Cloud Object Modeling and Observations for Climate Studies

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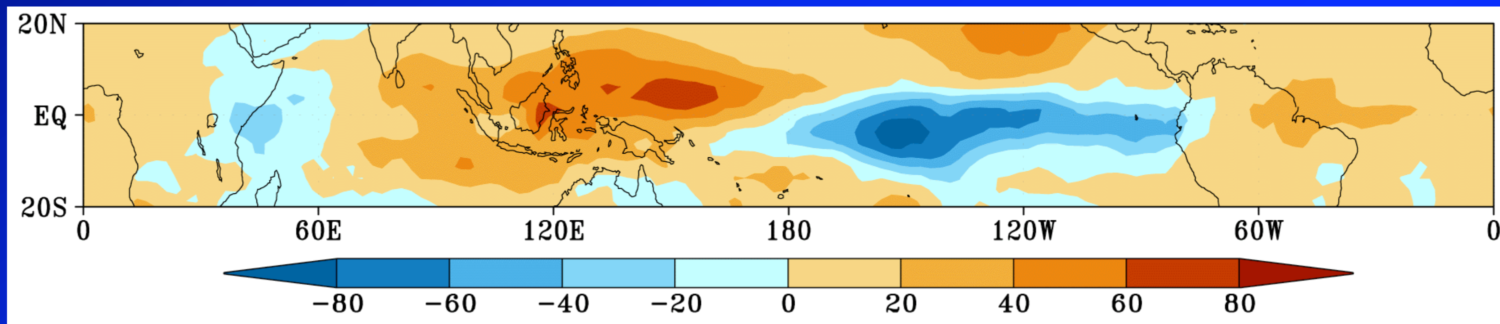
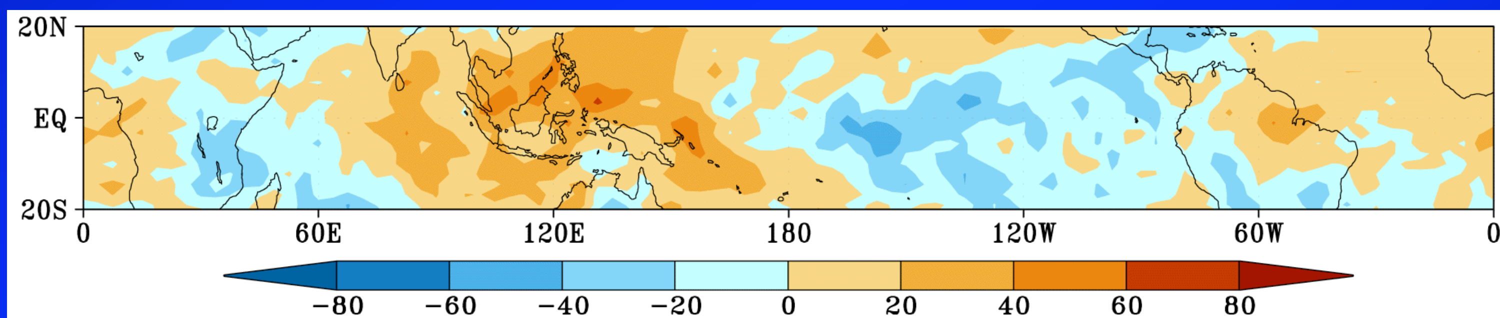
Jan/Feb 98 El Nino TOA LW Flux Anomalies

(relative to ERBE 1985-1989 average)

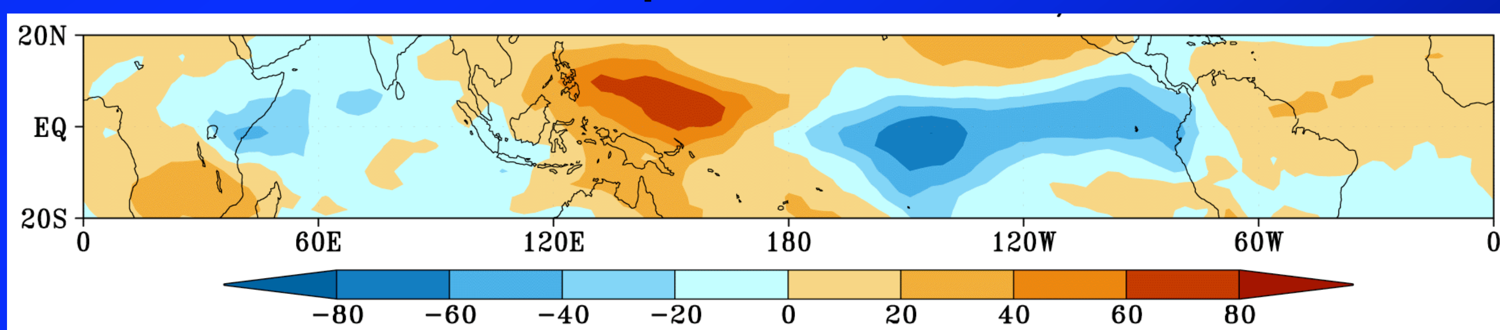
CERES ERBE-Like LW Flux Observations



NOAA GFDL Standard Climate Model

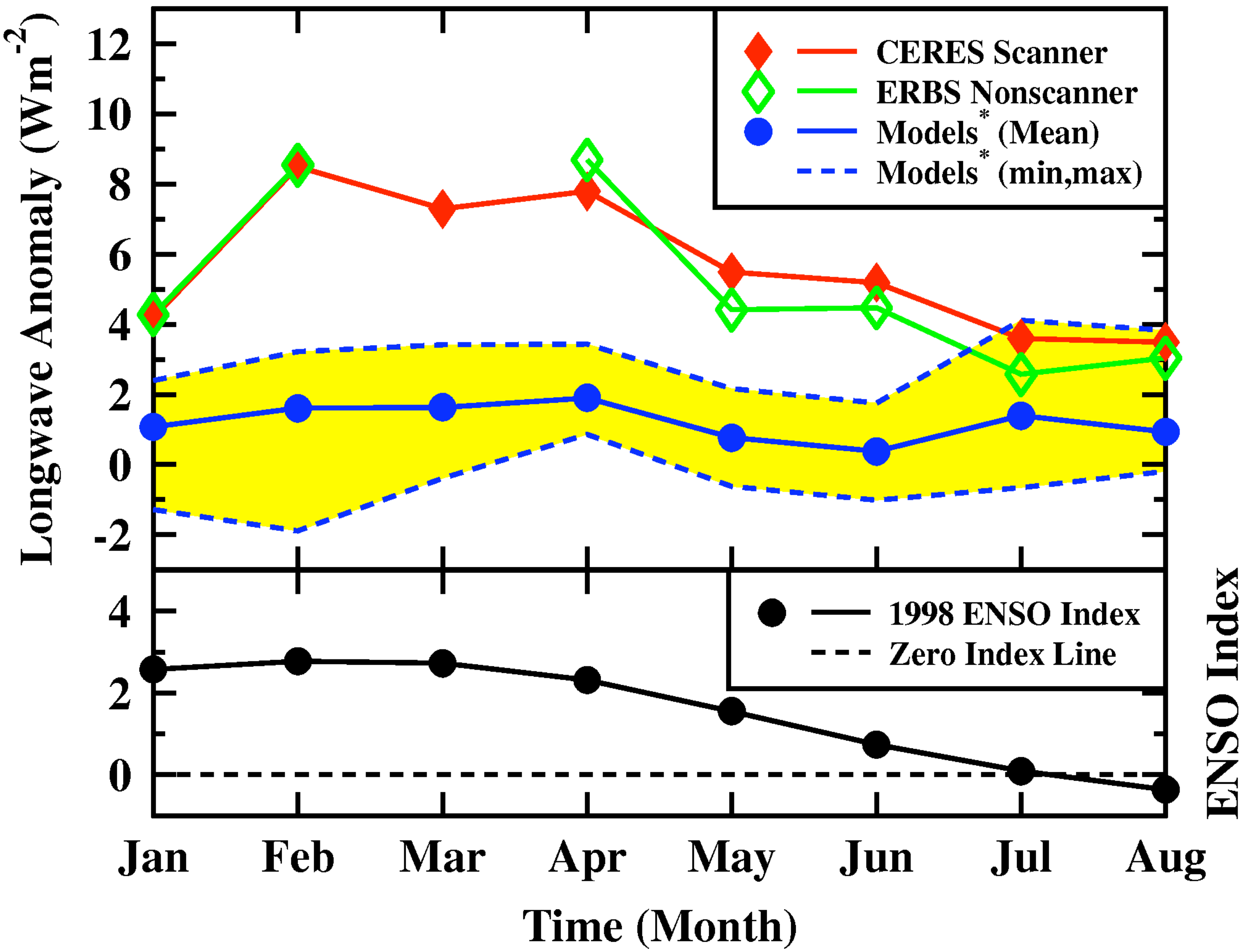


NOAA GFDL Experimental Prediction Model



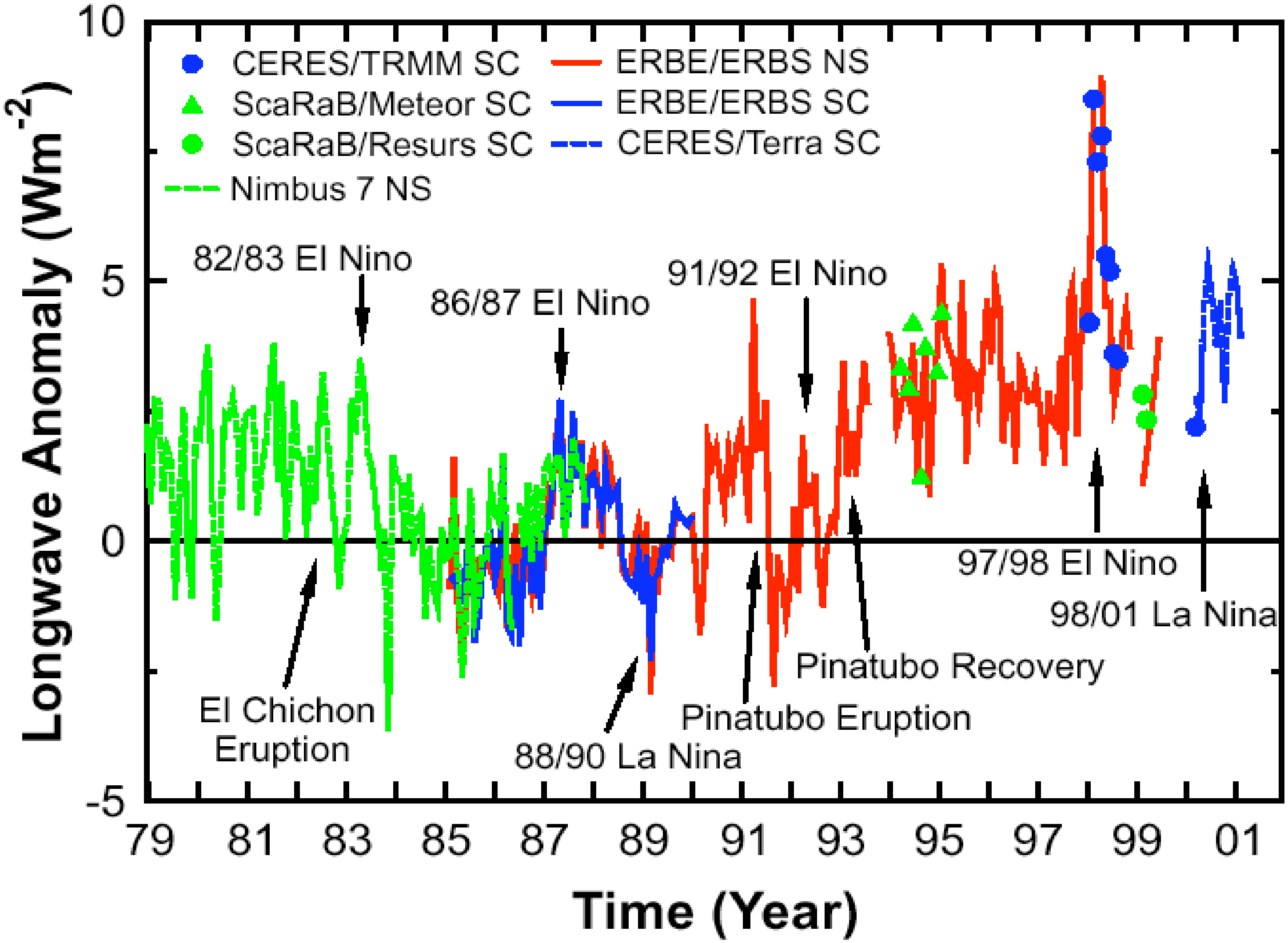
1998 El Nino Tropical Mean (20S - 20N) Longwave Flux Anomalies

(Anomalies Referenced to 1985 through 1989 Baseline)

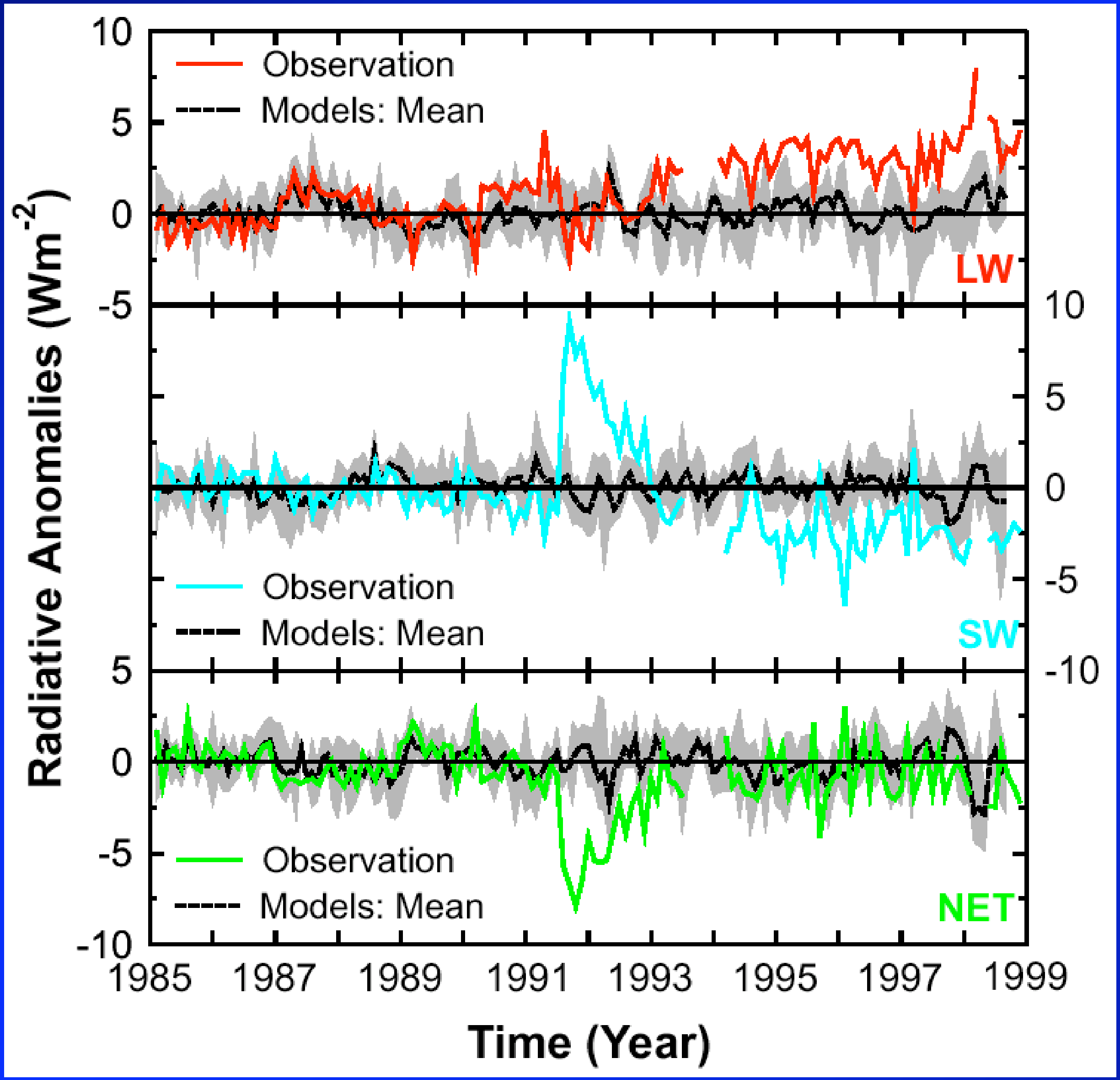


*5 Climate Models and NCEP Re-analysis; All used observed SSTs; Climate Models: NCAR-CSM (Kiehl) UKMO (Allan, Slingo), GFDL and GFDL-EP (Soden, Gordon), CSU (Randall)

An overlapping Earth radiation climate record: 22 years from Nimbus 7 to Terra.



Comparison of Observed Decadal Tropical Radiation Variation with Current Climate Models



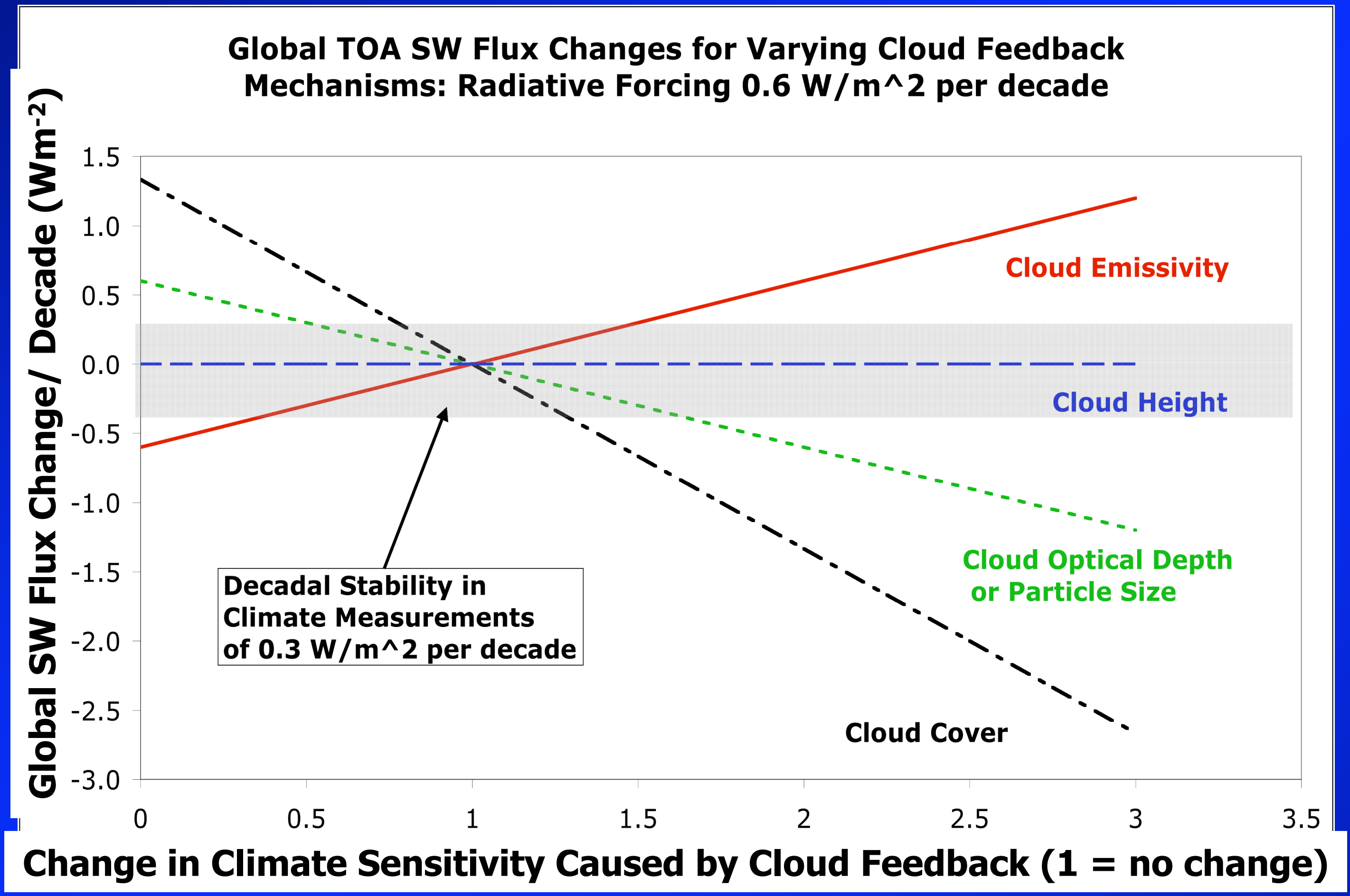
LW:
Emitted Thermal Fluxes

SW:
Reflected Solar Fluxes

Net:
Net Radiative Fluxes

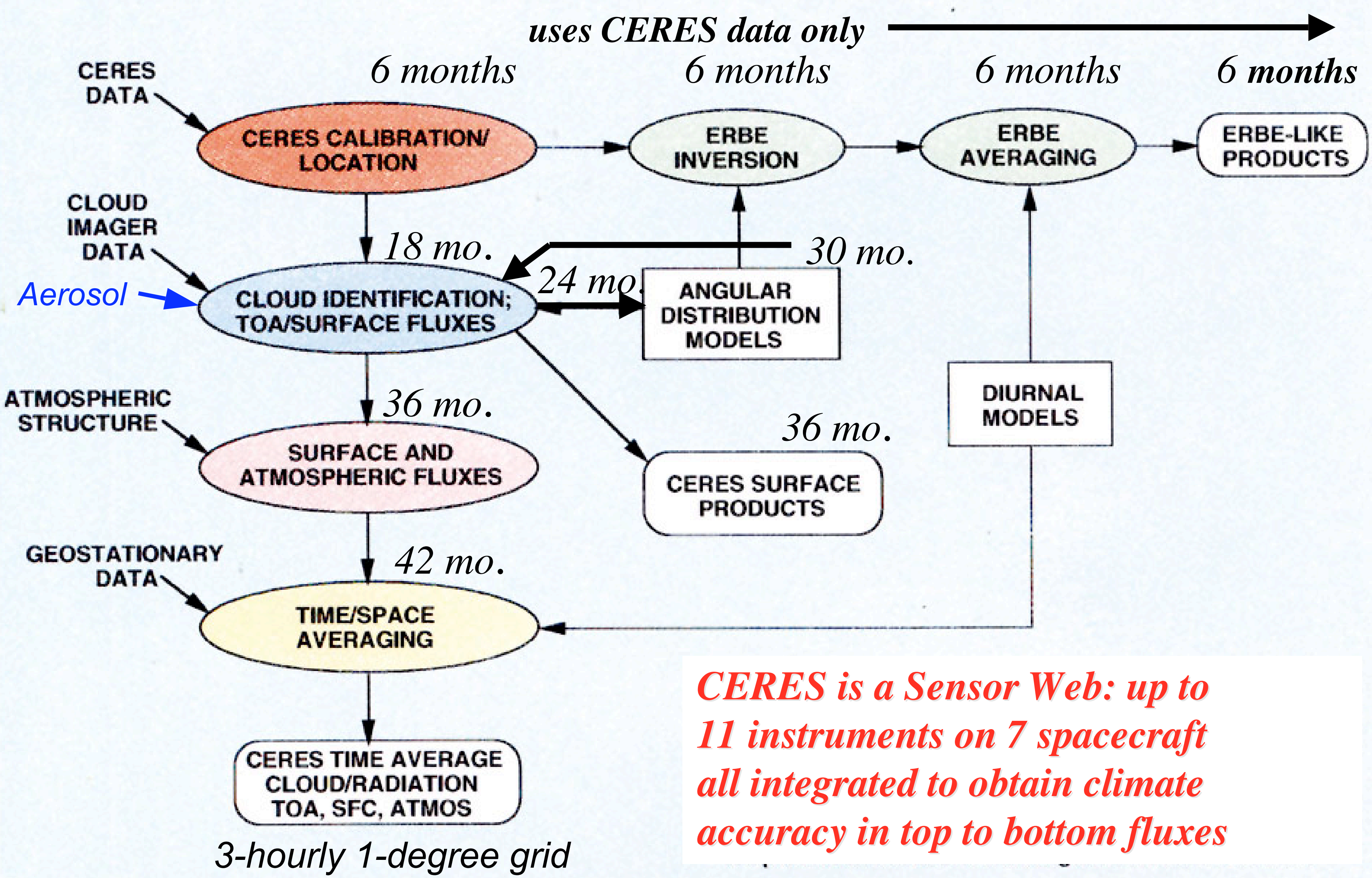
Models less variable than the observations:
- ***missing feedbacks?***
- ***missing forcings?***
- ***clouds physics?***

How accurate to constrain equilibrium global cloud feedback?



- Regional changes will be larger: but no regional "constraint" and global mean still must be accurately known for global feedback.
- UKMO ensemble climate noise for annual tropical mean SW and LW fluxes ~ 0.3 Wm^{-2}: this might be a reasonable lower limit on accuracy.

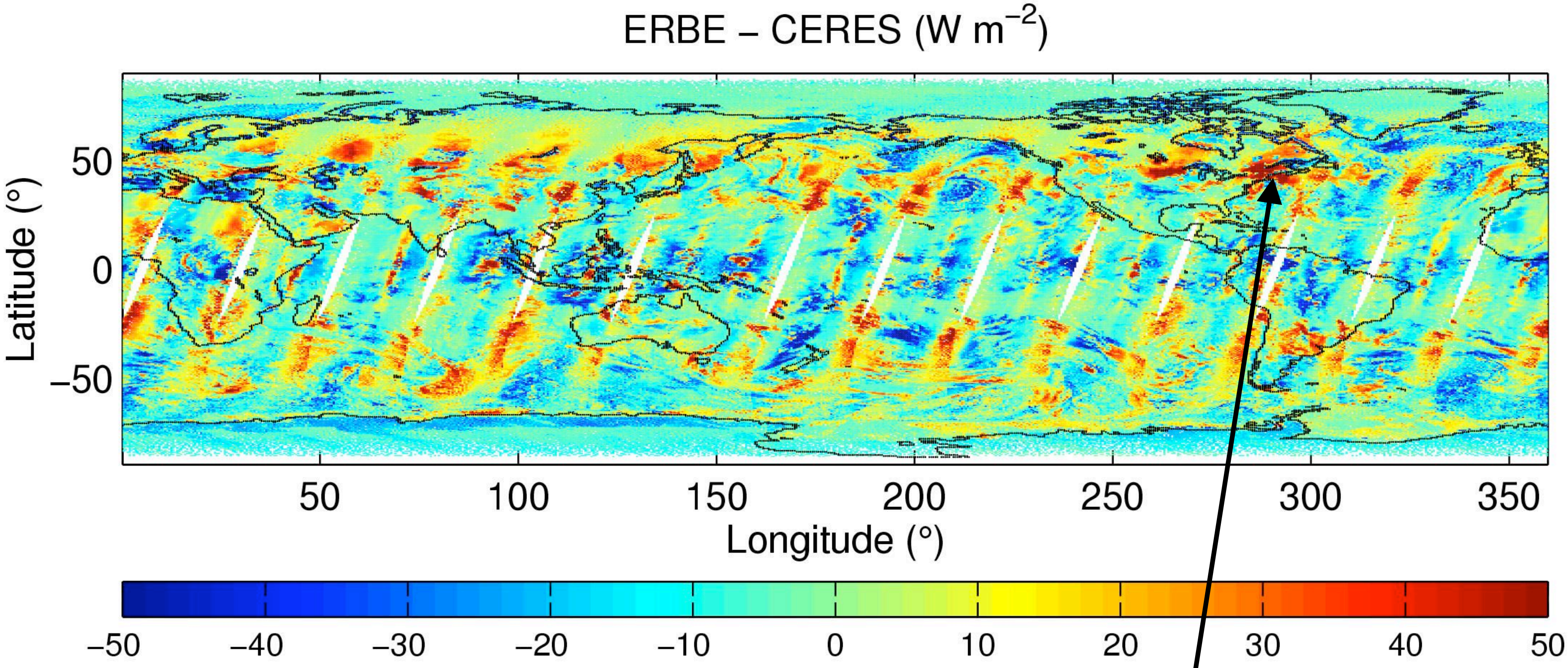
CERES DATA PROCESSING FLOW



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

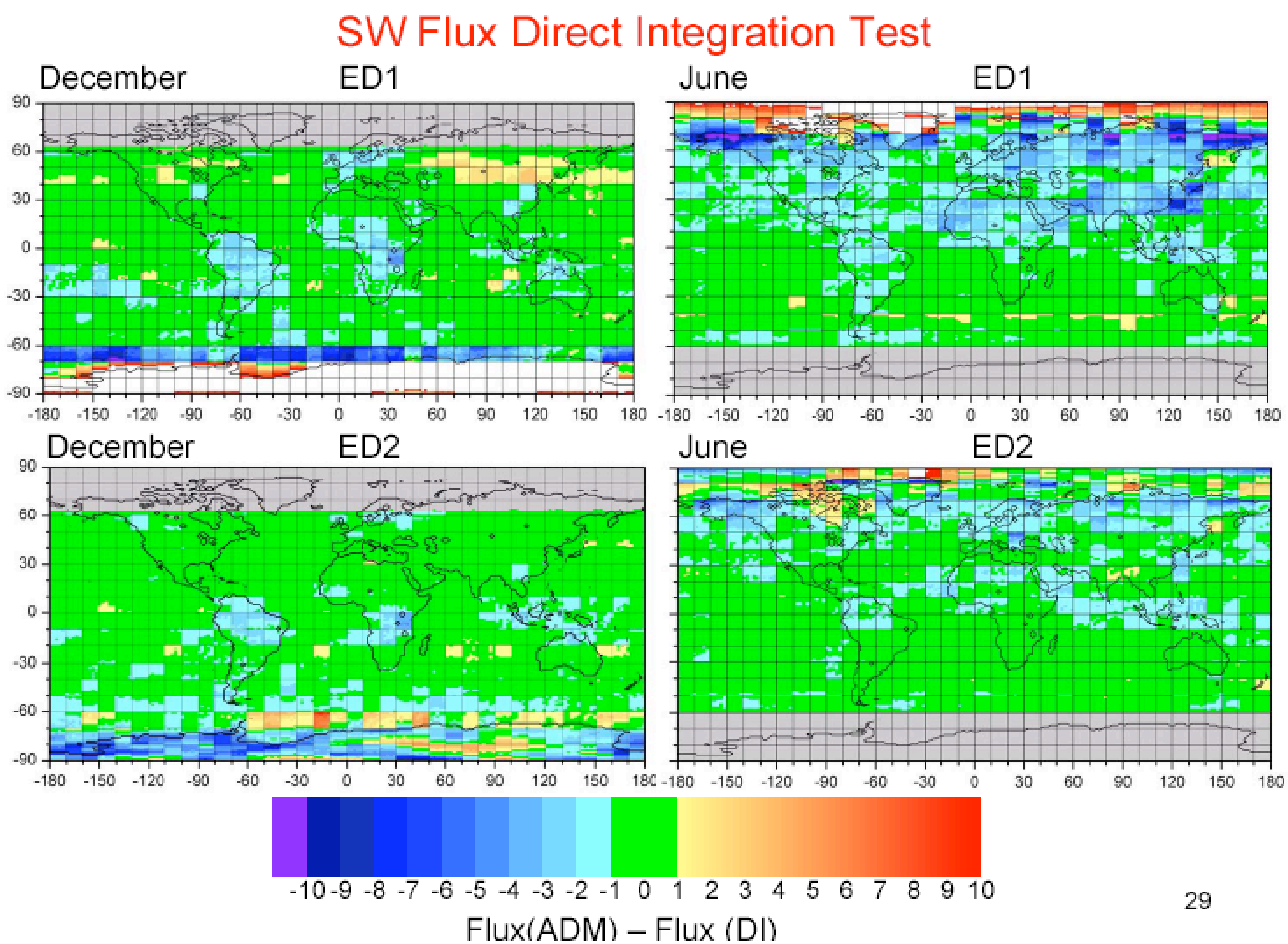
New CERES ADMs greatly improve instantaneous fluxes

Key to constraining more accurate surface fluxes
Key to accurate cloud fluxes by cloud type
Key to accurate matched satellite/surface fluxes for aerosol absorption



CERES TOA instantaneous shortwave fluxes differ from ERBE by +/- 50 Wm^{-2} with a strong dependence on scene type & viewing angle

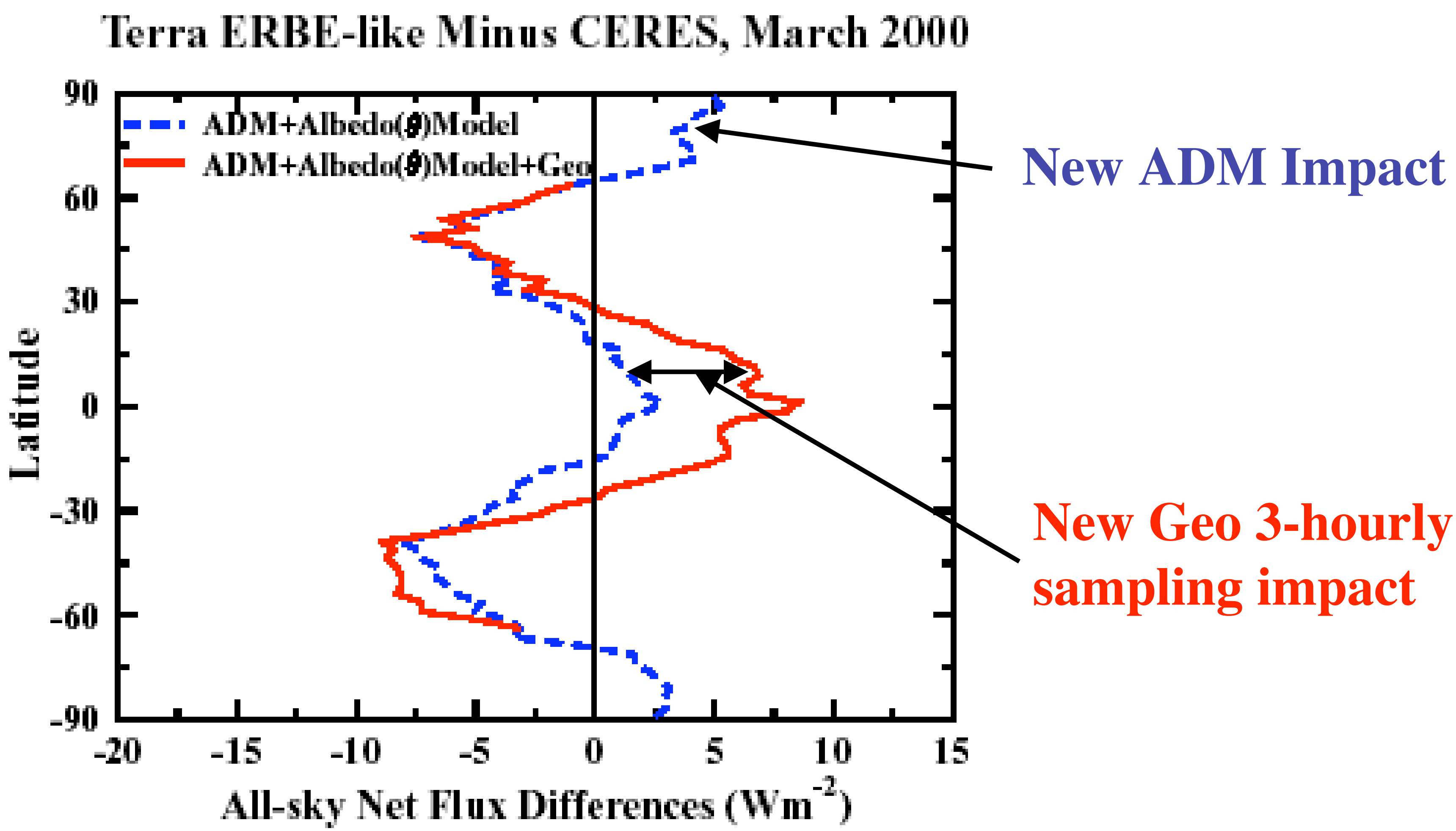
Use CERES Rotating Scanner hemispheric scans over two years to verify climate accuracy (large ensemble biases in new angular models: direct hemispheric radiance integration over 2 years provides truth. Factor of 2 to 10 improvement relative to ERBE. Edition 2 (ED2) are Terra ADMs used in new Edition 2 CERES Data Products



ED1 used TRMM ADMs and theory for snow/ice surfaces

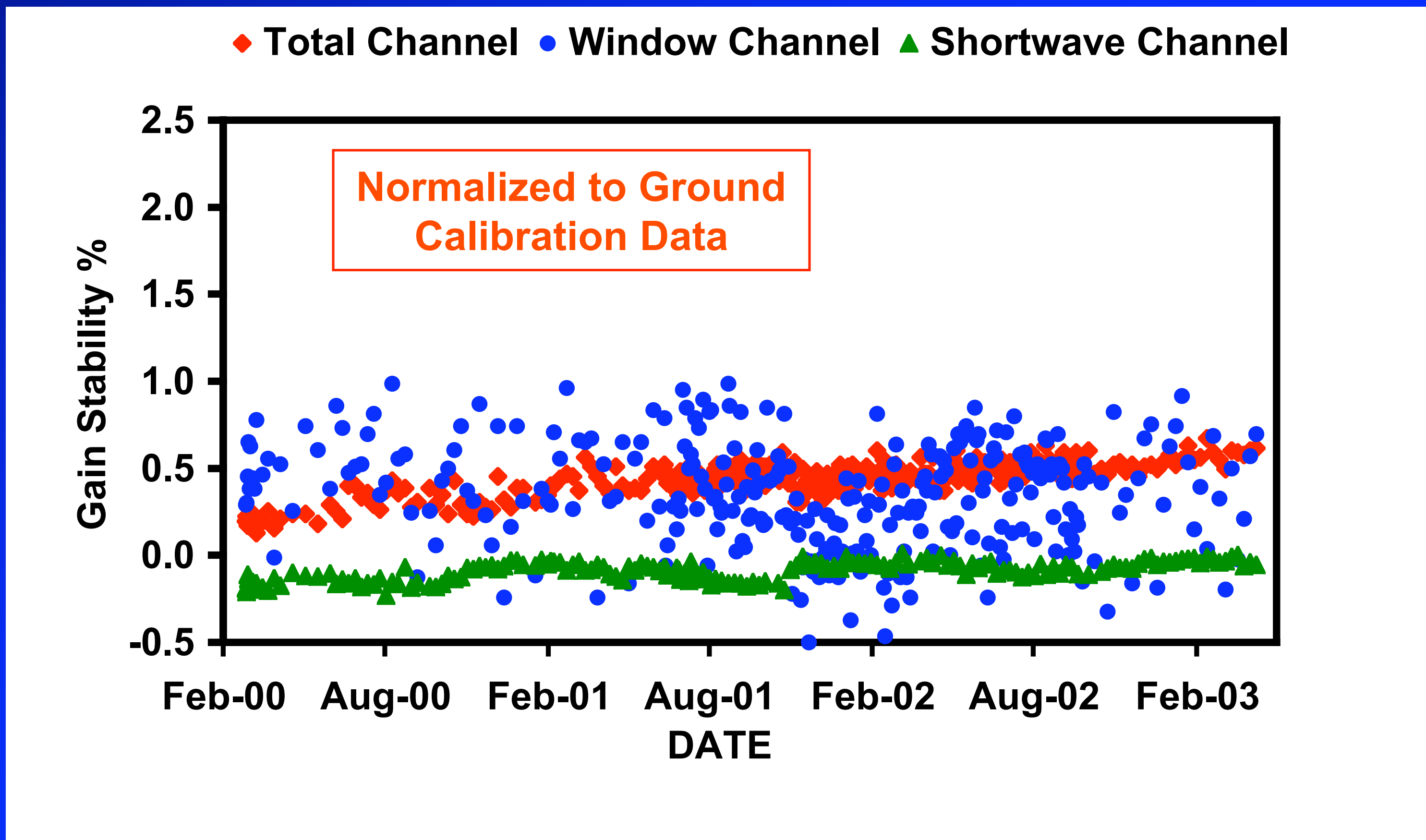
ED2 uses Terra ADMs and Terra observed snow/ice ADMs

Differences of new CERES SW fluxes from ERBE-Like zonal means for March 2000. Differences up to 8 Wm^{-2}.
Will impact equator to pole transport, surface flux constraints with ARGO on ocean mixing processes, climate model validation



Terra/Flight Model 1
Lifetime Radiometric Stability

Determined with the Internal Calibration Module

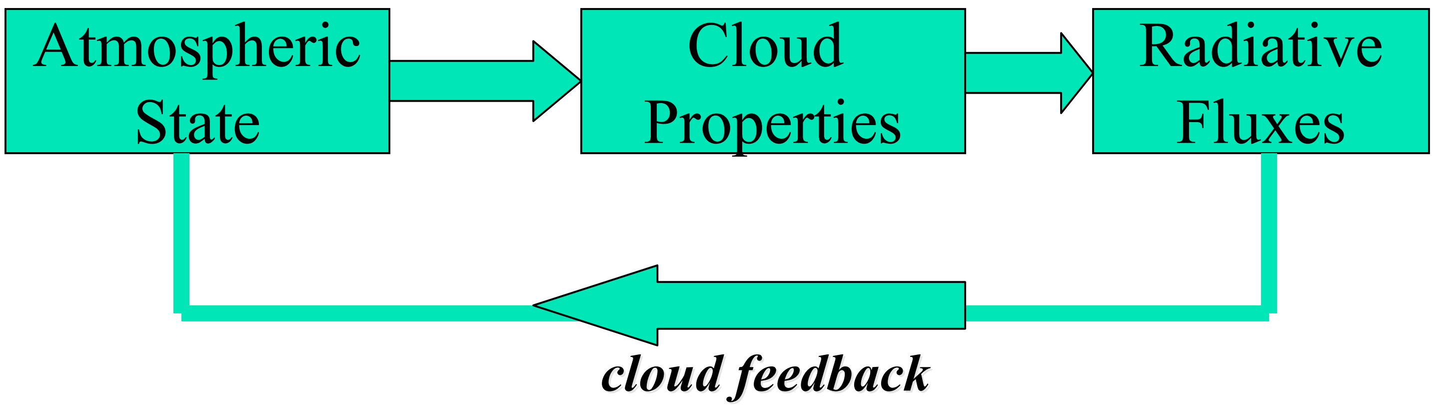


Absolute Calibration:
0.5% LW
1% SW
1% Window

Stability Goal: better than 0.5% per 5 years

While changes accounted for in CERES processing, ideal situation is change < 0.1% per mission.

Motivation



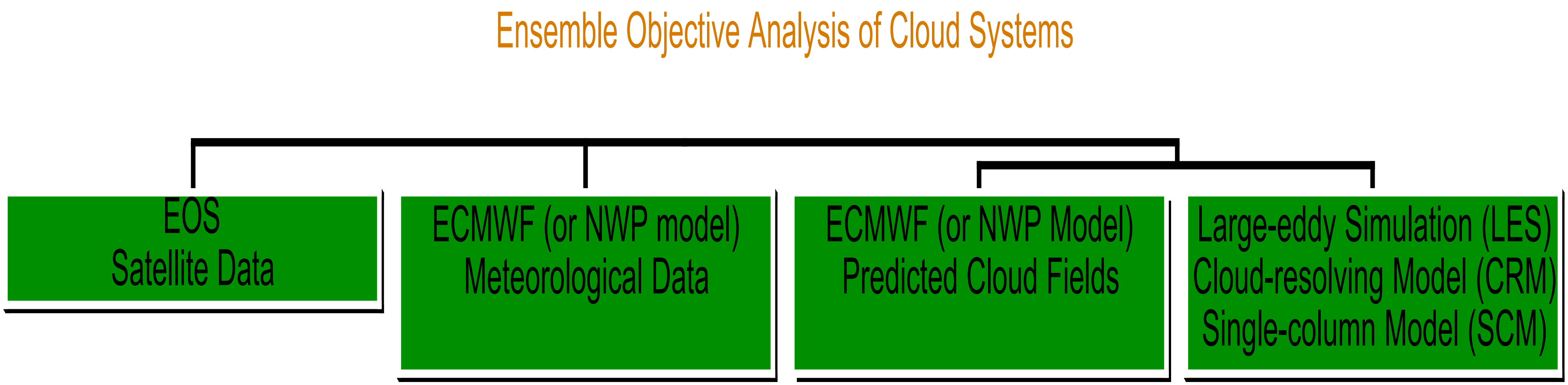
- Nonlinearity of cloud processes requiring observations on all relevant modeling scales (in space and in time)
- Existing methods of cloud model evaluation are incomplete

Traditional methods for cloud model evaluation

- **Regional field experiments (DOE ARM, TOGA-COARE, ASTEX, GATE, etc.)**
  - Detailed measurements of cloud properties and atmospheric states
  - Limited cases at selected locations for a short period
  - Extrapolate limited cases to global conditions
  - Cloud models may perform well for certain cloud-system types, but not all major types

- **Global and regional monthly mean data (CERES, ISSCP, ERBE, etc.)**
  - Large regions and many different cloud-system types
  - Measure only a few variables
  - Impossible to unscramble the nonlinear cloud feedback processes, due to spatial and temporal averaging
  - Cloud models may perform well for the wrong reasons, due to cancellations of errors in GCMs

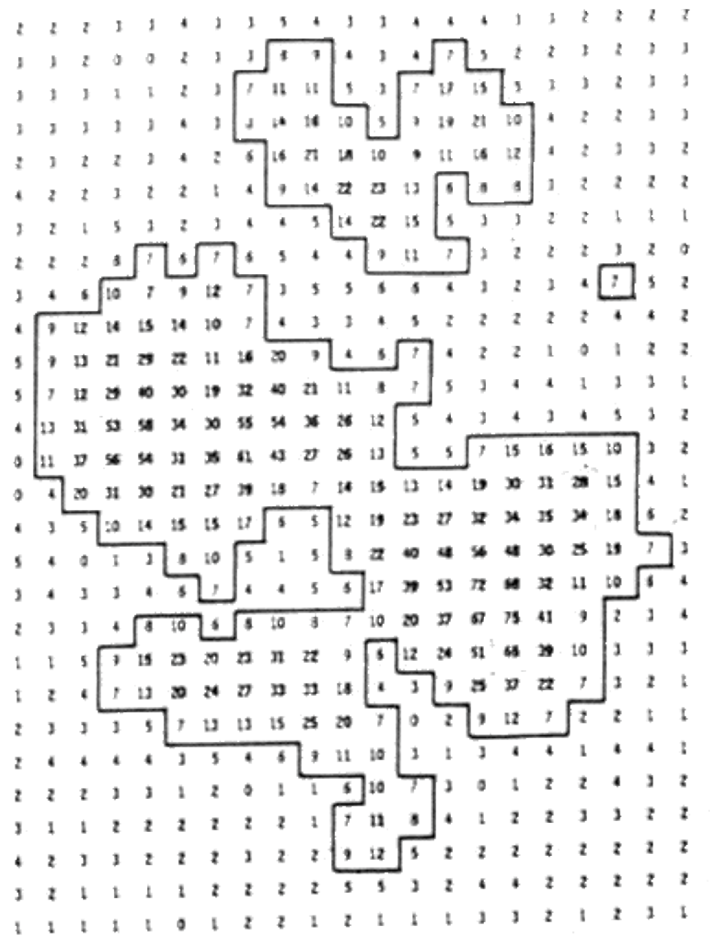
A new method of satellite data analysis for cloud model evaluation



- Analyze the statistics of subgrid characteristics of cloud systems, *not* the mean
- Matching the CERES SSF (Single Scanner Footprint …) cloud and radiative data with ECMWF meteorological data (T, q, u, v and advective tendencies)
- New CERES angular models allow accurate fluxes by cloud type
- Cloud Resolving Model simulations driven by ECMWF advective tendencies
- Evaluate the ECMWF parameterizations using predicted cloud fields

Satellite data analysis method

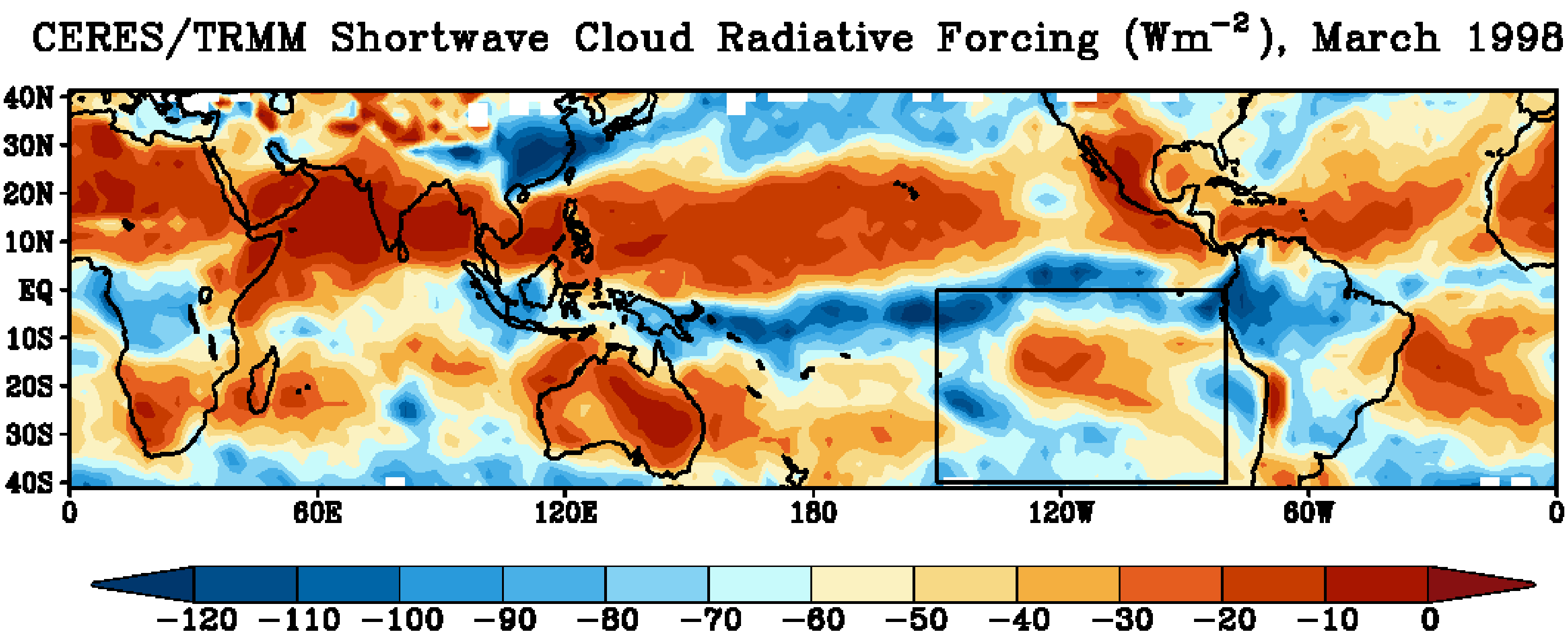
- Define a cloud system as a contiguous region of the Earth with a **single dominant** cloud type (e.g. stratocumulus, stratus, and deep convection)
- Determine the shapes and sizes of the cloud systems by the satellite data and by the cloud property selection criteria (e.g. Wielicki and Welch 1986)



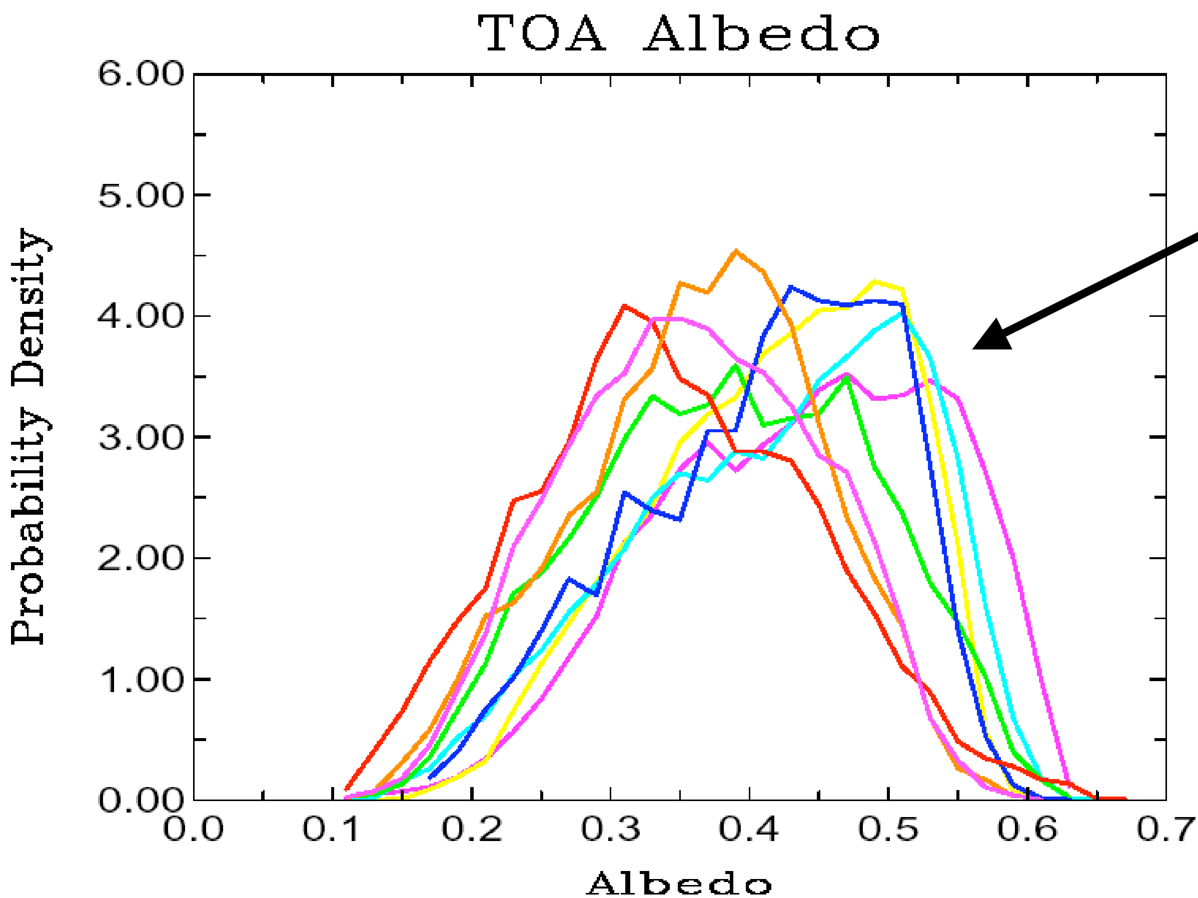
Cloud system selection criteria

- Tropical deep convective system
  - Z > 10 km, τ > 10, 25° S ~ 25° N, overcast CERES fovs
- Trade/shallow cumulus
  - Z < 3 km, cloud cover: 0.1 – 0.4, 40° S ~ 40° N
- Transition stratocumulus
  - Z < 3 km, cloud cover: 0.4 – 0.99, 40° S ~ 40° N
- Stratocumulus
  - Z < 3 km, cloud cover: 0.99 – 1.0, 40° S ~ 40° N

Boundary Layer Cloud Object Region, Southeast Pacific, March 1998

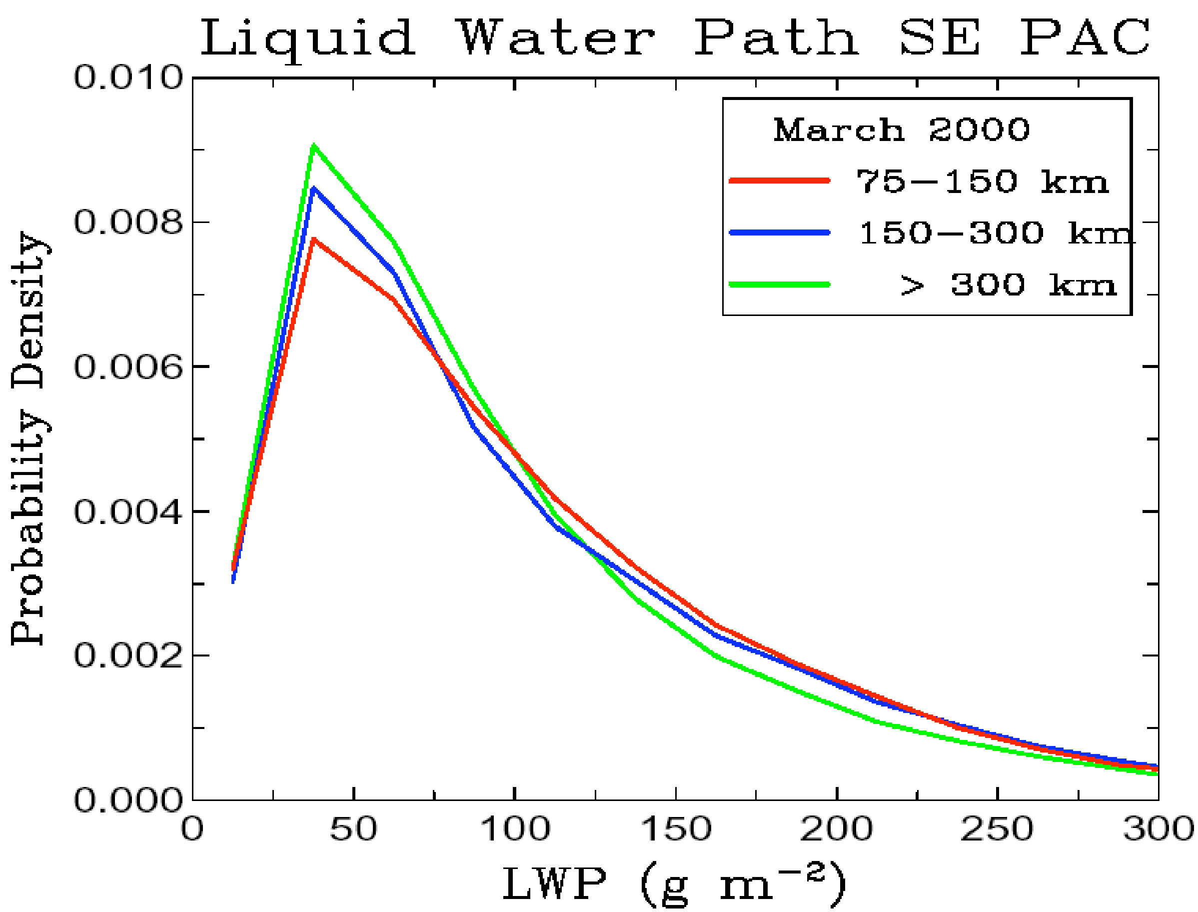


Overcast Boundary Layer: Observed CERES Cloud Object Pdfs for March, 1998



Sample individual pdfs for just 8 of the stratus cloud systems (CERES SSF TOA albedo)

Overcast Boundary Layer: Observed CERES LWP Pdfs for March, 2000

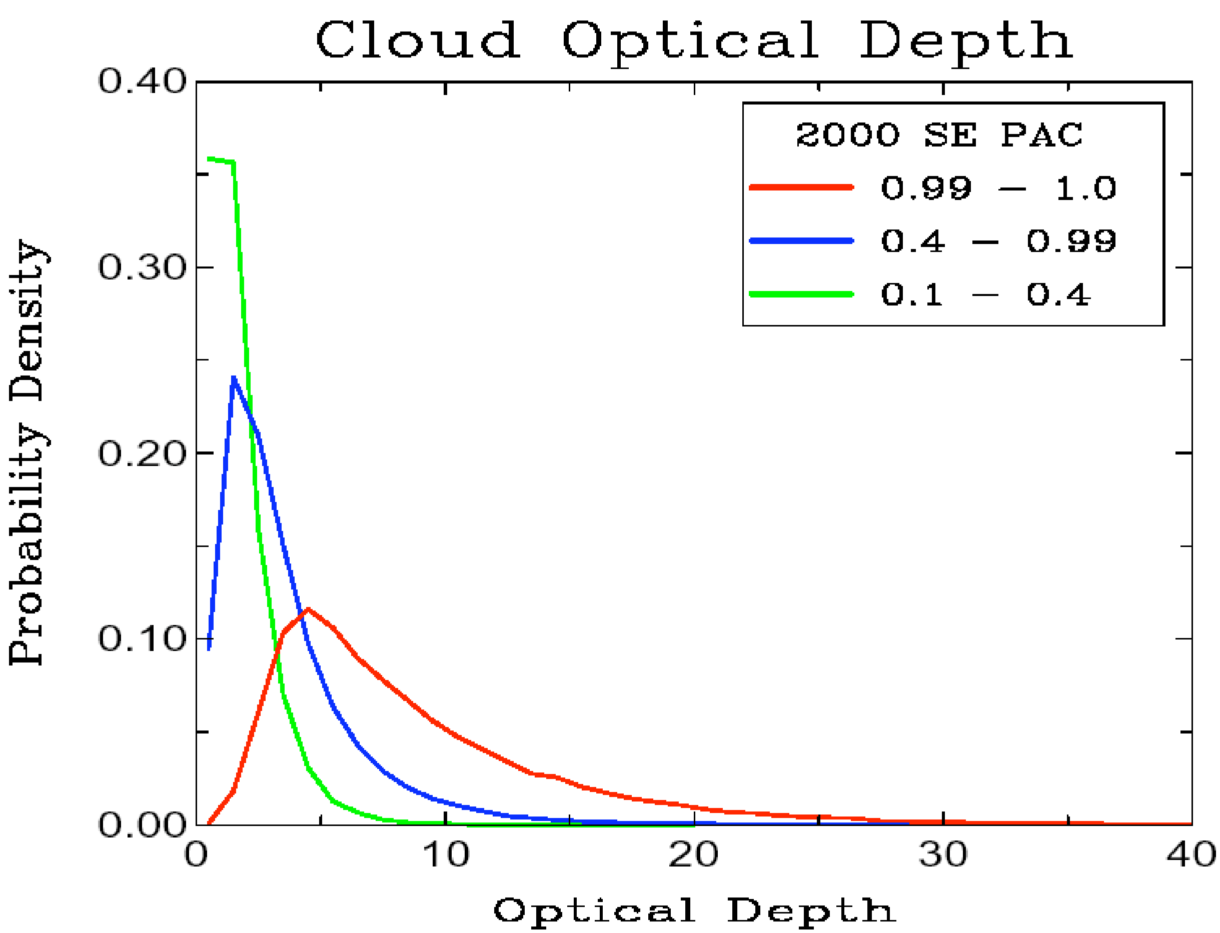


Stratus:
Cloud Fraction = 1
Zcld < 3 km
Water phase
LWP from tau(vis),reff

CERES SSF cloud
retrieved using VIRS imager

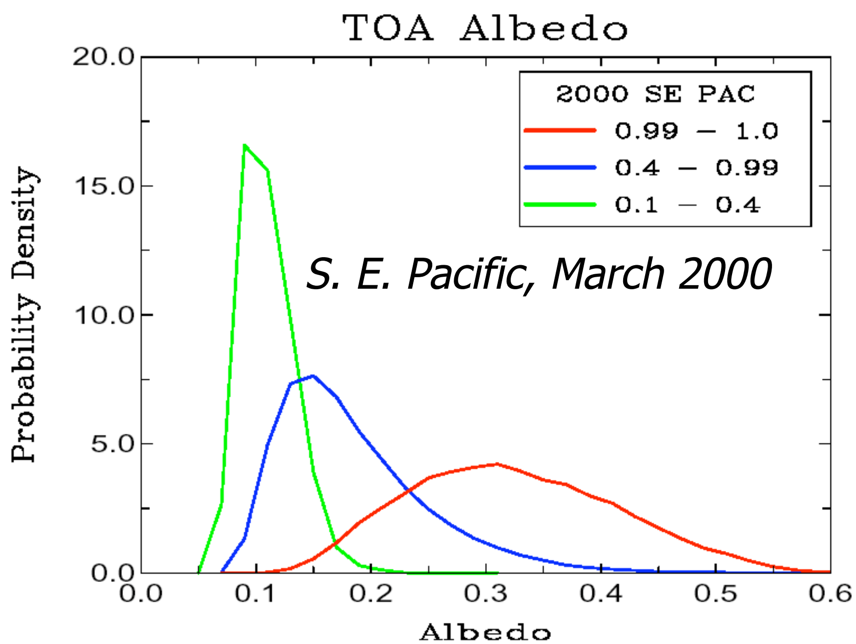
Surprisingly, larger stratus decks do not have larger LWP amounts

Boundary Layer: Observed CERES Visible Optical Depth Pdfs for March, 2000

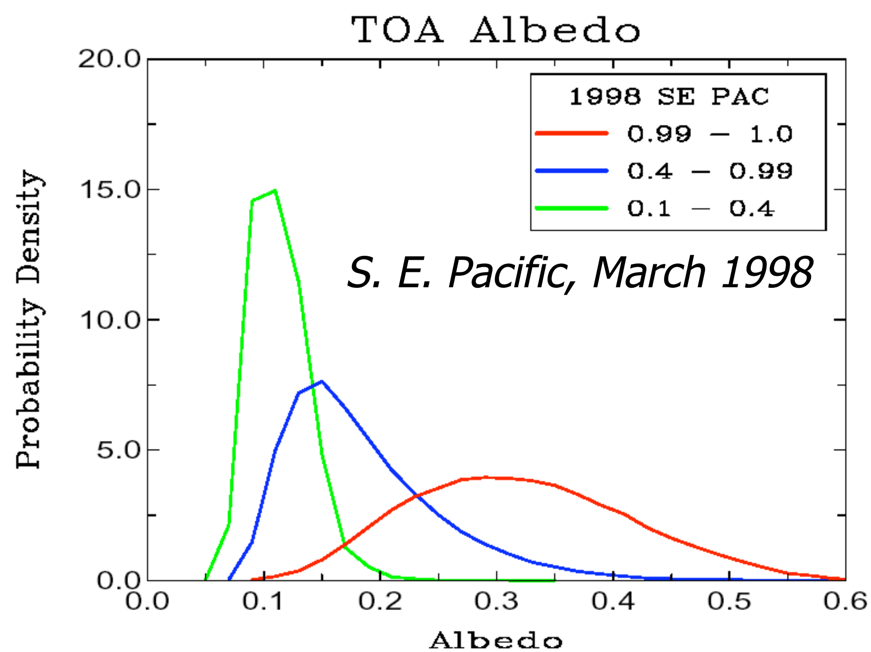


Similar to Landsat Pdfs but from a large ensemble of boundary layer cloud systems using 10 to 20km fov spatial scale: skewed distributions remain....

Boundary Layer: Observed CERES TOA Albedo Pdfs for March, 2000 vs March, 1998

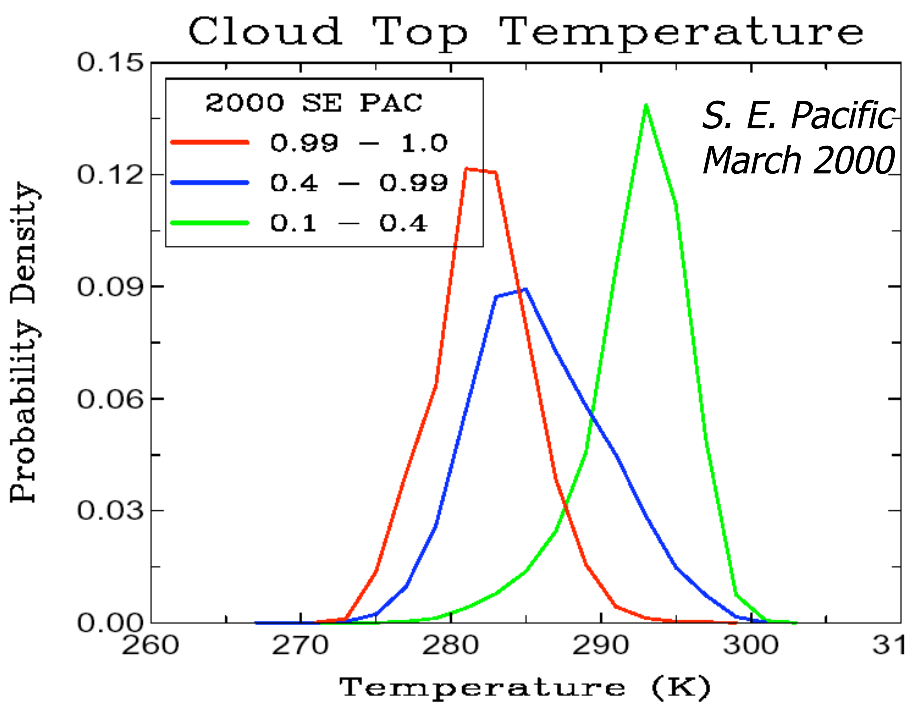


No apparent difference in the S.E. Pacific, even though the Walker Cell strength reduced, Hadley cell strengthened...

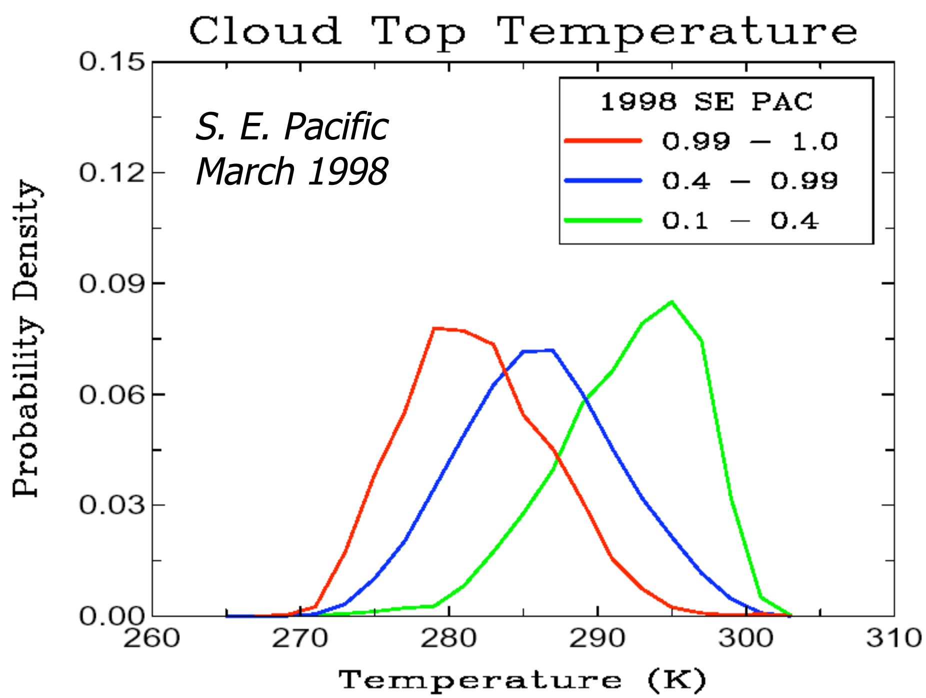


Suggests stable properties by cloud type: next step to quantify how stable....

Boundary Layer: Observed CERES Cloud Top Temperature Pdfs for March, 2000 vs March, 1998



March 2000: Colder SST (La Nina) & Colder Cloud Top Temperature, but Narrower Frequency Distribution

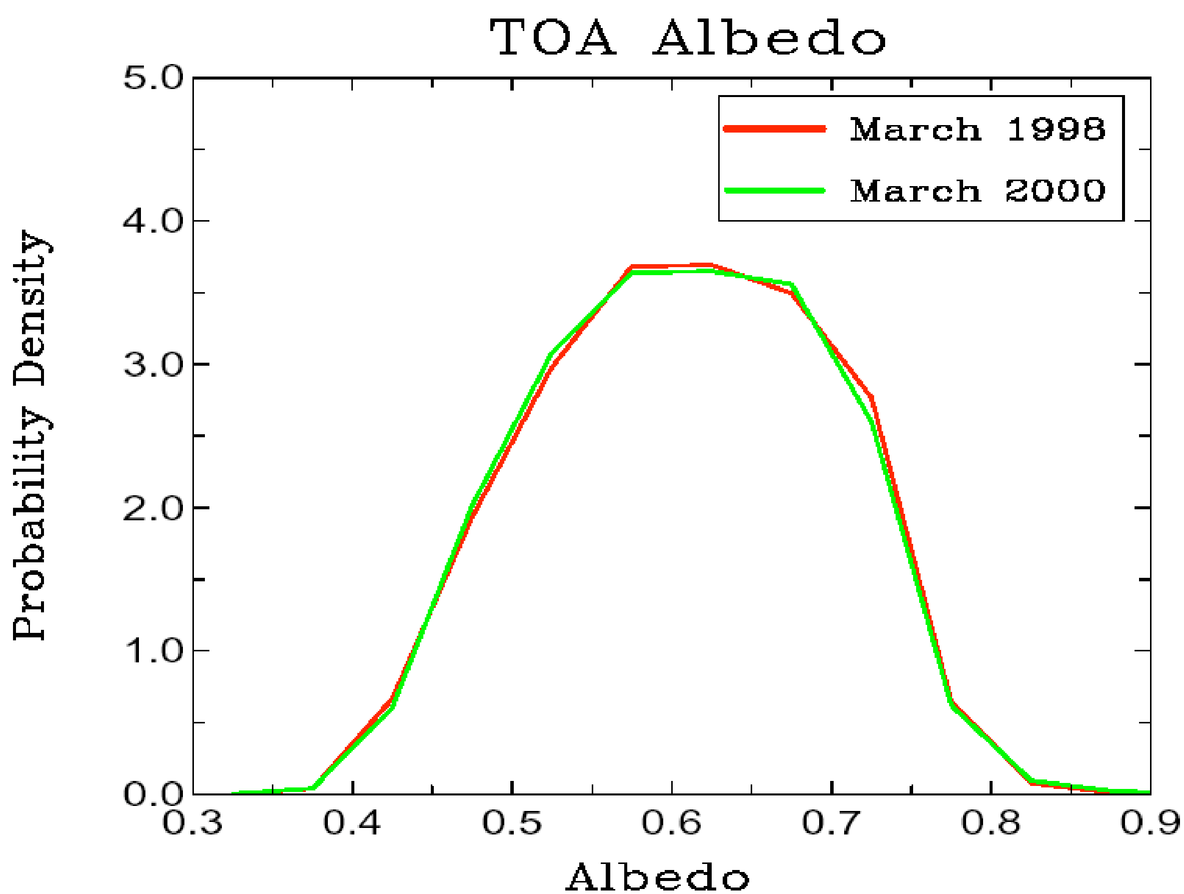


CERES Tropical Deep Convective Systems

- March 1998 and March 2000 CERES/TRMM data
- 29 cases of tropical convective systems with diameters greater than 300 km for March 1998: *Zcld>10km, tau>10, ice phase, overcast*
- Parameters analyzed from CERES SSF data product:

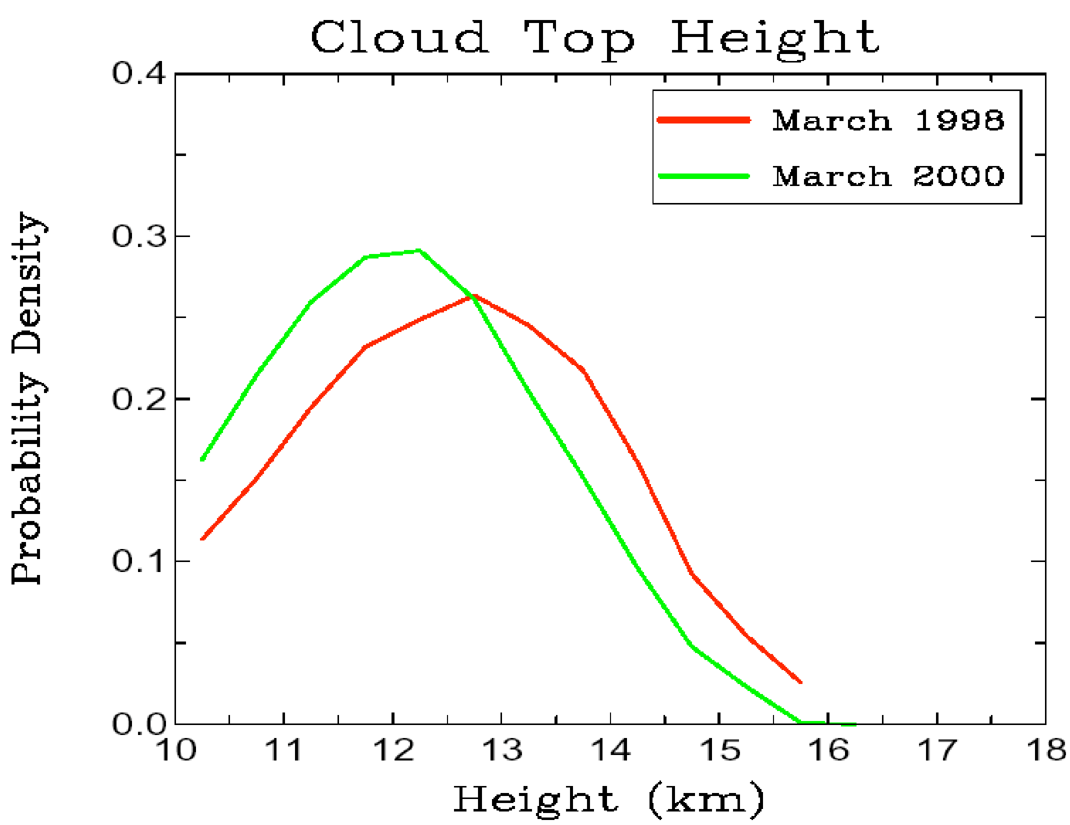
Cloud optical depth	Cloud top height
Cloud water path	Cloud top pressure
Ice diameter	Cloud top temperature
TOA SW flux	Liquid water path
TOA albedo	Water droplet radius
OLR, Emissivity	Cloud amount

Large Deep Convective Systems:
Zcld>10km, tau>10, Cf=1, Diameter > 300km
CERES TOA Albedo



Across the tropics (25N to 25S) large convective systems appear invariant between the 98 El Nino and 2000 La Nina phases of ENSO for TOA albedo pdf.

Large Deep Convective Systems:
Zcld>10km, tau>10, Cf=1, Diameter > 300km
CERES Cloud Height using MODIS

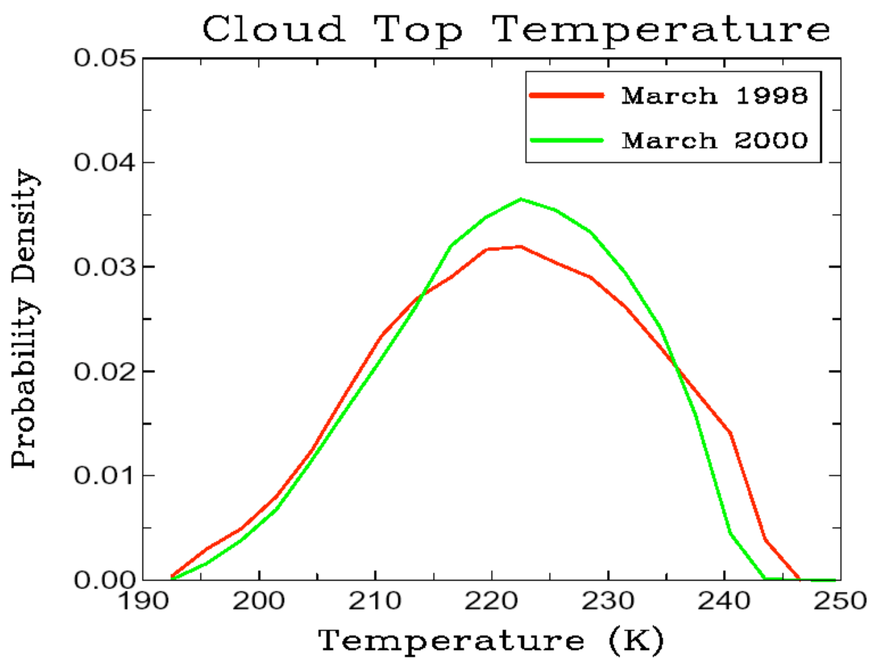


Across the tropics
(25N to 25S)
large convective
systems, however
appear to increase
cloud height by about
almost 1 km
during the 1998 El Nino

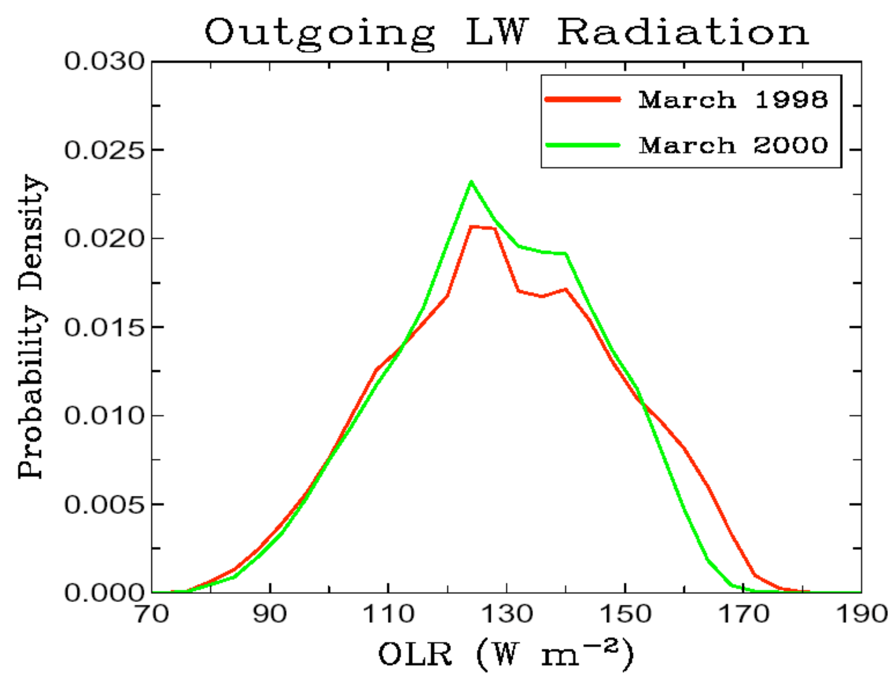
Large Deep Convective Systems:

Zcld >10km, τ >10, Cf =1, Diameter > 300km

CERES TOA LW Flux and Cloud Eff Temp using MODIS



Cloud height changes but much smaller cloud temperature and TOA LW flux changes: Hartmann hypothesis on radiative control of tropics?



Or just the dynamics of these large convective complexes?

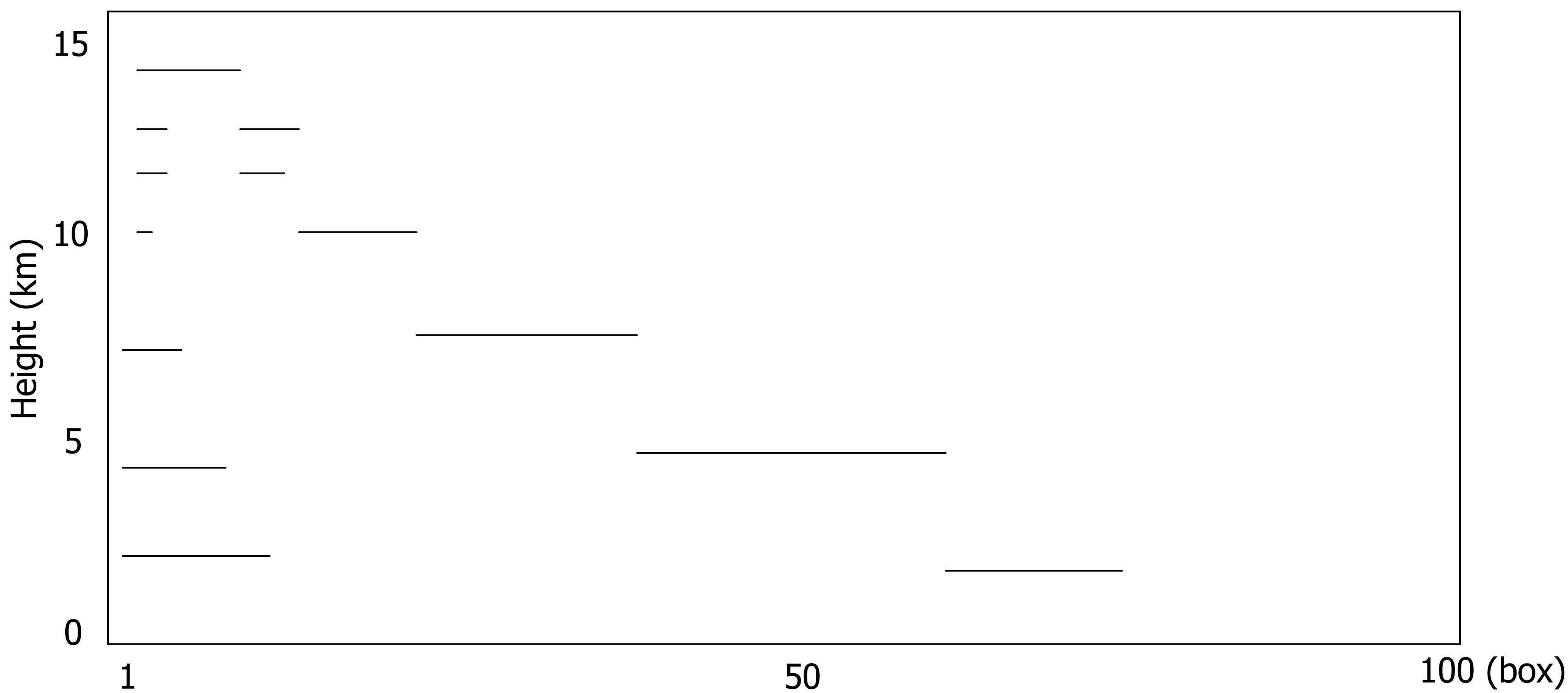
So what do models predict?

Analysis of ECMWF predicted cloud fields

- ECMWF meteorological data
  - 0.5° x 0.5° gridded, six hourly analysis from data assimilation
  - temperature, specific humidity, horizontal wind components
- ECMWF predicted cloud fields (prognostic parameterization)
  - 0.5° x 0.5° gridded, six-hour predictions
  - cloud liquid water content
  - cloud ice water content
  - cloud cover
- ECMWF grids are much bigger than some CERES SSF fovs (CERES TRMM range from ~ 10 to 20 km diameter)
- ECMWF does not provide cloud optical properties; we need to use the Fu-Liou radiation code, but it does not treat partially cloudy columns

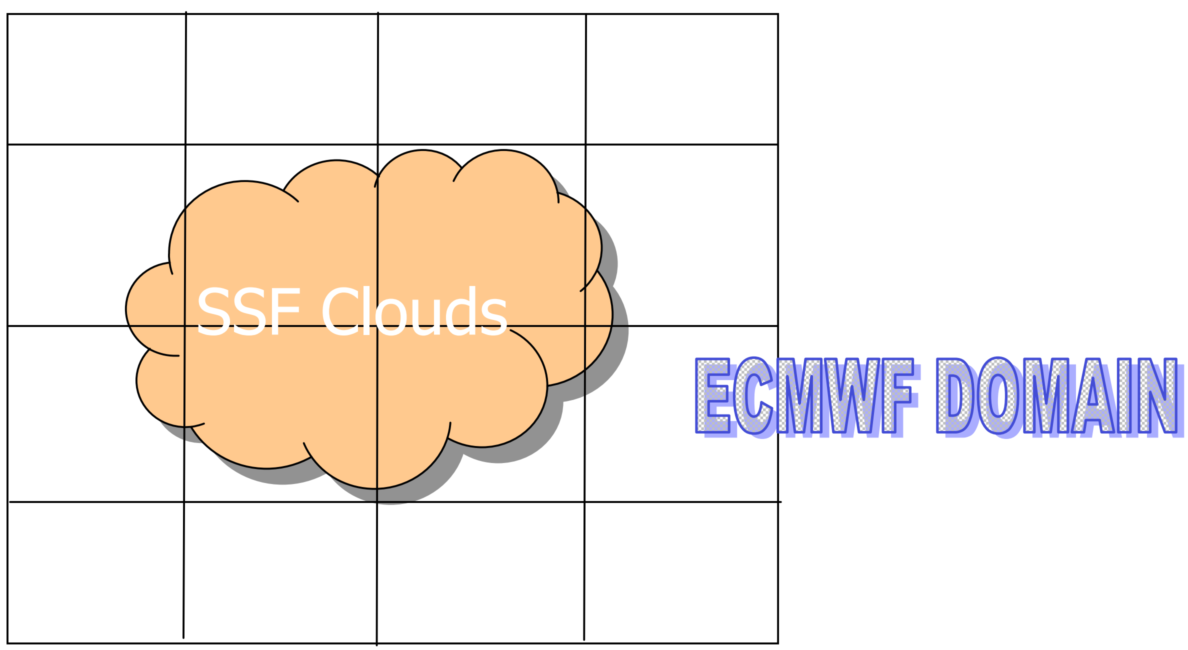
Analysis of ECMWF predicted cloud fields (cont.)

- Divide an ECMWF grid box into 30 subgrid boxes (~10km CERES flux scale)
- Use the maximum/random overlap assumption (Klein & Jacob 1999)
- Use the Fu-Liou radiation code to obtain cloud optical properties and radiative fluxes for each subgrid box



Comparison of SSF with ECMWF

- Only subgrid boxes with cloud top height > 10 and cloud optical depth > 10 are selected for statistical analysis
- Cloud top is defined as infrared absorption optical depth 1 into the cloud to be similar to satellite effective radiating cloud top
- Clouds within the near vicinity of the observed cloud systems are also included



Cloud resolving model simulation:
What is a cloud-resolving model (CRM)?

- Sufficient spatial and temporal resolution to resolve individual cloud elements (~ 1 km)
- Sufficient large domain and long time scale for statistical analyses of cloud systems
- Explicitly resolve cloud-scale and mesoscale dynamical processes
- Need to parameterize turbulence, cloud microphysics and radiative transfer
- Often used as a tool for cloud parameterization development for GCMs
- Used as a “Super-Parameterization” inside GCM grid boxes.

Cloud-resolving model simulation:
Description of the models

LaRC2d CRM (UCLA/CSU; Krueger 1988; Xu and Randall 1995)

1. Two-dimensional, anelastic dynamics (no sound waves)
2. Third-moment turbulence closures (35 prognostic equations and one diagnostic equation)
3. Three-phase cloud microphysics parameterization (Lin et al. 1983; Krueger et al. 1995)
4. Harshvardhan et al. (1987) radiative transfer parameterization

LaRC3d CRM (Advanced Regional Prediction System; Xue et al. 2000)

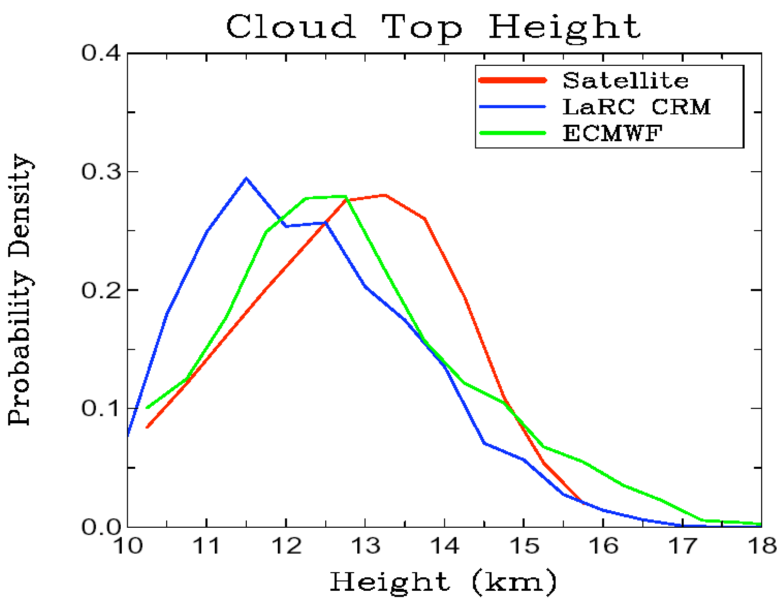
1. 2-D or 3-D fully compressible dynamics
2. Prognostic turbulent kinetic energy (TKE) closure
3. Three-phase cloud microphysics parameterization (Lin et al. 1983)
4. Chou (1990, 1992) and Chou and Suarez (1994) radiative transfer parameterization

Cloud resolving model simulation:
Design of simulation

- 2-D (x-z), horizontal grid size is 2 km
- Prescribe large-scale advective tendencies that are calculated from ECMWF data and averaged over an square area three times as great as the satellite observed cloud system
- The advective tendencies are assumed to be quasi-steady
- Simulation lasts for 24 h
- Only the last 12 h is analyzed

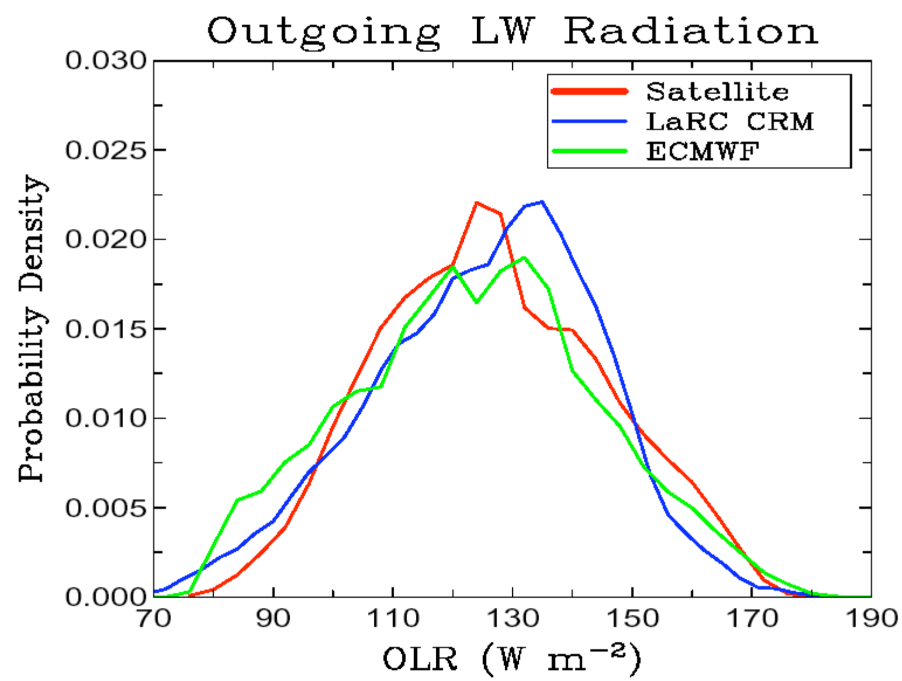
Large Deep Convective Systems:

Zcld>10km, tau>10, Cf=1, Diameter > 300km
March, 1998, 25N to 25S, 29 cloud systems



Cloud top height differences between model and observed cloud heights as large as changes from El Nino to La Nina phase. ECMWF heights closer than CRM.

TOA LW Flux differences also show systematic differences, but not as clear as the cloud height differences: critical or not? enough samples?



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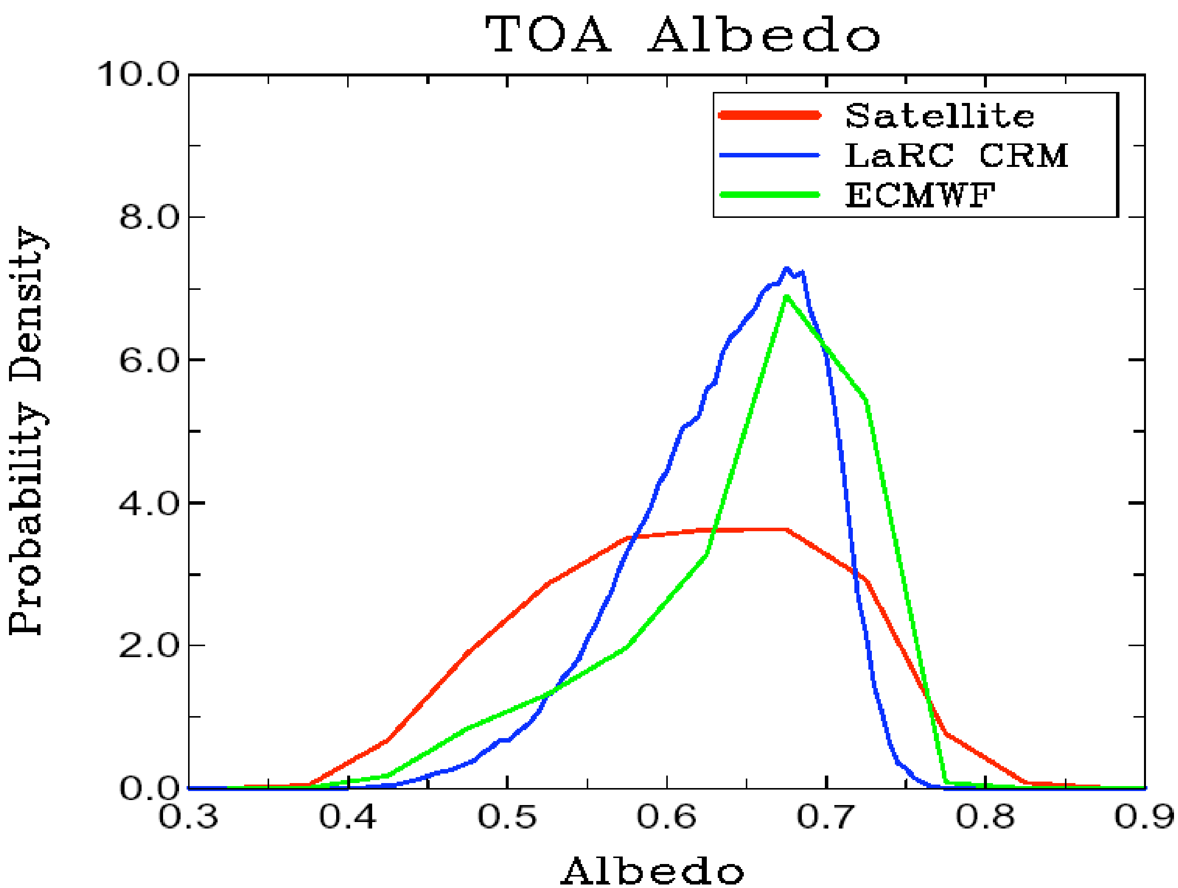
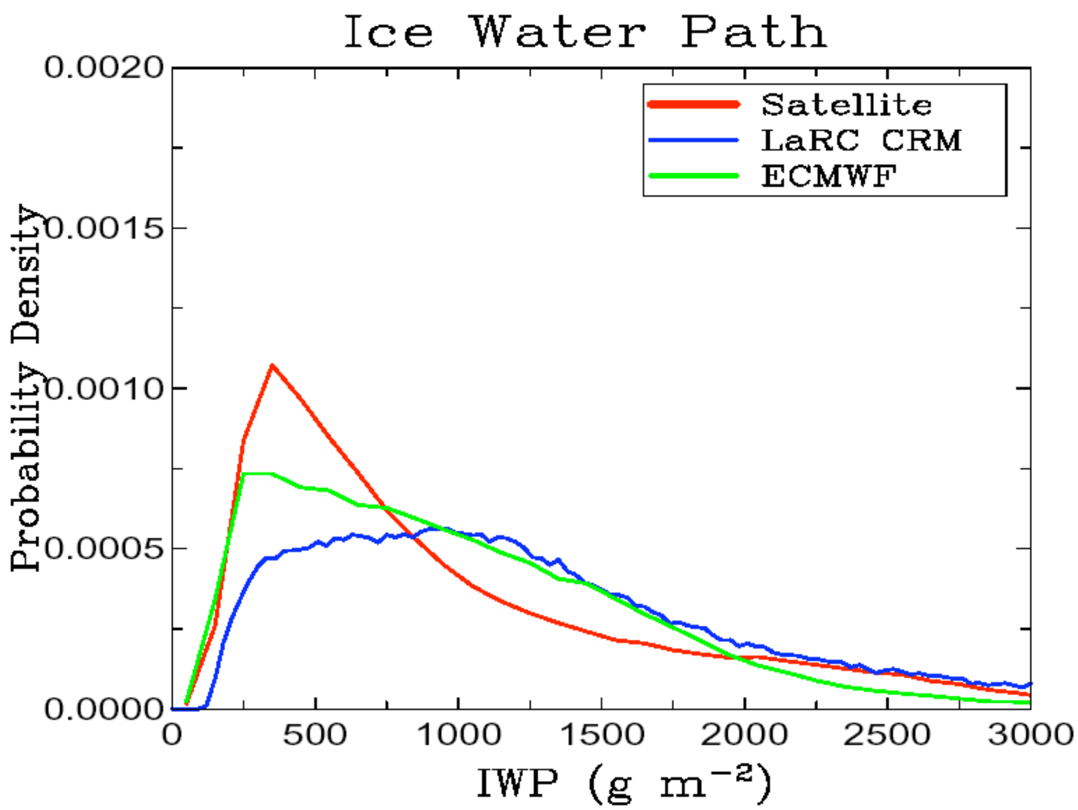


TOA Albedo
differences are large
ECMWF clouds are too optically thick, with insufficient variability.
CRM is an improvement but still needs substantial improvement:
CRM and especially ECMWF will overestimate cloud surface cooling

Large Deep Convective Systems:

Zcld>10km, tau>10, Cf=1, Diameter > 300km
March, 1998, 25N to 25S, 29 cloud systems



Satellite IWP from VIRS Imager tau, reff:

Here satellite estimates not well validated, but show substantial differences that appear qualitatively consistent with the TOA albedo results: models have too much ice.

Need ARM/A-train improved IWP validation.

Conclusions

- *Cloud objects useful for examining cloud changes by cloud type*

- *Climate change can be separated into:*
  - *changing frequency of cloud type (dominant?)*
  - *changing properties of a cloud type (secondary?)*
  - *test how well models do each cloud change*
  - *with larger ensembles, separate by meteorological state*
    - *e.g. SST, stability, vertical velocity, wind shear, etc*
  - *do models handle the partial derivative of cloud properties versus atmospheric state change? key for cloud feedback*

- *How accurate should models and data agree?*
  - *statistical noise: can beat down with larger samples*
  - *new radiative flux ensemble errors by cloud type very small*
  - *what level differences are key to climate change? critical TBD!*
  - *errors in atmospheric input state: evolve over time, test sensitivity*

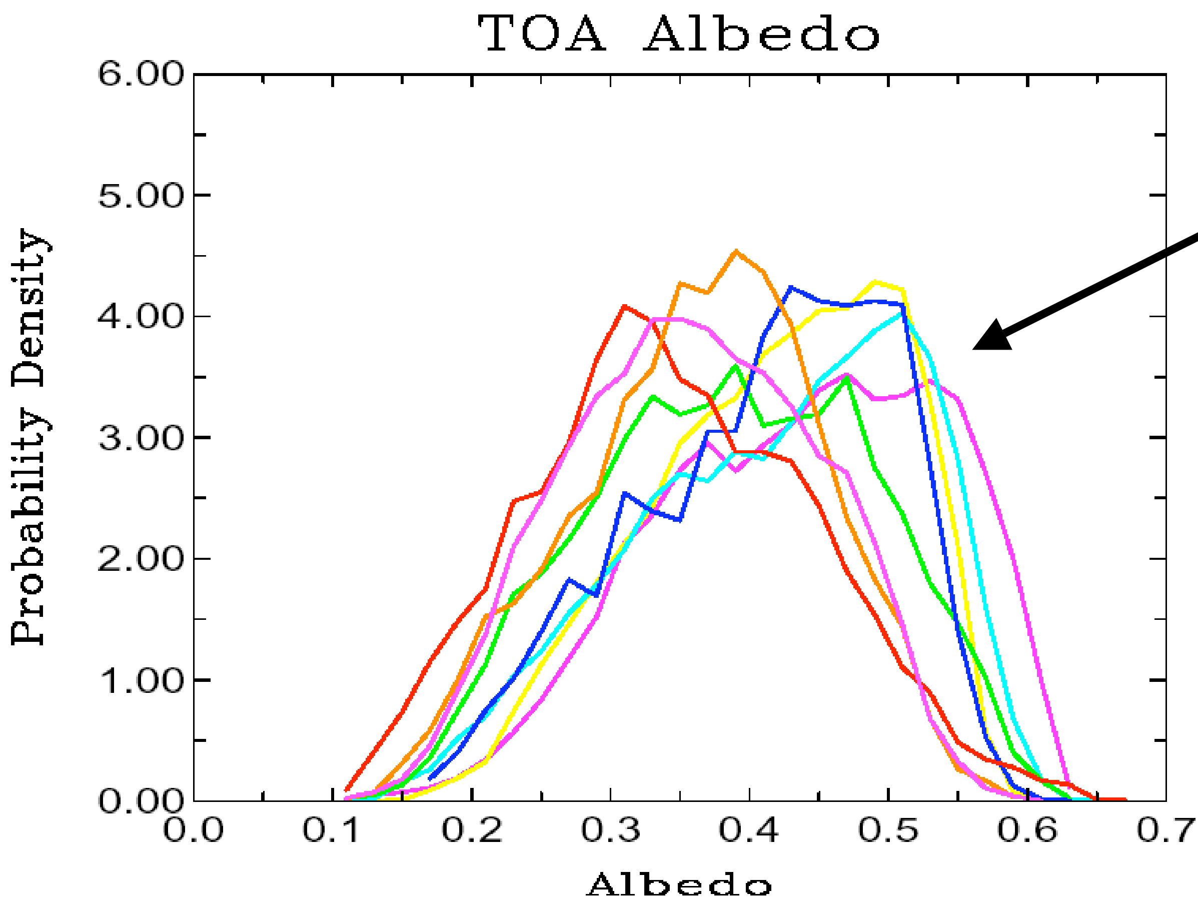
Comparison of CRMs with SSF:
Summary and Model Improvements

- The CRM convective clouds tend to be shallower and warmer than those observed with the SSF for both LaRC2d and LaRC3d models.
- Inadequate ice-phase microphysics and the forcing method (single profile) are two possible causes for the CRM results
- Sensitivity tests to the advective forcings, eliminating those cases with inconsistent advective forcings
- Two-column advective forcings, instead of single-column ones
- Improvements to model physics [ice microphysics, radiation and turbulence closure (LaRC3d CRM)]

Next Steps

- *Boundary Layer cloud model runs for March 1998 and 2000*
- *Web site for community access of the matched satellite/meteorological state data*
- *Convective cloud model runs for March 2000*
- *Statistical analysis of model/data difference significance*
- *Additional months to get sufficient statistics to subset by meteorological state and examine partial derivatives in observations and compare to models.*
- *Some hard thinking about how well models should agree:*
  - *requirements by cloud type: model vs. observations ensembles within 1, 2, 5, 10 Wm^{-2}?*
  - *how to relate this requirement to cloud feedback uncertainty*
  - *define completeness of cloud types, atmospheric states*
- *A good approach for using A-train cloud/aerosol/radiation data*

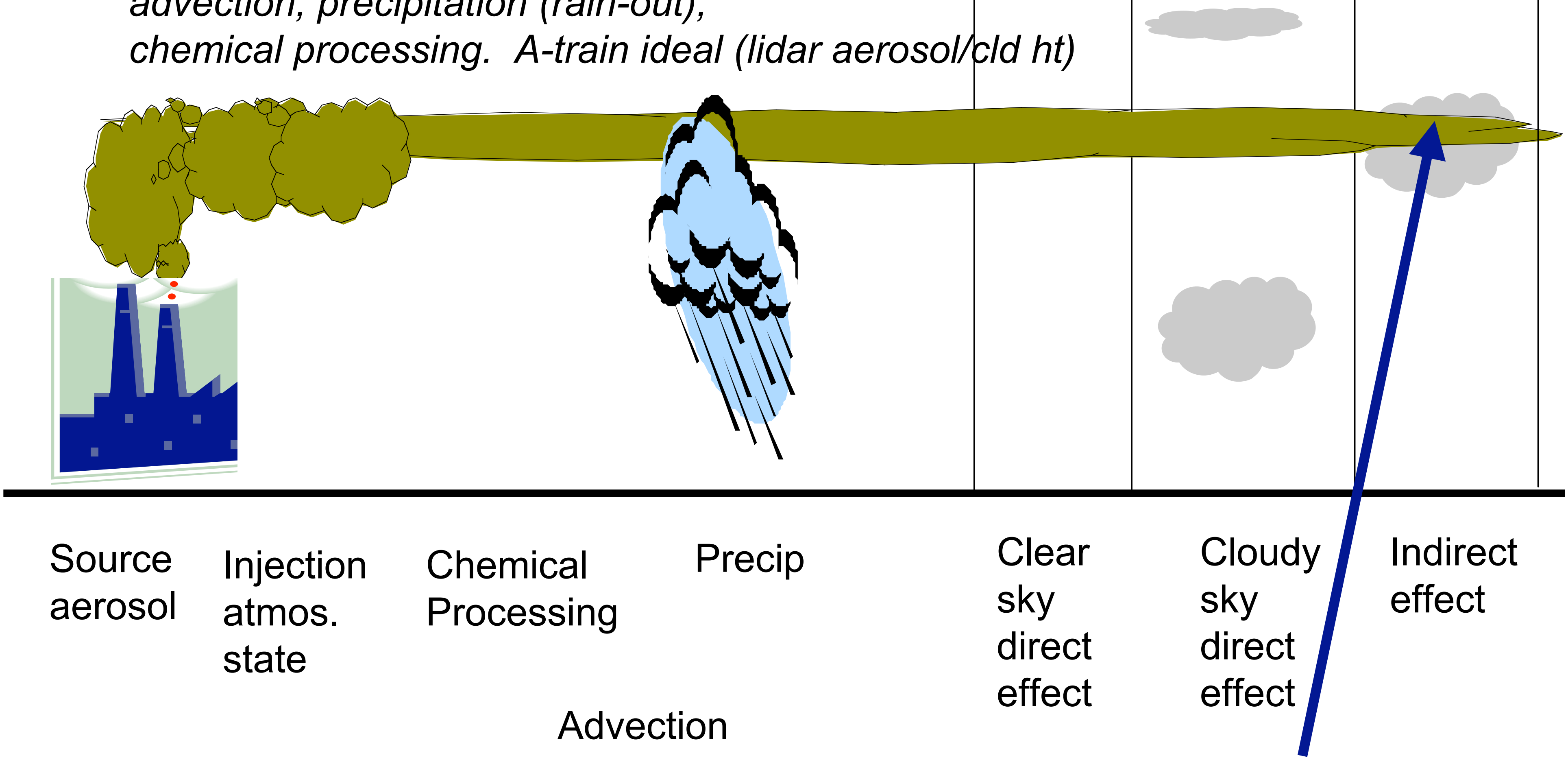
Overcast Boundary Layer: Observed CERES Cloud Object Pdfs for March, 1998



Can we predict why these stratus systems differ as a function of dynamic state?

Aerosol lifetime and radiative impacts

Use backtrajectories to tie radiative impact to aerosol source regions and chemistry, as well as to isolate processes of vertical mixing advection, precipitation (rain-out), chemical processing. A-train ideal (lidar aerosol/cld ht)



Must unscramble cloud fluxes/properties and dynamic state in order to isolate cloud indirect effect….