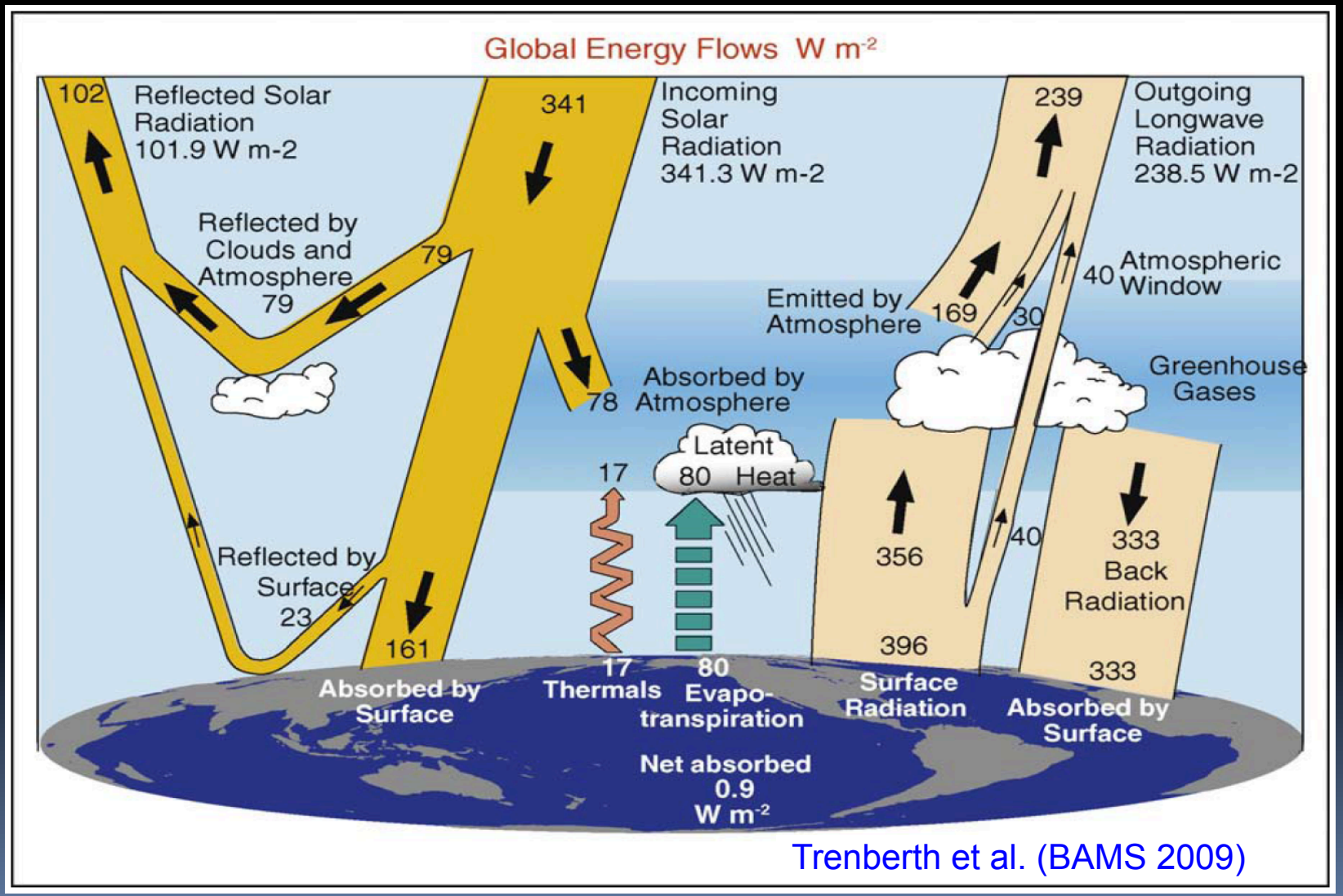
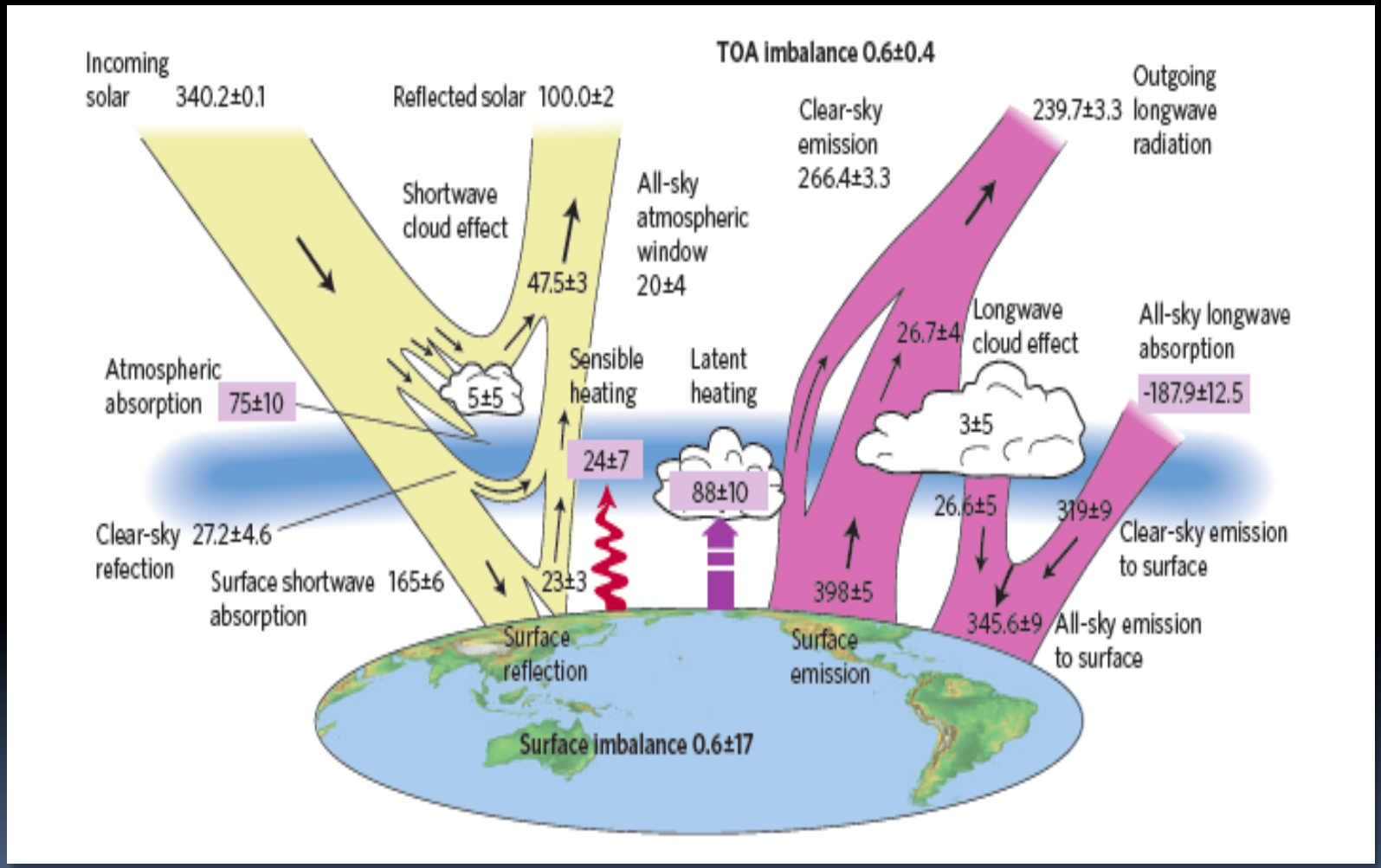
Objective closure of surface energy fluxes

Trenberth et al. (2009)



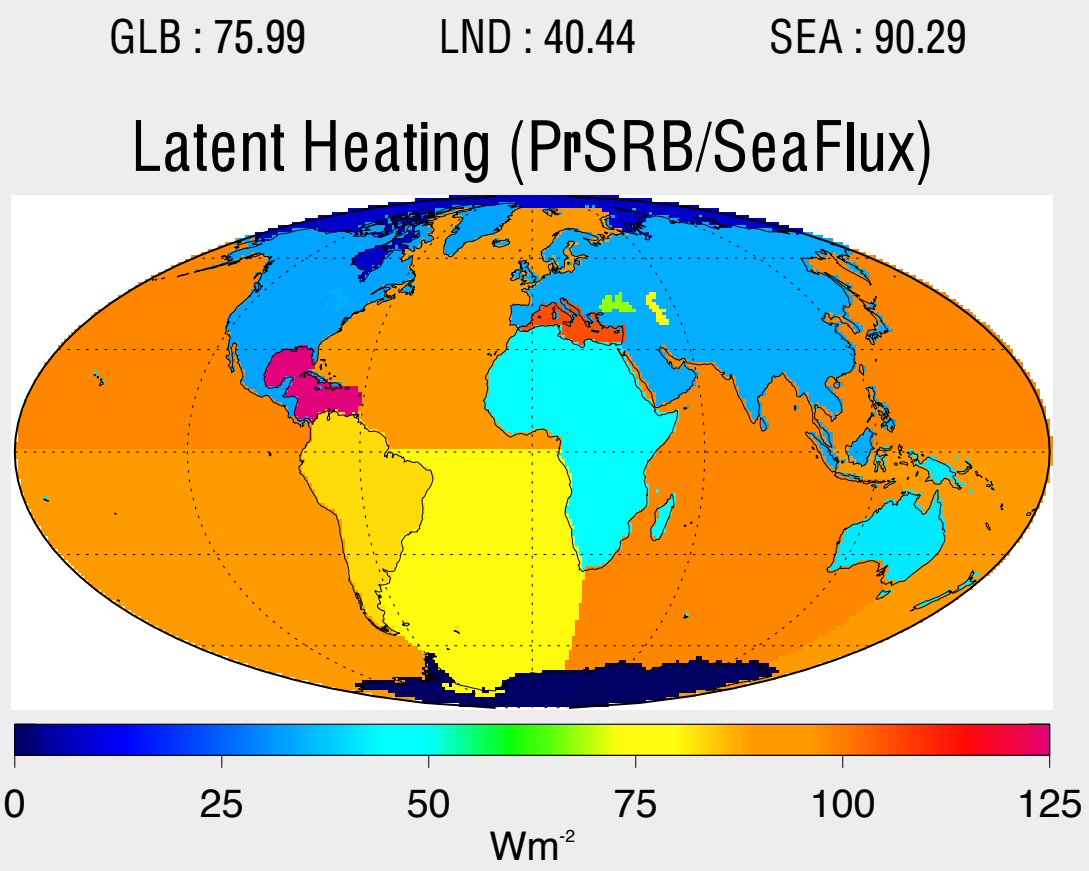
Trenberth et al. (BAMS 2009)

Stephens et al (2012)



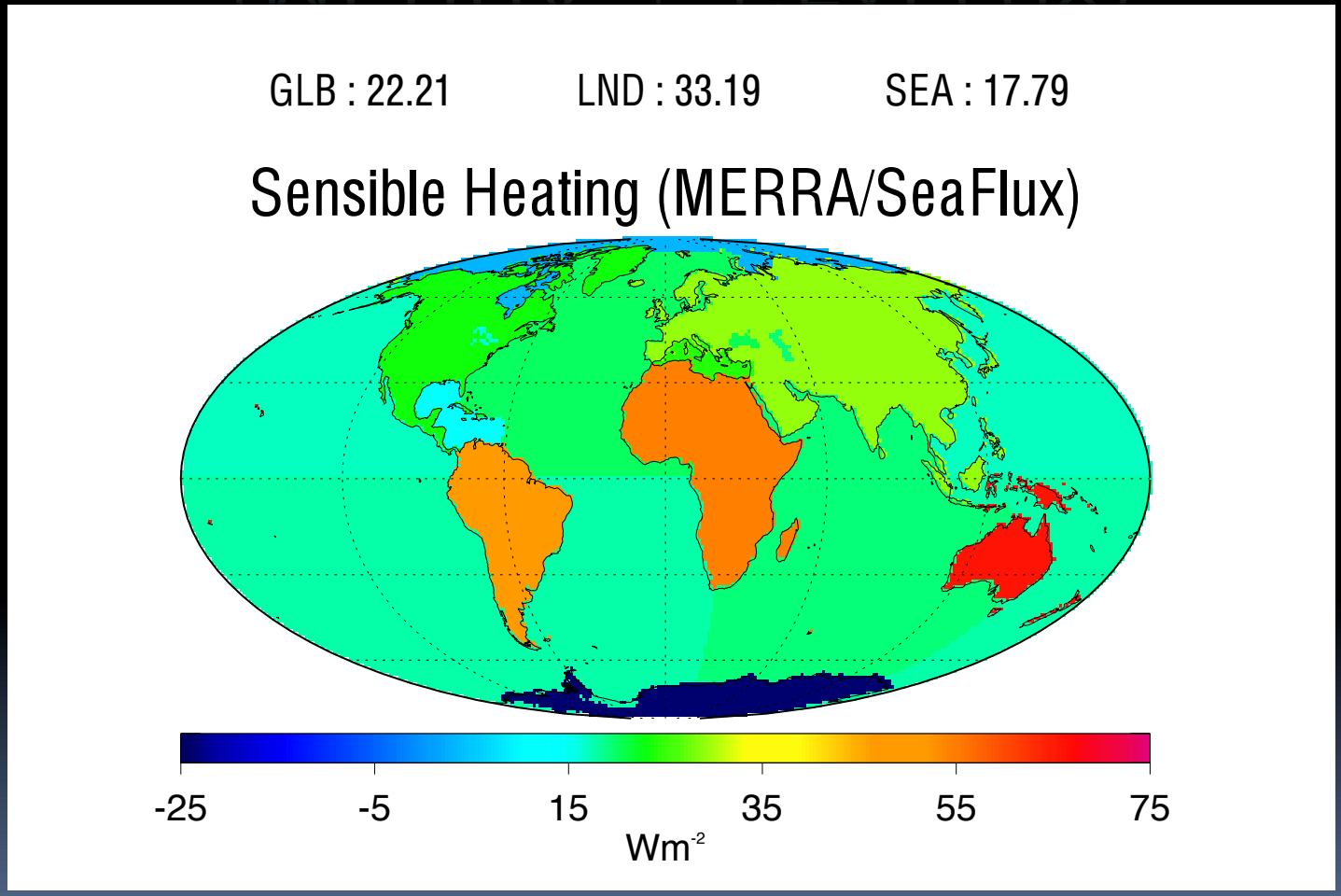
SH 7 Wm^{-2} higher; 8 Wm^{-2} higher; DLR 12 Wm^{-2} higher

Latent Heating (Princeton-SRB + SeaFlux)



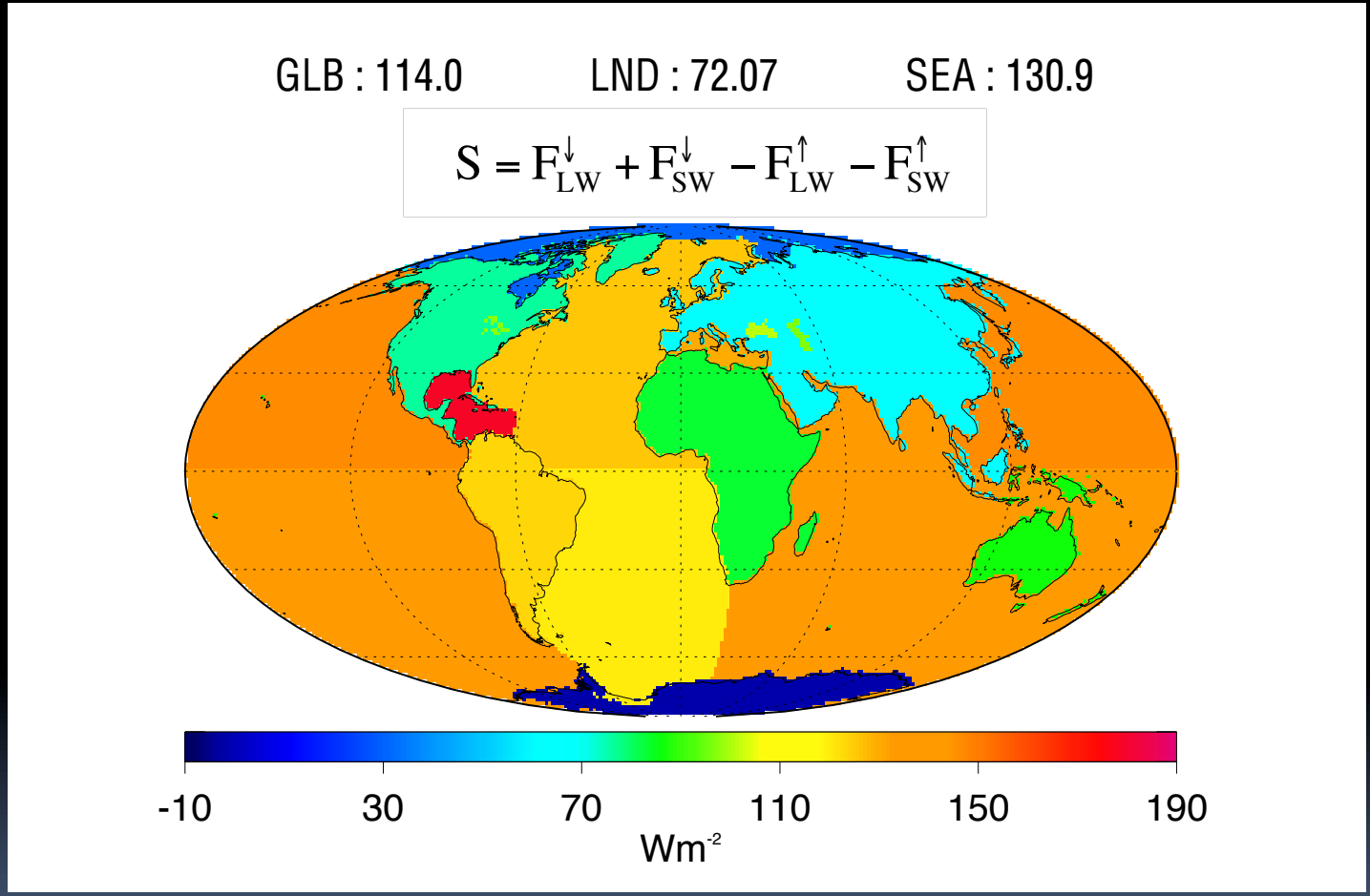
ET ~ 4 Wm^{-2} less than Trenberth et al; 12 Wm^{-2} less than Stephens et al

Sensible Heating (MERRA + SeaFlux)



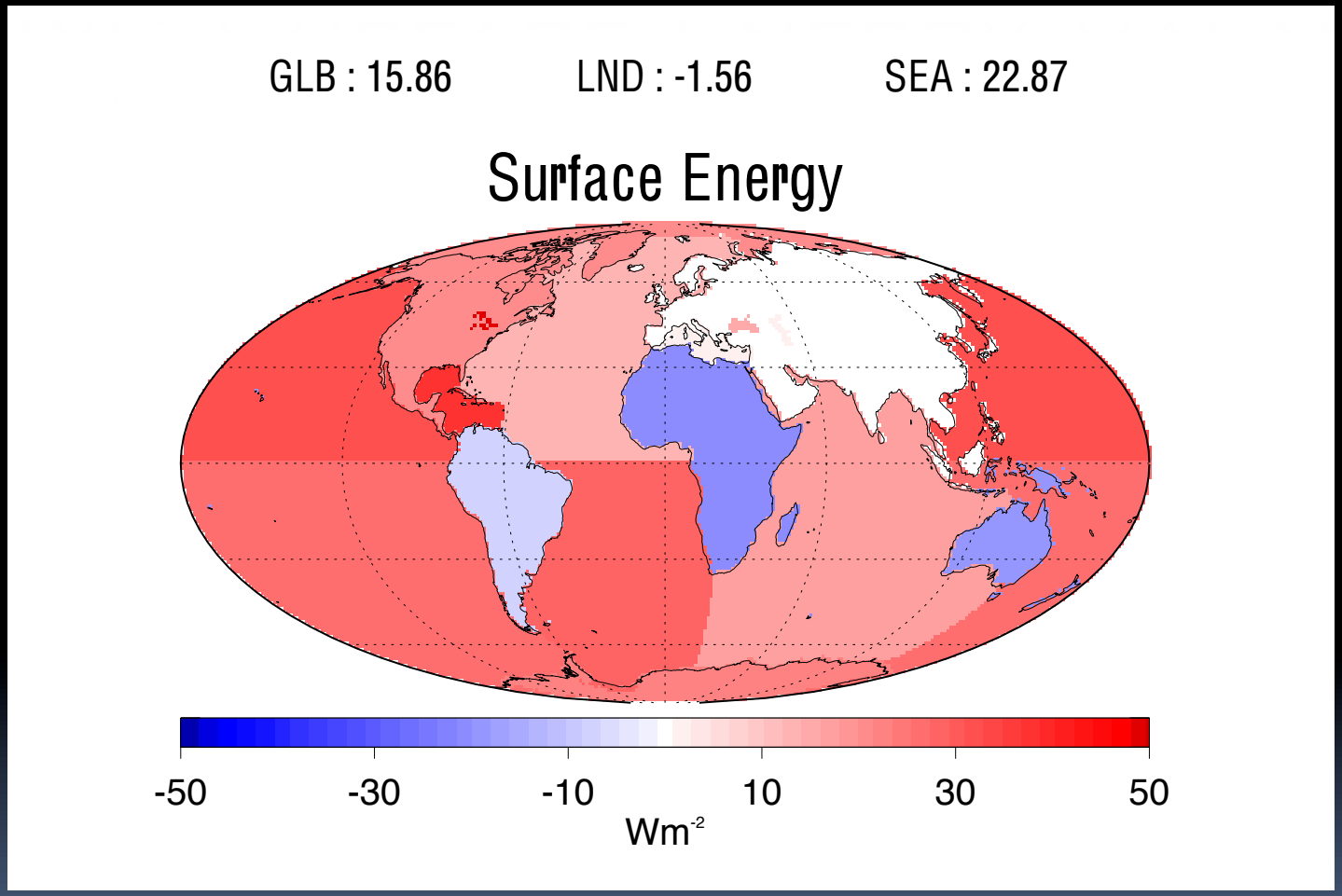
SH 5 Wm^{-2} larger than Trenberth; 2 Wm^{-2} less than Stephens et al

Surface Net Radiation (SRB)



DLR 11 Wm^{-2} larger than Trenberth et al; DSR 7 Wm^{-2} larger
DLR 1 Wm^{-2} smaller than Stephens et al; DSR 3 Wm^{-2} larger

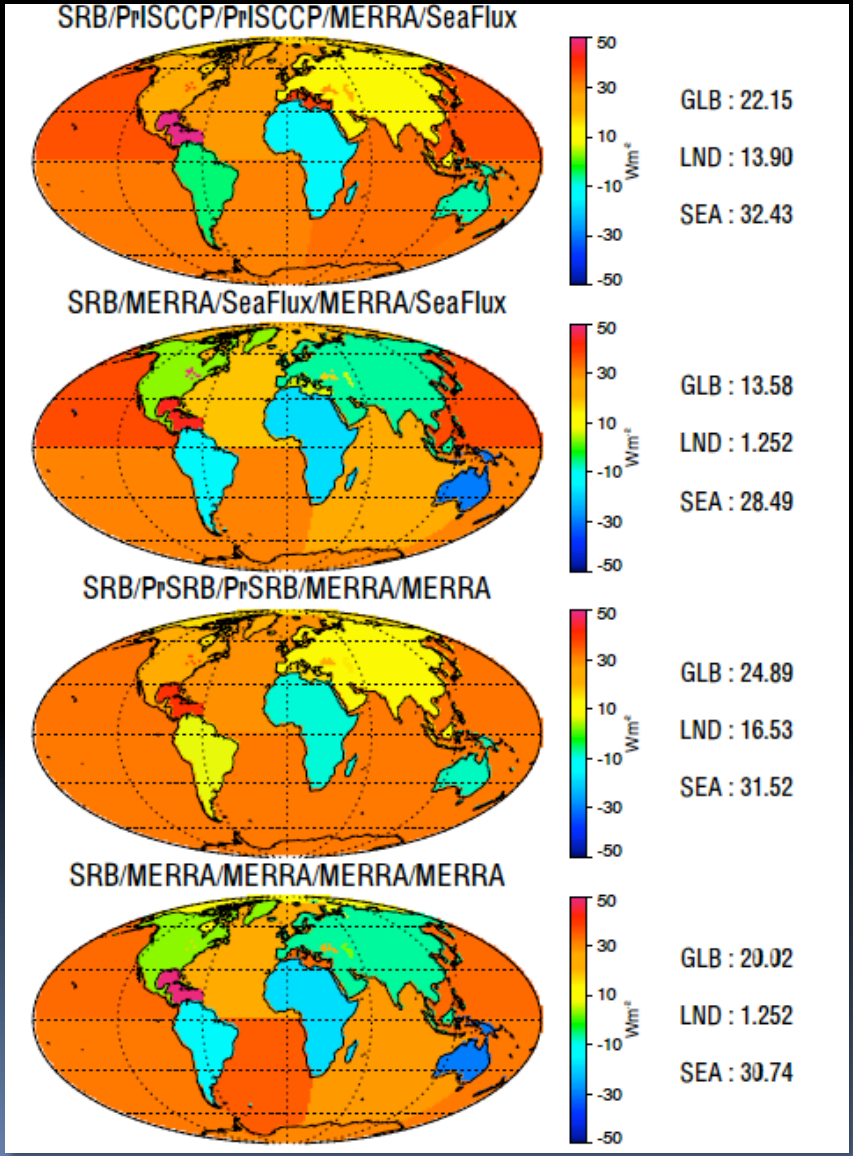
NEWS Surface Energy Balance

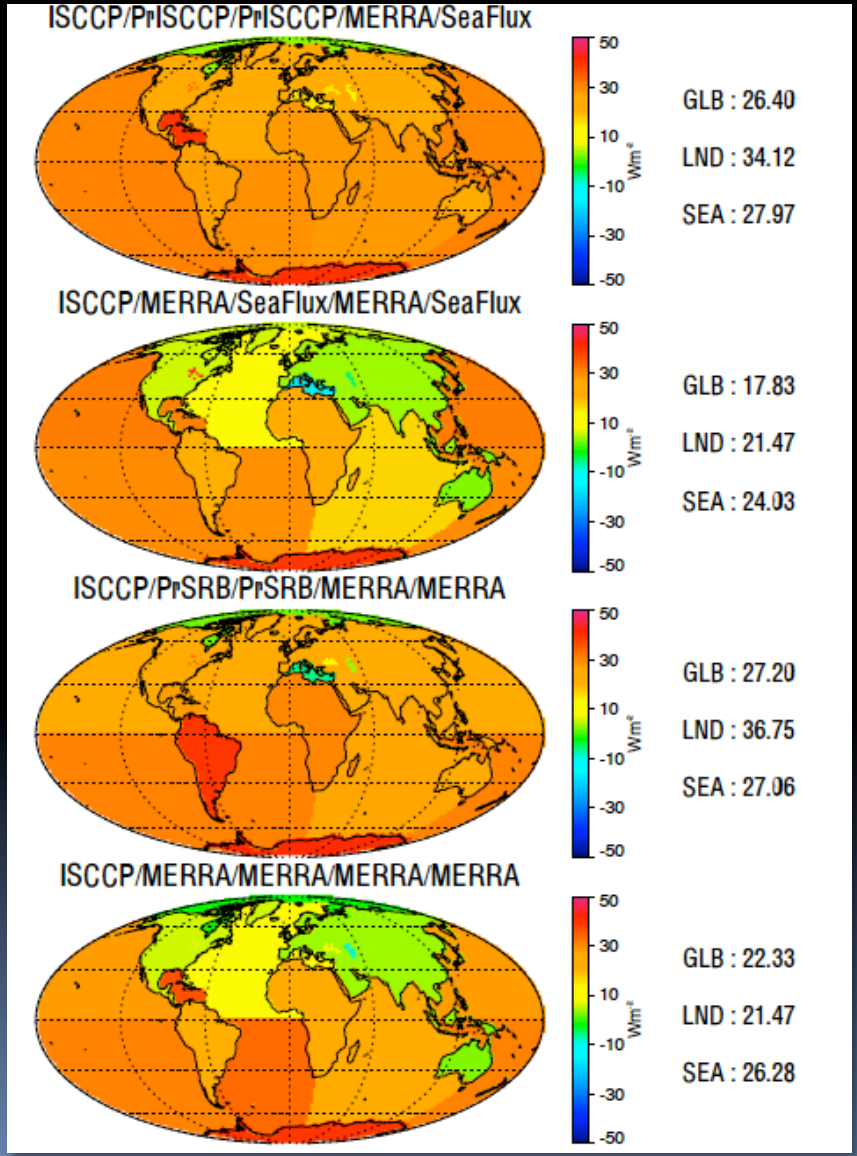


$$S = F_{LW}^{\downarrow} + F_{SW}^{\downarrow} - F_{LW}^{\uparrow} - F_{SW}^{\uparrow} - LH - SH$$

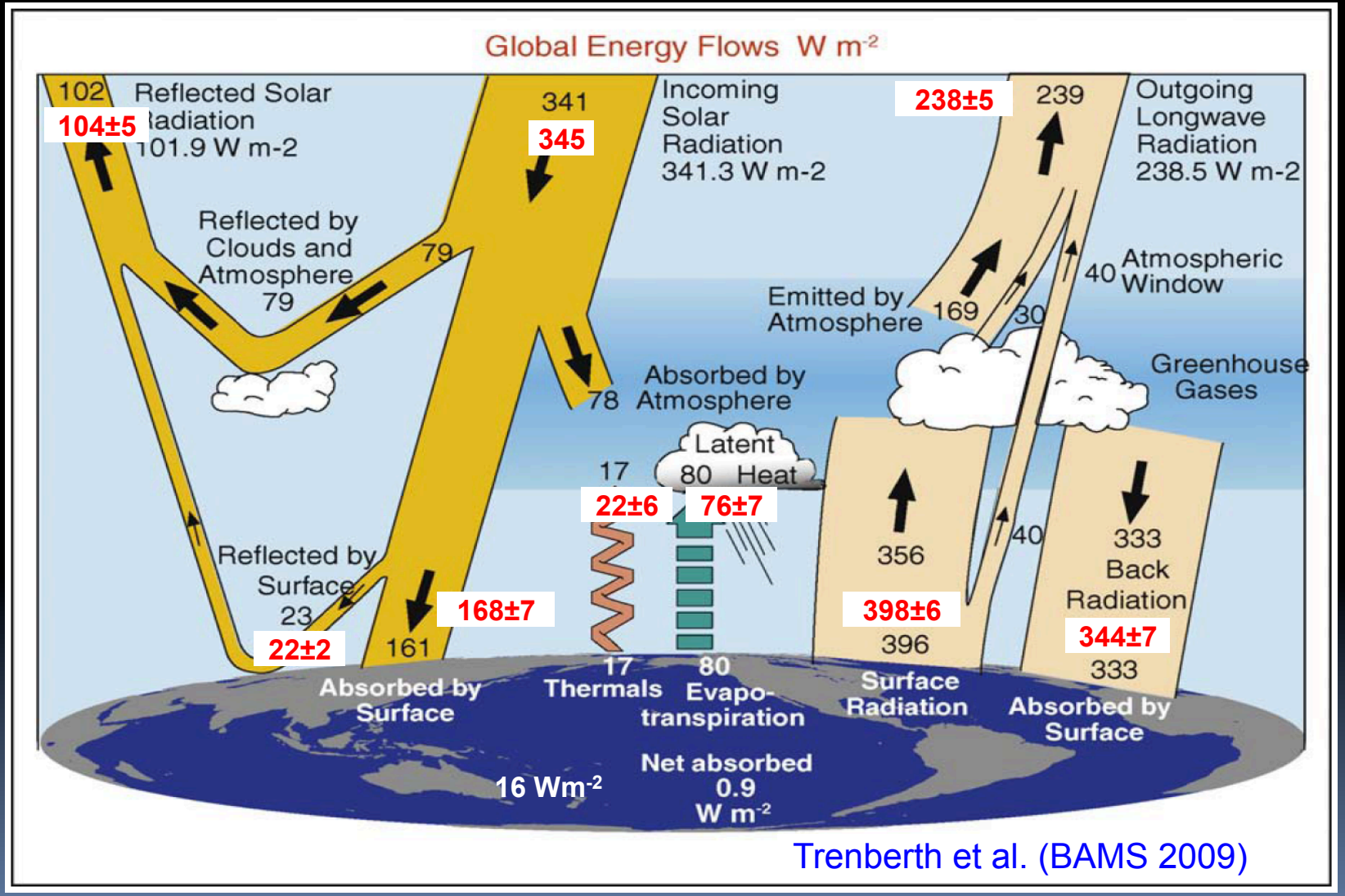
➔ Surface energy imbalance of ~16 Wm^{-2}

Other Flux Combinations





Raw Observations



Trenberth et al. (BAMS 2009)

Objective Addition of "Soft" Balance Constraints

General budget equation:

$$R = \sum_{i=1}^{M} F_i - \sum_{o=1}^{N} F_o$$

Surface Energy Budget:

$$S = F_{LW}^{\downarrow} + F_{SW}^{\downarrow} - F_{LW}^{\uparrow} - F_{SW}^{\uparrow} - LH - SH$$

Surface Water Budget:

$$Q = P - LH$$
$$(E)$$

- Equations are valid for all continents on annual time-scales.
- Similar equations apply to the world oceans (cannot separate basins since transports are not known).
- Additional constraints:
  - S = 0 for all continents
  - S = 1 for world oceans based on ocean heat content measurements

$$\sum_{\text{continents}} Q_L = \sum_{\text{basins}} Q_O$$

Variational Minimization Procedure

If errors are assumed to be Gaussian, balance constraints can be imposed by minimizing the cost function:

$$J = \left(\mathbf{F} - \mathbf{F}_{obs}\right)^{\mathrm{T}} \mathbf{S}_{obs}^{-1} \left(\mathbf{F} - \mathbf{F}_{obs}\right) + \left(\mathbf{R} - \mathbf{R}_{obs}\right)^{\mathrm{T}} \mathbf{S}_{R}^{-1} \left(\mathbf{R} - \mathbf{R}_{obs}\right)$$

Minimum occurs when:

$$\mathbf{F} = \mathbf{F}_{\mathbf{obs}} - \mathbf{S}_{\mathbf{F}} \mathbf{K}^{\mathrm{T}} \mathbf{S}_{\mathbf{y}}^{-1} \left(\mathbf{R}_{obs} - \mathbf{K}\mathbf{F}_{\mathbf{obs}}\right)$$

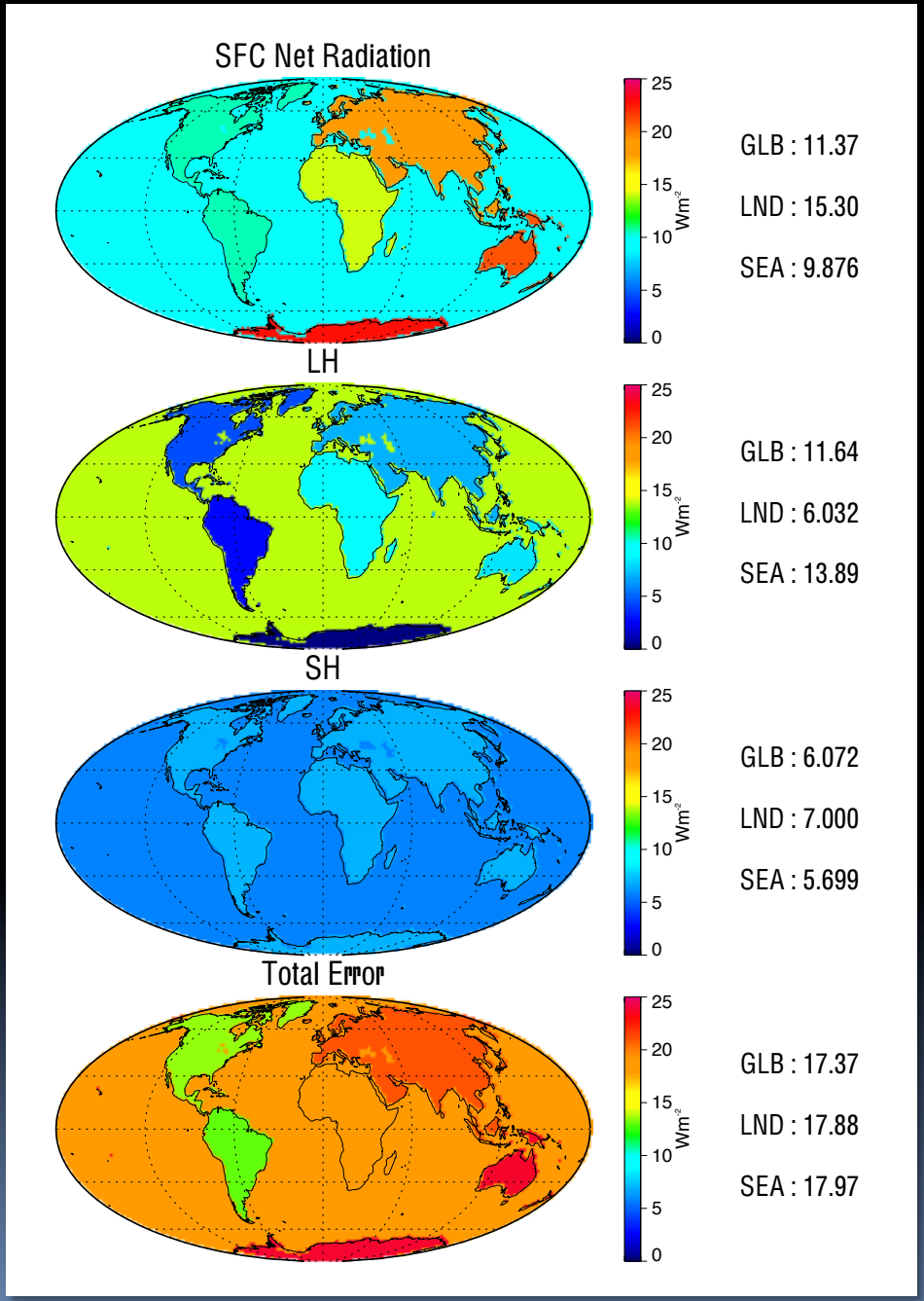
$$\mathbf{S}_{\mathbf{F}} = \left(\mathbf{K}^{\mathrm{T}} \mathbf{S}_{\mathbf{y}}^{-1} \mathbf{K} + \mathbf{S}_{\mathbf{obs}}^{-1}\right)^{-1}$$

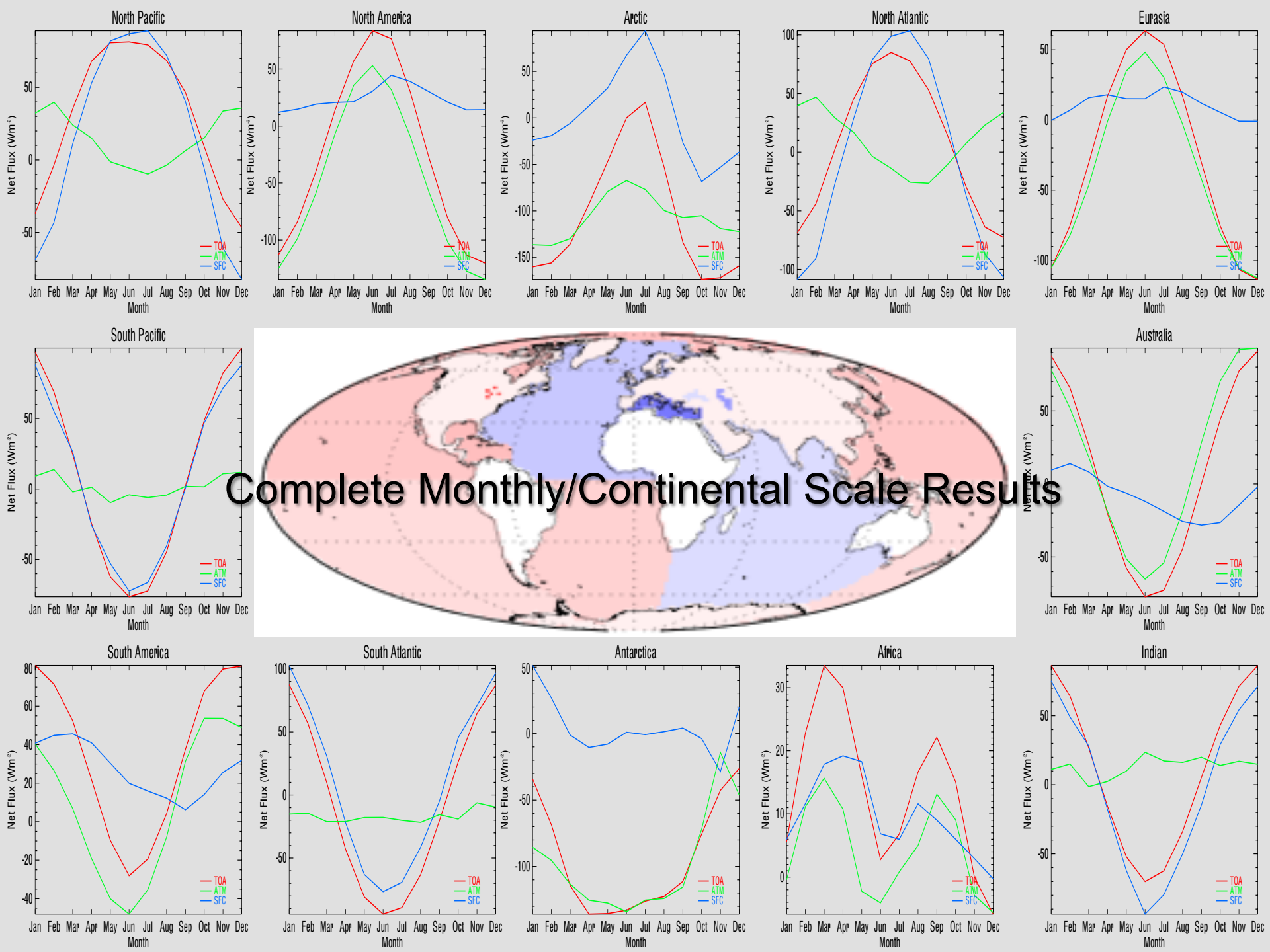
Since balance constraints are linear in the various fluxes, this solution collapses to the minimum variance solution if errors are assumed to be uncorrelated.

Uncertainties

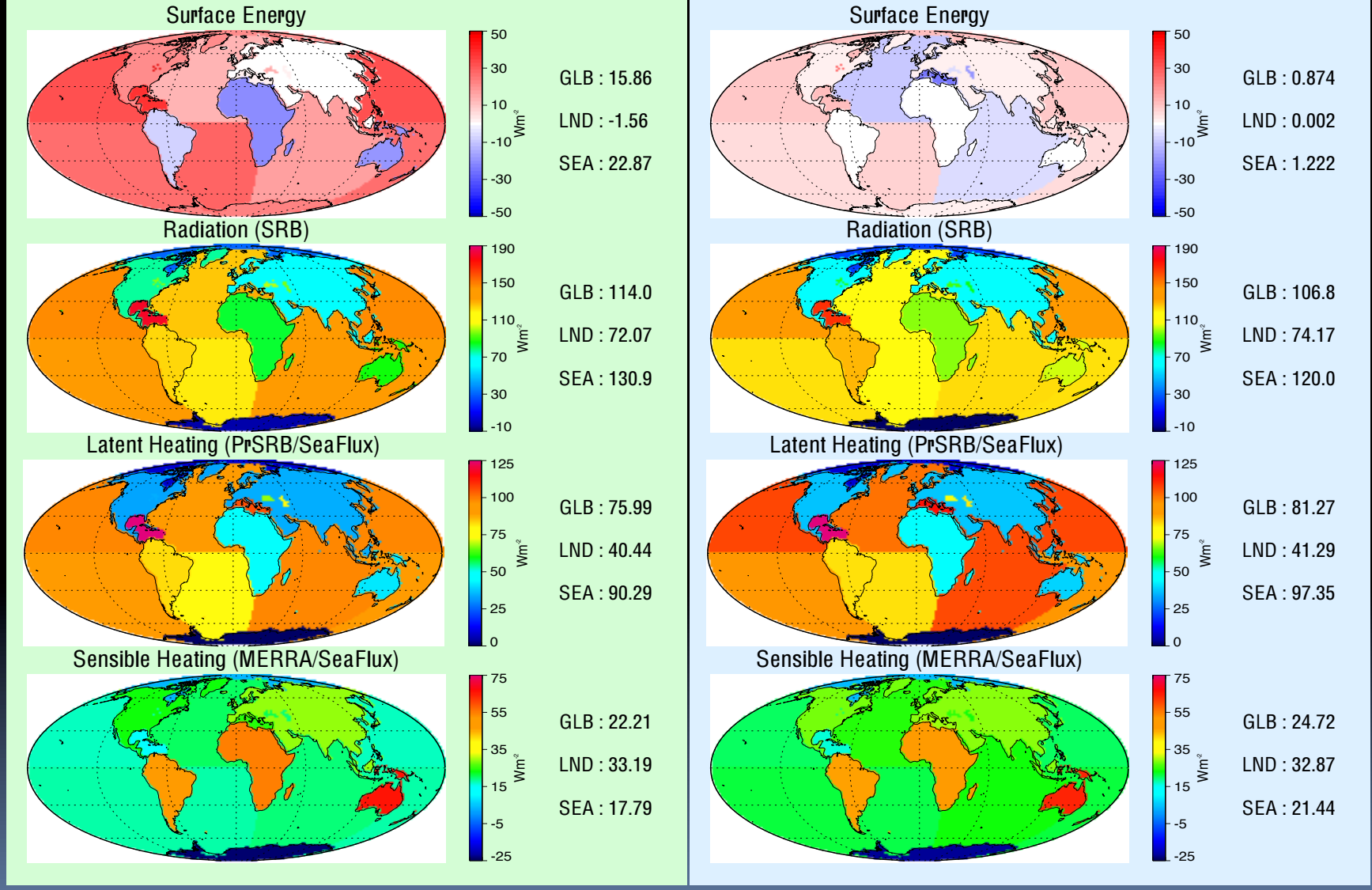
- Key is determining uncertainties to weight the various flux terms (represented by the error covariance $\mathbf{S}_y$)

- Error estimates based on a combination of product inter-comparisons, comparisons with ground observations, and sensitivity studies.




North Pacific
North America
Arctic
North Atlantic
Eurasia
South Pacific
Australia
South America
South Atlantic
Antarctica
Africa
Indian
Net Flux (Wm⁻²)
Month
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
TOA
ATM
SFC
Complete Monthly/Continental Scale Results

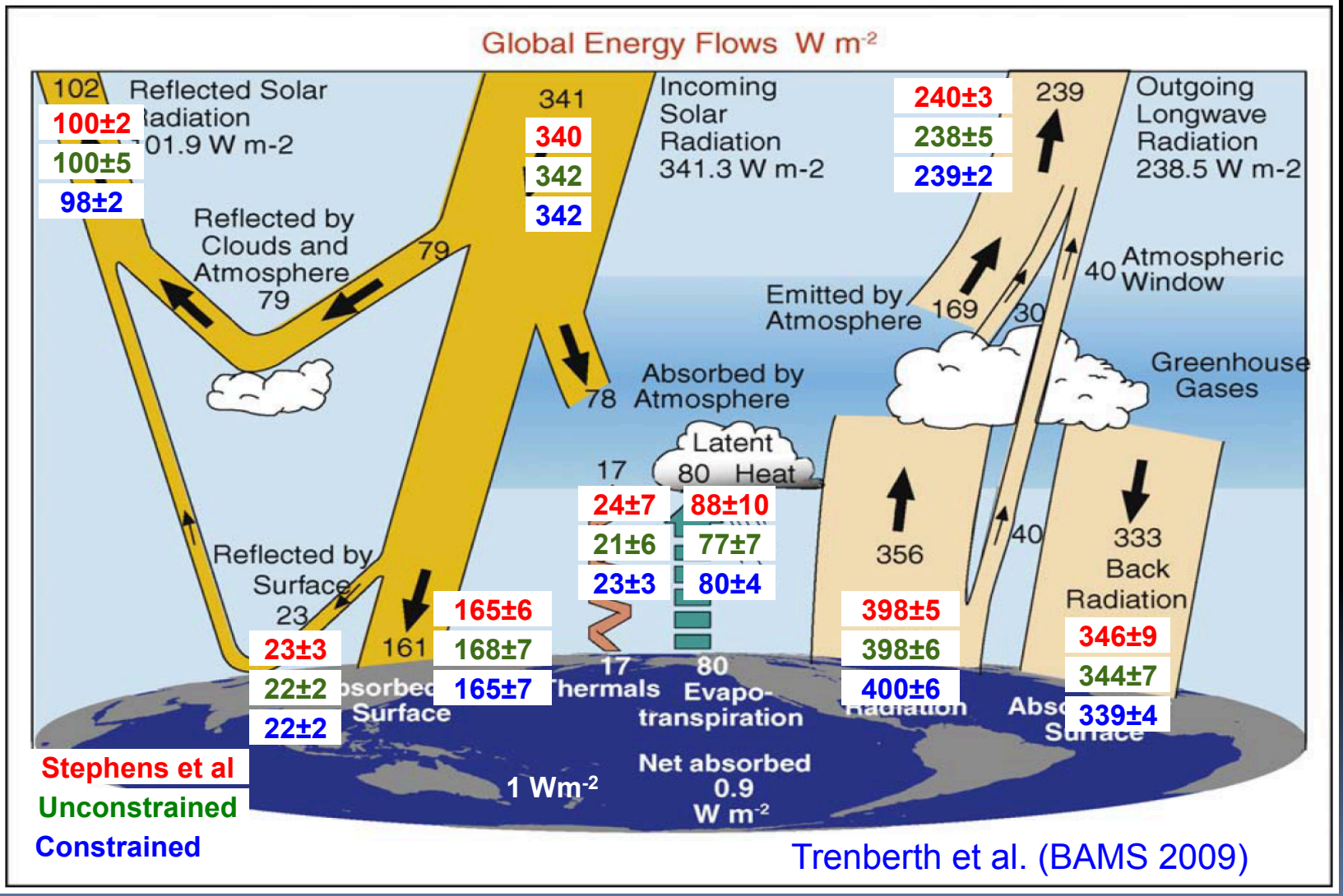
Annual E&WC



Raw Obs.

Constrained

Constrained Energy Budget



Trenberth et al. (BAMS 2009)

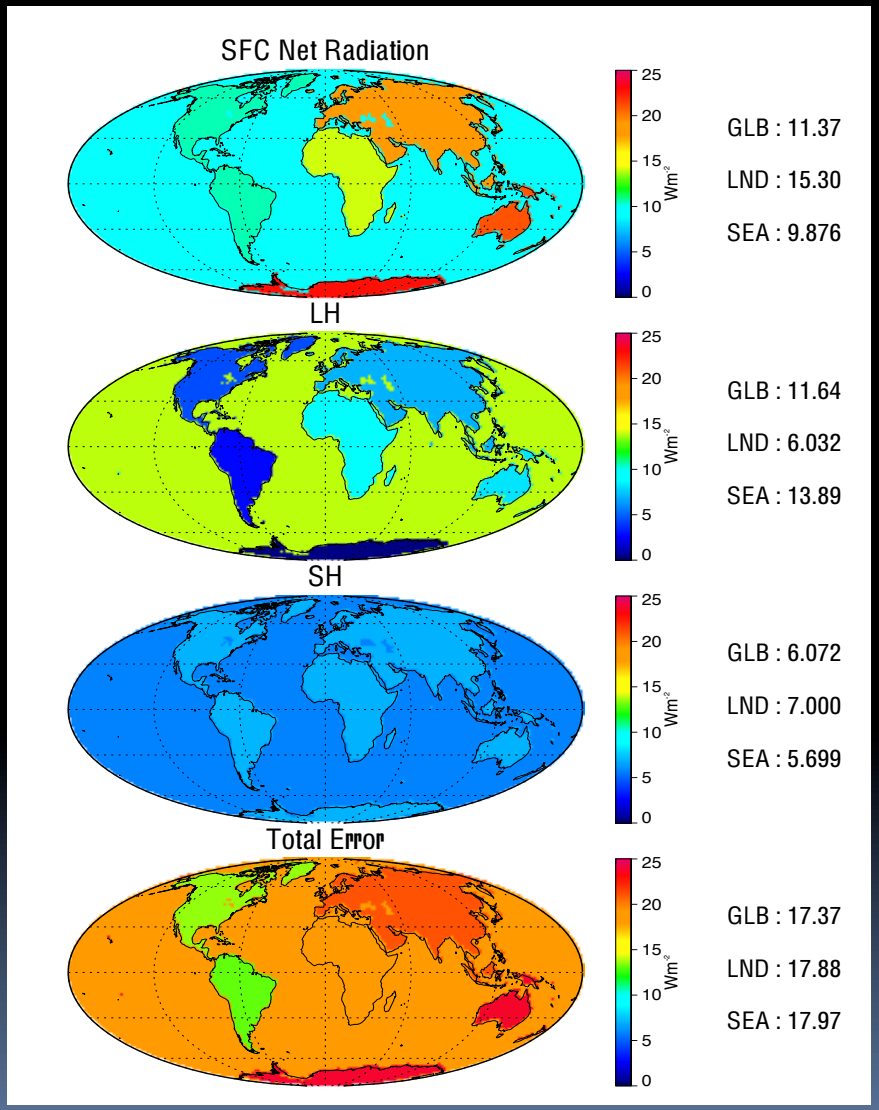
Advantages

- Objective approach based on estimated uncertainties in component fluxes
- Energy and water cycle constraints are satisfied simultaneously
- "Goodness of Fit" (χ^2) helps answer 'can balance be achieved within current uncertainties?'

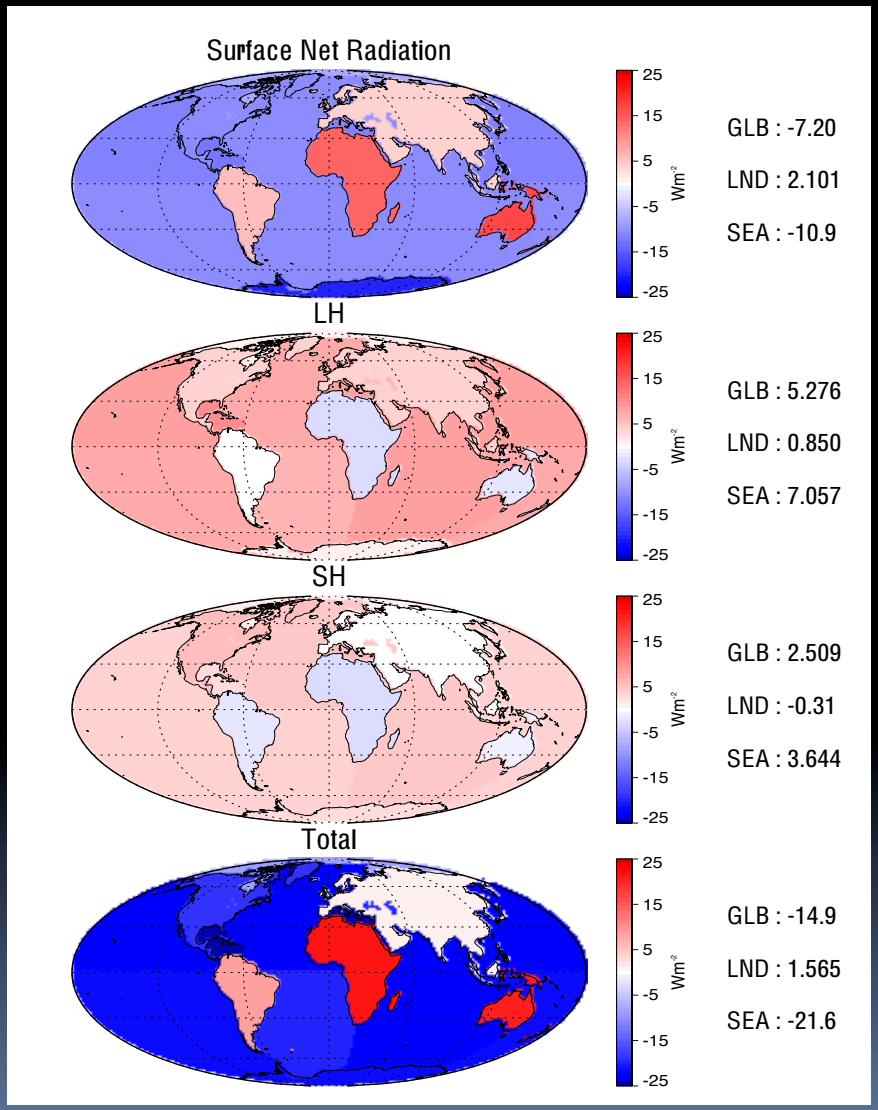
$$\chi^2 = \left(\mathbf{F} - \mathbf{F}_{obs}\right)^{\mathrm{T}} \mathbf{S}_{obs}^{-1} \left(\mathbf{F} - \mathbf{F}_{obs}\right) + \left(\mathbf{R} - \mathbf{R}_{obs}\right)^{\mathrm{T}} \mathbf{S}_{R}^{-1} \left(\mathbf{R} - \mathbf{R}_{obs}\right) = 22$$

- Updated error estimates that account for additional information supplied by constraints

Are the Adjustments Realistic?



Original Uncertainties

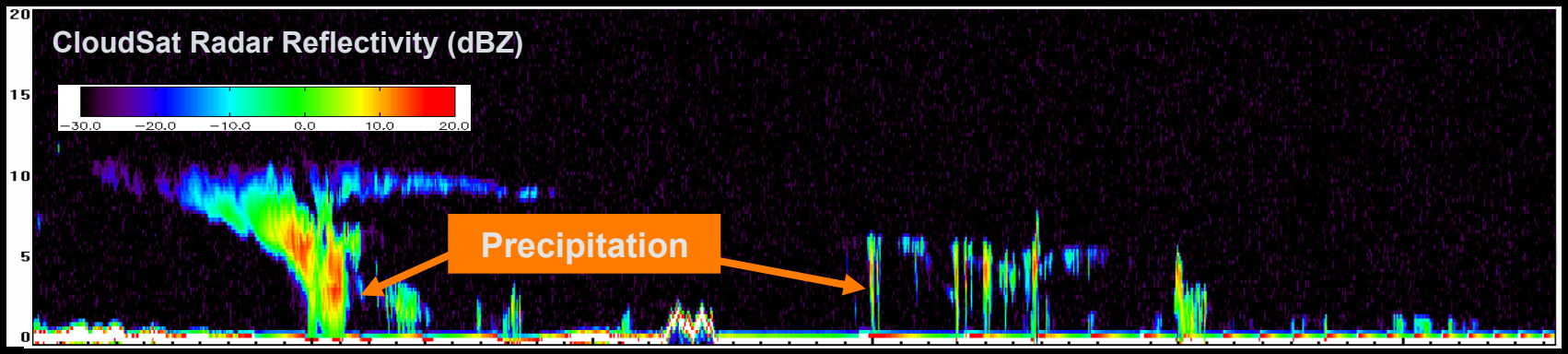


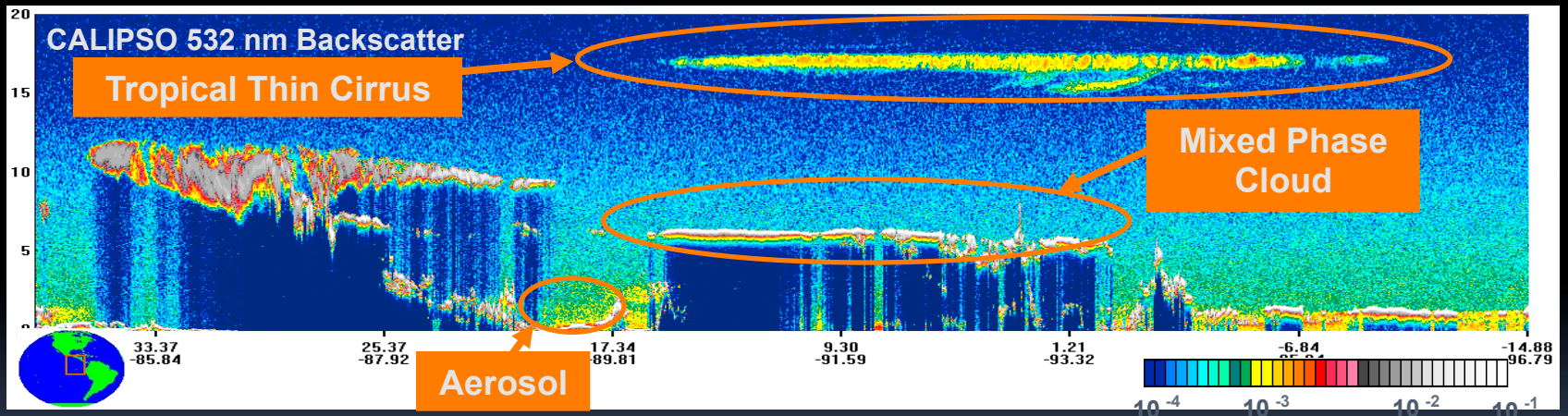
Flux Changes

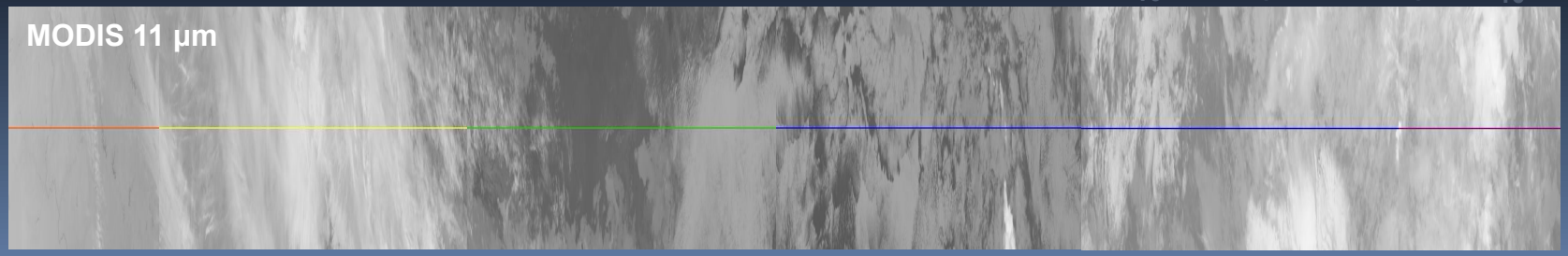
Insights into error sources in A-Train flux estimates

RADIATIVE FLUXES

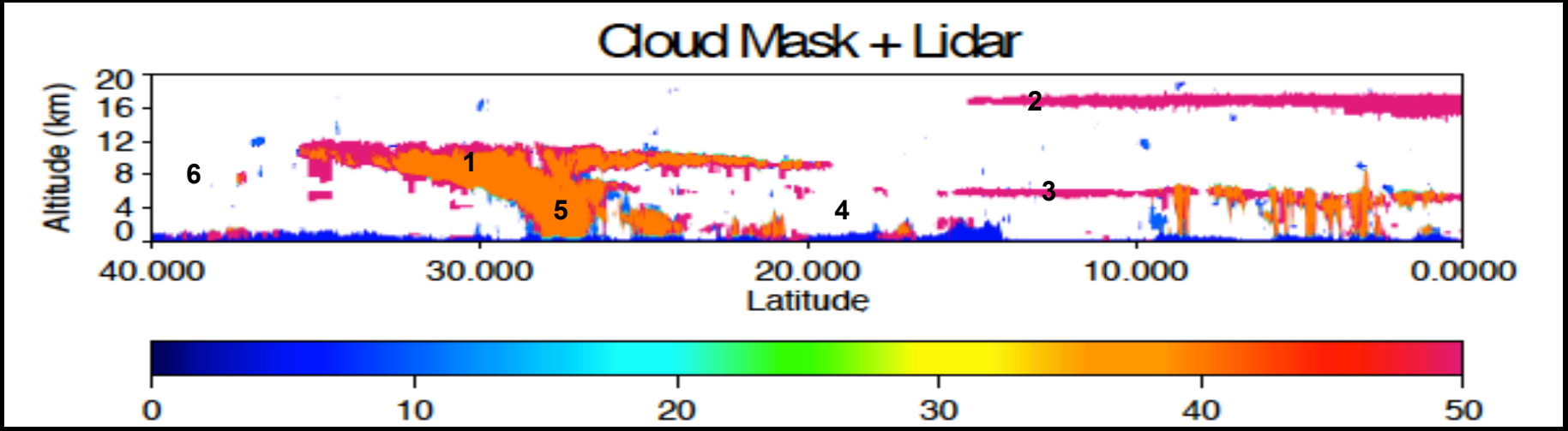
2B-FLXHR Algorithm





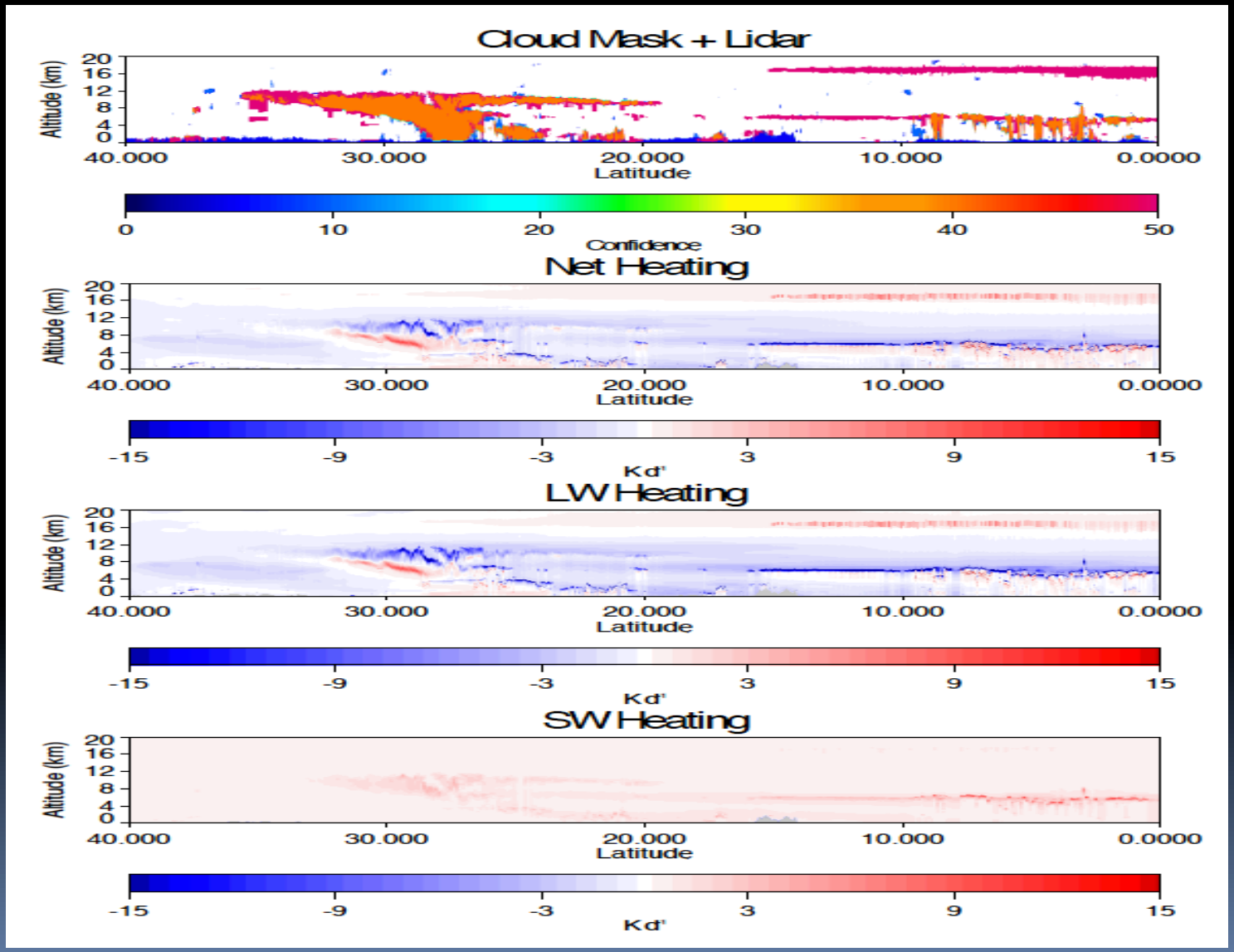


2B-FLXHR



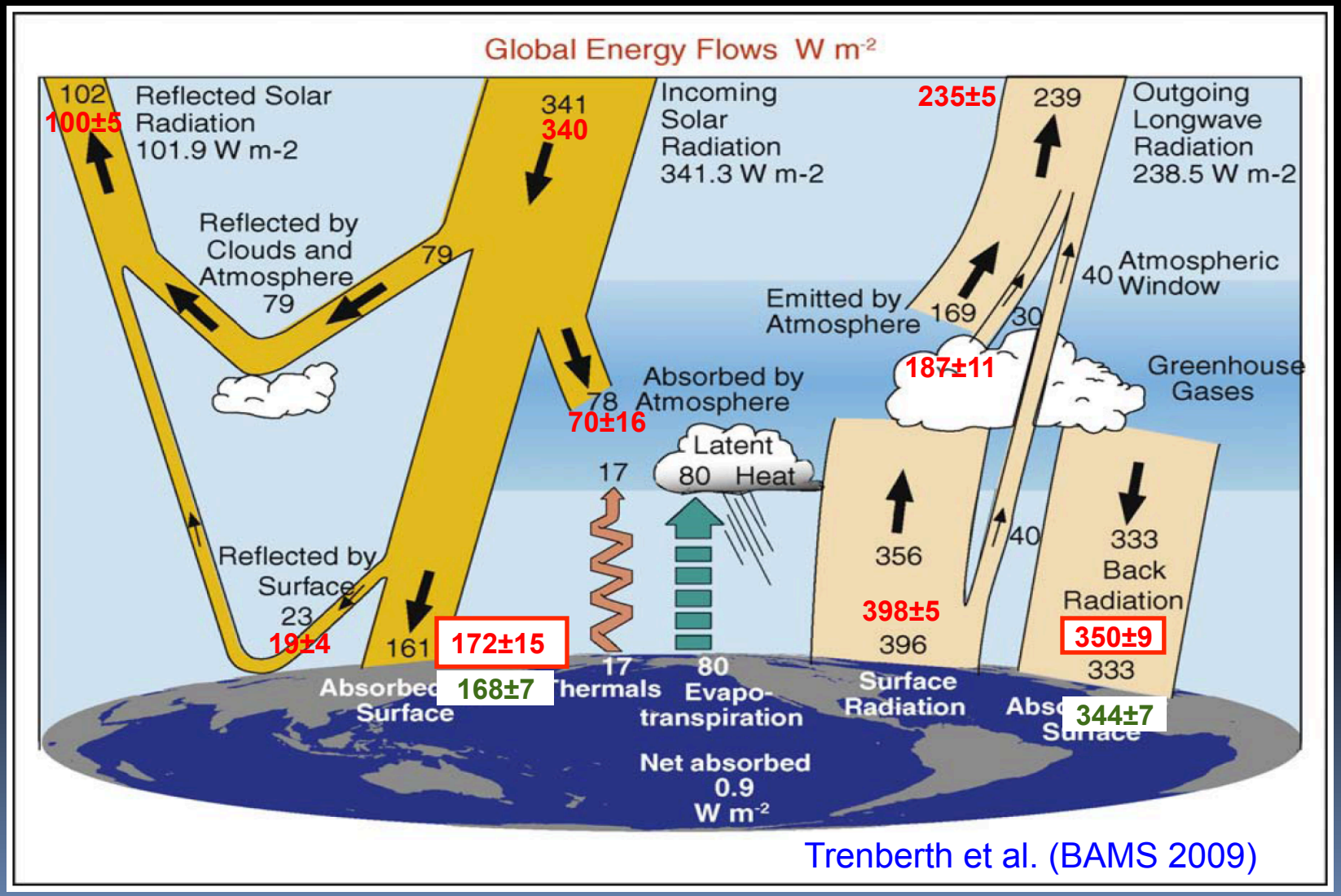
1. Clouds – CloudSat CPR + MODIS optical depth
2. Sub-visual Cirrus – CALIPSO (5 km Cloud Layer Product)
3. Stratus/mixed-phase – CALIPSO (identification) + MODIS (microphysical properties)
4. Aerosol – CALIPSO (5 km Aerosol Layer Product)
5. Precipitation – explicit rain DSD and CloudSat 2C-PRECIP-COLUMN (identification/LWP)
6. Temperature & Humidity – ECMWF/AIRS (in progress)

Pixel-Level Heating Rates



L'Ecuyer et al., *J. Geophys. Res.*, 2009

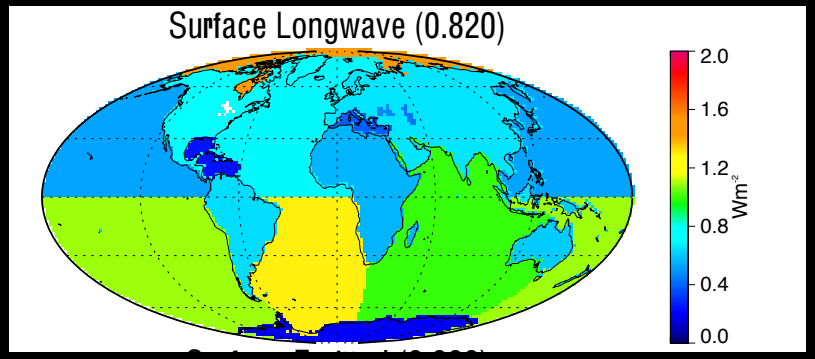
Global Radiation Budget in FLXHR-Lidar



Trenberth et al. (BAMS 2009)

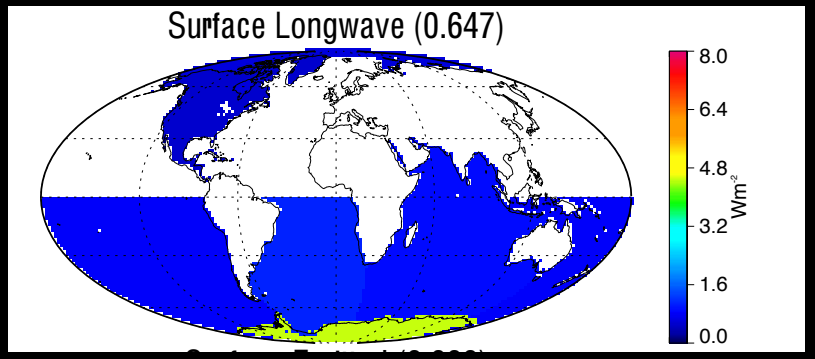
SENSITIVITY STUDIES

Cloud Impacts on DLR



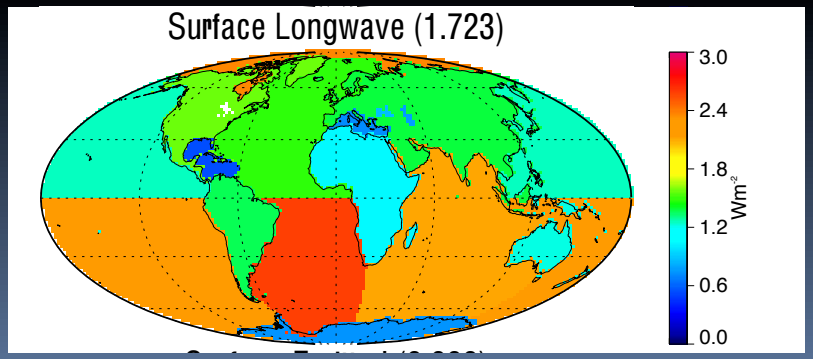
Effective Radius/LWP

(CloudSat Errors + CALIOP clouds)



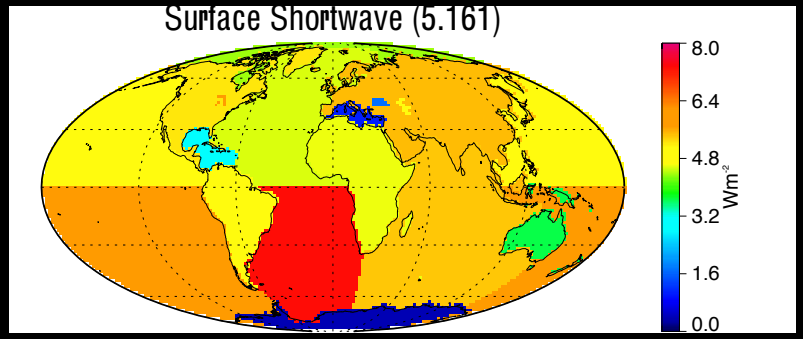
Effective Radius/IWP

(CloudSat Errors + CALIOP clouds)



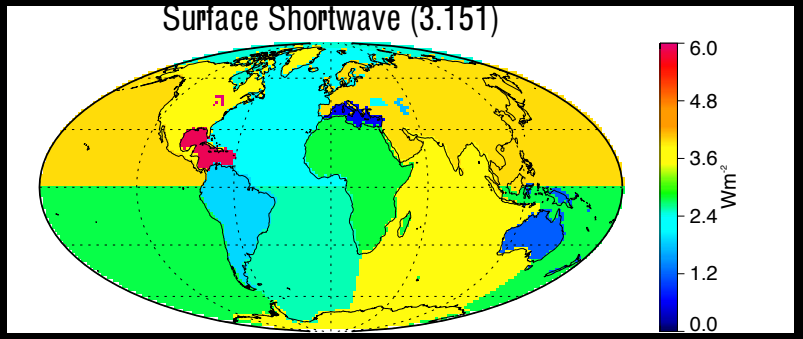
Geometric Thickness (±240 m)

Cloud Impacts on DSR



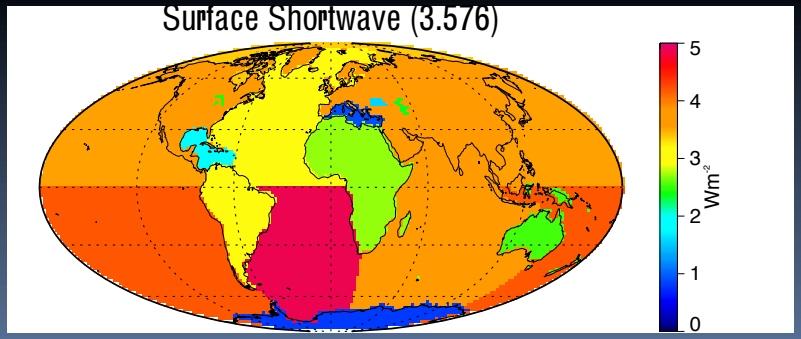
Effective Radius/LWP

(CloudSat Errors + CALIOP clouds)



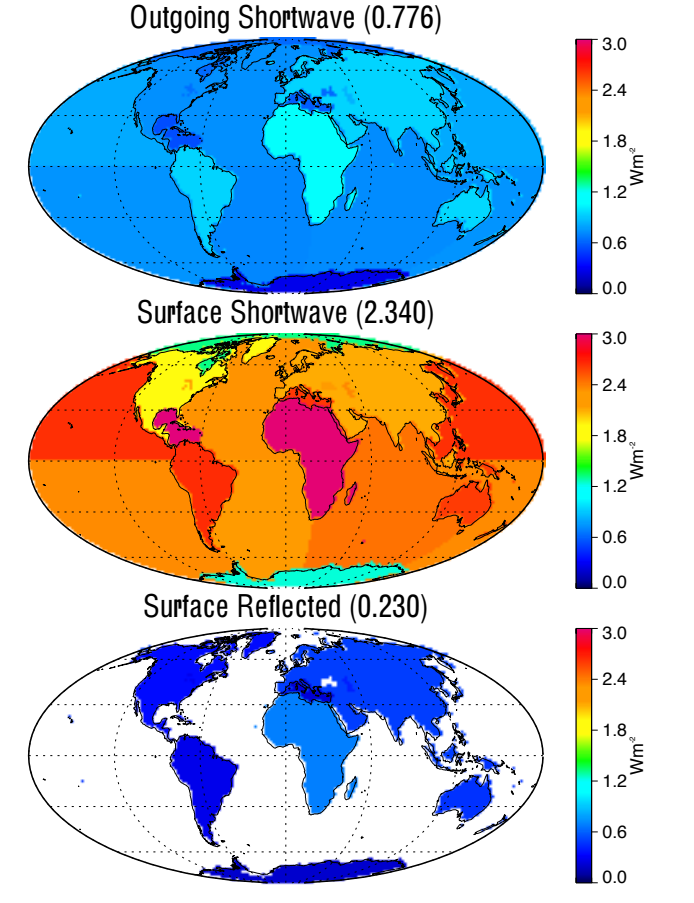
Effective Radius/IWP

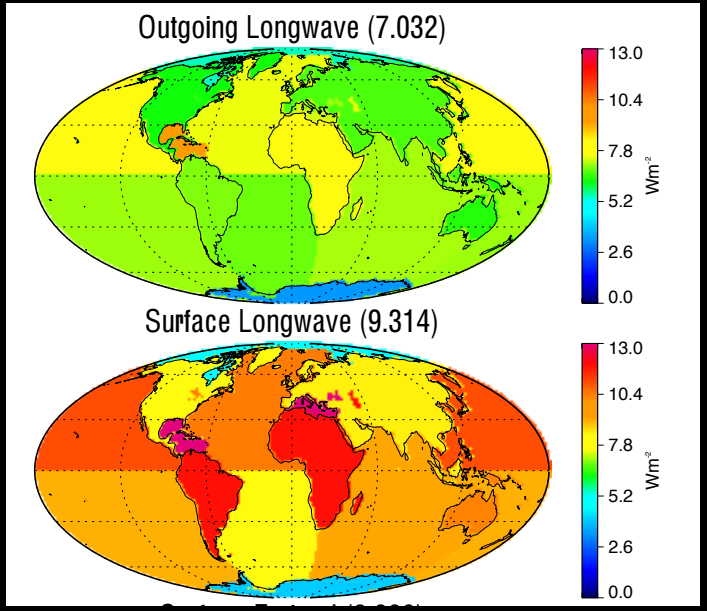
(CloudSat Errors + CALIOP clouds)



Geometric Thickness (±240 m)

Atmospheric Properties

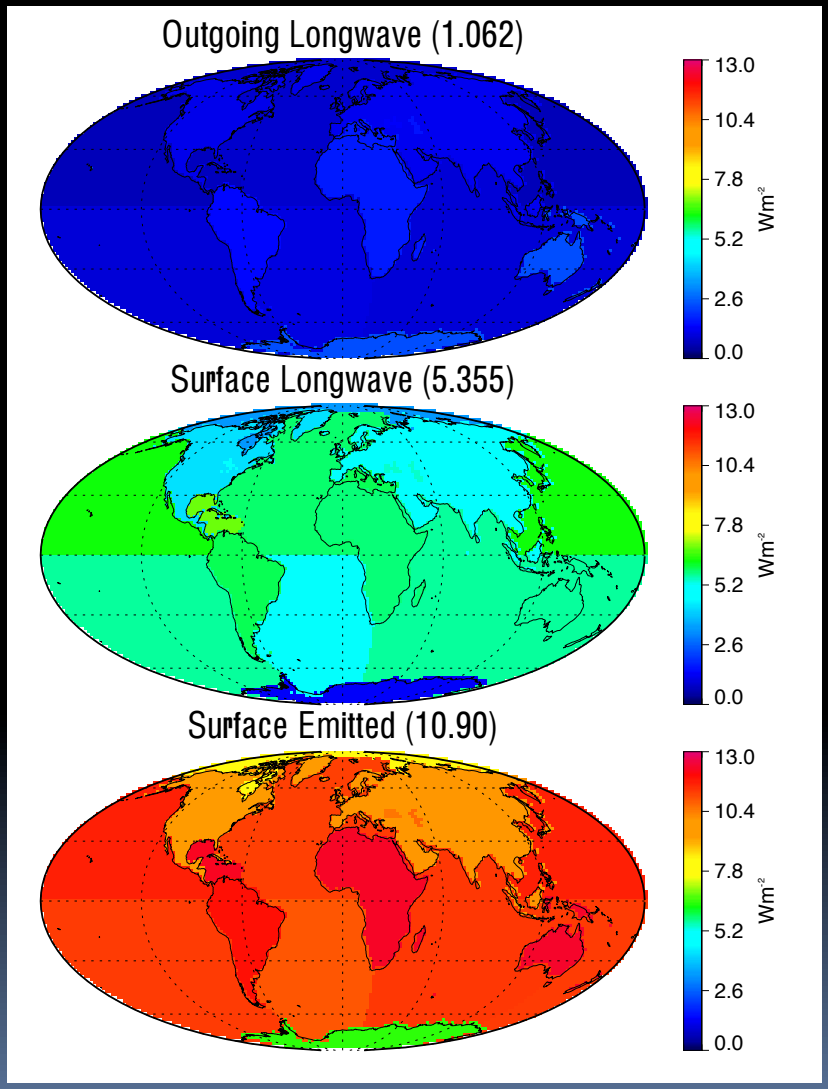




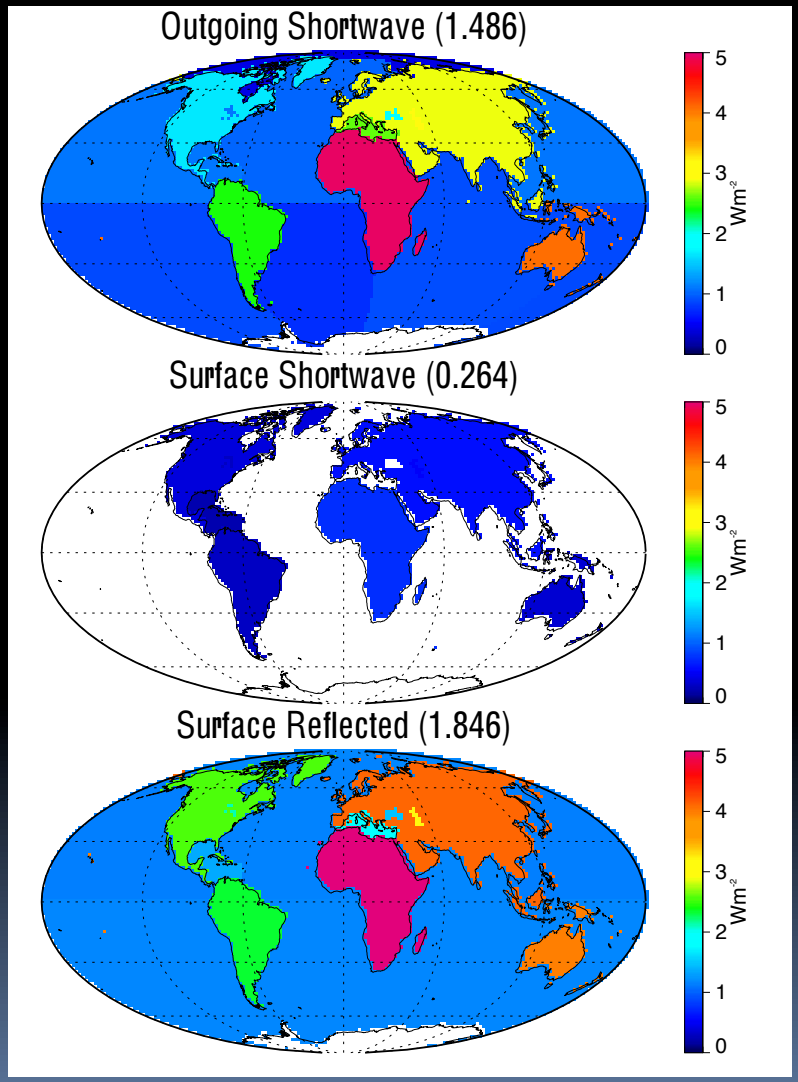
ECMWF Specific Humidity ±25 %

ECMWF Temperatures ±2 K

Surface Properties

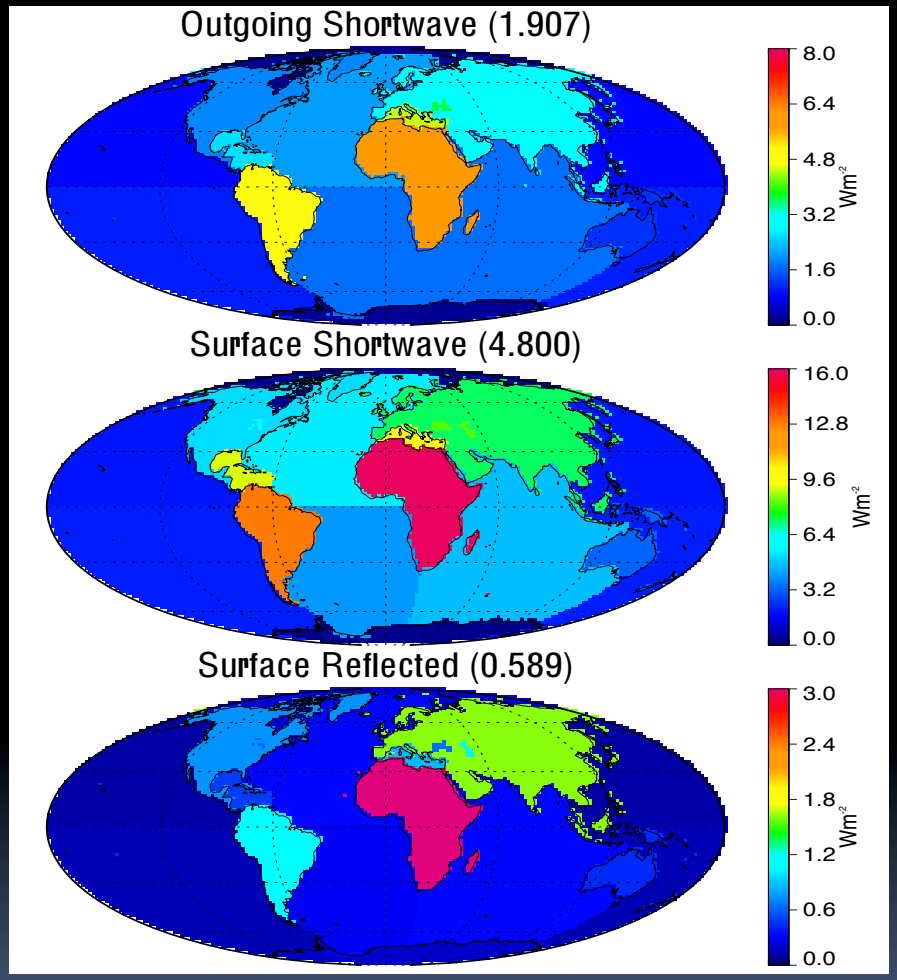


Surface T ±2K



Surface Albedo ±0.02

Aerosols (AOD/Composition)



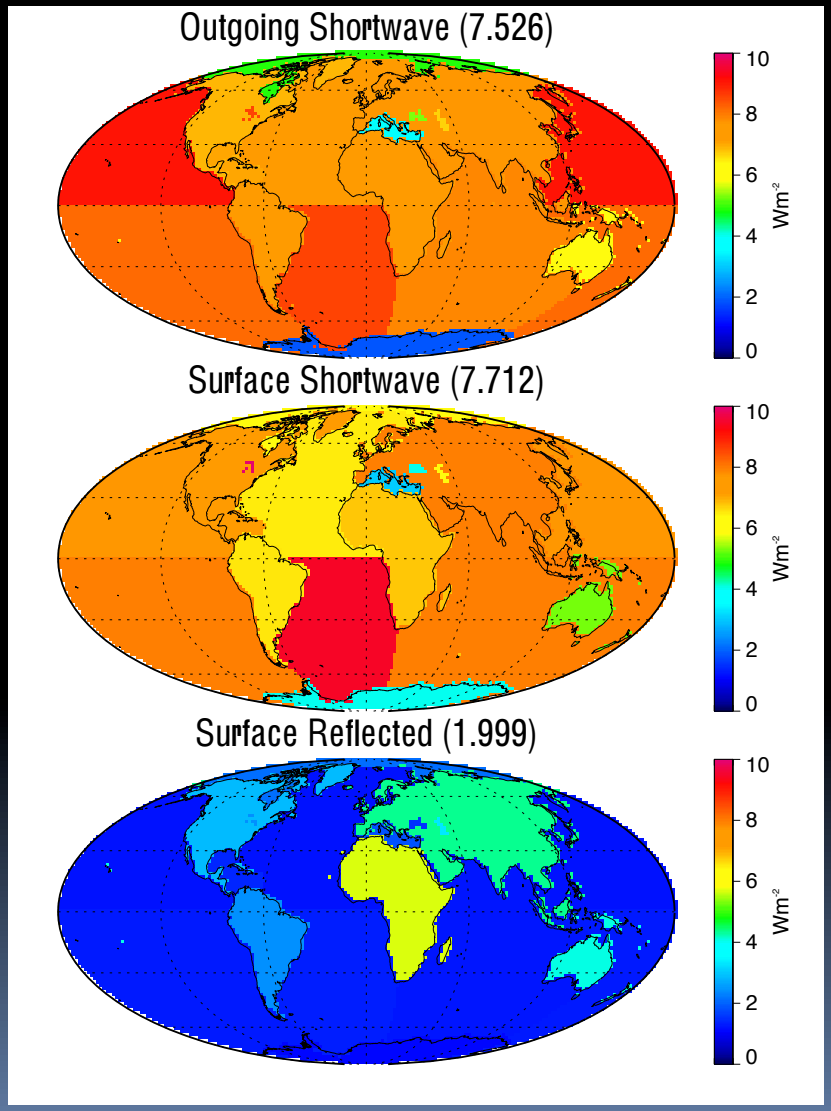
AOD Doubled/Halved

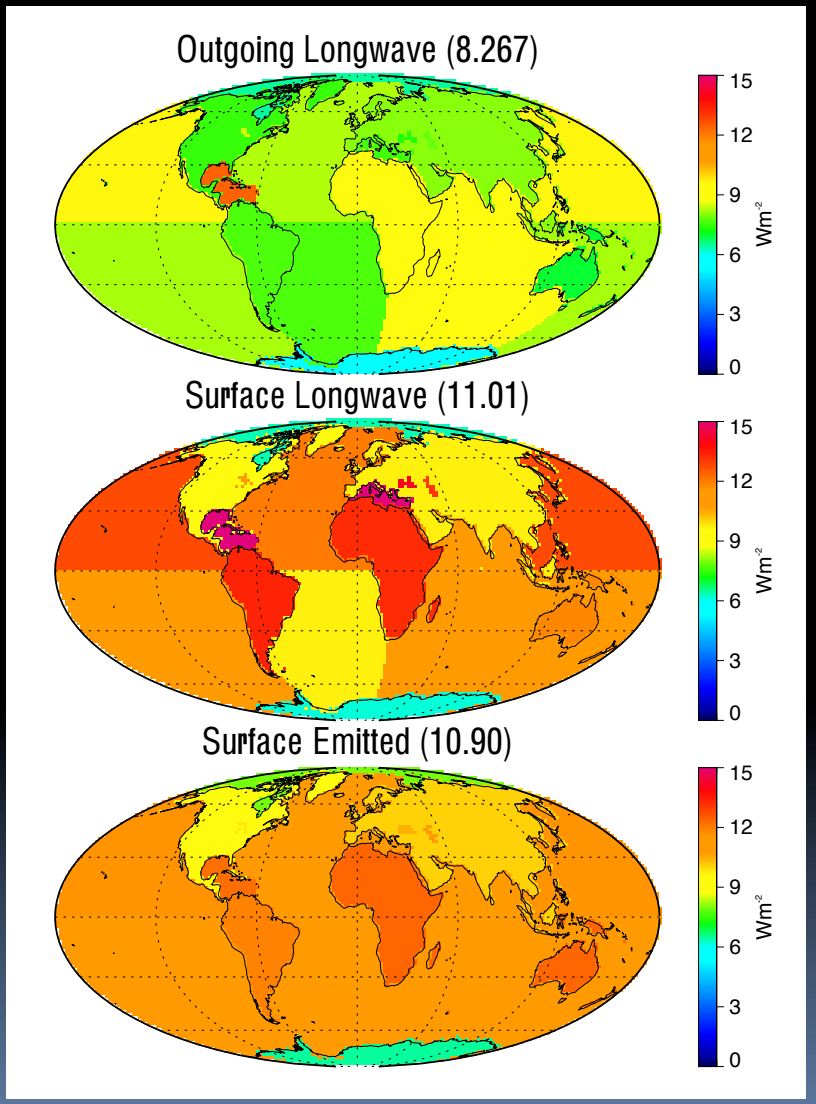
SSA/g Modified between Dust and Smoke Extremes

Summary

Error Source	DLR	DSR	OLR	OSR
Low Cloud Properties	1	**5**	1	**5.5**
High Cloud Properties	1	3	**4**	3
Cloud Thickness	2	3.5	0.5	3.5
Atmospheric Properties	**9**	2.5	**7**	1
Aerosols	0	**5**	0	2
Surface Properties	5	0.3	1	1.5

Combined Errors

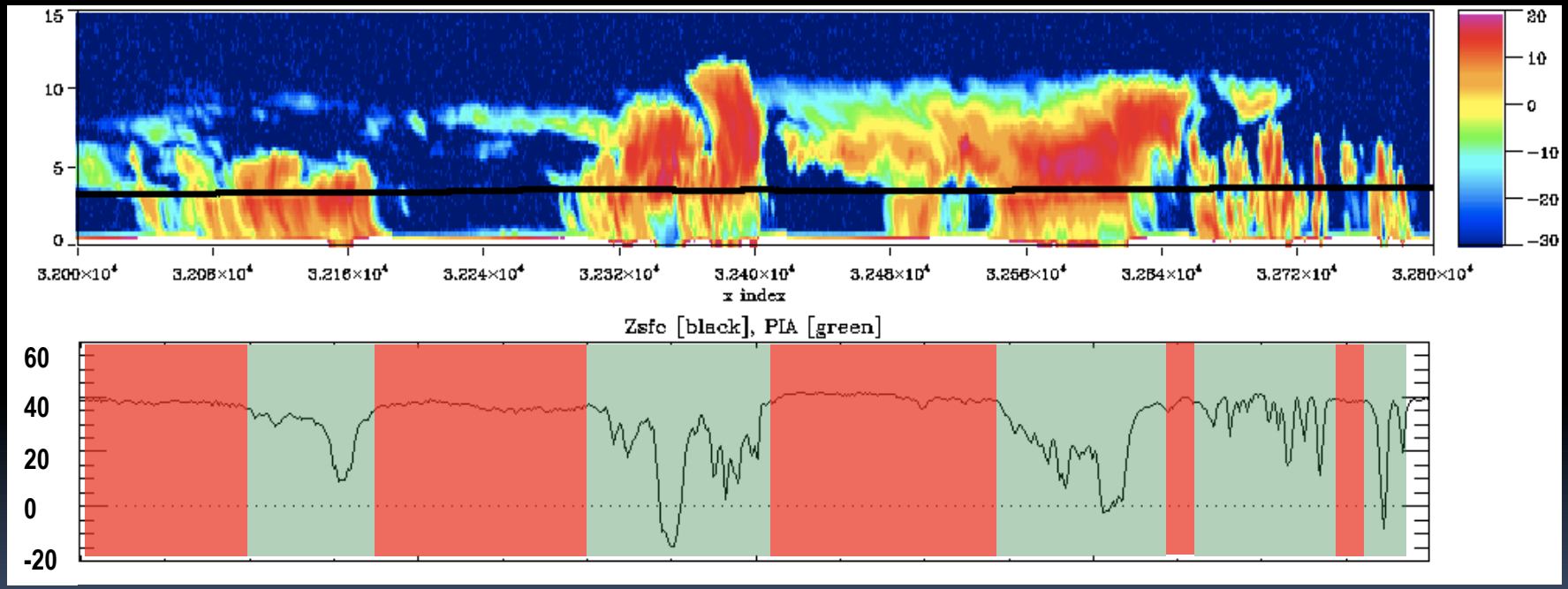




Latent heating from light rain and snow

CloudSat Rainfall Algorithm

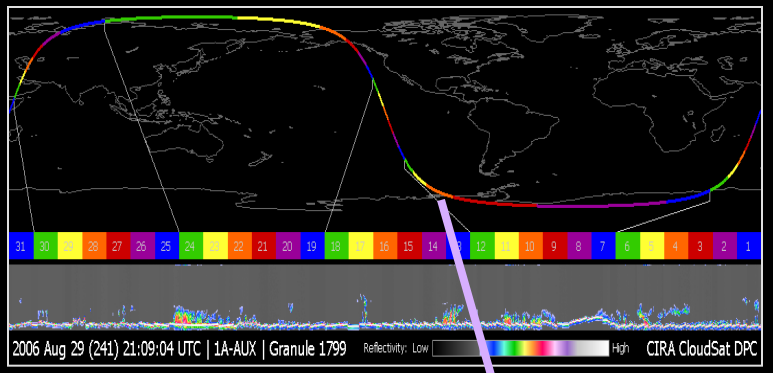
- Path integrated attenuation calculated using a SST and wind speed-dependent clear-sky estimate of surface reflectivity, provides an indicator of rainfall and a crude intensity estimate.

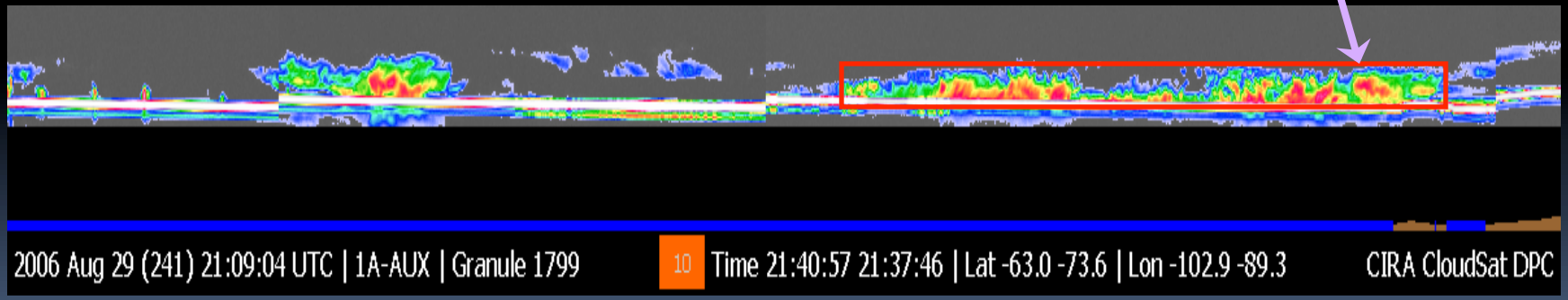


Are If signal is significantly attenuated, areas are likely to be raining unlikely to contain rain

Haynes et al., *J. Geophys. Res.*, 2009

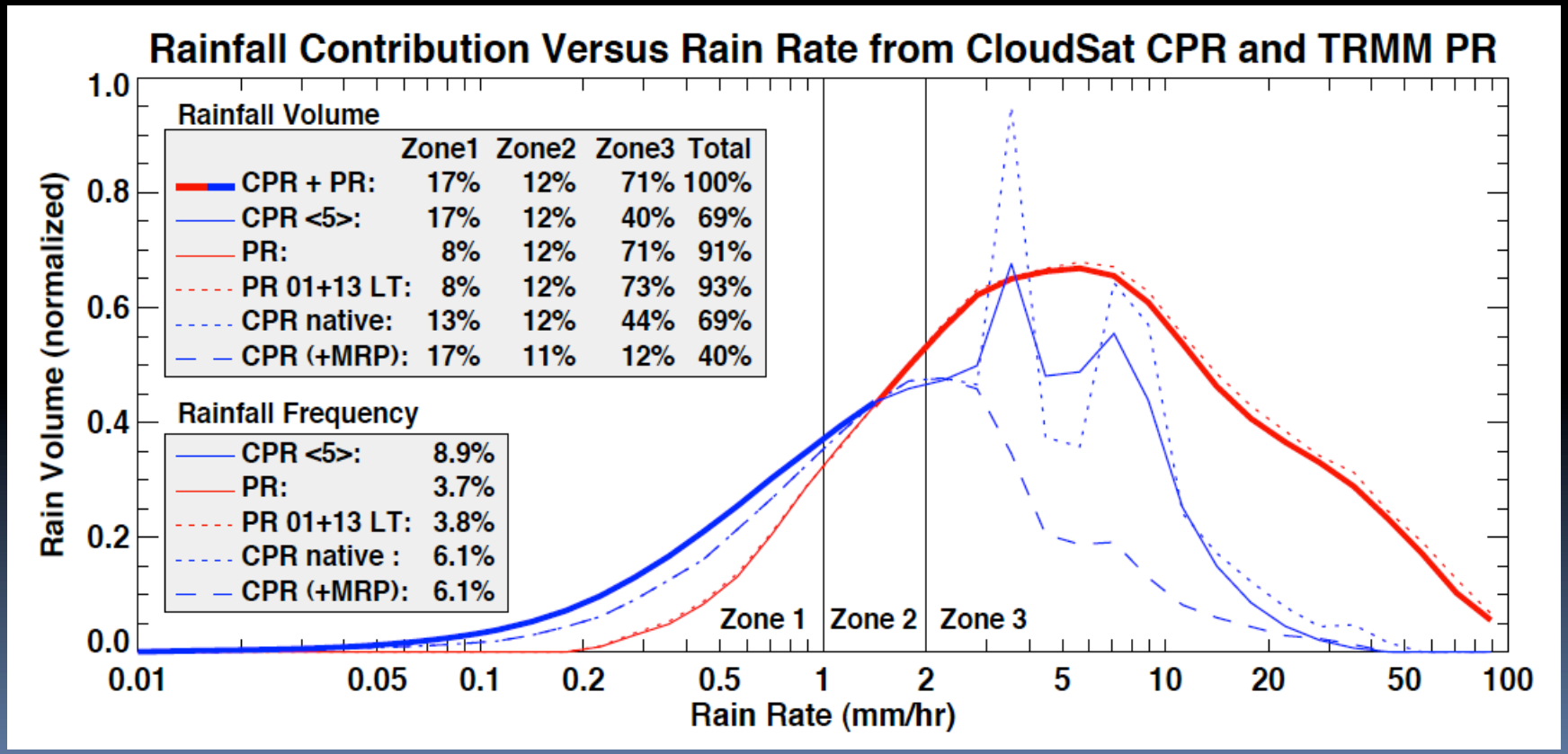
Snowfall


2006 Aug 29 (241) 21:09:04 UTC | 1A-AUX | Granule 1799
Reflectivity: Low
High
CIRA CloudSat DPC


2006 Aug 29 (241) 21:09:04 UTC | 1A-AUX | Granule 1799
10
Time 21:40:57 21:37:46 | Lat -63.0 -73.6 | Lon -102.9 -89.3
CIRA CloudSat DPC

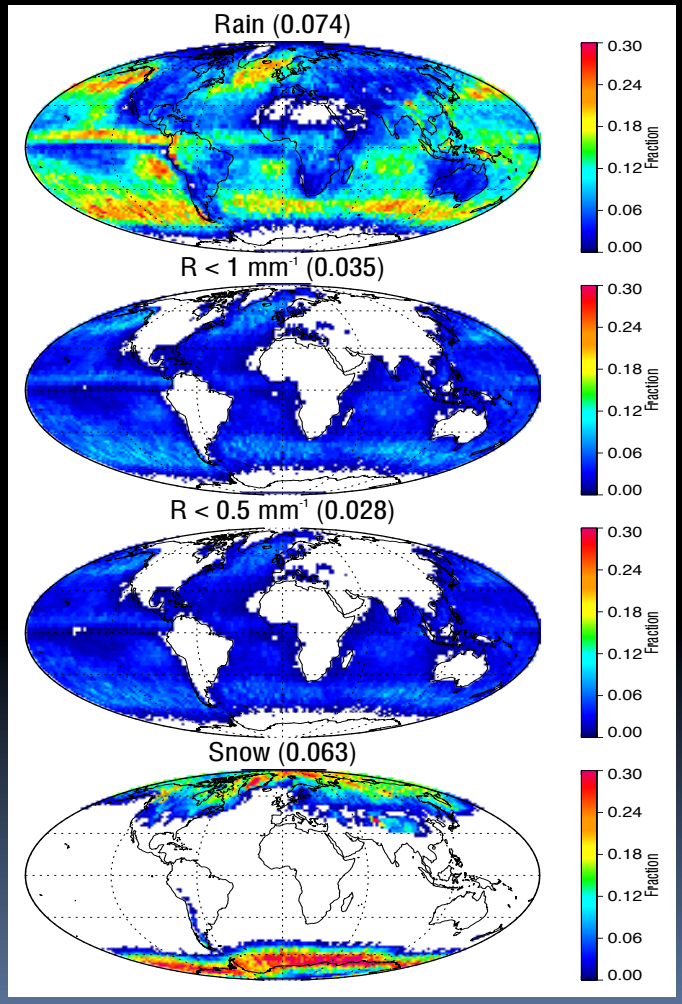
Tropics: CloudSat + PR

- R < 1 mm h^{-1}: CPR accumulation is 0.47 mm/d, PR's is 0.19
- R > 5 mm h^{-1}: CPR accumulation is 1.35 mm/d, PR's is 1.86
- Light rain accounts for ~10% of total accumulation in tropics.

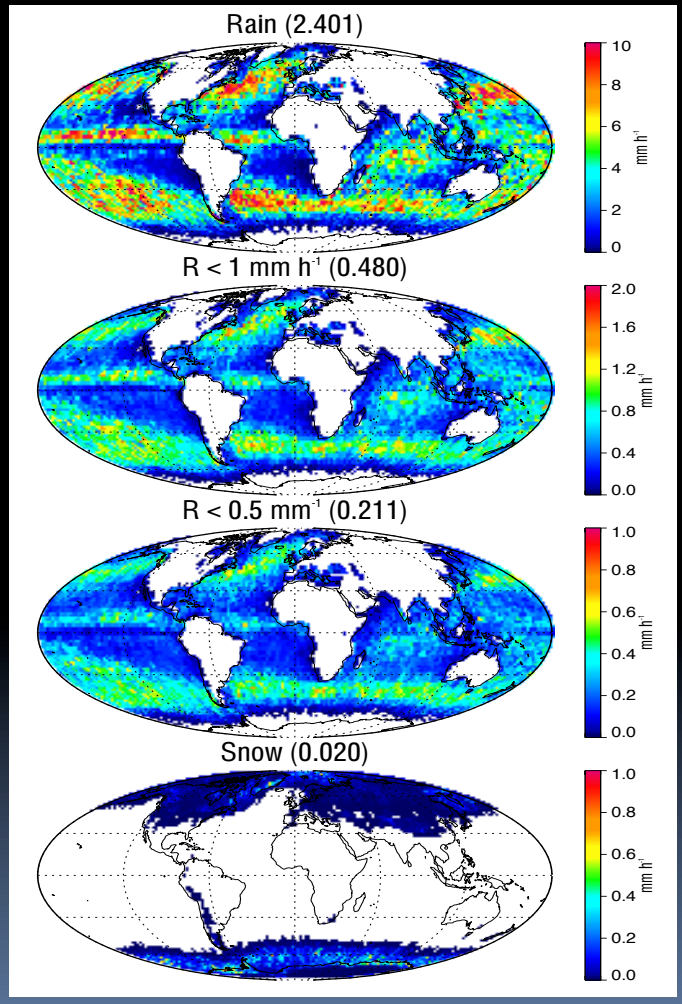


Berg and L'Ecuyer, *J. Climate*, 2010

Global Distribution of Light Precipitation

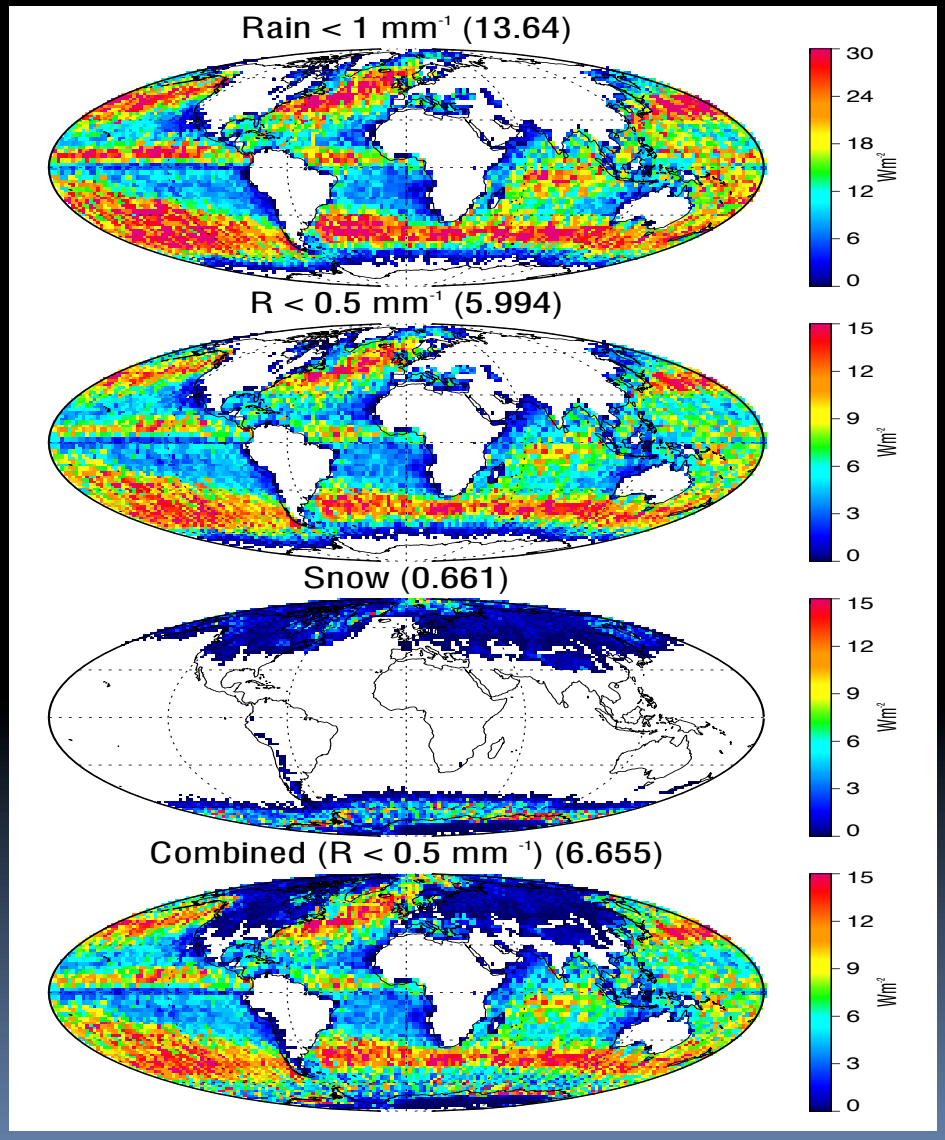


Occurrence



Amount

Implied Latent Heating

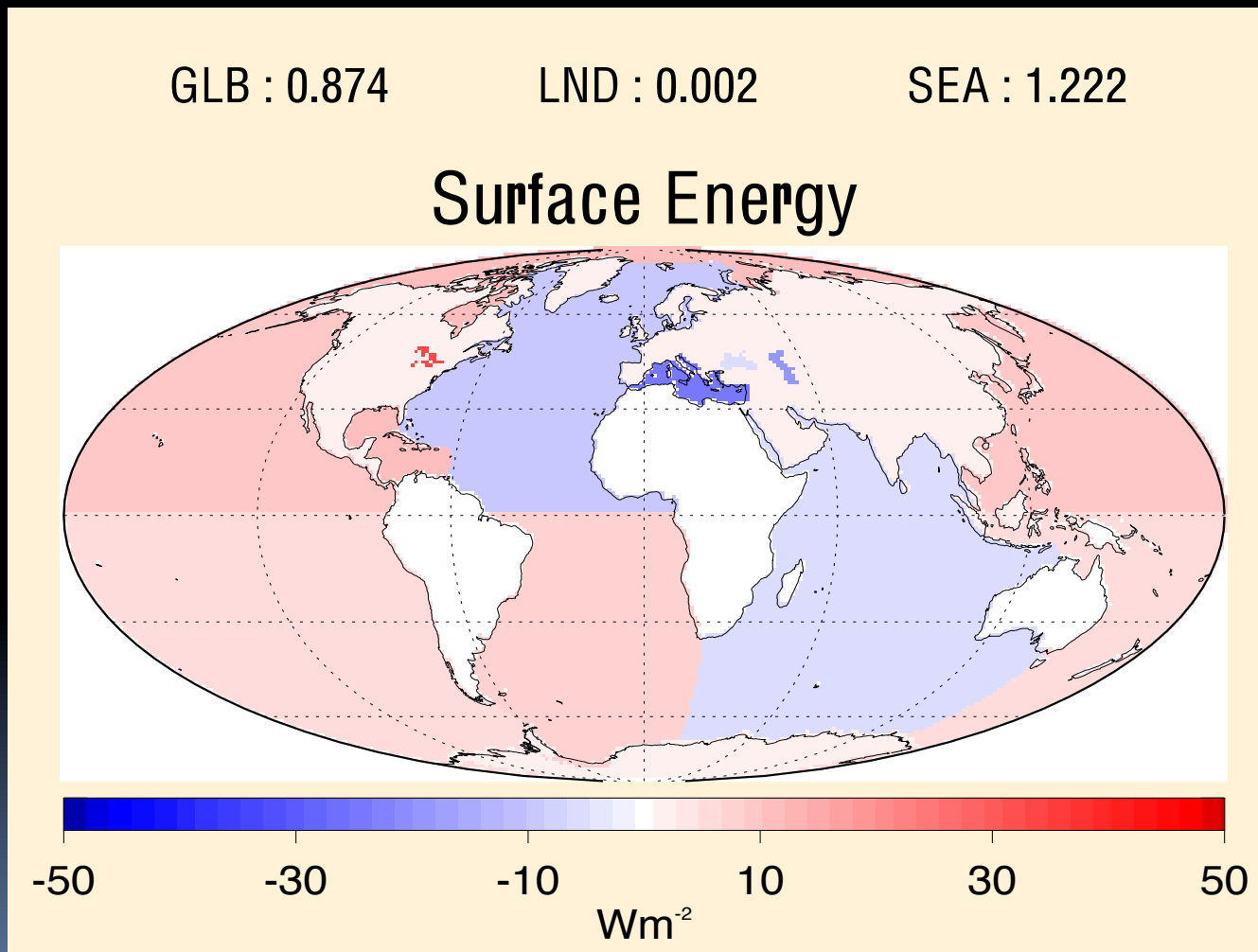


Conclusions

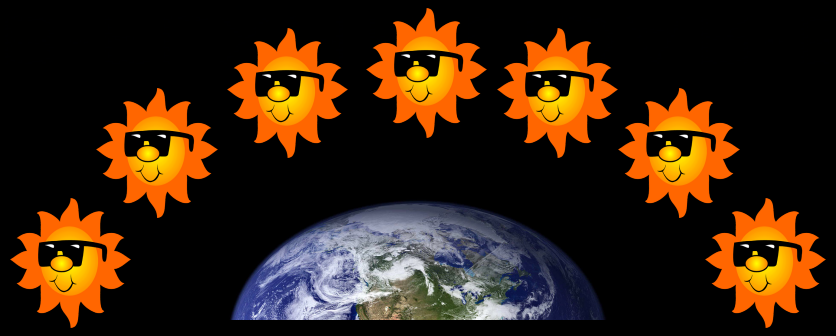
- Energy and Water Cycle can be objectively balanced at annual and continental scales within realistic error estimates
  - Results like between those from recent competing studies
- The addition of active CloudSat and CALIPSO measurements appears to drive DLR further away from balance (350 Wm^{-2})
- DLR errors in FLXHR-lidar are dominated by atmospheric properties as opposed to cloud properties but could still be up to 10 Wm^{-2}
- LH from light rainfall observed by CloudSat (R< 0.5 mm h^{-1}) is to be ~6 Wm^{-2}
- LH release from snowfall may be ~1 Wm^{-2}

Closure?

GLB : 0.874 LND : 0.002 SEA : 1.222

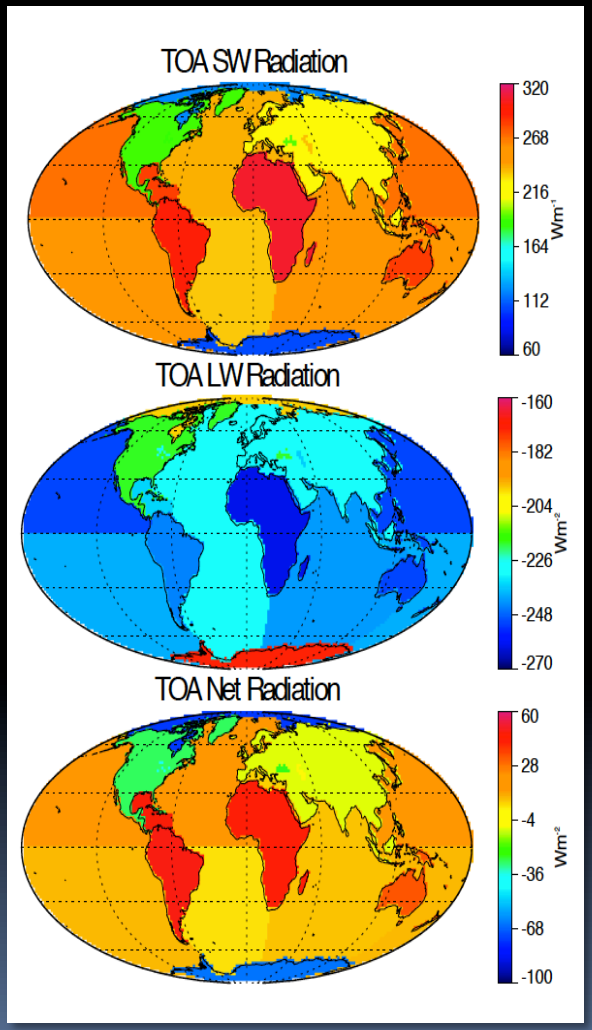


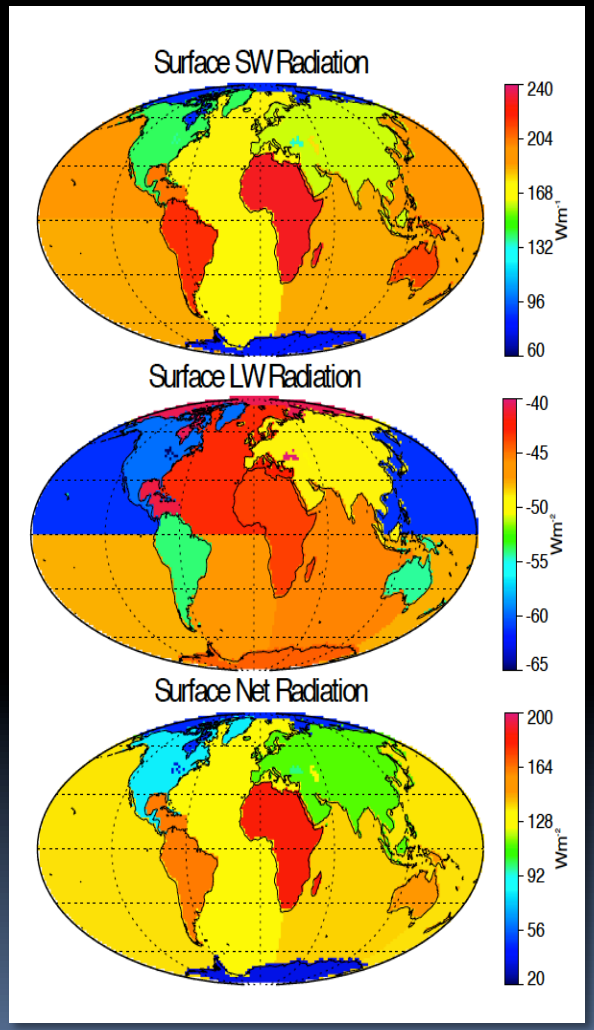
2B-FLXHR-LIDAR-ERB

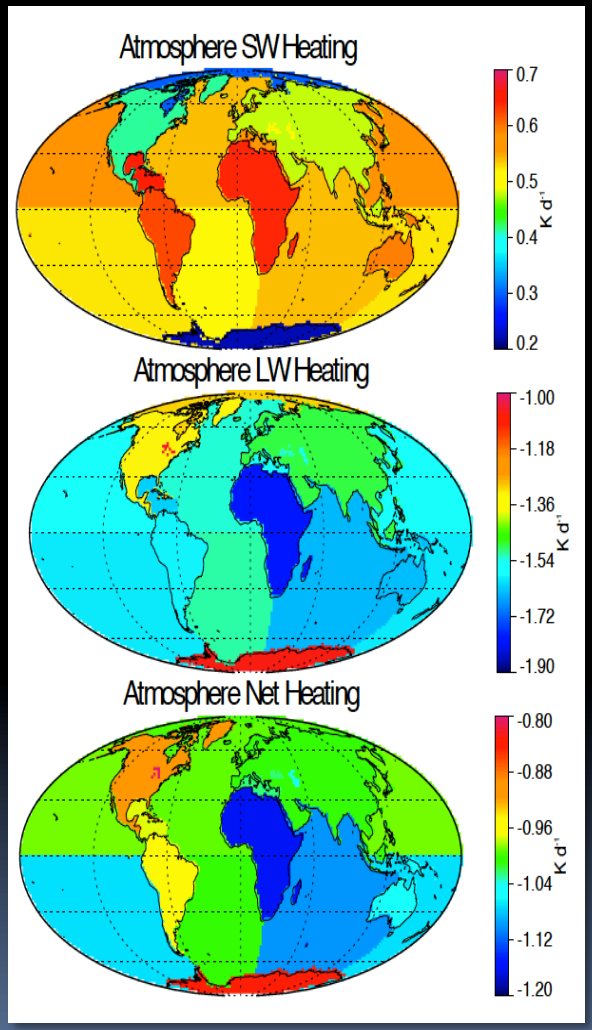


- Can't sample the diurnal cycle of clouds and precipitation but can at least model the solar cycle.
- Due to the high along-track sampling of CloudSat, we simply move the sun by 2 hours in each successive pixel
- The complete diurnal cycle of SZA is, therefore, sampled every 12 pixels along track

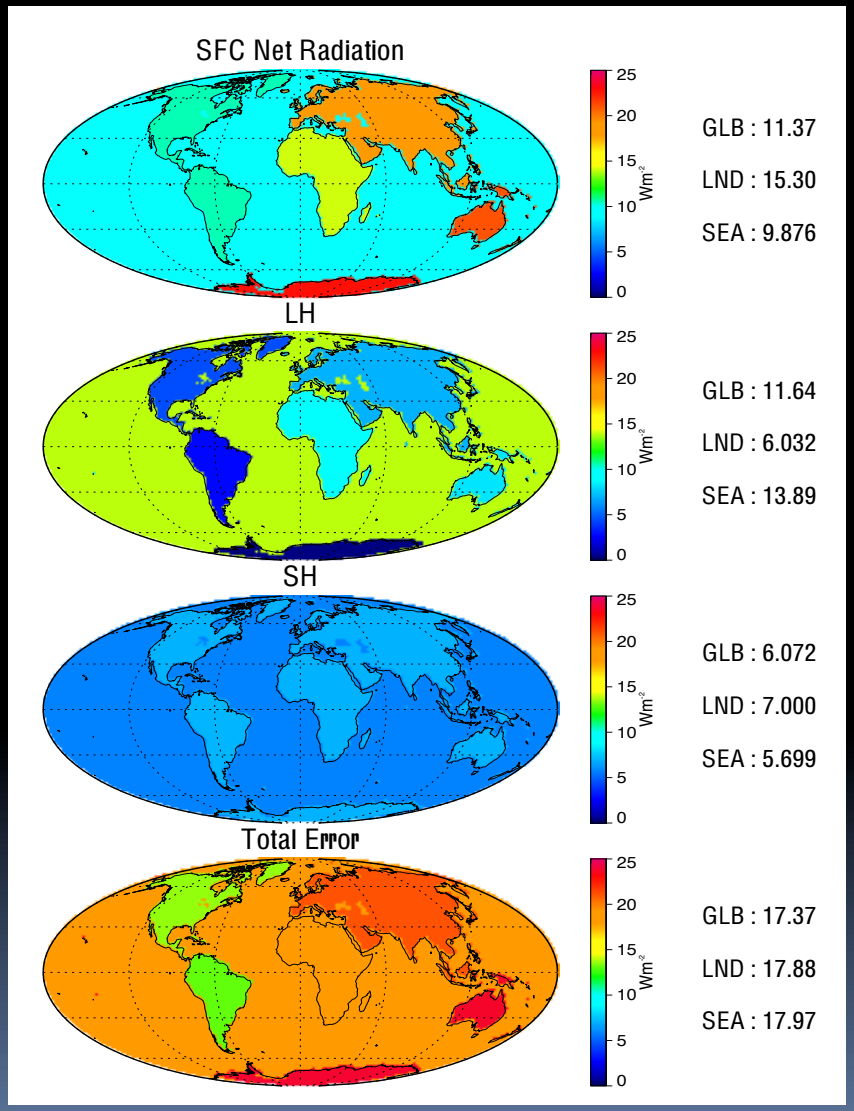
Regional Radiation Budgets



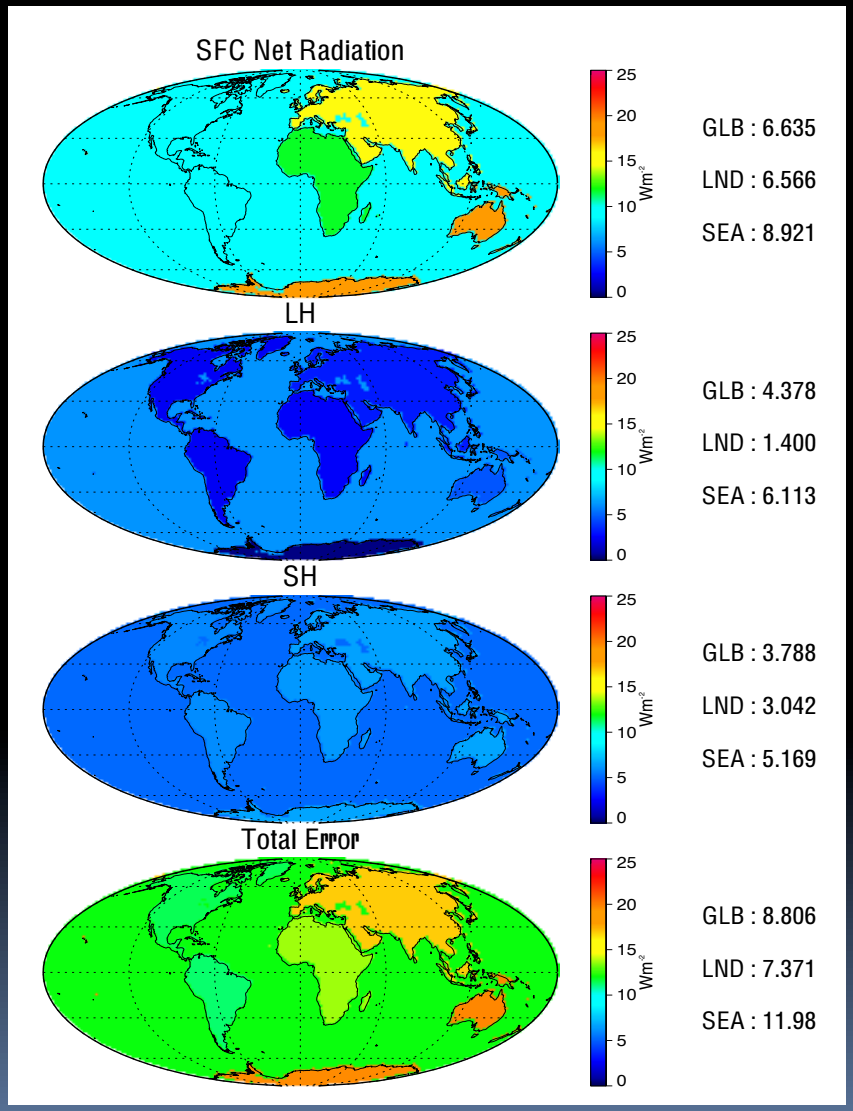


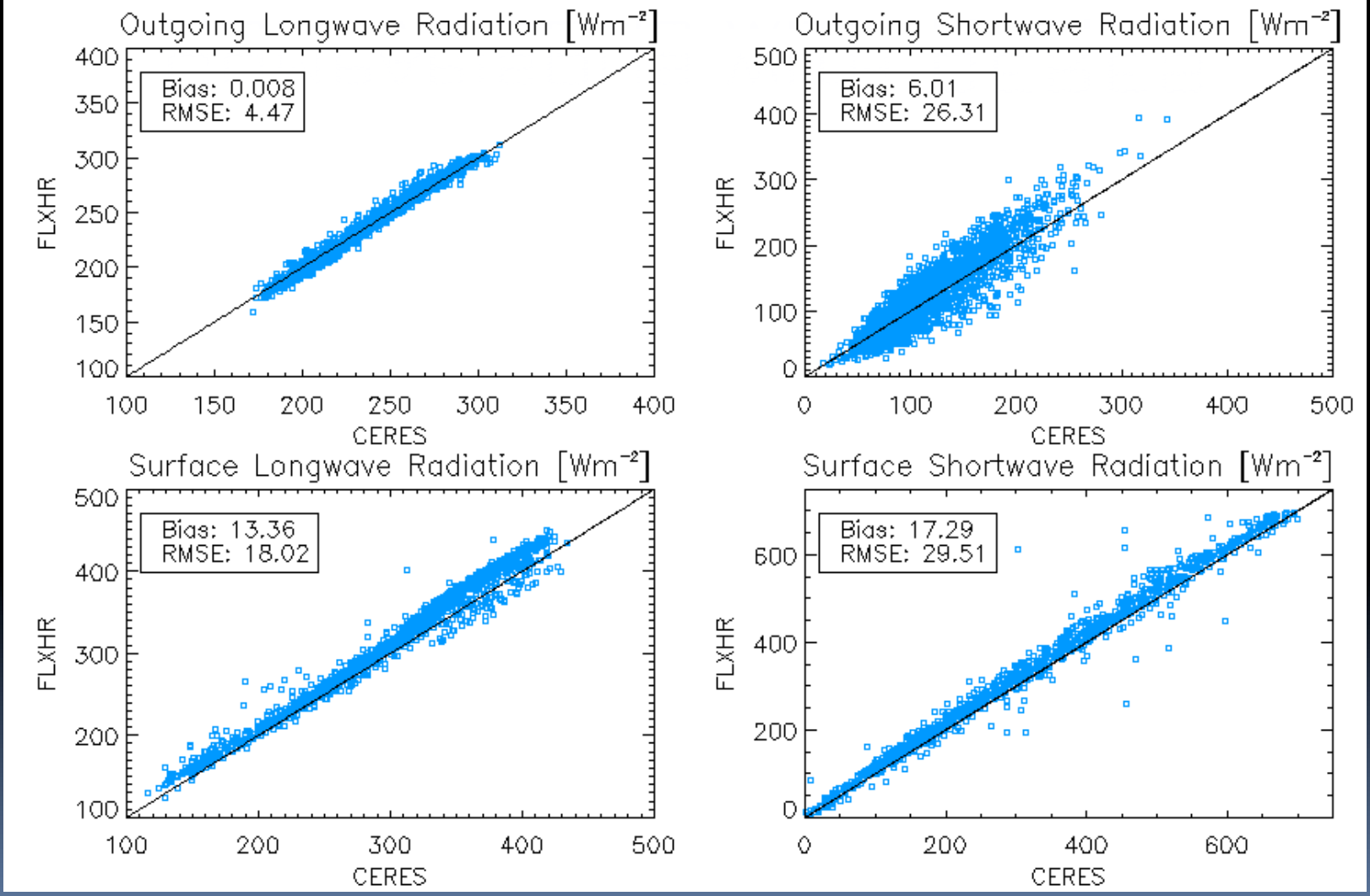


Uncertainties



Original Datasets



Constrained Fluxes

Comparisons with CERES