Radiative Heating Profile Products from TRMM and CloudSat

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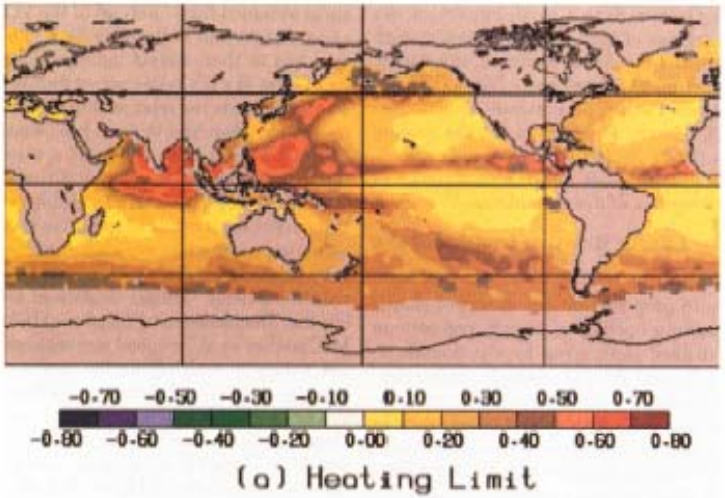
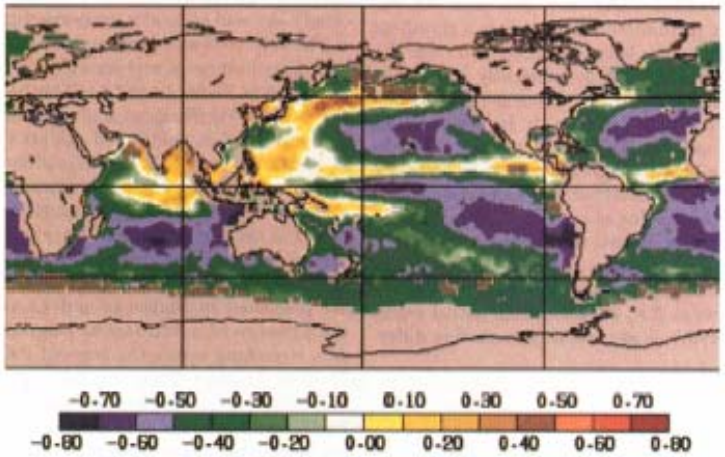
STEPHENS ET AL.: EARTH'S RADIATION BUDGET



(a) Heating Limit



(b) Cooling limit

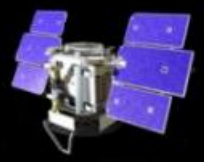
Plate 3. (a) The heating limit of clouds on the column radiative cooling rate and (b) the cooling limit defined assuming a cloud base temperature that is 2 K less than the SST. Both results are for July 1988.

We introduce the effects of clouds on the column cooling rate in terms of the following difference quantity

$$\Delta\left(\frac{dT}{dt}\right) = \left(\frac{dT}{dt}\right)_{\text{cloudy}} - \left(\frac{dT}{dt}\right)_{\text{clear}},$$

which, in flux form, is

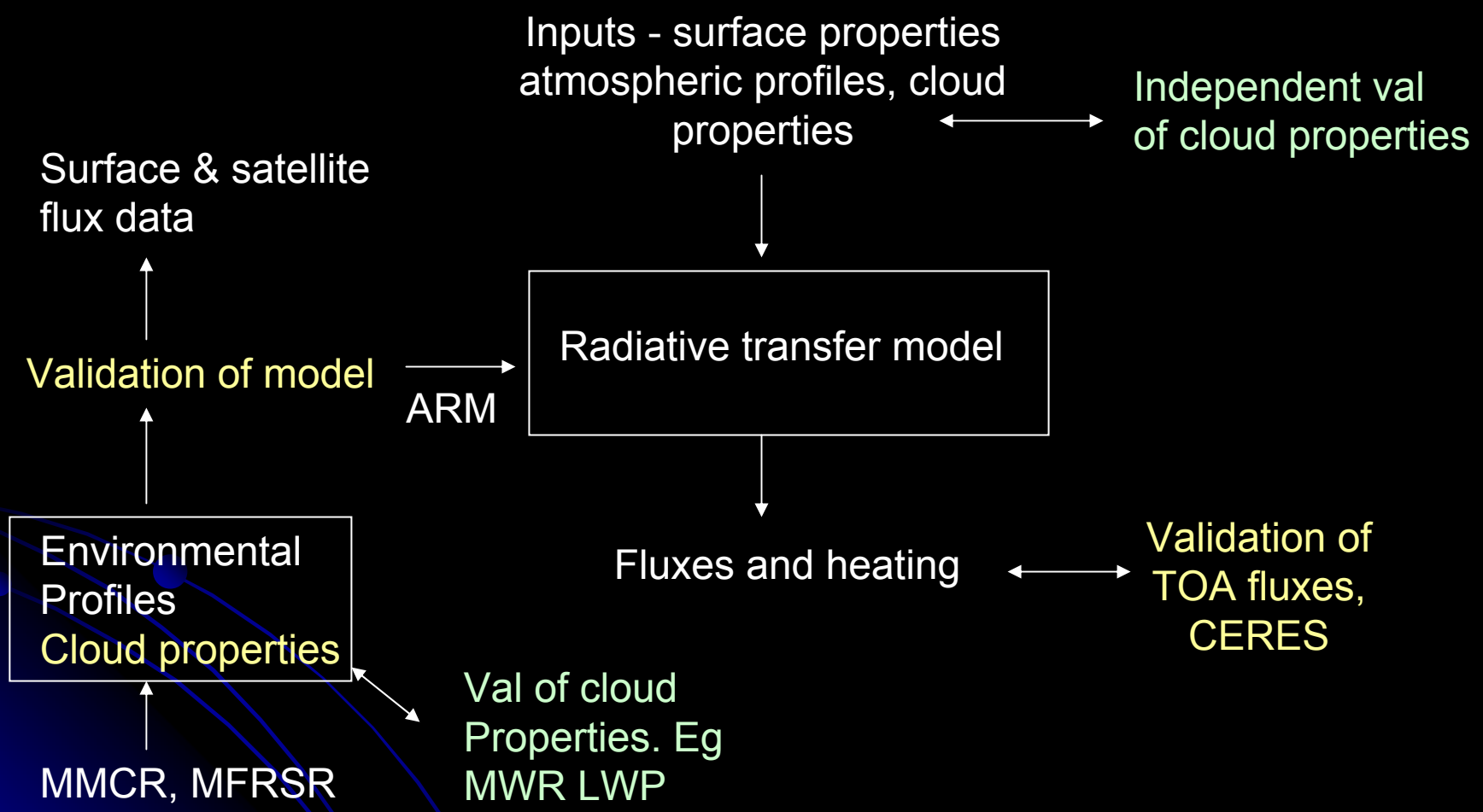
$$\Delta\left(\frac{dT}{dt}\right) = -\frac{gF_\infty}{c_p p_s}[\Delta F_g + \Delta F_\infty], \qquad (12)$$



Objectives

- To estimate profiles of atmospheric radiative heating on the global scale using multi-sensor satellite observations (specifically TRMM and CloudSat) as input.
- To assess the role of clouds in modifying atmospheric radiative heating and determine the spatial distribution of these impacts.
- To compile a long-term large-scale dataset for studying the role of cloud-radiation feedbacks in climate change.
- To use these data to evaluate parameterized physics in global climate models.

The philosophy



Shortwave Longwave

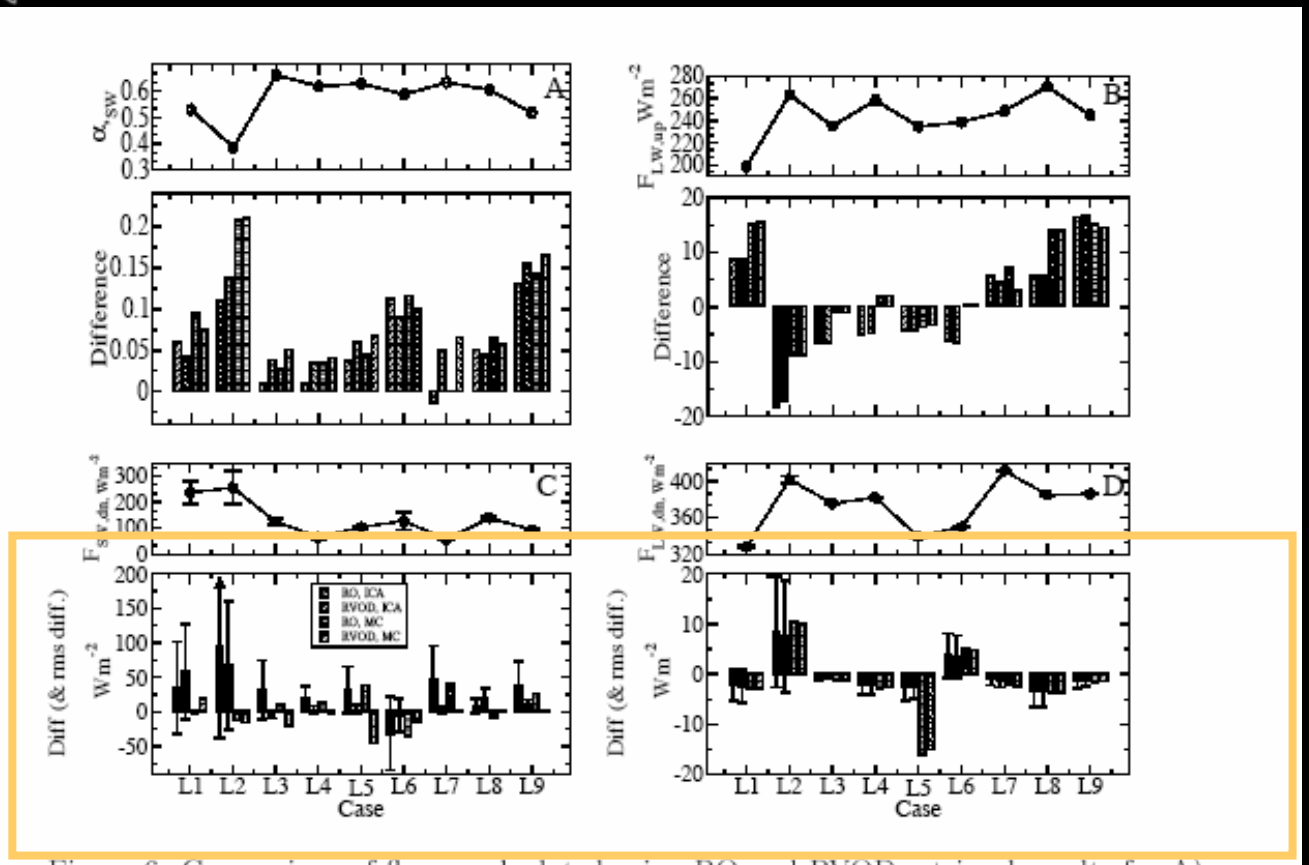


Figure 6: Comparison of fluxes calculated using RO and RVOD retrieval results for A) upwelling TOA shortwave, B) upwelling TOA longwave, C) downwelling surface shortwave and D) downwelling surface longwave. For each panel, the upper graph shows the observed flux or albedo while the lower graph shows differences between model results and observations. For the surface fluxes, the error bars on the fluxes themselves show the temporal variation (standard deviation) of the observed fluxes. The error bars for the ICA results on the bar graphs show the RMS differences between the time series of ICA fluxes and the time series of surface flux observations over each of the 20 minute domains.

Example of ARM 'validation' - ARM cloud inputs into RT model and comparison to surface fluxes

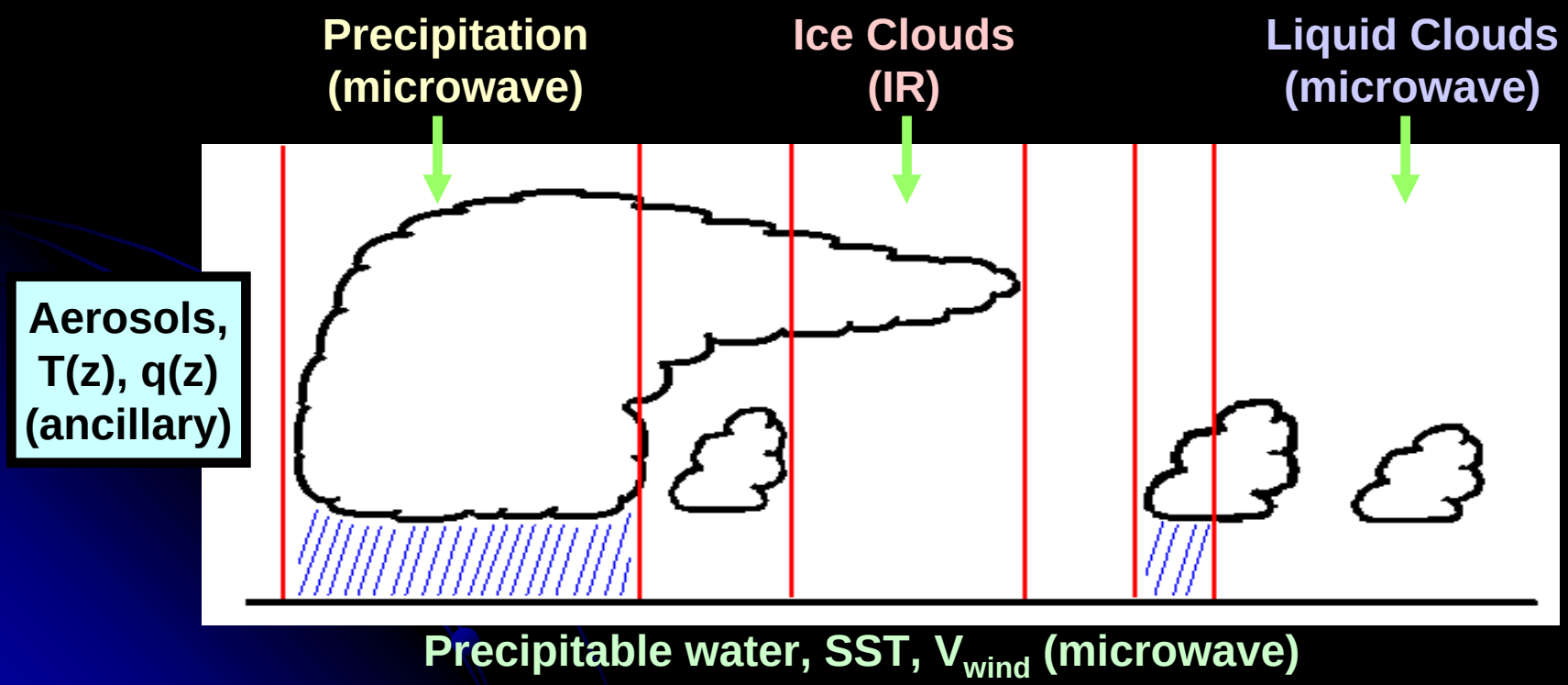
SW sfc flux
Bias ~6%
RMS~10%

Wood et al., 2007

TRMM Analysis Approach

L'Ecuyer and Stephens, 2003;2007

- Product is vertical profiles of upwelling and downwelling LW and SW fluxes and implied heating rates at 0.25º resolution.



Input Data and Uncertainties

Component	Parameters	Source	Technique	Uncertainties
Precipitation	LWC(z), IWC(z), R, etc.	TMI*	Multi-freq. Bayesian (GPROF)	R/LWP: 50 % IWP: 100 %
Non-precipitating Ice Clouds	IWP, r_e, and T_c	VIRS**	Optimal-estimation split-window (10.8 and 12 μm)	IWP: 30-50 % R_e: 50-100 %
Non-precipitating Liquid Clouds	LWP	TMI	De-polarization of surface emission at 19 and 37 GHz	LWP: 40-60 %
Background Atmosphere	T(z) and q(z)	ECMWF	Re-analysis	T(z): 3 K q(z): 30 %
Background Surface	SST, CWV, and V_{wind}	TMI	Multi-freq. physical (RSS-Wentz)	SST: 2 K CWV: 10 %
Aerosol	Optical props. (τ, g, ϖ_0)	GACP	Composite from various sources	Varies based on local σ

* TMI – Tropical Rainfall Measurement Mission (TRMM) Microwave Imager

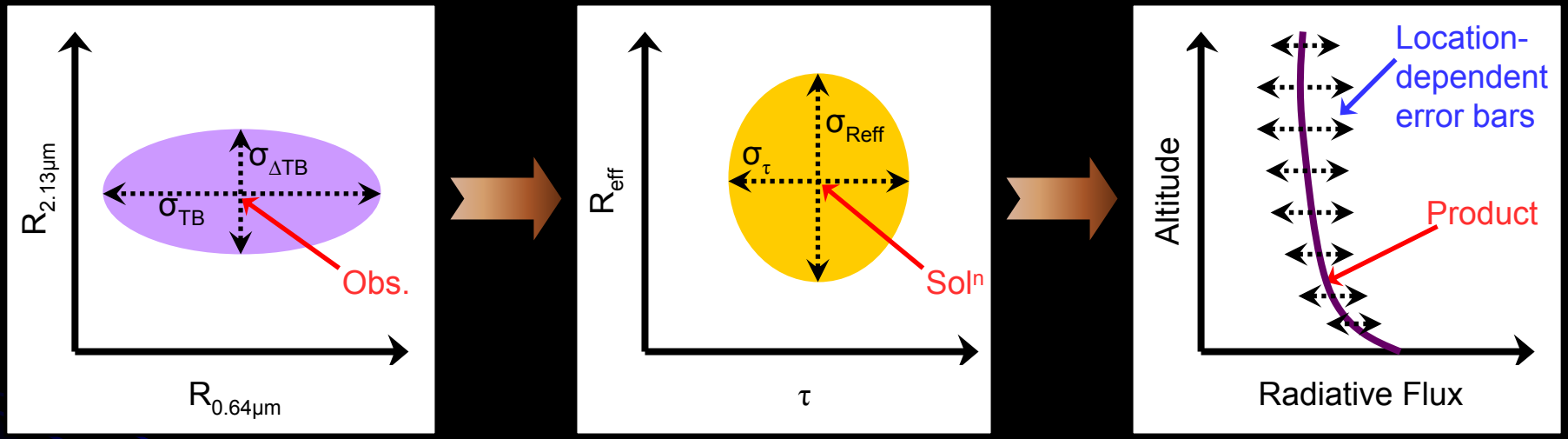
** VIRS – Visible and Infrared Scanner (also aboard TRMM)

Evaluation of Uncertainties

Bi-variate PDF of (sim. – obs.) measurements. Width dictated by measurement error and uncertainty in forward model assumptions.

Error in product from width of posterior distribution from application of Bayes theorem.

Resulting errors are translated into errors in radiative fluxes through sensitivity studies.



- Sequence:
  - specify uncertainties due to measurements and algorithm assumptions
  - propagate these uncertainties through the inversion to yield explicit estimates of errors in products
  - use these errors in subsequent sensitivity studies to generating estimates of uncertainties in derived radiative fluxes

Impact on Monthly-Mean Fluxes

Parameter	Perturbation	$\Delta F^{\uparrow}_{LW,TOA}$	$\Delta F^{\downarrow}_{LW,SFC}$	$\Delta F^{\uparrow}_{SW,TOA}$	$\Delta F^{\downarrow}_{SW,SFC}$
SST	±2 K	±1 Wm^{-2}	±6 Wm^{-2}	--	--
Atmos. T	±2 K	±5 Wm^{-2}	±2 Wm^{-2}	--	--
WV (>500hPa)	±30 %	±2 Wm^{-2}	--	--	--
WV (<500hPa)	±15 %	±3 Wm^{-2}	±7 Wm^{-2}	±1 Wm^{-2}	±4 Wm^{-2}
IWP	±30 %	±2 Wm^{-2}	--	±1 Wm^{-2}	±1 Wm^{-2}
Ice Re	±60 %	±3 Wm^{-2}	--	±2 Wm^{-2}	±2 Wm^{-2}
Ice Cloud T	±7 K	±2 Wm^{-2}	--	--	--
LWP	±40 %	--	--	±4 Wm^{-2}	±4 Wm^{-2}
Liquid Re	±5 μm	--	--	±7 Wm^{-2}	±8 Wm^{-2}
Precipitation	±100 %	--	--	±1 Wm^{-2}	±1 Wm^{-2}
SFC Albedo	±0.03	--	--	±7 Wm^{-2}	±1 Wm^{-2}

*Note: Sensitivities less than 0.5 Wm^{-2} are represented by --.

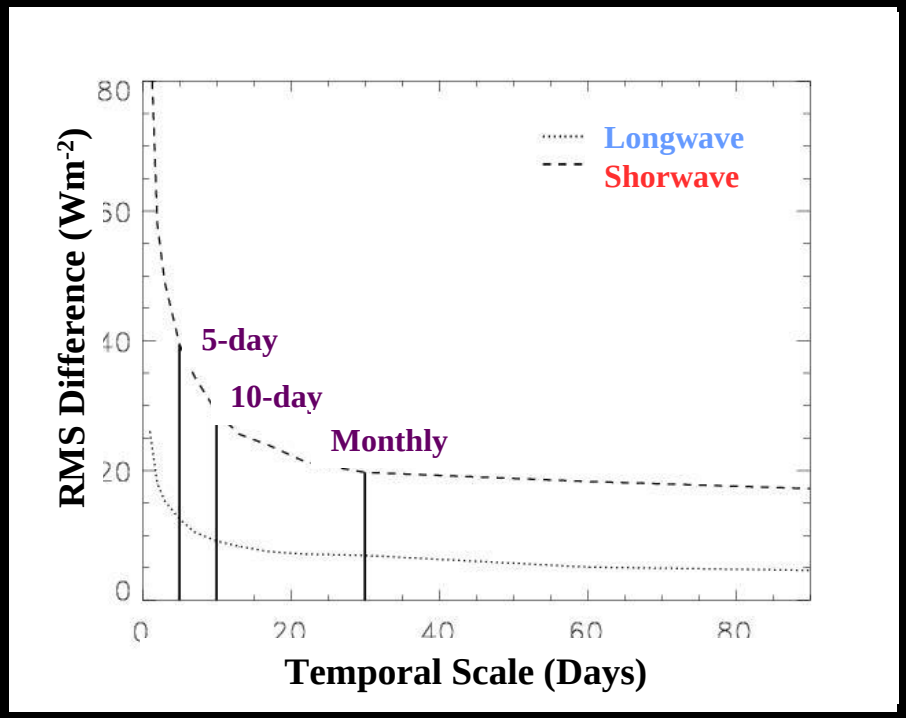
Uncertainty Estimates (V1)

Sensitivity Studies

1. **Longwave**: errors ~10 Wm^{-2} primarily due to uncertainties in ice cloud temperature and water vapor profile.

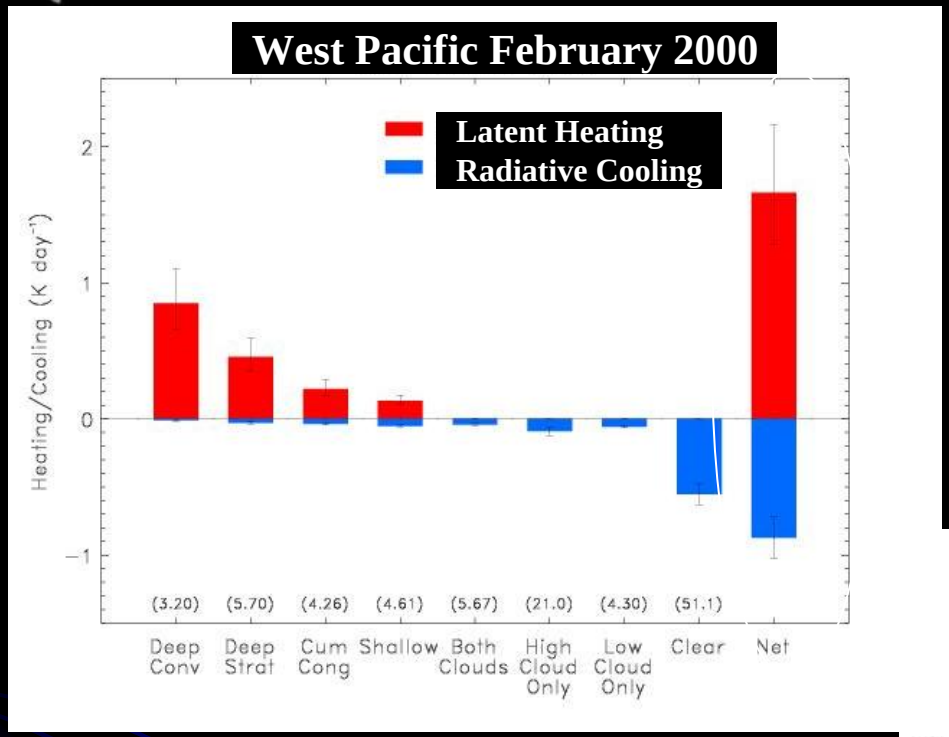
2. **Shortwave**: errors ~20 Wm^{-2} primarily due to liquid cloud detection, water path, and particle size.

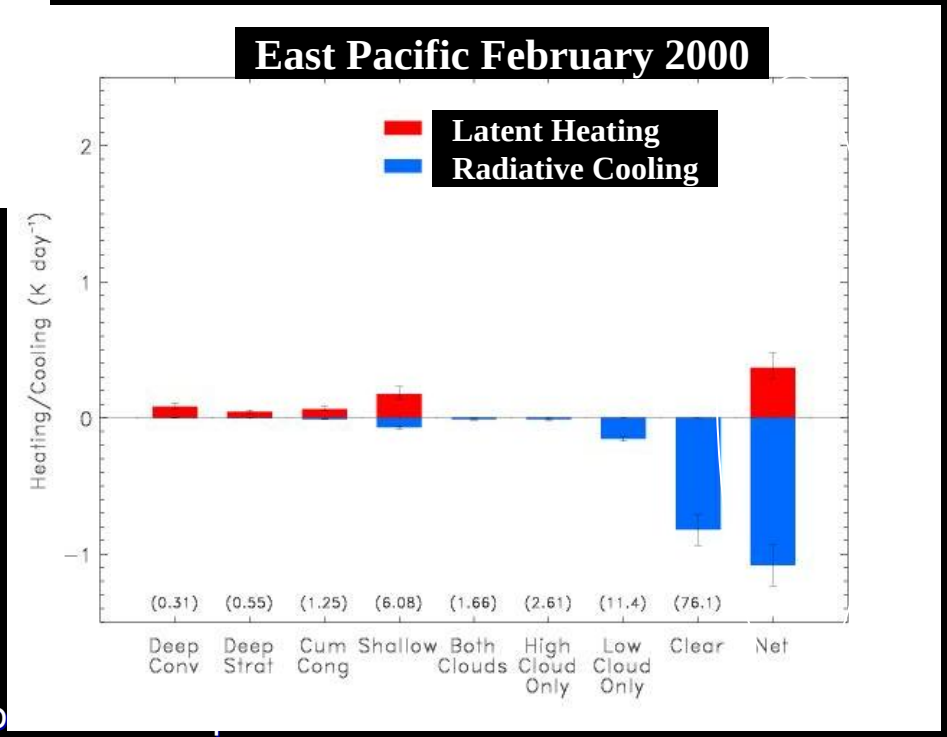
Comparison with CERES



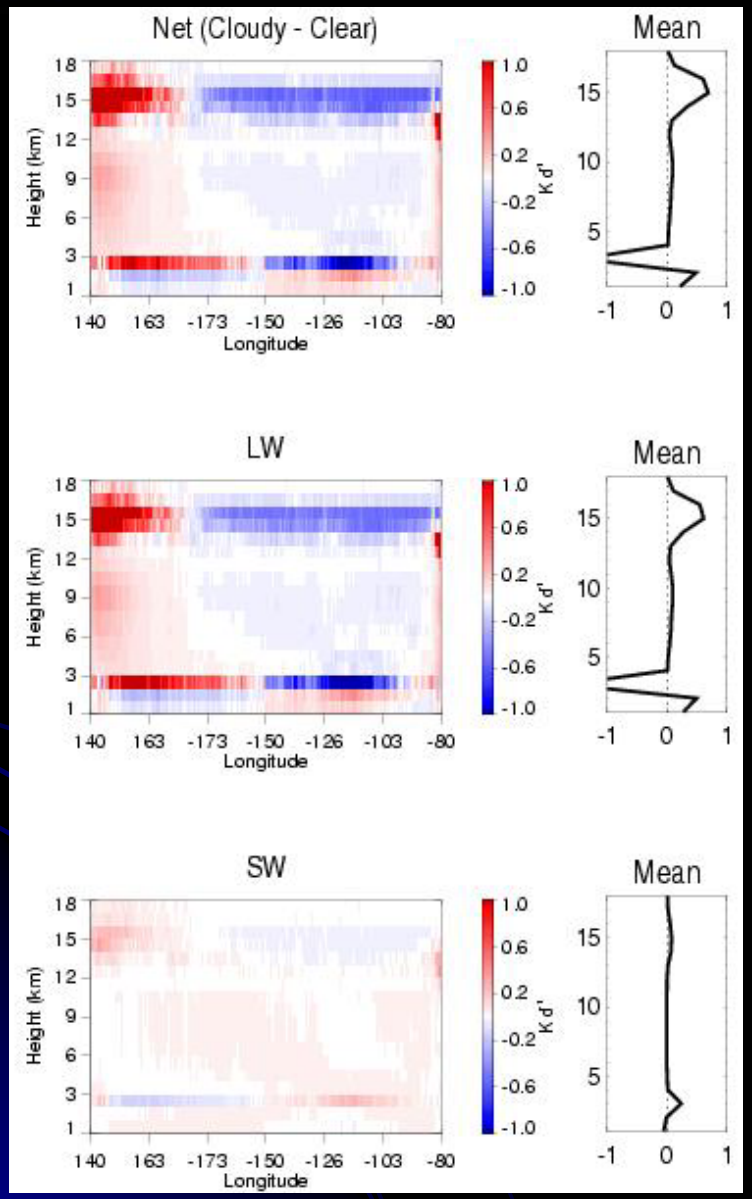
- **LW flux** errors range from 30 Wm^{-2} instantaneous to 5 Wm^{-2} on seasonal timescales
- **SW flux** errors range from 80 Wm^{-2} instantaneous to 15 Wm^{-2} on seasonal timescales

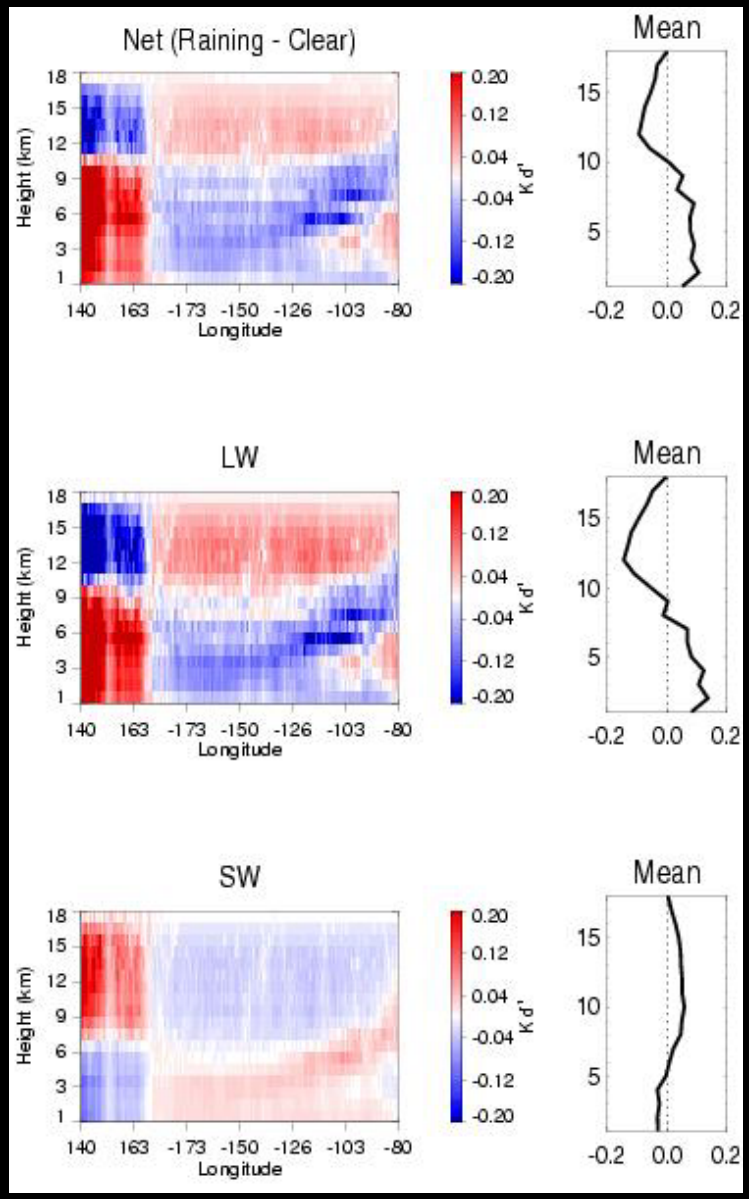
Tropical Pacific





Cloud Impacts





CloudSat FLXHR Algorithm

Reflectivity

Cloud Mask

Cloud Type

Initial Water Content

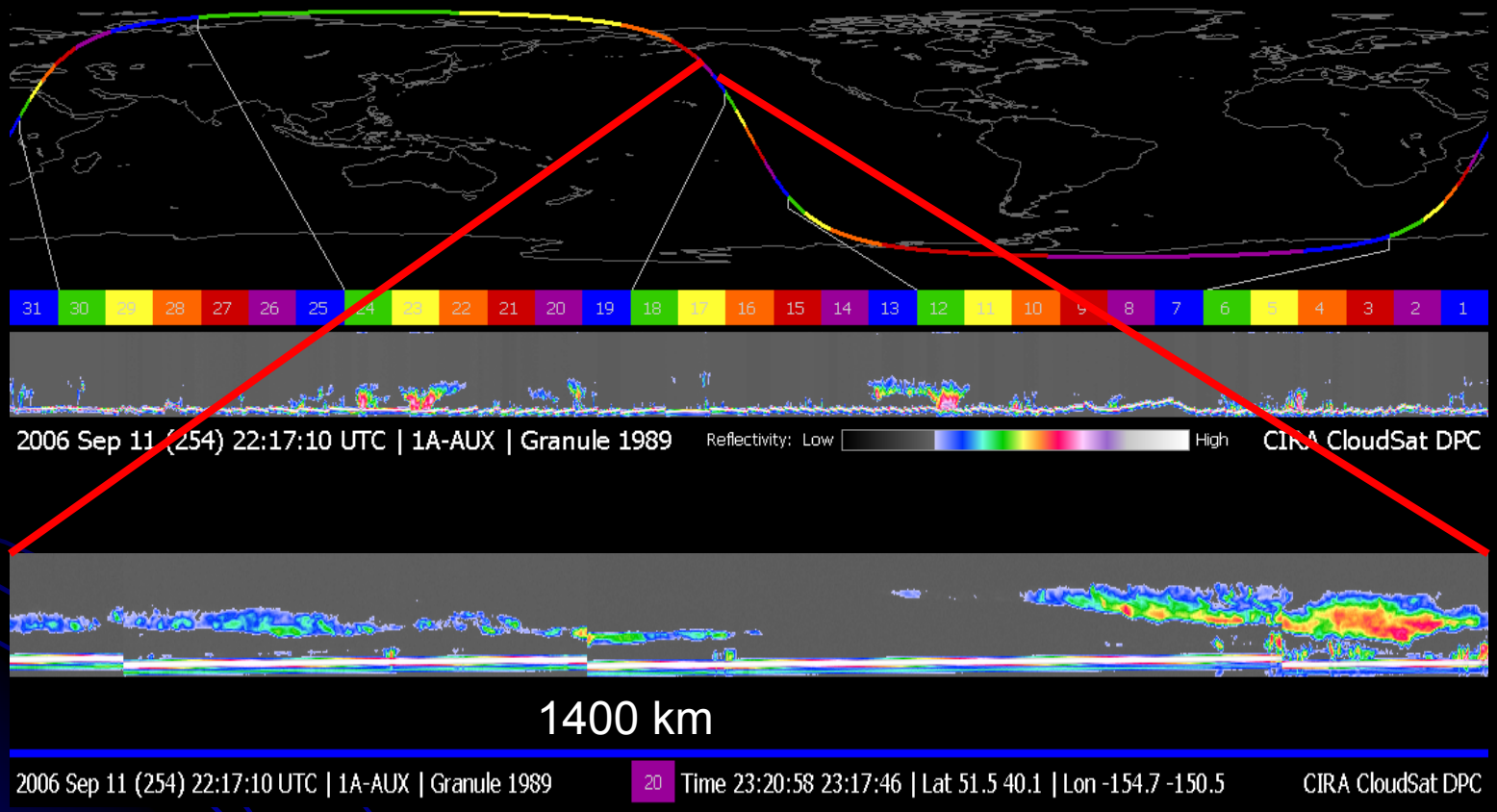
Optical Depth

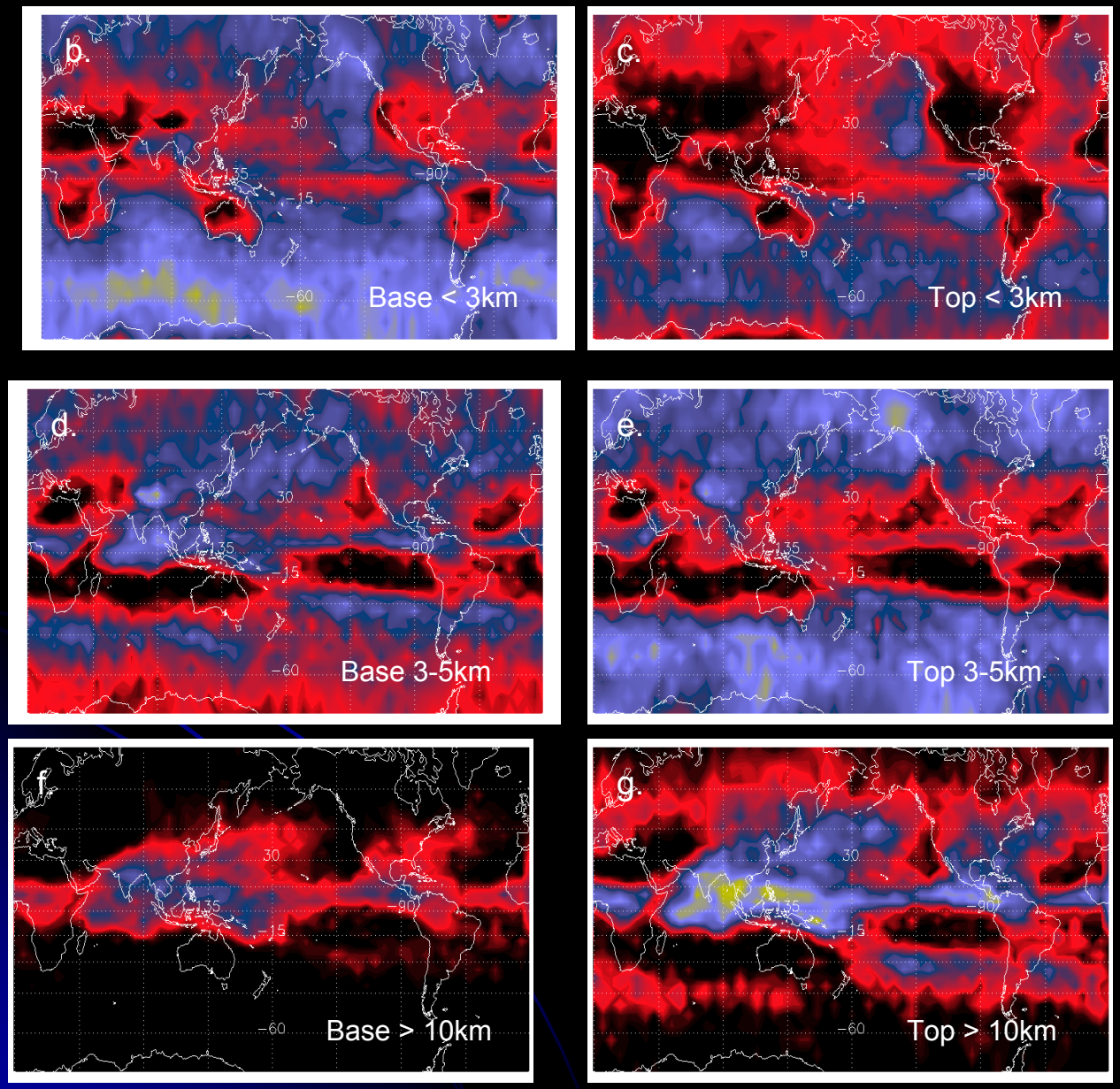
Constrained Water Content

Fluxes/Heating Rate ⟷ CERES/ssflux

- Inputs (blue):
  - LWC/IWC profiles from CloudSat level-2B algorithms
  - Gas extinction profiles from ECMWF analyses
  - Surface albedo, solar zenith angle, etc. from ancillary datasets
- Procedure:
  - Composite geophysical parameters
  - Run broadband RT model (BUGSrad)
  - Compute heating rate profiles
- Outputs (green):
  - Output consists of vertical profiles of upwelling and downwelling LW and SW fluxes at CPR resolution.
  - Profiles of radiative heating.

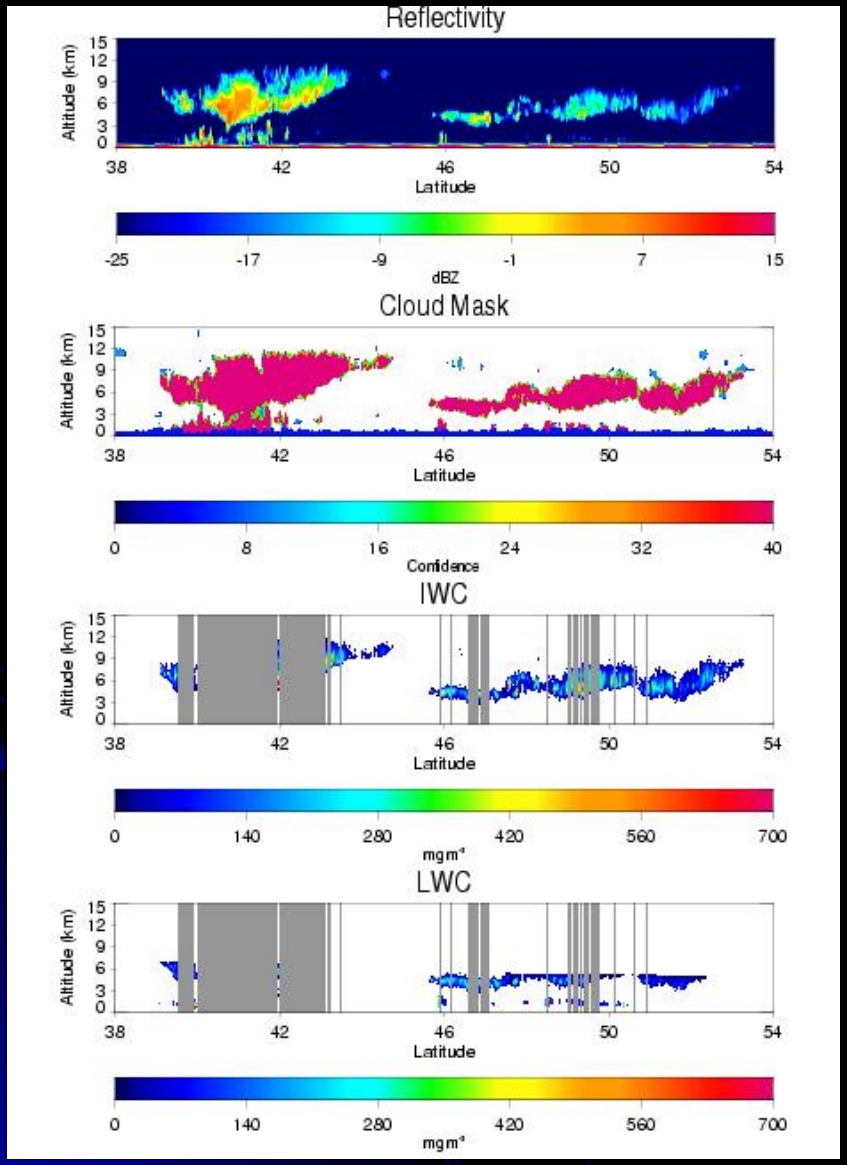
Example

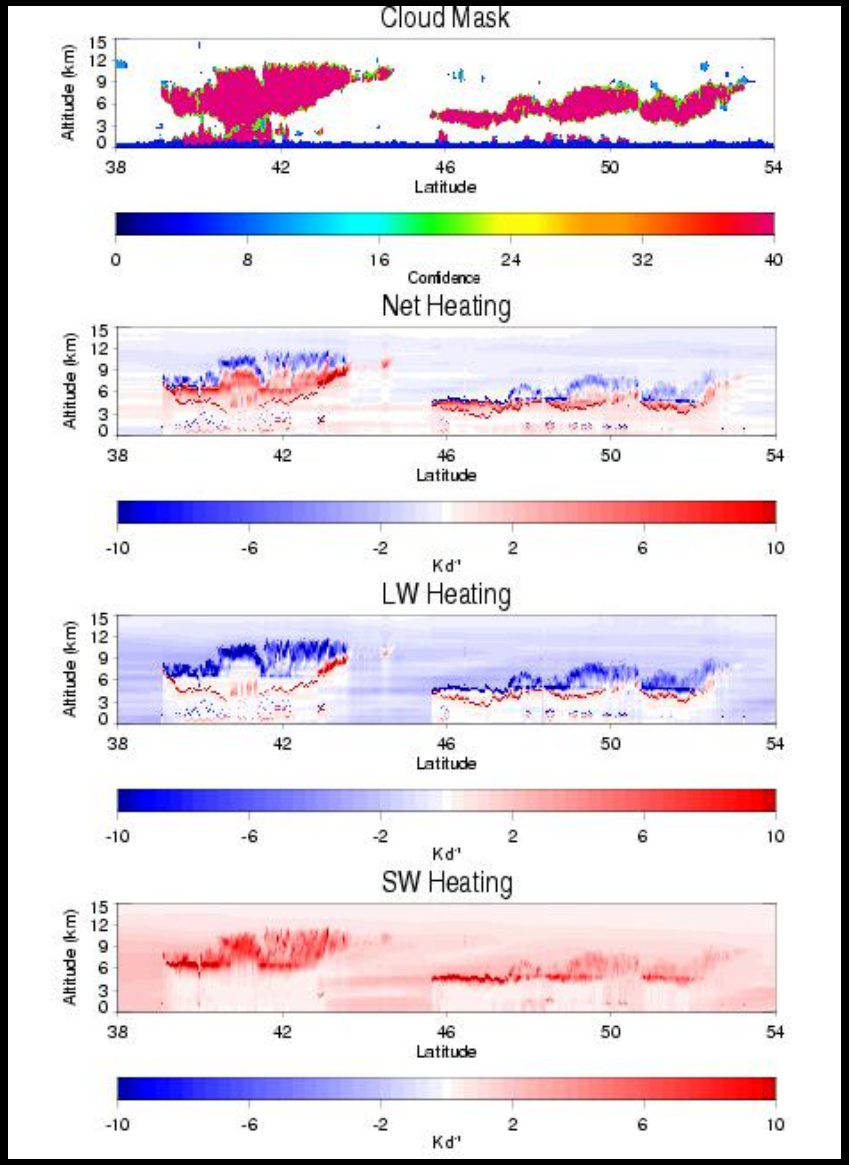

31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
2006 Sep 11 (254) 22:17:10 UTC | 1A-AUX | Granule 1989
Reflectivity: Low
High
CIRA CloudSat DPC
20 km
1400 km
2006 Sep 11 (254) 22:17:10 UTC | 1A-AUX | Granule 1989
20
Time 23:20:58 23:17:46 | Lat 51.5 40.1 | Lon -154.7 -150.5
CIRA CloudSat DPC

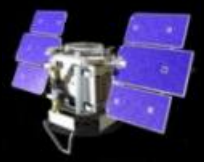


Documenting cloud vertical structures - Mace et al., 2007 (geoprof)

Products


Reflectivity
Altitude (km)
Latitude
dBZ
Cloud Mask
Confidence
IWC
LWC
mgm⁻³


Cloud Mask
Altitude (km)
Latitude
Confidence
Net Heating
LW Heating
SW Heating
Kd⁻¹



Discussion Points

1. To date, profiles of radiative heating from TRMM have been generated for 1998-2000 and will ultimately be extended to the full TRMM period. At TOA LW fluxes are accurate to 10 Wm^{-2} and SW fluxes to ~25 Wm^{-2} with errors dominated by the vertical placement of clouds.

2. CloudSat's vertically-resolved cloud property products allow the resolution and accuracy of radiative heating rate profile products to be significantly increased and extend their coverage to higher latitudes. Products are still in development but will be released very shortly.

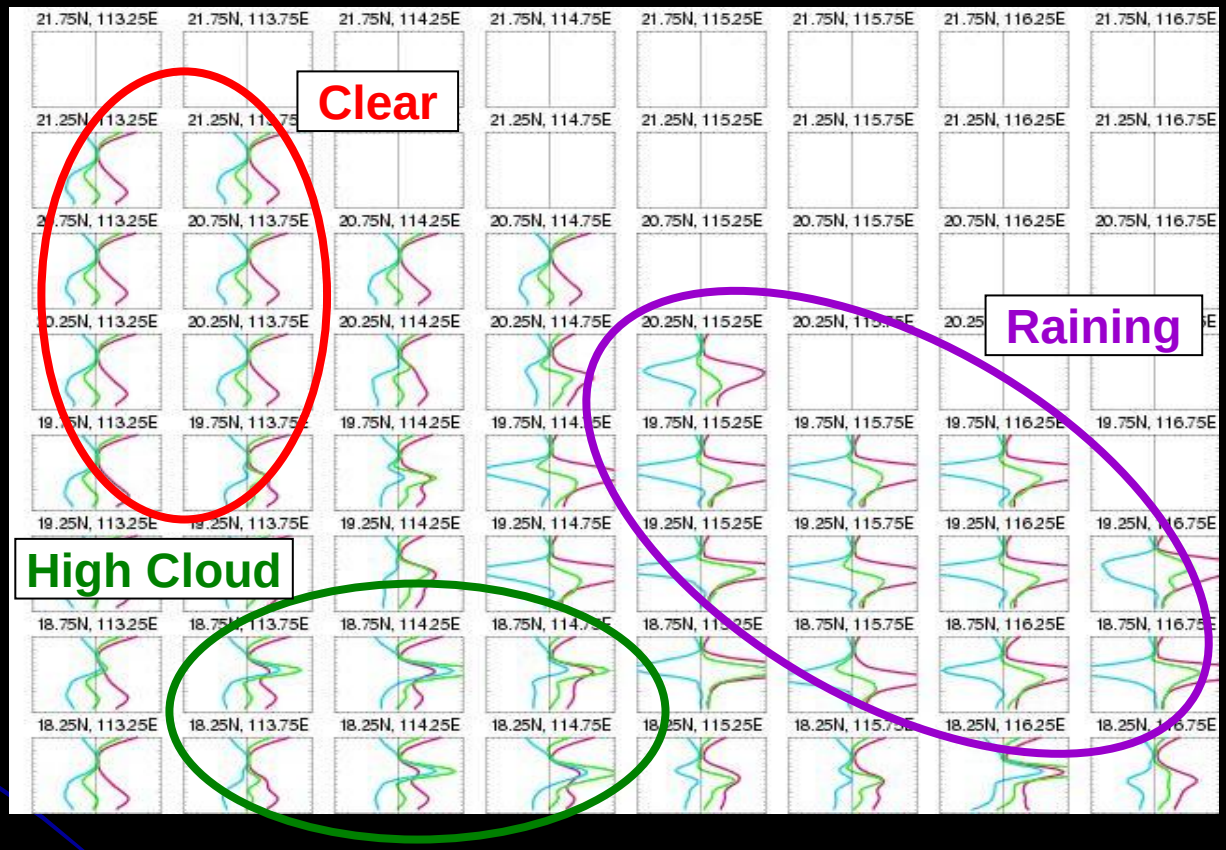
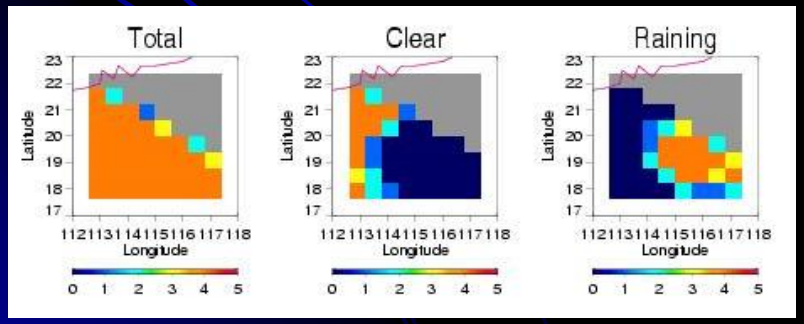
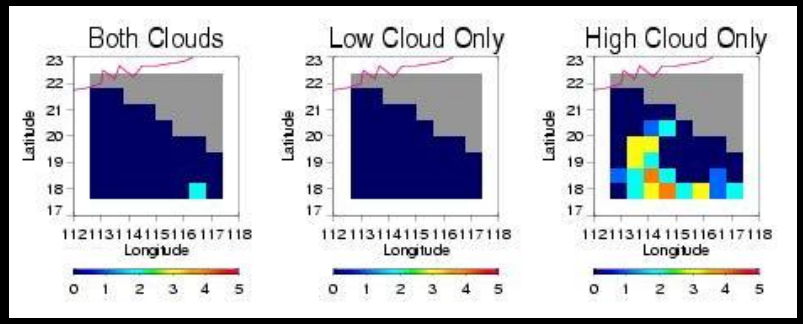
3. Validation of both products is ongoing. Plans include detailed inter-comparisons with ARM surface flux measurements and radiative heating profile estimates.

Back-up Slides

Notes

- Cover general idea of the "forward-modeling" approach contrasting it with the TOA-constrained CERES approach. Note synergy with ARM – satellite products offer the potential to extend more accurate ground-based products to larger scales.
- Emphasize unique error analysis from algorithms through products and summarize estimates from sensitivity analyses and comparisons of TOA fluxes (validation is ongoing). Table and plot gives ball-park estimates of errors and highlight most important sources – cloud properties dominate!
- TRMM examples: Large-scale heating rate profiles across the Pacific averaged over Dec. 1998-Feb. 1999 between 7.5 N/S. Line plot summarizes means while longitude-height cross-sections show anomalies. Non-precipitating clouds can be separated into two types: high clouds tend to heat the upper atmosphere while low clouds cool below. Rain tends to cool upper levels and warm lower levels. Cloud impacts are stronger due their frequency of occurrence. More thick high cloud in the West Pacific/more shallow precipitation and thinner high clouds in the east. Problem with using exclusively passive obs. is evident – cloud thicknesses are fixed and constrain the heating/cooling to unrealistically thin layers (particularly evident in low clouds).
- Enter CloudSat: Note the benefits afforded by satellite-based radar (i.e. to constrain cloud boundaries) and focus remaining CloudSat discussion on the sequential processing from reflectivity to heating rate.
- Conclude by noting the availability of products and the importance of ARM estimates for validation purposes (again note the role of these products in extending ARM-RH products to larger scales).

Examples from SCSMEX

1-18 km

±5 Kd^{-1}