Are cloud changes over recent decades a response to global warming?

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UCLA Atmospheric and Oceanic Sciences Seminar

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A Little Help from My Friends

Collaborators:

- Bob Allen (UCR)
- Amato Evan and Seethala Chellappan (SIO)
- Mark Zelinka and Steve Klein (LLNL)
- Tim Myers (was SIO but now UCLA)
- Michael Olheiser (Winona State)

Funders:

NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION U.S. DEPARTMENT OF COMMERCE

NSF

NASA

2°C Equilibrium Global Warming?

$D T = - D F / l$

$l = l_{BB} + S\, l_{i}$

$- D F_{2xCO2} = 3.7 \text{ W m}^{-2}$

$l_{BB} = -3.2 \text{ W m}^{-2} \text{ K}^{-1}$

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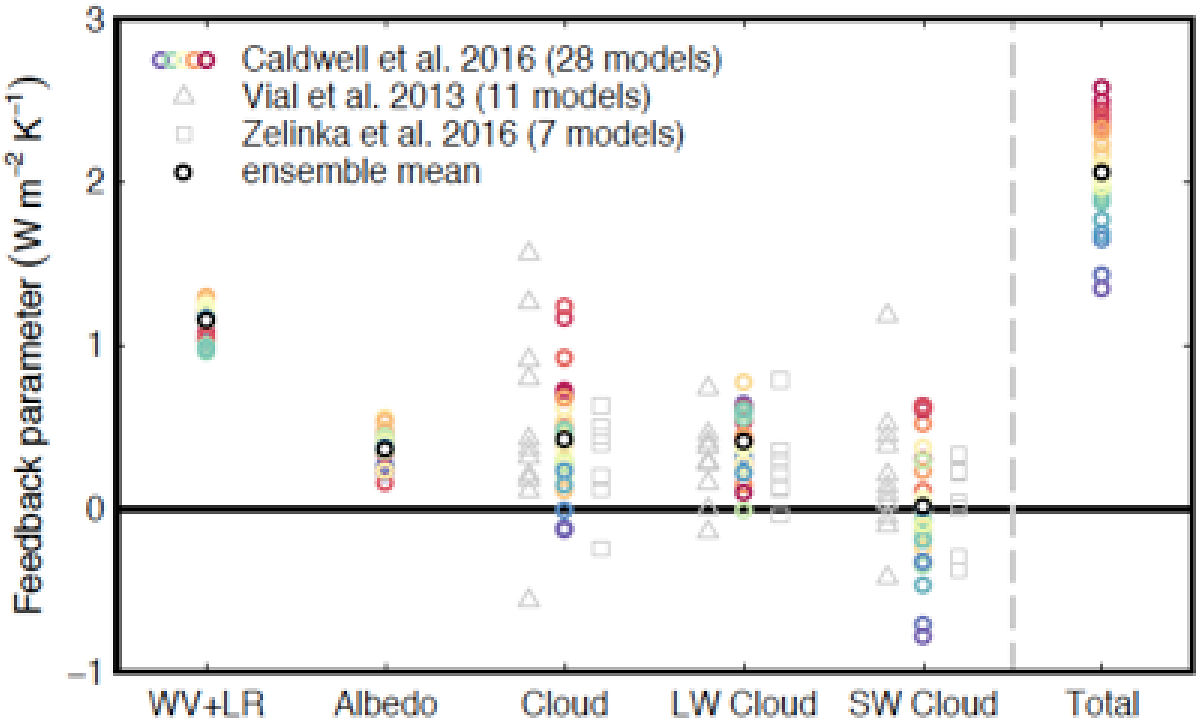
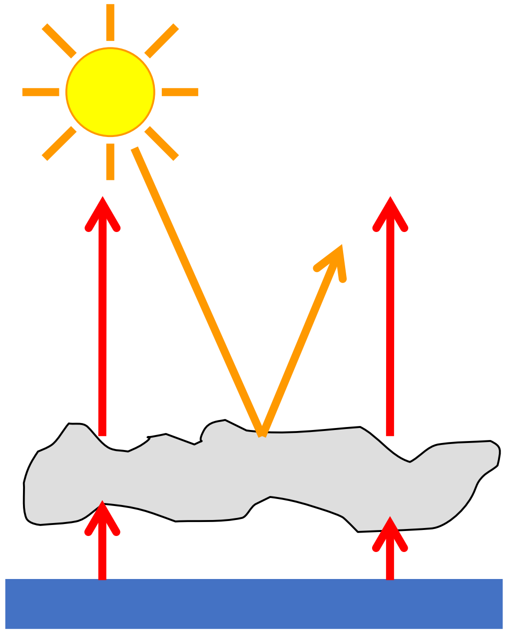


courtesy of Steve Klein

Clouds as a Reflective Blanket

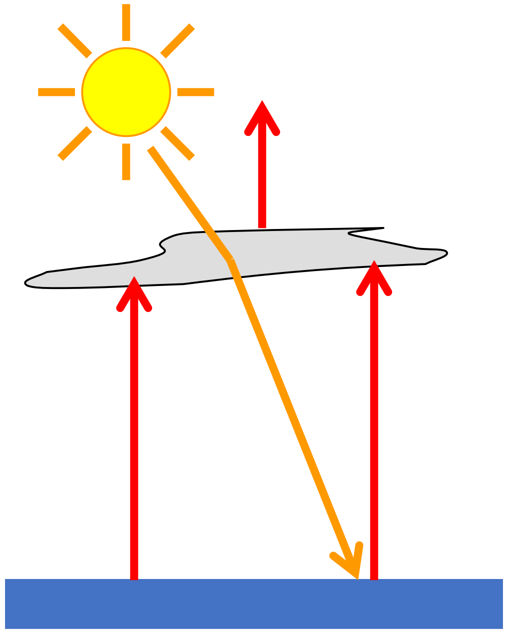


low-level cloud

strong reflection

weak greenhouse

cools the earth

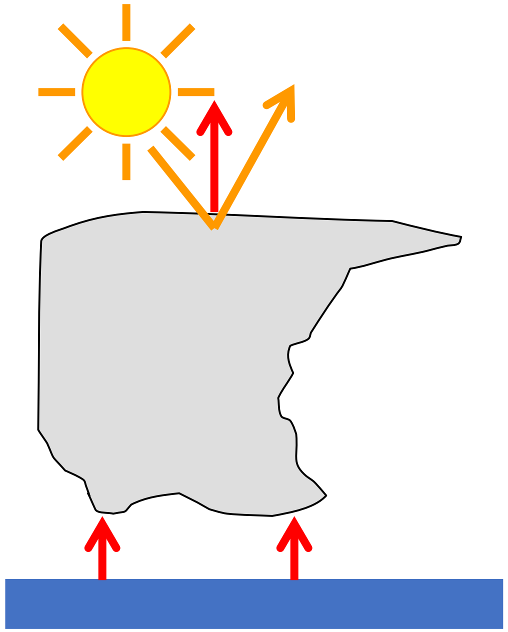


high-level cloud

weak reflection

moderate greenhouse

warms the earth



thick cloud

strong reflection

strong greenhouse

near-zero effect

Global Cloud Radiative Effect

- Current reduction of solar absorption by clouds:

  $-48\ \mathrm{W\ m^{-2}}$

- Current greenhouse effect by clouds:

  $+26\ \mathrm{W\ m^{-2}}$

- Current net effect of clouds:

  $-21\ \mathrm{W\ m^{-2}}$

Global Cloud Radiative Effect

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  $-21\ \mathrm{W\ m^{-2}}$

Greenhouse effect from 40% increase in CO_2 since 1850:

$+1.6\ \mathrm{W\ m^{-2}}$

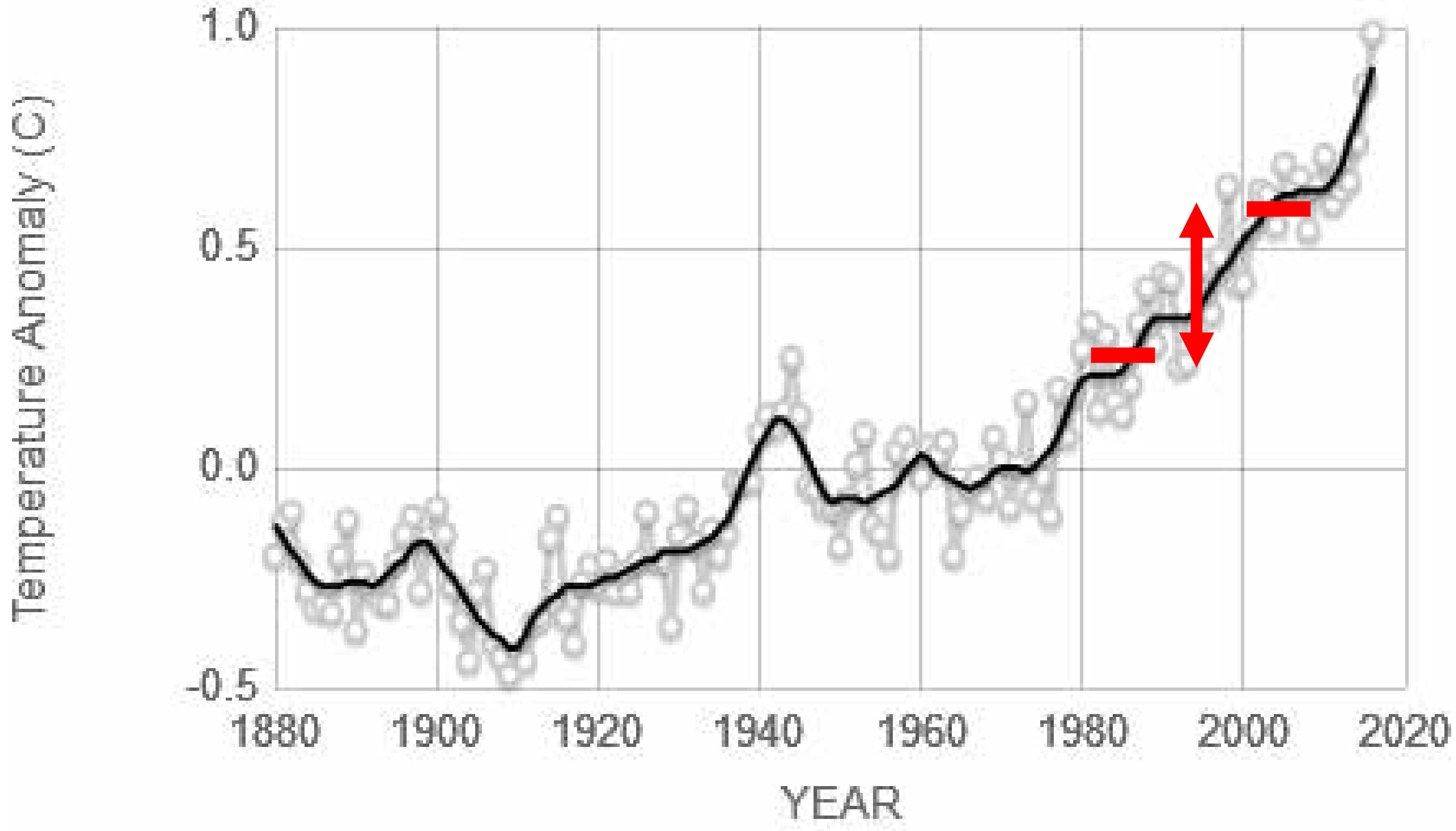
= 3% change in cloud reflection effect

= 5% change in cloud greenhouse effect

Small changes in clouds are important!

Substantial Global Warming from 1980s to 2000s

How have clouds changed during the satellite era?



Source: climate.nasa.gov

Questions

- Global climate models exhibit agreement for some types of cloud changes in response to global warming.

  Is there observational confirmation?

- Global climate models exhibit disagreement for other types of cloud changes in response to global warming.

  Can observations show what cloud change is correct?

High-Level Cloud Top Rise

Most global climate models exhibit increasing high-level cloud top height as the tropopause rises with global warming

Change in Cloud

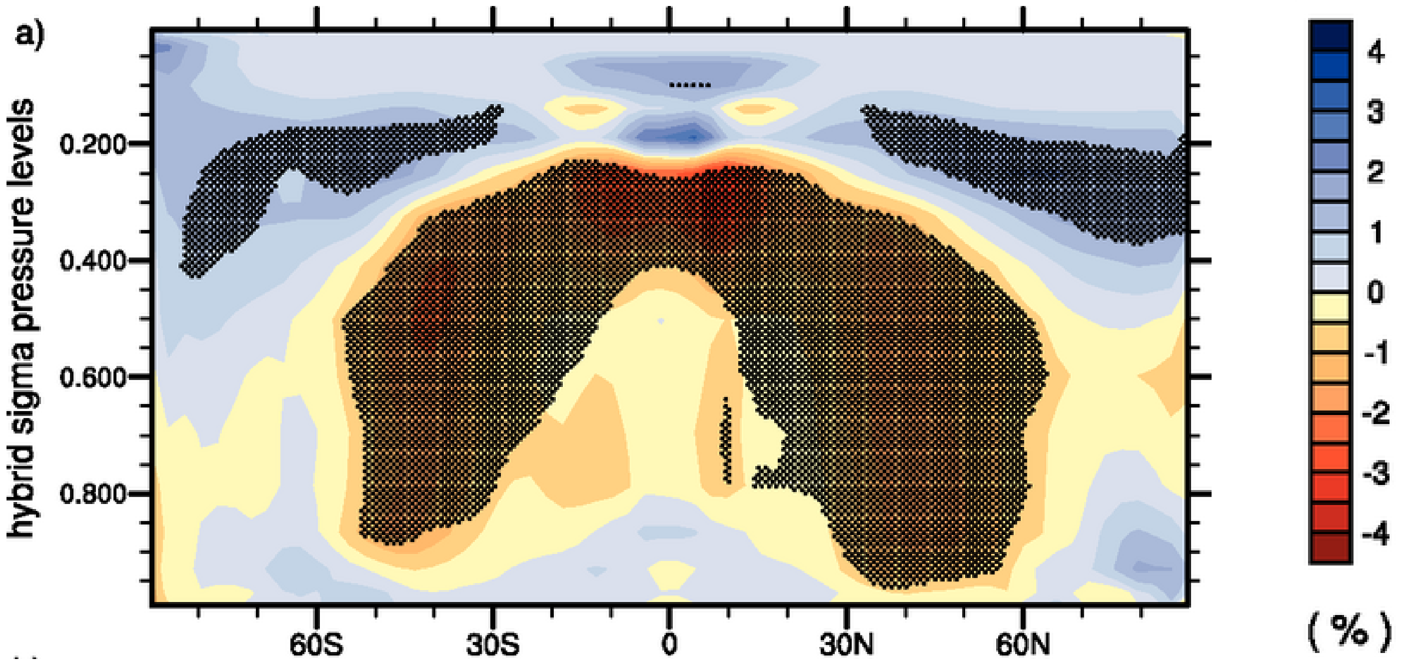
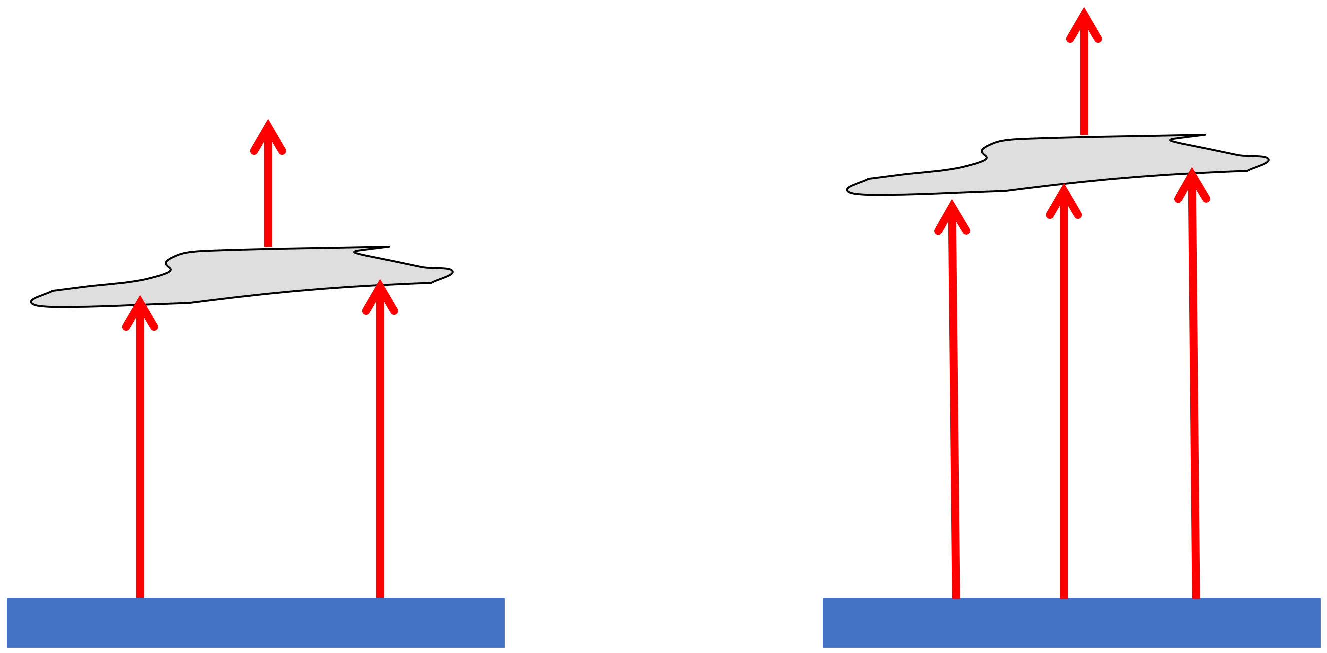


Fig. 10.10 from IPCC AR4 WG I Report

High-Level Cloud Top Rise

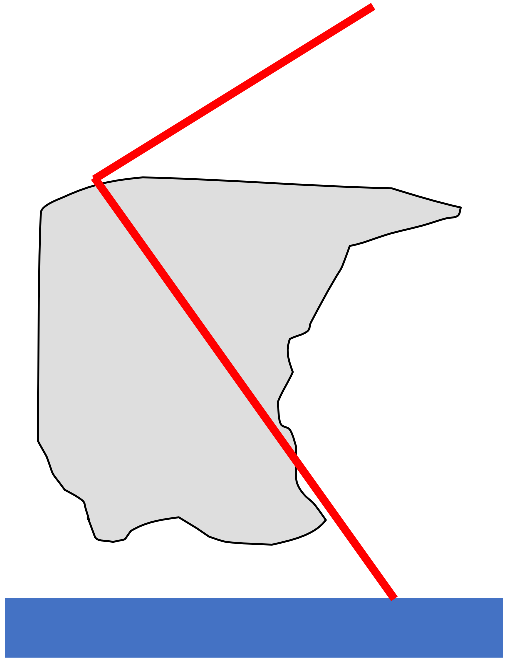
- Less thermal emission by higher cold clouds relative to the warmer surface
- **Positive feedback, exacerbates global warming**



Before After

Theory for High-Level Cloud Top Rise

- Increased greenhouse gas concentration warms troposphere but cools stratosphere
- Fixed Anvil Temperature hypothesis (Hartmann and Larson 2002)



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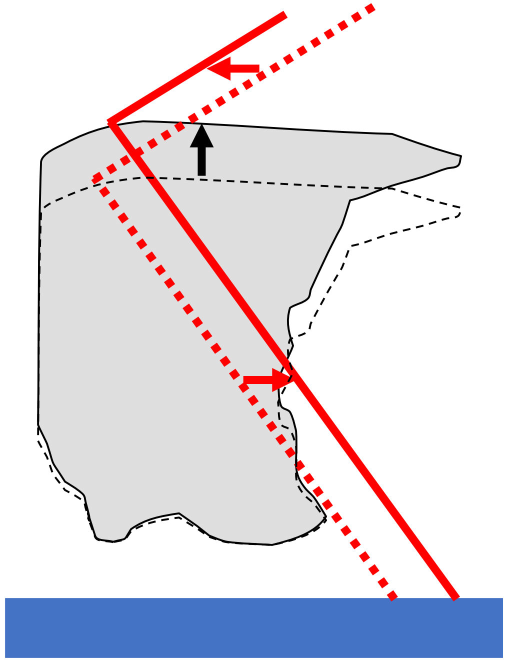


Expansion of the Dry Subtropical Zone

Most global climate models exhibit decreasing cloud cover at the subtropical boundary as tropics expand with global warming

Change in Cloud Cover

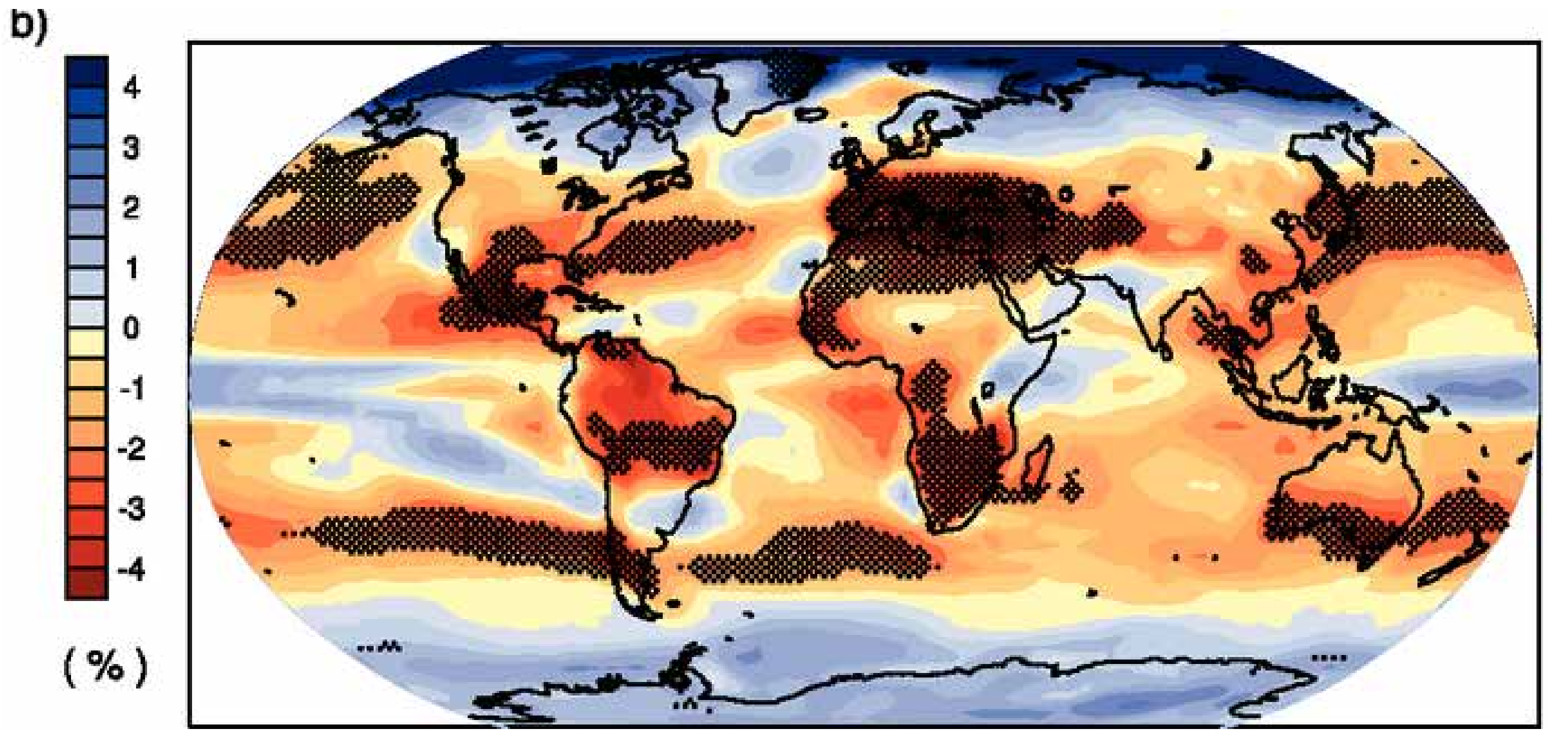
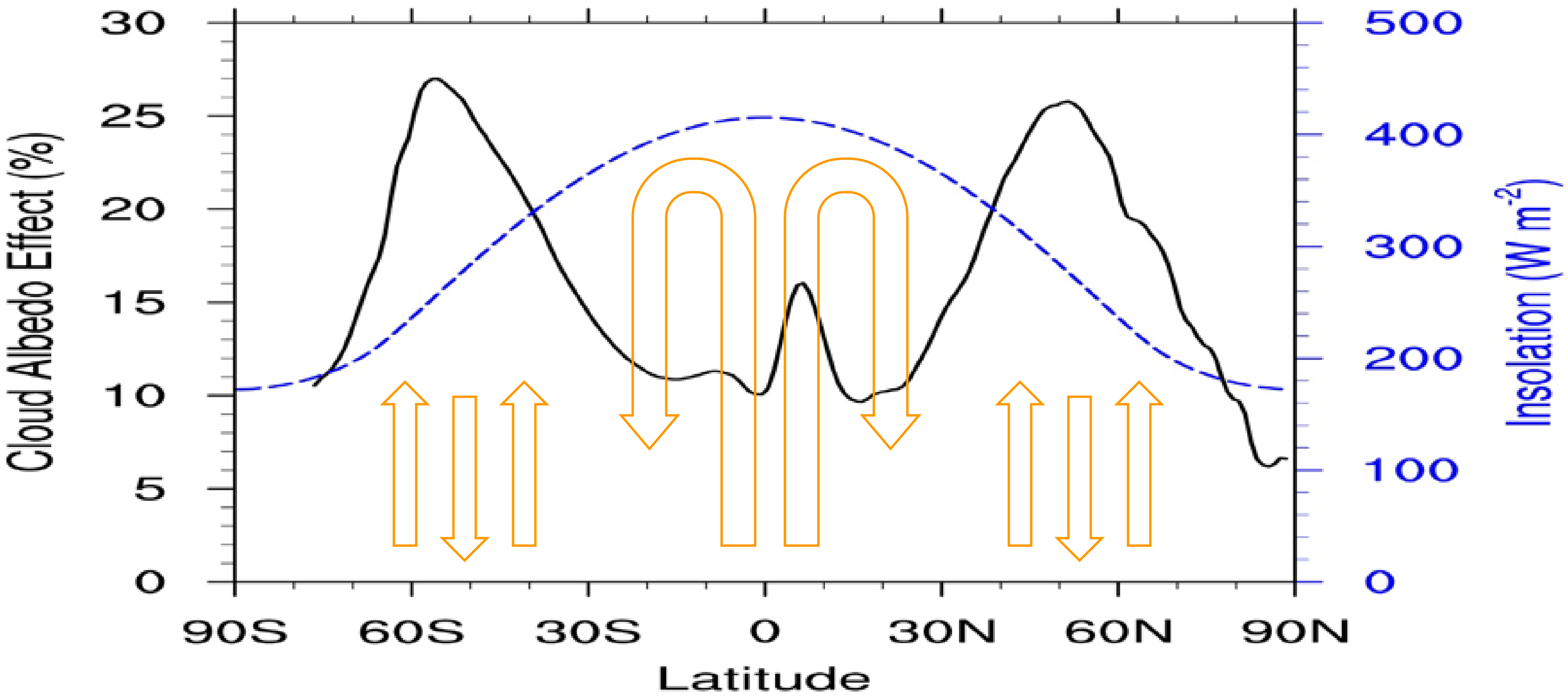


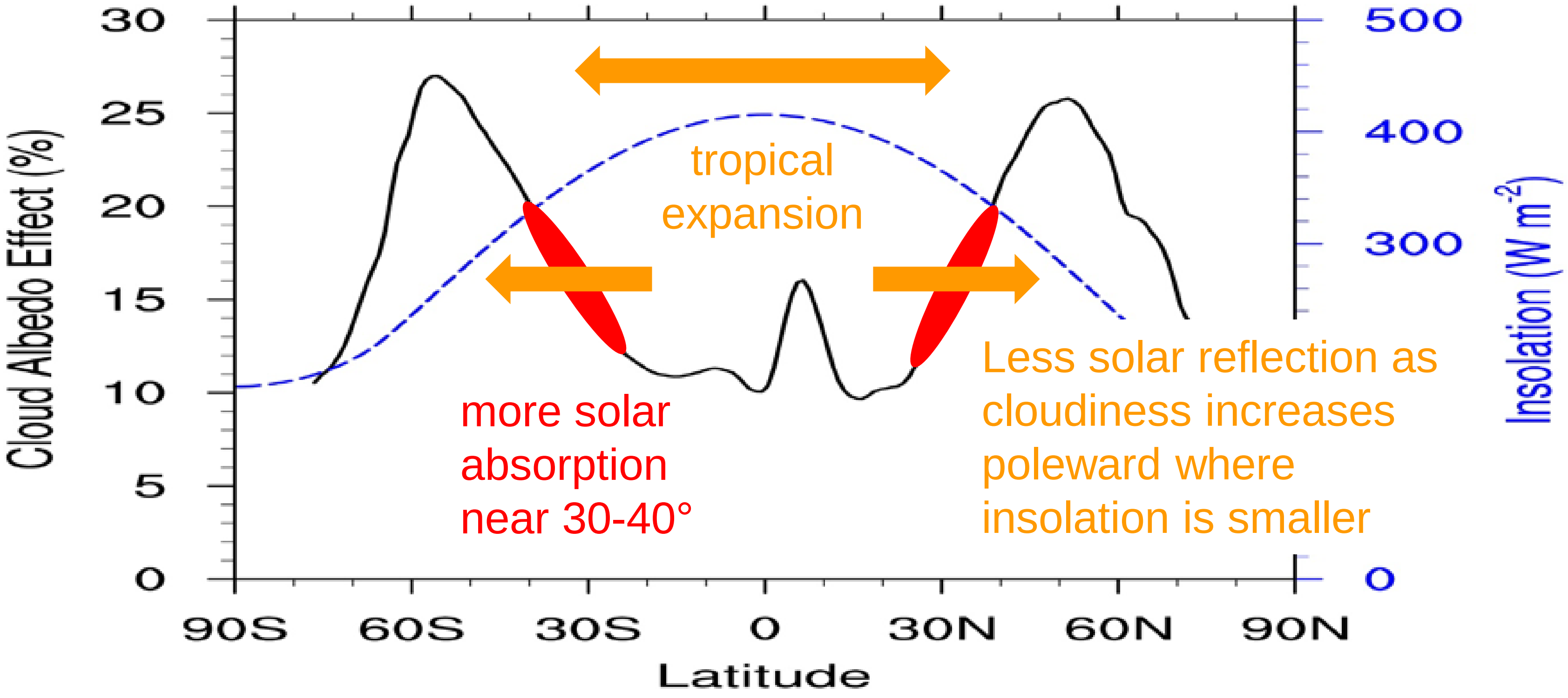
Fig. 10.10 from IPCC AR4 WG I Report

Expansion of the Dry Subtropical Zone



ocean-only CERES SW CRE / S_0

Expansion of the Dry Subtropical Zone



Positive feedback, exacerbates global warming

Theory for Expansion of the Subtropical Dry Zone

Held and Hou (1980)

Hadley Cell conserves momentum and matches thermal wind at boundary

$$\phi_{Hadley} \sim \left(\frac{H \Delta_T}{\Omega^2 T_0} \right)^{1/2}$$

Hadley Cell expands because tropopause *H* rises

Contraction for weaker equator-to-pole temperature gradient!

Held (2000)

Hadley Cell boundary determined by latitude of onset of baroclinic instability

$$\phi_{Hadley} \sim \left(\frac{NH}{\Omega} \right)^{1/2}$$

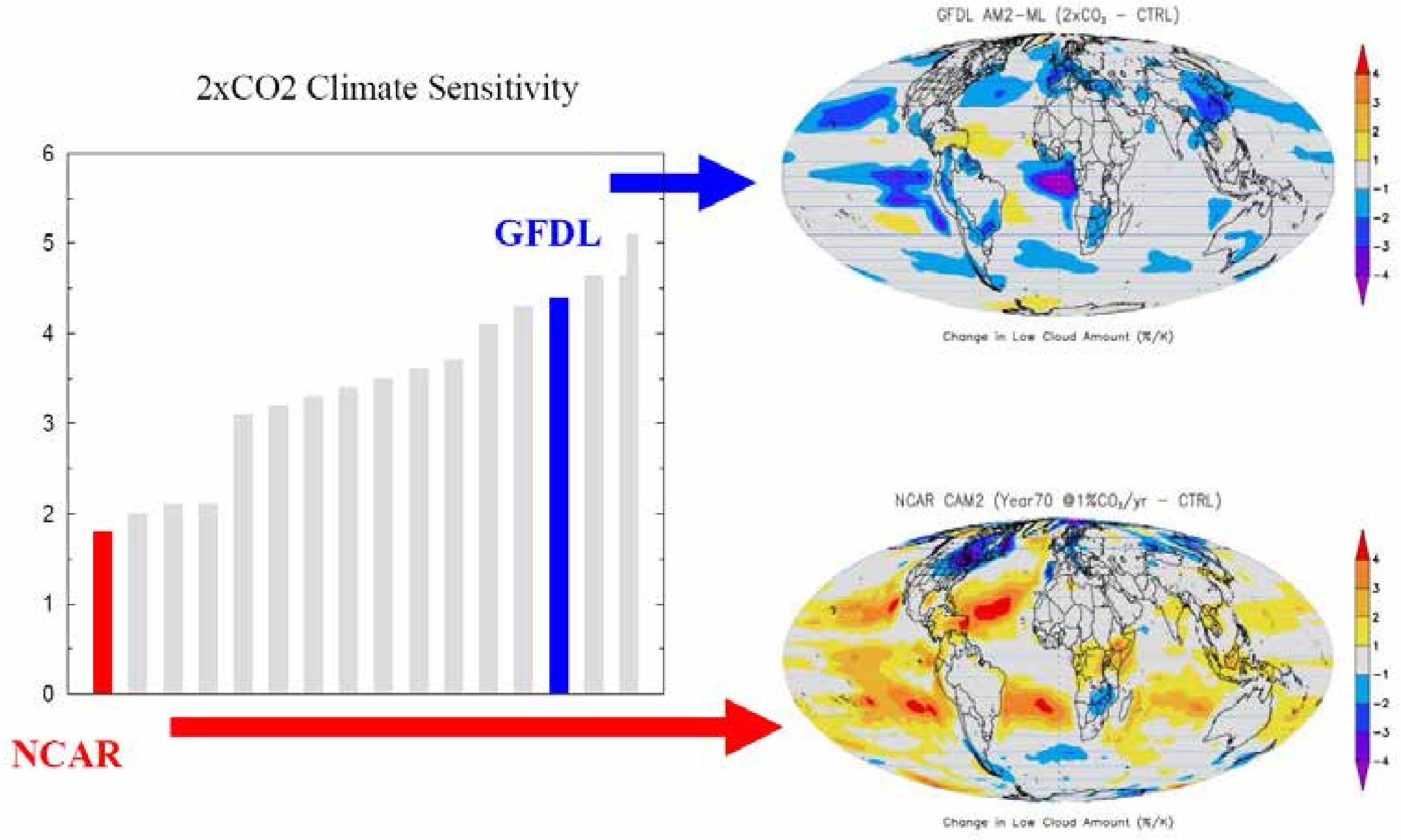
Hadley cell expands because stratification *N* increases and tropopause *H* rises

Analysis of GCMs suggests this is dominant process (Lu et al. 2007)

Change in Low-Level (Sub)Tropical Clouds

Will low-level cloudiness increase or decrease with global warming?

Largest source of disagreement between global climate models (Bony 2005)



Courtesy of Brian Soden

Theory for Change in Low-Level Clouds

- No fundamental theory
- Interannual observations suggest reduced low-level cloud with warming (Qu et al. 2015, Myers and Norris 2016)
- Large eddy simulations suggest reduced low-level cloud with warming (Bretherton 2015)
- **If so, positive feedback, exacerbates global warming**

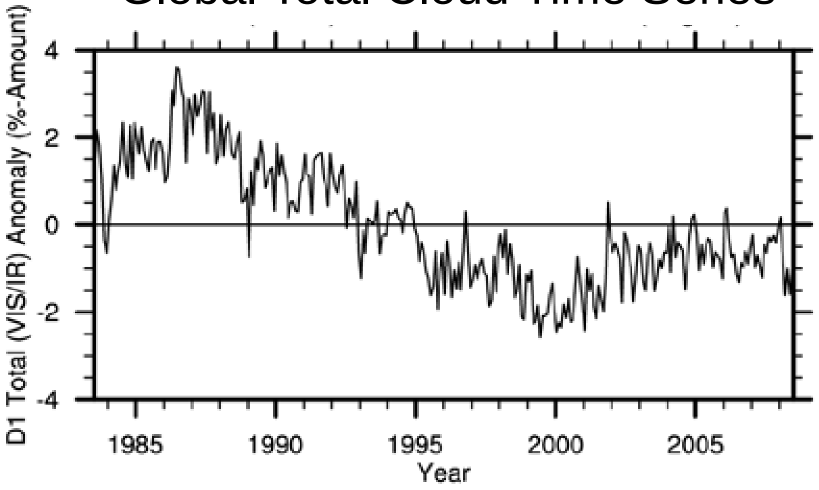
What Do Satellite Observations report?

- 2000-present Terra+Aqua CERES global albedo ~0.29
- 1985-1989 ERBS global albedo ~0.30

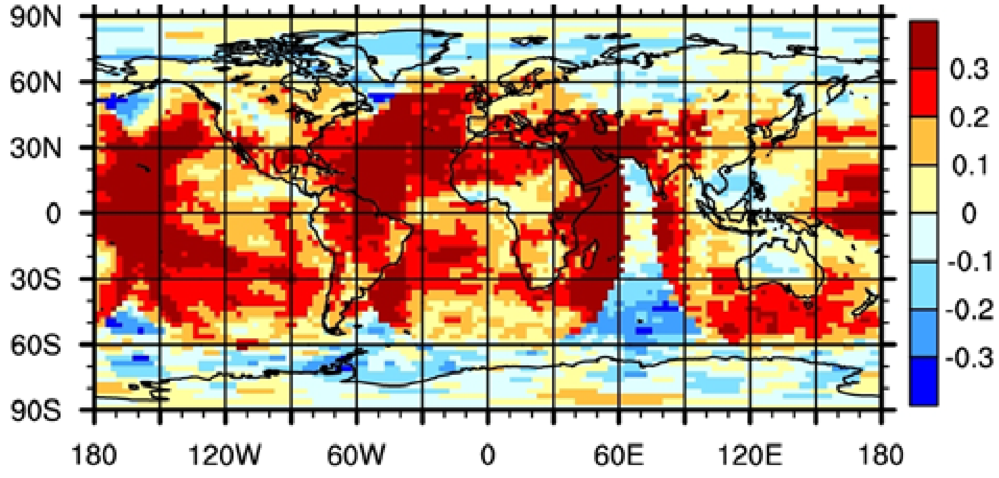
- Difference in albedo à ~3 W m^{-2} more solar radiation absorbed during 2000s than during 1980s
- But in reality, no absolute calibration between satellites

What Do Satellite Observations Report?

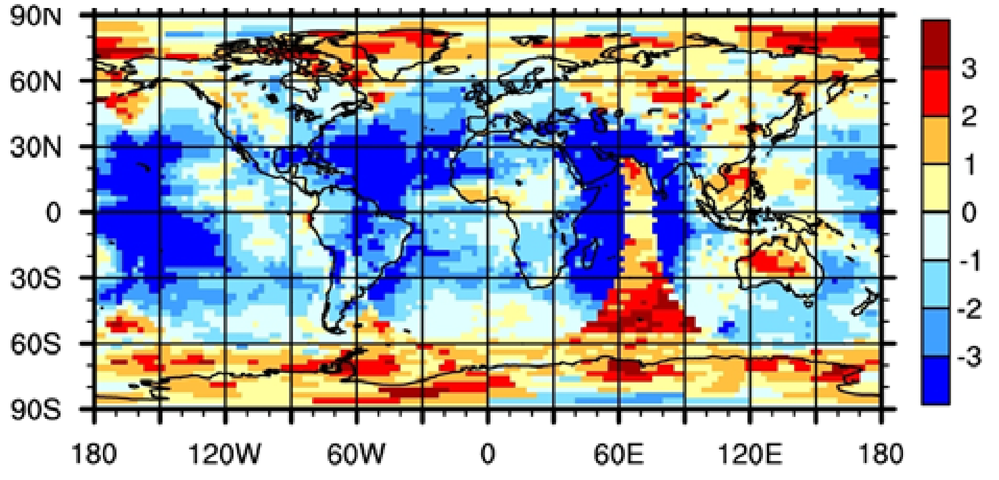
Global Total Cloud Time Series



Local Correlation with Global Series



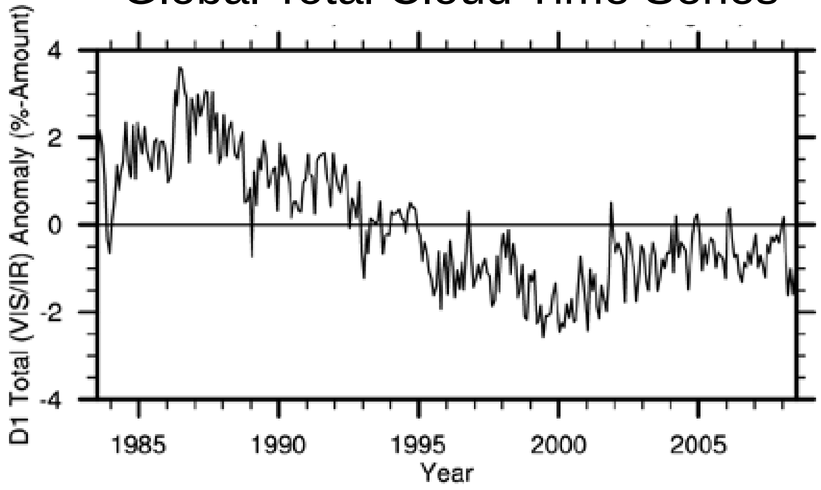
Local Trends (%-Amount per Decade)



International Satellite Cloud Climatology Project (ISCCP)

What Do Satellite Observations Report?

Global Total Cloud Time Series



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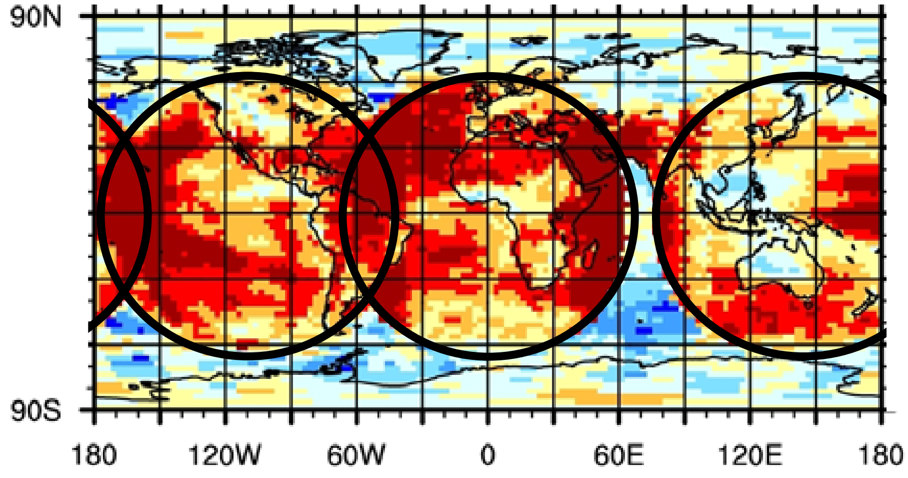
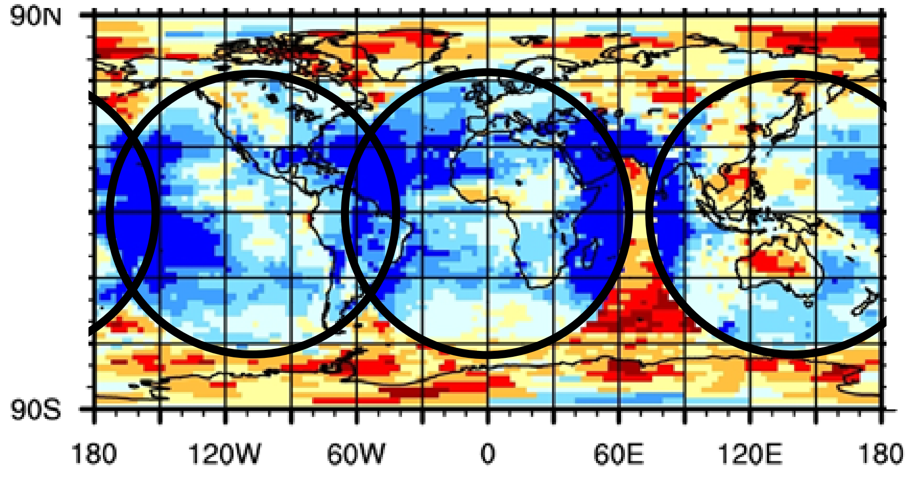


Local Trends (%-Amount per Decade)

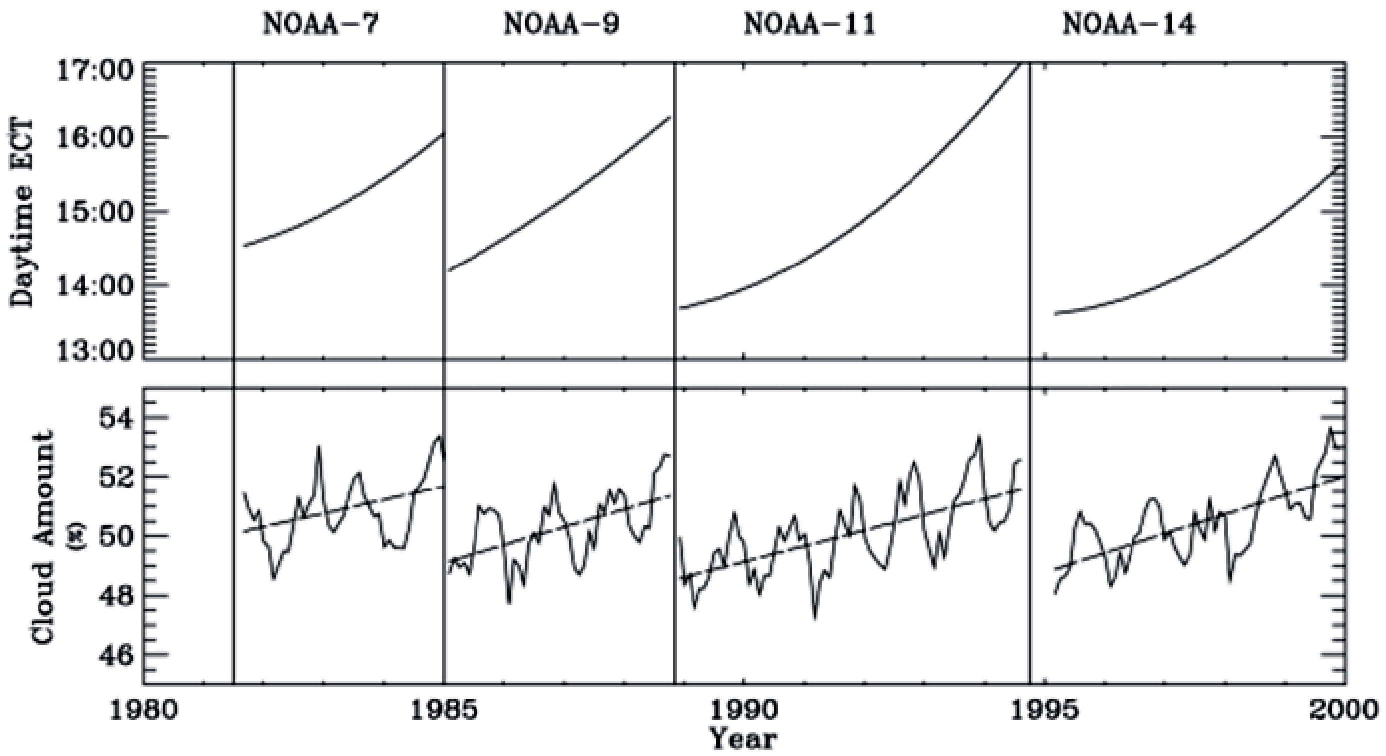


Obvious artifacts associated with satellite view angles far from nadir and view areas of geostationary satellites

What Do Satellite Observations Report?

Pathfinder Atmospheres – Extended (PATMOS-x)

Obvious artifacts associated with satellite transitions and drift through local time of equatorial crossing



From Jacobowitz et. al. (2003)

What now?

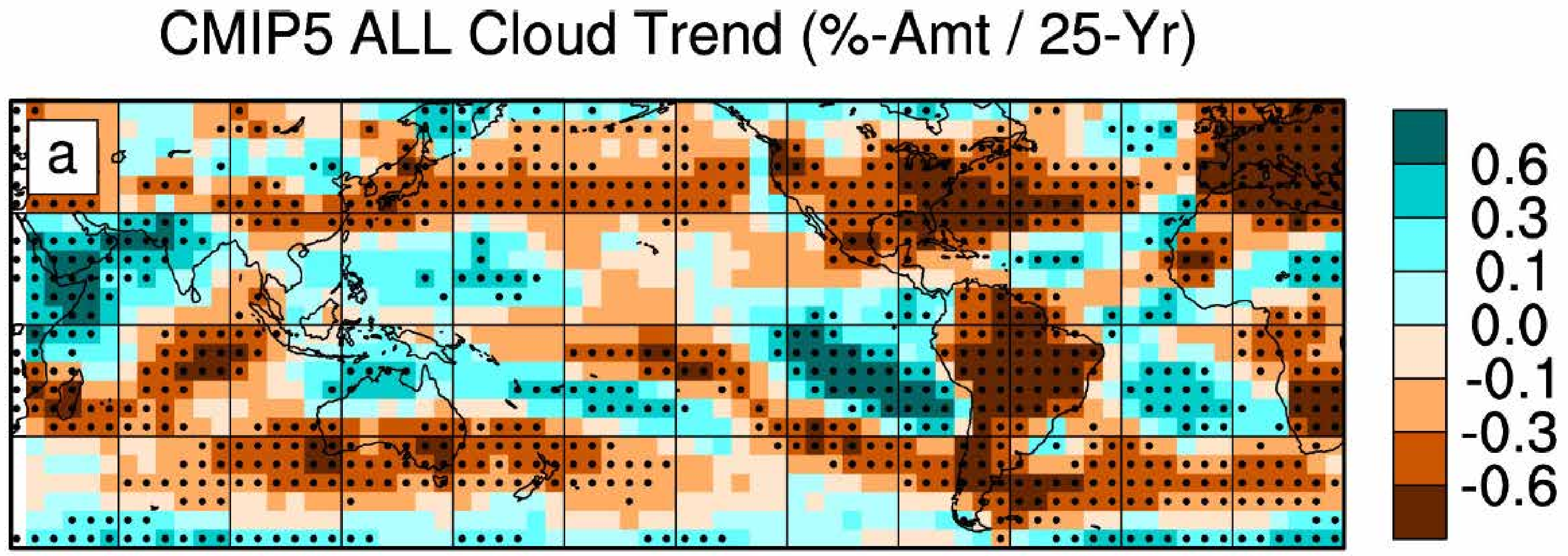
- Impossible to determine observed global mean cloud change

But…

- Cloud response to warming in global climate models is generally not spatially uniform
- Can we look at spatial patterns of change rather than global mean change?

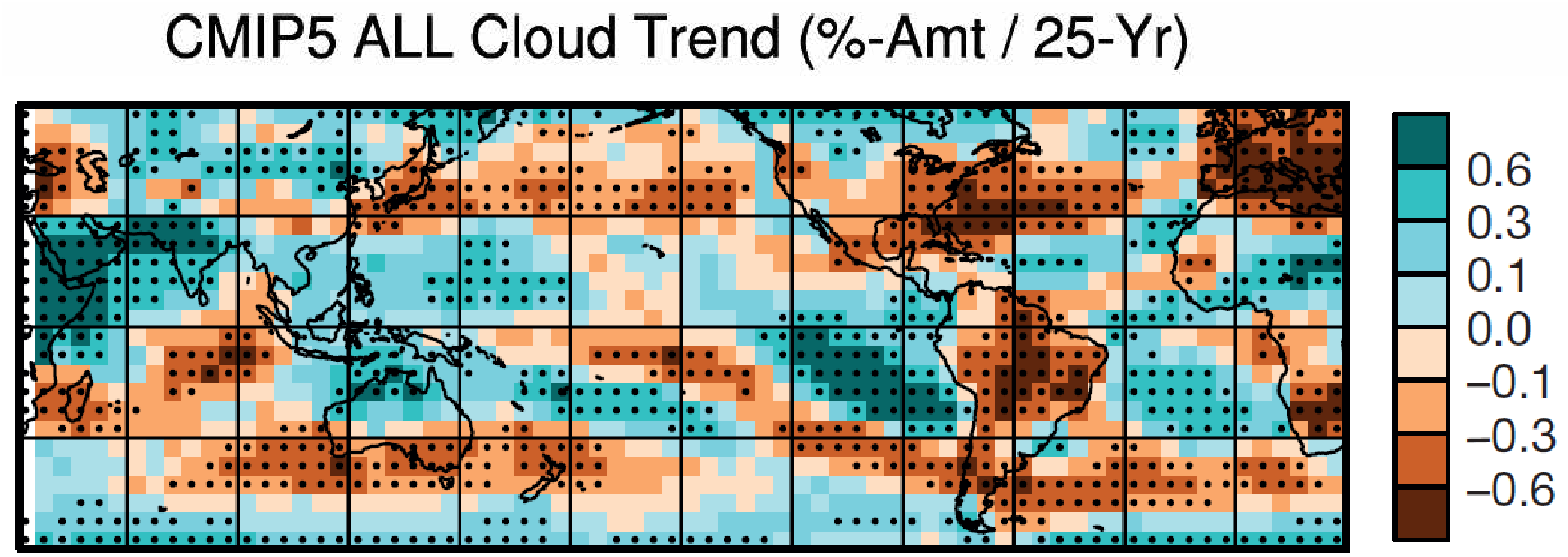
Solution: remove global mean cloud change from models and observations and compare patterns

Model Cloud Change due to Historical Forcing



Ensemble mean cloud change between 1983 and 2009 for simulations with historical changes in greenhouse gases, anthropogenic aerosol, ozone, and volcanic aerosol (33 models and 107 realizations)

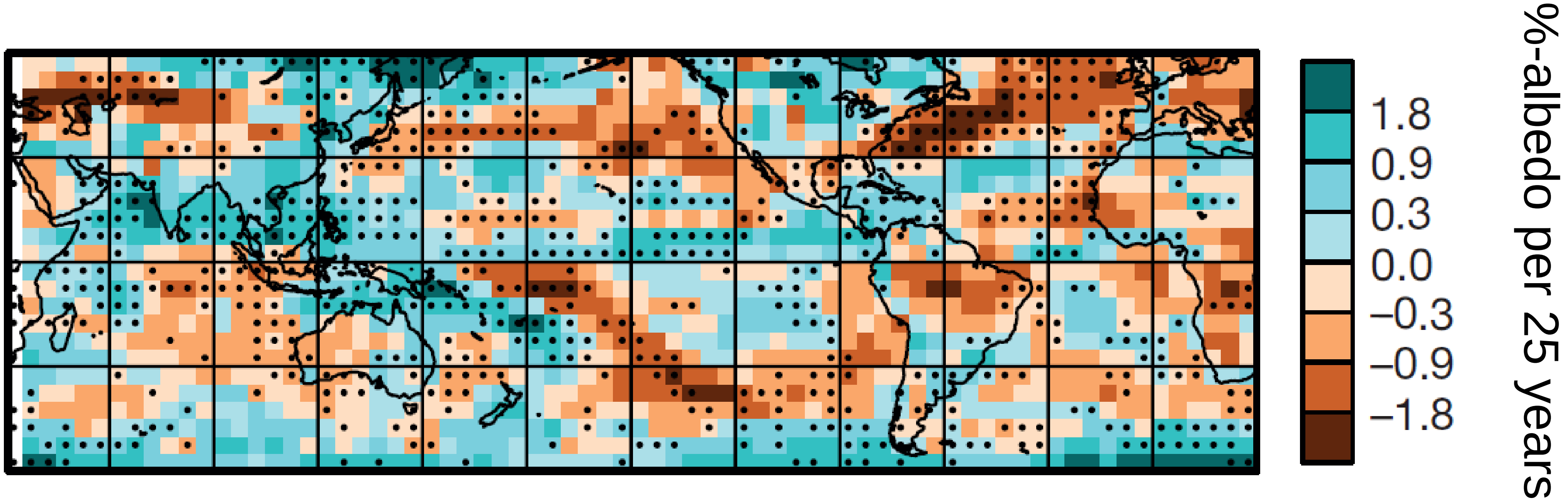
Model Cloud Change due to Historical Forcing



After subtracting a global mean cloud trend of
0.13%-amount per 25 years from every grid box

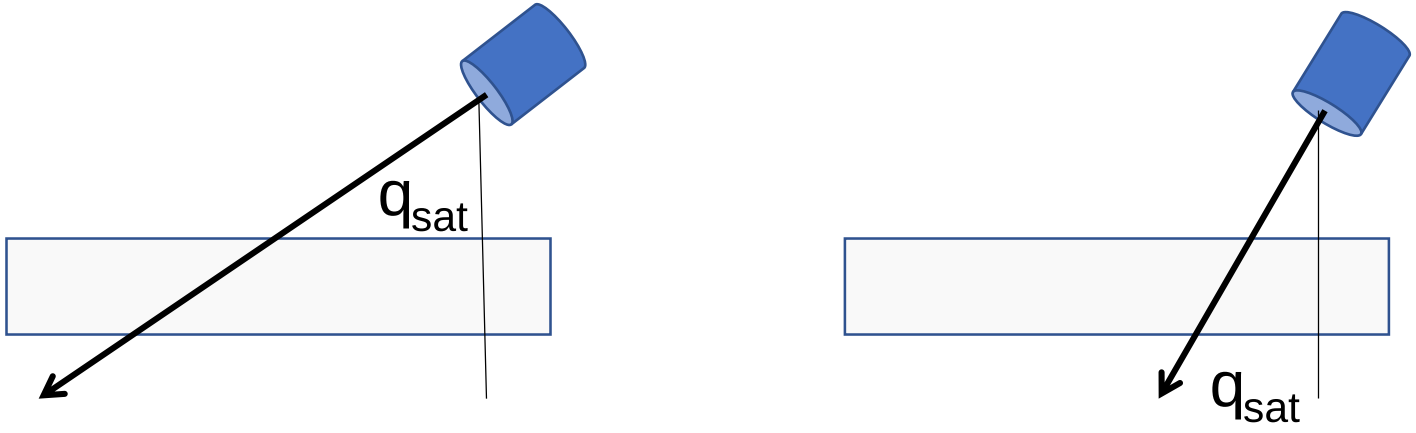
CERES-ERBS Albedo Change Pattern

- Multiply ERBS albedo values by constant factor so ERBS global mean albedo matches CERES global mean albedo
- Subtract ERBS 1985-1989 mean from CERES 2002-2014 mean



ISCCP Satellite View Angle Artifact

- Systematic changes in satellite view angle occur over time (Evan et al. 2007)



- Longer path length for large m_{sat} enables easier cloud detection
- Path length varies according to 1 / $\cos(q_{sat})$

<u>Removing the Satellite View Angle Artifact</u>

No universally applicable physical theory for how cloud retrievals vary with view angle

à *apply empirical procedure*

<u>Do for each grid box</u>

- Remove seasonal cycle and diurnal cycle to get anomalies
- Assume linear relationship between cloud C and $\mathrm{m} = \cos(\mathrm{q}_{sat})$

$$C(x,t) = A(x)\,\mathrm{m}(x,t) + R(x,t)$$

- Calculate A via linear regression
- Obtain residuals R from best-fit line

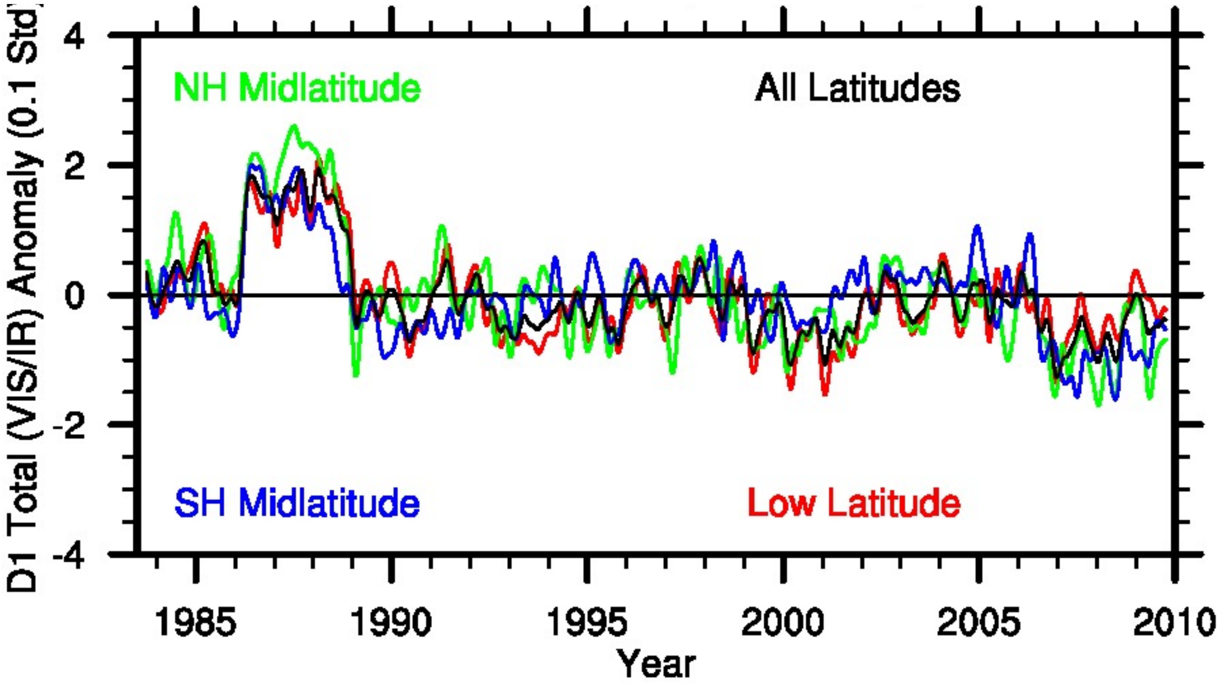
$$R = C - A\,\mathrm{m}$$

corrected cloud anomalies (R) do not vary with satellite view angle

ISCCP Satellite View Area Artifact

- ISCCP calibrates with gain and offset (linear)
- Miscalibration and/or errors in ancillary input data will produce similar relative changes for every location viewed by a satellite

Average Cloud Anomalies for European Geostationary Satellite



Spurious variability is ***coherent*** and ***very large-scale***

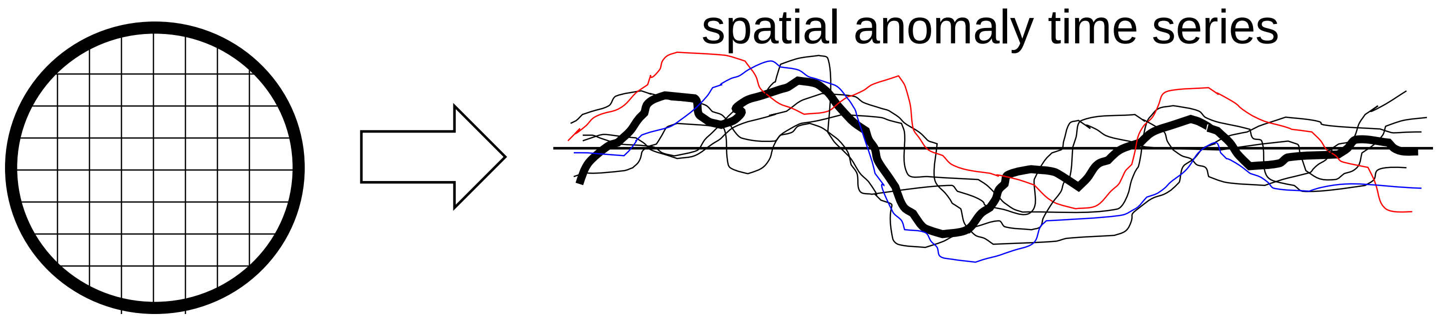
Removing the Satellite View Area Artifact

- Calibration and other problems produce artificial cloud changes that are spatially coherent at very large scales
- Local differences from the large-scale mean are mostly real

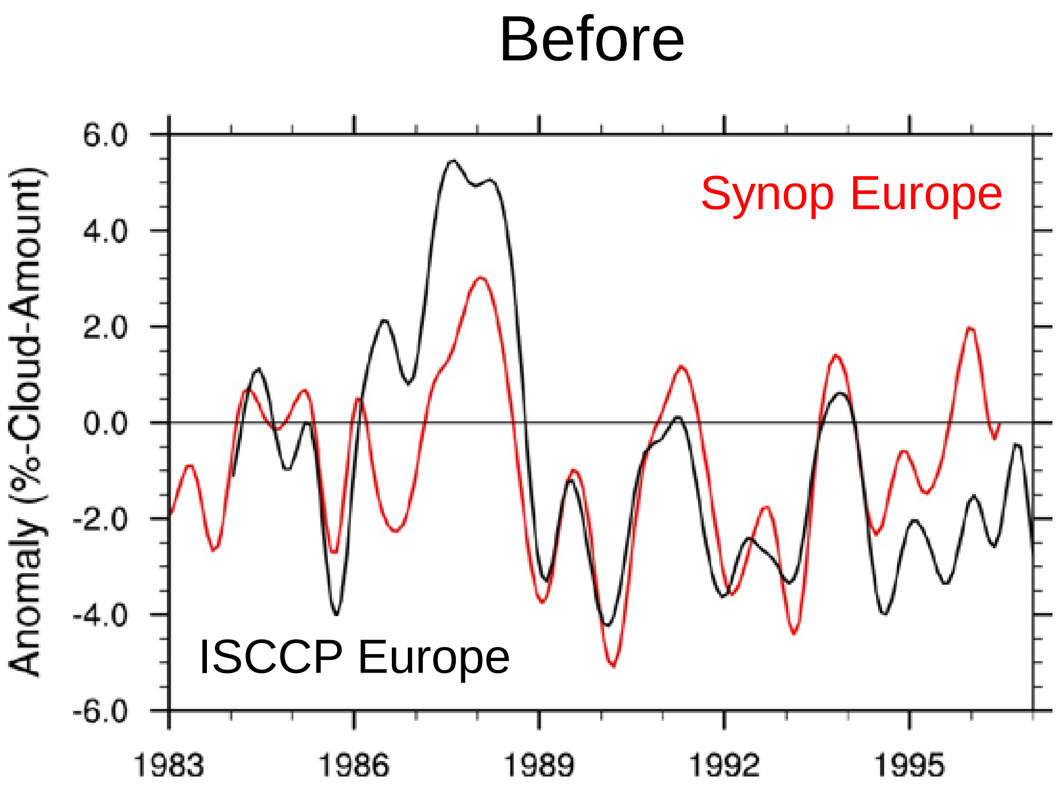
à Subtract large-scale mean time series from local time series

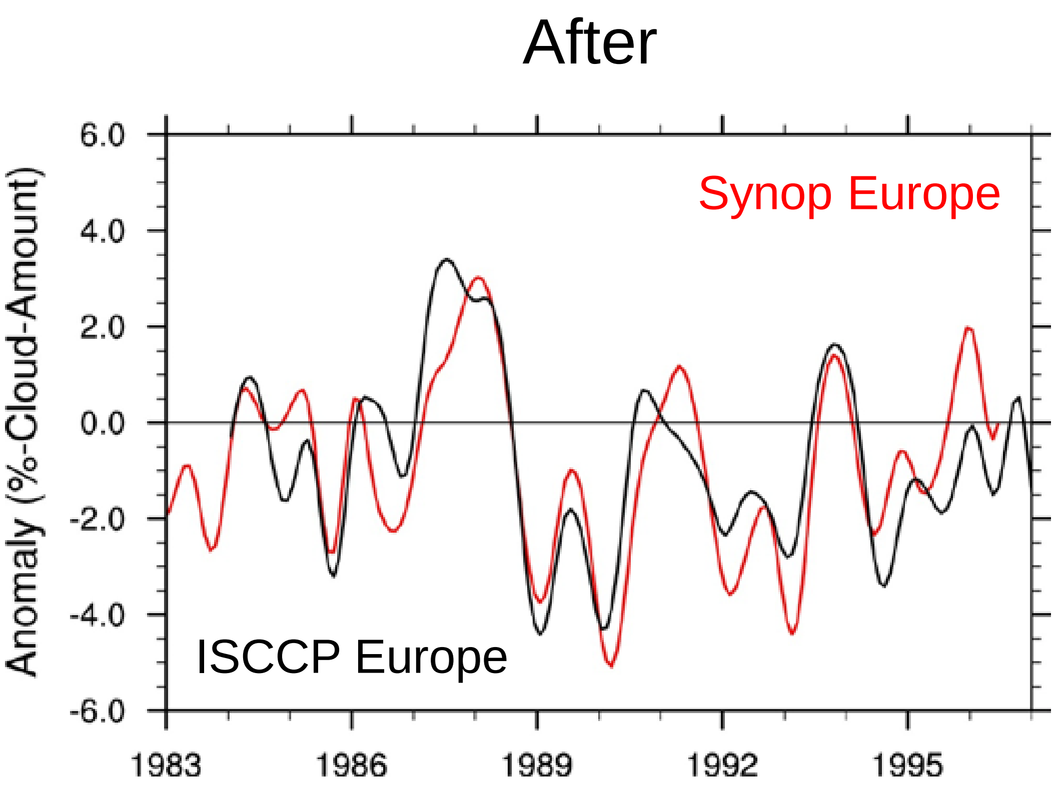
Can examine regional cloud changes

Cannot examine global mean cloud changes

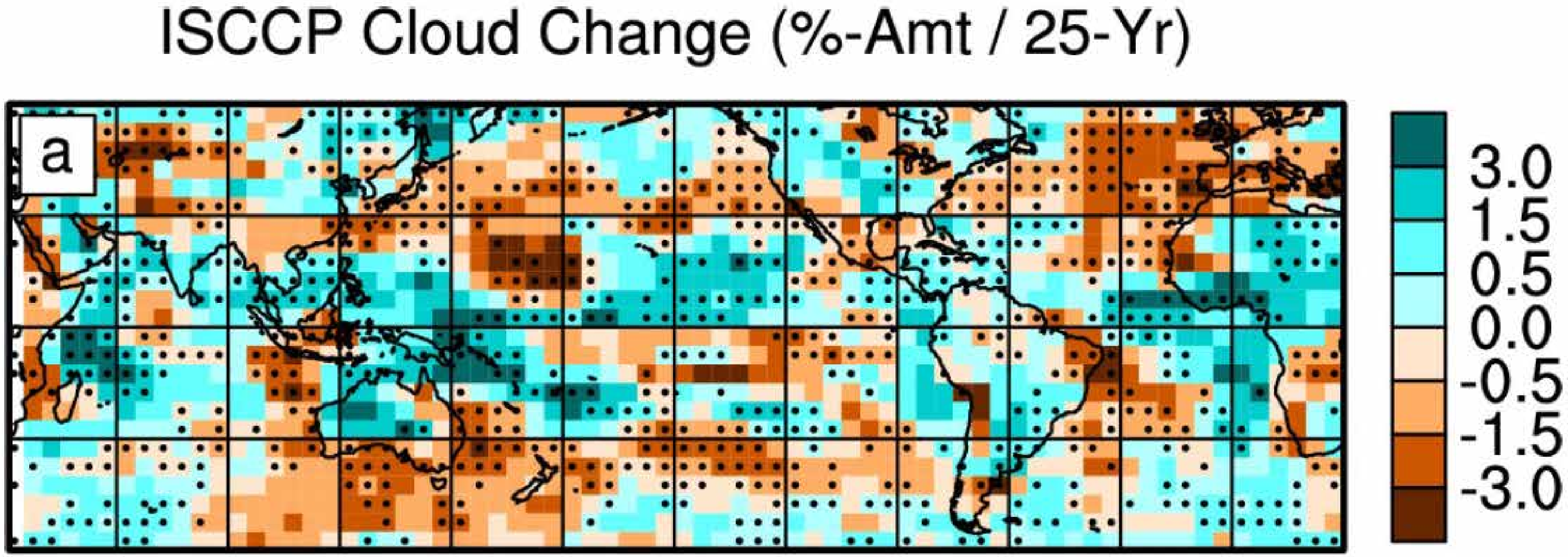


Before and After Satellite View Area Artifact Removal



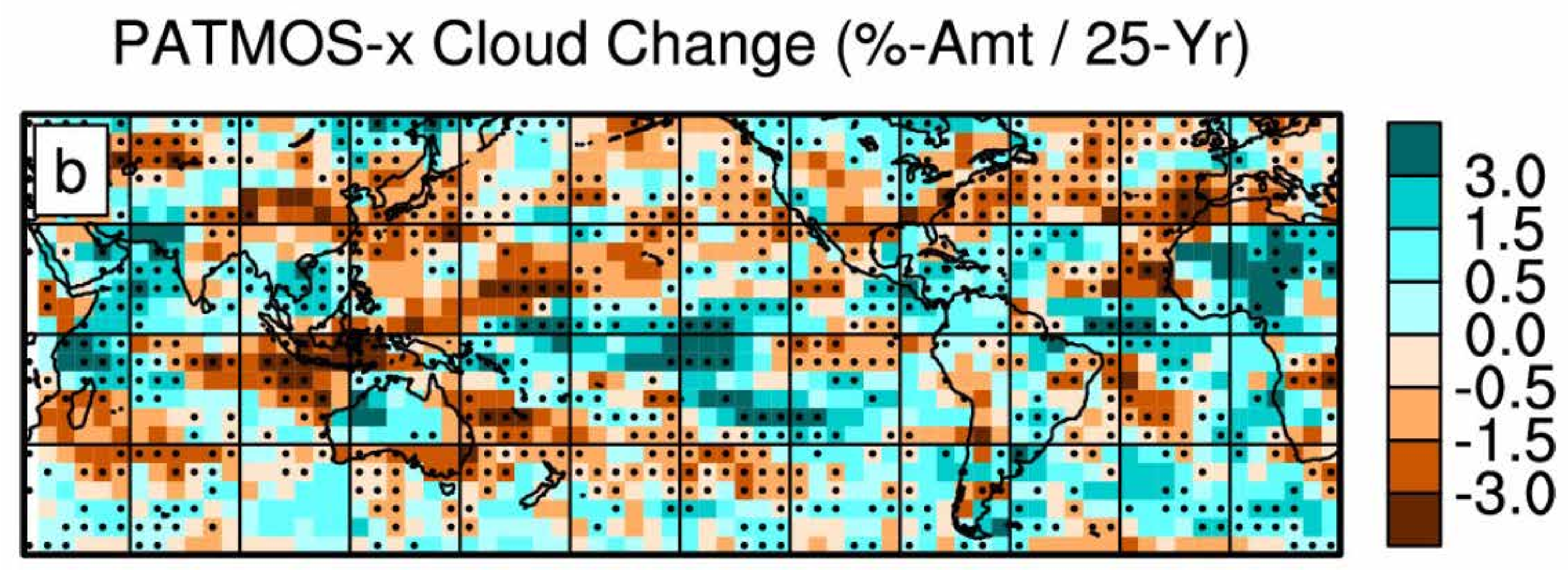


Corrected ISCCP Cloud Change During 1983-2009



Cloud trends are relative to an unknown global mean cloud trend, which could be zero.

Corrected PATMOS-x Cloud Change During 1983-2009



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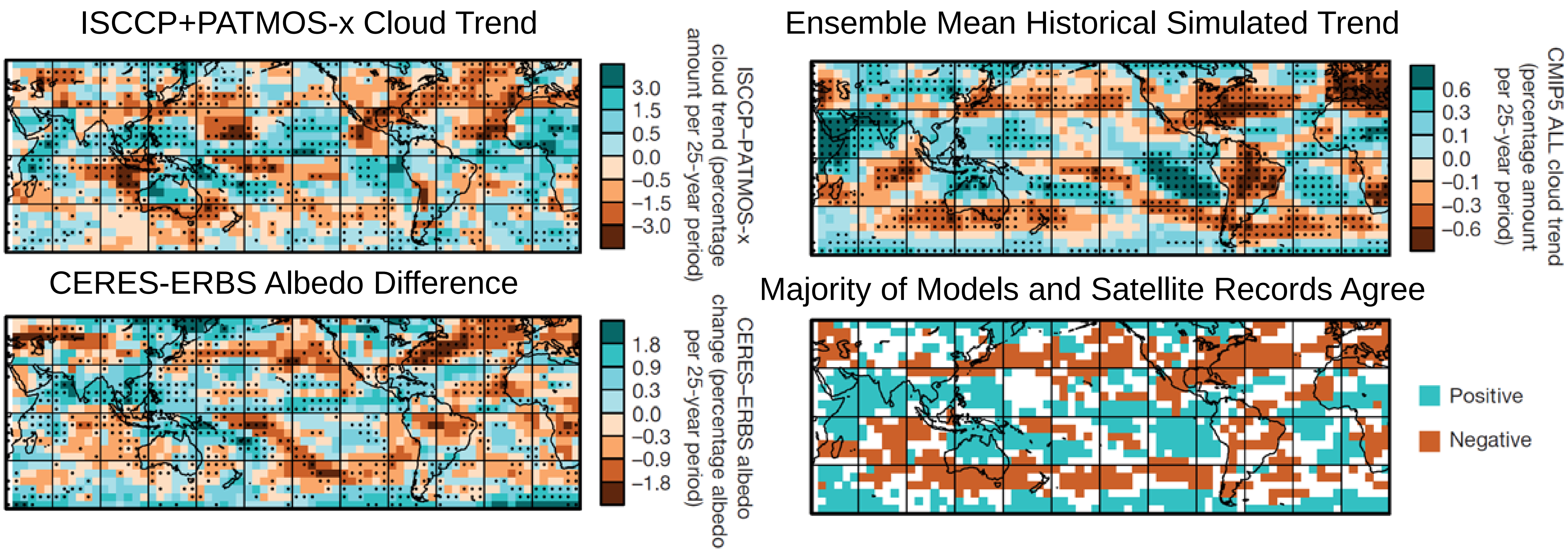
Agreement Between Models and Observations



Pattern of cloud change from the 1980s to the 2000s
(relative to global mean cloud change)

How Much Expansion?

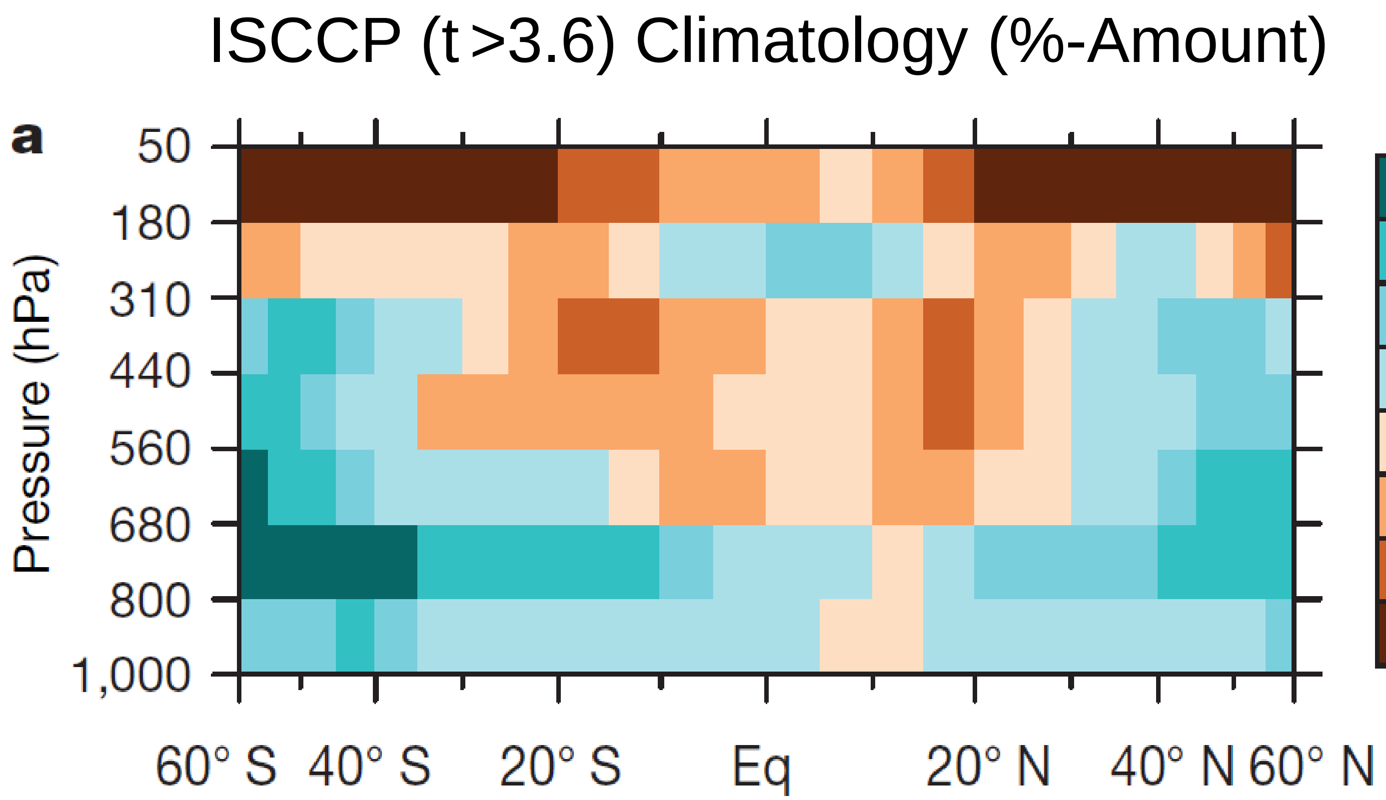
Estimate as

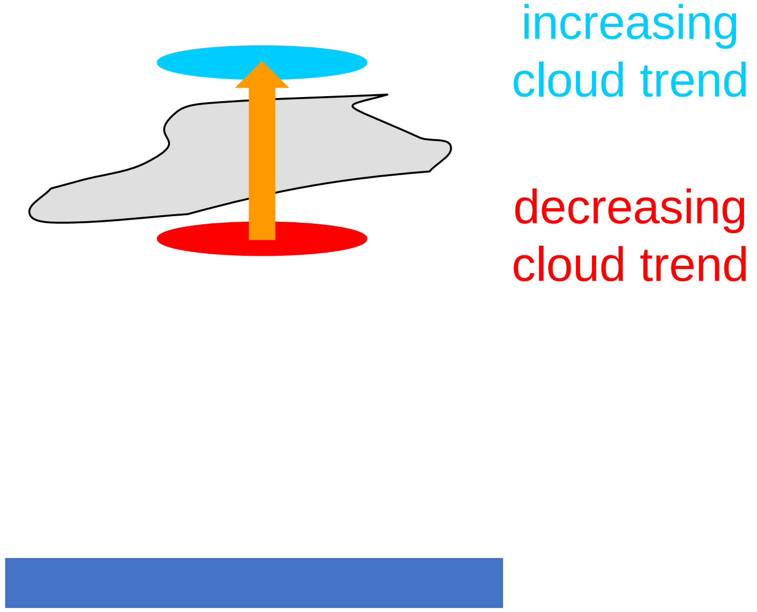
$$Df \sim DC / [dC/df\ ]_{clim}$$

1 %-amount per 25 years / 15 %-amount per 10°

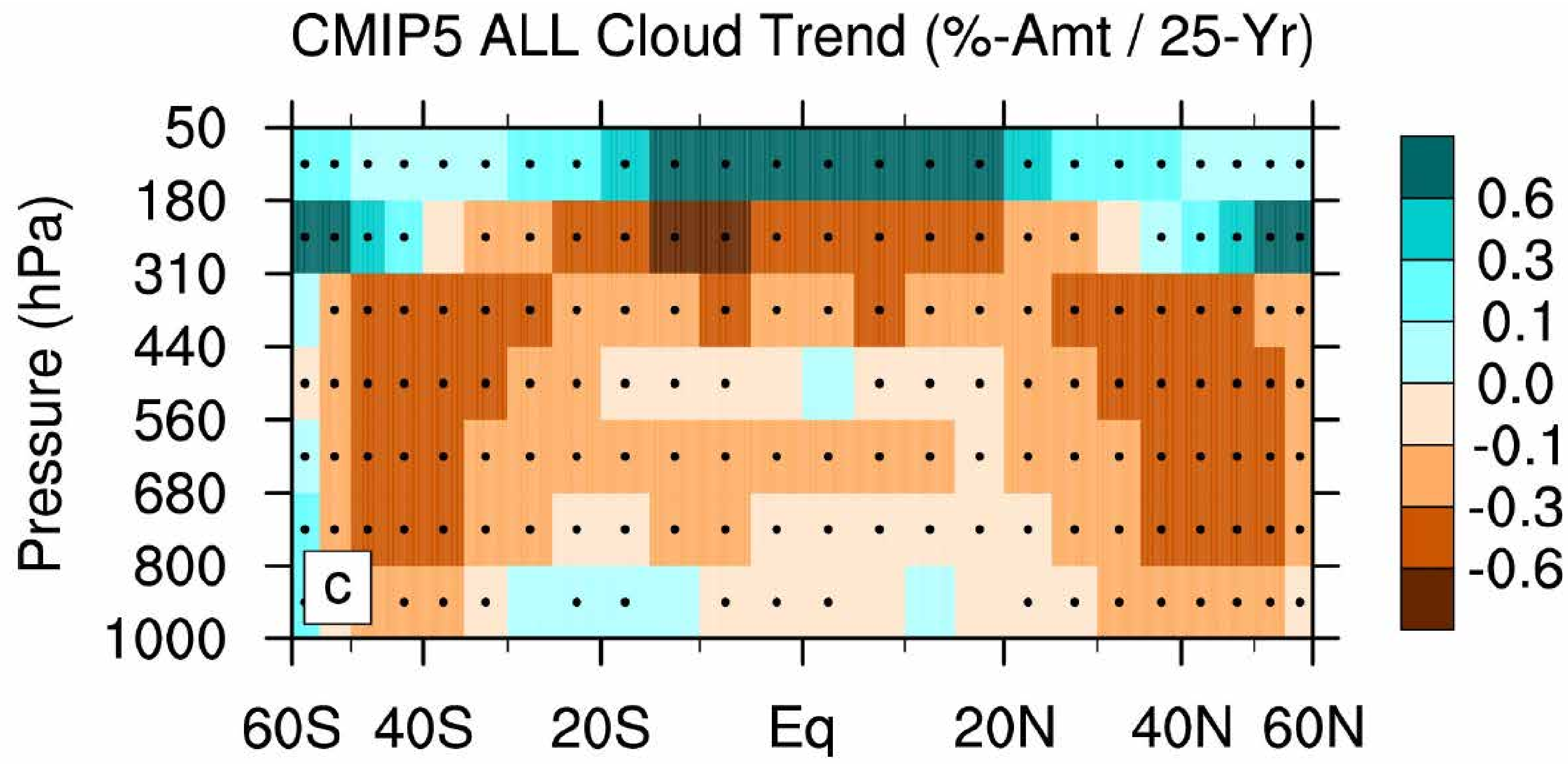
$Df \sim 0.67°$ latitude per 25 years

Rise of Zonal Mean High-Level Cloud Top



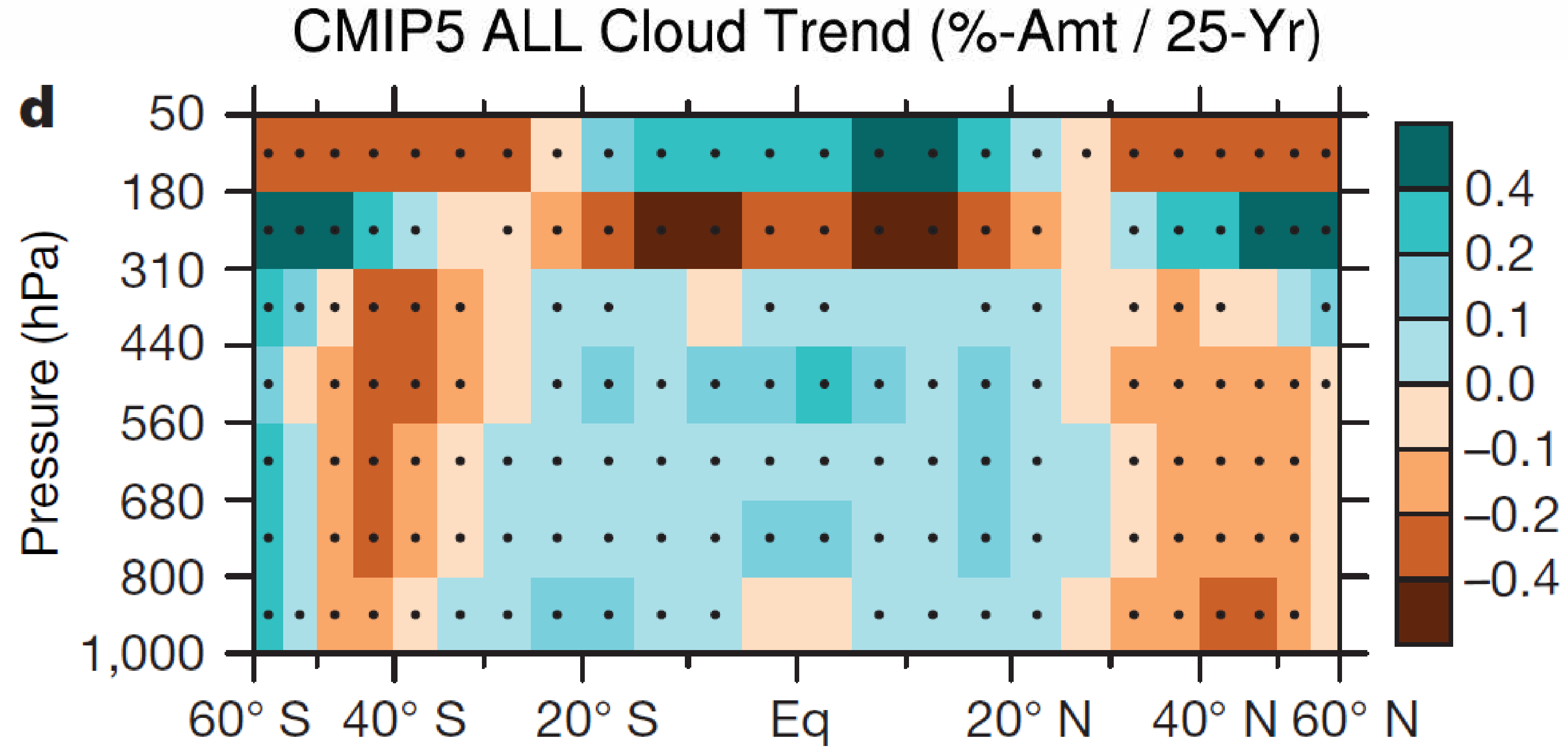


Model Cloud Change due to Historical Forcing



Ensemble mean cloud change between 1983 and 2009 for simulations with historical changes in greenhouse gases, anthropogenic aerosol, ozone, and volcanic aerosol

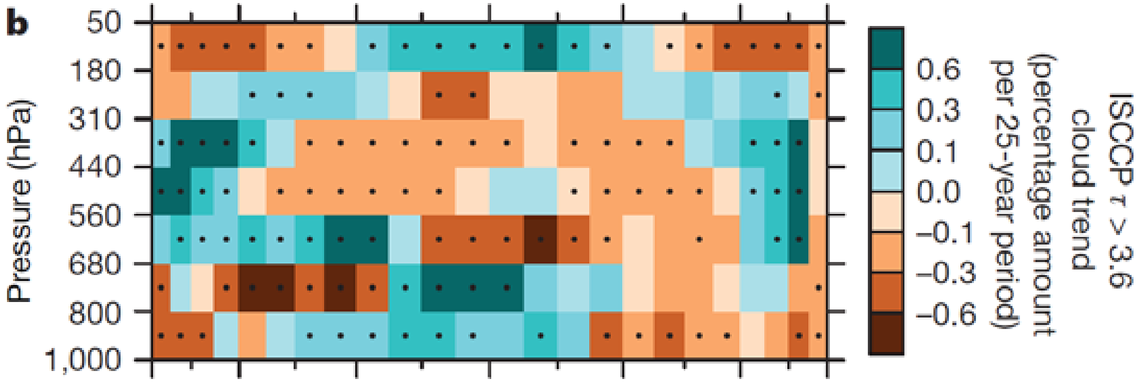
Model Cloud Change due to Historical Forcing



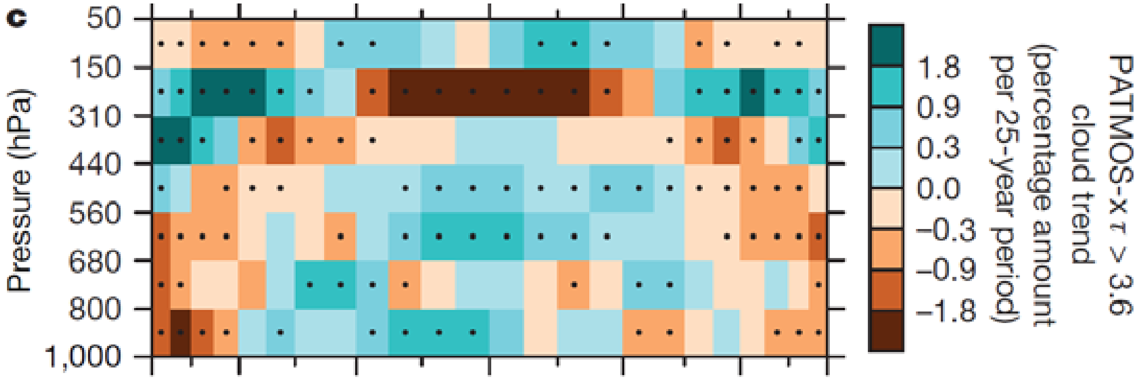
After subtracting global mean cloud trend at each pressure level

Agreement Between Models and Observations

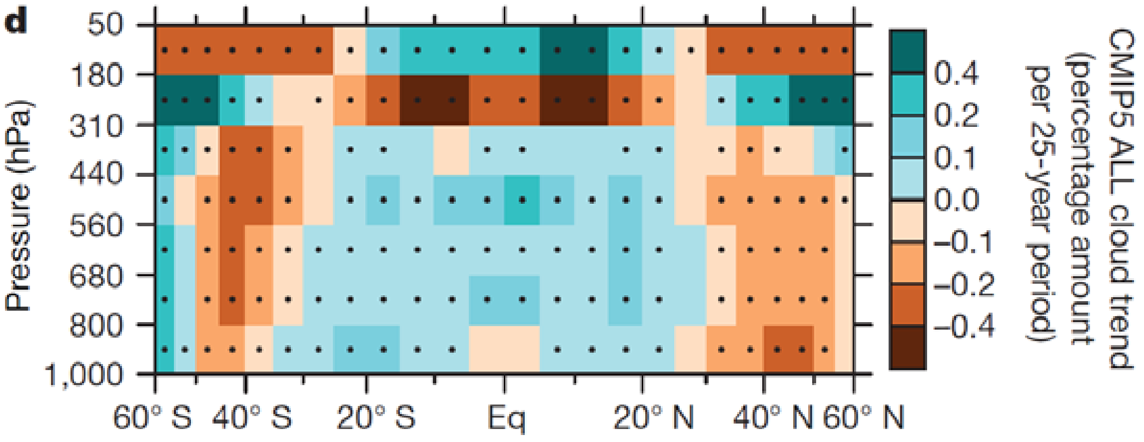
ISCCP Cloud Trend



PATMOS-x Cloud Trend



Ensemble Mean Historical Simulated Trend



Pattern of cloud change from the 1980s to the 2000s (relative to global mean cloud change)

How Much Rise?

Estimate as

$$\mathrm{D}p \sim \mathrm{D}C \,/\, [dC/dp]_{clim}$$

0.3 %-amount per 25 years / 3 %-amount per 130 hPa

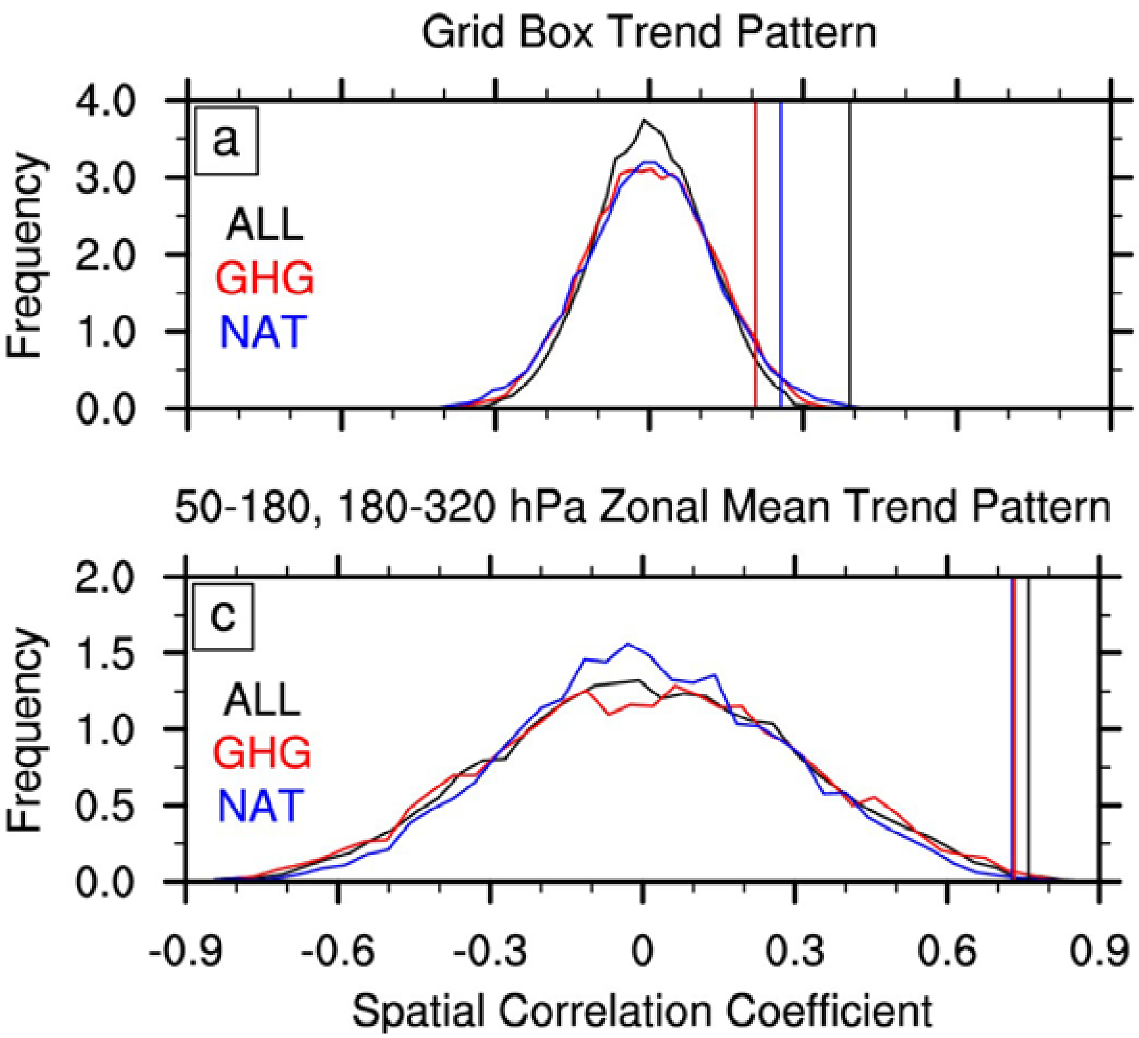
$\mathrm{D}p \sim$ 13 hPa per 25 years

Santer et al. (2003) report ~3-5 hPa per 25 years

Could Internal Variability Produce the Trend Patterns?

- Calculate cloud trend patterns for 27-year periods in 15000 years of pre-industrial simulations
- What is the frequency distribution of correlation between the externally forced pattern and the unforced trend patterns?
- How does the correlation between the observed pattern and the forced pattern compare?

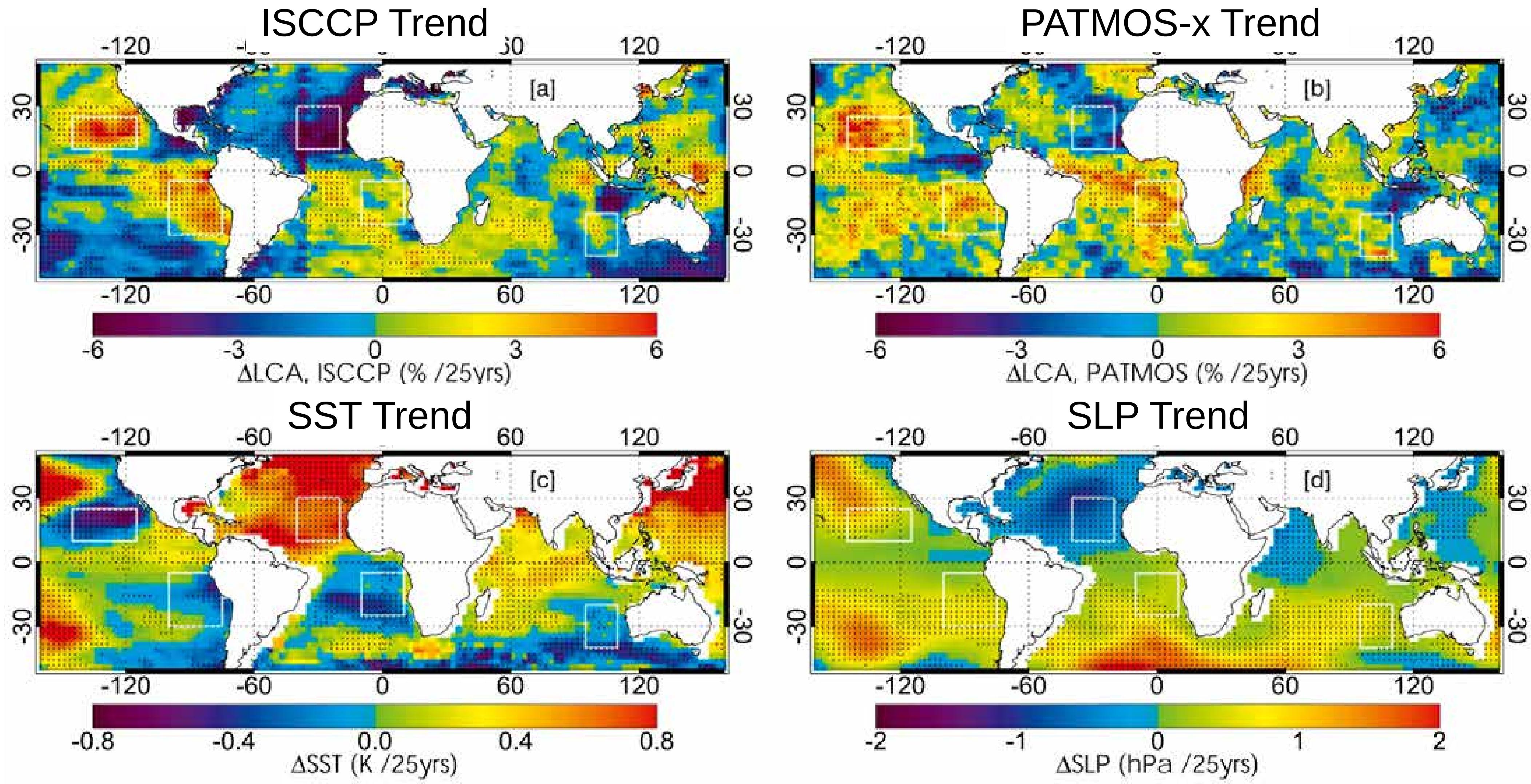
Could Internal Variability Produce the Trend Patterns?



It is extremely unlikely that the observed cloud changes from the 1980s to the 2000s could result from unforced internal variability

ALL = all radiative forcings
GHG = only greenhouse forcing
NAT = only volcanic forcing

Observed Trends in Low Cloud From 1984 to 2009

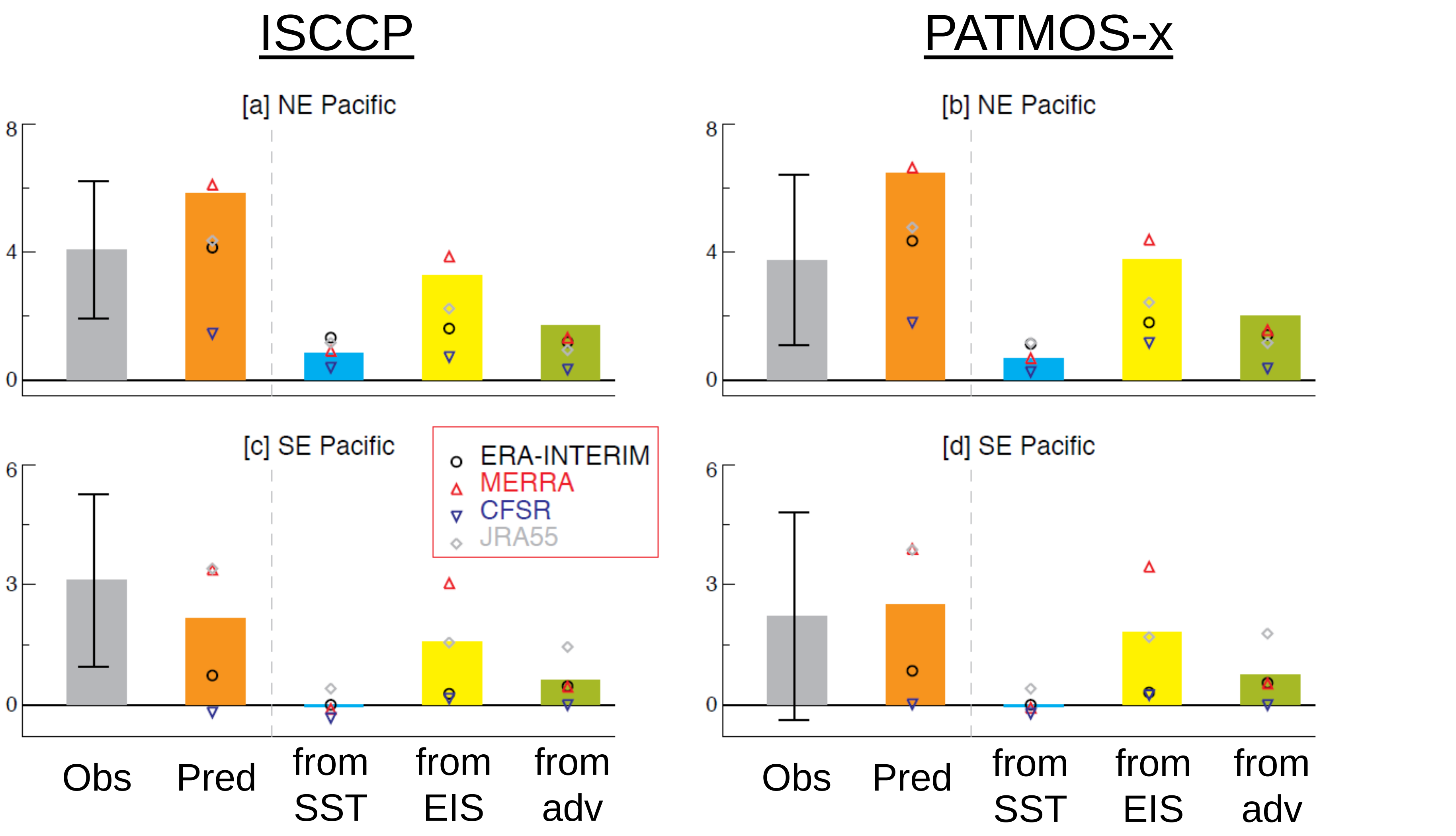


Prediction of 1984-2009 Observed Cloud Trends

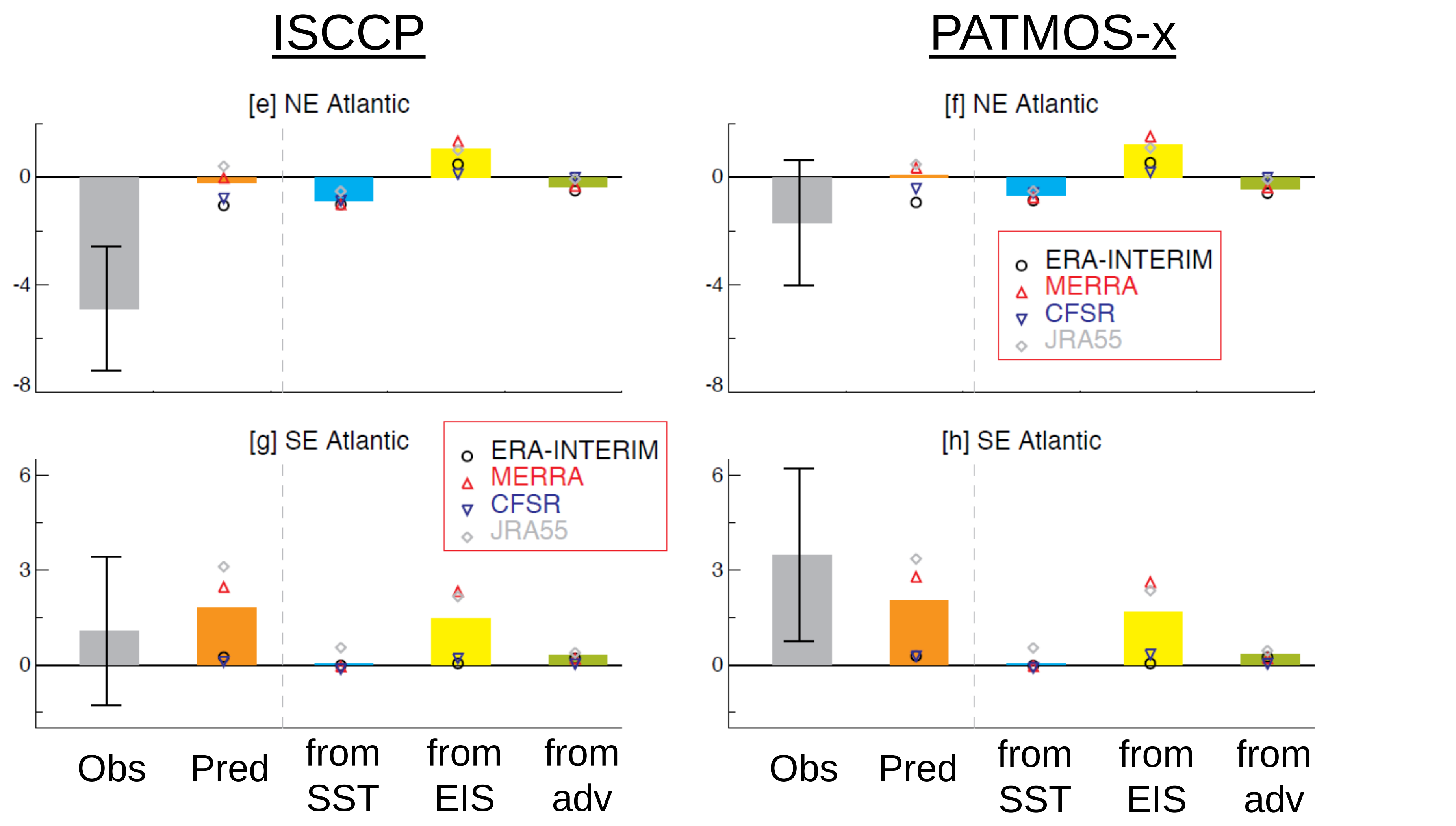
$$\Delta CF = \frac{\partial CF}{\partial SST}\Delta SST + \frac{\partial CF}{\partial EIS}\Delta EIS + \frac{\partial CF}{\partial SSTadv}\Delta SSTadv$$

- Can we use a multilinear regression model to predict the observed cloud trends?
- Coefficients calculated from interannual variability
- Cloud trend determined by multiplying coefficients by reanalysis meteorological trends

Prediction of 1984-2009 Observed Cloud Trends

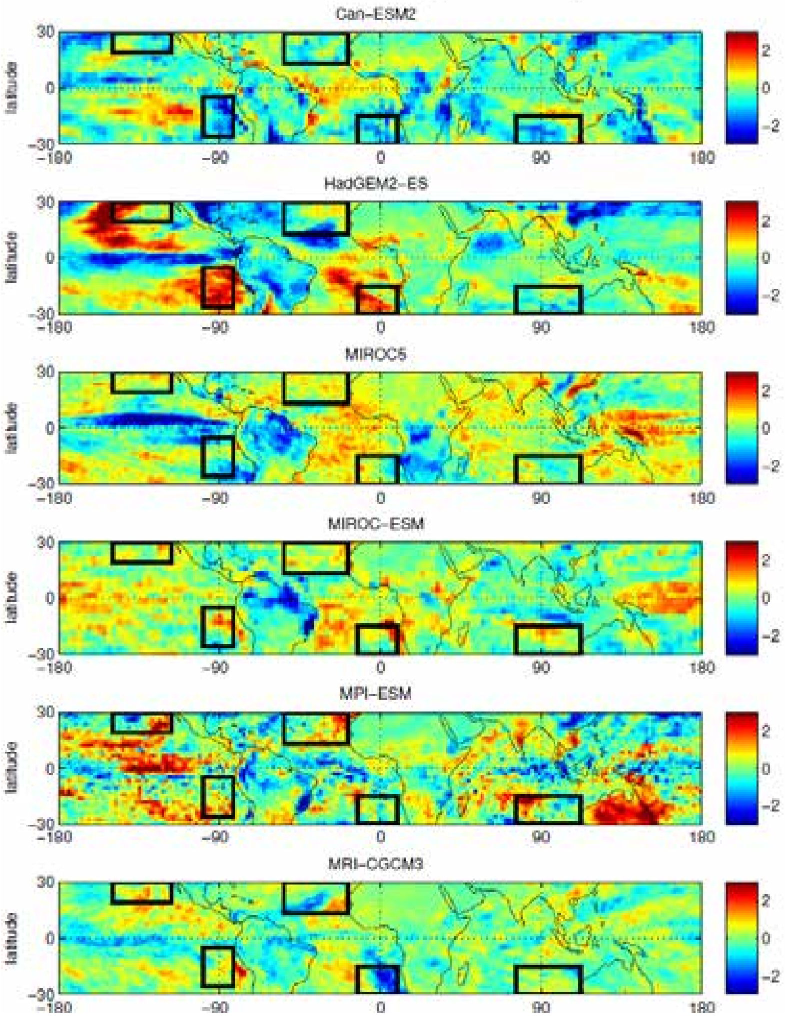


Prediction of 1984-2009 Observed Cloud Trends

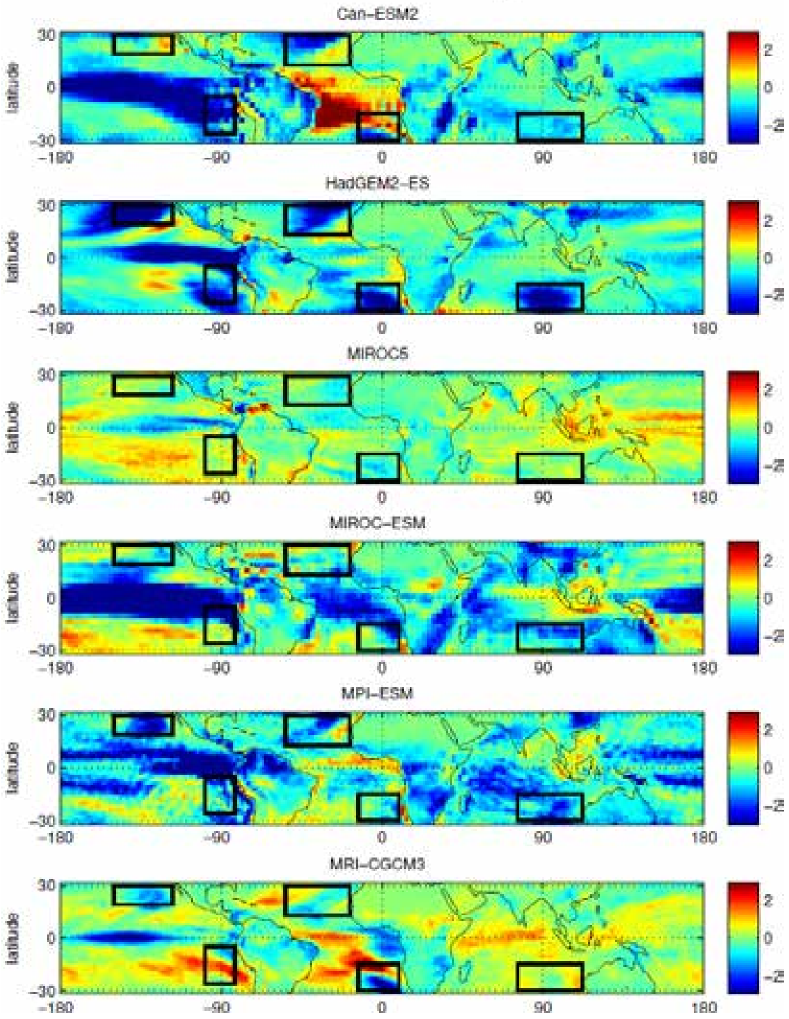


Historical and Equilibrium Model Change Patterns

1980s to 2000s Low-Level Cloud Change



4xCO_2 Equilibrium Low-Level Cloud Change



Summary

- Theory and climate models indicate that the subtropical dry zone will expand with global warming.

à *Observational confirmation from the satellite record*

- Theory and climate models indicate that the tops of the highest clouds will rise with global warming.

à *Observational confirmation from the satellite record*

- No fundamental theory and no agreement between climate models for changes in (sub)tropical low-level clouds

à *Internal decadal variability is too large and satellite record is too short*

Open Questions

- Change in global mean cloudiness
- Magnitude of cloud changes instead of just relative patterns
- Role of decadal variability compared to forced change