Cloud/Precipitation Assimilation Using the Forecast Model as a Weak Constraint

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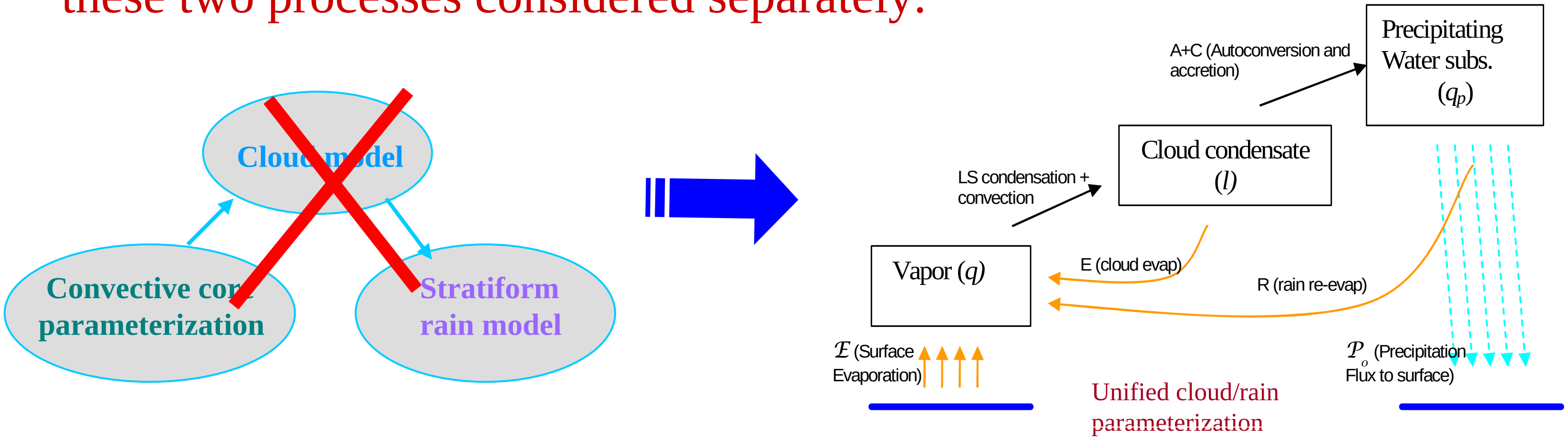
A unified approach to cloud/precipitation assimilation

- Errors in model clouds reflect not only errors in cloud parameterizations but also errors in detrained liquid/ice from convective processes or errors in the background humidity field (which in the tropics is ultimately linked to convective detrainments and the large-scale circulation).
- Similarly, one cannot address errors in rain and latent heating profiles without considering interactions of precipitation with cloud condensates and other cloud-scale processes.
- Sensitivity of the combined cloud/rain observation operator to state or model parameters can be quite different from the sensitivity of each of these two processes considered separately.



Cloud model

Convective core parameterization

Stratiform rain model

A+C (Autoconversion and accretion)

Precipitating Water subs. (q_p)

LS condensation + convection

Cloud condensate (l)

Vapor (q)

E (cloud evap)

R (rain re-evap)

$\mathcal{E}$ (Surface Evaporation)

$\mathcal{P}_o$ (Precipitation Flux to surface)

Unified cloud/rain parameterization

Model error a key issue in cloud/precipitation assimilation

- Conventional data assimilation algorithms do not address errors arising from model deficiencies.

- Yet model rain and clouds are based on parameterized physics, which can have large systematic errors. Unless these (largely unknown) model errors are accounted for in data assimilation, one cannot make full use of the information available from cloud/precipitation measurements.

- Basic problem: Observation operators for cloud/precipitation are not as accurate as those for conventional data or observables in clear-sky regions. Using these data effectively in the presence of model biases requires special considerations.

Two ways to proceed

- Restricting data usage to aspects of measurements for which observation operators are reasonably accurate; e.g.,
  - Radiance assimilation in selected passive microwave channels

- Assimilation of cloud/rain information using the forecast model as a weak constraint
  - Developing assimilation procedures within a given analysis framework to perform *online estimation and correction of model errors* to improve cloud/rain observation operators.

Perfect model assumption vs. tendency error correction: An example

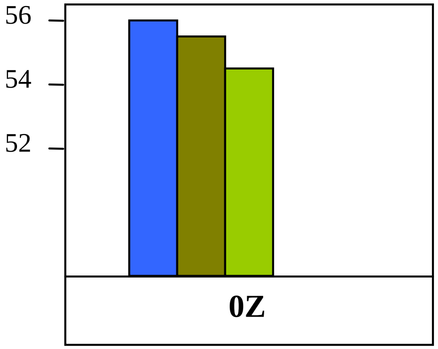
1+1D (column + time) variational assimilation of 6h rain accumulation

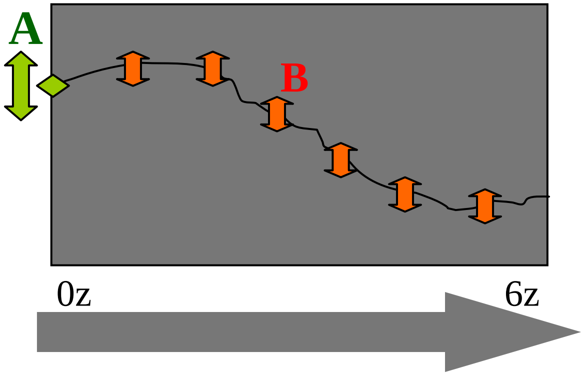
Forecast initialized with moisture consistent with the observed TCWV produces excessive rain over 6h, leading to a dry bias in the final moisture field.

Method A: adjustment of initial moisture profile assuming a perfect model

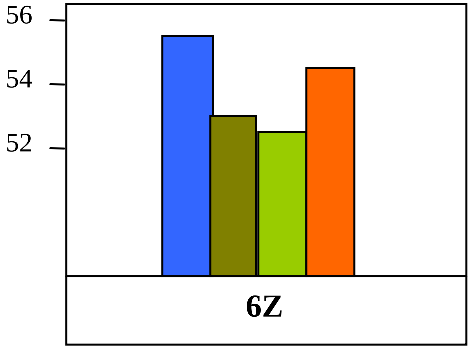
Method B: continuous correction of time-tendency of moist processes

Total column water vapor (mm)

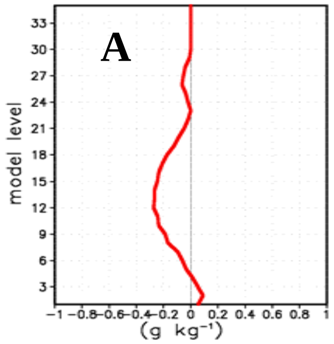




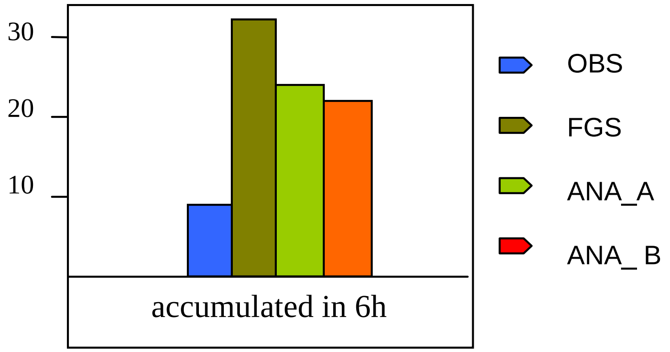
Total column water vapor (mm)



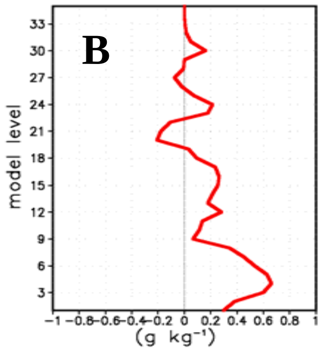
Initial moisture increment



Averaged rain rate (mm/day)



Time-tendency correction



Rainfall assimilation in the presence of moist physics errors by adjusting initial conditions can *degrade analyses of other variables and lead one to conclude 'rainfall data is worthless'.*

GSFC experiments using the model as a weak-constraint

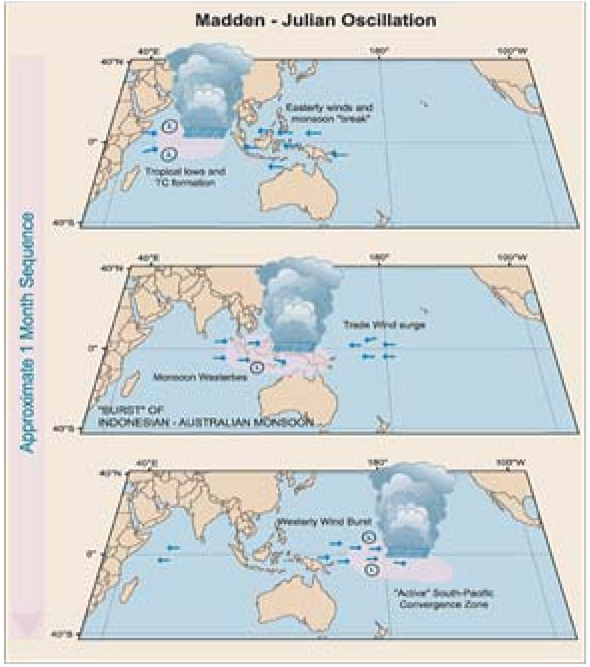
- Variational continuous assimilation of 6h surface rain accumulation using moisture tendency correction as a control variable
  - 1+1D observation operator based on 6h time-integration of the column model of moist physics with prescribed large-scale forcing
  - Online estimation and correction for 6h-mean moisture tendency error
  - Moisture tendency correction applied continuously over the 6h analysis window to achieve dynamical consistency
- Variational assimilation of 6h retrievals of convective and stratiform latent heating profiles using empirical parameters in the moist physics as control variables
  - Used in conjunction with rainfall assimilation to seek further improvements
  - Estimating empirical parameters consistent with *analyzed* rather than *simulated* atmospheric states - and accounting for sub-grid-scale variability not captured in conventional parameterization schemes
- Variational assimilation of cloud fraction and optical depth from ISCCP and MODIS using empirical cloud parameters as control variables
  - Estimation of empirical cloud parameters to improve the treatment of unresolved sub-grid-scale moisture variability, microphysical details, and cloud overlap.

Model error considerations in rainfall assimilation

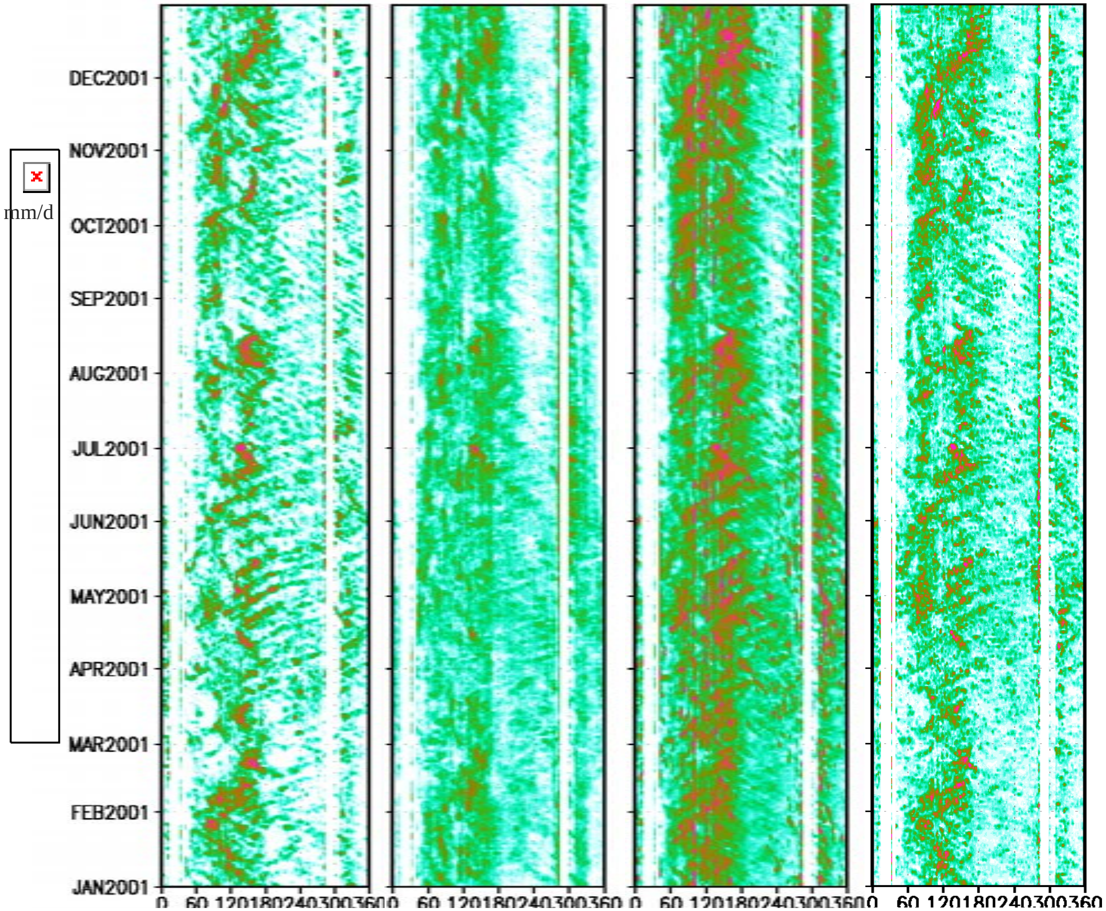
- Model rain is diagnosed from time-integrated change in specific humidity (time dimension is important)
  - ➡ Errors in model rain directly reflect errors in moisture tendency.
- Moisture forecast tendency errors arise from uncertainties in initial conditions and errors in model physics
  - ➡ Need strategies to address both IC and model errors.
- Tangent linear and adjoint models may not always be valid for nonlinear/discontinuous moist physics schemes
  - ➡ Use full nonlinear moist physics whenever possible.
- Parameterized convection with quasi-equilibrium assumptions is not designed to match instantaneous rain-rate observations
  - ➡ Assimilate rainfall accumulation instead of instantaneous rain rate.

Impact of VCA scheme on precipitation analysis

Current models and operational analyses do not replicate the intensity and propagation of tropical rainfall systems and intraseasonal oscillation patterns


Madden - Julian Oscillation

MJO signals in precipitation over tropical oceans (10N-10S): January-December 2001

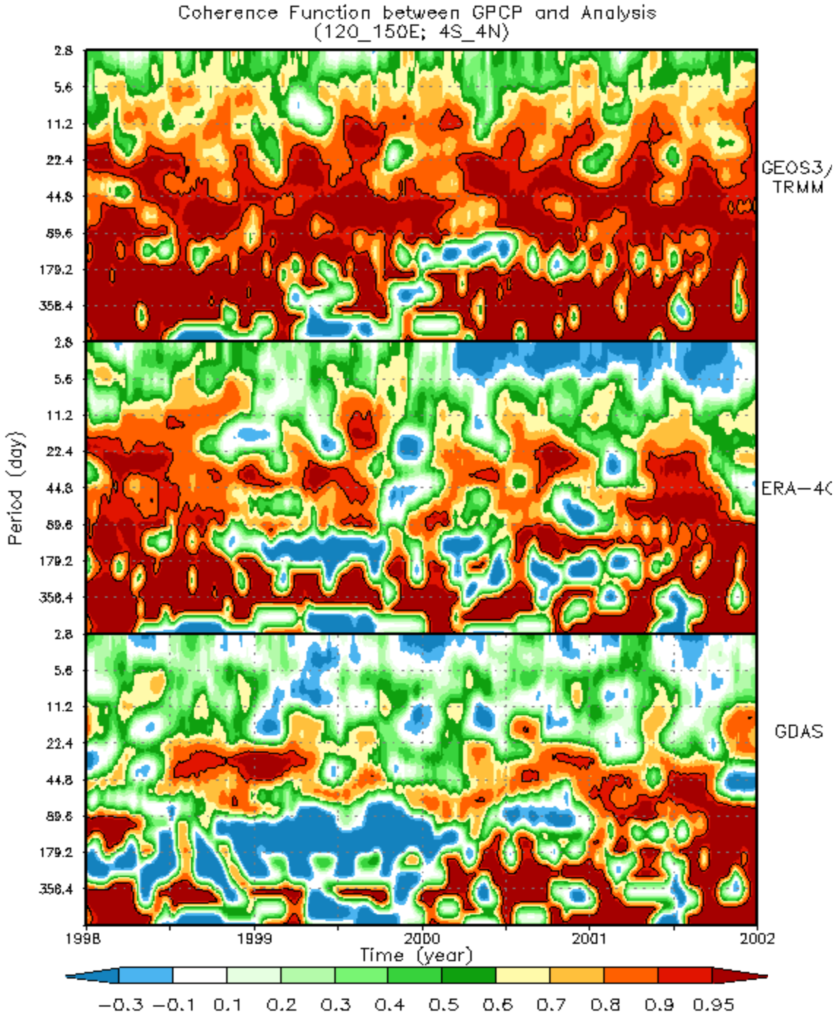

GPCP **NCEP GDAS** **ERA-40** **GEOS/TRMM**

Precipitation assimilation using the VCA procedure reduces biases in rainfall analysis and improves temporal and spatial patterns of tropical rain systems.

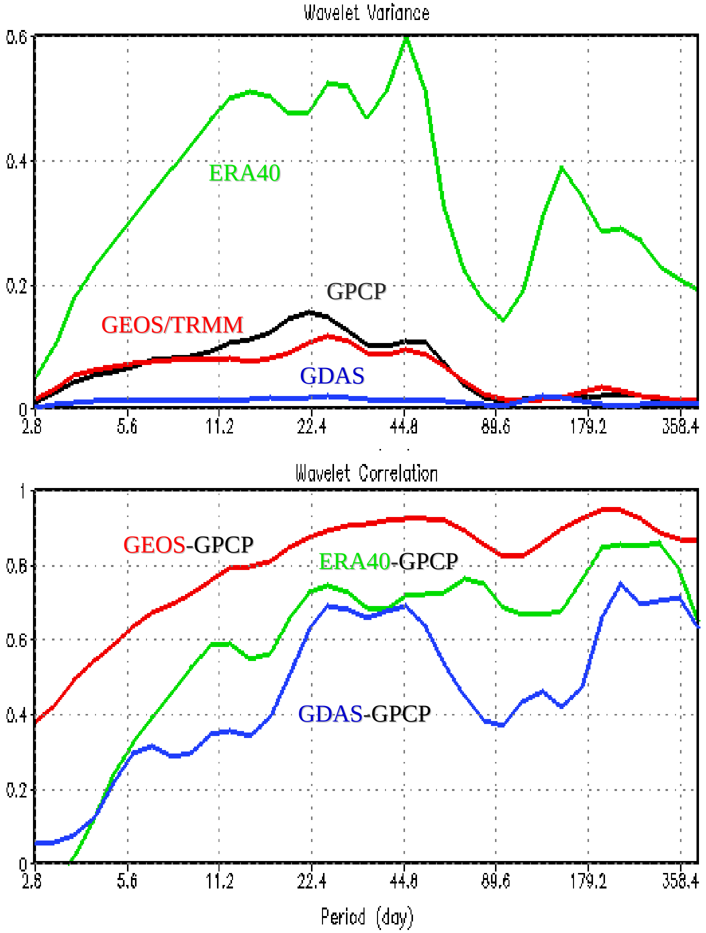
GEOS = Goddard Earth Observing System

Improved temporal variability

Enhanced frequency-time coherence between GPCP and GEOS-3 analysis



Precipitation (120-150E, 4S-4N)
(Morlet wavelet analysis)



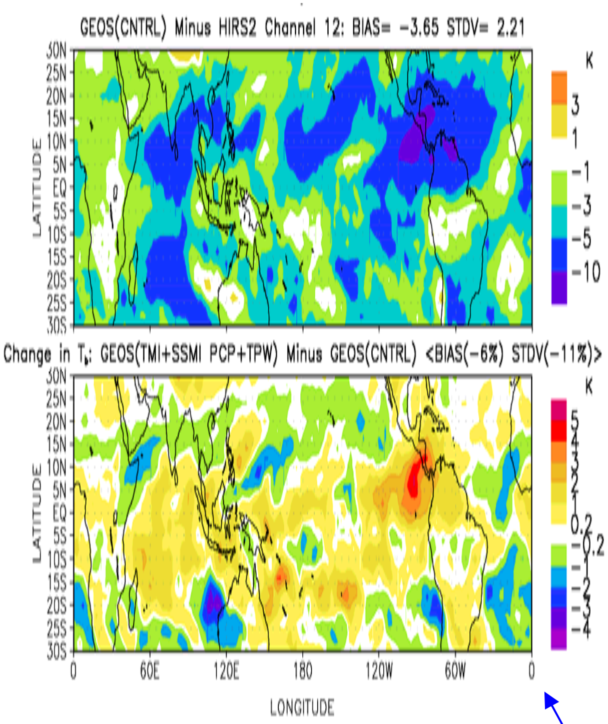
An improved atmospheric analysis dynamically consistent with observed rainfall variability

Impact on moisture, radiation, and forecast

Hou, Zhang, et al., 2004: *Monthly Weather Review*
Hou, Zhang, et al., 2001: *Bulletin of Amer. Meteoro. Soc.*

Improved upper-tropo. humidity
(verified against TOVS)

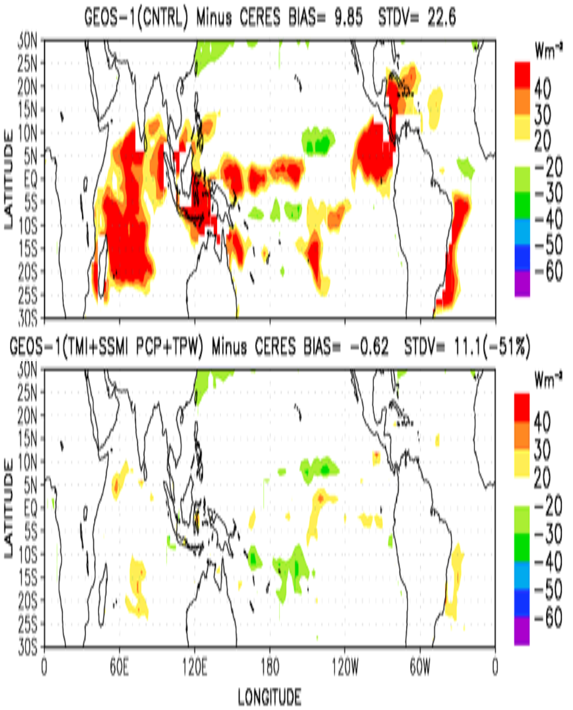
HIRS T_b for Channel 12



- * 6% reduction in bias
- * 11% reduction in error std dev

Improved TOA cloud/radiation
(verified against CERES)

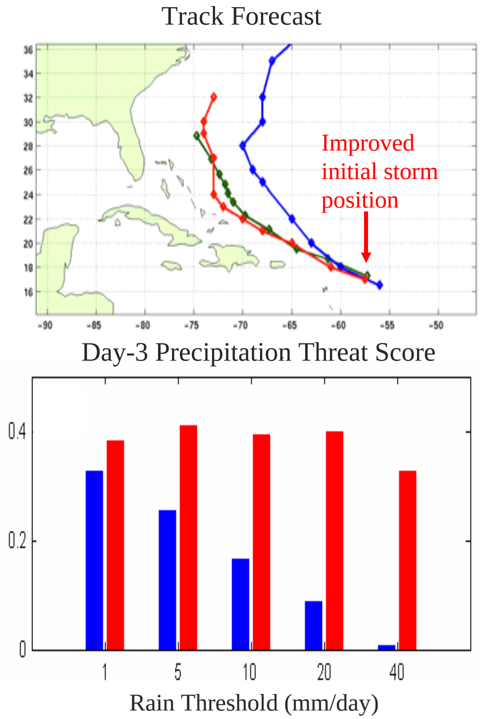
TOA IR cloud-radiative forcing



- * 94% reduction in bias
- * 51% reduction in error std dev

Improved hurricane forecast
(Hurricane Bonnie)

5-day forecast from 12UTC 8/20/98



Blue: Control forecast
Red: Forecast with TMI+SSM/I rainfall data in initial condition
Green: NOAA best track

Indirect evidence of improved large-scale circulation

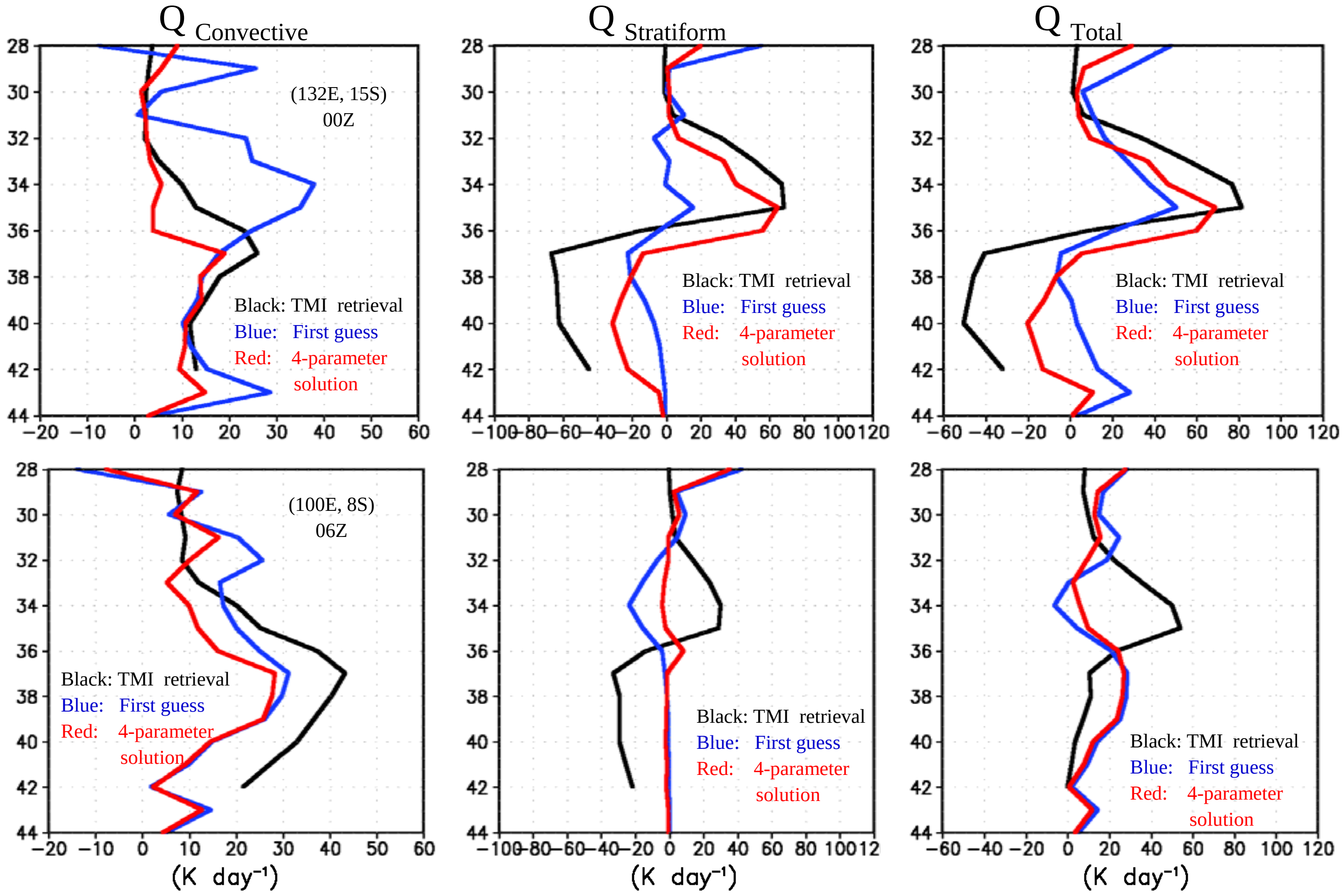
4-parameter minimization solutions: 04 July 2000

"Good match"

RMSE changes:
-55% for Q_c
-10% for Q_s
-12% for Q_T

"Poor match"

RMSE changes:
+3% for Q_c
-18% for Q_s
-13% for Q_T

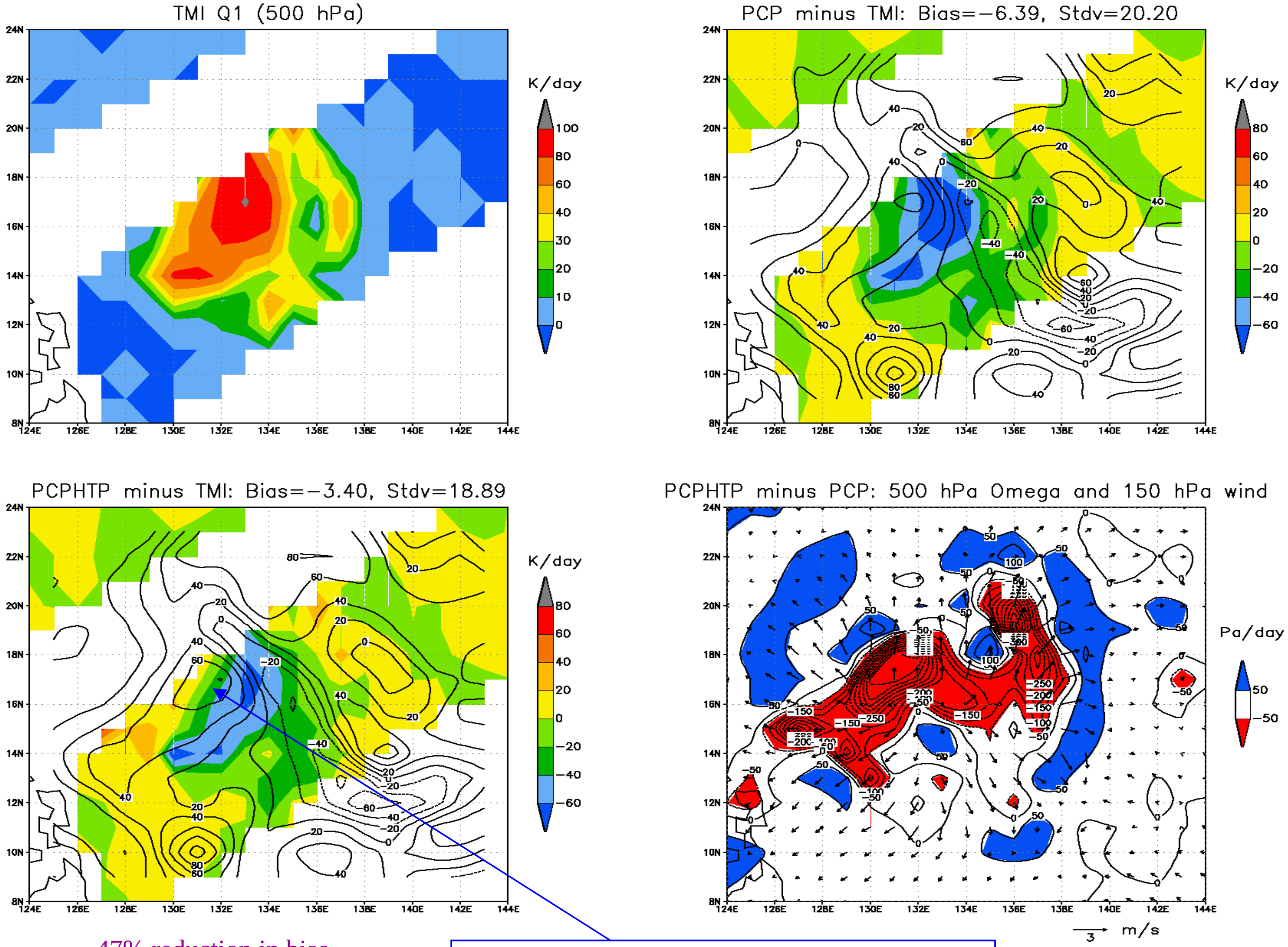


Control Variables

* Convective adjustment time (P1), * Critical RH for condensation (P2),

* Fraction of detrained liquid for anvil rain (P3), * Water/ice ratio in anvil rain (P4)

Impact on vertical motions and horizontal winds

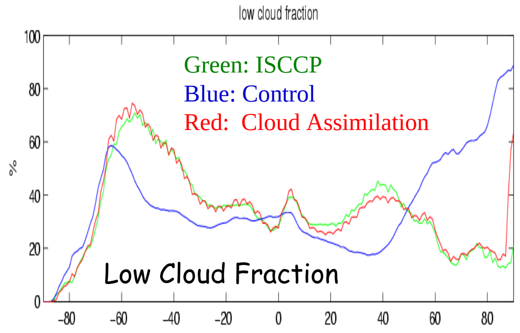


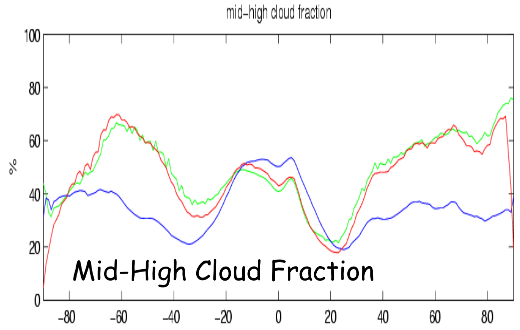
47% reduction in bias
6% reduction in err. std dev

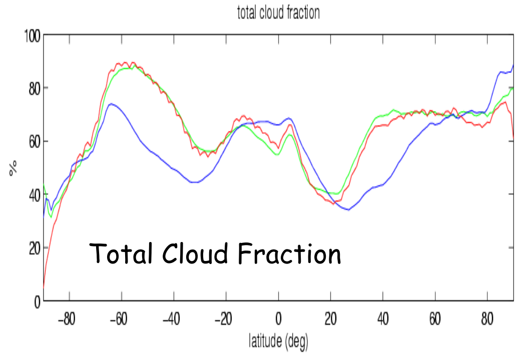
Contours show horizontal divergence in 10^{-6} s^{-1}

Assimilation of ISCCP cloud fraction/optical depth and SSM/I cloud LWP

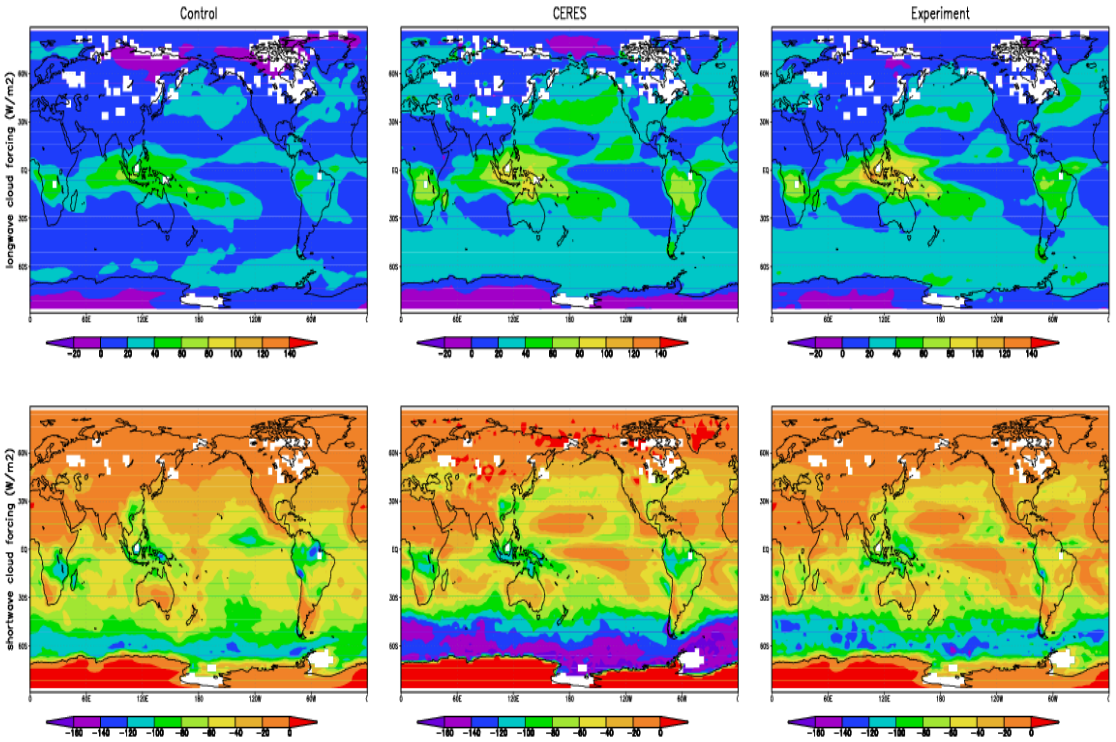
Improved Cloud Fraction







Improved TOA radiation verified against CERES



Control variables

- Critical RH* and the functional dependence of cloud fraction on RH (CCM3 physics generalized to a 2-parameter, S-shaped f(RH*, α))
- Reference LWC value in cloud water scheme for cloud liquid water
- Effective cloud overlap parameter for cloud optical depth

Summary and Plans

- Effective use of precipitation information in global data assimilation poses a special challenge because parameterization schemes can have significant errors, which must be addressed in the assimilation procedure in order to make full use of available observations. Research strategies should include:
  - Using the forecast model as a weak constraint
  - Understanding benefits of this approach relative to radiance assimilation using selected MW channels
  - Exploring ensemble DA techniques with the capability to update background error covariances and requiring no tangent linear approximations
  - Exploring cloud/precipitation assimilation via parameter estimation as a way to improve model physics by estimating empirical model parameters in the presence of *analyzed* rather than *simulated* atmospheric states
  - Using observation-constrained cloud-resolving models to identify deficiencies in moist physics schemes to guide selections of control variables for variational data assimilation

GPM

GPM Reference Concept

Improving weather, climate, and hydrological forecasts through more frequent and more accurate measurement of precipitation

Understand the Horizontal and Vertical Structure of Rainfall and Its Microphysica
Provide Training for Constellation Radiometers.

Provide Enough Sampling to Reduce Uncertainty in hort-term Rainfall ccumulations. Extend cientific and Societal pplications.

Core Spacecraft

- *Dual Frequency Rada*
- *Multi-frequency Radi*
- *H-IIA Launch*
- *TRMM-like Spacecra*
- *Non-Sun Synchronou*
- *~65° Inclination*
- *~400 km Altitude*
- *~5 km Horizontal Res*
- *250 m Vertical Resolu*

onstellation Satellites

- *Multiple Satellites with Microwave Radiometers*
- *Sampling Sufficient to Resolve the Diurnal Cycle*
- *Sun-Synchronous Polar and Other Orbits*
- *~600-900 km Altitudes*

Precipitation Validation Sites

- *Ground Truth and Calibration*
- *Cooperative International Research*

Global Precipitation Processing System

- *Capable of Producing Global Precipitation Data Products from Diverse Sensors and Sources*
- *Cooperative International Partnerships*

Submm Infrared Radiometer Ice Cloud Experiment

Need New Observations to study precipitation processes:

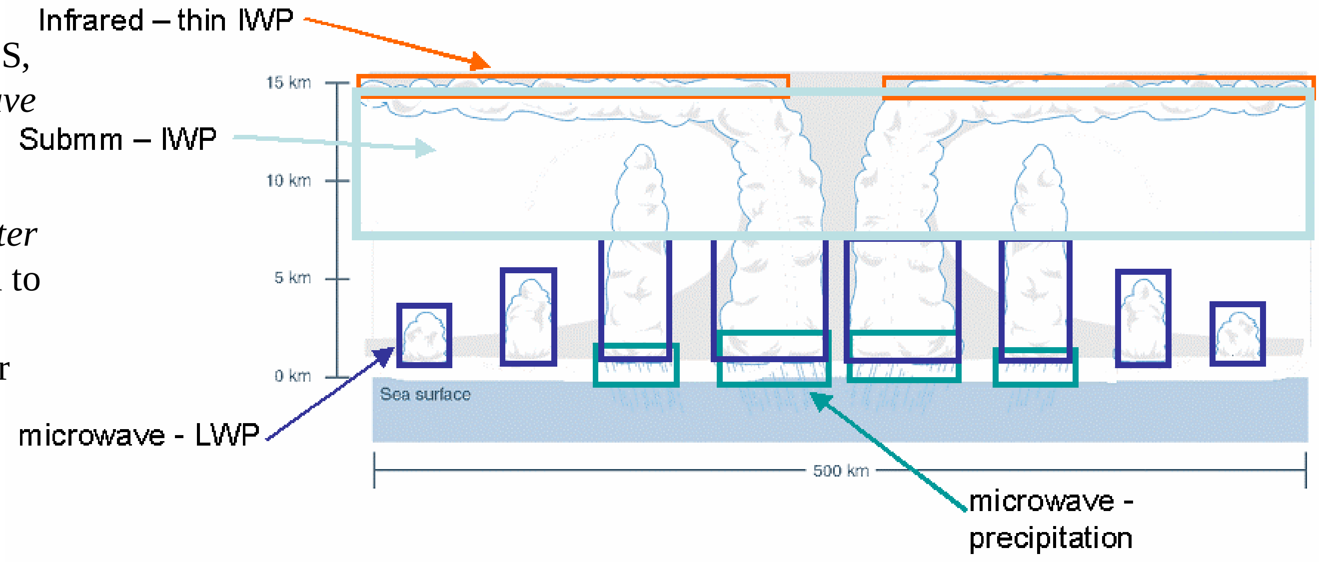
- Global observations of IWP and D_{me} are needed and important; but difficult to measure because of wide range of values

  IWP => 3 to 3000 g/m^2

  D_{me} => 20 to 800 μm.

- Best approach is to combine submillimeter and infrared observations; shown through sensitivity studies and aircraft observations
- Physics of measurements are well understood, as is retrieval algorithm
- Submm (~183 GHz – 880 GHz), with IR, Solar, and microwave scanning instruments provide need spectral coverage to measure cloud properties.

Submm observations with NPOESS, *CMIS* (*Conical Scanning Microwave Imager/Sounder)* measures precipitation (*VIIRS*) (*Visible/Infrared Imager/Radiometer Suite)* provides visible-wavelength to characterize cloud optical depth, SIRICE provides submillimeter for ice cloud properties



S. Ackerman et al.