Climate Model Test Discussion An Observational Perspective

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CERES Science Team Meeting
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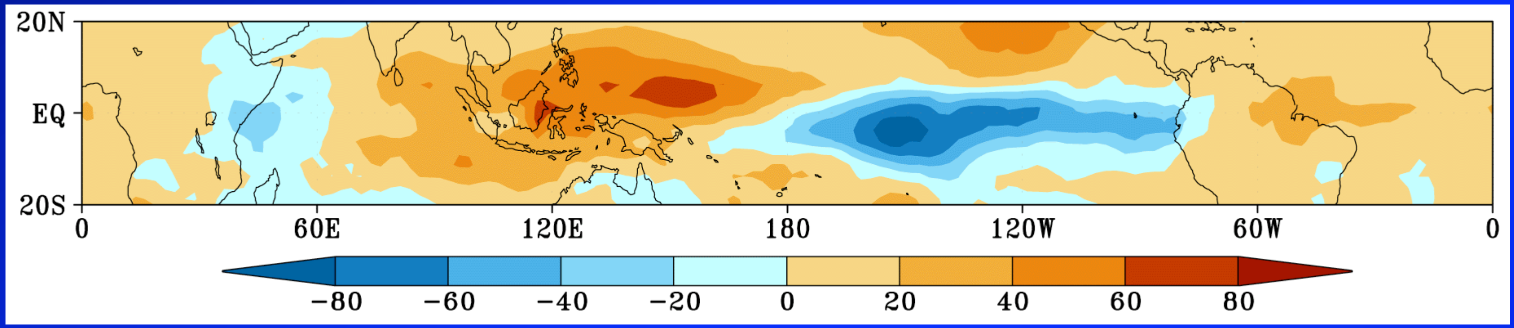
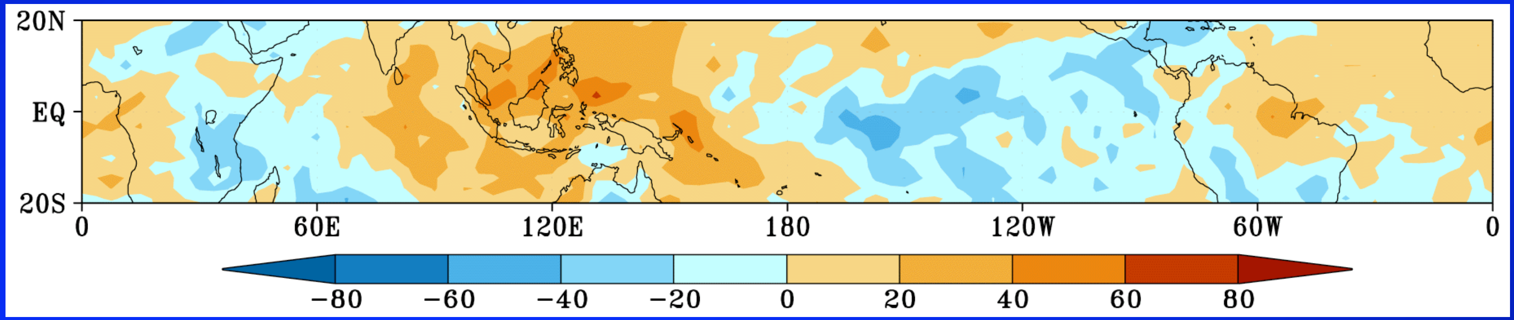
Jan/Feb 98 El Nino TOA LW Flux Anomalies

(relative to ERBE 1985-1989 average)

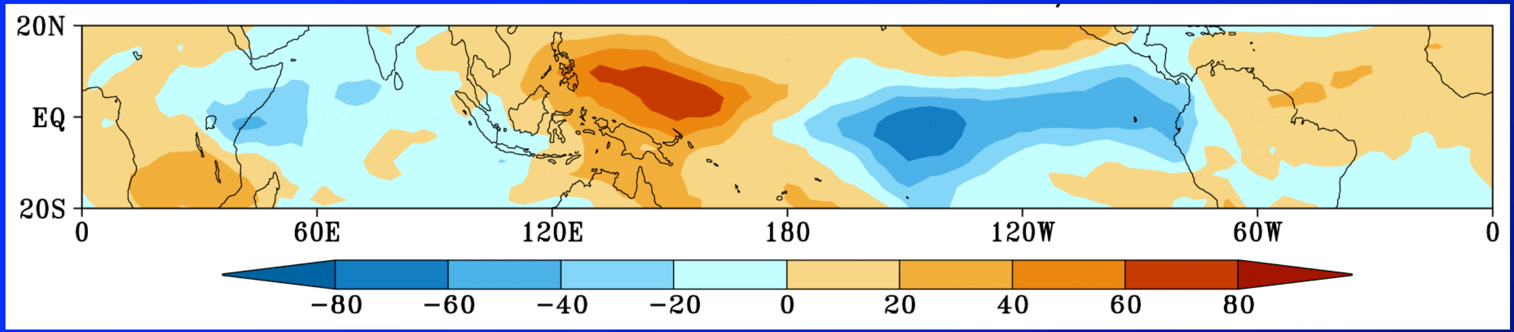
CERES ERBE-Like LW Flux Observations



NOAA GFDL Standard Climate Model

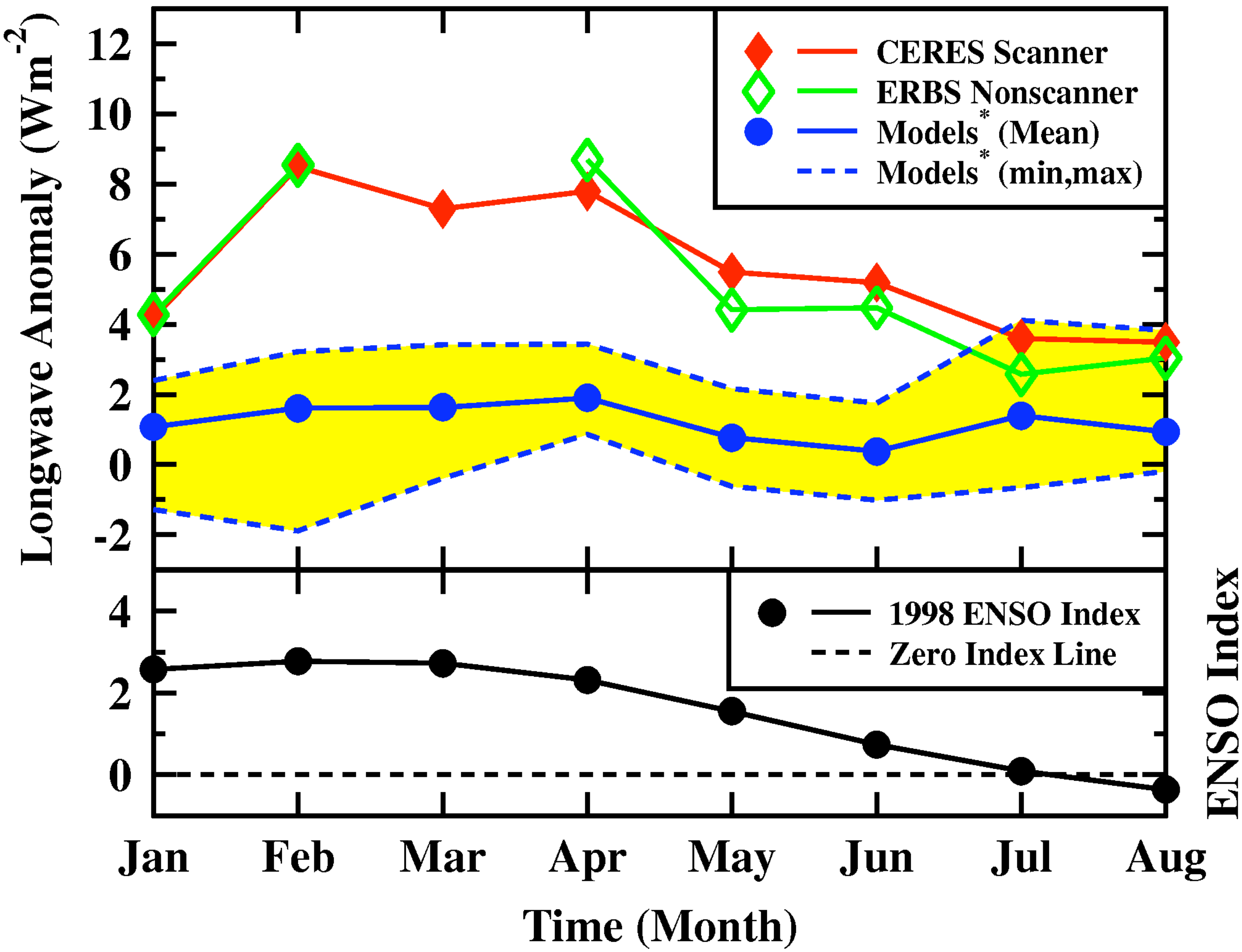


NOAA GFDL Experimental Prediction Model



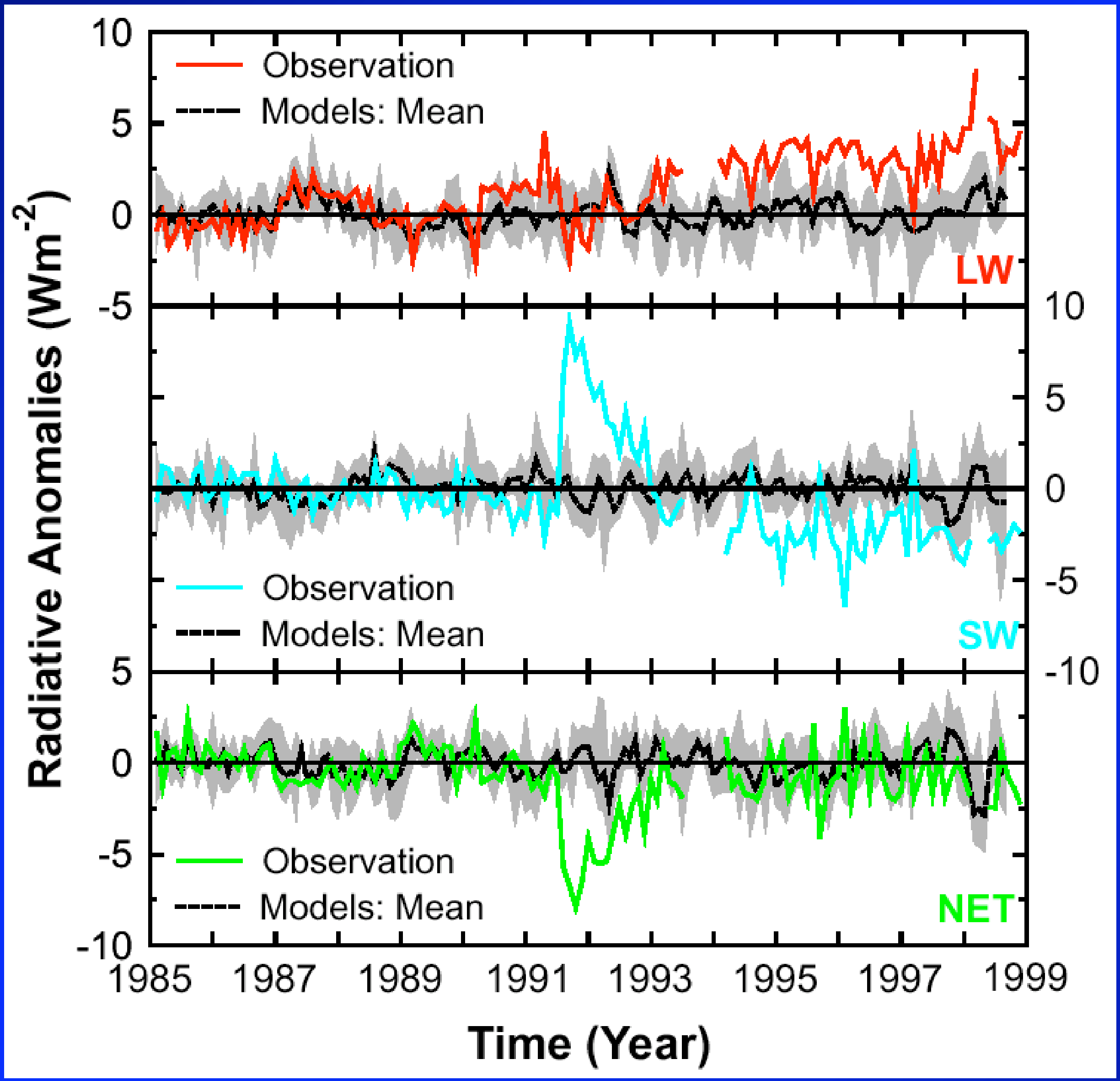
1998 El Nino Tropical Mean (20S - 20N) Longwave Flux Anomalies

(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)

Comparison of Observed Decadal Tropical Radiation Variation with Current Climate Models



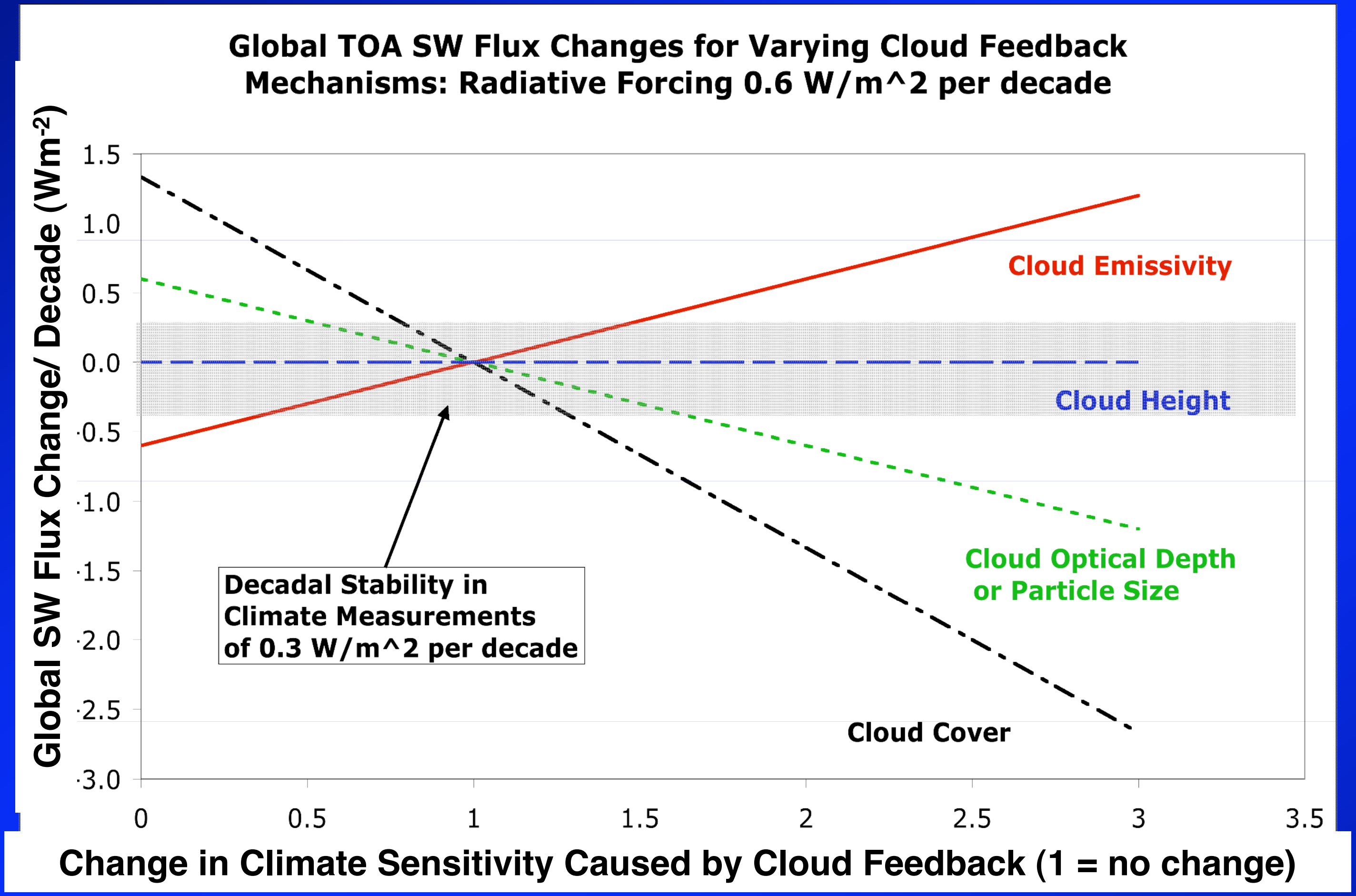
LW:
Emitted Thermal Fluxes

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?



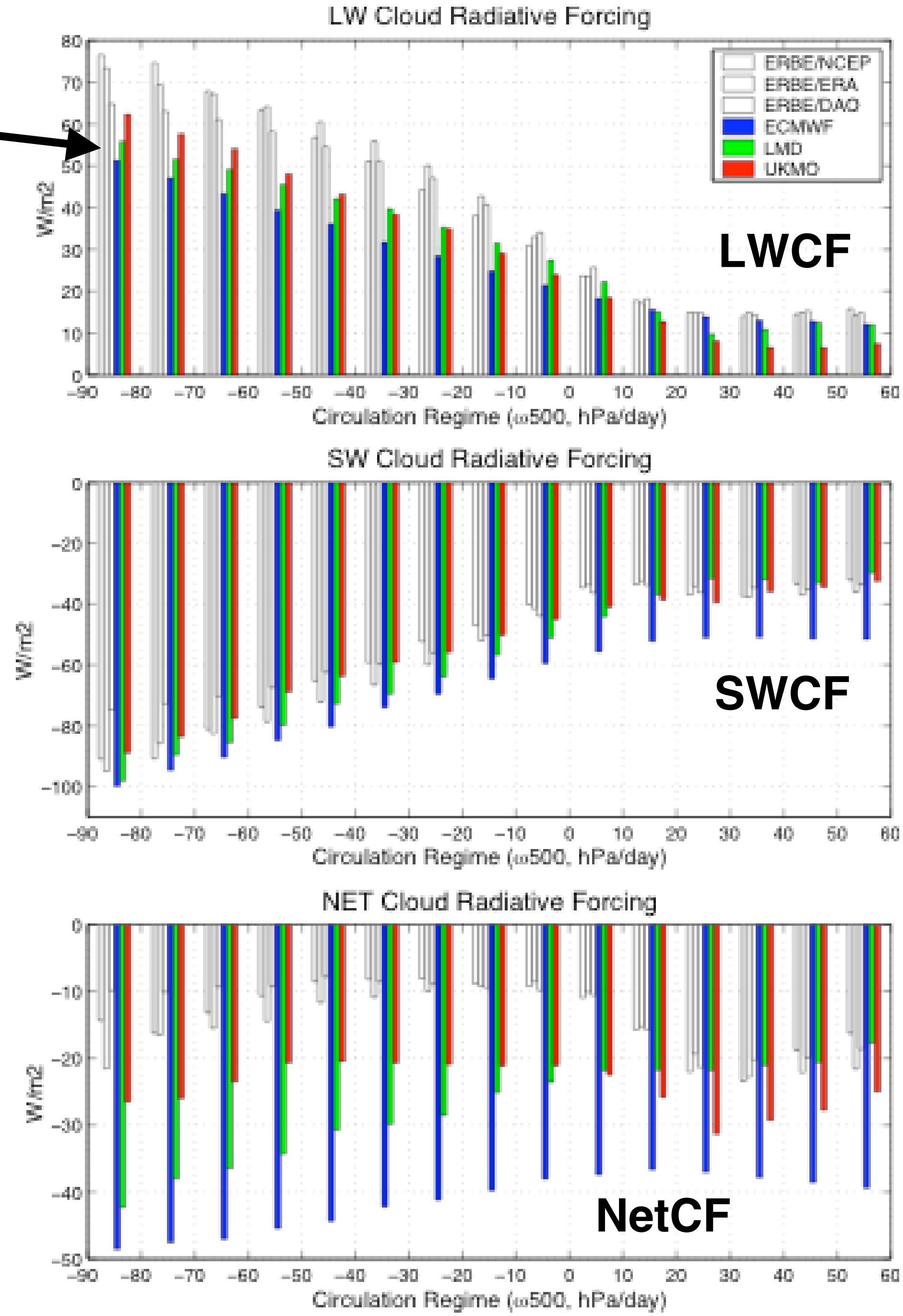
- Regional changes will be larger: but no regional "constraint" and global mean still must be accurately known for global feedback.
- UKMO ensemble climate noise for annual tropical mean SW and LW fluxes ~ 0.3 Wm^{-2}: this might be a reasonable lower limit on accuracy.

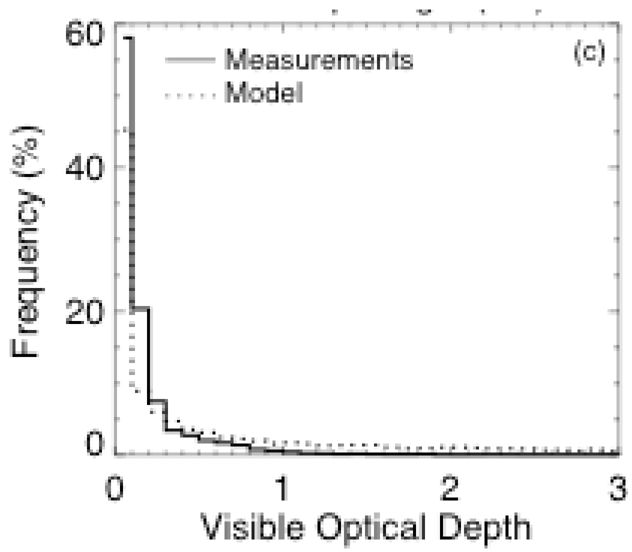
white: ERBE/NCEP, ERA, DAO
blue: ECMWF
green: LMD
red: UKMO

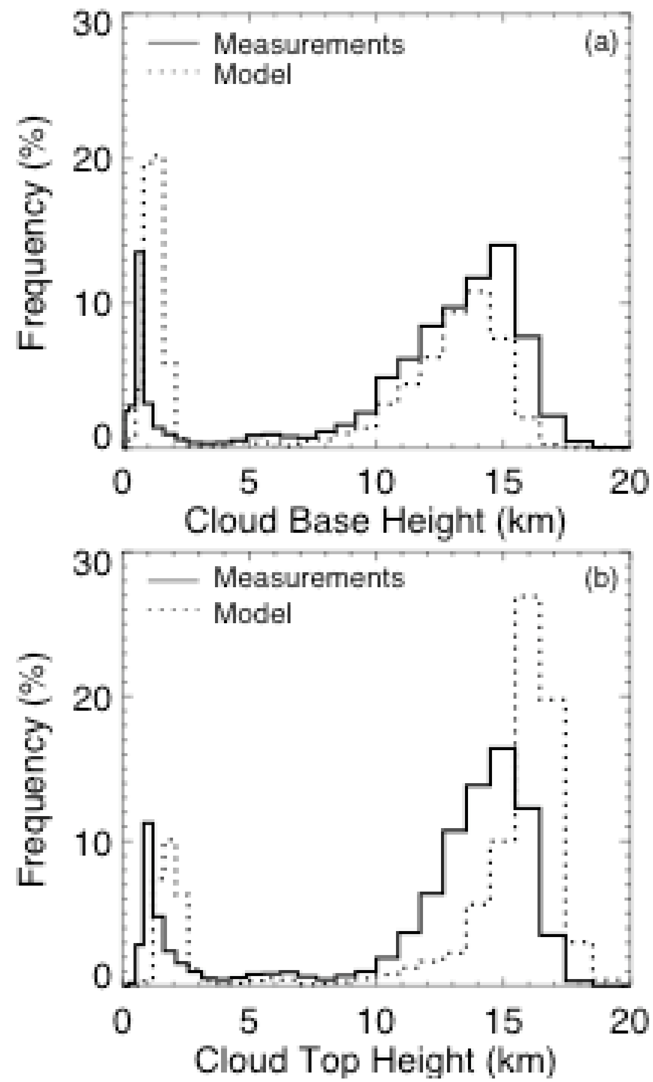
Model vs Data Intercomparisons by Dynamic Regime:

Vertical Velocity

(Bony et al., 2003)



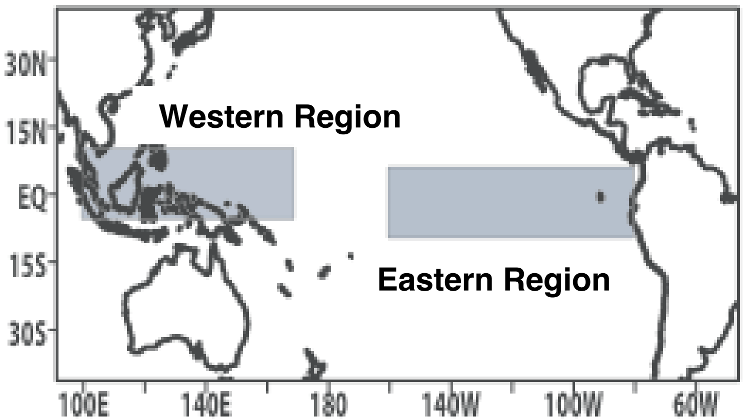




Model vs Data Intercomparisons

Pdfs at a Surface Site: Cloud Top Height/Base & Tau

(Comstock and Jacob submitted GRL, 2004

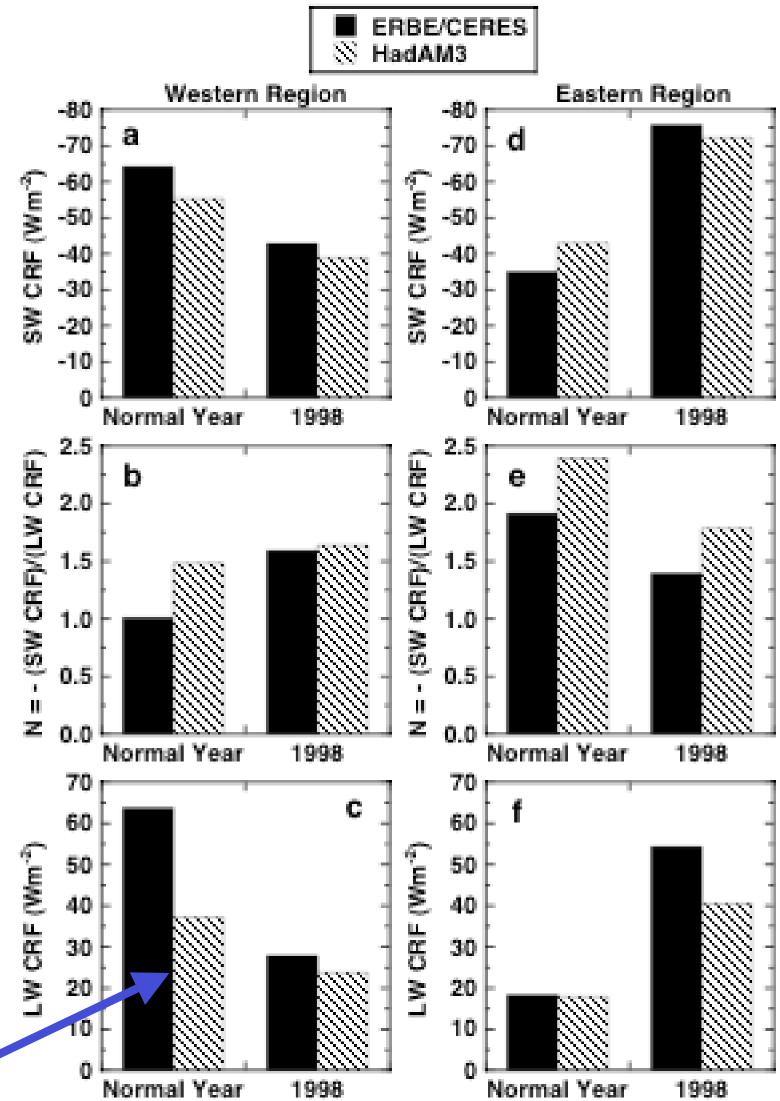


Model vs Data Intercomparisons

Cloud Forcing/Ratio Response to El Nino

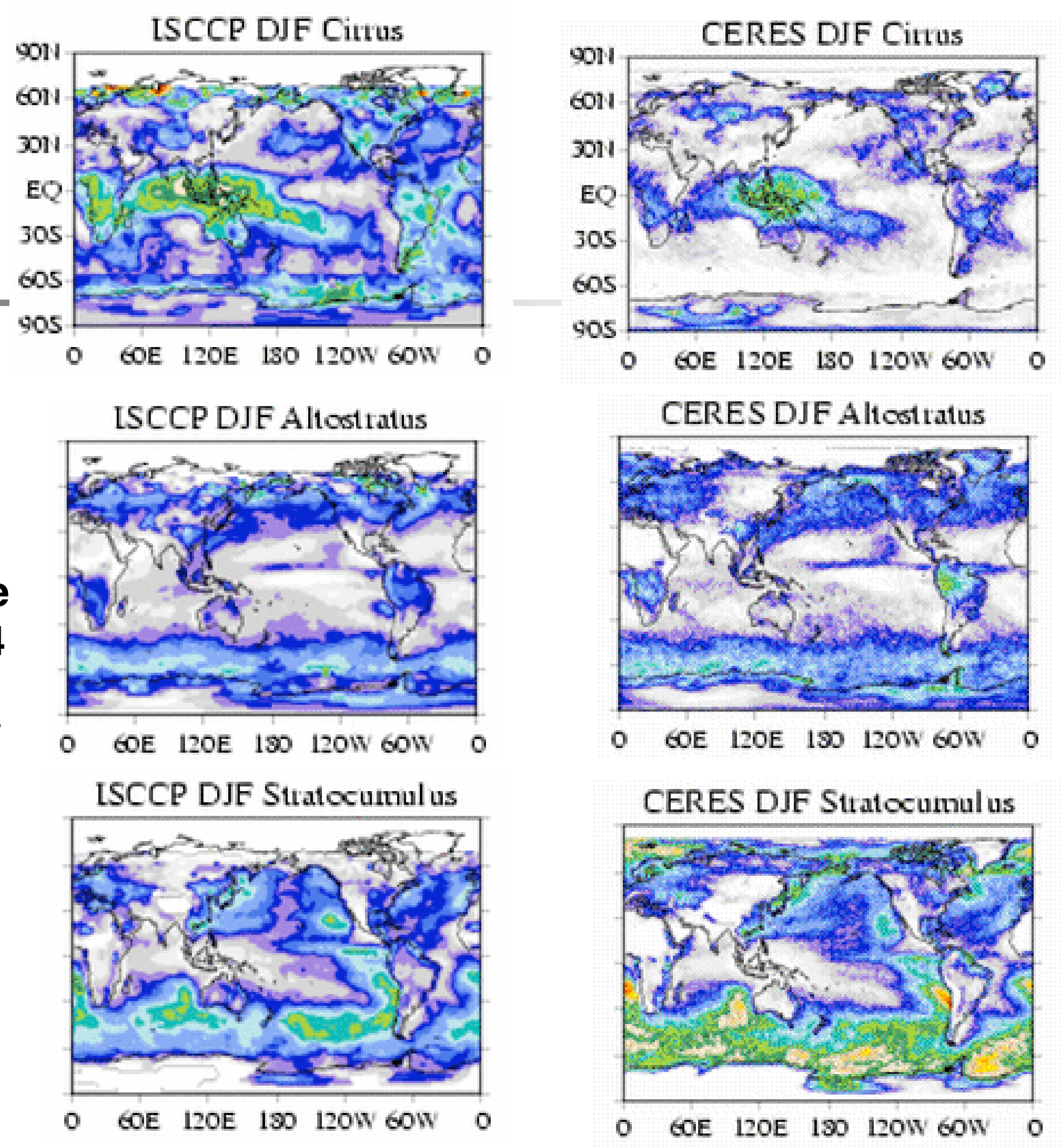
(Lu, Dong, Cess, Potter, 2004)

How close should models agree for a given feedback uncertainty?

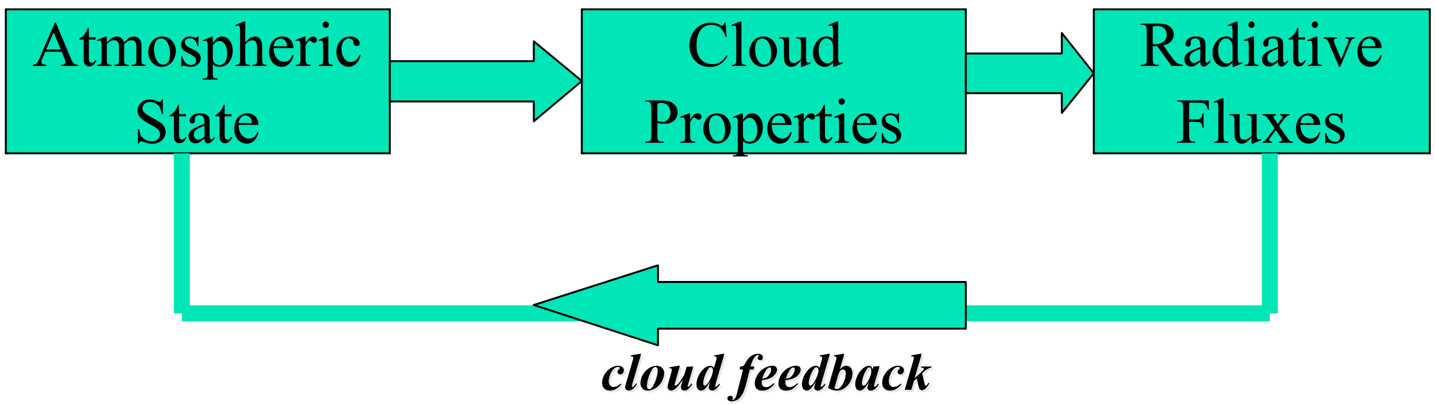


ISCCP vs. CERES
Cloud Type
Frequency of Occurrence
Wang, Loeb, Minnis 2004

GEWEX Radiation Panel
Cloud Property Data
and Radiative Flux Data
Assessments begins
late 2004

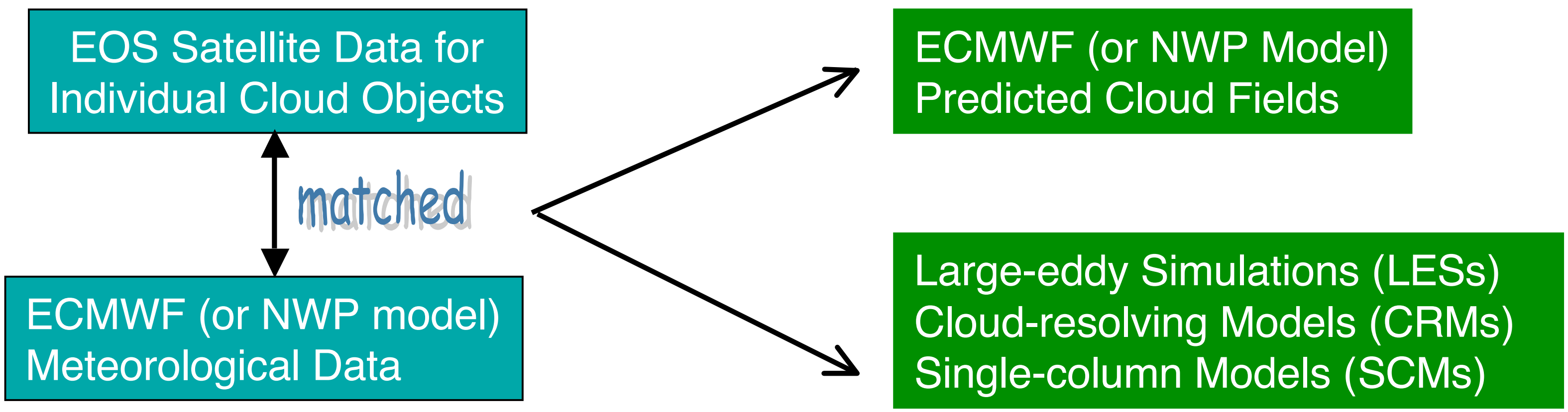


Motivation



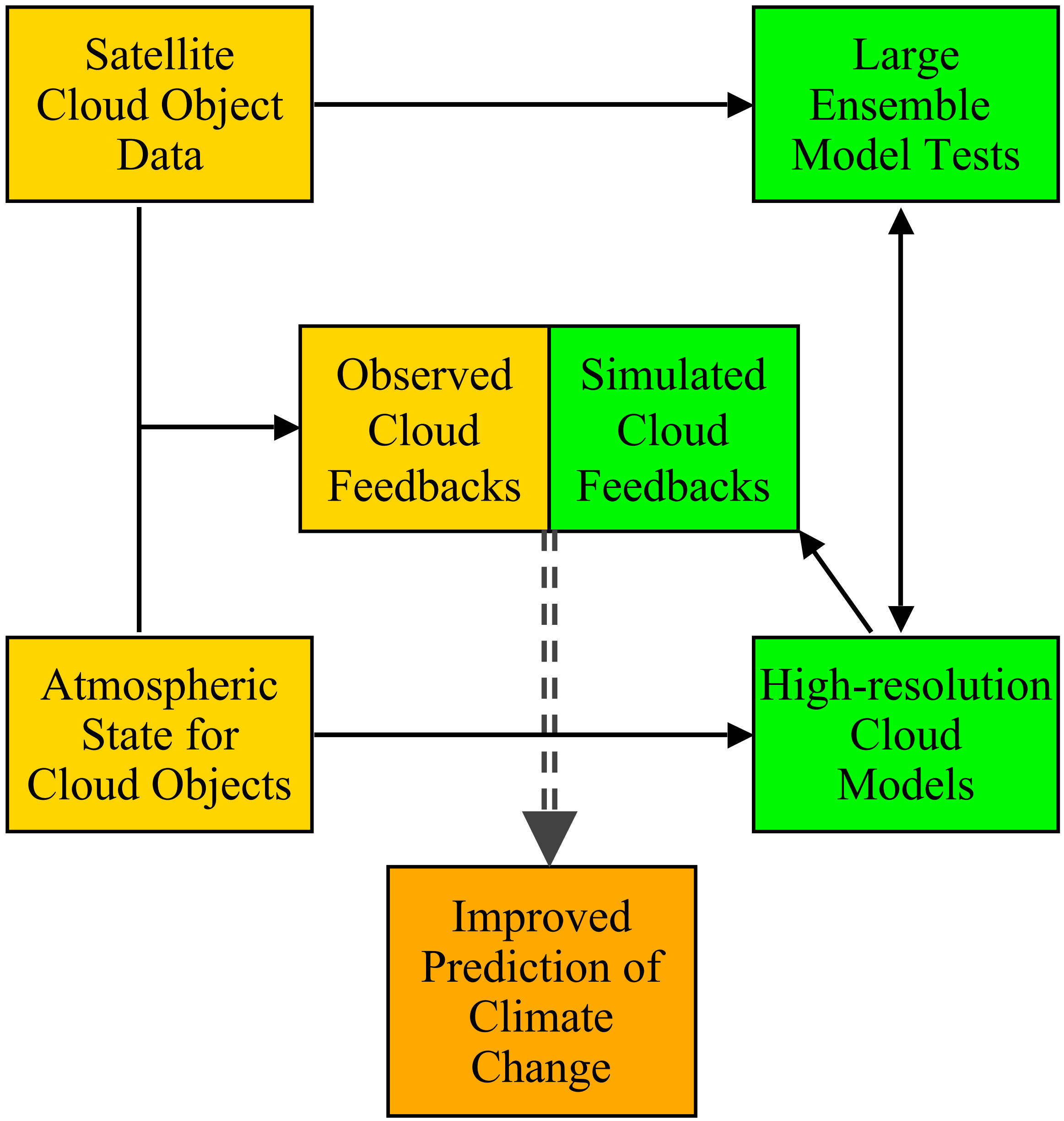
- ♣ Nonlinearity of cloud processes requiring observations on all
  relevant modeling scales (in space and in time)
- ♣ Existing methods of cloud model evaluation are incomplete

Using satellite cloud object data for evaluating and improving CRMs and cloud parameterizations



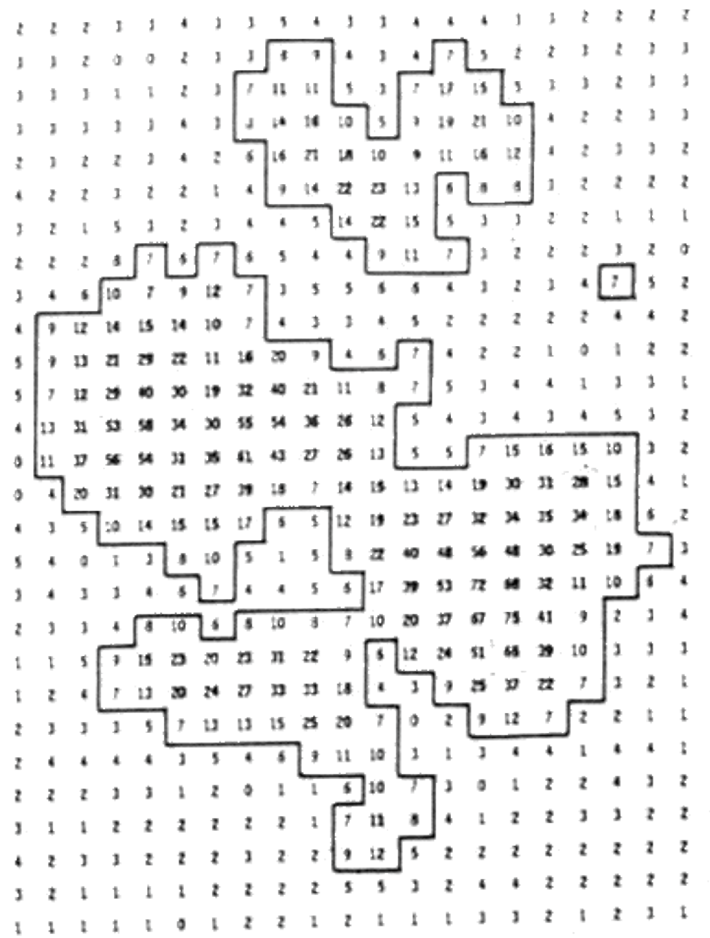
- Analyze the statistics of subgrid characteristics (PDFs) of satellite-observed cloud objects, *not* GCM gridbox means
- Match the CERES SSF (Single Scanner Footprint) cloud and radiation data with ECMWF meteorological data (T, q, u, v and advective tendencies)
- Perform cloud model simulations driven by ECMWF advective tendencies; an iterative process of improvement and evaluation of cloud models
- Also evaluate the ECMWF parameterization using its predicted cloud fields

A cloud modeling strategy

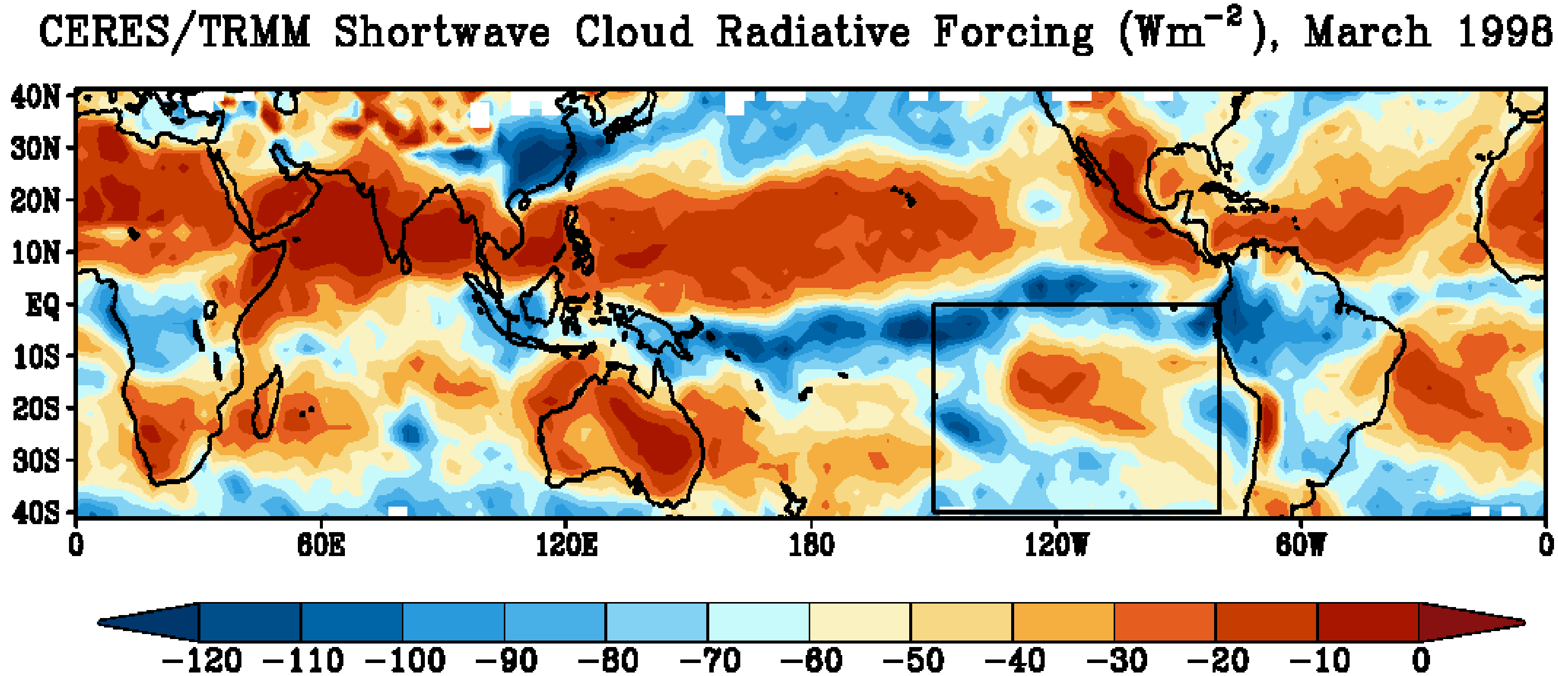


Satellite data analysis method

- ♣ 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)



Boundary Layer Cloud Object Region, Southeast Pacific, March 1998

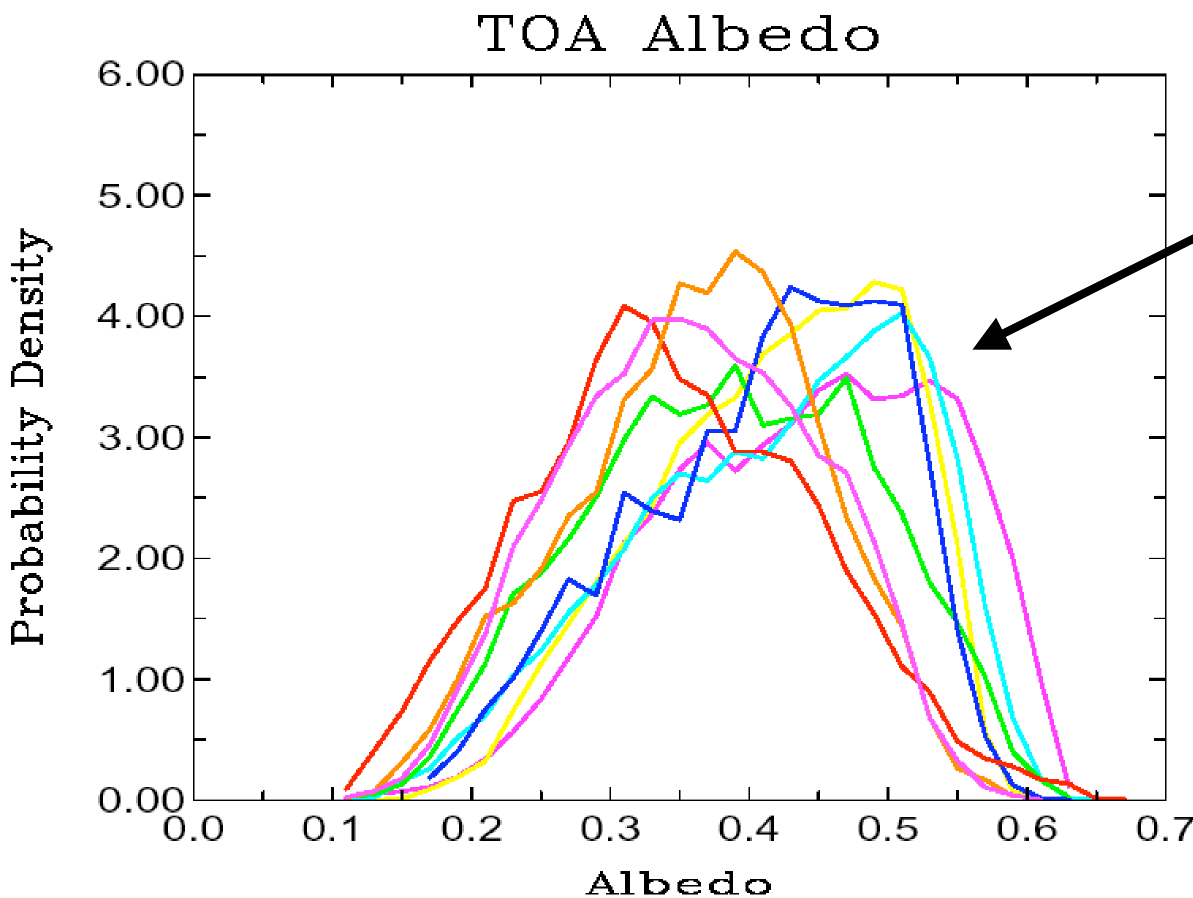


Solid Stratus: *0.99 - 1.00 cloud fraction,* $Z_{cld} < 3$ *km*

Stratocumulus: *0.40 – 0.99 cloud fraction,* $Z_{cld} < 3$ *km*

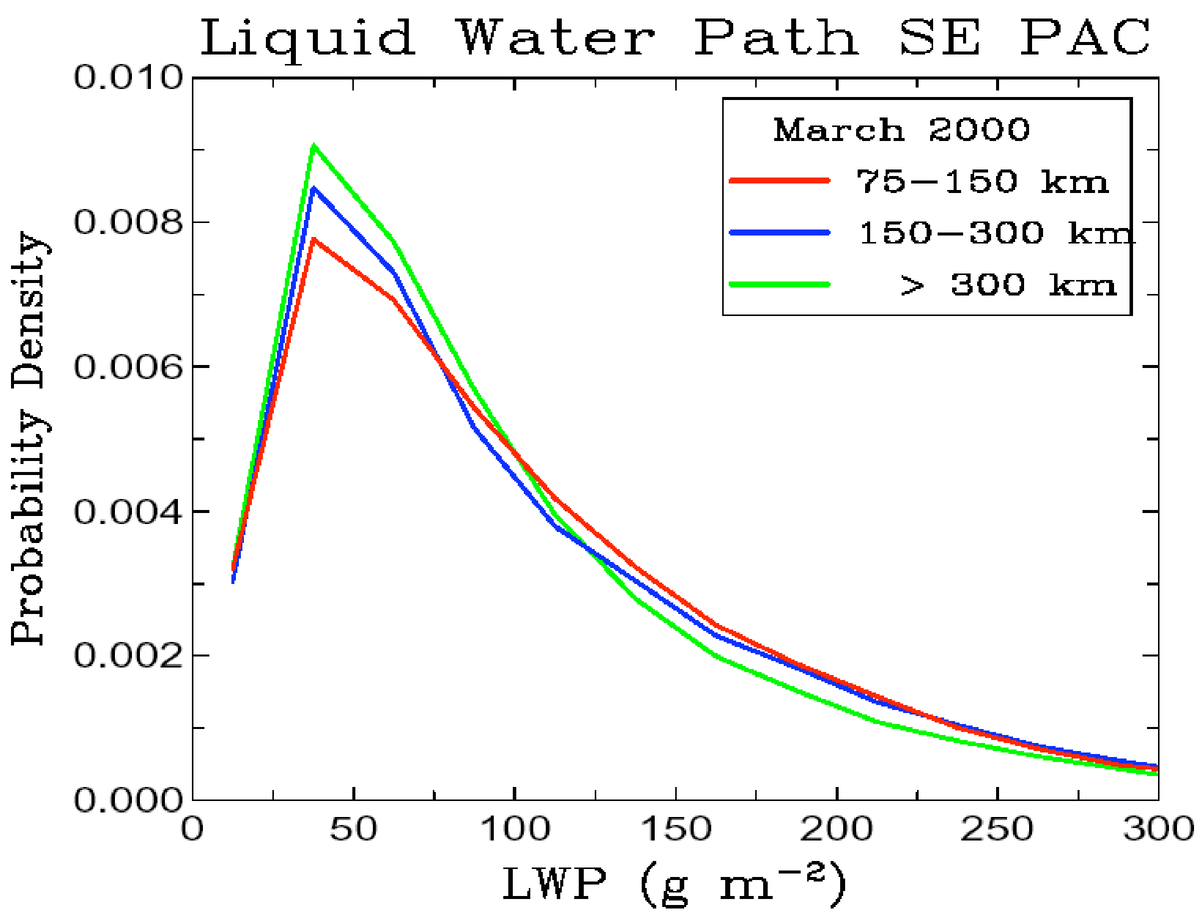
Cumulus: *0.10 – 0.40 cloud fraction,* $Z_{cld} < 3$ *km*

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

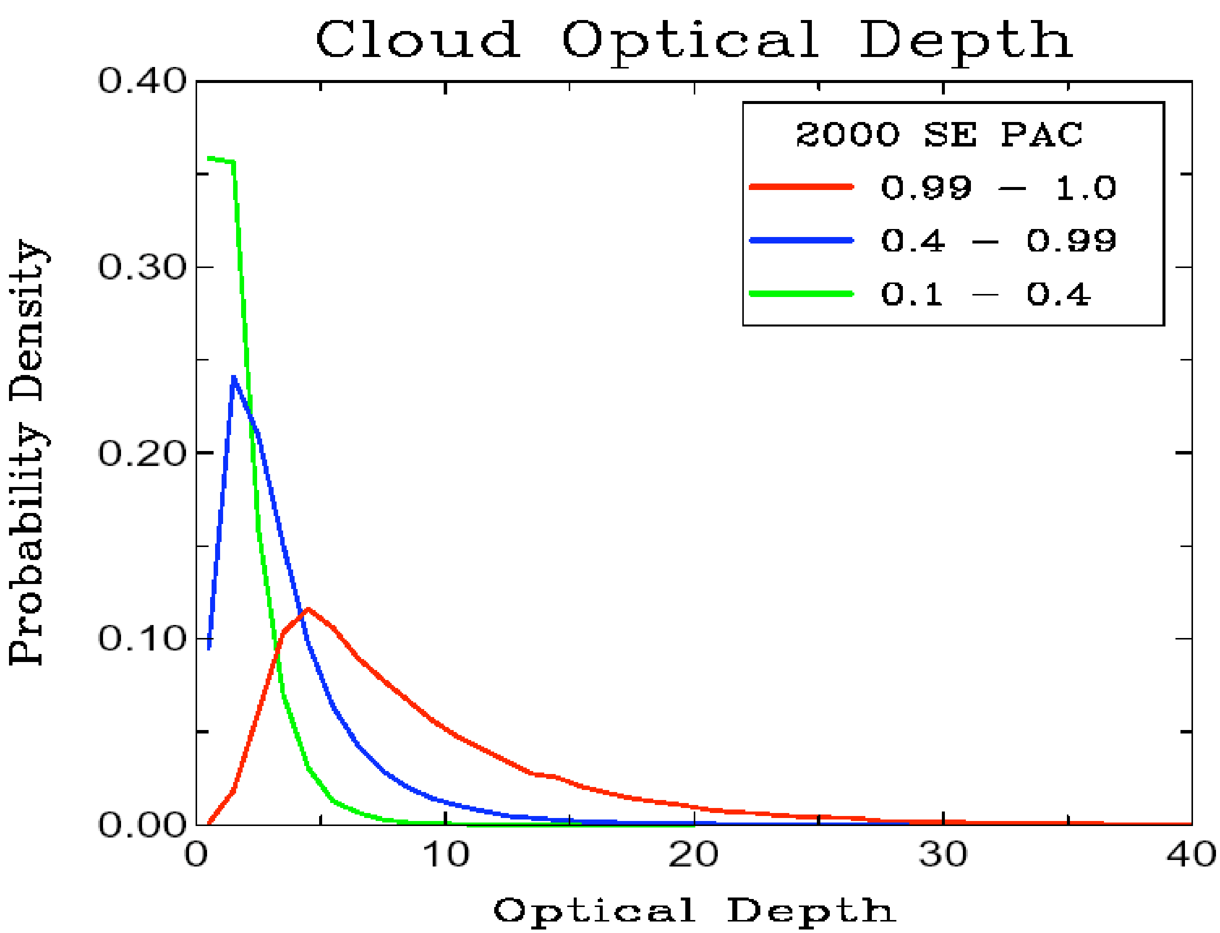


Stratus:
Cloud Fraction = 1
Zcld < 3 km
Water phase
LWP from tau(vis),reff

CERES SSF cloud retrieved using VIRS imager

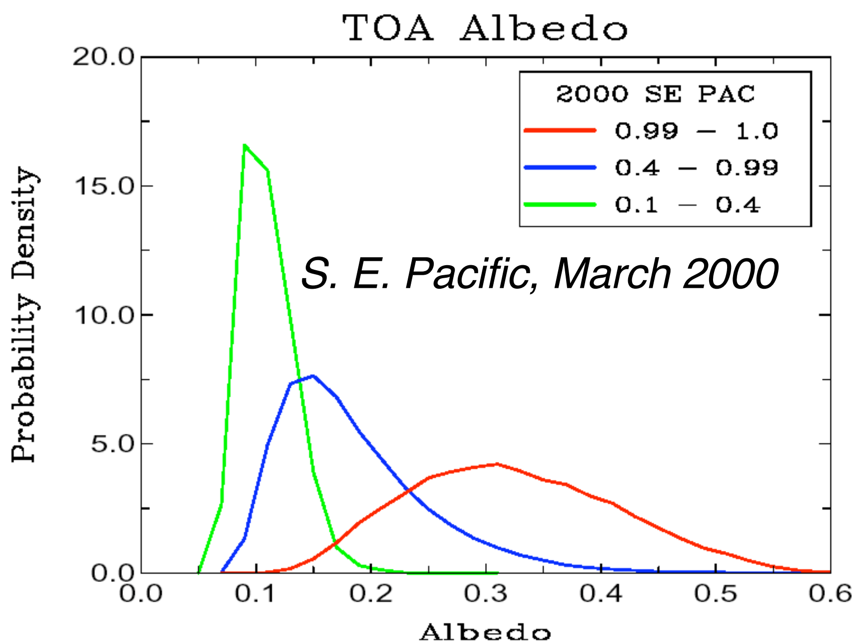
Surprisingly, larger stratus decks do not have larger LWP amounts

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

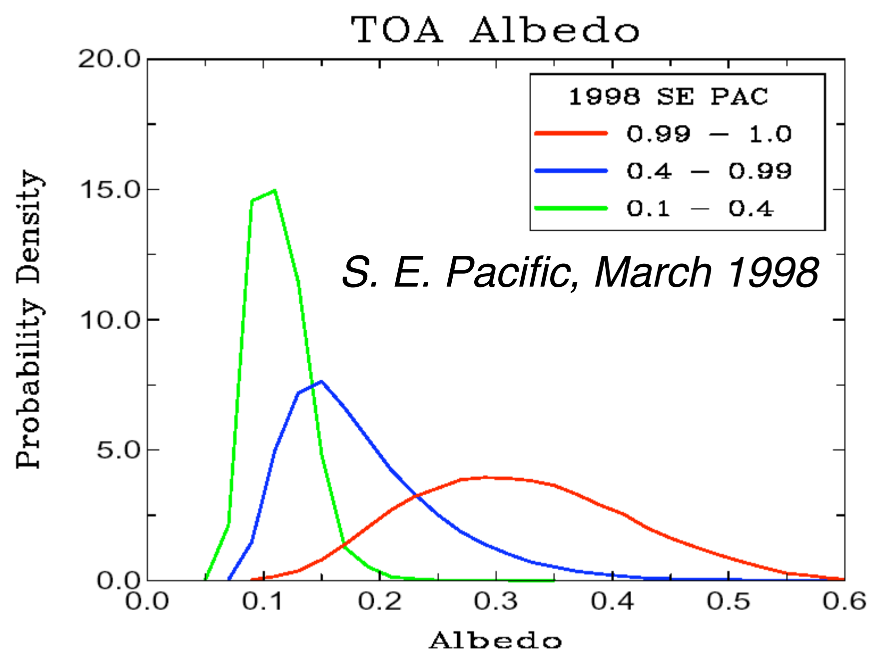


Similar to Landsat Pdfs but from a large ensemble of boundary layer cloud systems using 10 to 20km fov spatial scale: skewed distributions remain....

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

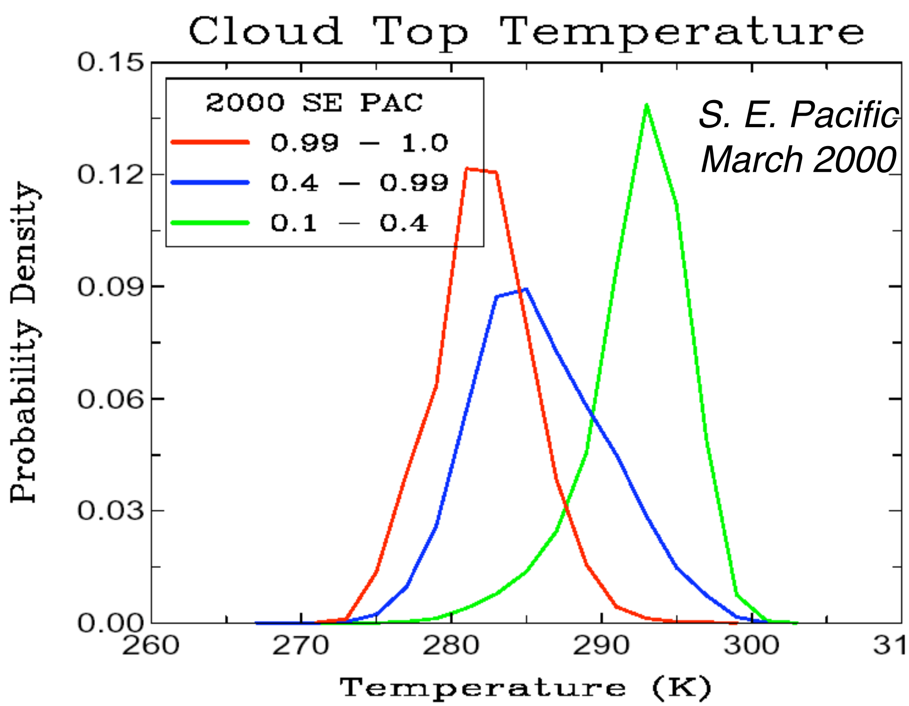


No apparent difference in the S.E. Pacific, even though the Walker Cell strength reduced, Hadley cell strengthened...

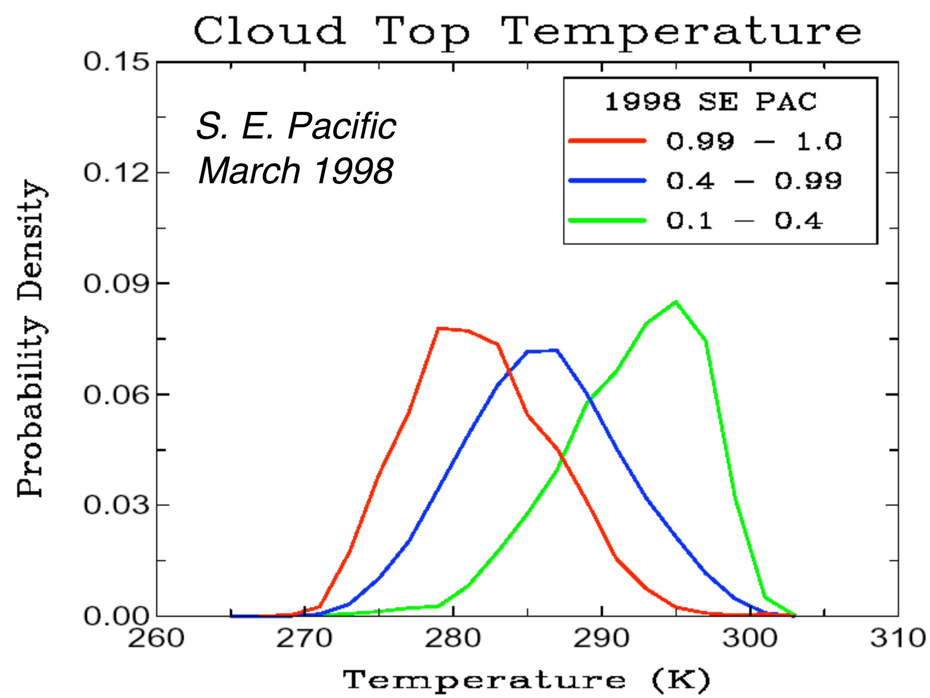


Suggests stable properties by cloud type: next step to quantify how stable....

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



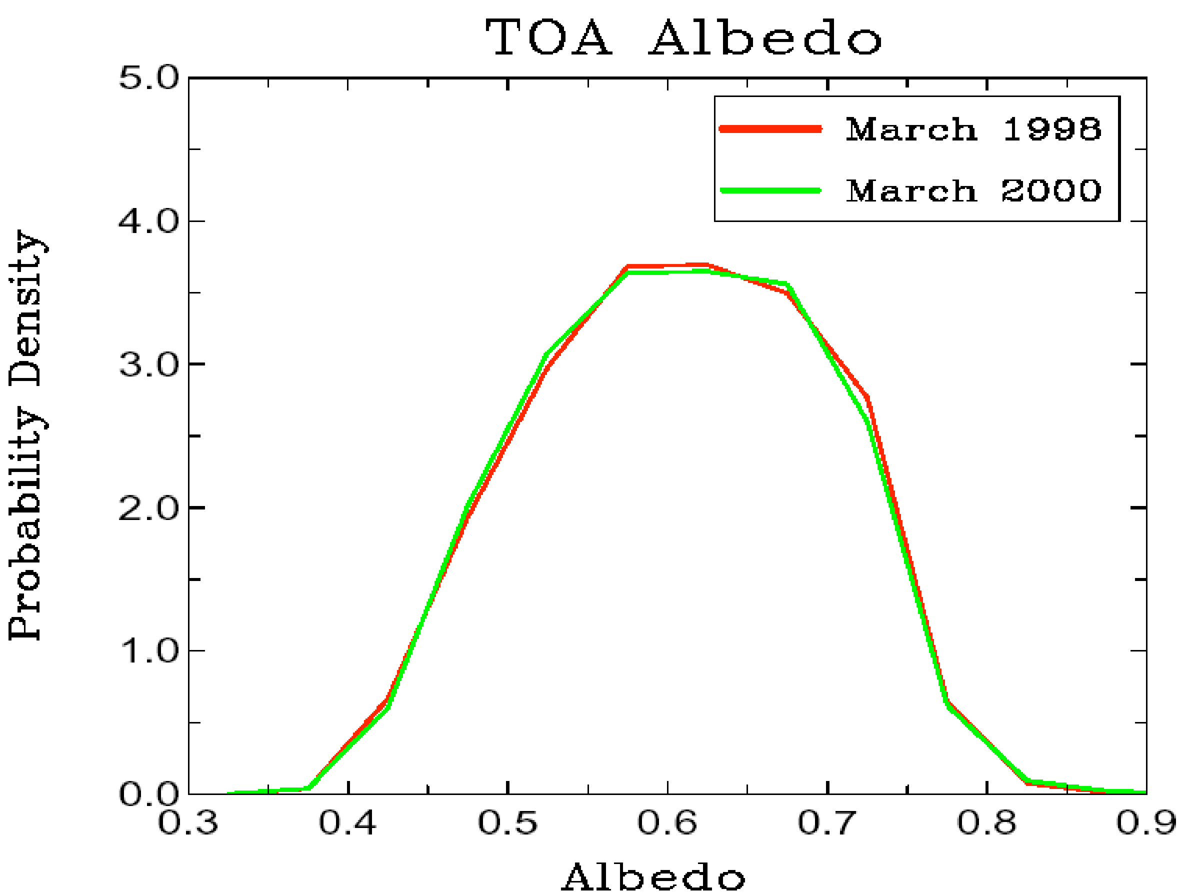
March 2000: Colder SST (La Nina) & Colder Cloud Top Temperature, but Narrower Frequency Distribution



Large Deep Convective Systems:

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

CERES TOA Albedo

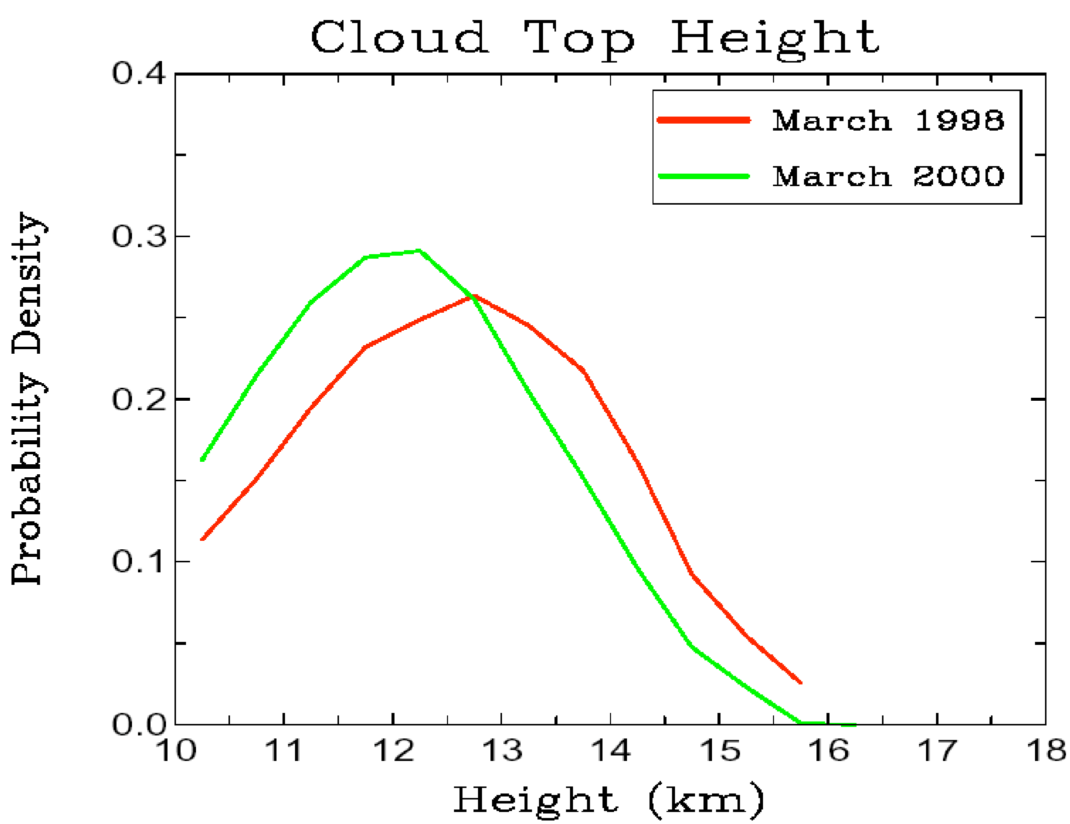


Across the tropics (25N to 25S) large convective systems appear invariant between the 98 El Nino and 2000 La Nina phases of ENSO for TOA albedo pdf.

Large Deep Convective Systems:

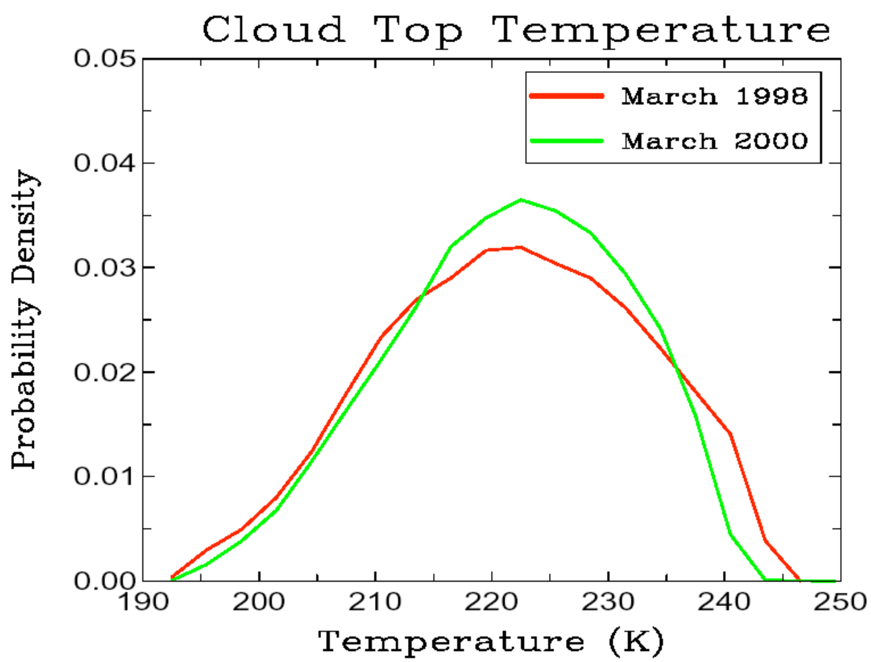
Zcld>10km, tau>10, Cf=1, Diameter > 300km

CERES Cloud Height using MODIS



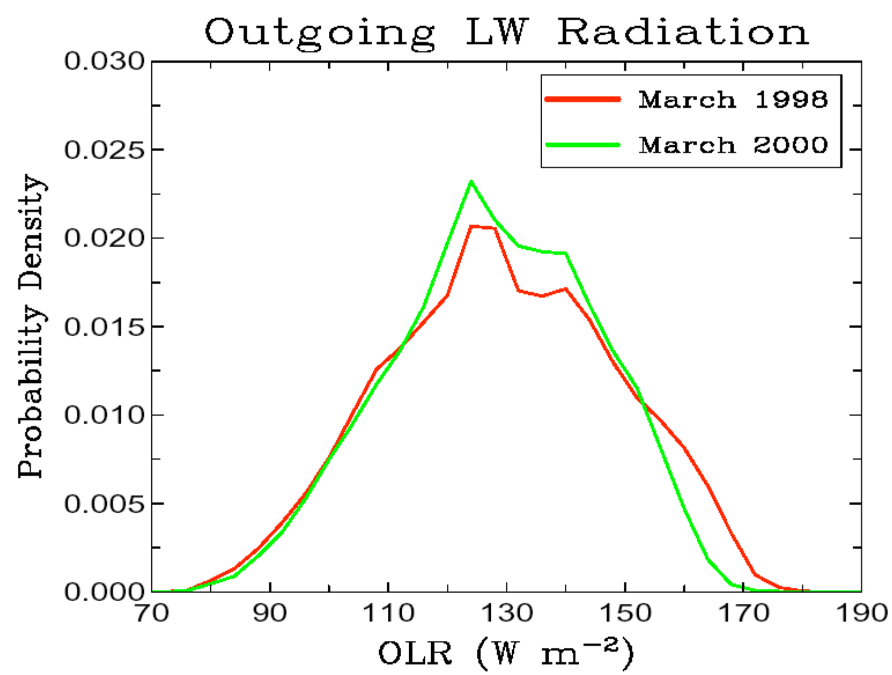
Across the tropics
(25N to 25S)
large convective
systems, however
appear to increase
cloud height by about
almost 1 km
during the 1998 El Nino

Large Deep Convective Systems:
Zcld >10km, τ >10, Cf =1, Diameter > 300km
CERES TOA LW Flux and Cloud Eff Temp using MODIS



Or just the dynamics of these large convective complexes?

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

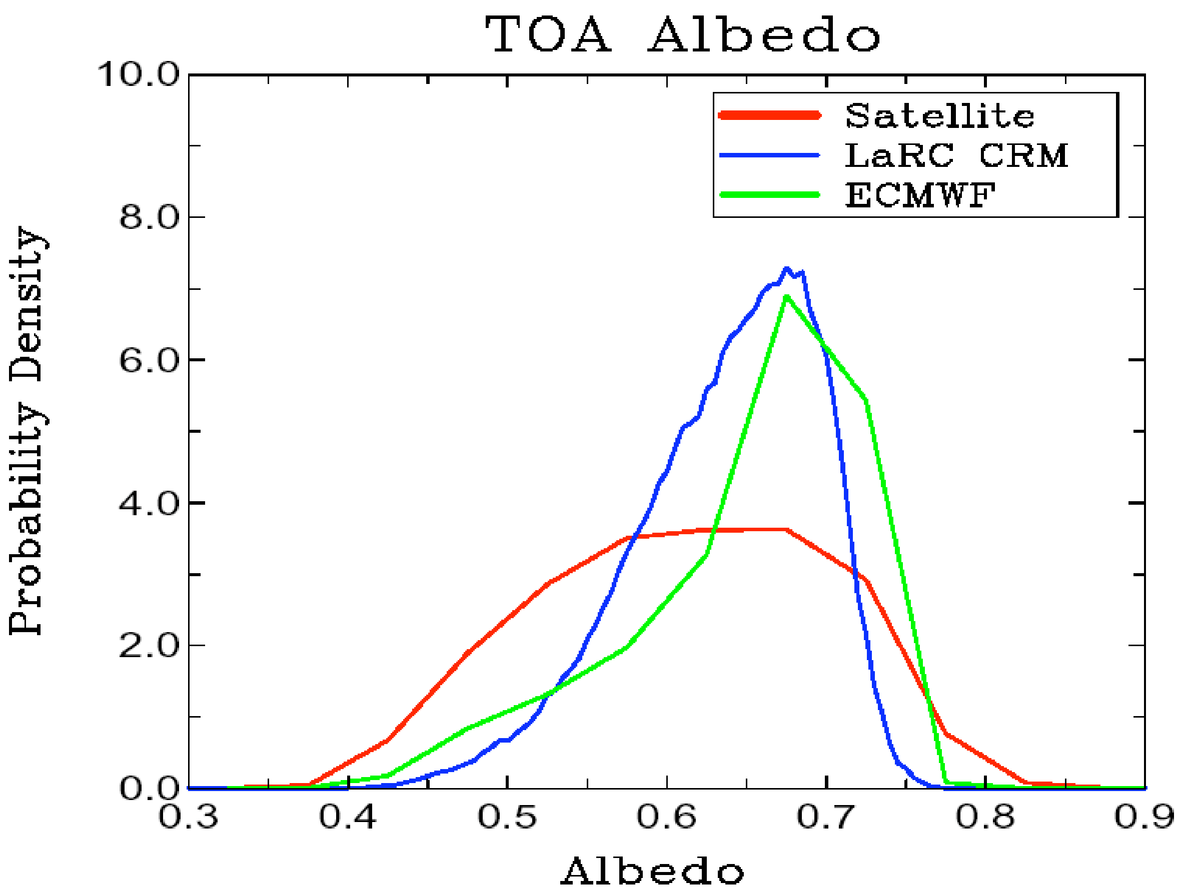


So what do models predict?

- ECMWF: 0.5 degree, 6-hourly assimilation analysis, including clouds
- CRM: LaRC2d CRM: 1 km resolution 2-D, 3rd order turb. closure (UCLA/CSU; Krueger 1988; Xu and Randall 1995)
- 29 cases of tropical convective systems with diameters greater than 300 km for March 1998: *Zcld>10km, tau>10, ice phase, overcast*

Large Deep Convective Systems:

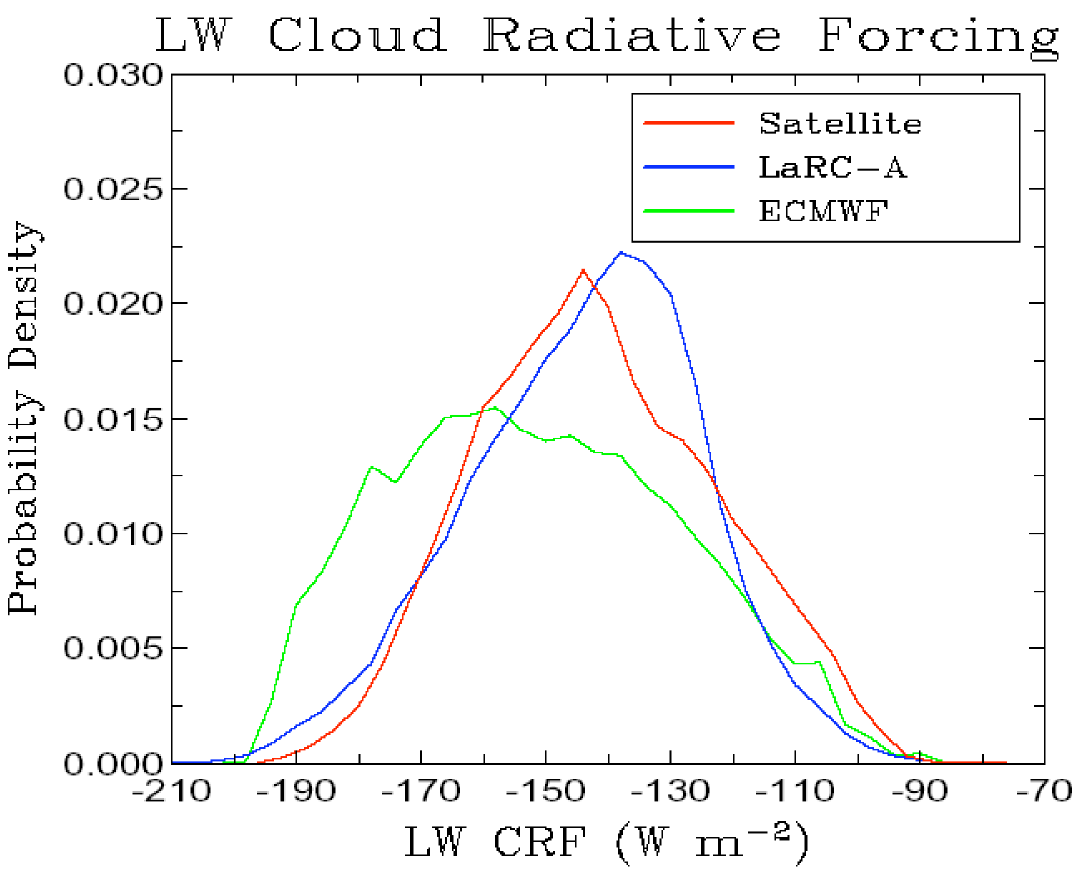
Zcld>10km, tau>10, Cf=1, Diameter > 300km
March, 1998, 25N to 25S, 29 cloud systems



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

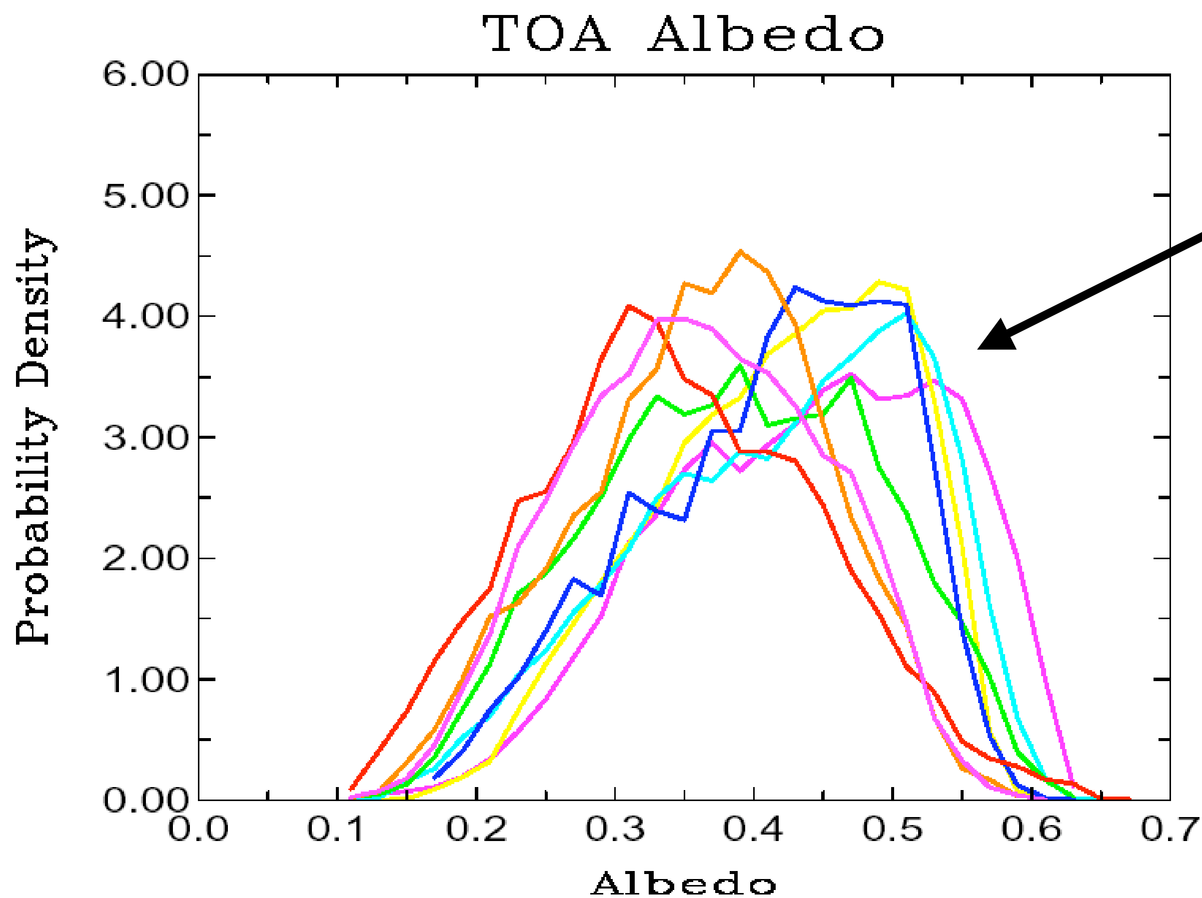


LW Cloud Radiative Forcing
ECWMF clouds too thick and cold. CRM a much better prediction of the LW cloud radiative effects.

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*

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?

Model/Data Comparison Methods

- **Radiation/Cloud Focused**
  - Classic: Monthly Mean Fluxes, Clouds, Aerosols
  - ISCCP 2-D Histograms of Cloud Height/Optical Depth/Frequency of Occurrence
  - By 2-D histogram principle components: the Jacob approach
  - By cloud type: The Xu approach

- **Atmospheric Dynamics Focused**
  - By vertical velocity: the Bony approach
  - By low/high surface pressure and fronts: the Tseuloudis approach.

- **dRadiation/dDynamics and dCloud/dDynamics**
  - Partial derivatives of cloud type/atmosphere state
  - Nonlinear approaches such as neural net

Model Test Types

- **Fully Coupled Ocean/Atmosphere/Land/Cryosphere**

- **AMIP style specified SST and Sea Ice**
  - Normal atmosphere GCM with SCM clouds
  - MMF atmosphere GCM with CRM clouds

- **Weather Prediction mode (initial condition large scale dynamics)**
  - SCM global cloud predictions
  - MMF CRM global cloud predictions
  - Regional SCM and CRM predictions by cloud type
  - Regional SCM and CRM predictions over surface sites (e.g. ARM)

Model Tests: Signal to Noise Issues

- **Internal climate noise: strong function of space/time scale**
  - i) red spectrum at weather scales
  - ii) blue spectrum at large time/space scales
  - iii) estimate using models and observations
  - iv) models a lower bound on climate noise?
  - v) results are a function of comparison type:
    grid box versus cloud type (eulerian/lagrangian)
  - vi) Is there a climate prediction limit analogous to weather prediction?
- **Data Errors**
  - i) strong function of time/space scale
  - ii) strong function of physical variable and cloud condition
  - iii) can also be a function of remote sensing conditions
    (e.g. viewing angle, solar zenith)
  - iv) function of comparison strategy: grid box versus cloud type very different
  - v) how can we better use models to set observing requirements?

Key Comparison Issues

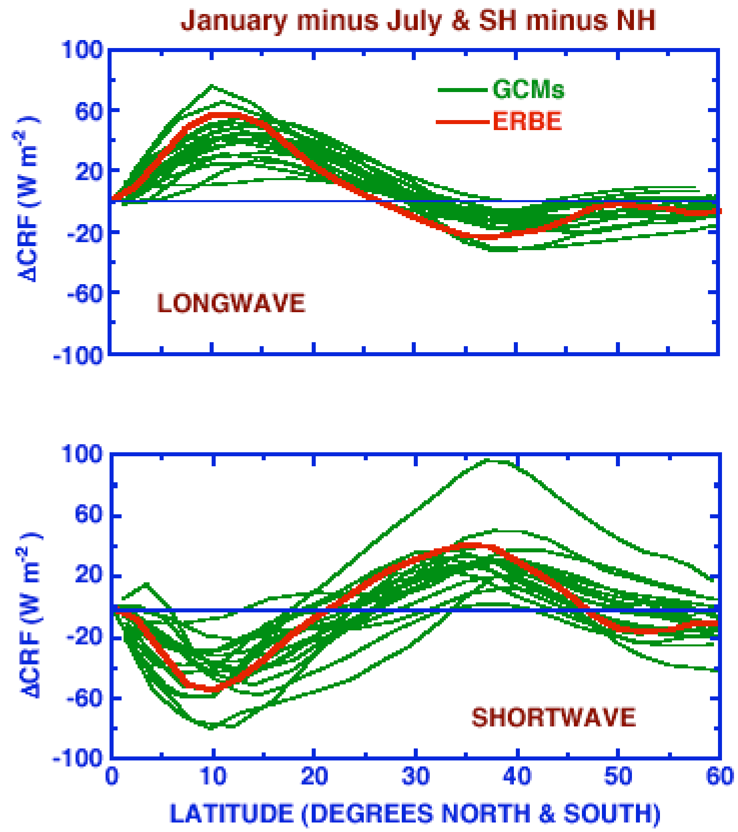
- **Accuracy requirements tests to constrain feedback to +/- X%?**
  - can limiting case thought experiments help?
  - can we use different climate models as “Earth plus N other Planets” to test comparison logic on how to tie model comparison accuracy to climate sensitivity accuracy?
  - What collection of tests might be sufficient? Is closure possible?
  - If aliens gave us 10 climate models and said one was perfect: how would we know which one? Could we tell if they were lying?

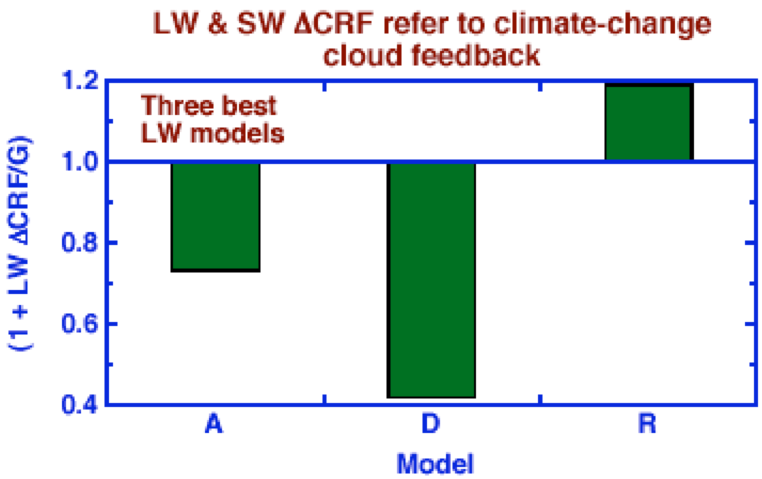
- **How do we verify completeness of tests? How do we measure it?**
  - completeness of dynamic states tested
  - completeness of cloud types tested
  - completeness of aerosol types tested

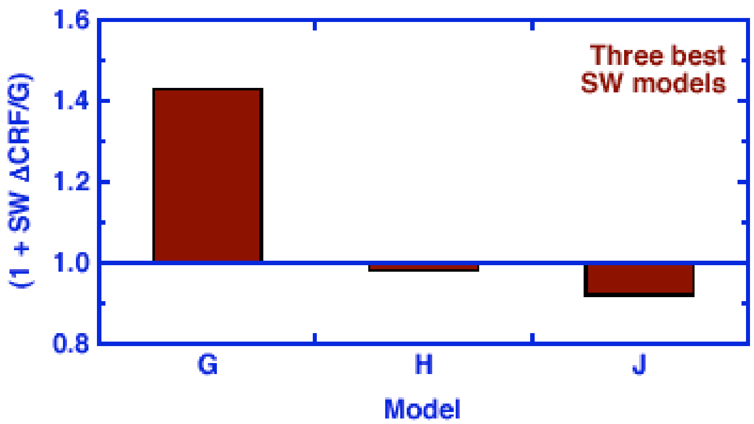
Model vs Data Intercomparisons

Seasonal Change Tests

(Cess et al)







Conclusion: Models Best at Seasonal Climate Change don't agree on century scale climate change: Necessary but not sufficient condition.

What collection of tests is sufficient?

Key Comparison Issues

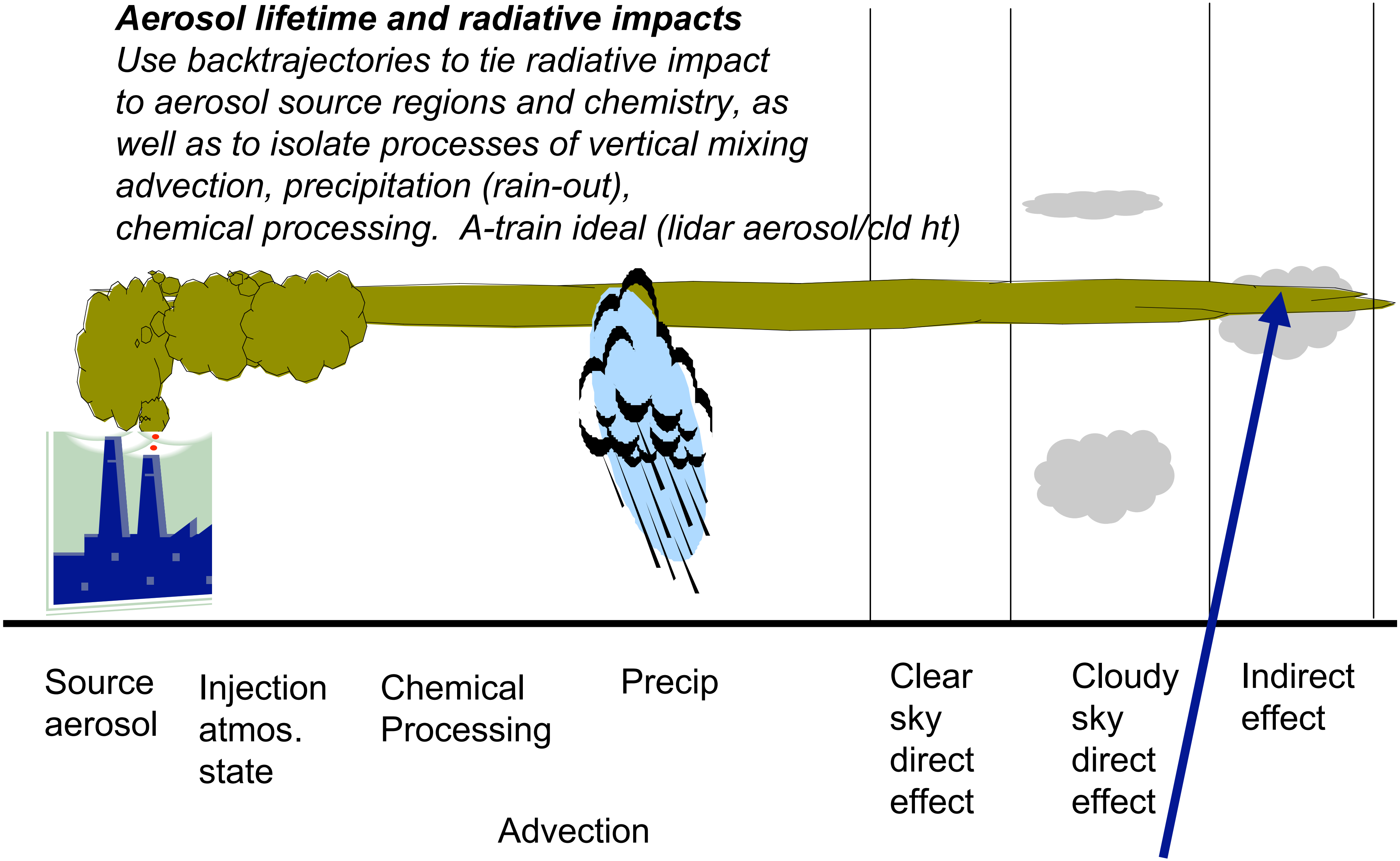
- **Can we predict the Cause/Effect power of tests? i.e. rapidity of forced “Eureka’s”**
- **For aerosol indirect effects with clouds: must decouple dynamics changes in clouds from aerosol changes: for any location/source two are strongly linked.**
  - example: azores with and without European aerosols in boundary layer.
  - this means aerosol “history” must be known for days prior to comparison.
- **Do cloud comparisons need past history of CCN for feedback? or only for forcing?**
- **Recent Xie article in BAMS: dcloud/dSST changes sign with spatial scale:**
  - positive at 1 to 10 km scale, but negative at hundreds of km scale (Klein and Hartmann).

Key Physical Processes

- Vertical Velocities
- Microphysics parameterizations
- Closure for boundary layer clouds even in CRMs: ultimately LES in CRM?
- How critical are 3-D radiation effects?
- Small scale clear/cloudy radiation are critical (recent MMF tests show this)

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....

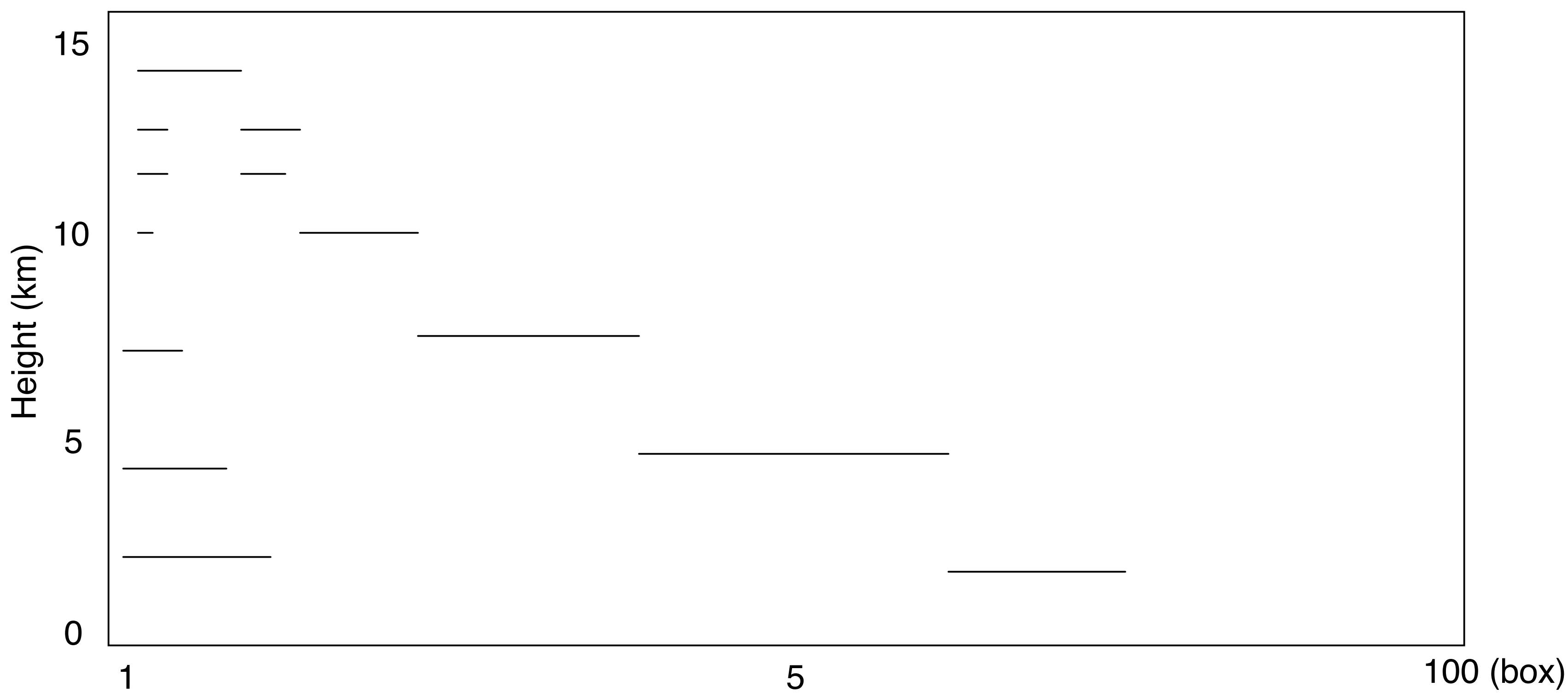
Backup Slides

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

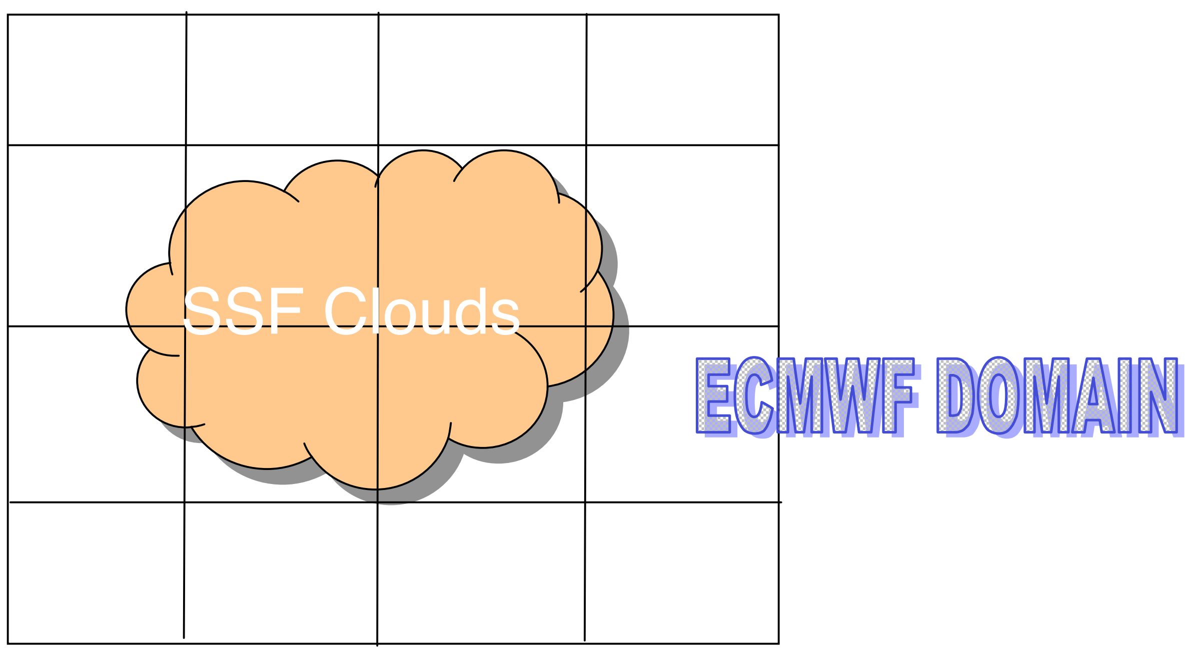
Analysis of ECMWF predicted cloud fields (cont.)

- 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