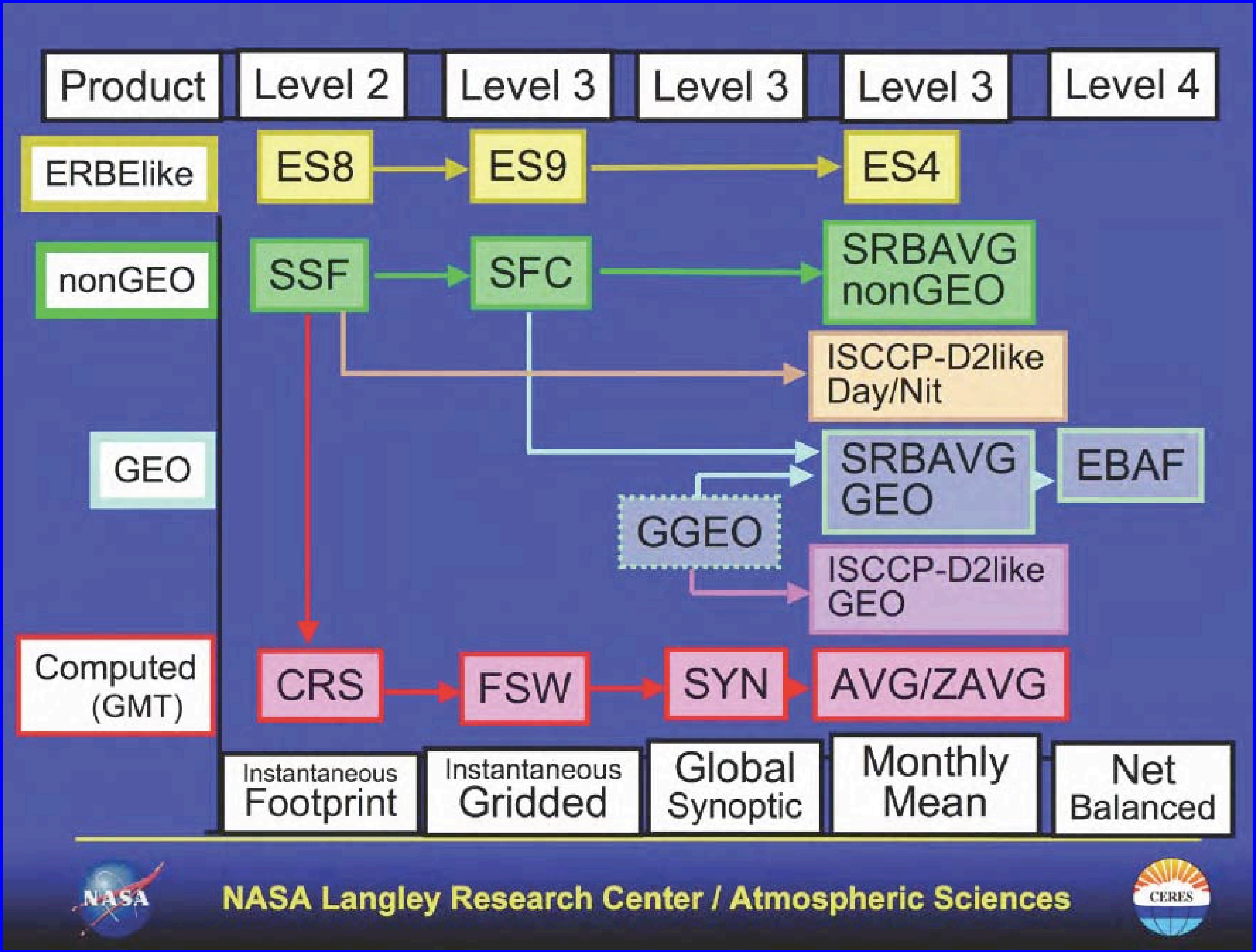
CERES DATA PROCESSING FLOW



CERES is a Sensor Web: up to 11 instruments on 7 spacecraft all integrated to obtain climate accuracy in top to bottom fluxes

CERES provides cloud-aerosol-radiation data products over several spatial and temporal scales in order to address a wide range of climate science problems.

CERES Data Products



CERES has 0.75M lines of production code; 1.7M lines of validation code

CERES Integrated Data for Radiation/Cloud/Aerosol
(TOA, Surface and Atmosphere Fluxes)

Input Data

CERES Crosstrack Broadband
CERES Hemispheric Scan ADMs
MODIS Cloud/Aerosol/Snow&Ice

Microwave Sea-Ice

Aerosol Assimilation Data

4-D Assimilation Weather Data
(fixed climate assimilation system)

Geostationary 3-hourly Data

Consistent Calibration

Output Data

ERBE-Like TOA Fluxes (20 km fov, 2.5 deg grid)

CERES Instantaneous TOA/Sfc/Atmosphere
- **20km fov (SSF, CRS products)**
- **1° gridded (SFC, FSW products)**
- **Fluxes, cloud & aerosol properties**

CERES Time Averaged TOA/Sfc/Atmosphere
- **3-hourly, daily, monthly**
- **1° gridded (SRBAVG, AVG, ZAVG products)**
- **Fluxes, cloud and aerosol properties**

- As a climate data record, CERES avoids algorithm changes (or "fixes") within a single Edition data product. The reason is to minimize aliasing algorithm changes into apparent and false climate change signals.
- When input data change (e.g. MODIS Collection 4 to 5; GEOS-4 to GEOS-5), careful analysis is performed to see if a new Edition is needed based on expected climate change magnitudes and accuracy goals.

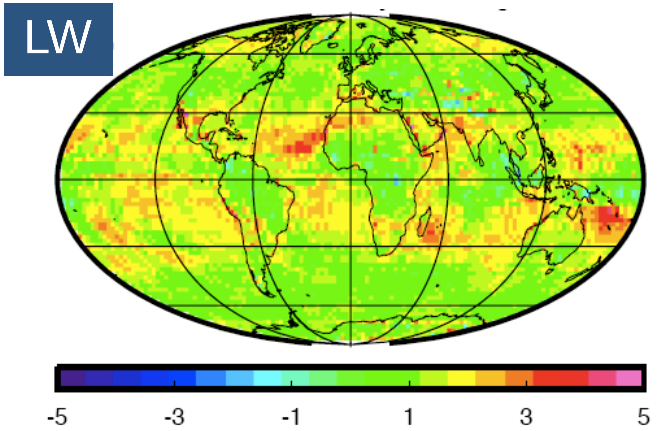
CERES-ERBE Algorithm Differences

	ERBE	CERES
Scene ID	- SW, LW Measurements - Maximum Likelihood Estimation Technique	- High-Res. Spectral Imager - Cloud Mask, Cloud Retrievals
Angular Models	- Developed from Nimbus-7 ERB scanner data. - 12 Scene Types	- Developed from CERES RAP data - Continuous function of cloud properties.
Temporal Averaging	- Constant Meteorology - ERBE diurnal albedo models	- Explicitly accounts for diurnal cloud changes. - Uses geostationary VIS/IR measurements calibrated against imager to capture shape of diurnal cycle. - Normalized with CERES.

CERES ERBE-Like minus nonGEO All-Sky TOA Flux Difference (2002)

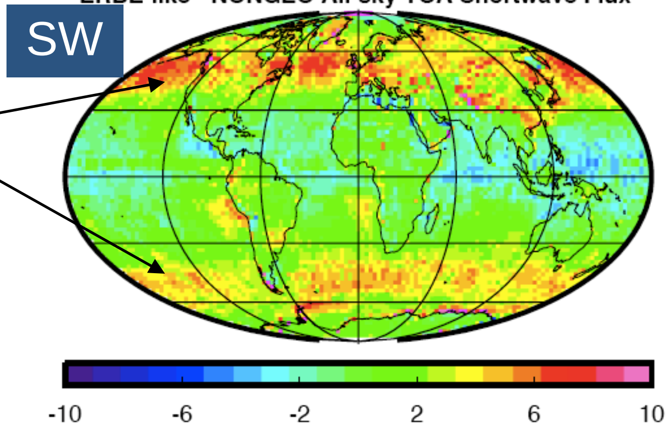
- Differences due to Scene iD + ADMs
- ERBE albedo increase with viewing geometry more pronounced at high latitudes.

Global Mean Difference



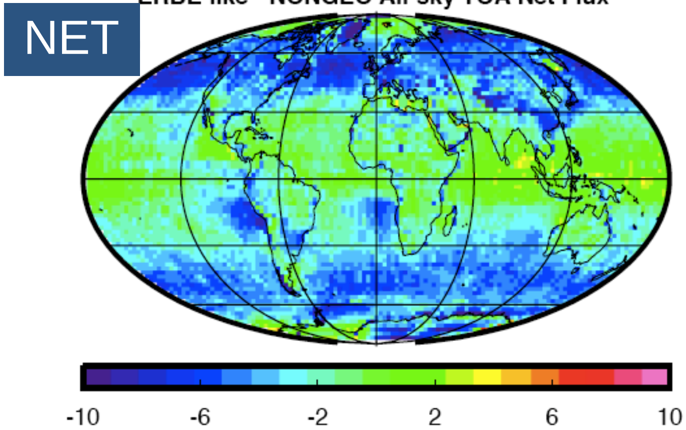
1.3 Wm^{-2}

ERBE-like - NONGEO All-sky TOA Shortwave Flux



1.7Wm^{-2}

ERBE-like - NONGEO All-sky TOA Net Flux

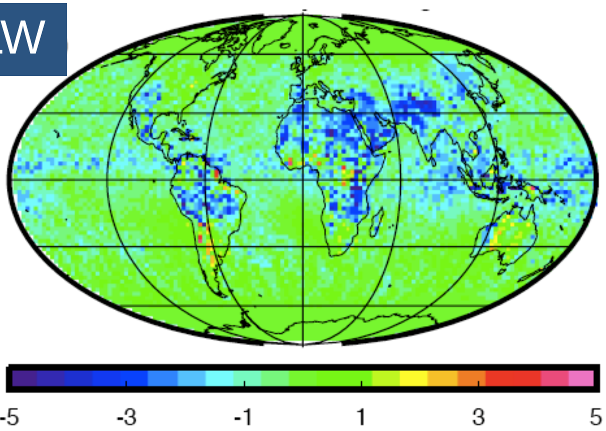


-3.0 Wm^{-2}

GEO minus NONGEO All-Sky TOA Flux Difference (2002)

Global Mean Difference

LW

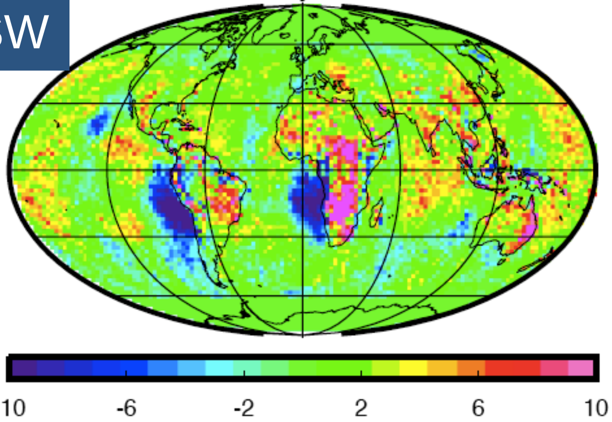


-0.6 Wm^{-2}

- Differences due to temporal interpolation

GEO - NONGEO All-sky TOA Shortwave Flux

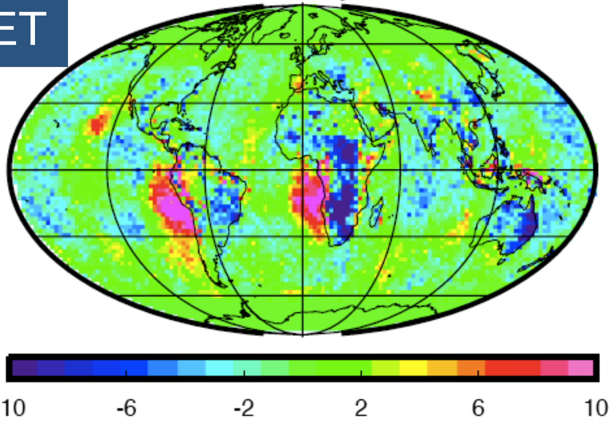
SW



1.1 Wm^{-2}

GEO - NONGEO All-sky TOA Net Flux

NET



-0.5 Wm^{-2}

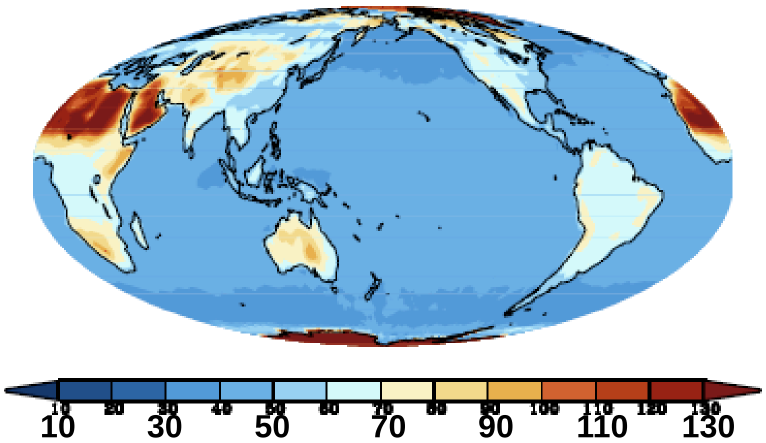
Mean TOA Flux Comparisons
ERBE (1985-1989) vs CERES (2000-2005)

Clear-Sky SW TOA Radiation (Wm^{-2})

(ERBE: 02/85-01/89; CERES: 03/00-02/05)

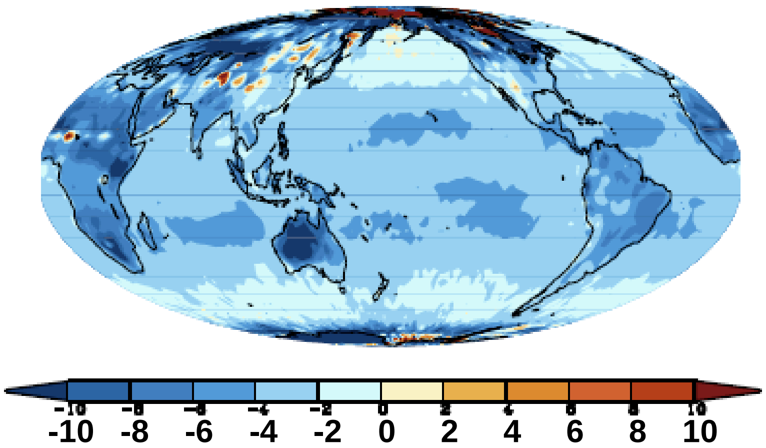
ERBE

Global Mean = 53.6



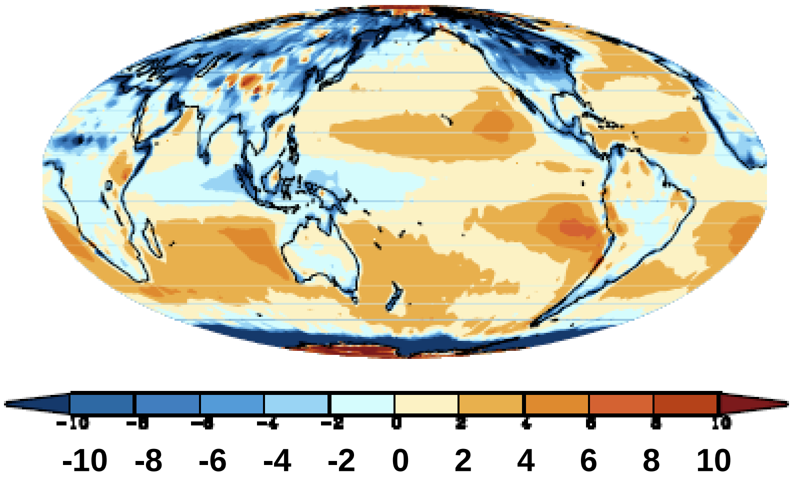
CERES ERBE−like − ERBE

Global Mean Difference = −4.5



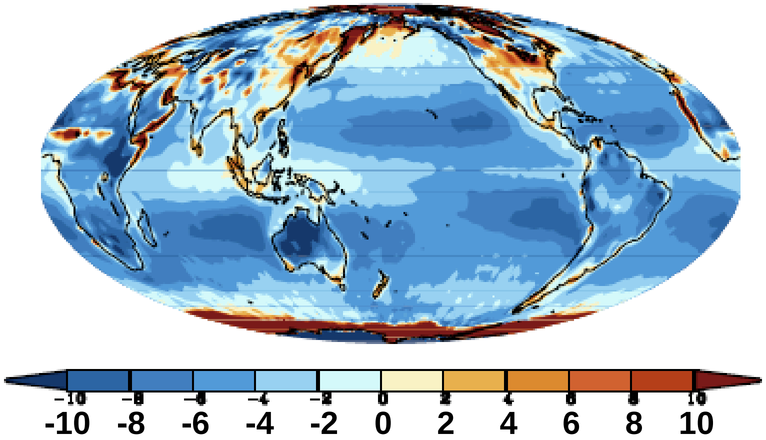
ERBE−like − SRBAVG/NONGEO

Global Mean Difference = −1.7



CERES SRBAVG/NONGEO − ERBE

Global Mean Difference = −2.8

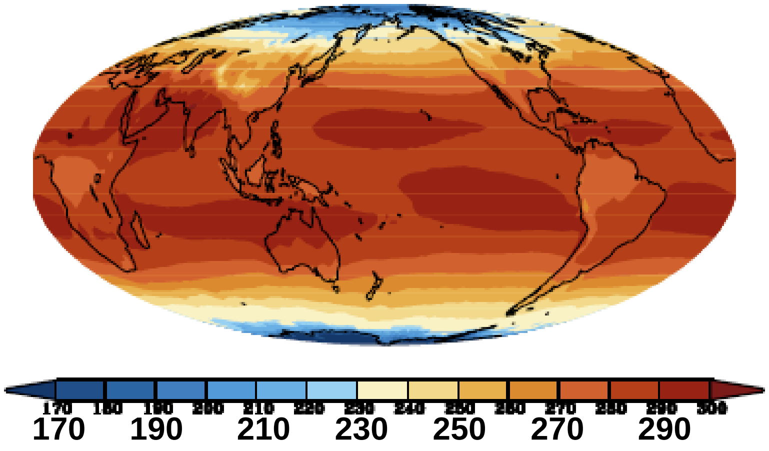


Clear-Sky LW TOA Radiation (Wm^{-2})

(ERBE: 02/85-01/89; CERES: 03/00-02/05)

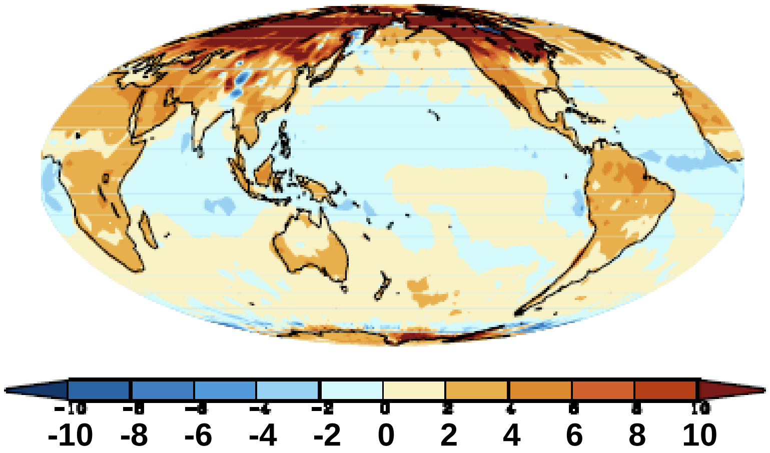
ERBE

Global Mean = 264.9



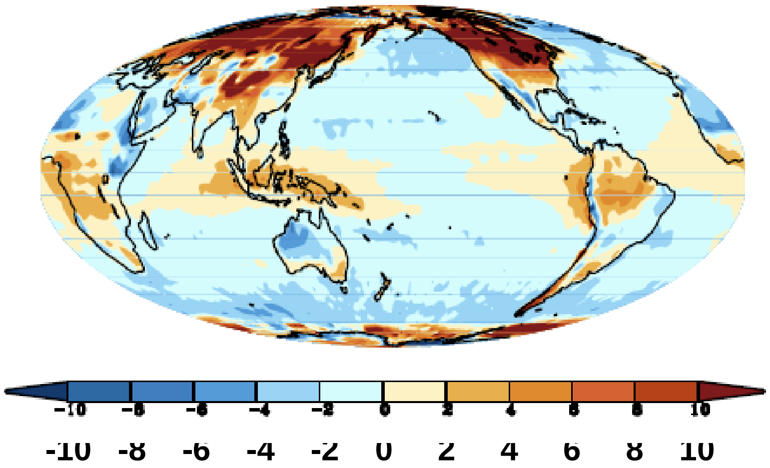
CERES ERBE−like − ERBE

Global Mean Difference = 1.8



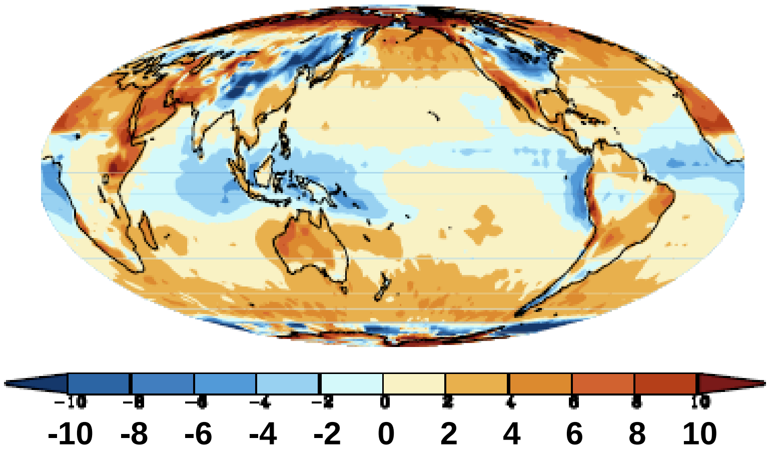
ERBE−like − SRBAVG/NONGEO

Global Mean Difference = 0.3



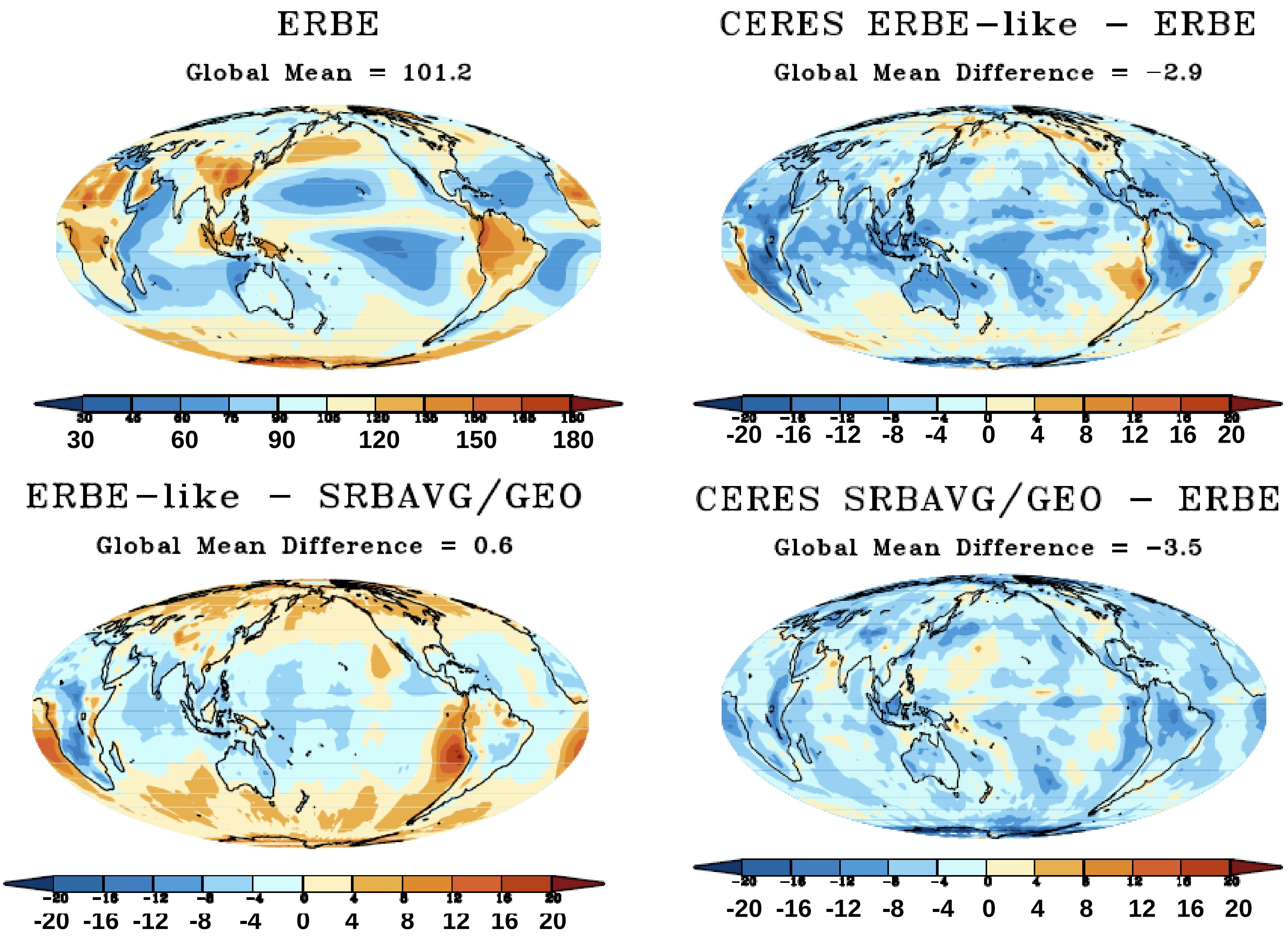
CERES SRBAVG/NONGEO − ERBE

Global Mean Difference = 1.5



All-Sky SW TOA Radiation (Wm^{-2})

(ERBE: 02/85-01/89; CERES: 03/00-02/05)



ERBE

Global Mean = 101.2

CERES ERBE−like − ERBE

Global Mean Difference = −2.9

ERBE−like − SRBAVG/GEO

Global Mean Difference = 0.6

CERES SRBAVG/GEO − ERBE

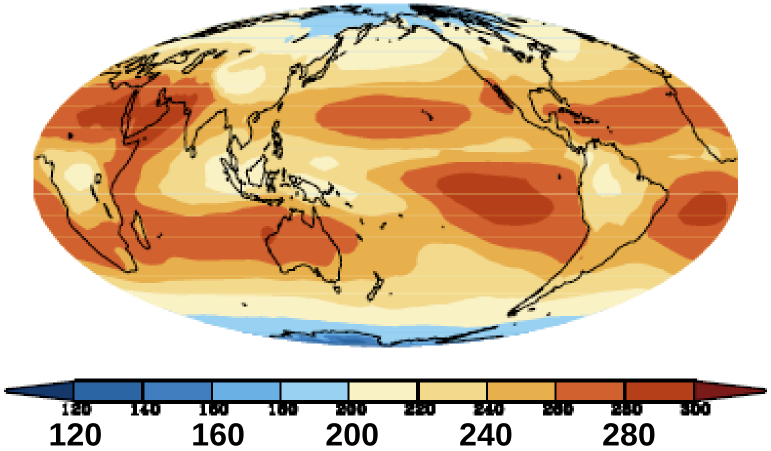
Global Mean Difference = −3.5

All-Sky LW TOA Radiation (Wm^{-2})

(ERBE: 02/85-01/89; CERES: 03/00-02/05)

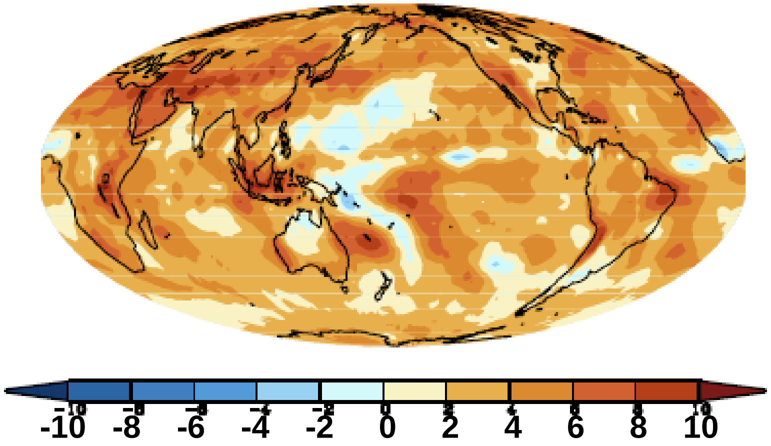
ERBE

Global Mean = 235.2



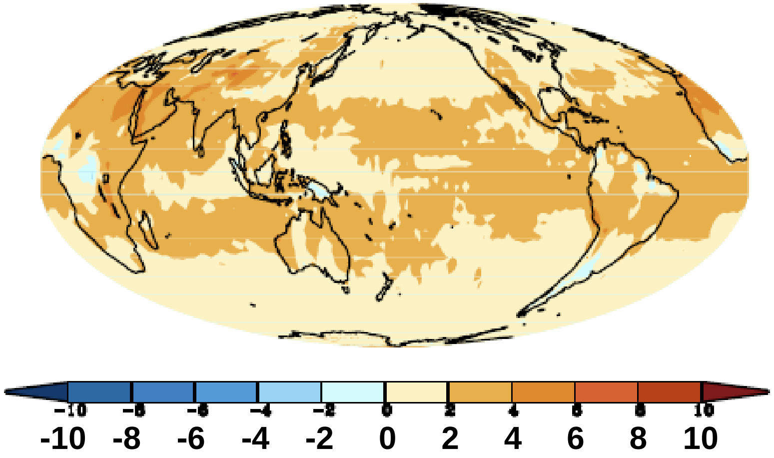
CERES ERBE–like – ERBE

Global Mean Difference = 3.7



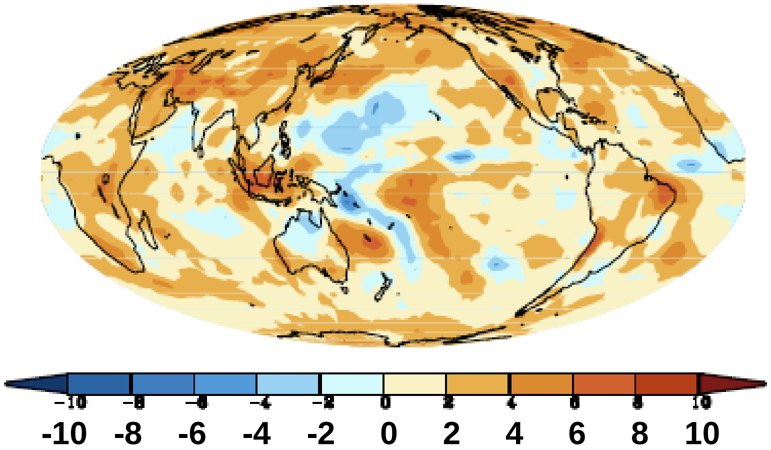
ERBE–like – SRBAVG/GEO

Global Mean Difference = 1.8



CERES SRBAVG/GEO – ERBE

Global Mean Difference = 1.9



Towards Optimal Closure of the Earth’s TOA Radiation Budget

Global Mean Clear and All-sky SW, LW and Net TOA Radiative Fluxes for Satellite-based Data Products

Product Name	ERBE S-4	CERES			GEWEX SRB Version 2.86	ISCCP FD
		ES-4 Ed2_rev1	SRBAVG-nonGEO Ed2D_rev1	SRBAVG-GEO Ed2D_rev1		
Time Period	02/85 Ğ 01/89	03/00 Ğ 02/2005				
Solar Irradiance	341.3	341.3	341.3	341.3	341.8	341.5
LW (All-sky)	235.2	239.0	237.7	237.1	240.4	235.8
SW (All-Sky)	101.2	98.3	96.6	97.7	101.7	105.2
Net (All-Sky)	**4.9**	**4.0**	**7.0**	**6.5**	**-0.3**	**0.5**
LW (Clear-Sky)	264.9	266.6	266.4	264.1	268.1	262.3
SW (Clear-Sky)	53.6	49.3	51.2	51.1	54.5	54.2
Net (Clear-Sky)	22.8	25.4	23.7	26.2	19.2	25.0
LW CRE	29.7	27.6	28.7	27.0	27.7	26.5
SW CRE	-47.6	-49.0	-45.4	-46.6	-47.2	-51.0
NET CRE	-17.9	-21.4	-16.7	-19.7	-19.5	-24.5

CERES TOA Flux Error Budget

	Bias Errors of Known Sign (Wm^{-2})				
Error Source	Incoming Solar	Outgoing SW	Outgoing LW	Net Incoming	Comment
Total Solar Irradiance	+1	0	0	+1	Recent solar irradiance measurement vs assumed solar irradiance in CERES
Spherical Earth Assumption	+0.29	+0.18 (+0.11)	-0.05 (-0.06)	+0.16 (+0.24)	Weighting latitude zones in geocentric vs geodedic coordinates.
Near-Terminator Flux	0	-0.3	0	+0.3 (+0.15)	Discretization uncertainty in time-space averaging algorithm at θ_o >85°
Heat Storage	0	0	0	+0.85	Hansen et al. (2005)

	Bias Errors of Unknown Sign (Wm^{-2})				
Source	Incoming Solar	Outgoing SW	Outgoing LW	Net Incoming	Comment
Total Solar Irradiance	±0.2	0	0	±0.2	Absolute Calibration (95% confidence)
Filtered Radiance	0	±2.0	±2.4 (N) ±5.0 (D)	±4.2	Absolute Calibration (95% confidence)
Unfiltered Radiance	0	±0.5	±0.25 (N) ±0.45 (D)	±1.0	- Instrument spectral response function - Unfiltering algorithm
Radiance-to-Flux Conversion	0	±0.2	±0.3	±0.4	Angular distribution model error
Flux Reference Level	0	±0.1	±0.2	±0.2	Uncertainty in assuming a 20-km reference level
Time & Space Averaging	0	±0.3	±0.3	±0.4	Geostationary instrument normalization with CERES
Heat Storage	0	0	0	±0.15	Hansen et al. (2005)

Expected Range in Net TOA Flux: -2.1 Wm^{-2} to 6.7 Wm^{-2}

Constrainment Algorithm

$$R_N = H + \varepsilon_{R_N}$$

H = Global average heat storage.

ε_{R_N} = Error in R_N arising due to uncertainties in several factors □$_i$ involved in determining R_N (e.g., instrument calibration, unfiltering, ADMs, etc.).

We wish to modify the parameters □$_i$ by some amount x_i such that the revised R_N is equal to *H*:

$$\hat{R}_N = R_N + \sum_i \frac{\partial R_N}{\partial p_i} x_i = H$$

$$\sum_i \frac{\partial R_N}{\partial p_i} x_i = -\varepsilon_{R_N}$$

The criterion for selecting the parameters to adjust is to choose the most likely set x_i that satisfy the above equations using a maximum likelihood estimate for the x_i.

This is solved using the method of Lagrange multipliers.

(Wm^{-2})	SRBAVG_GEO Ed2D_rev1		
	Original	Adjusted	Difference
Solar Irradiance	341.3	340.0	-1.3
LW (All-Sky)	237.1	239.6	2.5
SW (All-Sky)	97.7	99.5	1.8
Net (All-Sky)	6.5	0.87	-5.6

Results of Constraint Algorithm

	Adjusted ERBE (Feb 1985-Apr 1989)	Adjusted ERBE (Feb 1985-Apr 1989)	Adjusted CERES (Mar 2000–May 2004)	Adjusted CERES (This Study) (Mar 2000–Feb 2005)		
Product Name	Trenberth (1997)	Fasullo & Trenberth (2008)	Fasullo & Trenberth (2008)	CERES SRBAVG-nonGEO Ed2D_rev1_ADJ	CERES SRBAVG-GEO_Ed2Drev1_ADJ	CERES SRBAVG-GEO_Ed2Drev1_ADJ All-Sky & CERES-MODIS Clear-Sky
Solar Irradiance	**341.3**	341.3	341.3	340.0	340.0	**340.0**
LW (All-sky)	**234.4**	234.4	238.5	240.2	239.6	**239.6**
SW (All-Sky)	**106.9**	106.9	101.9	98.4	99.5	**99.5**
Net (All-Sky)	**0.0**	0.0	0.9	1.38	0.87	**0.87**
LW (Clear-Sky)	264.9*	264.9*	269.1**	269.2	266.9***	269.1
SW (Clear-Sky)	53.6*	53.6*	52.9**	52.1	52.0	52.9
Net (Clear-Sky)	22.8*	22.8*	18.0**	18.7	21.1	18.0
LW CRE	30.5*	30.5*	30.6**	29.0	27.3	29.5
SW CRE	-53.3*	-53.3*	-49.0**	-46.3	-47.5	-46.6
NET CRE	-22.8*	-22.8*	-18.4**	-17.3	-20.2	-17.1

High-Resolution Clear-sky Fluxes

- CERES SRBAVG clear-sky monthly mean TOA fluxes are provided for 1° x1° regions from CERES footprints identified as clear according to 1-km resolution MODIS data.

- Because of the coarse spatial resolution of CERES (20 km at nadir), only flux contributions from cloud-free regions occurring over relatively large spatial scales are considered.

  => Population is biased to certain meteorological conditions and geographical regions.

  => Clear-sky maps contain missing regions.

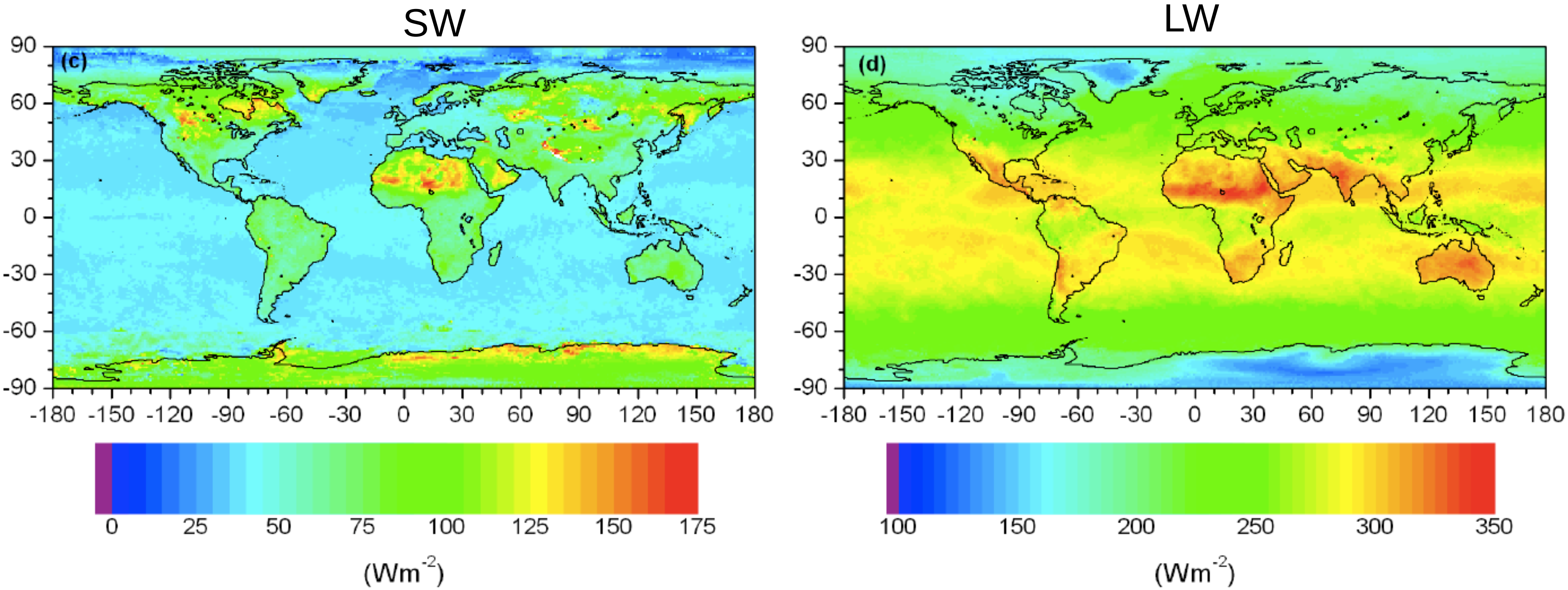
- An alternative approach is to recover clear-sky flux contributions at smaller spatial scales directly from MODIS radiances in cloud-free portions of CERES footprints.

That is, determine gridbox mean clear-sky flux from an area-weighted average of:

(i) CERES broadband fluxes from completely cloud-free footprints.

(ii) MODIS-derived “broadband” clear-sky fluxes estimated from the cloud-free portions of partly and mostly cloudy CERES footprints

High-Resolution Clear-Sky TOA Flux
(March 2002)

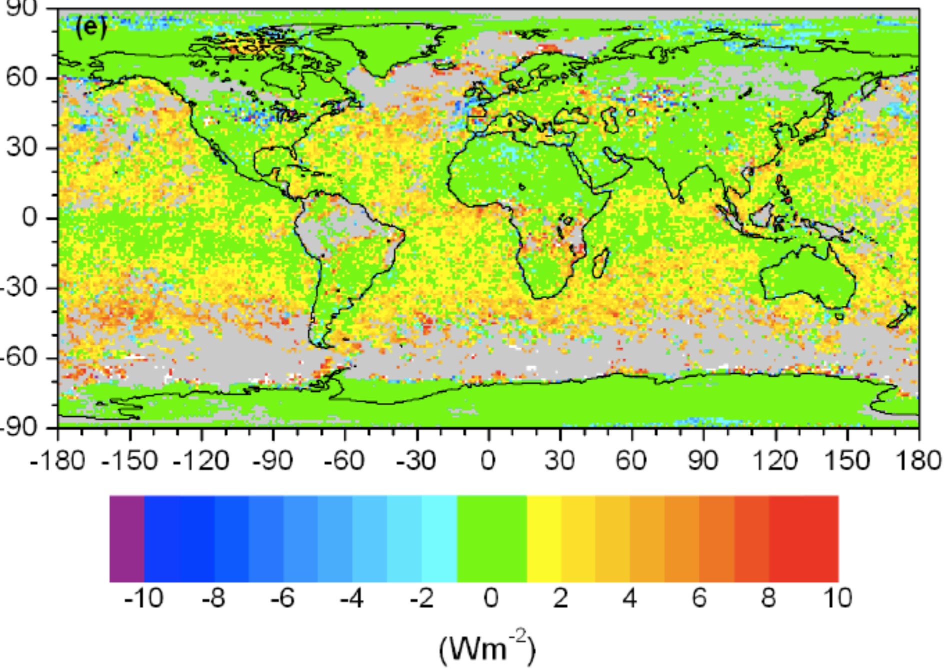


SW

LW

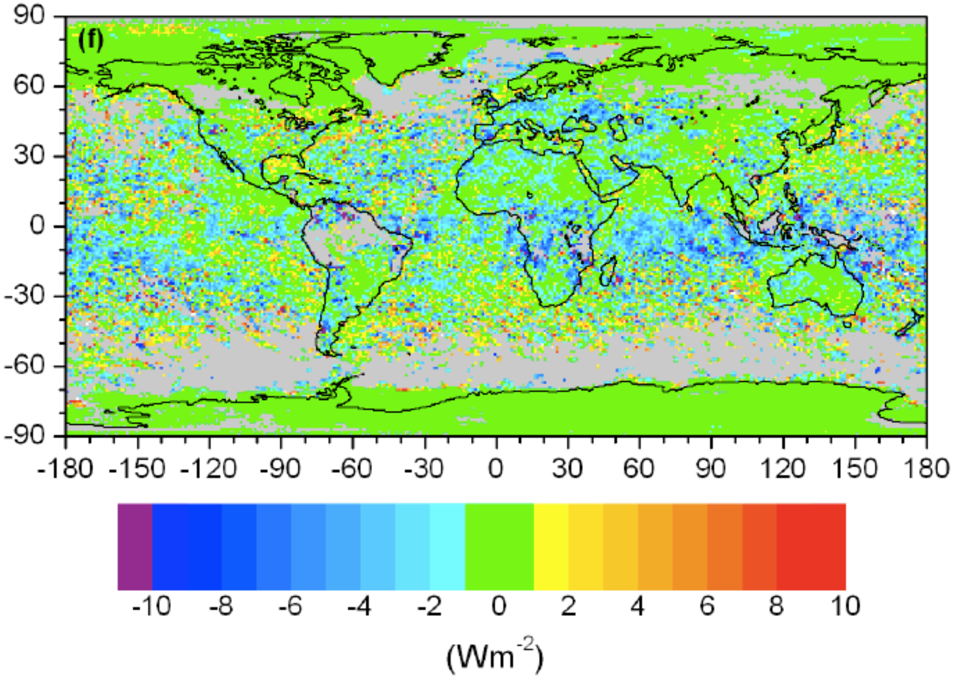
High-Resolution Minus CERES-Only Clear-Sky TOA Flux (March 2002)

SW



Difference: 0.9 Wm^{-2}

LW



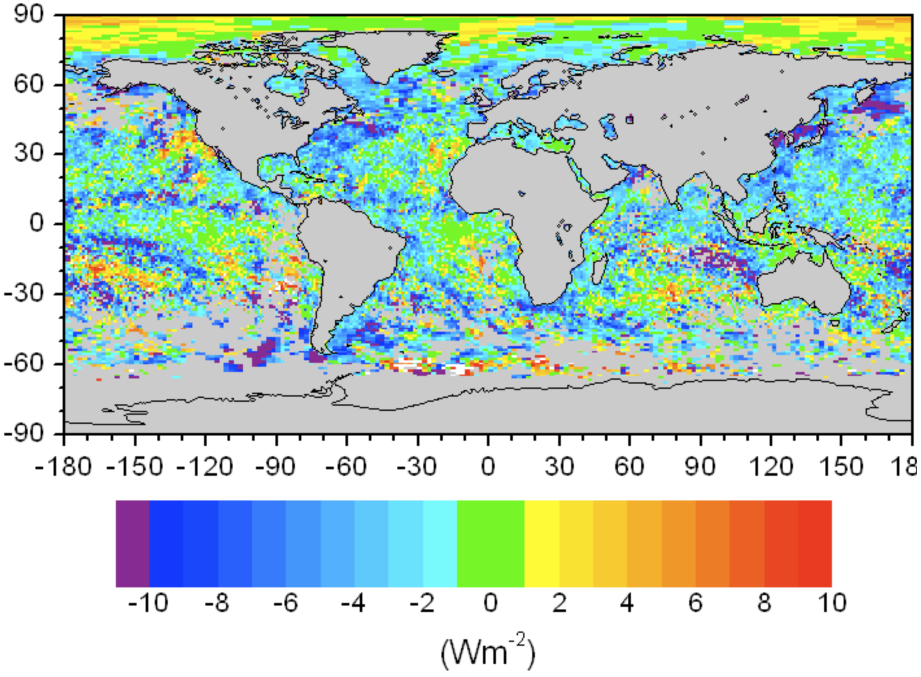
Difference: -0.3 Wm^{-2}

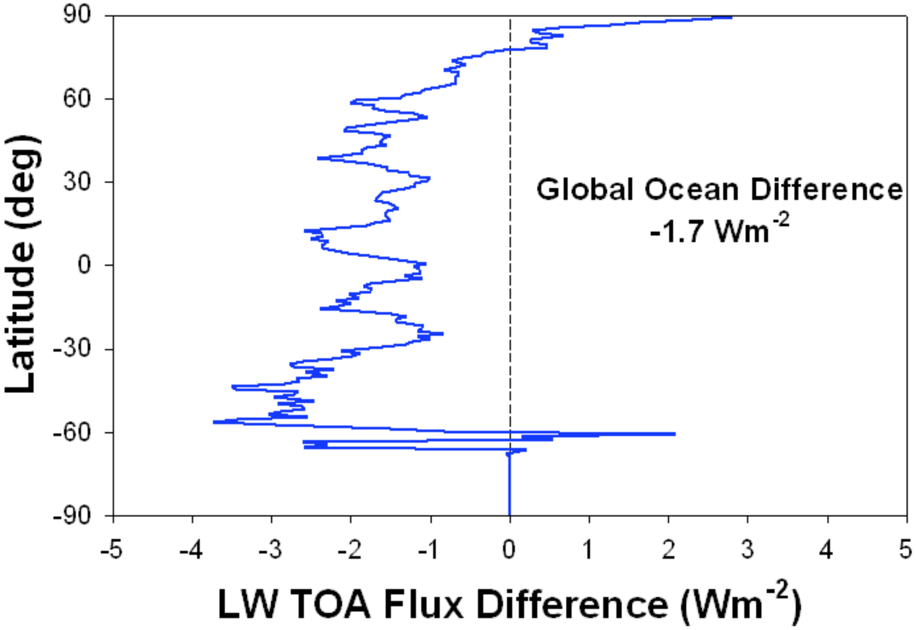
Global Mean Clear-Sky TOA Fluxes

(Wm^{-2})	ERBE S4	CERES ES8	CERES SRBAVG	EBAF
LW	264.9	266.6	266.4	269.1
SW	53.6	49.3	51.2	52.9
Net	22.8	25.4	23.7	18.0

Clear-sky OLR Sensitivity to Spatial Sampling

All Gridbox minus CERES-Footprint Clear LW TOA Flux Difference
(CERES_Terra_CRS_Ed2B; July 04)

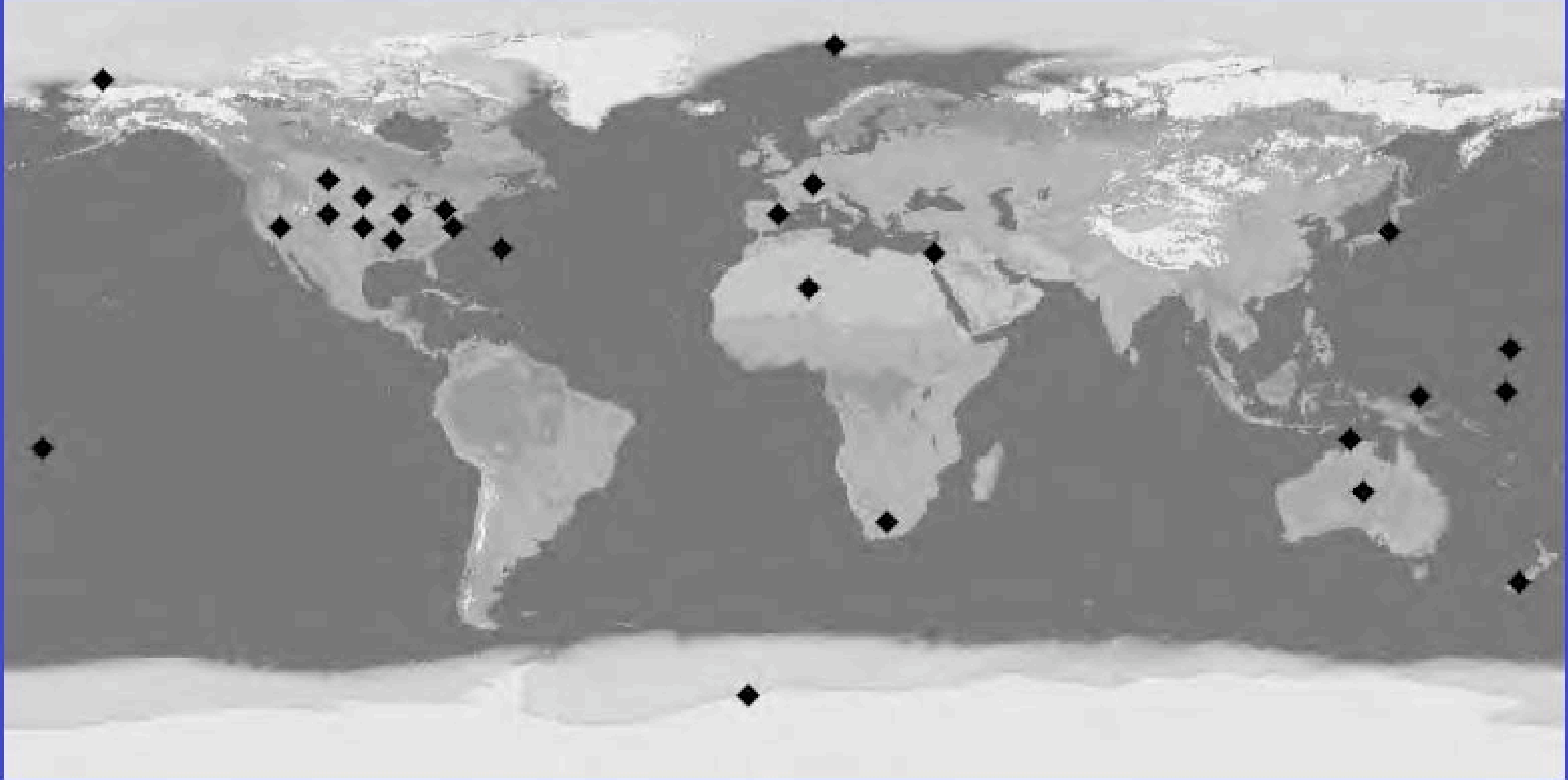




- Computing clear-sky OLR using all-gridboxes results in a ~2 Wm^{-2} reduction in flux compared to calculation that includes only cloud-free CERES footprints.

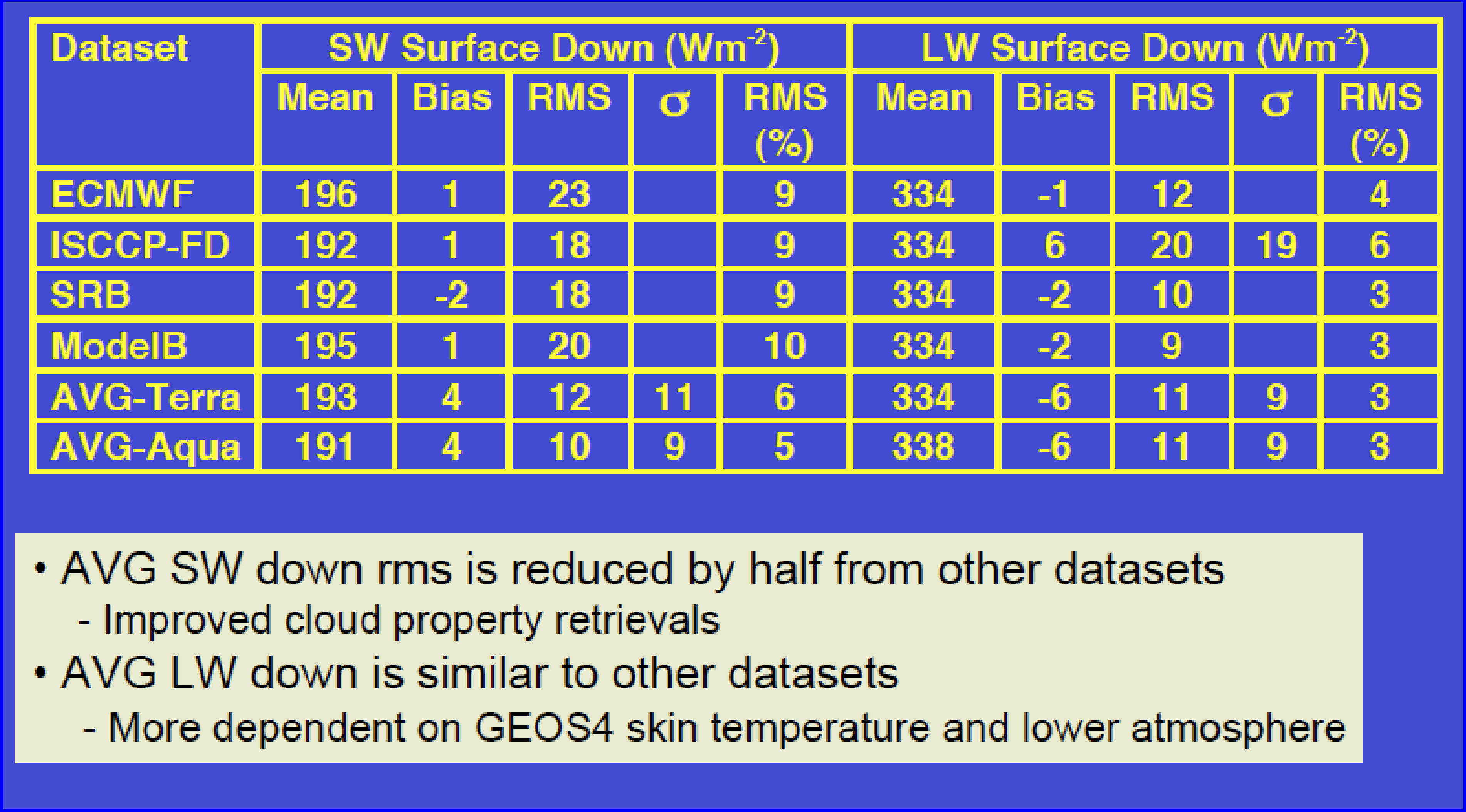
Surface and Within-Atmosphere Radiation Budgets

The 26 CAVE Sites Used in Surface Comparisons



- Ground based radiometer fluxes are used as “truth”
- Mostly located over land regions

Satellite and Ground Site Surface Flux Comparisons (Monthly Means for Seasonal Months for Apr00 – Oct05)

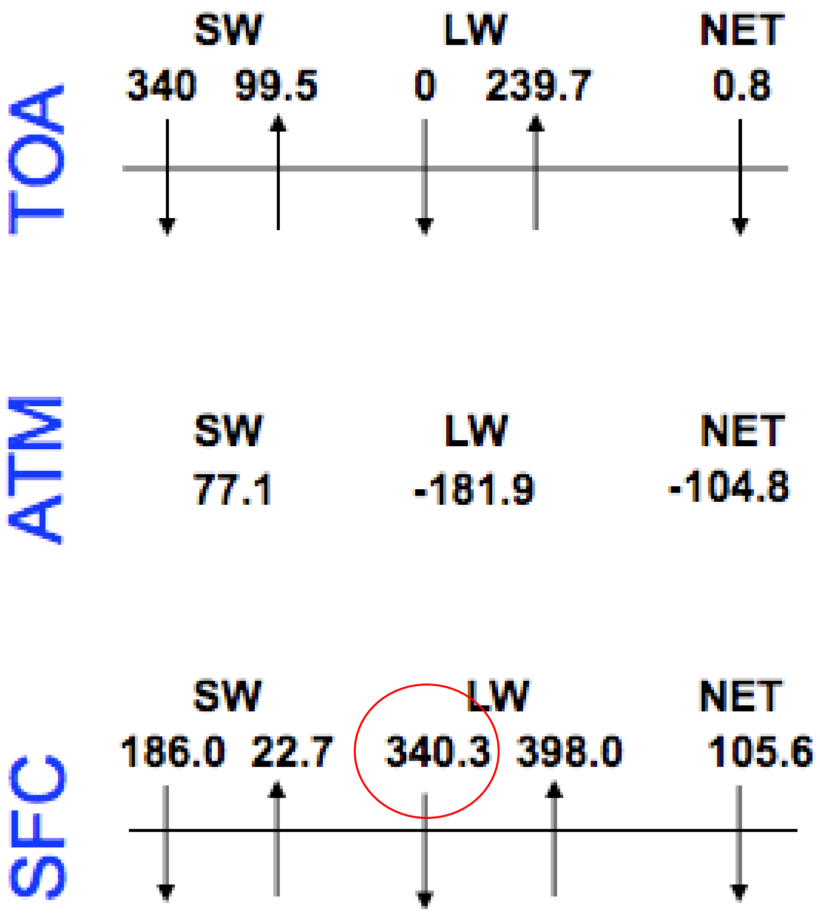


Dataset	SW Surface Down (Wm^{-2})					LW Surface Down (Wm^{-2})				
	Mean	Bias	RMS	σ	RMS (%)	Mean	Bias	RMS	σ	RMS (%)
ECMWF	196	1	23		9	334	-1	12		4
ISCCP-FD	192	1	18		9	334	6	20	19	6
SRB	192	-2	18		9	334	-2	10		3
ModelB	195	1	20		10	334	-2	9		3
AVG-Terra	193	4	12	11	6	334	-6	11	9	3
AVG-Aqua	191	4	10	9	5	338	-6	11	9	3

- AVG SW down rms is reduced by half from other datasets
  - Improved cloud property retrievals
- AVG LW down is similar to other datasets
  - More dependent on GEOS4 skin temperature and lower atmosphere

All-Sky Global Radiation Budget

EBAF



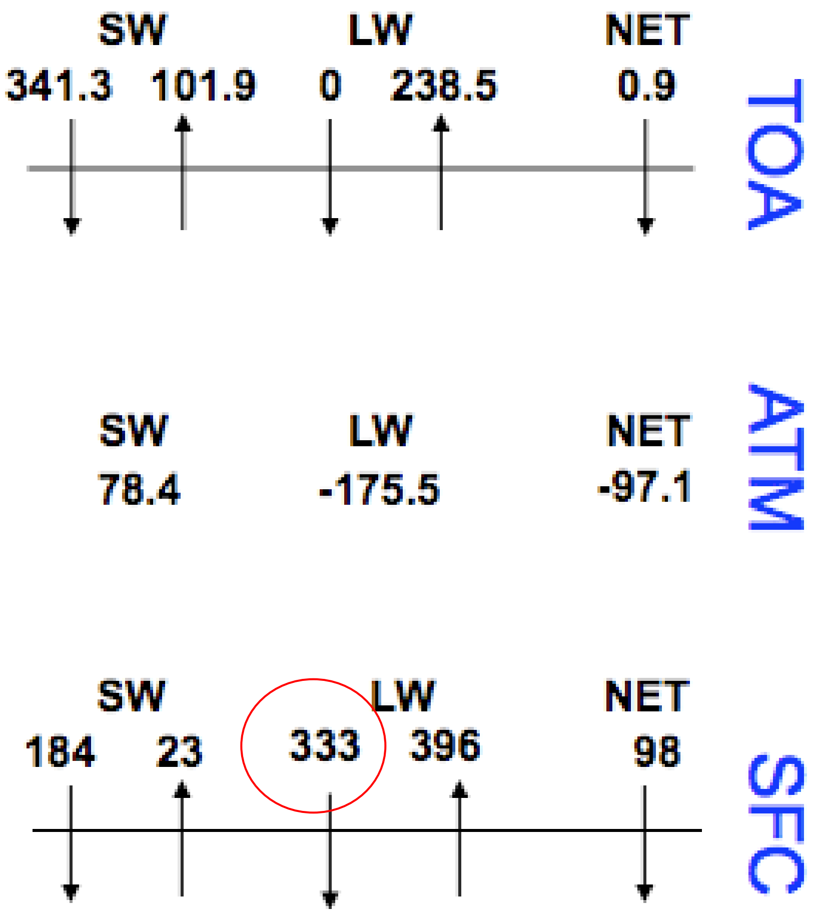
TOA
SW 340 99.5
LW 0 239.7
NET 0.8

ATM
SW 77.1
LW -181.9
NET -104.8

SFC
SW 186.0 22.7
LW 340.3 398.0
NET 105.6

- CERES EBAF & CERES AVG

Trenberth et al. (2009)



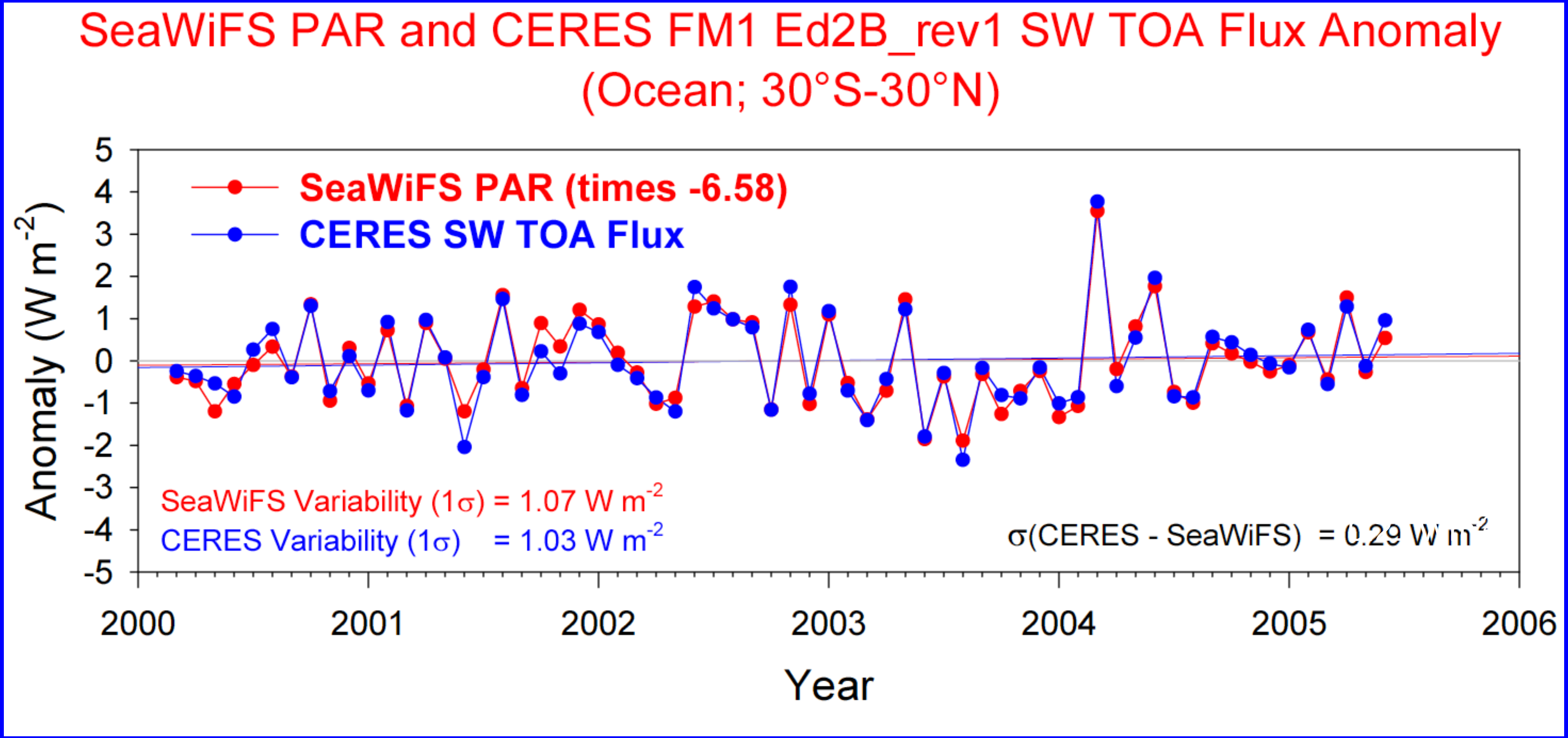
TOA
SW 341.3 101.9
LW 0 238.5
NET 0.9

ATM
SW 78.4
LW -175.5
NET -97.1

SFC
SW 184 23
LW 333 396
NET 98

- CERES for TOA
- Reanalysis, GPCP, Kim & Ram08 for within-atmosphere and surface terms

Cloud-Radiation Variability



SeaWiFS PAR and CERES FM1 Ed2B_rev1 SW TOA Flux Anomaly (Ocean; 30°S-30°N)

SeaWiFS Variability (1σ) = 1.07 W m^{-2}

CERES Variability (1σ) = 1.03 W m^{-2}

σ(CERES - SeaWiFS) = 0.29 W m^{-2}

Shows consistent calibration stability at < 0.3 Wm^{-2} per decade (95% conf)

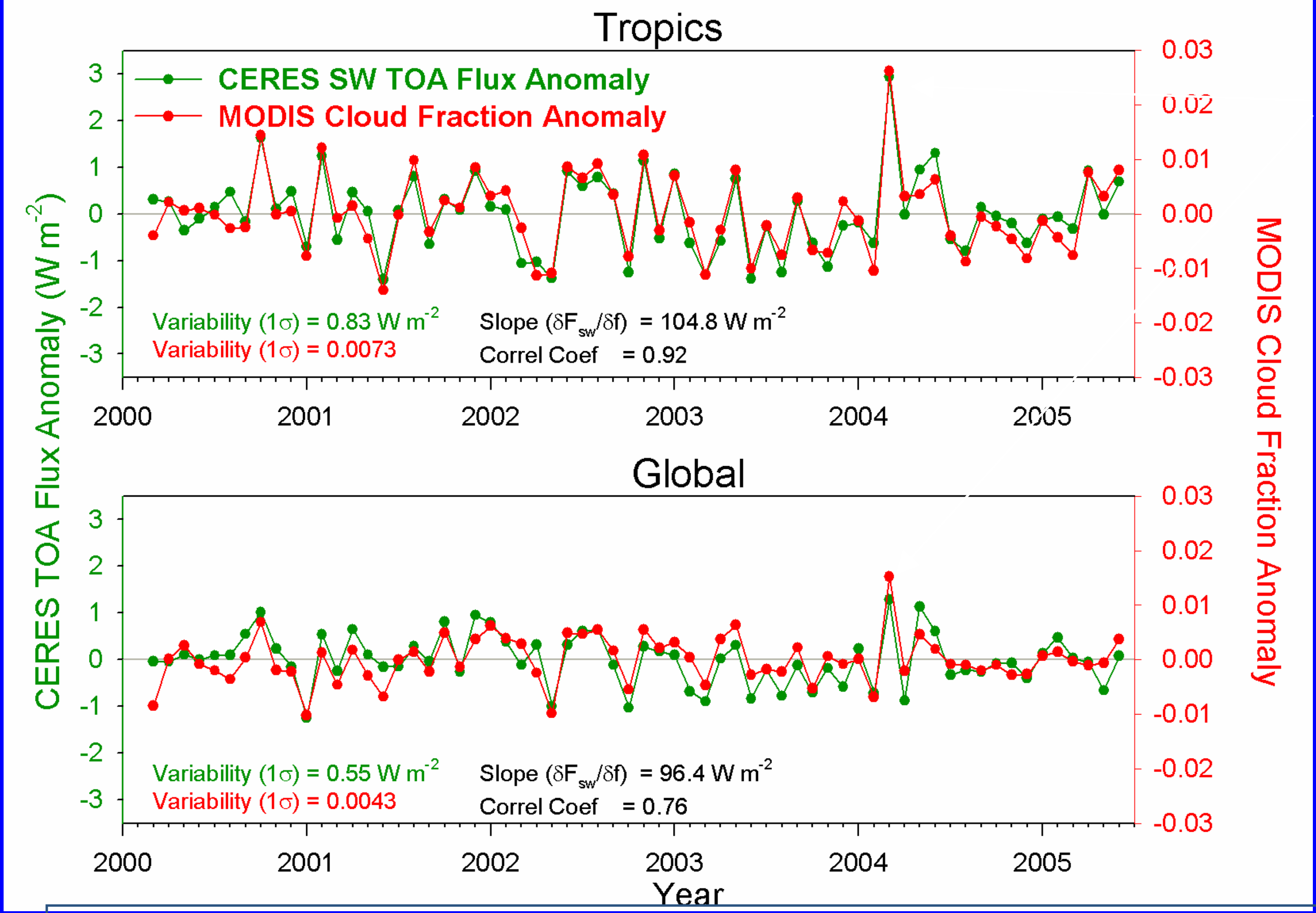
Unfortunately only works for tropical mean ocean (nband vs bband issues)

Regional trends differ by +2 to -5 Wm^{-2}/decade SeaWiFS vs CERES

Loeb et al. 2007

J. Climate

CERES Shortwave TOA Reflected Flux Changes: Ties to Changing Cloud Fraction



Tropics drive global albedo variations:

global is in phase with tropics and 1/2 the magnitude

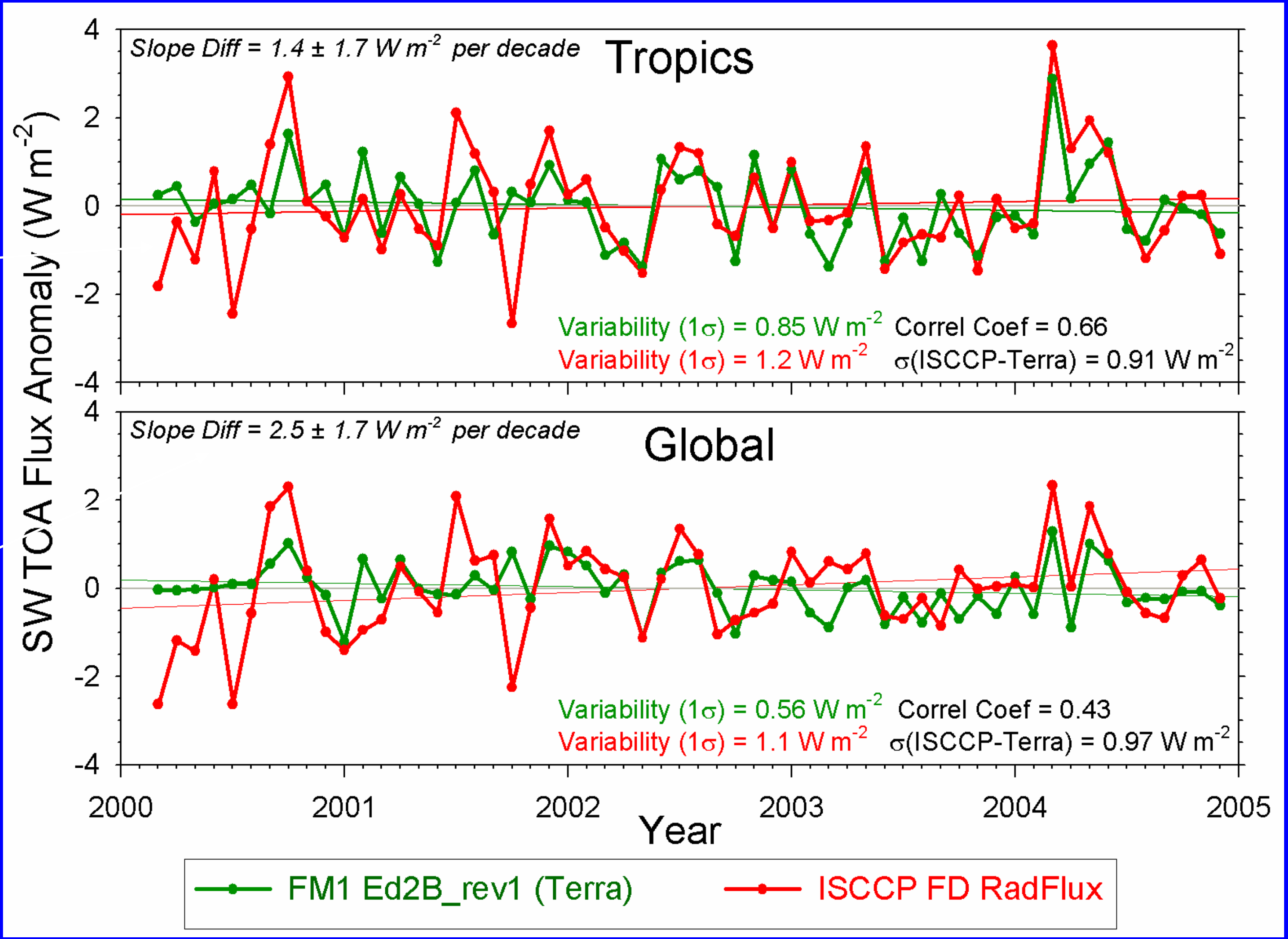
Cloud fraction variations are the cause (not optical depth)

Unscrambling climate signal cause and effect requires complete parameter set at climate accuracy, e.g. for forcing/response energetics: radiation, aerosol, cloud, land, snow/ice, temperature, humidity, precipitation

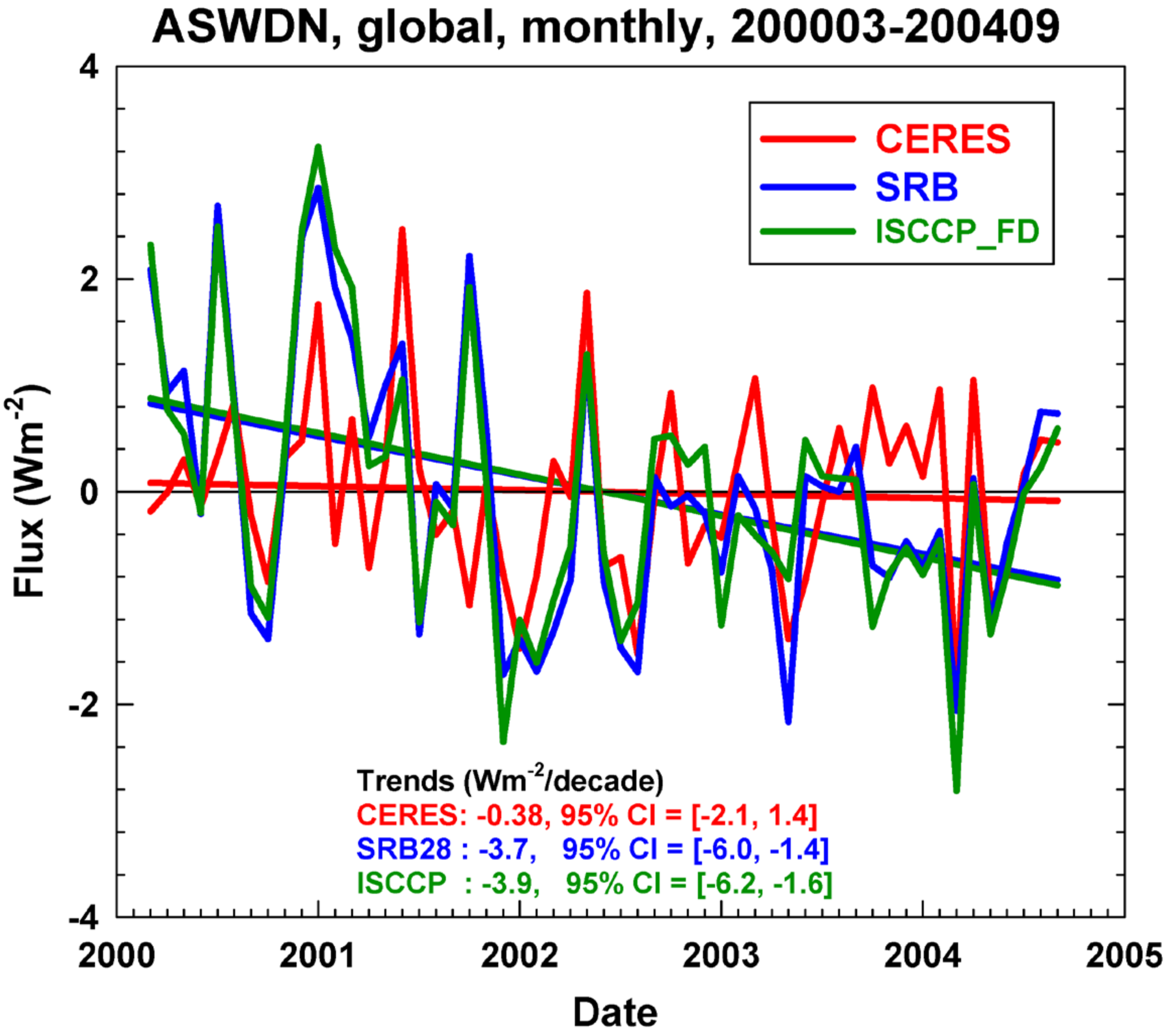
How well can we pull climate records from meteorological satellite data like ISCCP from geostationary?

Geo calibration & sampling errors dominate inter-annual signals

Uncertainty in Geo trends are a factor of 10 larger than climate goal: can we learn how to improve past data sets?



Loeb et al., 2007 J. Climate



ASWDN, global, monthly, 200003-200409

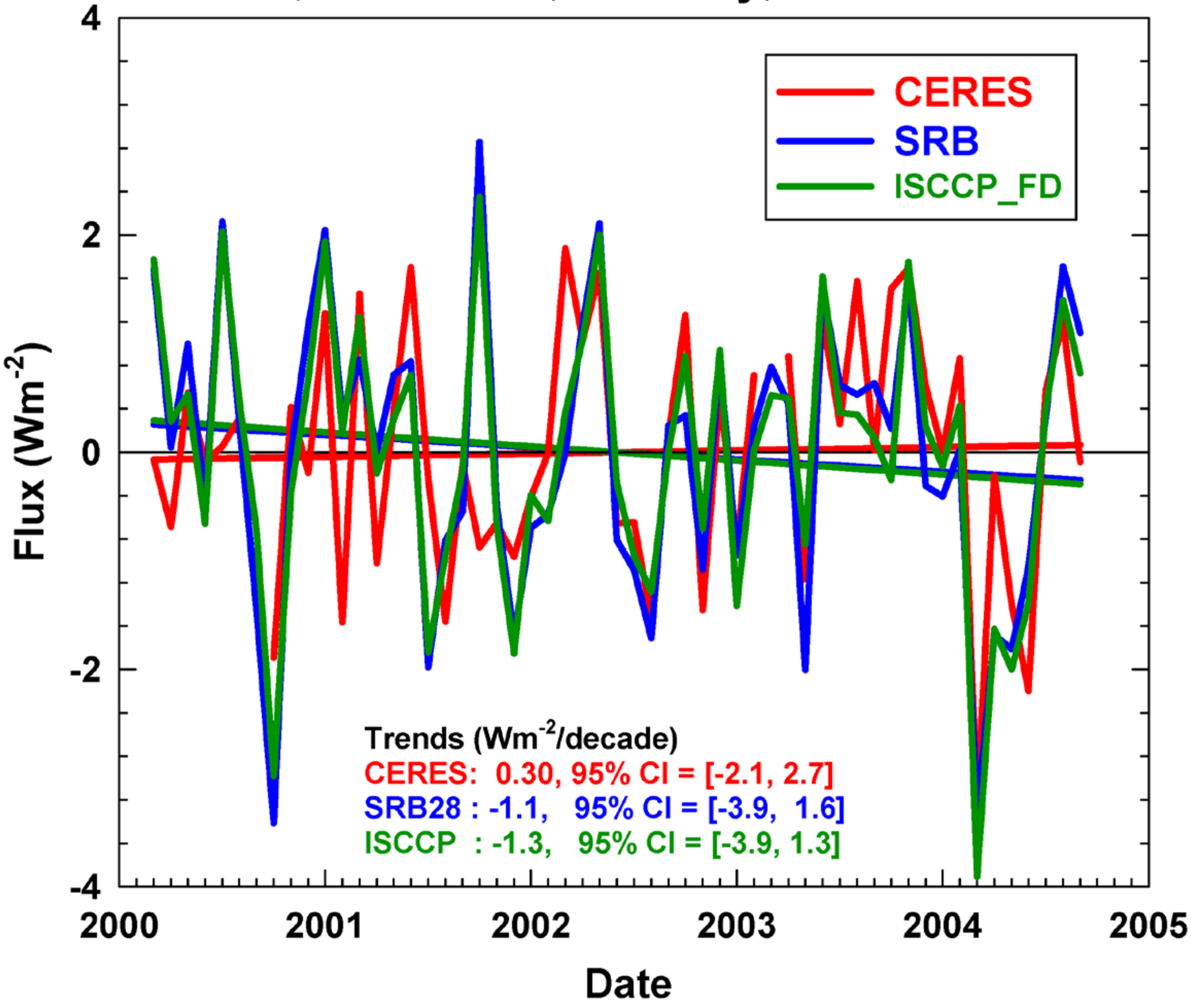
Trends (Wm^{-2}/decade)

CERES: -0.38, 95% CI = [-2.1, 1.4]

SRB28 : -3.7, 95% CI = [-6.0, -1.4]

ISCCP : -3.9, 95% CI = [-6.2, -1.6]

ASWDN, 30°S-30°N, monthly, 200003-200409

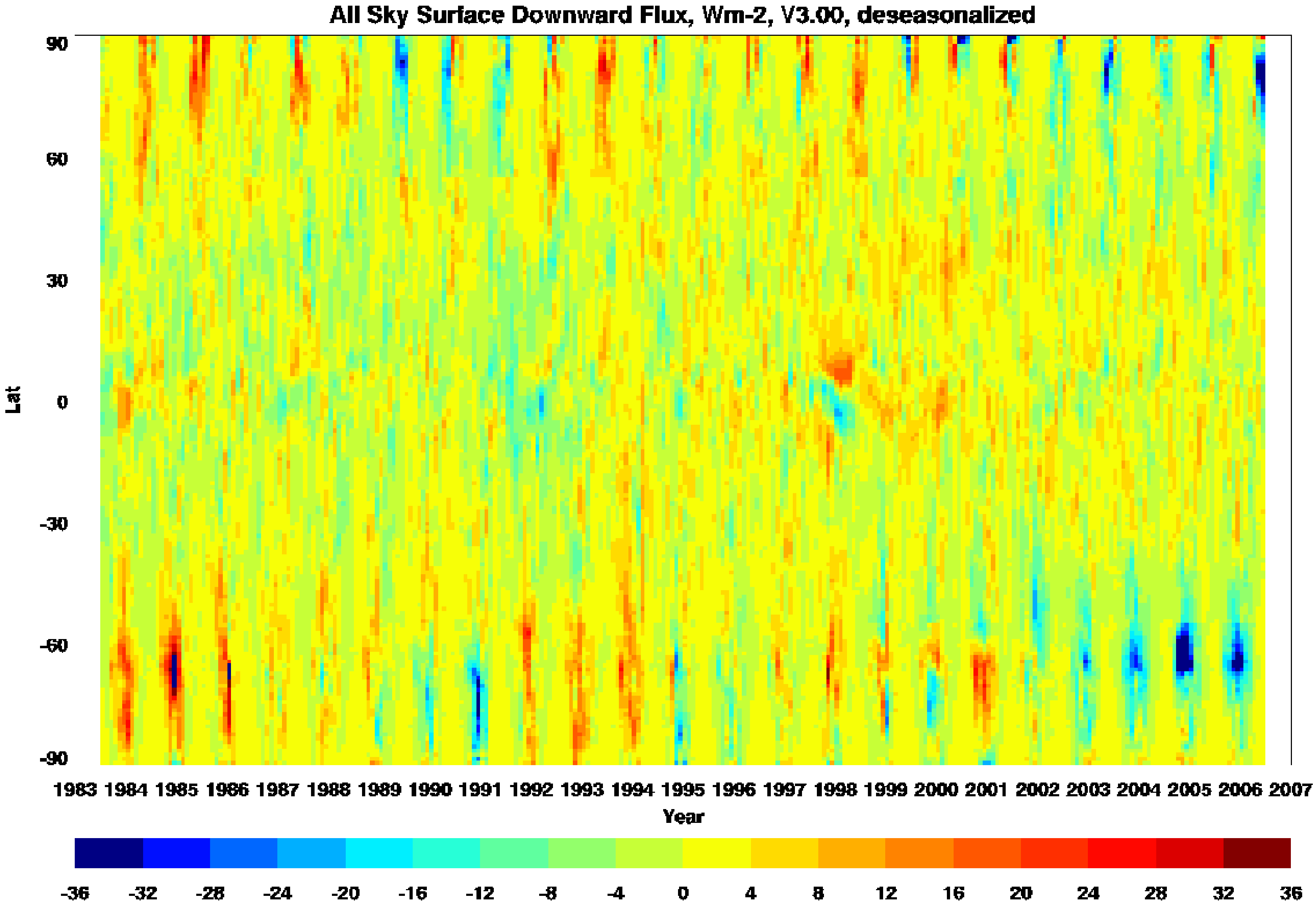


Trends (Wm^{-2}/decade)

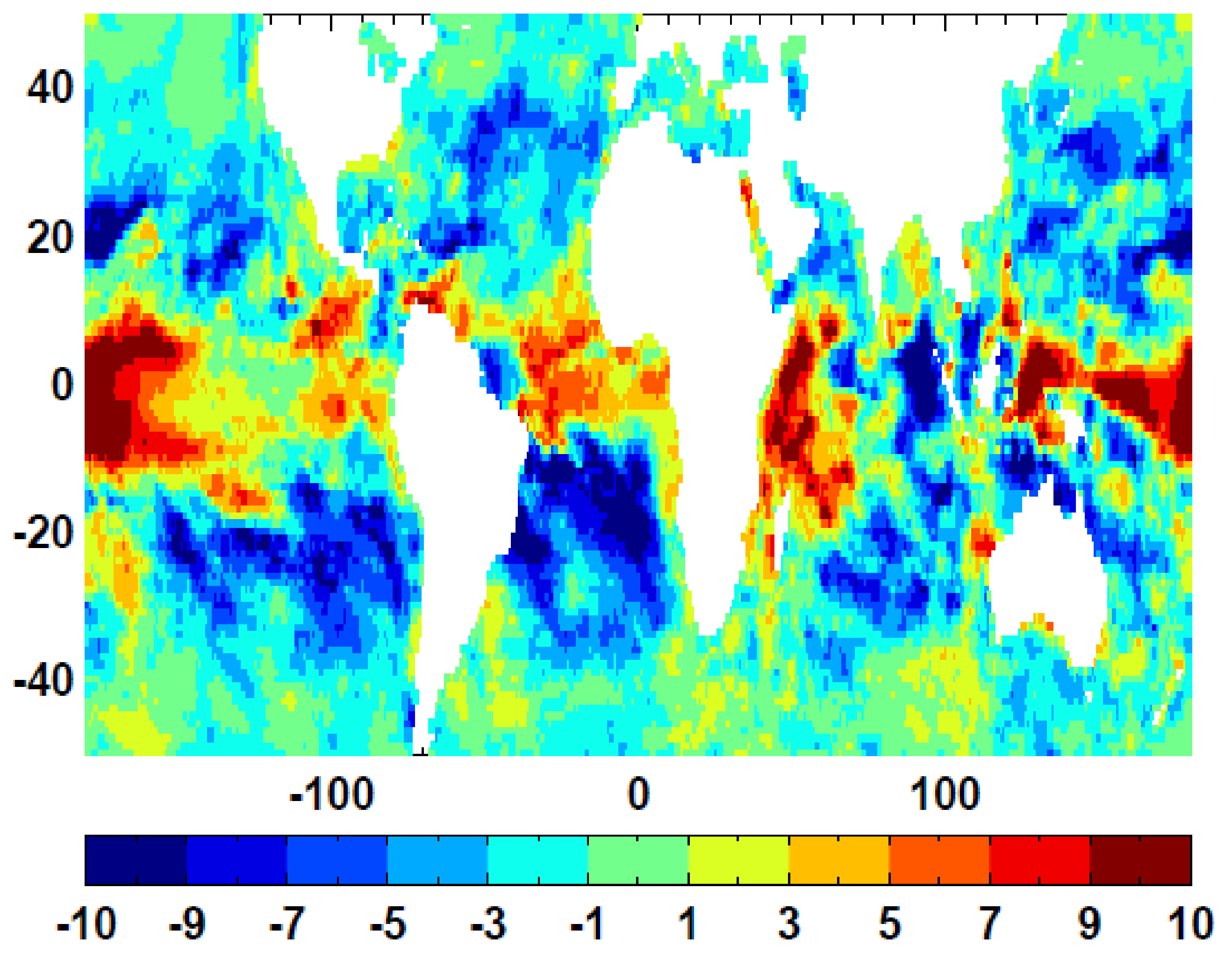
CERES: 0.30, 95% CI = [-2.1, 2.7]

SRB28 : -1.1, 95% CI = [-3.9, 1.6]

ISCCP : -1.3, 95% CI = [-3.9, 1.3]

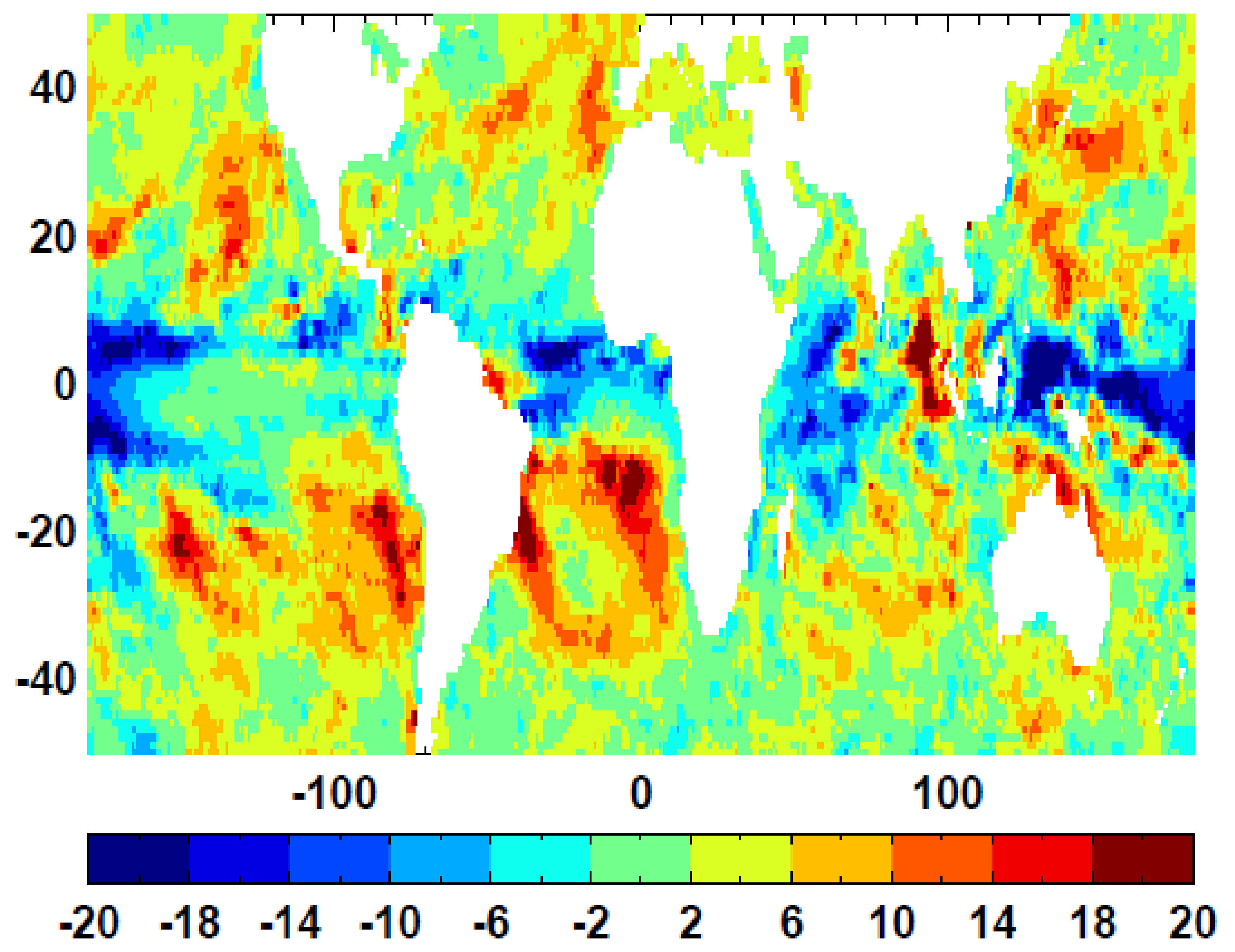

All Sky Surface Downward Flux, Wm-2, V3.00, deseasonalized
90
60
30
0
-30
-60
-90
Lat
1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007
Year
-36 -32 -28 -24 -20 -16 -12 -8 -4 0 4 8 12 16 20 24 28 32 36

Change in total cloud fraction with SST (%/K)



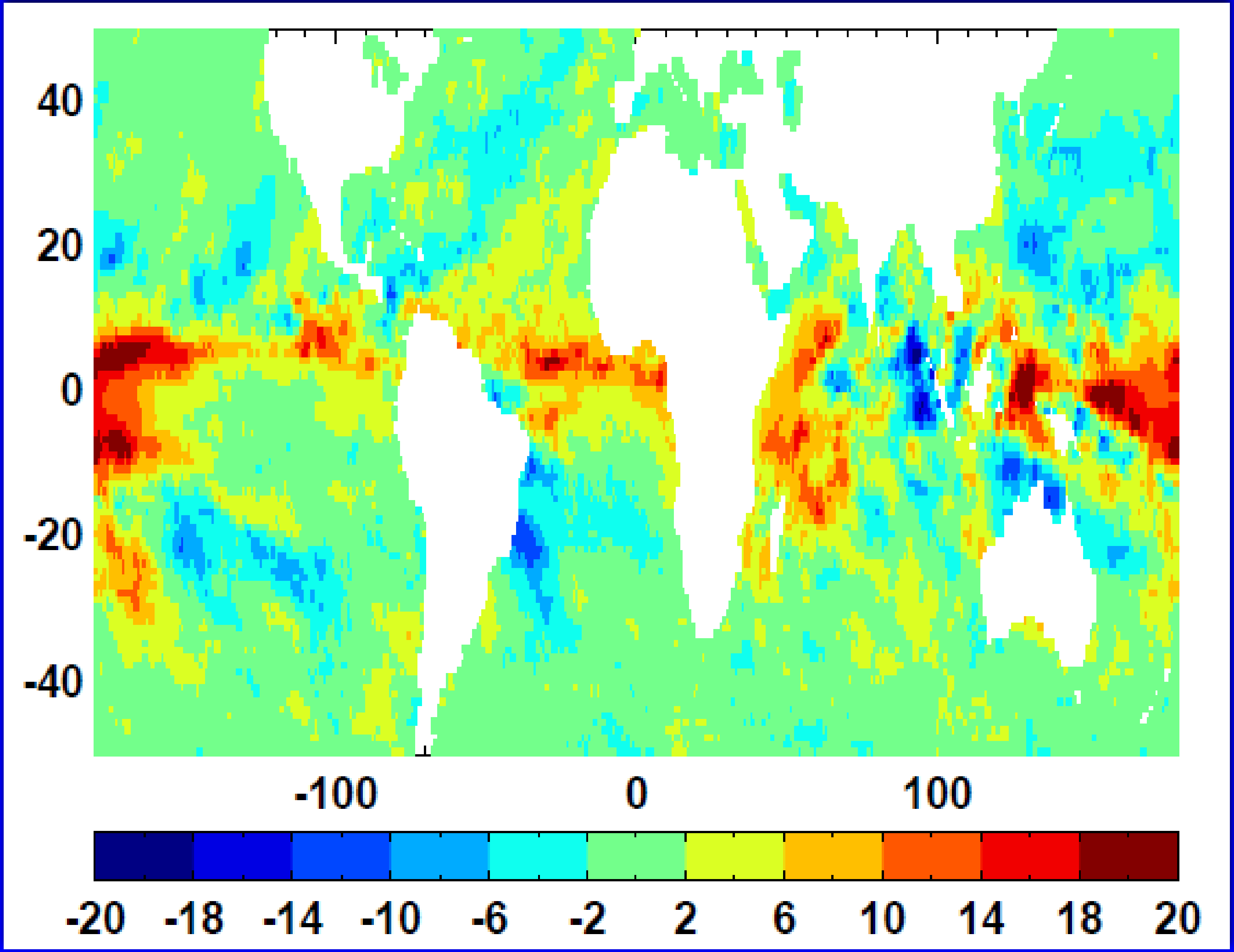
Z. Eitzen

Change in SW CRE with SST (W m^{-2} K^{-1})



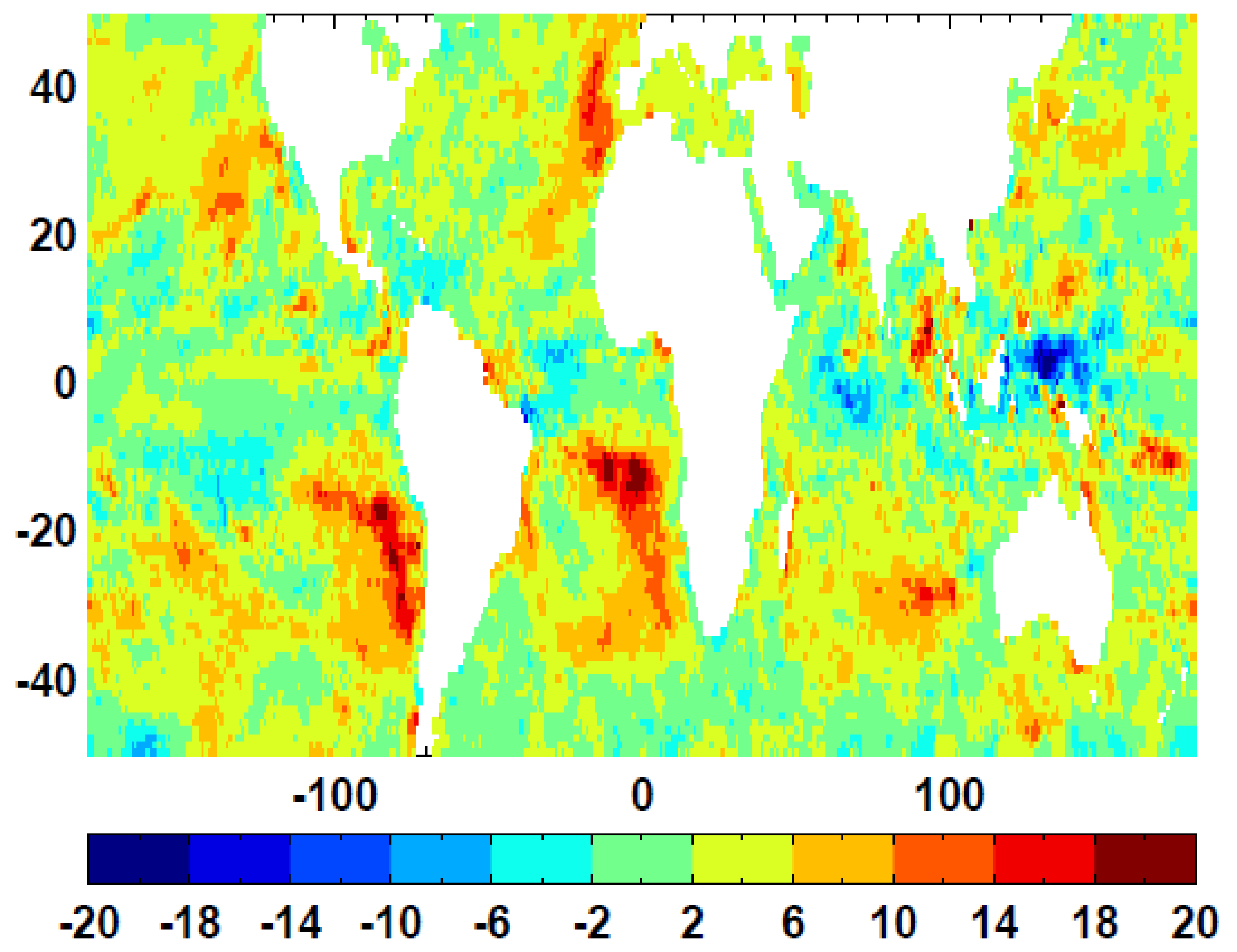
Z. Eitzen

Change in LW CRE with SST (W m^{-2} K^{-1})



Z. Eitzen

Change in Net CRE with SST (W m^{-2} K^{-1})

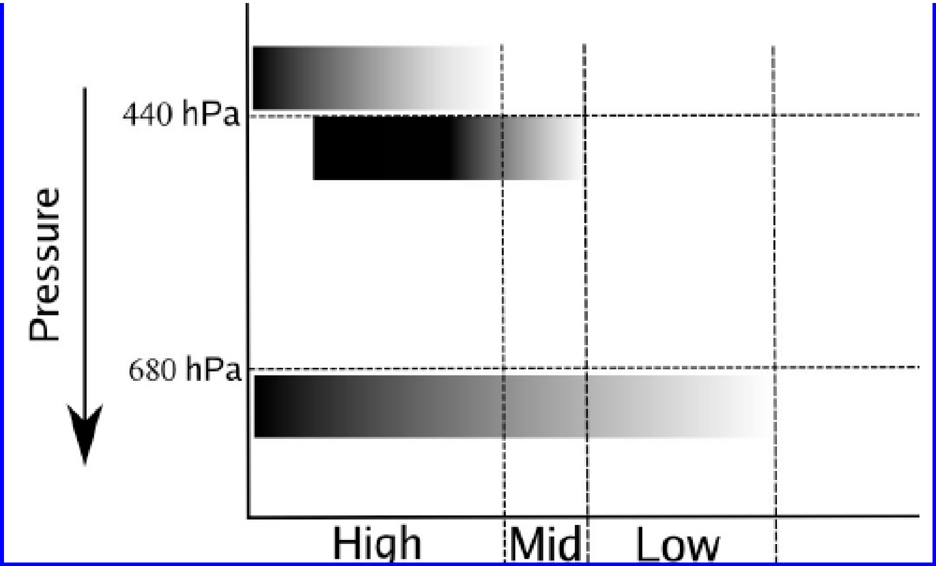


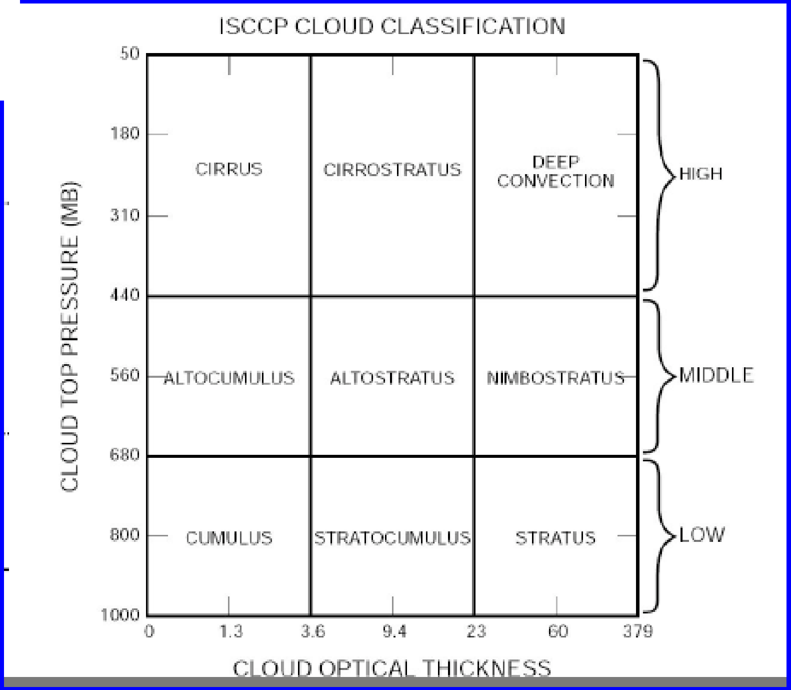
Z. Eitzen

New Approach for Testing GCM Representation of Cloud Structure

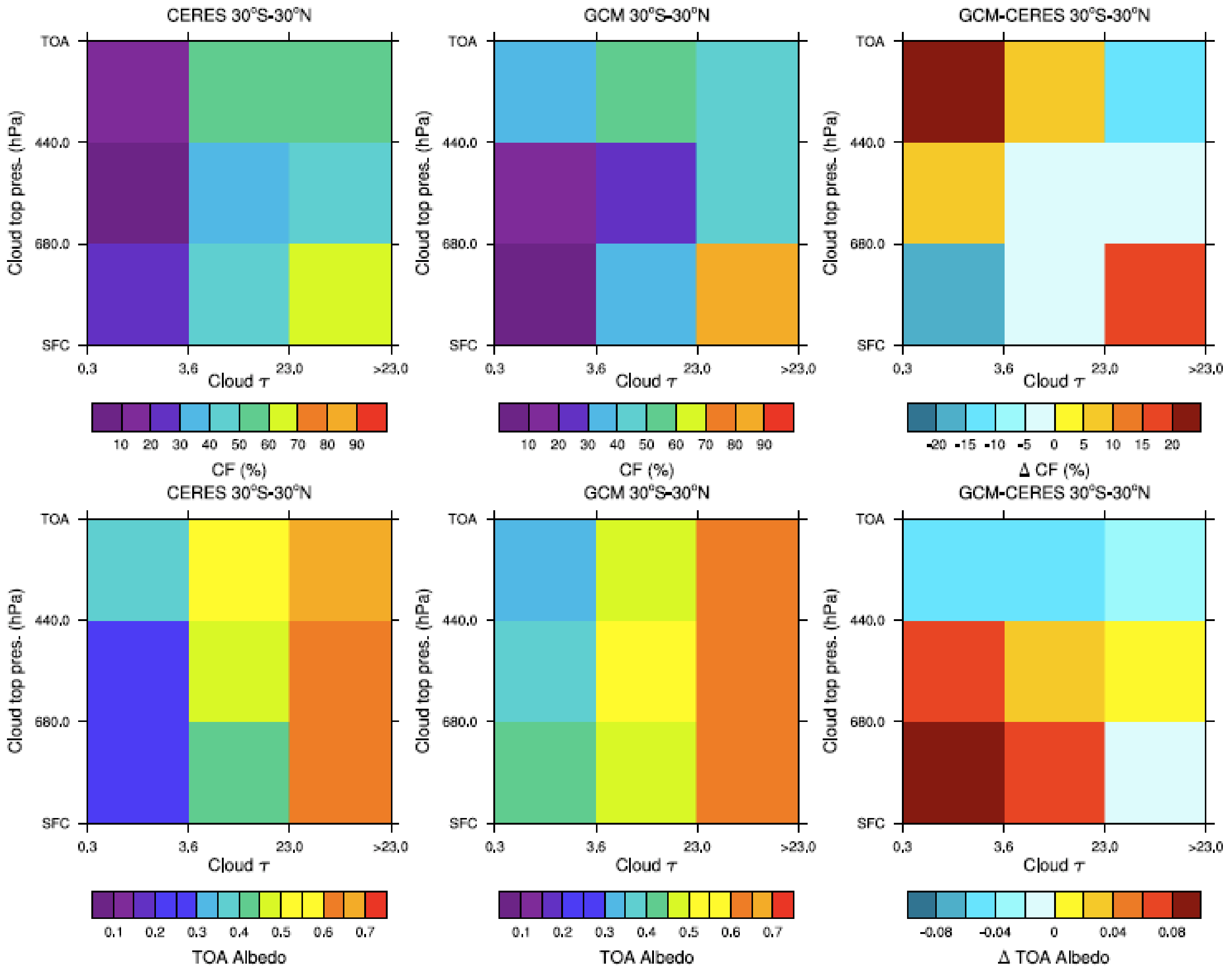
- Identify the portions of a GCM gridbox that are exposed to space (i.e., that a passive instrument would see).
- Directly compare albedos from these regions with those inferred from CERES.
- GCM uses a stochastic cloud generator, ISCCP simulator and McICA RT solver (randomly samples stochastically-generated subgrid-scale columns during spectral integration).

$$\langle R \rangle_{ICA} = (1 - C_{tot}) R(\tau = 0) + \sum_{m=1}^{M} C_m \int_0^{\infty} R(\tau) p_m(\tau) d\tau$$





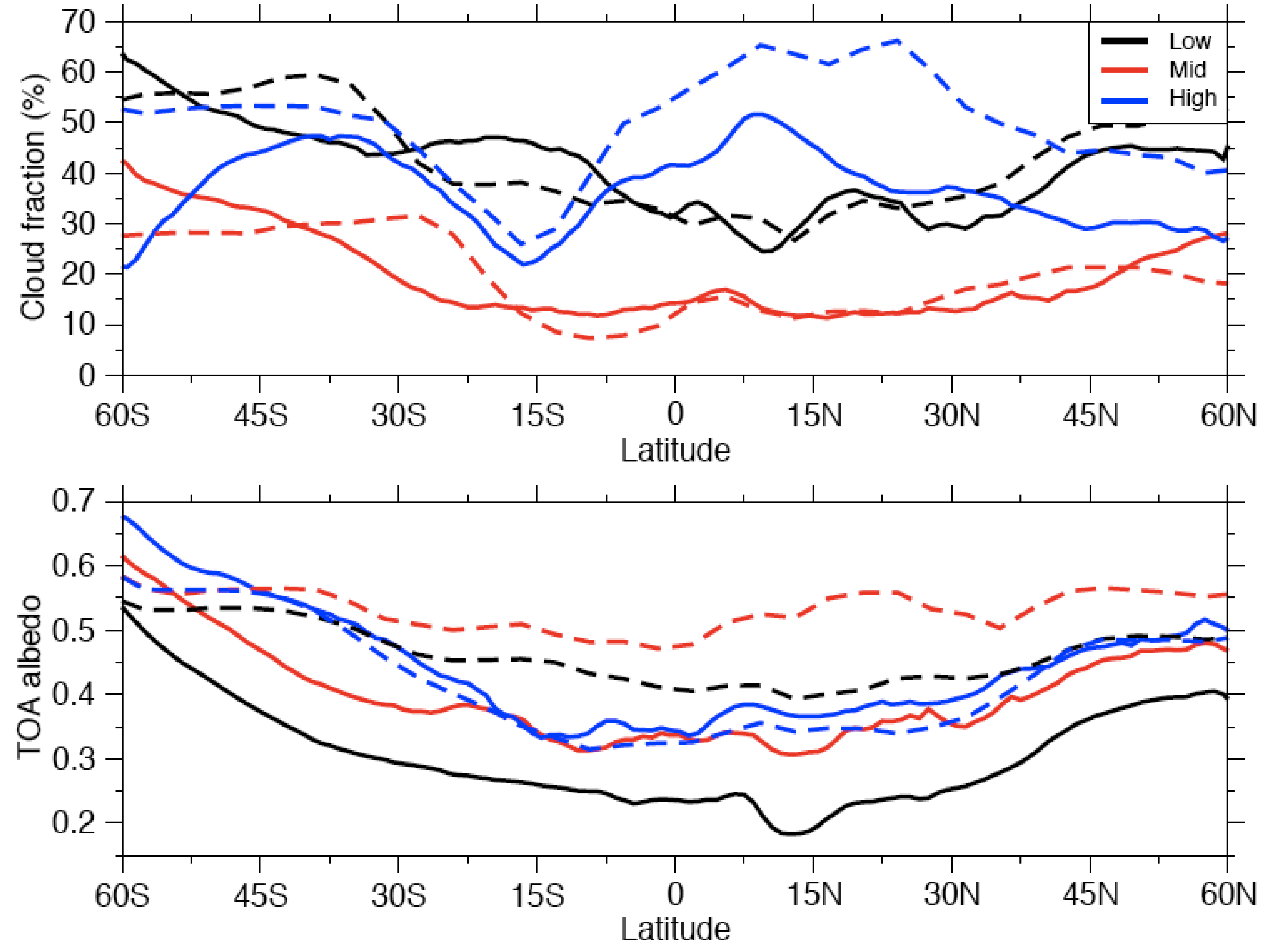
Cloud Fraction & Albedo for Clouds Exposed to Space (Jan 30S-30N)



Cloud Fraction

Cloud Albedo

CCCma GCM—CERES Zonal Mean Cloud Fraction and TOA Albedo (Jan 2001-2005)



Solid - CERES, Dashed - GCM

Conclusions

- Changes in the Earth’s radiation budget at TOA, within-atmosphere and surface have profound influence on climate:
  - In phase with variability in ocean heat storage
  - Constraint on (thermosteric) sea-level rise
  - TOA radiation anomalies more variable than suggested by models
  - Hopeful about commitment by NASA and NOAA to collect a long-term climate data record of cloud and ERB observations.
- CERES goes far beyond its predecessor, ERBE:
  - Improved calibration accuracy and stability
  - New cloud data and clear-sky screening by merging with MODIS
  - New anisotropic models
  - Improved diurnal accuracy by combining with Geostationary satellites
  - New surface and atmosphere radiative fluxes
- Despite Improvements, significant imbalance in TOA flux persists:
  - Main reason is absolute calibration uncertainty.
- CERES data more radiometrically stable than absolutely accurate
  - Ideal for examining interannaul variability, relationships between cloud and radiation anomalies.
  -

- Data available free from the LaRC Atmospheric Sciences Data Center at: http://eosweb.larc.nasa.gov/PRODOCS/ceres/table_ceres.html

BACKUP

What is CLARREO?

- Climate Absolute Radiance and Refractivity Observatory
- A climate-focused mission:
  - <u>Calibration</u>: The foundation is on-orbit traceability of instrument accuracy.
  - <u>Long-Term Trend Detection</u>: Accurately calibrated radiances provide a benchmark from which climate change can be conclusively determined.
  - <u>Testing and Validation of Climate Models</u>: The benchmark radiance measurements provide a consistency check for the climate data records and the climate models.
  - <u>Intercalibration of operational sensors</u>: CLARREO measurements can be used to accurately calibrate other space sensors.
- This mission will be the start of a key long-term climate data record in conjunction with TSIS and CERES.

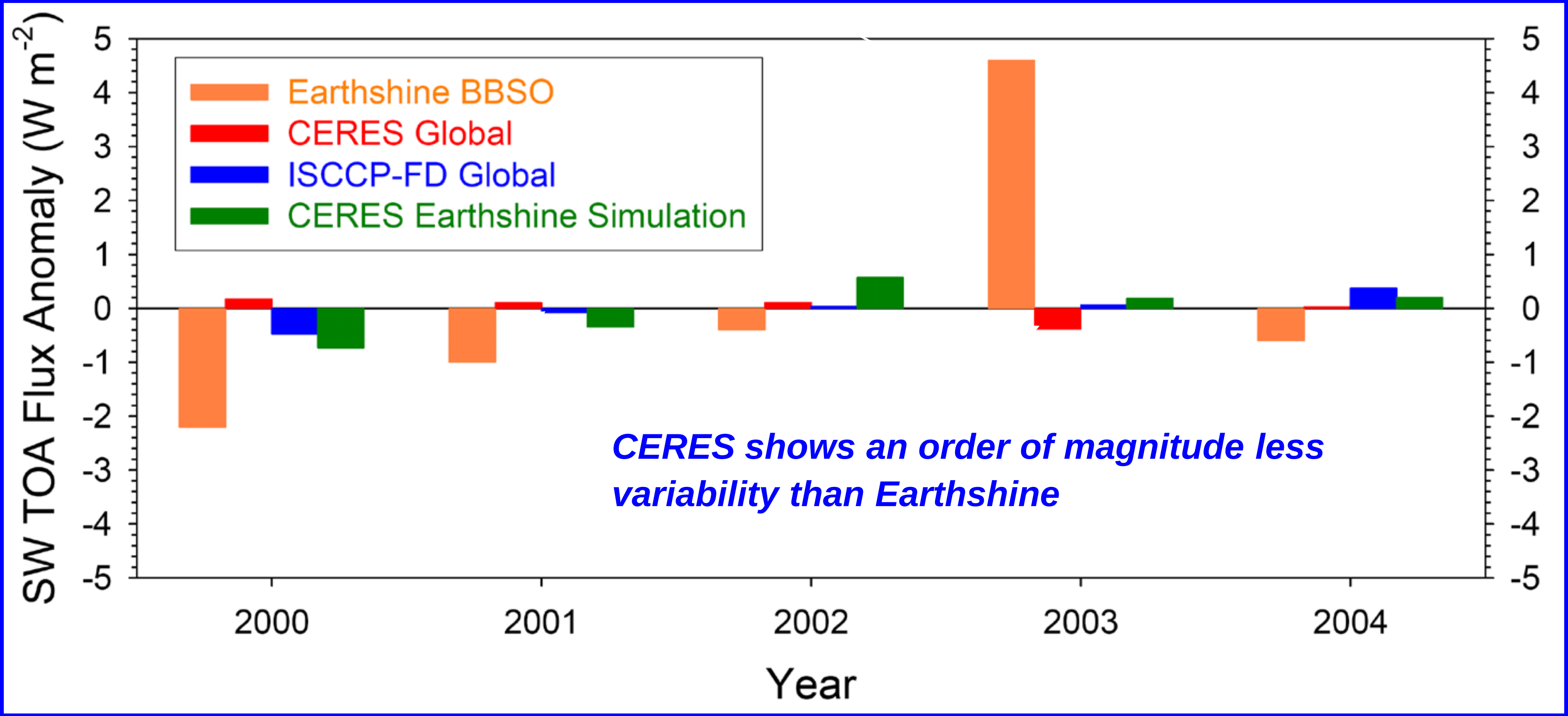
NASA Planning For CLARREO

- Engage community
  - Decadal Survey
  - Three workshops between July 2007 and May 2009
- Pre Phase A studies (May 2008 - September 2009)
  - Define primary science objective from the DS
  - Identify gaps from workshop
  - Directed studies focused on key cost drivers
  - Direct involvement of climate modeling community
- Technology Risk Reduction Using IIPs
  - Use Instrument Incubator program to address the key technology development

Annual Mean Global SW TOA Flux Anomaly

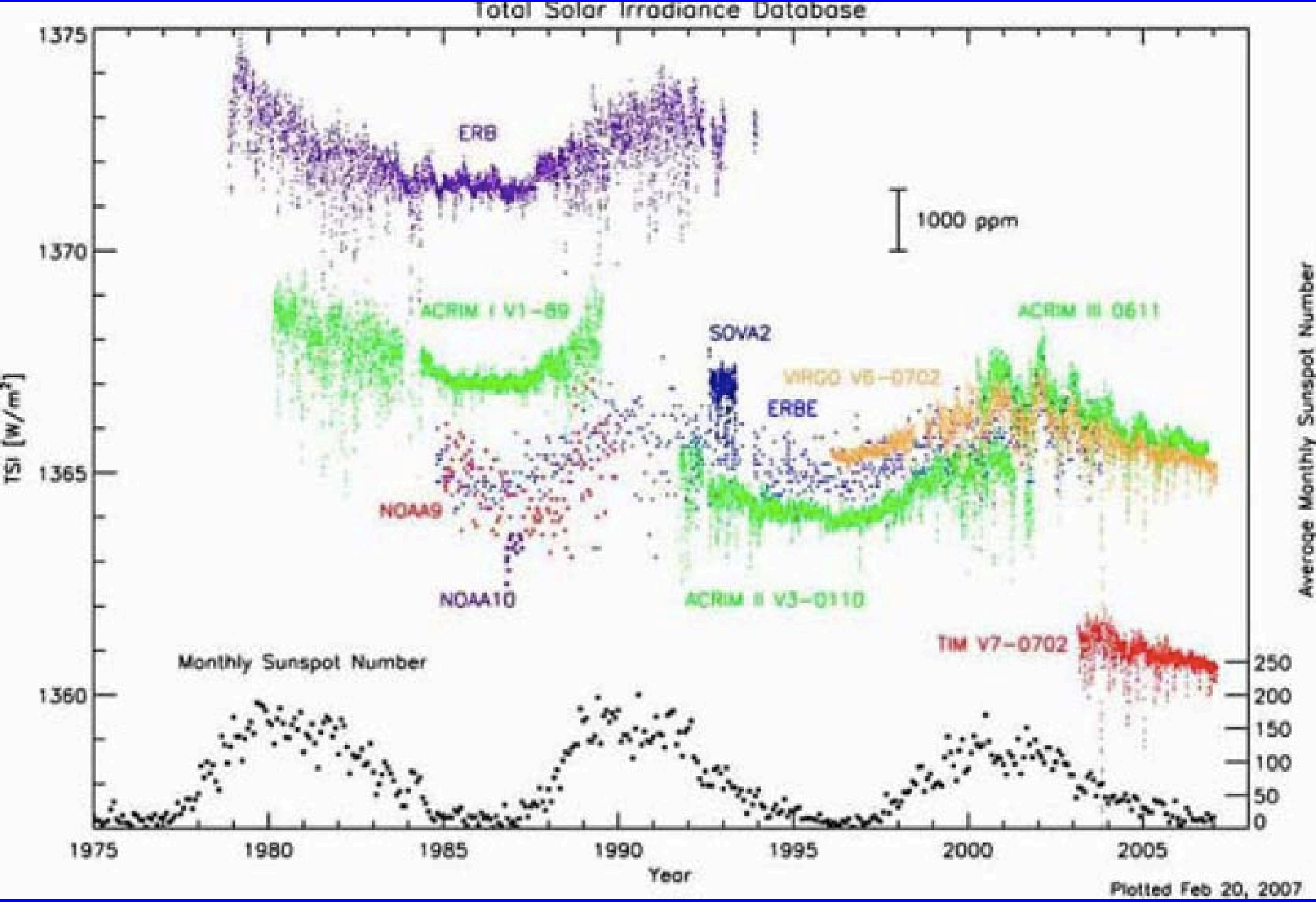
(Earthshine versus CERES: 2000 to 2004)

Earthshine data implies large change of 6 Wm^{-2} in global reflected SW flux: is the Earth's albedo changing? (Palle et al., Science, 2004)



CERES shows an order of magnitude less variability than Earthshine

Earthshine approach is incapable of capturing changes in global albedo at climate accuracy.


Total Solar Irradiance Database
1375
1370
1365
1360
TSI [W/m²]
ERB
1000 ppm
ACRIM I V1-89
ACRIM III 0611
SOVA2
VIRGO V6-0702
ERBE
NOAA9
NOAA10
ACRIM II V3-0110
TIM V7-0702
Monthly Sunspot Number
Average Monthly Sunspot Number
250
200
150
100
50
0
1975
1980
1985
1990
1995
2000
2005
Year
Plotted Feb 20, 2007

Use of Satellite Cloud Object Data to Validate Tropical Cloud Properties of ECMWF ERA-40 and ERA Interim Reanalyses

Kuan-Man Xu, NASA LaRC

- To evaluate the performance of NWP/GCM cloud parameterizations beyond the scope provided by the ISCCP data set.

Data sets:

- Footprint (level 2) CERES cloud physical & radiative properties analyzed as “cloud objects” and “extended cloud objects”
- Meteorological data from two ECMWF reanalyses (ERAs)

Cloud object & extended cloud object

CLOUD OBJECT:

- A contiguous patch of cloudy regions with a single dominant cloud-system type; no mixture of different cloud-system types
- The shape and size of a cloud object is determined by:

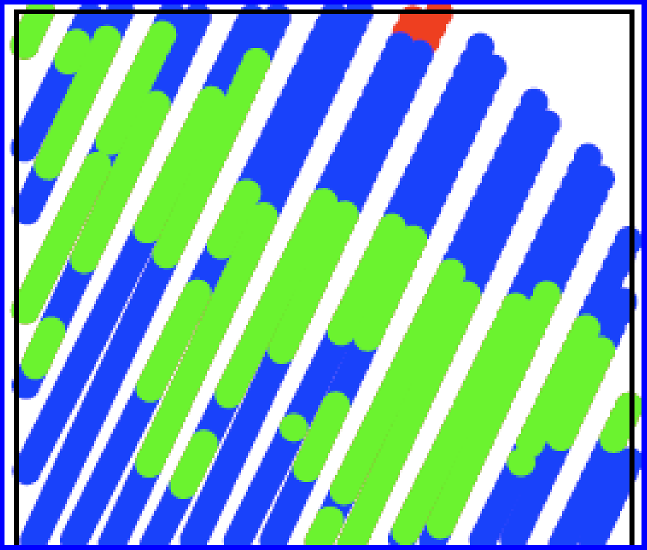
  - the satellite footprint data

  - the footprint selection criteria

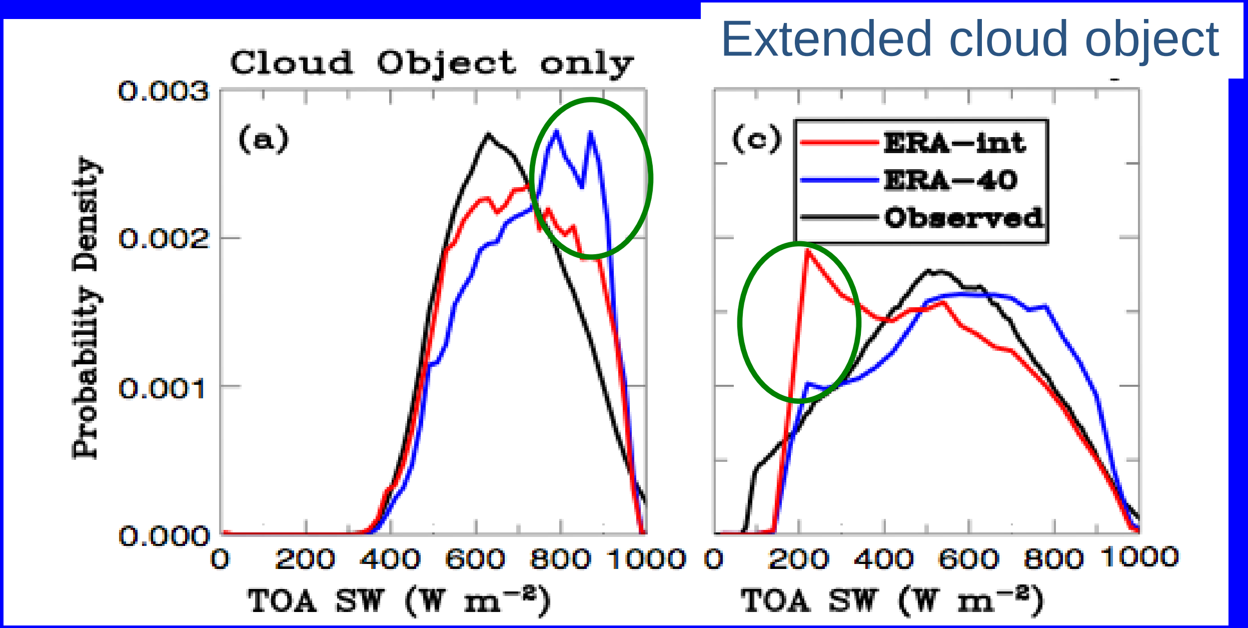
- For example, selection criteria for deep convective cloud objects:
  - Cloud top height $z_{top} > 10$ km,
  - Cloud optical depth $\tau > 10$, and
  - Footprint cloud fraction: 100%

EXTENDED CLOUD OBJECT (ECO):

- Include all cloudy footprints within the minimum/maximum latitudes and longitudes of a cloud object
- May include some footprints satisfying the cloud object selection criteria



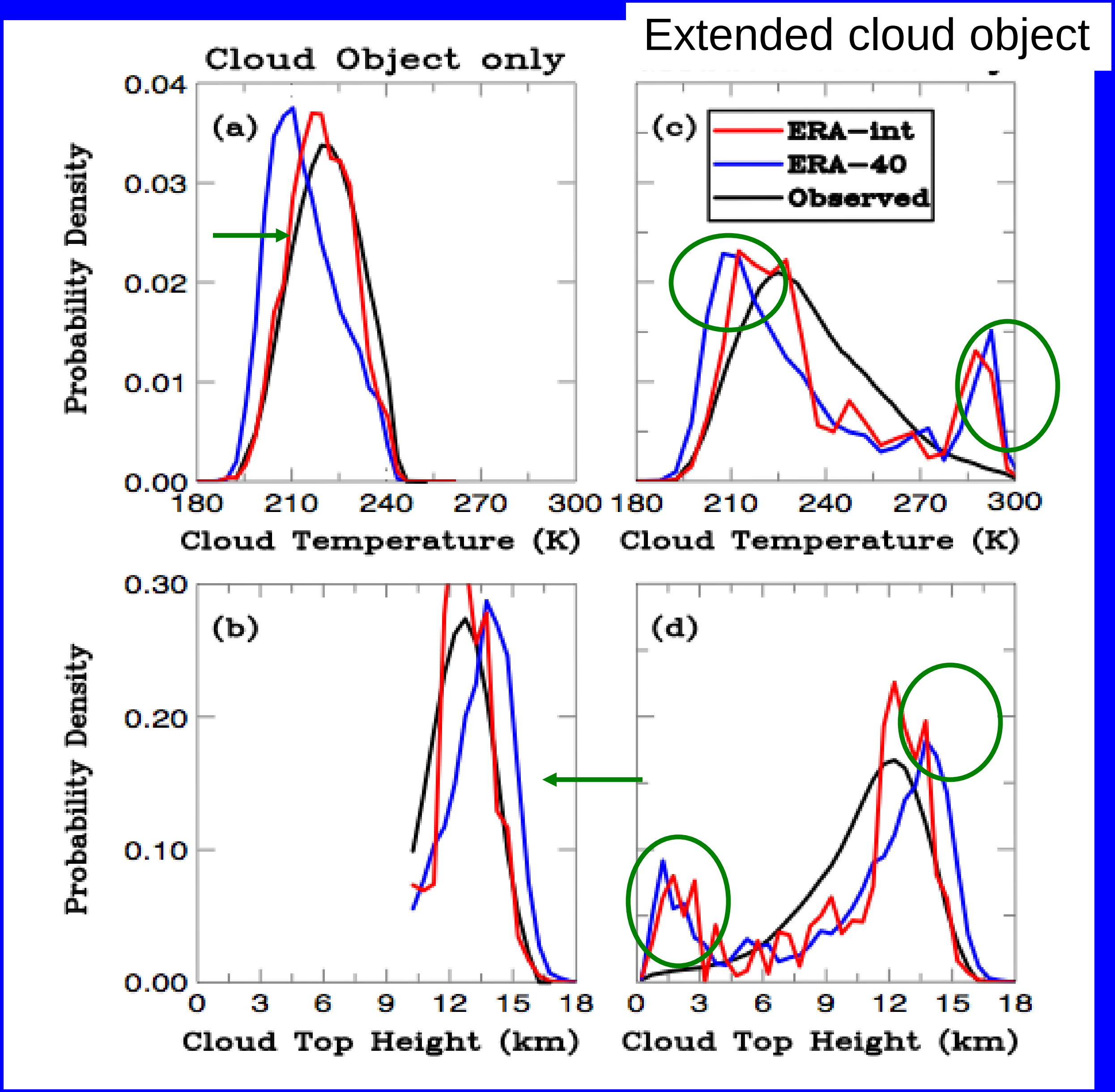
PDFs of TOA SW radiative fluxes



- The ERA Interim agrees with cloud-object observations better than the ERA-40, but the opposite is true for extended cloud objects (ECOs)
- The differences in TOA SW between the two analyses are much greater than those in cloud optical depth; implying there may be differences in the vertical structure of cloud extinctions ($\tau/\Delta z$)
- The excessive non-DC (neighboring clouds with small τ) population in ERA Interim is responsible for the large peak around 200 W m^{-2}

Kuan-Man Xu

PDFs of cloud-top temperature and height


Extended cloud object

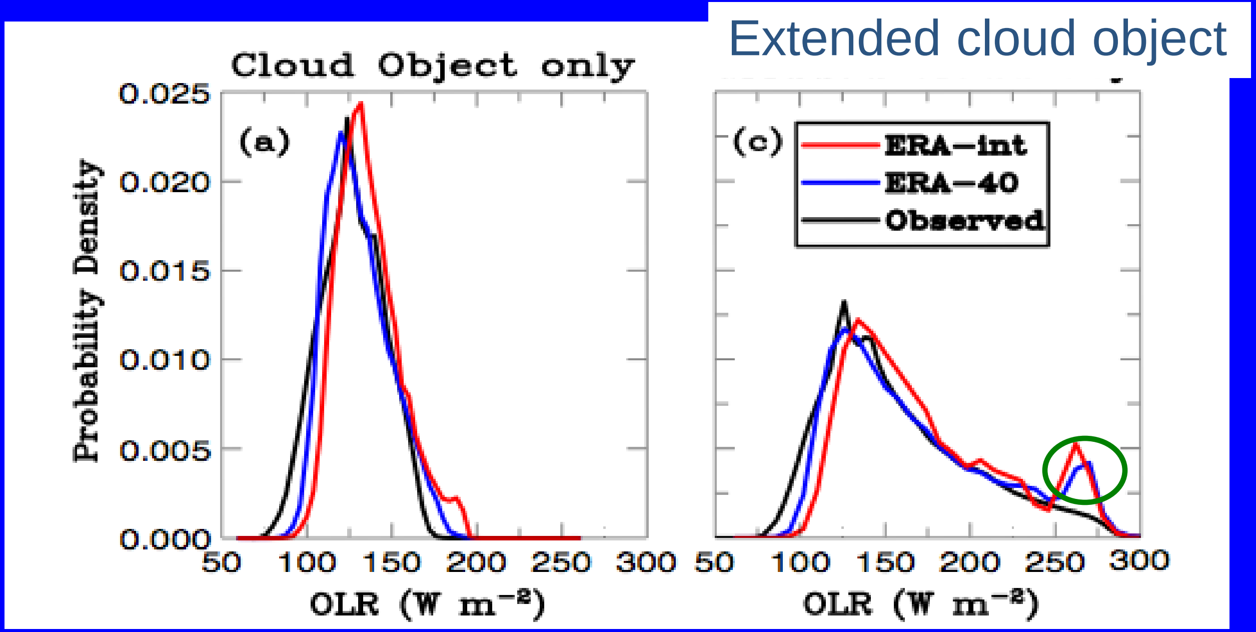
ERA Interim captures the highest clouds well, but these clouds are over-estimated in ERA-40.

Shallow clouds (0.2-3 km range) and deep clouds (12-15 km) are over-estimated at the expenses of middle clouds (5-11 km);

The binary feature (shallow or deep updrafts) of the Tiedtke cumulus parameterization is responsible for these discrepancies

Kuan-Man Xu

PDFs of TOA LW radiative fluxes



- The TOA LW radiative fluxes from ERA-40 agree better with observations than ERA Interim, despite of larger disagreement in cloud macrophysical properties noted earlier.
- There are consistent overestimates of OLR by ERA Interim; suggesting underestimates of cloud emissivity above the diagnosed cloud top ($\tau = 1$).
- Overestimate of OLR around 270 W m^{-2} is due to overestimate of low-level clouds; but underestimate of mid-level clouds does not impact OLR pdfs.

Kuan-Man Xu

Observing the Earth's Global Radiation Budget

By it's very nature, observing & characterizing the Earth's radiation budget requires the highest level of data fusion.

Instrument calibration (absolute and relative)

- CERES uses a rigorous cal/val protocol to minimize calibration uncertainties.

Spectral sampling

- CERES measures broadband radiation from 0.3 μm to 200 μm.
- Uses MODIS imager to determine cloud and aerosol properties.

Spatial sampling

- CERES uses crosstrack measurements that sample from limb-to-limb to provide global coverage each day.

Angle sampling

- On Terra & Aqua, a second CERES instrument was flown to acquire sufficient angle sampling to develop angular models for radiance-to-flux conversion. These models will be used for NPP and future missions.

Temporal sampling

- CERES merges 3-hourly geostationary data to sample the diurnal cycle of radiation.