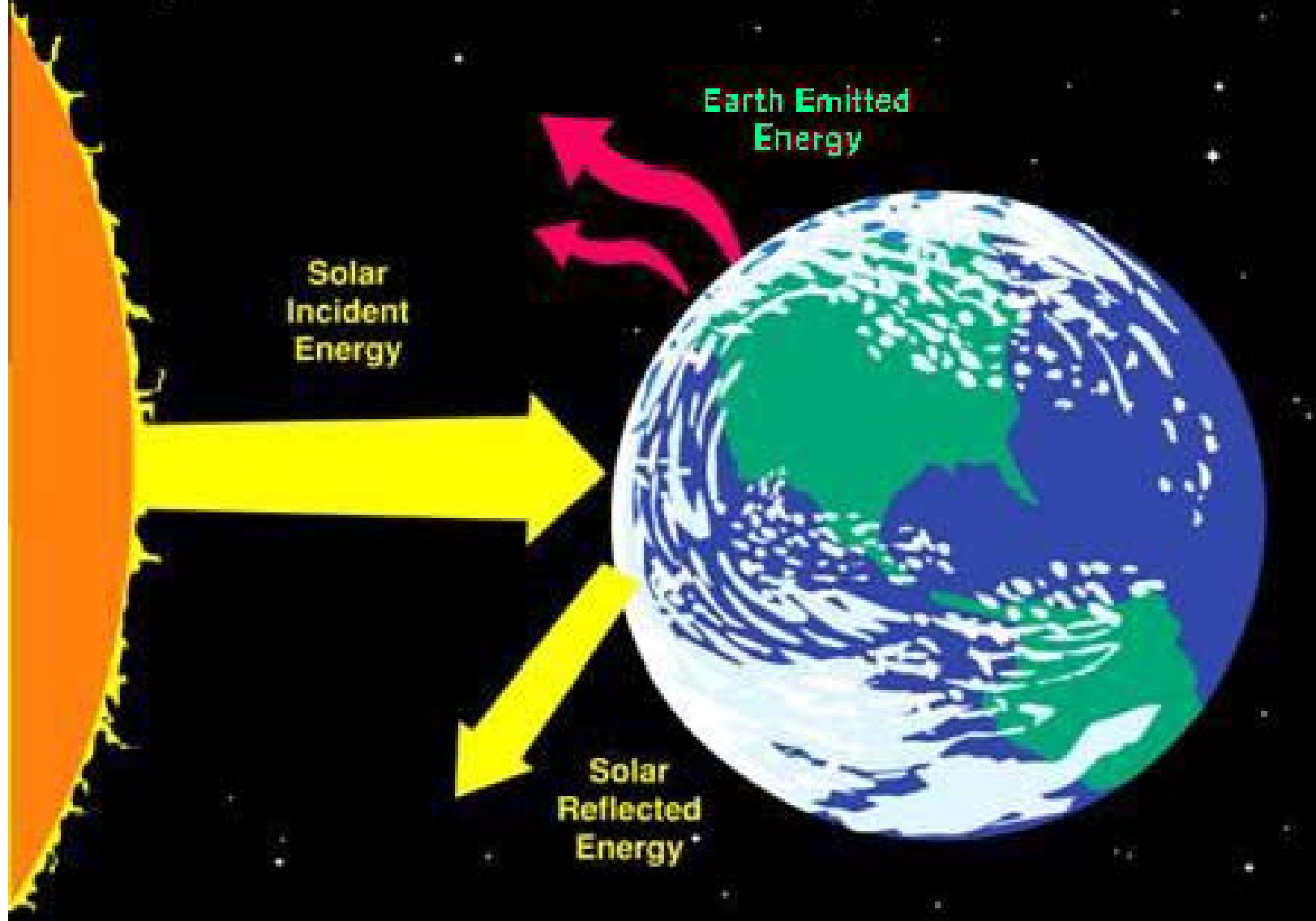


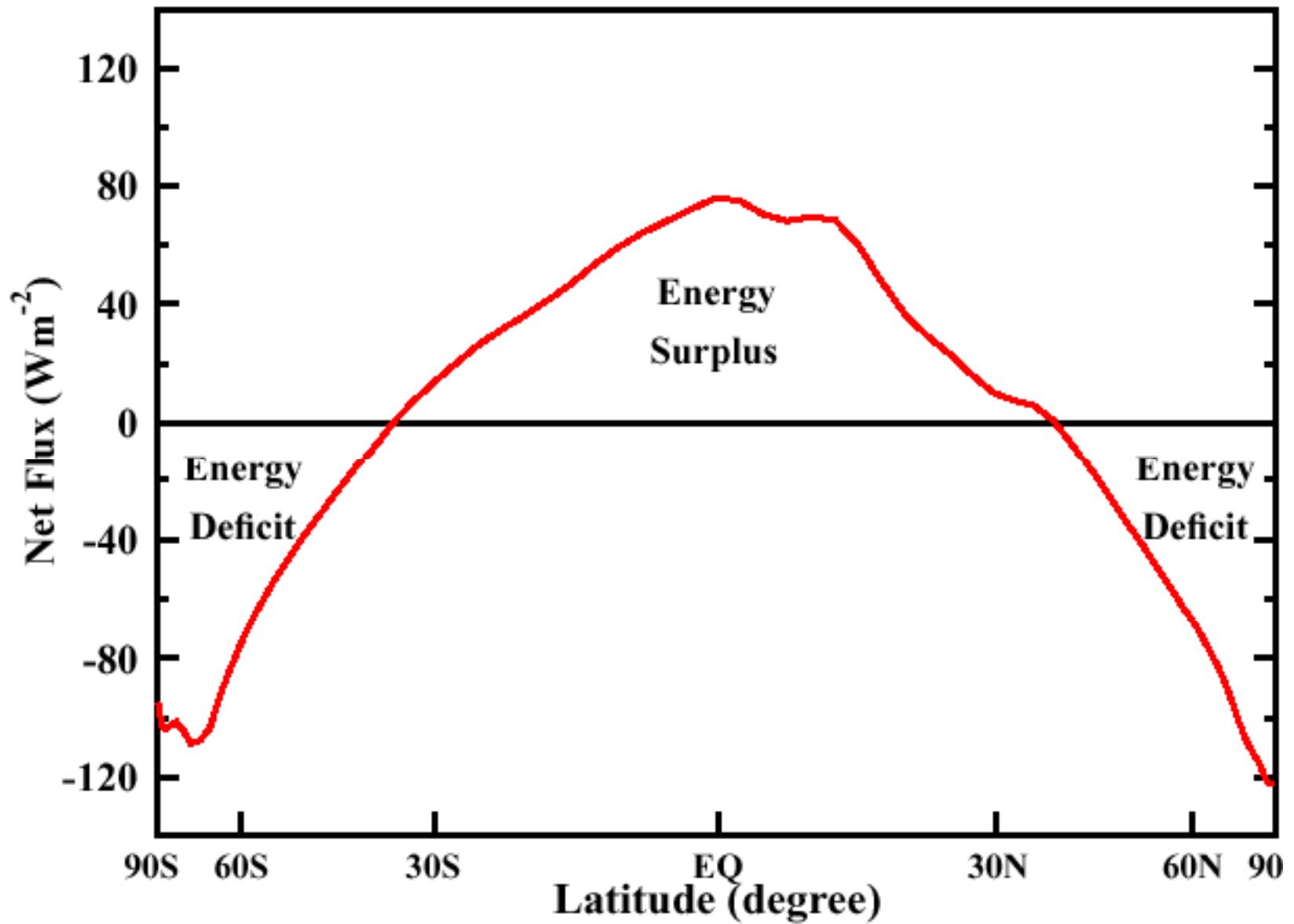
Lesson 19:
Earth's Radiation Budget

Earth Radiation Components

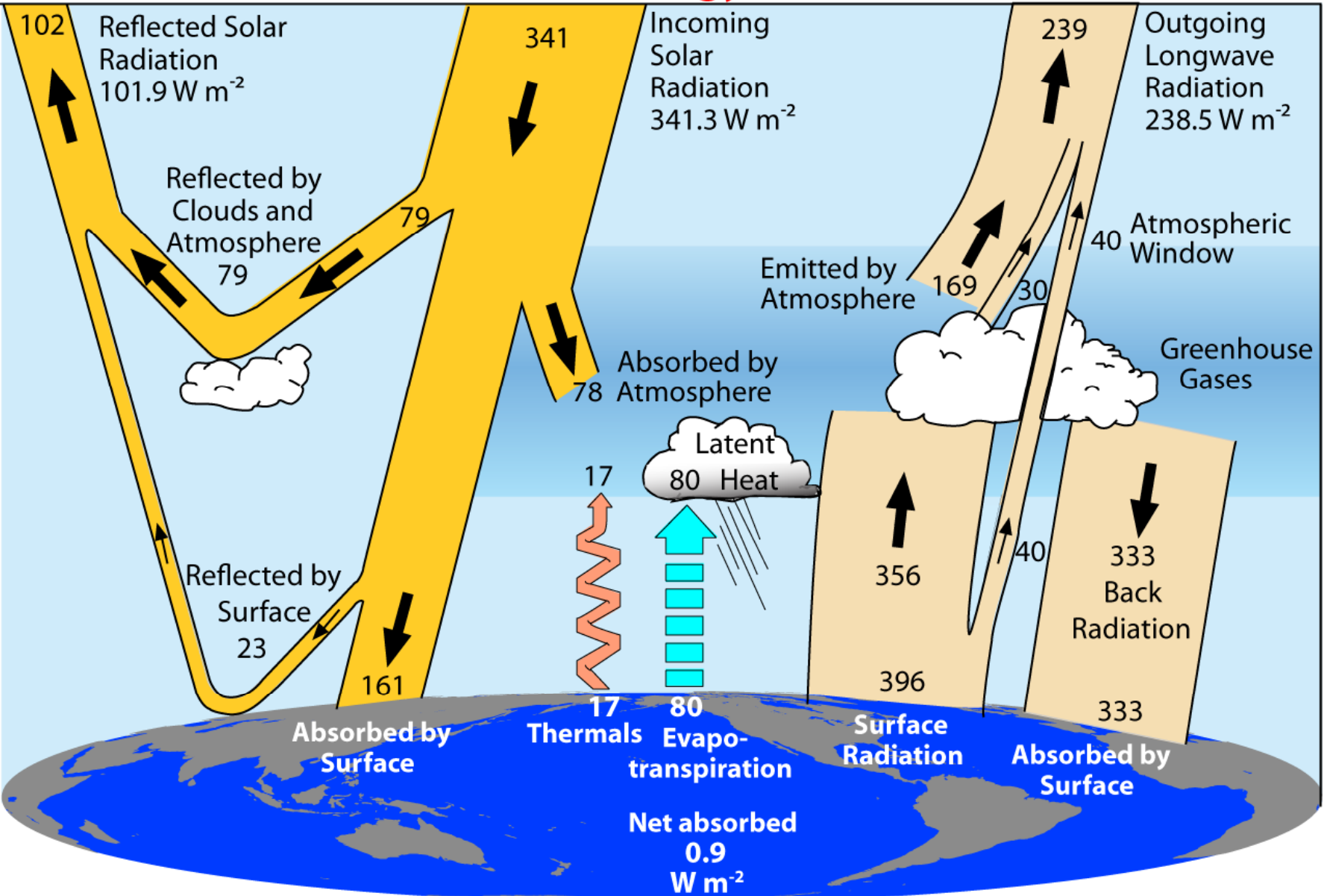


Annual Averaged Zonal Mean Net Flux Profile

CERES/TERRA, March 2000 to February 2001



Global Energy Flows $W m^{-2}$



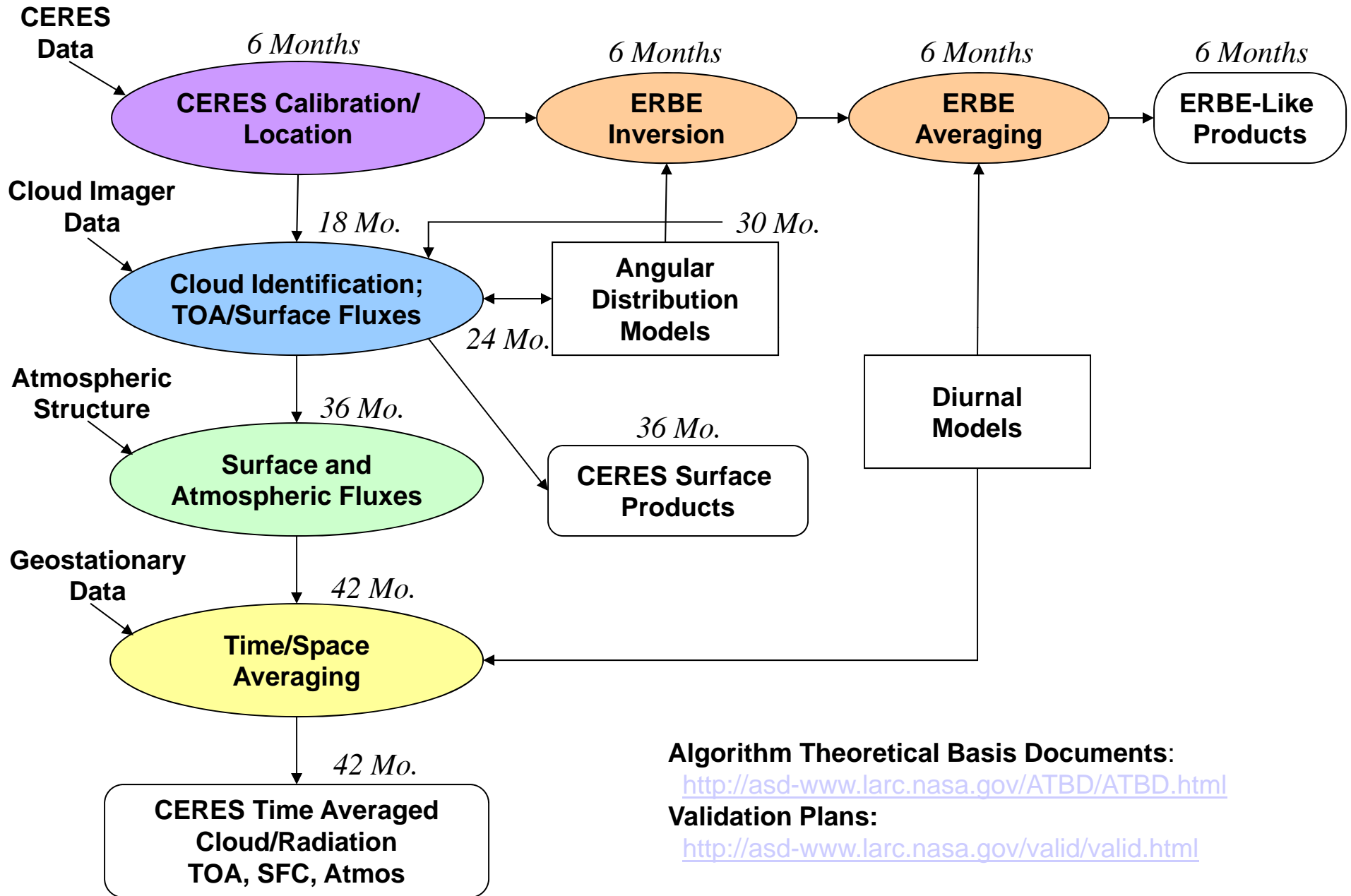
The global annual mean Earth's energy budget for 2000-2004 ($W m^{-2}$). The arrows indicate the flow of energy in proportion to

A brief history of ERB missions

Satellite Missions	Launch Year(s)	Lifetime	Altitude (km)	Inclination (degree)	Orbit Time
<u>First-Generation Missions</u>					
Explorer 7	1959	7 months	550-1,100	51	drifter
TIROS 2	1960	1-5 months	717-837	48	drifter
TIROS 7	1963	1 year	713-743	58	drifter
<u>Second-Generation Missions</u>					
Research/ESSA	1960s	3-15 months	1,500	102	0900/1500
Nimbus 3	1969	1 year	1,100	99	noon
NOAA	1970s	years	1,500	102	0900
TIROS-N/NOAA GMS	1978	> 10 years	840	99	1500/0730
<u>Third-Generation Missions</u>					
Nimbus 7 ERB	1978	> 9 years	950	99	noon
<u>Fourth-Generation Missions</u>					
ERBS	1984	> 5 years	610	57	drifter
NOAA 9/ERBE	1984	> 5 years ¹⁾	872	98	1430
NOAA 10/ERBE	1986	> 3 years ²⁾	833	98	0730

1) Scanner failed in 1987; 2) Scanner failed in 1989.

CERES Data Processing Flow



CERES Advances over Previous Missions

- Calibration Offsets, active cavity calib., spectral char.
- Angle Sampling Hemispheric scans, merge with imager matched surface and cloud properties
new class of angular, directional models
- Time Sampling CERES calibration + 3-hourly geo samples
new 3-hourly and daily mean fluxes
- Clear-sky Fluxes Imager cloud mask, 10-20km FOV
- Surface/Atm Fluxes Constrain to CERES TOA, Fu-Liou, ECMWF
imager cloud, aerosol, surface properties
- Cloud Properties Same 5-channel algorithm on VIRS,MODIS
night-time thin cirrus, check cal vs CERES
- Tests of Models Take beyond monthly mean TOA fluxes
to a range of scales, variables, pdfs
- ISCCP/SRB/ERBE overlap to improve tie to 80s/90s data.
- CALIPSO/Cloudsat Merge in 2006 with vertical aerosol/cloud

CERES Instrument



TRMM:

**Jan-Aug 98
and Mar-Apr 2000
overlap with Terra**

Terra:

**Mar 00 - present
planned life: 2006**

Aqua:

**July 02 start
Now in checkout
Planned life to 2008**

NPOESS:

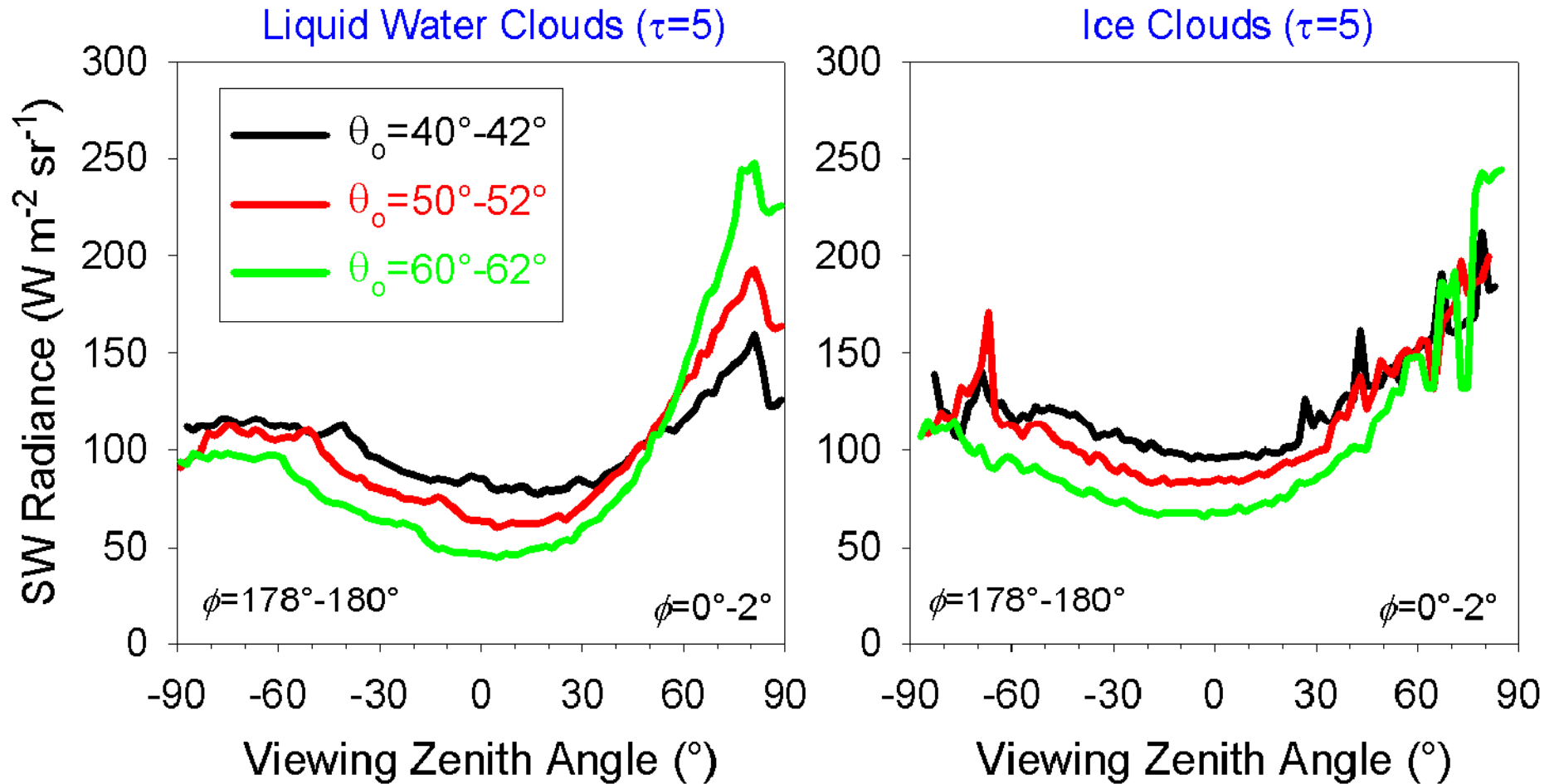
**TBD: gap or overlap?
2008 to 2011 launch**

**Uncertainties in the state-of-the-art estimates of
Earth's Radiation Budget at the Top of the
Atmosphere from ERBE (Wielicki et al. 1995)**

	Instantaneous Pixel	Monthly Regional
Calibration	6.0	2.0
Angle sampling	37.5	3.3
Time sampling	0.0	3.9
Space sampling	0.0	0.3
Total	38.0	5.5

*Wielicki et al
(1995)*

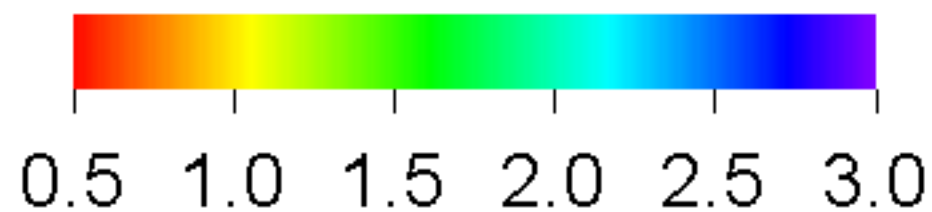
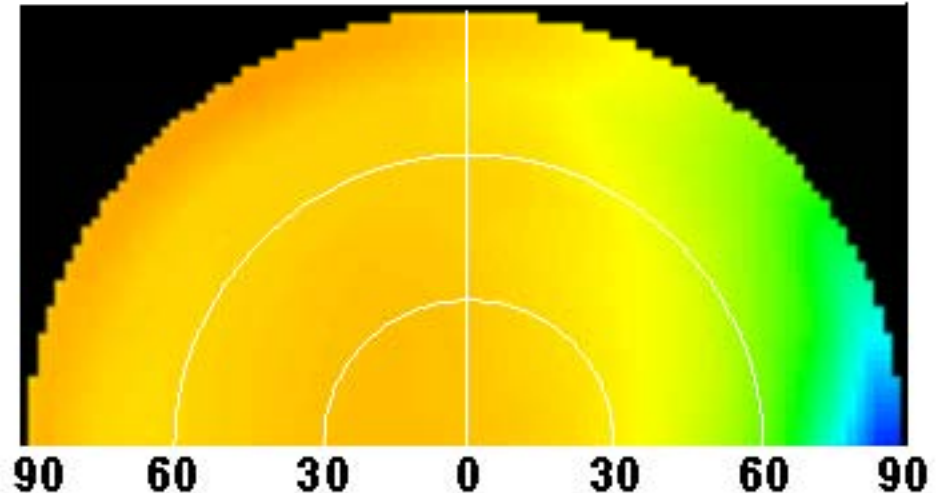
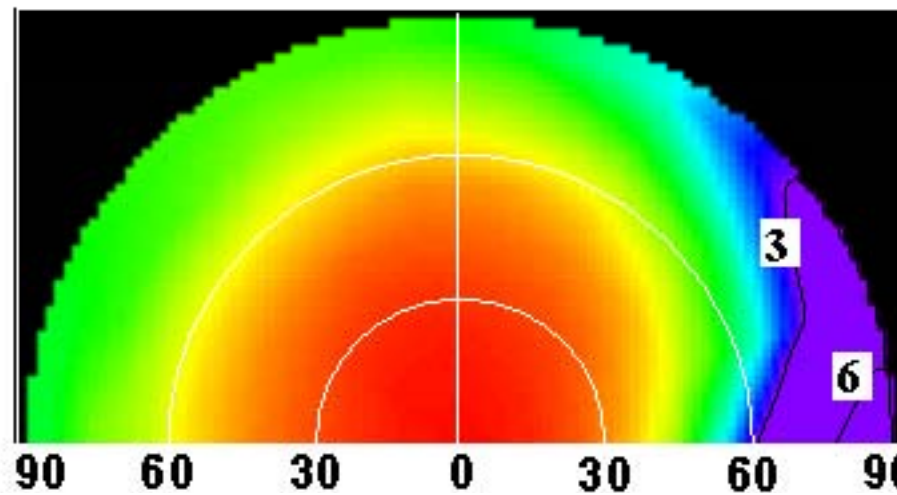
CERES SW Radiances vs Viewing Zenith Angle (Principal Plane; 4 Months Terra over Ocean)



CERES SSF ADMs
(Overcast Ice Clouds; $\theta_o=60^\circ-70^\circ$)

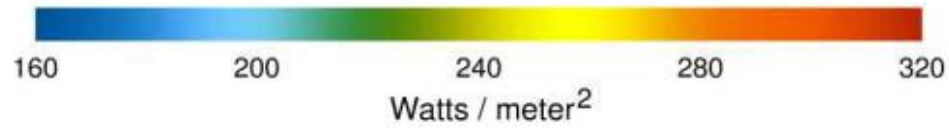
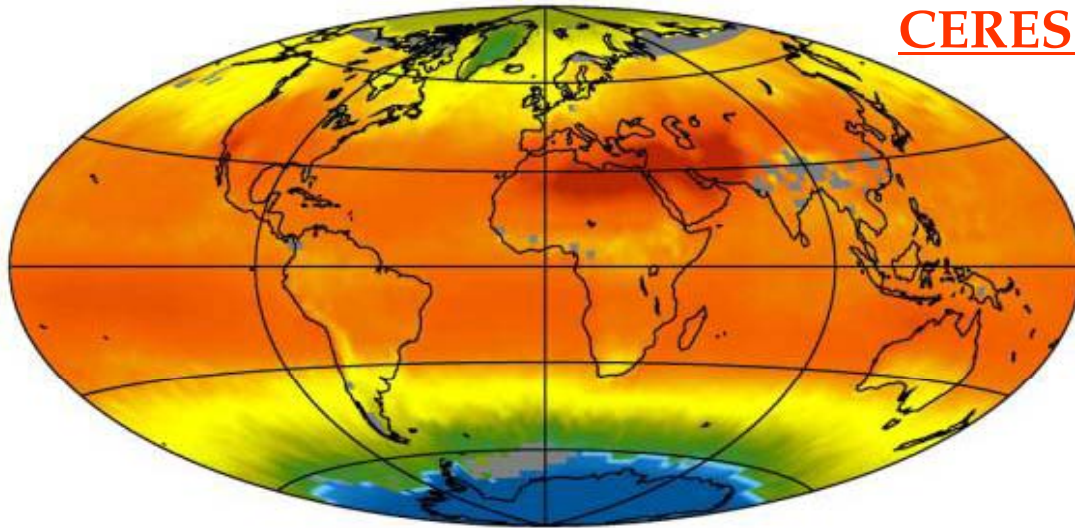
$\tau < 1$

$\tau > 50$

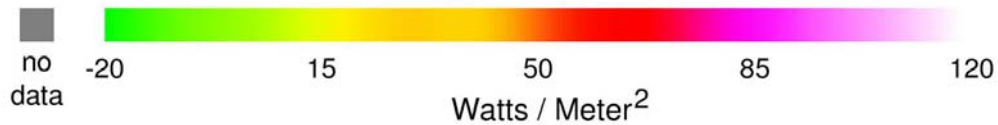
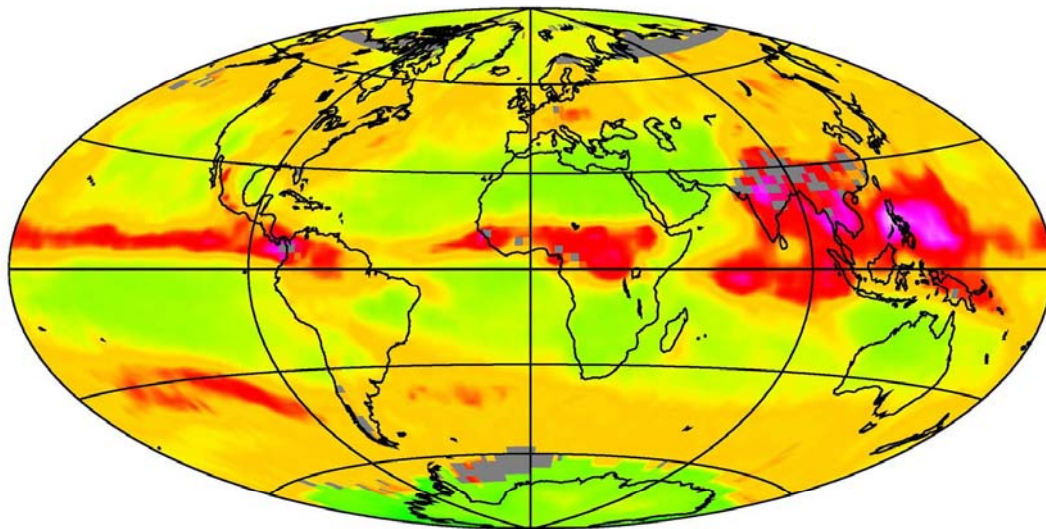


SW Anisotropic Factor (R)

CERES LW Terra Results - July 2000

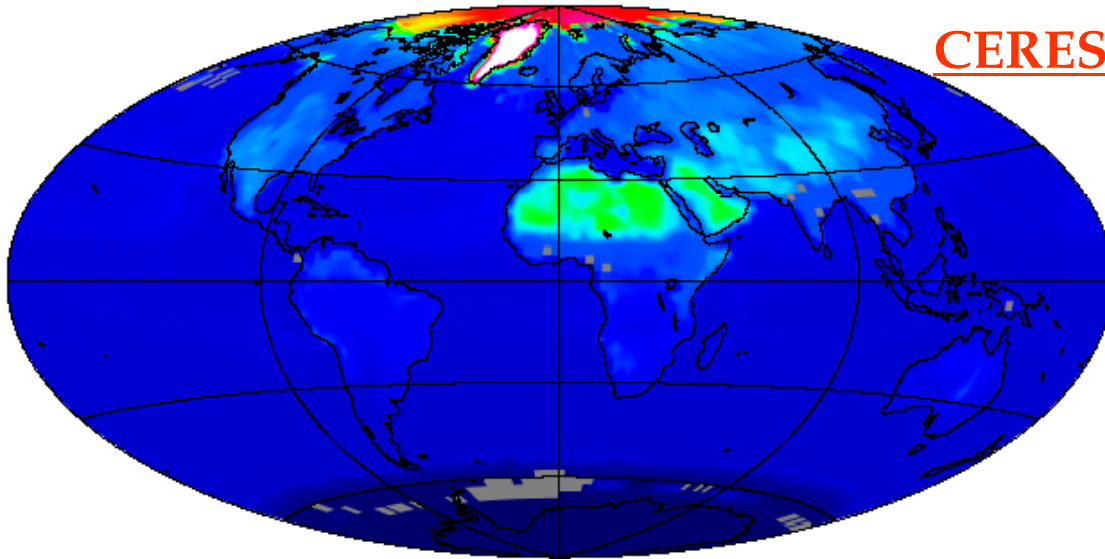


**CERES Clear-Sky TOA
Longwave Flux (W m^{-2})**

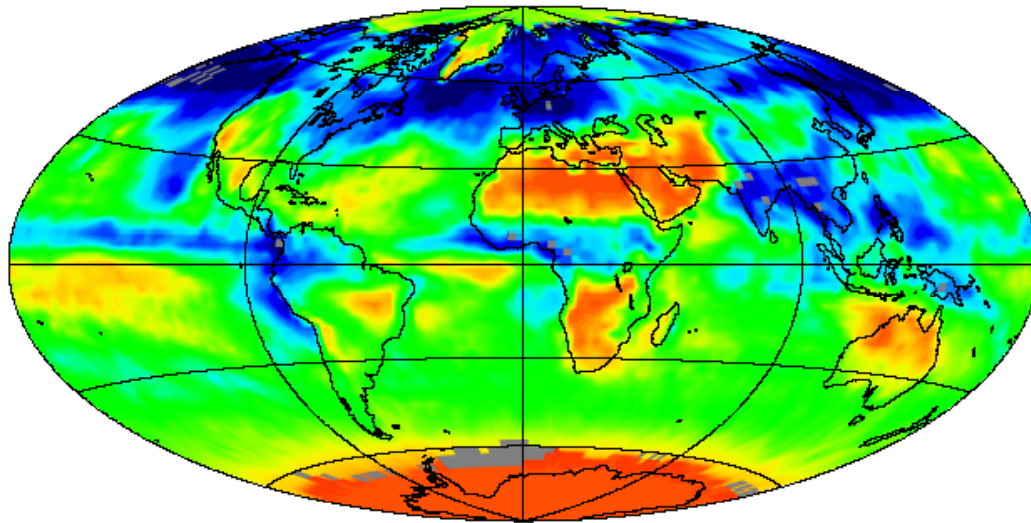
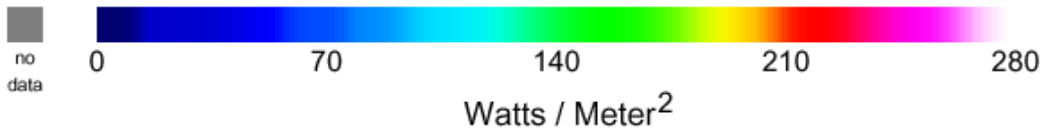


**CERES TOA Longwave
Cloud Forcing (W m^{-2})**

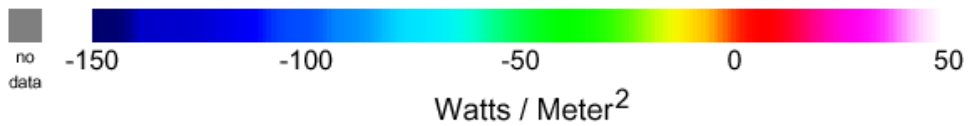
CERES SW Terra Results - July 2000



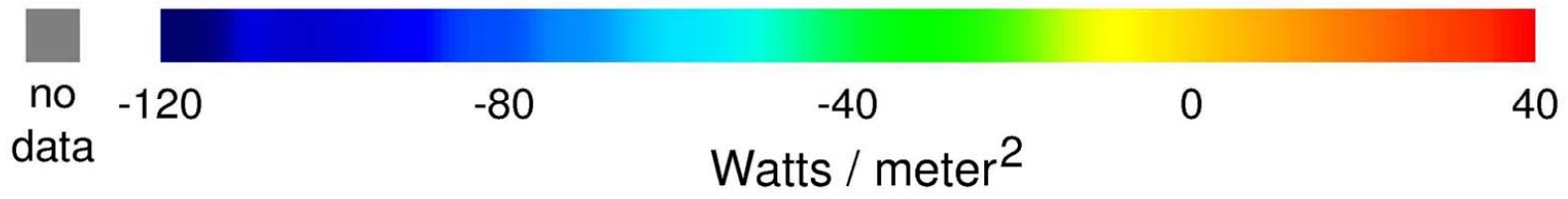
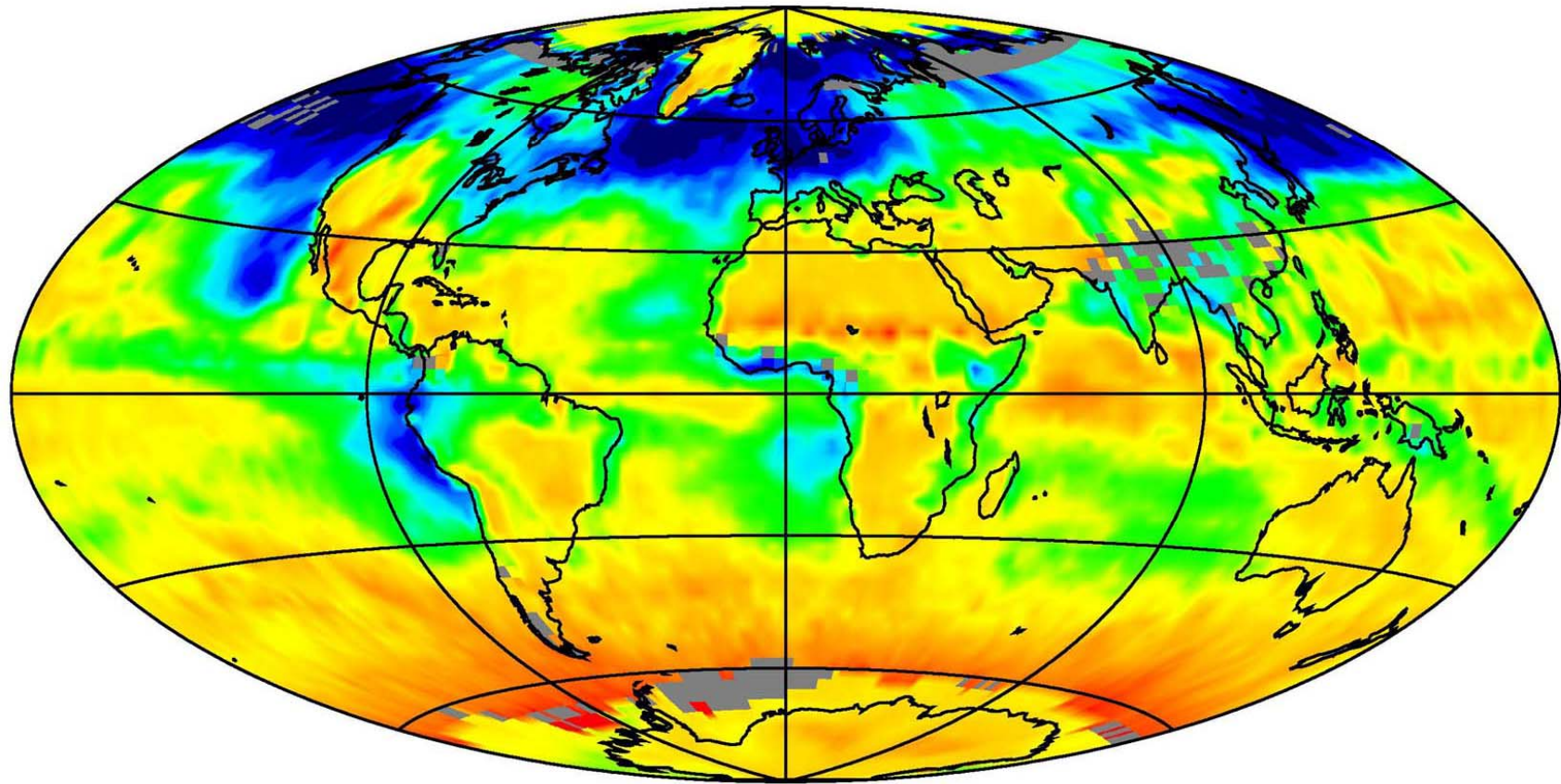
**CERES Clear-Sky TOA
Shortwave Flux ($W m^{-2}$)**



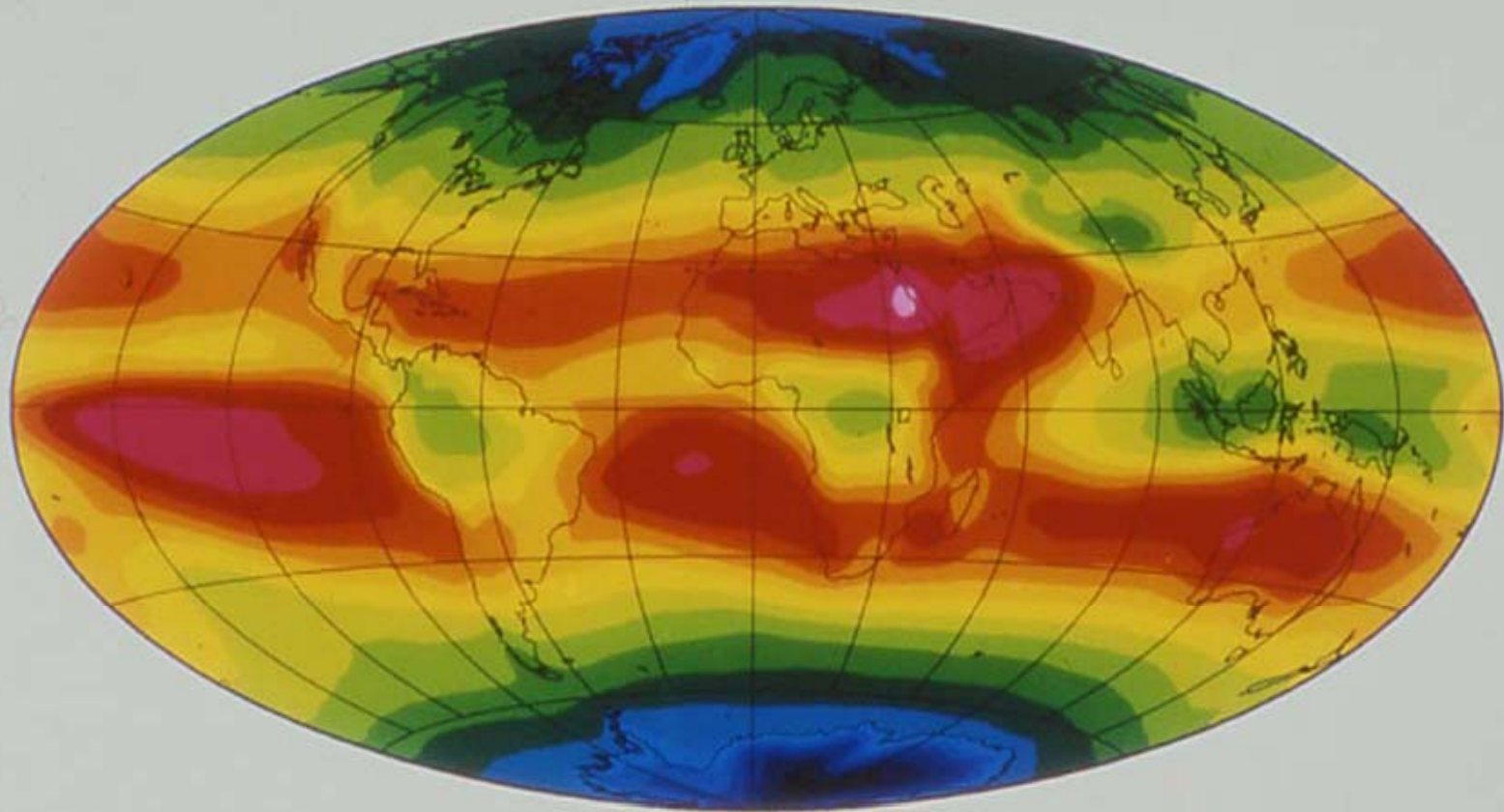
**CERES TOA Shortwave
Cloud Forcing ($W m^{-2}$)**



CERES Net Cloud Forcing (July, 2000)



Longwave Radiation
1985-1986

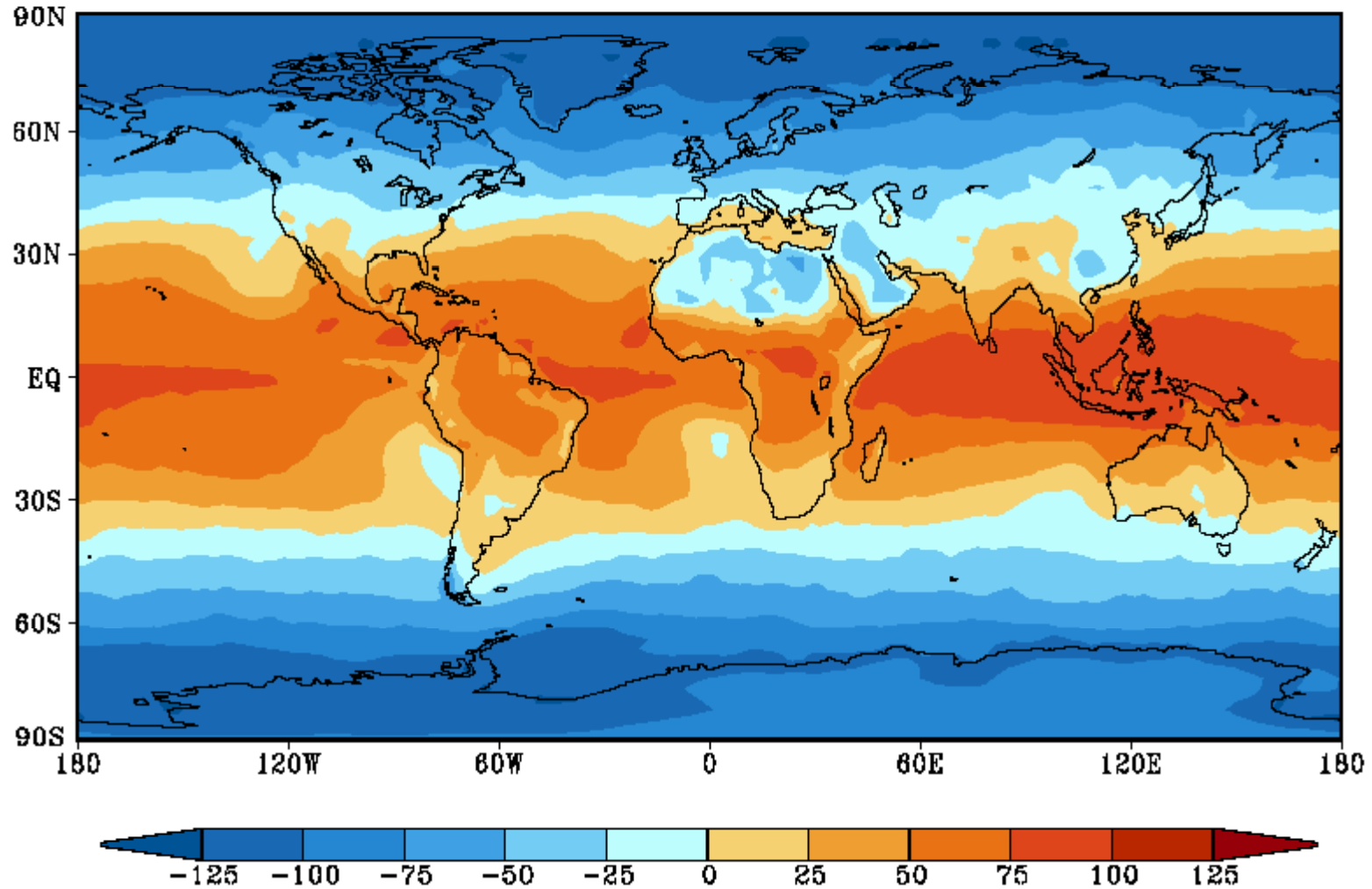


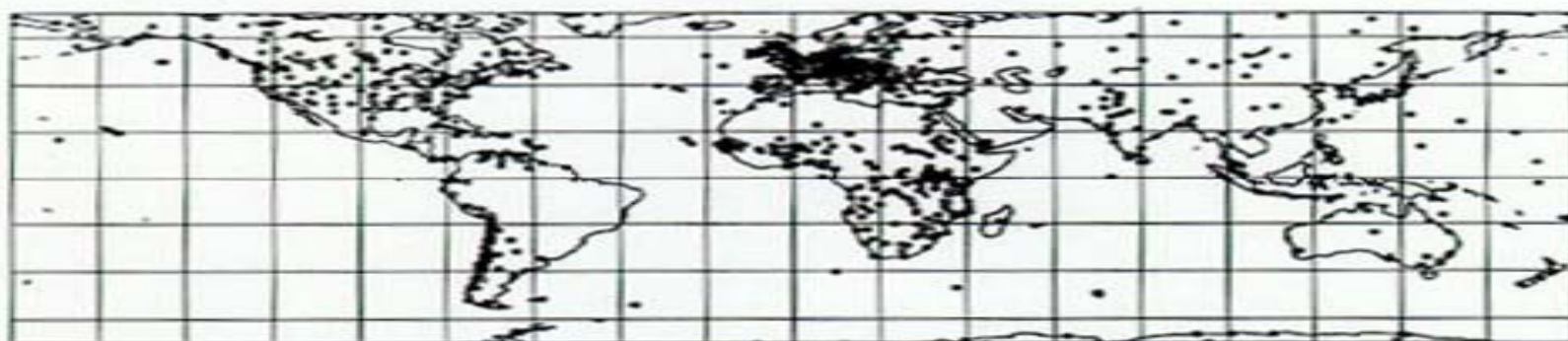
W/m**2

Net Radiation

CERES/Terra, 2.5-degree ERBE-Like, 1st Full Year Mean

Global Mean (90S-90N) = 2.6 Wm^{-2}





Distribution of the stations archived in the GEBA
as of January 1, 1992

from Ohmura & Gilgen (1992)

Overview of Algorithms

$$1 = r_t + a_a + a_s$$

$$a_s = (1 - r_g) t$$

1. Indirect Approach

Known: r_t

Unknowns: r_g, a_a, t

a. Statistical model

Investigators

Fritz *et al.* (1964), Hanson *et al.* (1967), Suomi and Vonder Harr (1969), Tarpley (1979), Brakke and Kanemasu (1981), Klink and Dollhopf (1986) *etc.*

Tool

Statistical analysis of matched satellite and surface observations.

Principle

For given atmospheric and surface conditions,

$$t = f(r_t)$$

Comments

b. Physical model

Investigators

Raschke *et al.* (1979); Gautier *et al.* (1980), Nunez *et al.* (1984), Pinker and Ewing (1985), Buriez *et al.* (1986), Dedieu *et al.* (1987), Darnell *et al.* (1988), *etc.*

Tool

Radiative transfer computation

Principle

$$\begin{aligned} r_g &= f_1(r_t, \text{atmos.}) \quad (\text{clear sky}) \\ \text{cloud} &= f_2(r_t, r_g, \text{atmos.}) \\ t &= f(\text{atmos.}, \text{cloud}, r_g) \end{aligned}$$

Accuracy

Insolation:

Hourly 20%; Daily 10%; Monthly 5%

Net Solar ?

Comments

2. Direct Approach

Known: I_t

Unknowns: a_s, a_a

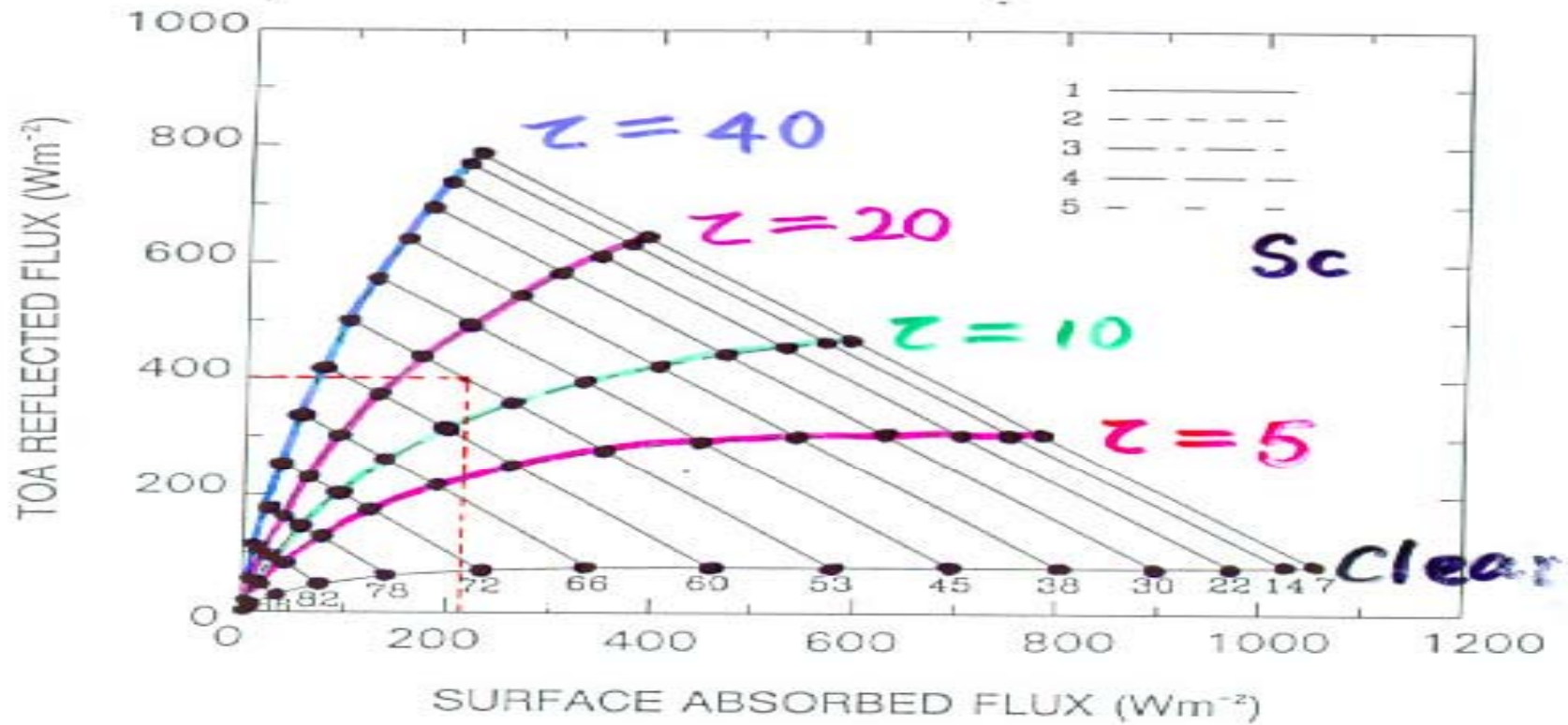
a. Old Relationship Varying Solar Zenith Angle

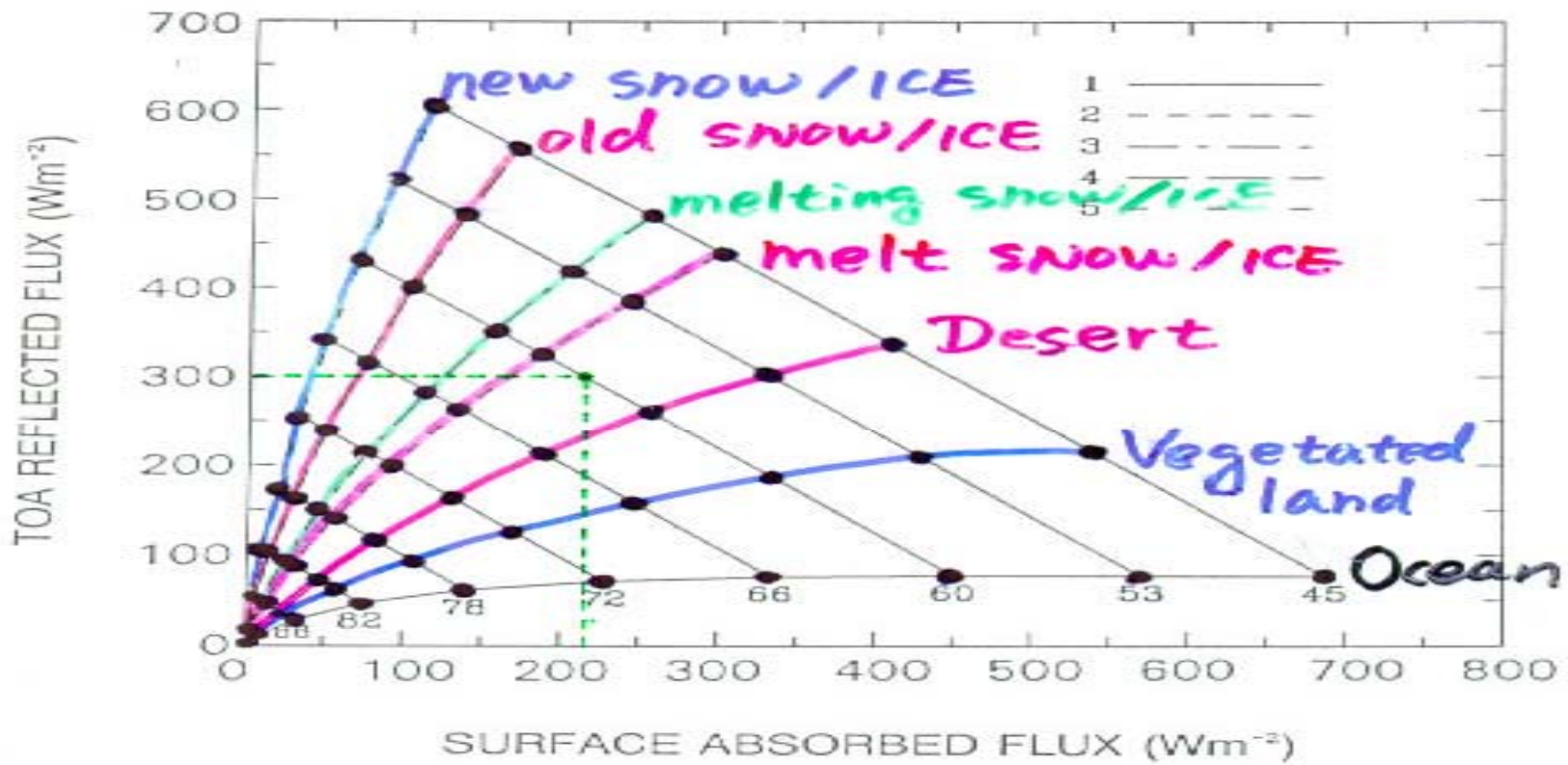
Ramanathan (1986)

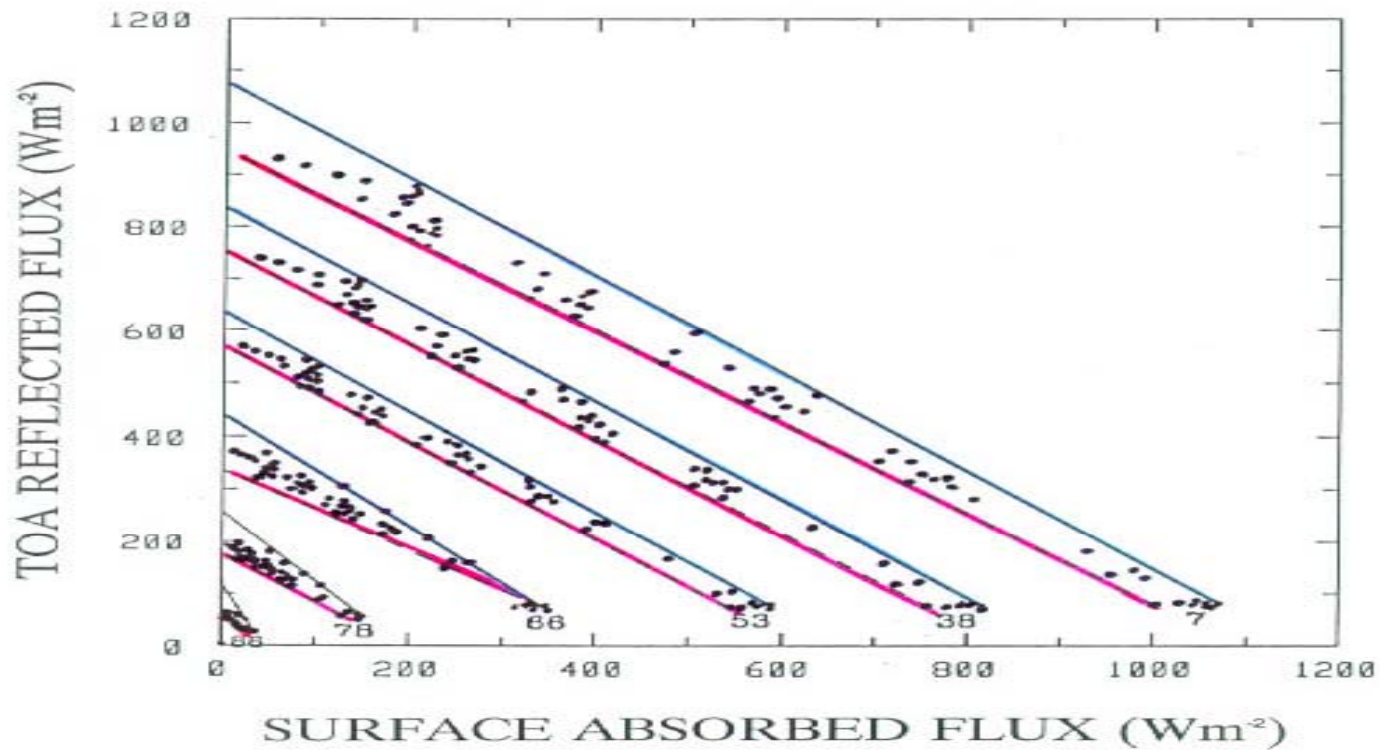
Cess and Vulis (1989)

b. New Relationship Fixed Solar Zenith Angle

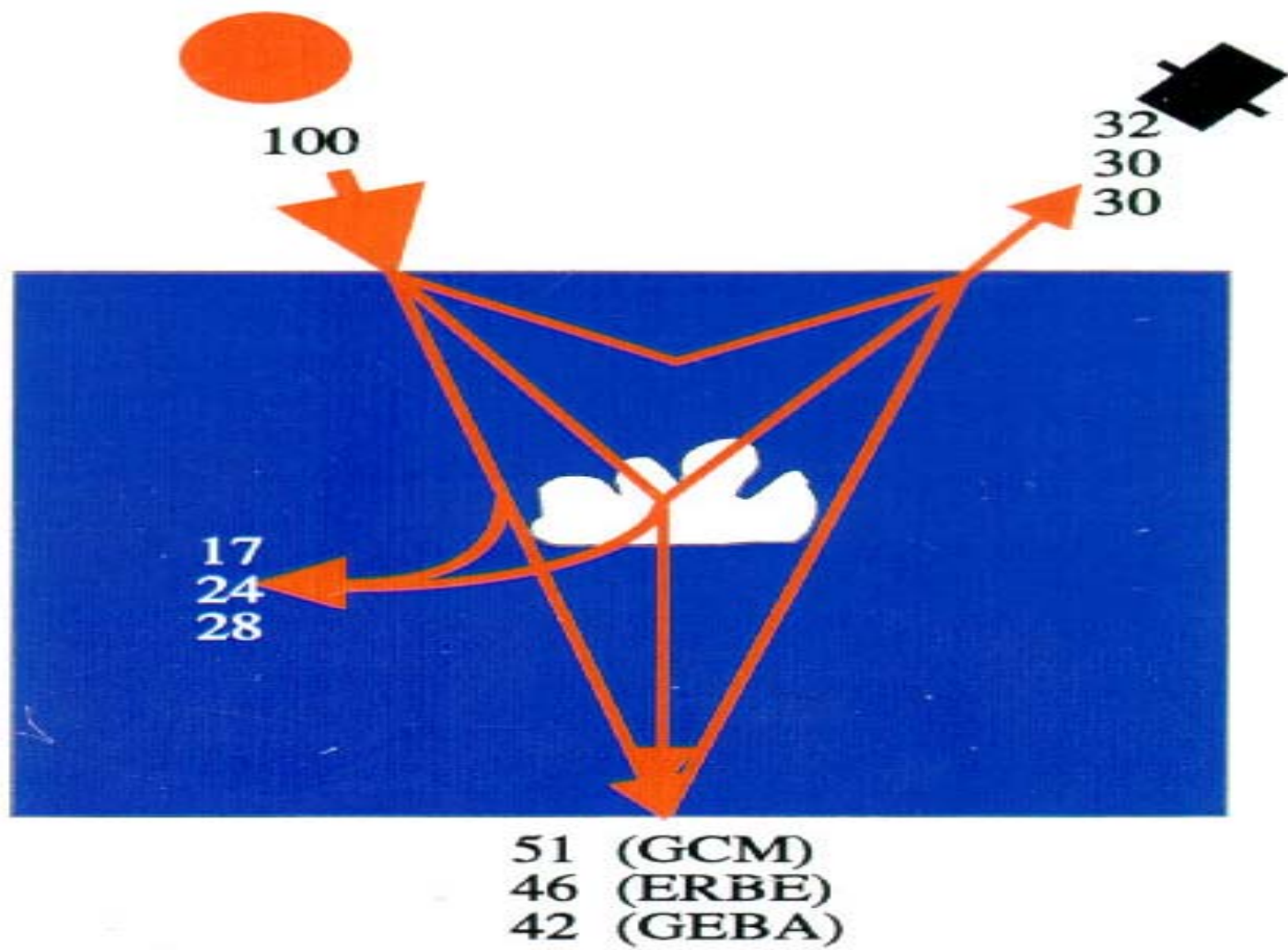
Li *et al* . (1993)





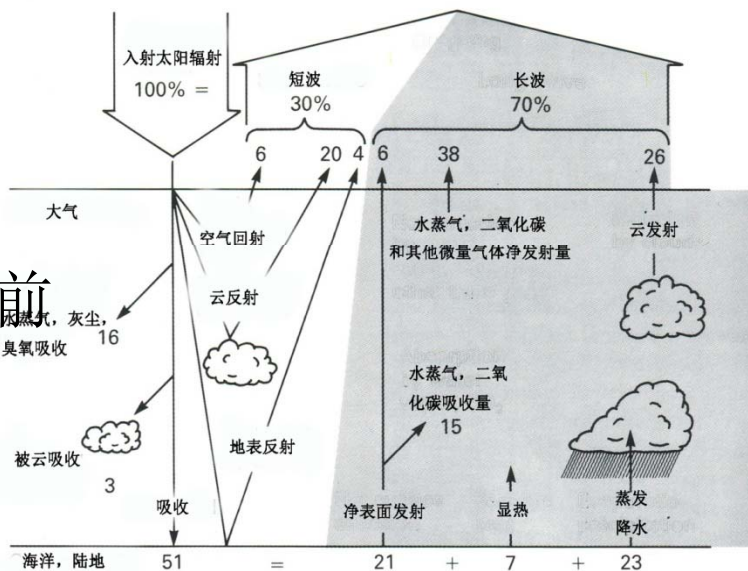


70 COMBINATIONS OF 7 SURFACE
TYPES, 5 H_2O , 3 HAZE LOADINGS
4 CLOUD TYPES, 4 OPTICAL THICKNESSES

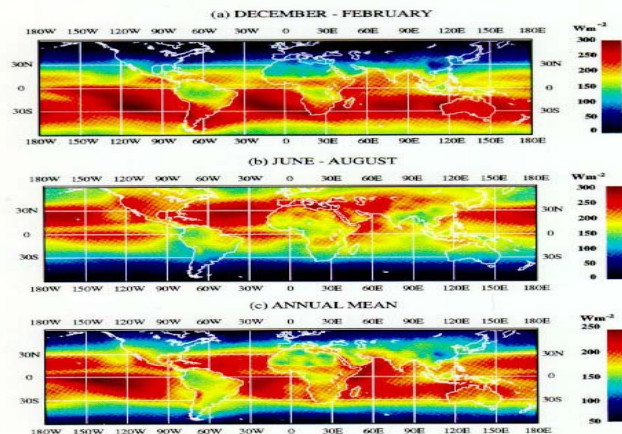


地球能量再分配估算的演变

90年代前
教科书

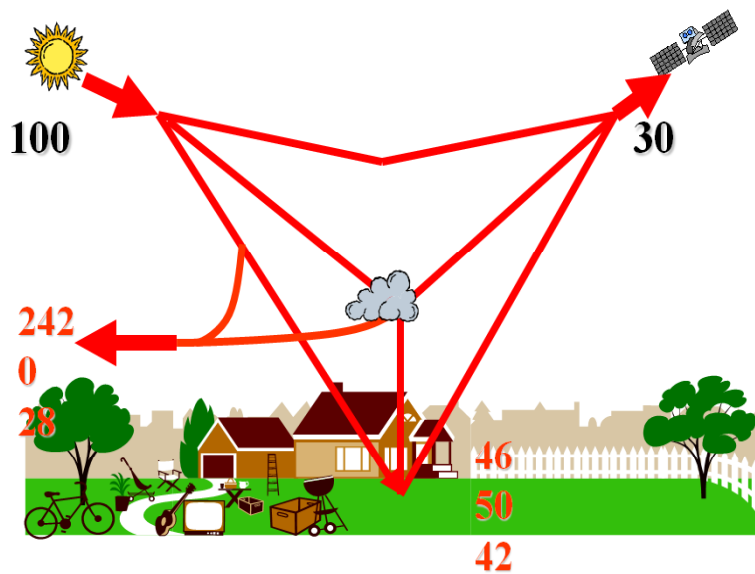
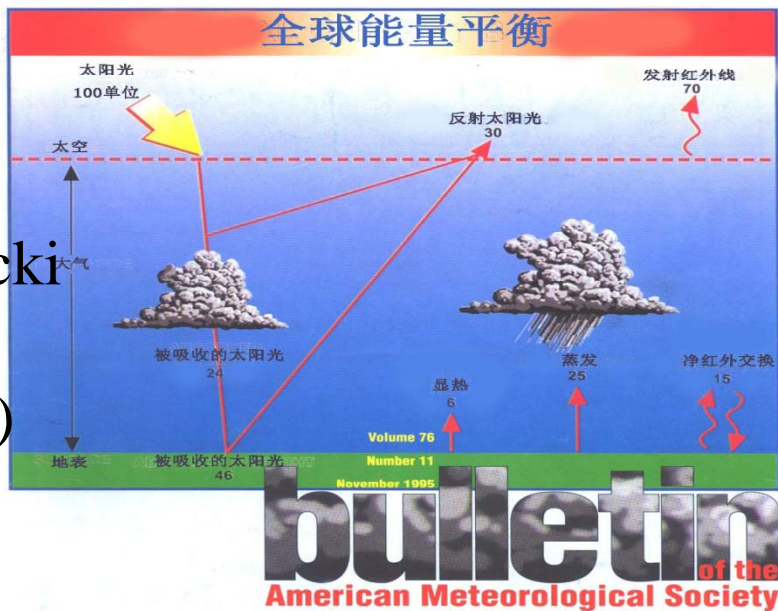


ALL-SKY SURFACE NET SOLAR RADIATION FROM ERBE



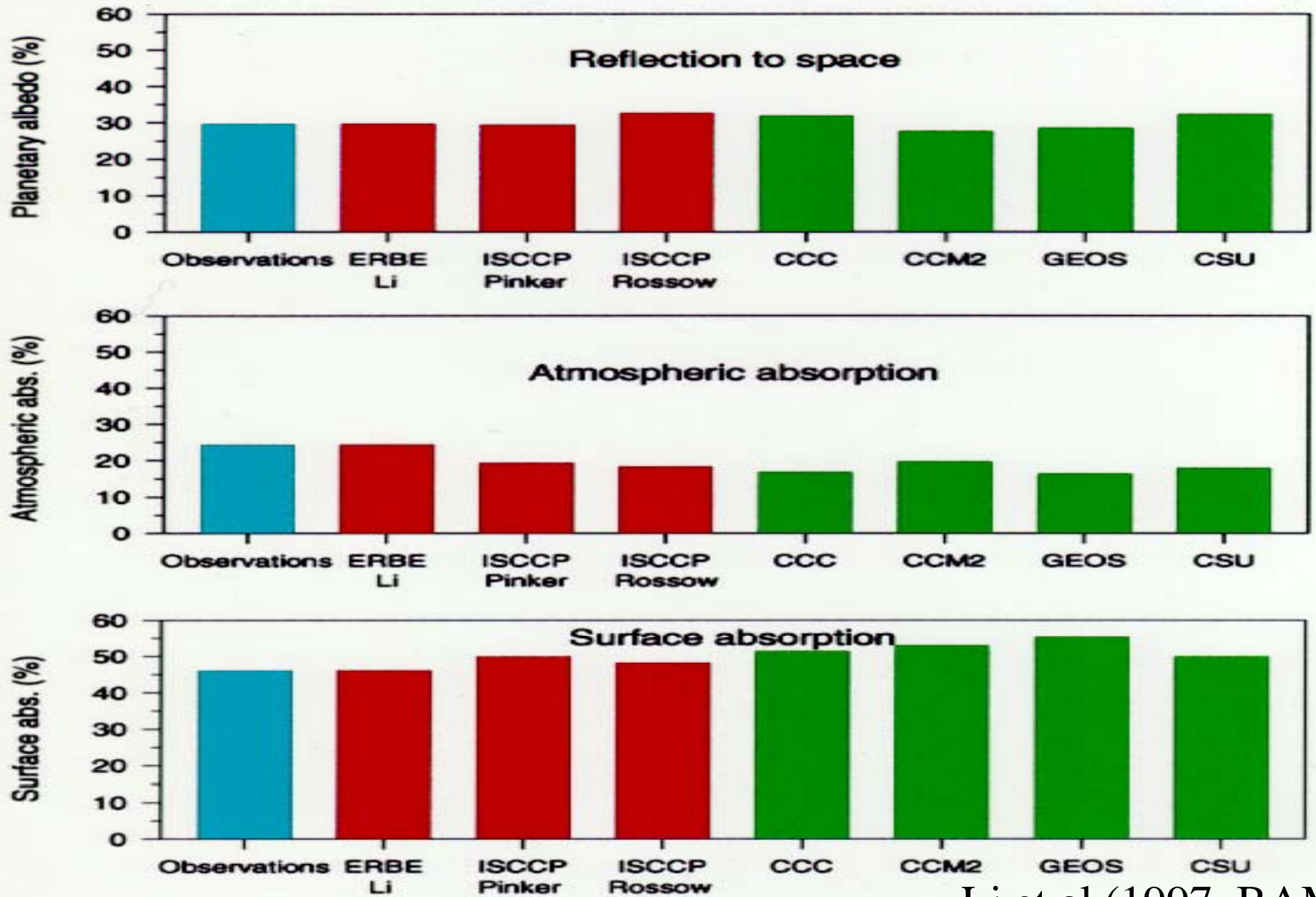
Li et al
(1993)

Wielicki
et al.
(1995)



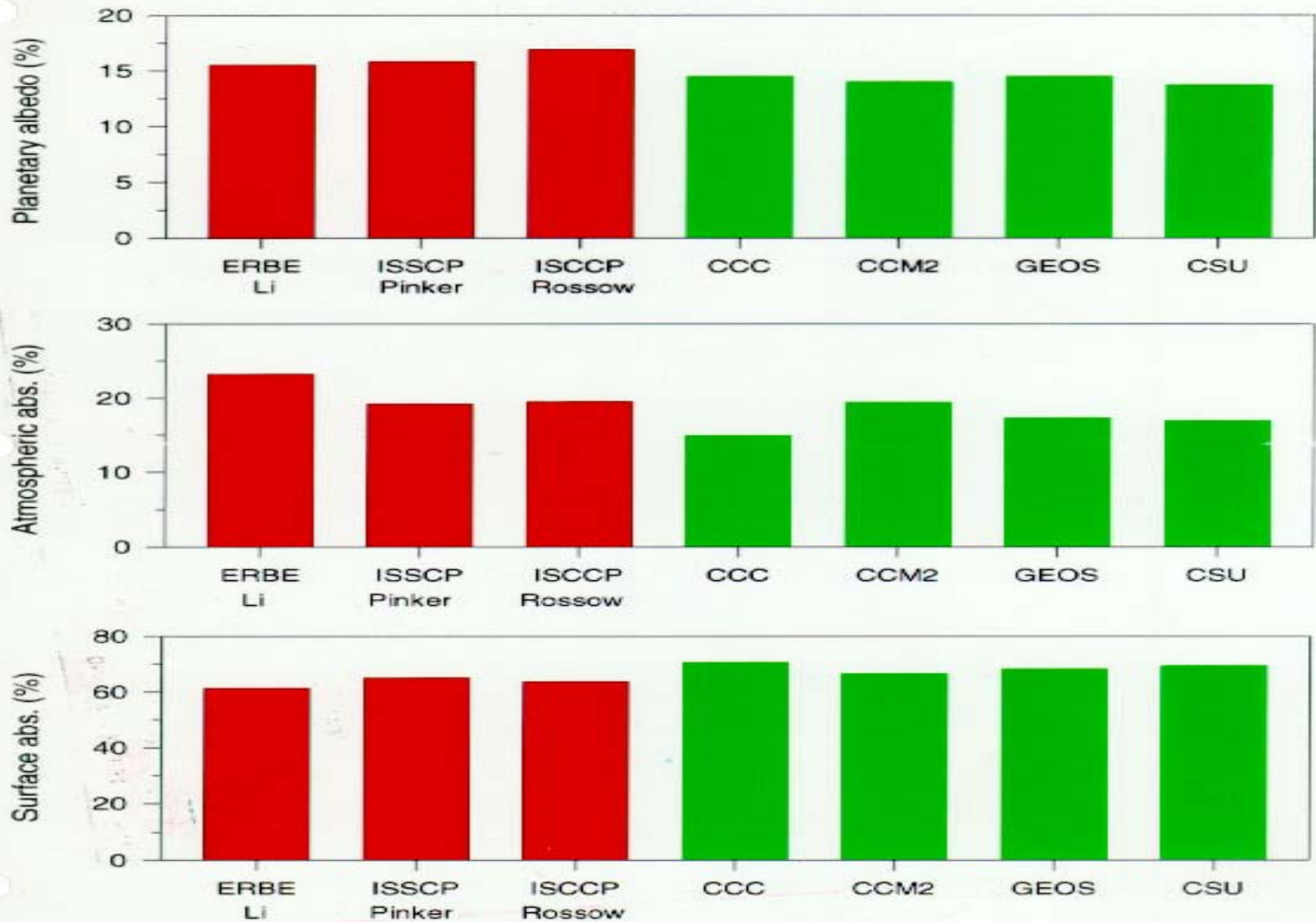
Li et al
(1997)

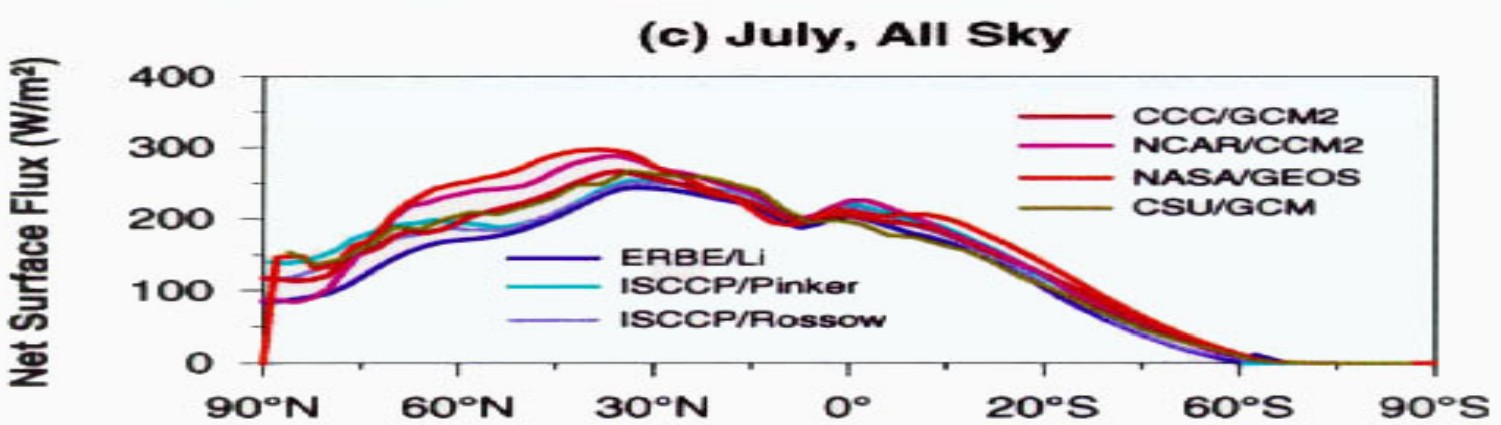
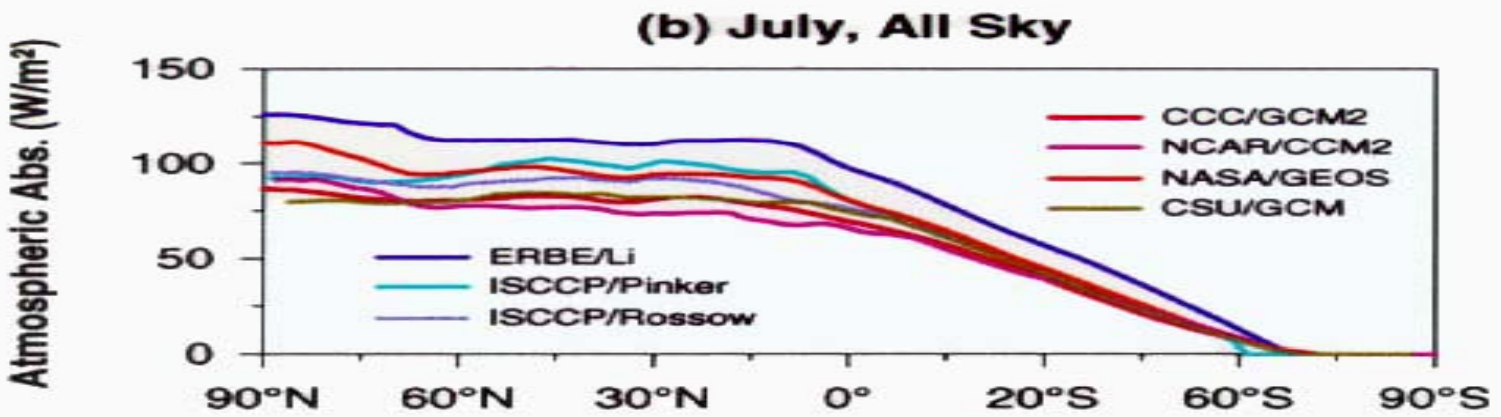
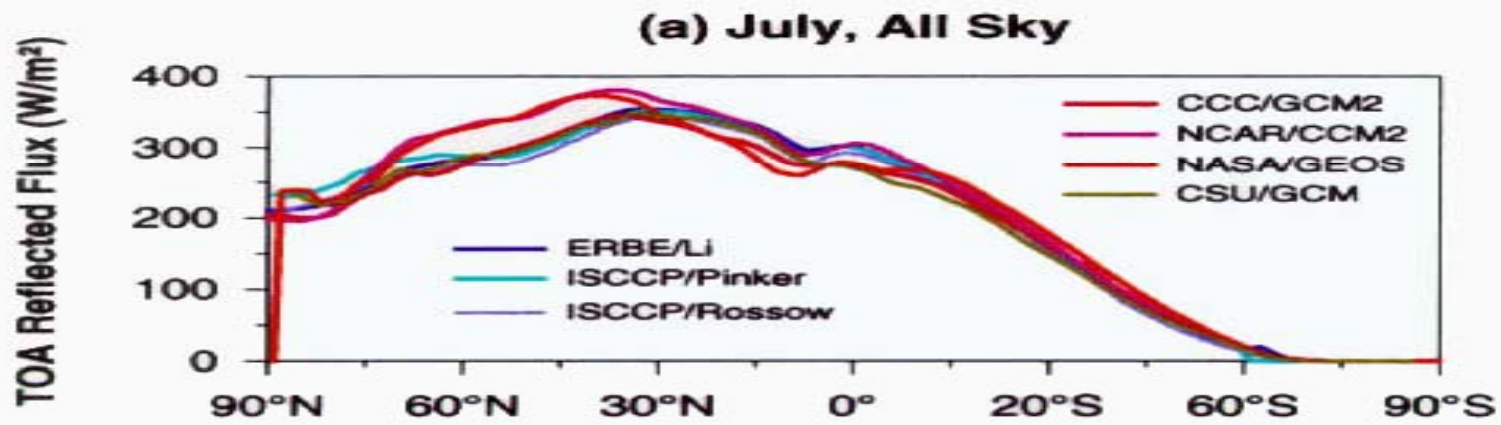
Solar Energy Disposition From Various Sources Annual Average



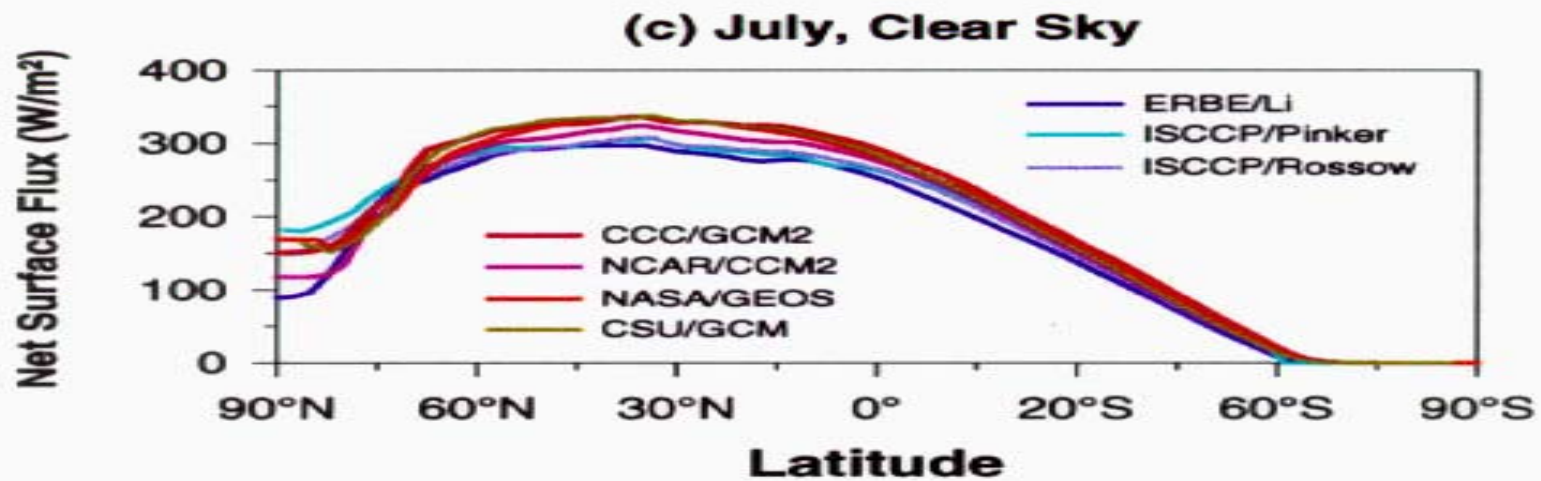
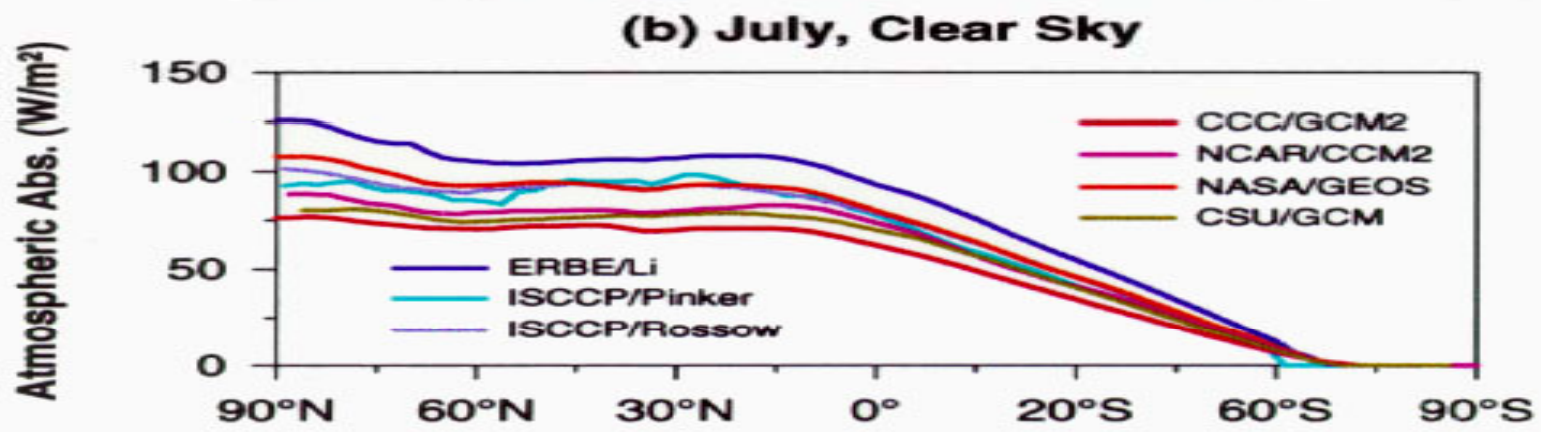
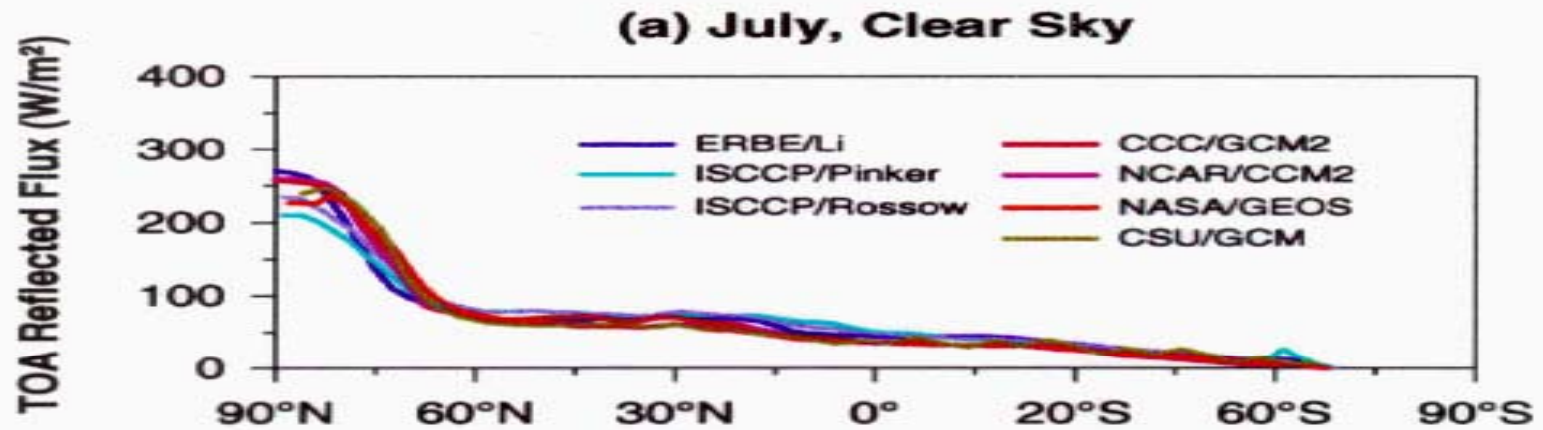
Li et al (1997, BAMS)

Solar Energy Disposition From Various Sources Annual Average, Clear Sky





Li et al (1997, BAMS) Latitude



Assessment of
Cloud Absorption and Earth's
Radiation Budget

Observational Studies on Cloud Absorption Anomaly (CAA) In favor of CAA

Cess et al. (1995, 1996, 1999)

Satellite-surface data, a few sites in different regions

Ramanathan et al. (1995)

Satellite-surface data, warm-pool

Pilewskie and Valero (1995)

Aircraft, tropical ocean

Valero et al. (1997, 1999)

Aircraft, ARESE/ARM

Zender et al. (1997)

Surface/Aircraft, ARESE/ARM

Wendisch and Keil (1999)

Aircraft radiation and cloud measurements

Against CAA

Li et al. (1995); Li (1998)

Global GEBA and ERBE data

Imre et al. (1996)

ARM data

Hayasaka et al. (1996)

Aircraft measurements

Chou et al. (1998)

TOGA-COARE data

Li et al. (1999)

ARESE aircraft, spacecraft and ground data

Asano et al. (1999)

Aircraft measurements

Modeling Studies on CAA

Cloud macro- and micro-physical properties

Chou (1995), Li and Moreau (1996)

Conclusion: Cloud absorption varies with cloud, atmospheric and surface conditions with an overall nil effect on column atmospheric absorption

3-D Effects

Byrne et al. (1996), O'Hirok and Gautier(1996)

Conclusion: some enhancement

Marshak et al. (1997), Barker et al. (1998)

Conclusion: little or no enhancement

Cloud Droplet Size

Lubin et al. (1996)

Conclusion: minor enhancement

Molecular clusters

Chylek et al. (1996, 1998)

Conclusion: minor enhancement

Aerosol and cloud microphysics

O'Hirok et al. (2000)

Conclusion: no sound adjustments to aerosol and cloud optical properties can bring ARESE measurements and model calculation into agreements.

Ramanathan et al. (1995)

Science

essel cruises (8). The one exception is $C_s(S)$: Lack of adequate surface solar radiation observations combined with a lack of understanding of cloud-radiation interactions within cirrus clouds prevent us from estimating this quantity directly. Instead, we estimate it as a residual from Eqs. 1 and 2. Our best estimates for the terms

in Eqs. 1 and 2 are shown in Fig. 1. Monthly and interannual standard deviation, 1σ , of the quantities are needed to assess the uncertainty in the long-term annual means. For values of S and F , the observational records are not of sufficient duration to estimate 1σ . We obtained monthly and interannual 1σ values from a

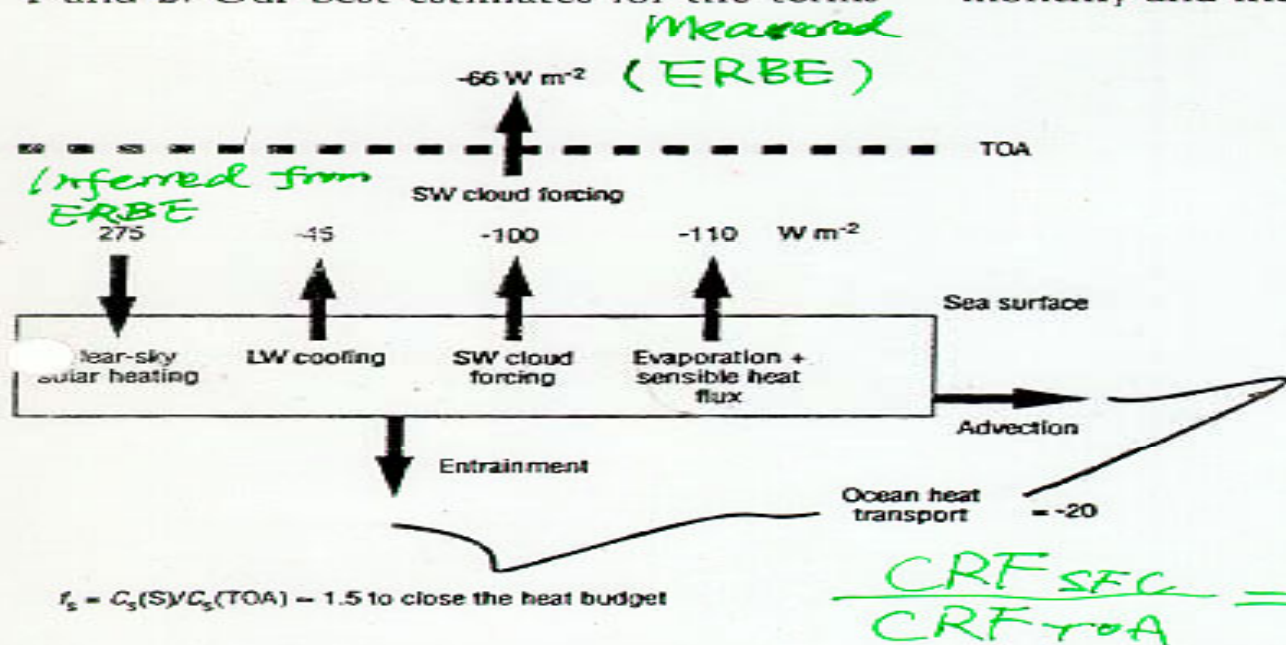


Fig. 1. Annual mean budget of the WP. Energy loss terms are shown as negative values, with outward arrows to facilitate presentation.

Table 1. Comparison of estimated clear-sky solar absorption (S_a) with in situ measurements.

S_a	Present ($W m^{-2}$)	Surface observation ($W m^{-2}$)	Source for surface observation
2°S and 168°E to 158°W (7 March to 16 March 1993)	302	306	CEPEX pyranometer data (14)
14.25°S and 170.56°W (annual mean for 1985)	268	271	Pyranometer data; American Samoa (15)

Table 2. Observed and estimated LW cooling at the WP sea surface. Dates and locations for the data are as follows: TOGA-COARE, 2°S and 156°E, 1 February to 28 February 1993; CEPEX, 2°S and 160°E to 170°W, 7 March to 13 March 1993; pre-TOGA-COARE, 0°N to 4°S and 150°E to 151°E, 7 May to 20

Physical Meaning of CRF Ratio

$$\text{CRF} = \text{NETcld} - \text{NETclr}$$

$$\text{CRFtoa} = \text{CRFsfc} + \text{CRFatm}$$

$$\begin{aligned} R &= \text{CRFsfc} / \text{CRFtoa} \\ &= 1 - \text{CRFatm} / \text{CRFtoa} \end{aligned}$$

$$\begin{aligned} \text{CRFatm} &= (R-1) (\text{REFcld,toa} - \text{REFclr,toa}) \\ &= \text{ABScl,atm} - \text{ABSclr,atm} \end{aligned}$$

Since $\text{REFcld,toa} > \text{REFclr,toa}$,

$$R > 1, \quad \text{ABScl,atm} > \text{ABSclr,atm}$$

$$R = 1, \quad \text{ABScl,atm} = \text{ABSclr,atm}$$

$$R < 1, \quad \text{ABScl,atm} < \text{ABSclr,atm}$$

ent and the clear-sky fit provided values for C_s for each measurement. The dayside means were $C_s(S) = -92.6 \text{ W m}^{-2}$ and $C_s(\text{TOA}) = -63.2 \text{ W m}^{-2}$, or $C_s(S)/C_s(\text{TOA}) = 1.46$, virtually identical to the values obtained in the warm pool analysis (1). Because theoretical models typically yield a value for the ratio of $C_s(S)/C_s(\text{TOA})$ of ≈ 1 , the observed value of 1.46 means that the cloudy atmosphere is absorbing roughly 30 W m^{-2} more SW

radiation than expected, which here is the difference between $C_s(\text{TOA})$ and $C_s(S)$.

This analysis, however, has two drawbacks. First, only surface insolation, rather than net downward SW at the surface, was available at the other sites. Second, an unambiguous clear-sky identification at the surface, using the linear-fit approach (Fig. 1B), was not applicable at some other sites. This was because of a common phenomenon in which broken clouds that do not shadow a pyranometer can actually supply diffuse radiation to it, so that the surface insolation can exceed that for clear skies. This broken cloud effect was pronounced in the data for Wisconsin and for American Samoa in late 1986 and throughout 1987 (during El Niño), as was evident from scatter plots similar to Fig. 1B.

We therefore used an alternate approach patterned after a study of Antarctic clouds

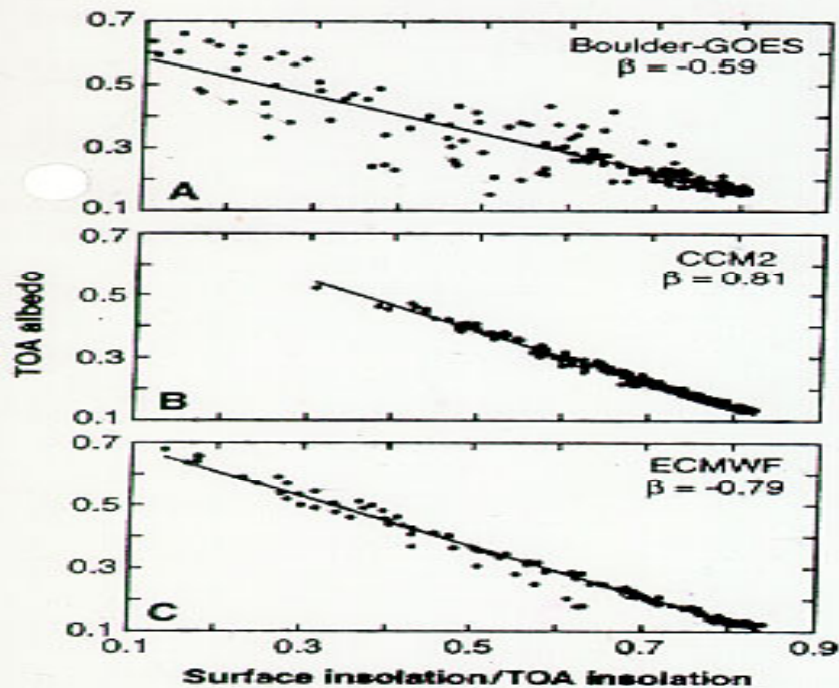


Fig. 2. (A) Scatter plot of the GOES TOA albedo as a function of surface insolation (measured at the BAO tower) divided by the TOA insolation. (B) The same as (A) but for CCM2. (C) The same as (A) but for the ECMWF GCM. In (A) through (C), the solid line represents a linear root mean square fit.

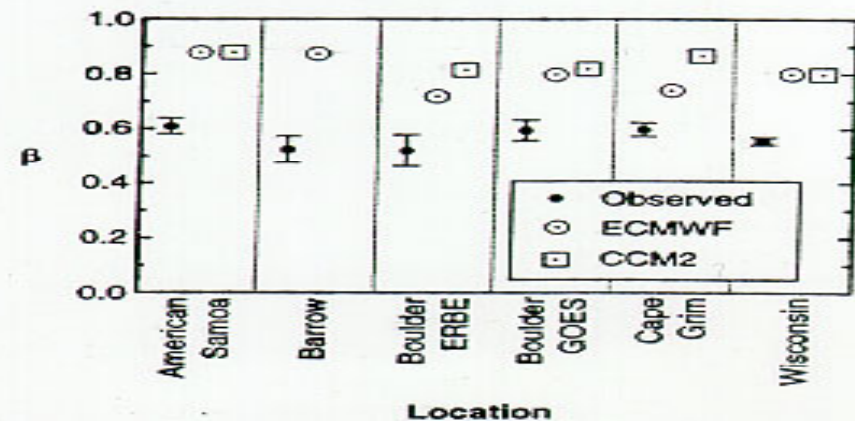


Fig. 3. Comparison of values of β (determined from the ECMWF GCM and CCM2) with the observed values. The vertical bars denote the 95% confidence intervals of the observations.

Physical Meaning of S

$$R_{toa} = a + s T_{atm}$$

$$R_{toa} = 1 - A_{atm} - (1 - R_{sfc})T_{atm} - L$$

$$A_{atm} = b + c R_{toa} \quad L = d + e R_{toa}$$

$$R_{toa} = (1-b) / (1+c) - (1-R_{sfc}) / (1+c) T_{atm}$$

$$s = - (1 - R_{sfc}) / (1 + c)$$

$$S = - (1 - R_{sfc}) / (1 + c + e)$$

Relationship between R and S

$$A_{sfc} = a - r R_{toa}$$

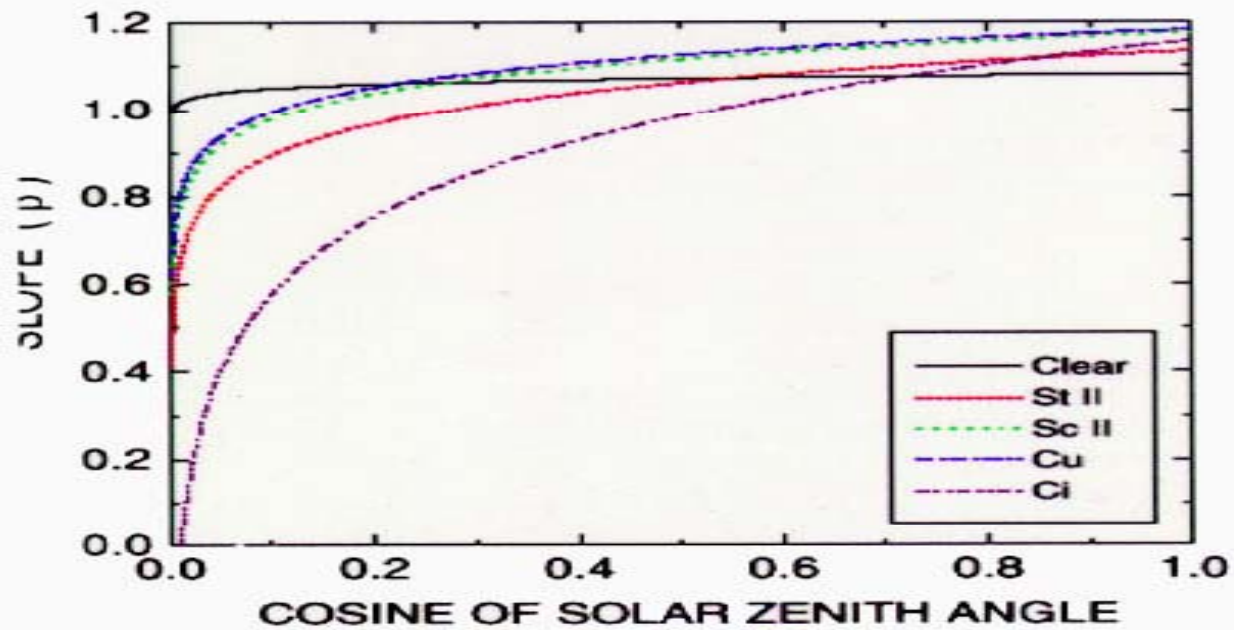
$$A_{sfc} = 1 - A_{atm} - R_{toa}$$

$$A_{sfc} = (1 - b) - (1 + c) R_{toa}$$

$$r = 1 + c$$

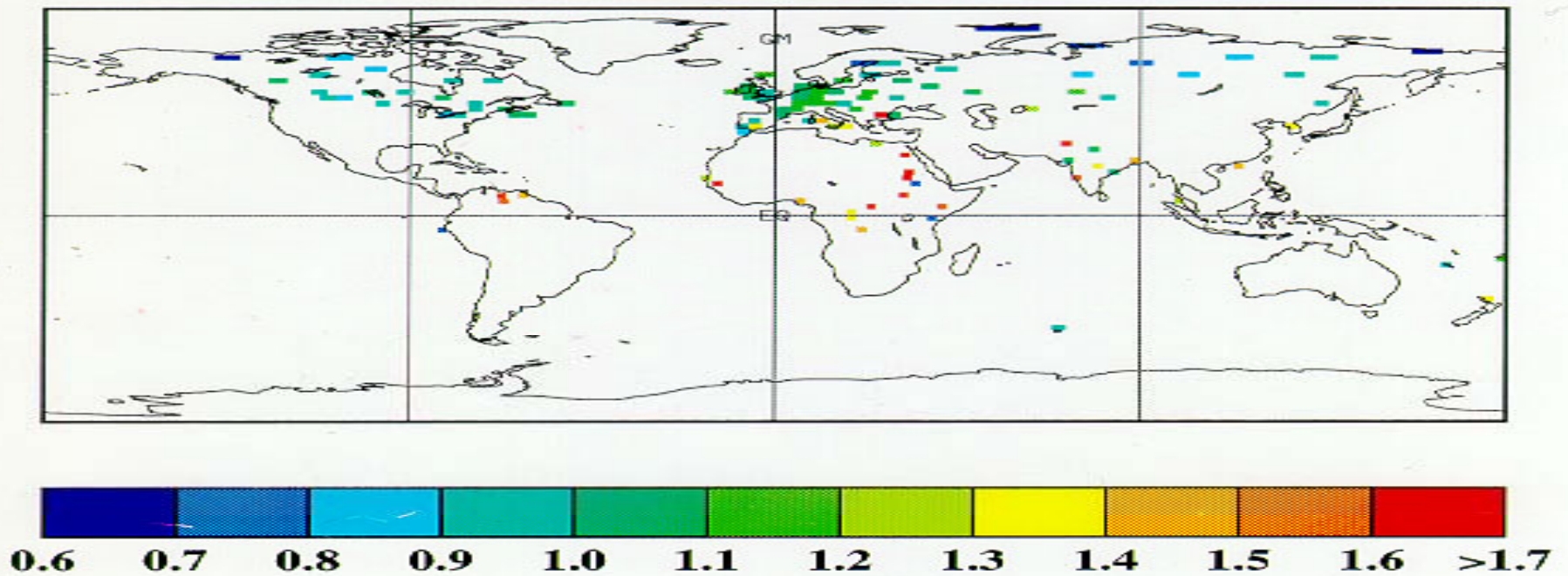
$$s = - (1 - R_{sfc}) / r$$

Dependence of R on cloud type

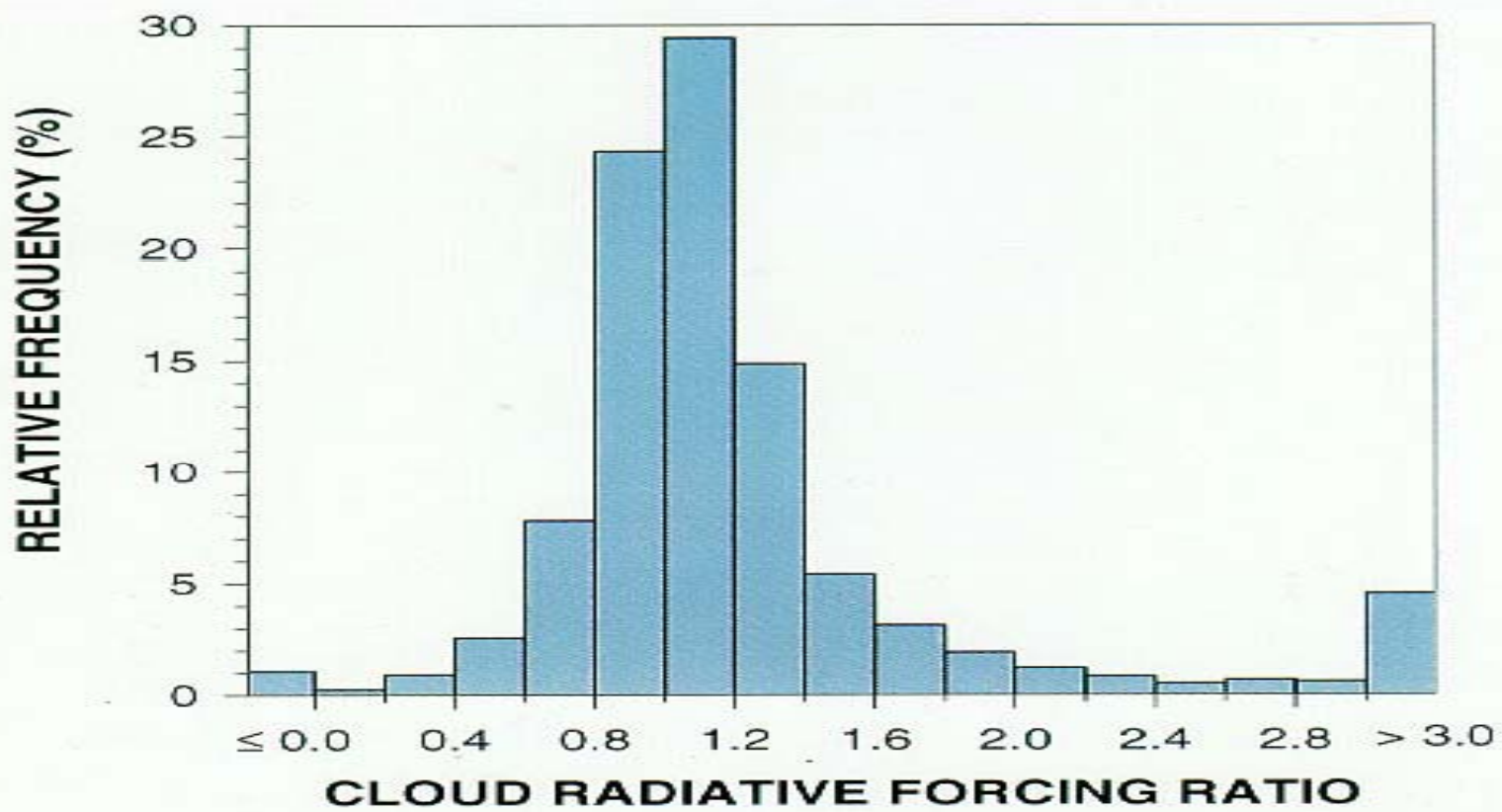


Li et al. (J. Climate, 1993)

SURFACE AND TOA CLOUD FORCING RATIO



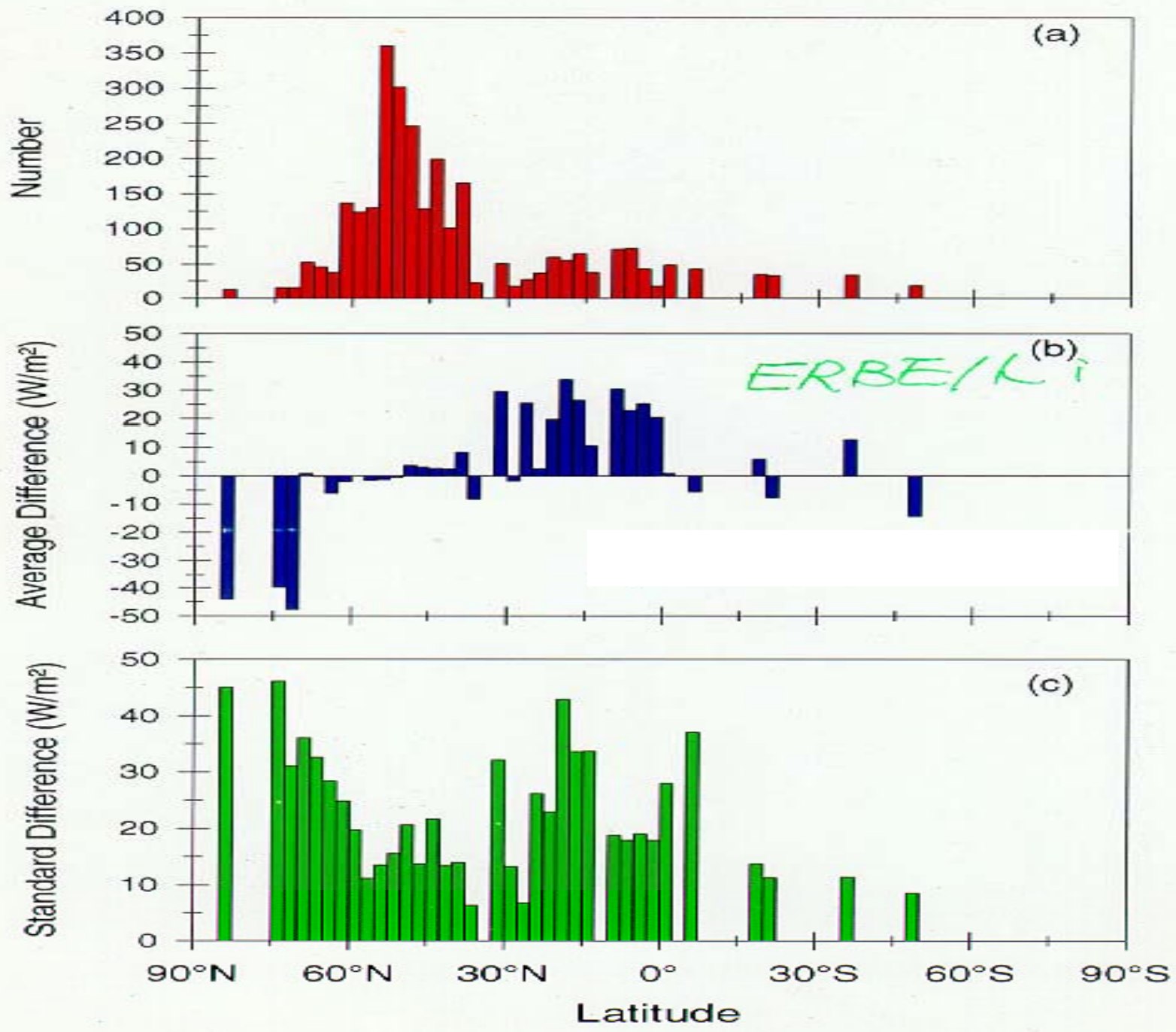
Li et al. (Nature, 1995)

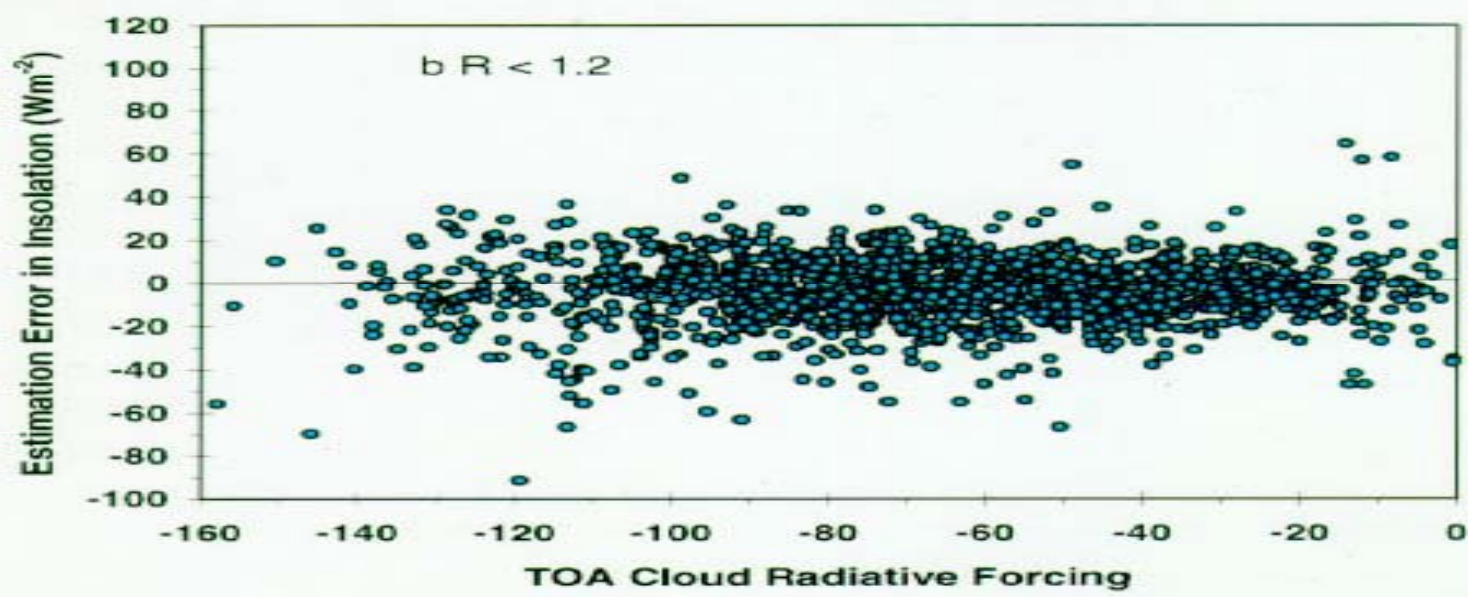
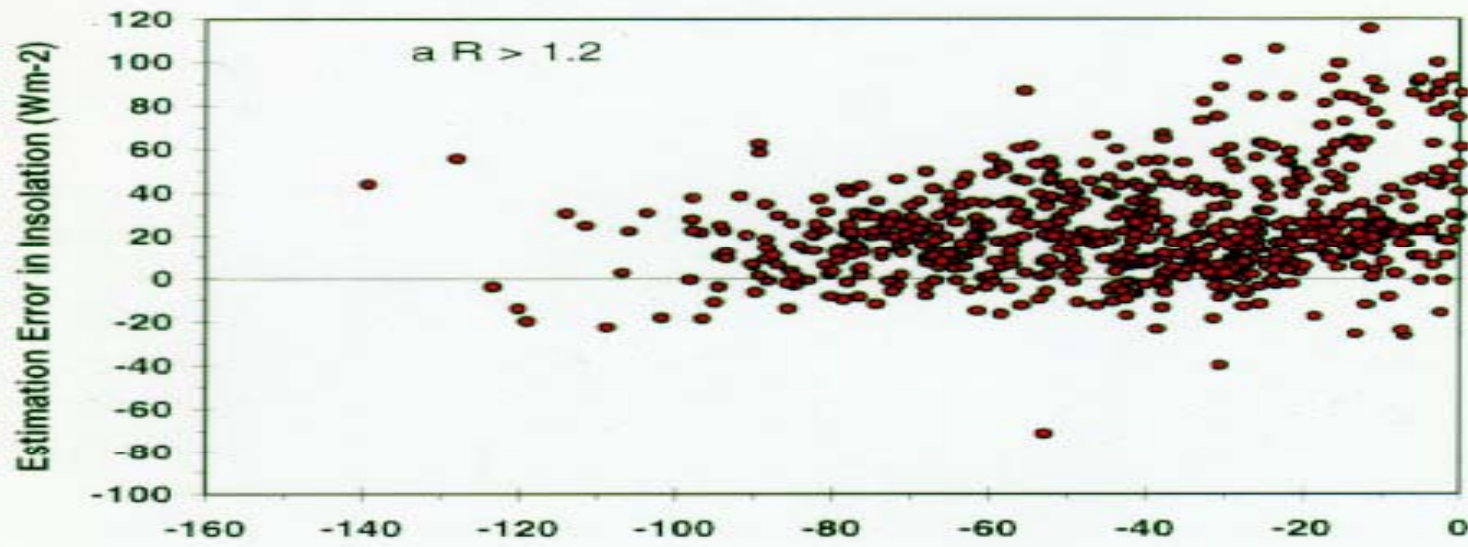


Validation of satellite SRB estimates to check if
the difference increases with cloud cover

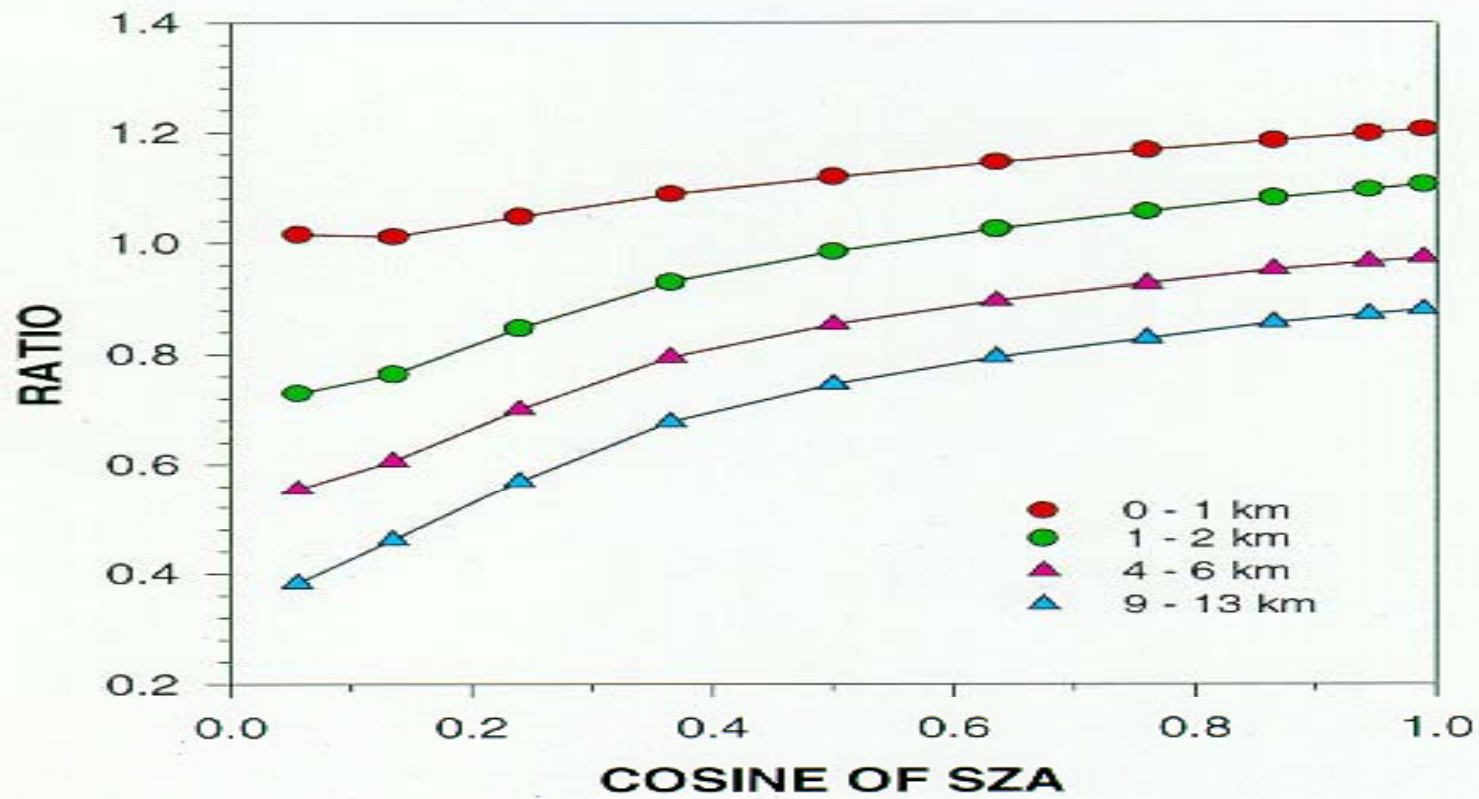
Hypothesis to be tested

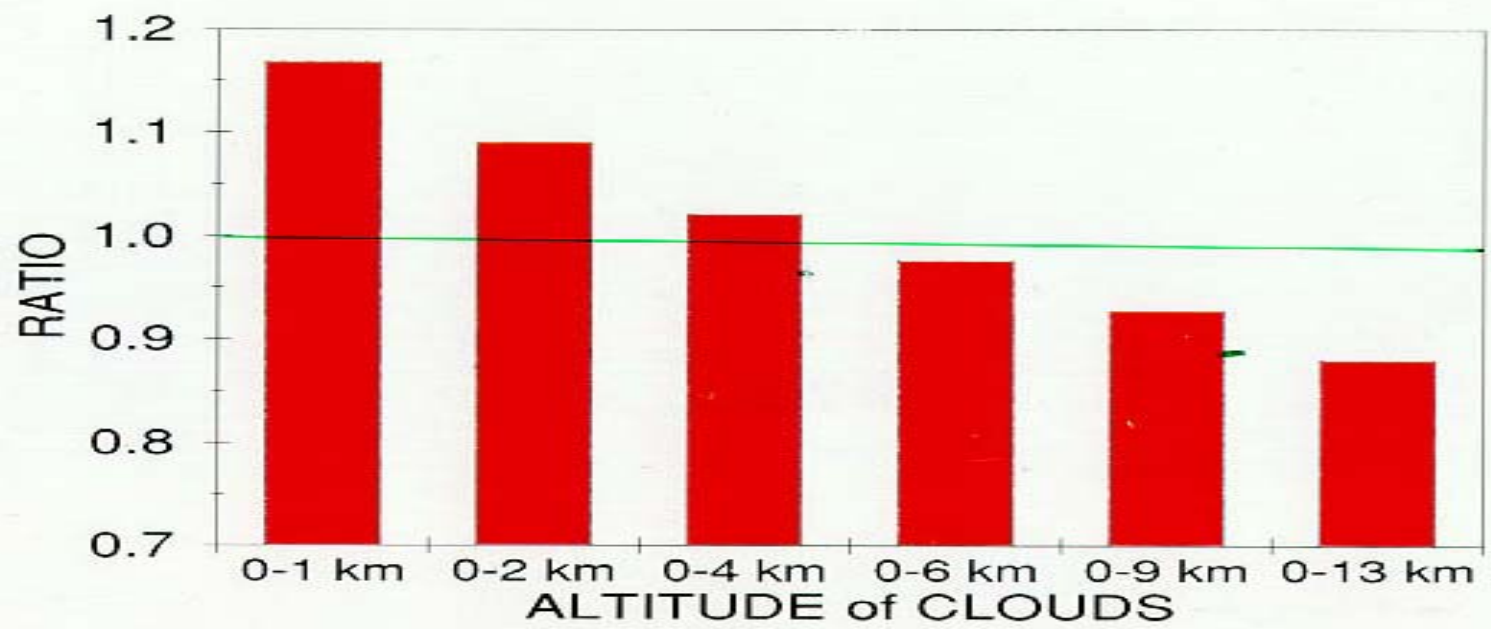
If CAA exists, satellite retrieval of SRB would
not agree with ground-based observations,
and the difference would increase with cloud
amount

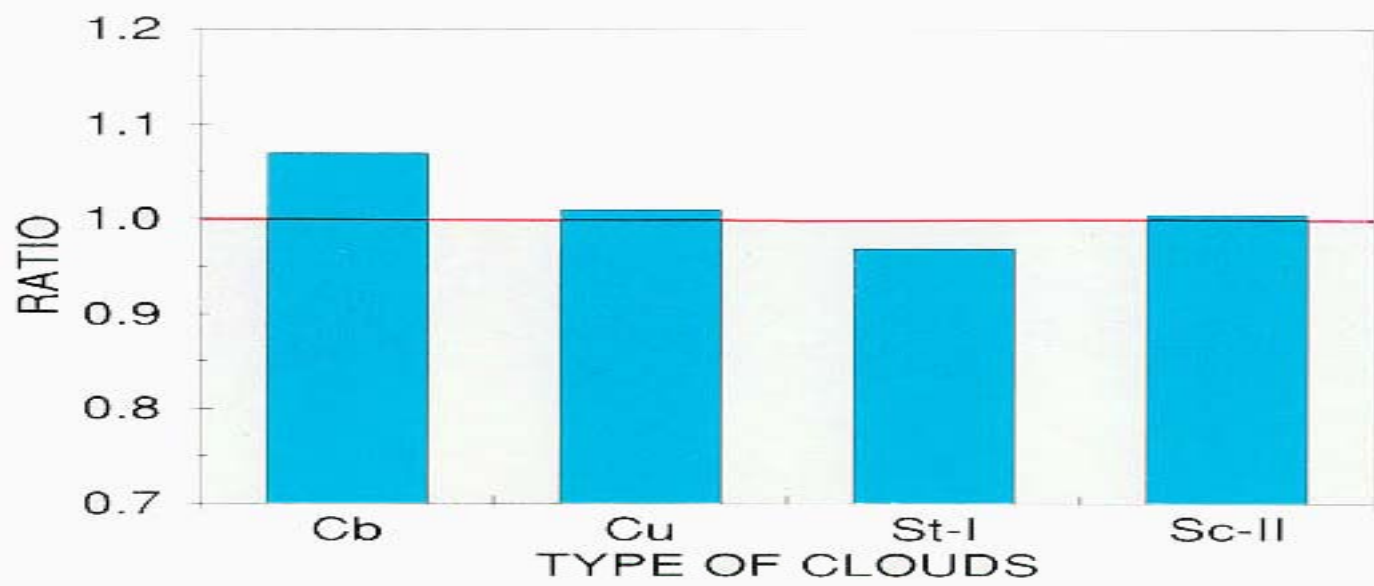




Li (J. Climate, 1998)







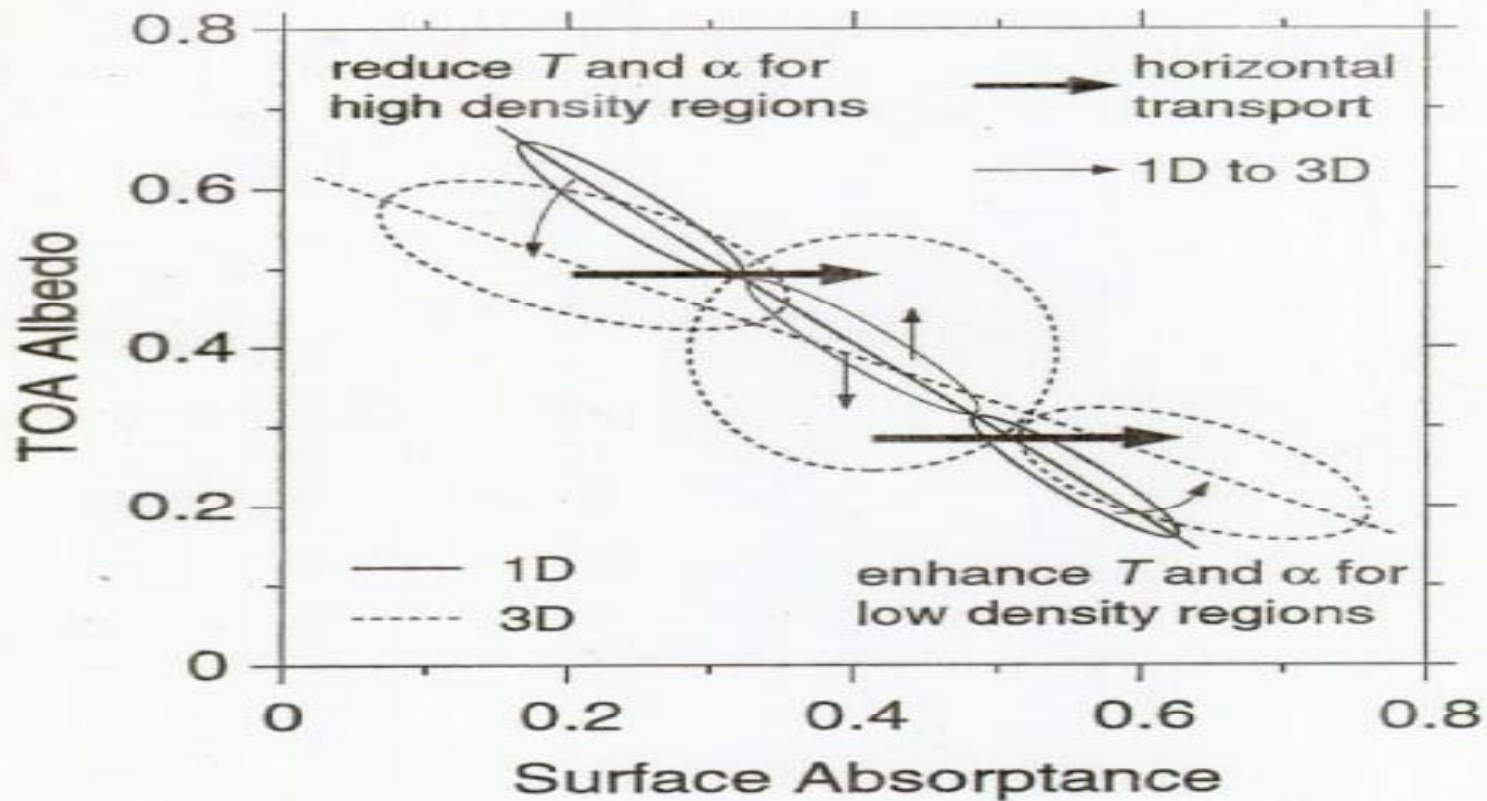
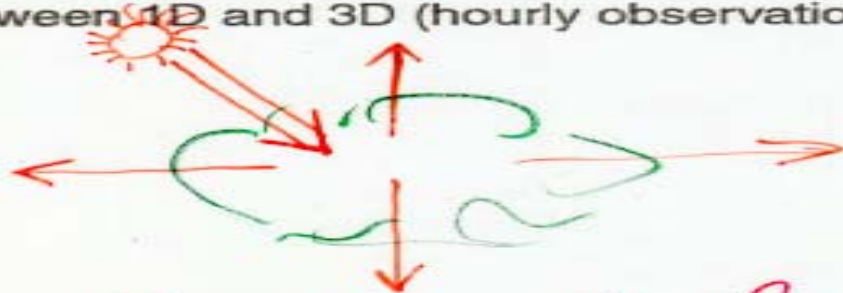


Fig. 3 Schematic α vs. T plot depicting expected differences between 1D and 3D (hourly observational) data.



Barker & Li (1997)

Physical Meaning of S

$$R_{toa} = a + s T_{atm}$$

$$R_{toa} = 1 - A_{atm} - (1 - R_{sfc})T_{atm} - L$$

$$A_{atm} = b + c R_{toa} \quad L = d + e R_{toa}$$

$$R_{toa} = (1-b) / (1+c) - (1-R_{sfc}) / (1+c) T_{atm}$$

$$s = - (1 - R_{sfc}) / (1 + c)$$

$$S = - (1 - R_{sfc}) / (1 + c + e)$$

Relationship between R and S

$$A_{sfc} = a - r R_{toa}$$

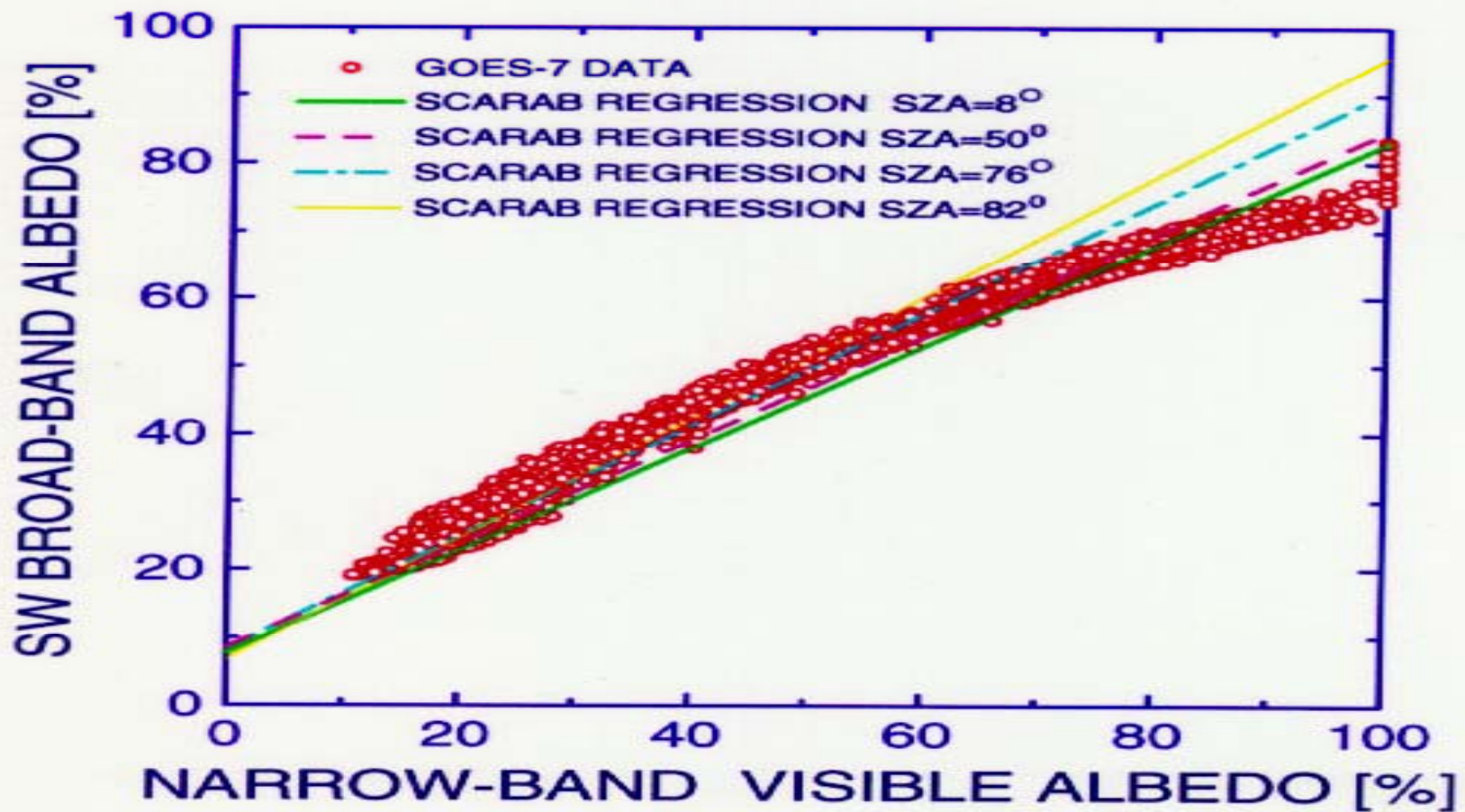
$$A_{sfc} = 1 - A_{atm} - R_{toa}$$

$$A_{sfc} = (1 - b) - (1 + c) R_{toa}$$

$$r = 1 + c$$

$$s = - (1 - R_{sfc}) / r$$

RELATIONSHIP BETWEEN NARROW AND BROAD-BAND ALBEDOS



Project 3 (Due April 19)

1. An important application of a radiative transfer model is to help develop remote sensing algorithm to retrieve quantities at surface or in the atmosphere from satellite measured radiance. The essence of developing an algorithm is to establish relationships explicitly (e.g. parameterization) or inexplicitly (e.g. look-up-table) between a quantity to be retrieved and a quantity measured by a space-borne sense. The objective of this project is to get acquainted with the procedure of algorithm development by reproducing the results as presented in Li et al. (1993, J. Climate) which can be downloaded from my homepage. The algorithm has been used for retrieving surface solar radiation budget from reflected fluxes at the top of the atmosphere (TOA) measured by various space-borne sensors such as the ERBE (Li and Leighton, JGR 1993) and CERES (Krats et al.. 2010).

Use a RTM such as SBDART (<http://arm.mrcsb.com/sbdart/html/sbdart-intro.html>) to

- 1) Compute TOA reflected, surface absorbed and atmospheric absorbed fluxes for cloud optical depths at 0, 10, 20, & 40 to reproduce the results in slide 21 for a fixed solar zenith angle (SZA) at 60o
- 2) Calculate atmospheric absorptance (flux absorbed in the entire atmospheric column divided by incoming flux at the top of the atmosphere, TOA) and parameterize their relationship as a function of TOA albedo. Repeat this for SZA at 0, 30, 60, 75 degrees, and for cloud cloud tops at 850, 500, and 300 mb.
- 3) Discuss the results in terms of the sensitivity of atmospheric absorption to cloud optical depth, sun angle and cloud top height.
- 4) Based on the results of 1)-3), state the fundamental principles of the retrieval of surface absorbed fluxes from TOA reflected fluxes.

2. Read the following papers, write your own assessment of the cloud absorption anomaly (CAA) debate

- 1) Derive the relationships between the slope of Albedo-transmittance (S), the ratio of TOA and surface SW radiative forcing, and the slope in the retrieval of surface absorbed flux and TOA reflected flux. Confirm it with the above modeling results from problem1.
- 2) Elaborate major evidences presented in support and against the CAA
- 3) Flaws or mis-conceptions leading to the apparent CAA
- 4) What you learn from such a debate for the advancement of science?

Papers to Read

- Stephens, G.L., and S.-C. Tsay, 1990: On the cloud absorption anomaly, *Quart. J. Roy. Meteor. Soc.*, **116**, 671-704.
- Cess. R.D., M.H. Zhang, and co-authors, 1995: Absorption of solar radiation by clouds: Observations versus models. *Science*, **267**, 496-499.
- Ramanathan, V., B. Subasilar, and co-authors, 1995: Warm pool heat budget and shortwave cloud forcing: A missing physics, *Science*, **267**, 499-503.
- Li, Z., H. Barker, and L. Moreau, The variable effect of clouds on atmospheric absorption of solar radiation, *Nature* (article), 376, 486-490.1995:
- Li, Z., and L. Moreau, 1996: Alteration of atmospheric solar absorption by clouds: Simulation and observation, *J. Appl. Meteor.*, 35, 653-670.
- Li, Z., T.P. Ackerman, W. Wiscombe, G.L. Stephens, 2003, Have clouds darkened since 1995, *Science*, 302, 1151-1152.
- Li, Z., 2004, On the solar radiation budget and cloud absorption anomaly debate
- Li, Z., H.G. Leighton, K. Masuda, and T. Takashima, 1993: Estimation of SW flux absorbed at the surface from TOA reflected flux, *J. Climate*, 6, 317-330.