Observed Cloud Cover Trends and Global Climate Change

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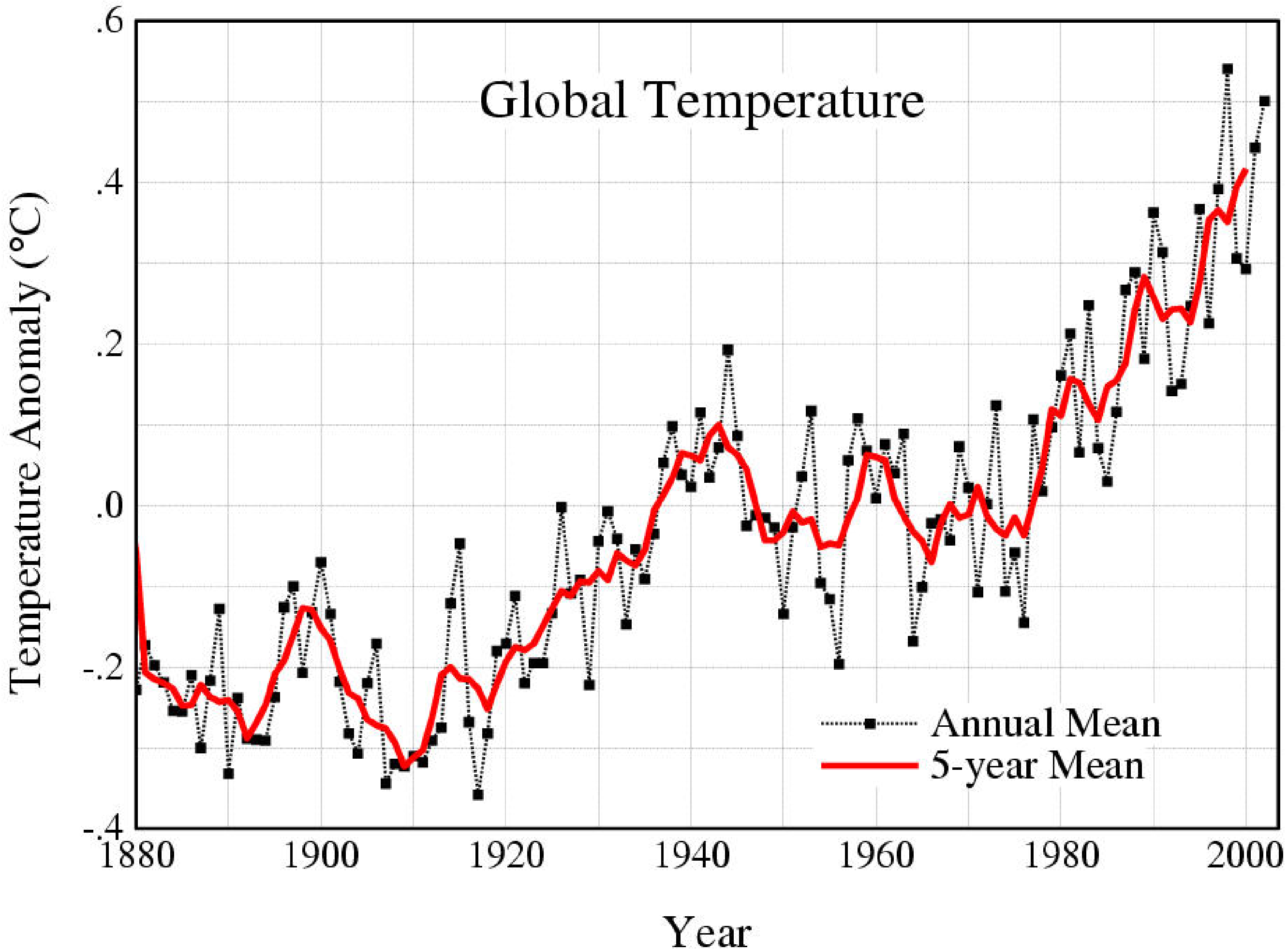
Increasing Global Temperature



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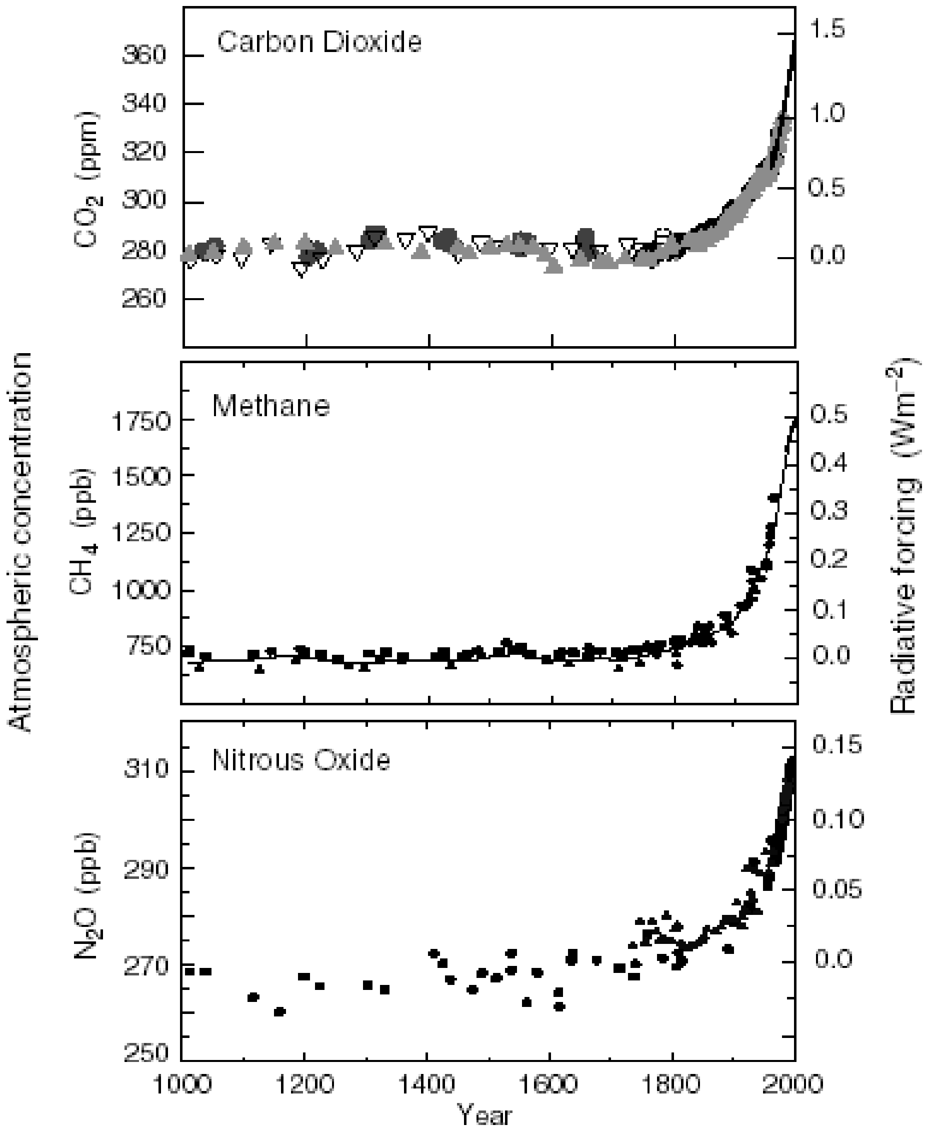
Increasing Greenhouse Gases



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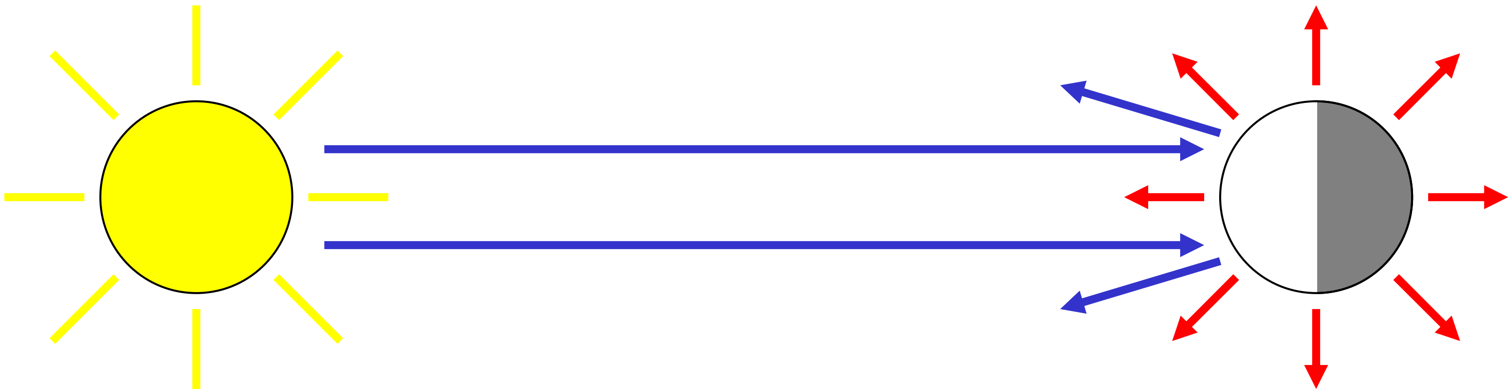
Some Questions

- How much of the observed warming is due to anthropogenic greenhouse gases?
- What is the impact of other anthropogenic activities on climate?
- Does the internal climate response exacerbate or mitigate the warming?
- What future warming can be expected if anthropogenic activities continue?
- What are the greatest uncertainties and how can they be reduced?

Outline

- planetary radiation budget
- external radiative forcing, cloud radiative properties, climate feedbacks, climate sensitivity
- uncertainties in external forcing and climate feedbacks
- satellite-measured radiation and surface-observed cloud cover
- measured and estimated cloud and radiation variability
- attribution of cloud and radiation variability

Planetary Radiation Budget

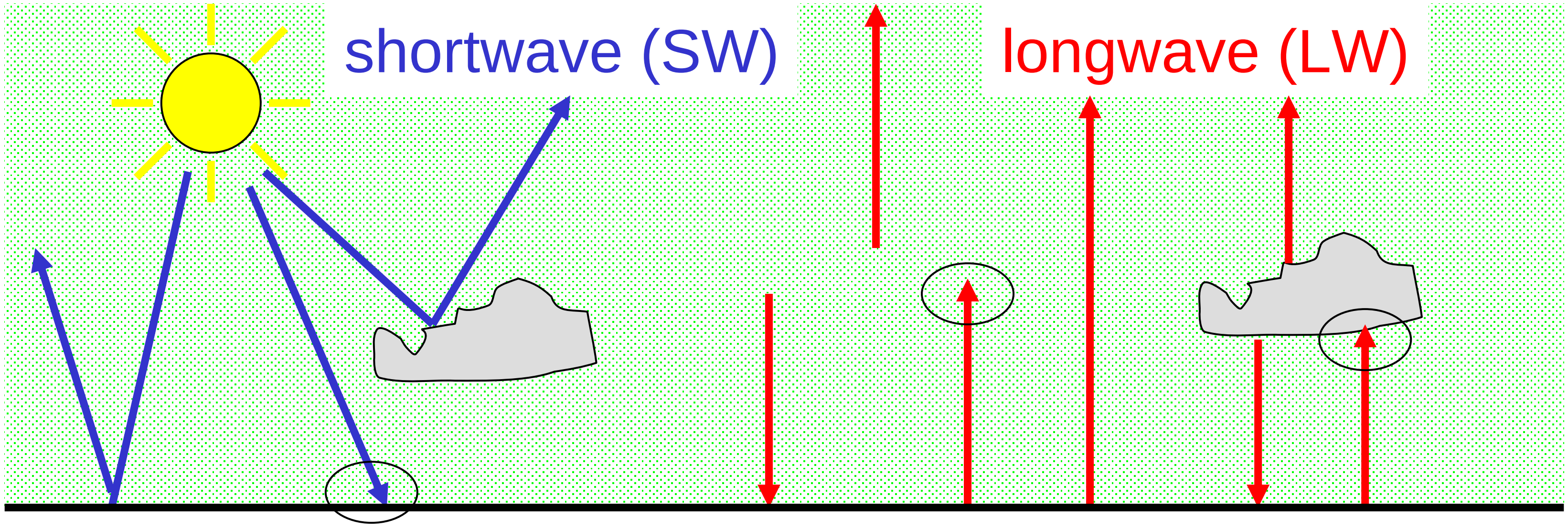


$$\sigma T_e^4 = (1 - \alpha)S/4$$

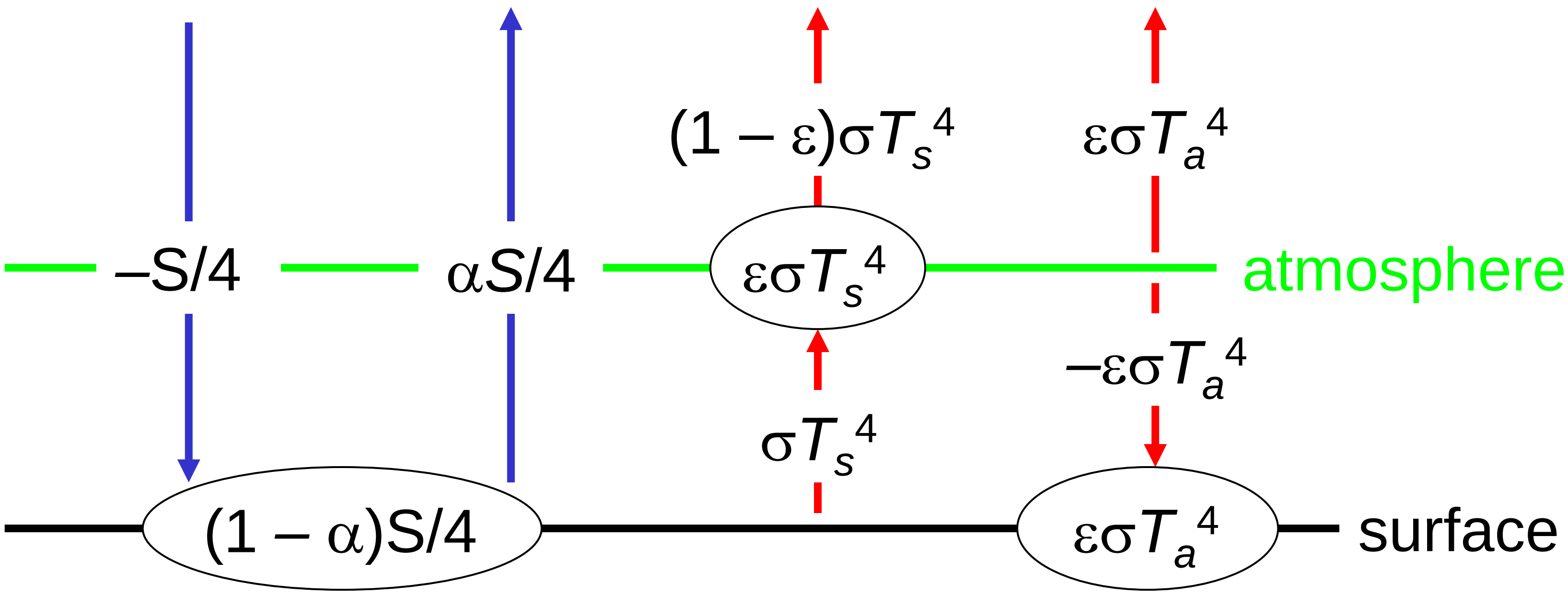
F = net radiation flux (positive upwards)
S = solar "constant" (1370 Wm^{-2})
α = planetary albedo (0.30)
T_e = blackbody emission temperature (255 K)
σ = Stefan-Boltzmann constant
$R_\oplus$ = radius of Earth

Greenhouse Atmosphere

- greenhouse gases: H_20, CO_2, O_3, CH_4, N_2O, CFCs
- additional greenhouse contributors: clouds and aerosols (haze, dust, smog particles)



Radiation Budget with an Atmosphere



ε = atmospheric emissivity/absorptivity
T_a = atmospheric temperature
T_s = surface temperature

(surface emissivity = 1)

Radiation Budget with an Atmosphere

$$T_s = (2)^{1/4} T_a$$

$$T_s = \left(\frac{2}{2 - \varepsilon} \right)^{1/4} T_e$$

if ε increases then T_s increases

some numbers…

for $\varepsilon = 0.8$ and $T_e = 255$ K,

$T_s = 290$ K and $T_a = 244$ K

A Simple Model of the Climate System

let $F = \underline{M}(\boldsymbol{E}, \boldsymbol{I}, T_s)$ where

F = top-of-atmosphere (TOA) net radiation flux

$\underline{M}$ = linear model of the climate system

T_s = surface temperature

$\boldsymbol{E}$ = $\{E_1, E_2, E_3, \ldots\}$ external parameters, $E_j \neq E_j(\underline{M})$

$\boldsymbol{I}$ = $\{I_1, I_2, I_3, \ldots\}$ internal parameters, $I_k = I_k(\underline{M})$

Some External Parameters

- anthropogenic greenhouse gases (strong effect on LW radiation)
- anthropogenic aerosol (albedo effect and weak LW effect)
- solar irradiance
- volcanic aerosol (albedo effect and weak LW effect)
- orbital changes (latitudinal and seasonal distribution of solar irradiance)
- land/ocean/mountain distribution

Some Internal Parameters

- clouds (strong albedo and strong LW effects)
- water vapor (strong LW effect)
- ice and snow surfaces (strong albedo effect)
- natural greenhouse gases (strong LW effect)
- natural aerosols (albedo effect and weak LW effect)
- atmospheric and oceanic circulation
- land vegetation (albedo effect)

Climate Response to Radiative Forcing

$$\Delta F = \sum_j \frac{\partial F}{\partial E_j}\Delta E_j + \frac{\partial F}{\partial T}\Delta T_s + \sum_k \frac{\partial F}{\partial I_k}\frac{dI_k}{dT_s}\Delta T_s$$

for equilibrium $\Delta F = 0$ and

$$\Delta T_s = \frac{-\lambda_{BB}\Delta R}{1+\lambda_{BB}\sum_k \frac{\partial F}{\partial I_k}\frac{dI_k}{dT_s}}$$

where $\Delta R = \sum_j \frac{\partial F}{\partial E_j}\Delta E_j$ *change in external radiative forcing*

and $\frac{1}{\lambda_{BB}} = \frac{\partial F}{\partial T_s} = 4\sigma T_s^3$ *rate of increase of blackbody emission*

Zero-Feedback Climate Response

if no changes in internal parameters, i.e. $\sum_k \frac{\partial F}{\partial I_k} \frac{dI_k}{dT_s} = 0$

then $\Delta T_0 = -\lambda_{BB} \Delta R = \frac{-\Delta R}{4\sigma T_s^3}$

some numbers…

$4\sigma T_s^3 = 5.4\ \mathrm{Wm^{-2}\ K^{-1}}$ ($T_s = 288$ K)

Since 1950 (source IPCC):

total anthropogenic radiative forcing $\Delta R = -0.8\ \mathrm{Wm^{-2}}$

zero-feedback temperature change $\Delta T_0 = +0.15$ K

observed temperature change $\Delta T_s = +0.4$ K

Climate Response with Feedbacks

if changes in internal parameters are included then

$$\Delta T_s = \frac{\Delta T_0}{1 + \lambda_{BB} \sum_k \frac{1}{\lambda_k}} \qquad \text{where} \quad \frac{1}{\lambda_k} = \frac{\partial F}{\partial I_k} \frac{dI_k}{dT_s}$$

or $$\Delta T_s = \Delta T_0 \frac{1}{1 - f} \quad \text{where} \quad f = \sum_k f_k = \sum_k -\frac{\lambda_{BB}}{\lambda_k}$$

f_k = climate feedback from internal parameter I_k

f = total feedback from all internal parameters

radiative equilibrium is not possible when $f \geq 1$

Positive and Negative Feedbacks

consider the additional change in ΔT_s caused by climate feedbacks

$$\Delta T_s - \Delta T_0 = \frac{\sum_k f_k}{1 - \sum_k f_k} \Delta T_0$$

positive feedbacks ($f_k > 0$) amplify the zero-feedback temperature response

negative feedbacks ($f_k < 0$) diminish the zero-feedback temperature response

For a linear climate model the total feedback is the sum of the individual feedbacks

Ice Albedo Feedback

A_{ice} = ice cover internal climate parameter

$$\frac{\partial F}{\partial A_{ice}} > 0$$

increase in ice cover increases reflection of SW radiation to space

$$\frac{dA_{ice}}{dT_s} < 0$$

increase in global temperature decreases ice cover

$$f_{ice} = -\lambda_{BB} \frac{\partial F}{\partial A_{ice}} \frac{dA_{ice}}{dT_s} > 0$$

ice albedo feedback is positive

Water Vapor Feedback

q = water vapor mixing ratio internal parameter

$$\frac{\partial F}{\partial q} < 0$$

increase in water vapor decreases outgoing LW radiation

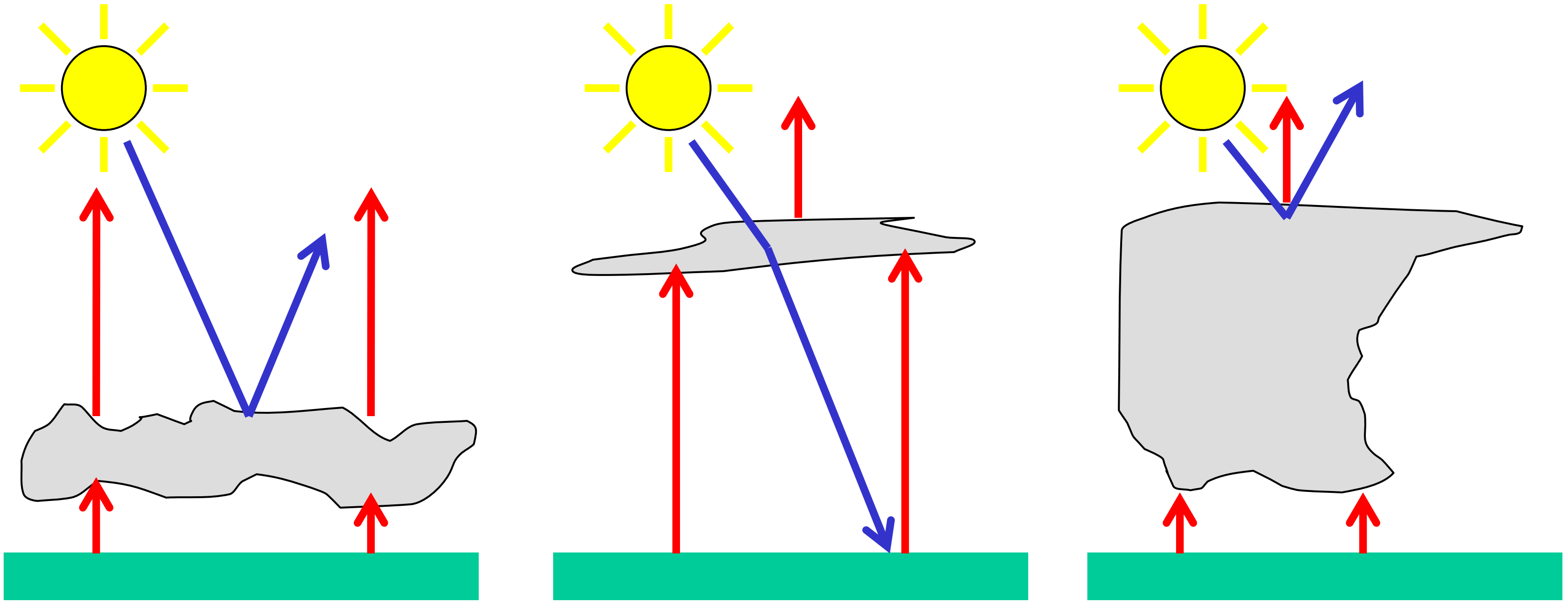
$$\frac{dq}{dT_s} > 0$$

water vapor increases with temperature for constant relative humidity

$$f_q = -\lambda_{BB} \frac{\partial F}{\partial q} \frac{dq}{dT_s} > 0$$

water vapor feedback is positive (probably)

Cloud SW and LW Radiative Effects



low-level cloud	high-level cloud	thick cloud
reflection >> 0	reflection ~ 0	reflection >> 0
greenhouse ~ 0	greenhouse << 0	greenhouse << 0
cools the earth	*warms the earth*	(reflection + greenhouse) ~ 0

Low-Level Cloud Types

low-level cumuliform cloud (cumulus)

weak reflection
weak greenhouse

low-level stratiform cloud (stratocumulus)

strong reflection
weak greenhouse

Upper-Level Cloud Types

high-level cloud
(cirrus)

weak reflection
strong greenhouse

mid-level cloud
(altostratus)

intermediate reflection
intermediate greenhouse

Thick Cloud Types

deep convective cloud (cumulonimbus)

strong reflection
strong greenhouse

frontal cloud (nimbostratus)

strong reflection
strong greenhouse

Albedo Cloud Cover Feedback

C_α = cloud cover (considering impact on albedo)

$$\frac{\partial F}{\partial C_\alpha} > 0$$

increase in cloud cover increases reflection of SW radiation to space

$$\frac{dC_\alpha}{dT_s} \ ?$$

uncertain how cloud cover responds to a change in global temperature

$$f_{C\alpha} = -\lambda_{BB} \frac{\partial F}{\partial C_\alpha} \frac{dC_\alpha}{dT_s} \ ?$$

sign of albedo cloud cover feedback is uncertain

LW Cloud Cover Feedback

C_{LW} = cloud cover (considering impact on LW)

$$\frac{\partial F}{\partial C_{LW}} > 0$$

increase in cloud cover decreases emission of LW radiation to space

$$\frac{dC_{LW}}{dT_s} \; ?$$

uncertain how cloud cover responds to a changes in global temperature

$$f_{CLW} = -\lambda_{BB} \frac{\partial F}{\partial C_{LW}} \frac{dC_{LW}}{dT_s} \; ?$$

sign of LW cloud cover feedback is uncertain

Other Cloud Feedbacks

- Feedbacks can result from changes in other cloud properties besides cloud cover
- A shift from ice crystals to liquid droplets changes cloud reflectivity and emissivity
- An increase in condensed water increases cloud reflectivity
- An increase in cloud top height decreases LW emission due to colder temperature

Climate Sensitivity

climate sensitivity λ is the ratio of climate response to external forcing

$$\lambda = -\frac{\Delta T_s}{\Delta R}$$

alternative formulations:

$$\lambda = \frac{\lambda_{BB}}{1-f} \qquad \frac{1}{\lambda} = \frac{1}{\lambda_{BB}} + \sum_k \frac{1}{\lambda_k}$$

some numbers… $\lambda_{BB} = (4\sigma T_s^3)^{-1} = 0.2$ K (Wm^{-2})$^{-1}$

Since 1950: $\lambda = -\Delta R \,/\, \Delta T_s = 0.5$ K (Wm^{-2})$^{-1}$

$f = (\lambda - \lambda_{BB}) \,/\, \lambda = 0.6$

Uncertainties in Determining Sensitivity

determining the magnitude of climate sensitivity is critical for predicting future warming

$$\Delta T_s = -\lambda \Delta R$$

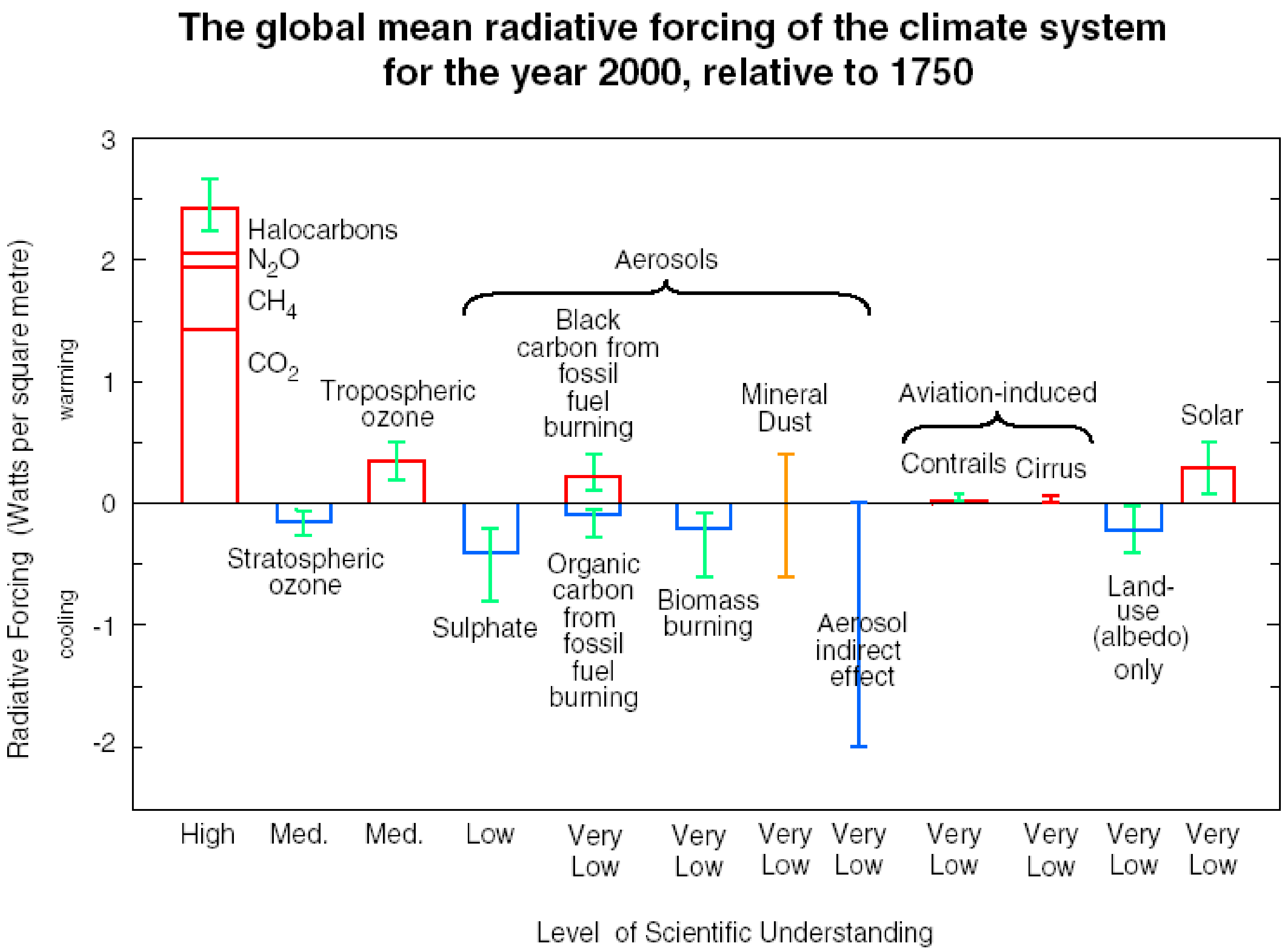
error in the magnitude of external forcing causes large error in calculated climate sensitivity

$$e_\lambda = \frac{\lambda}{\Delta R} e_R$$

error in the magnitude of climate feedback causes large error in calculated climate sensitivity

$$e_\lambda = \frac{\lambda}{1-f} e_f$$

Uncertainties in External Forcing



from ess.geology.ufl.edu

Anthropogenic Aerosol Radiative Forcing

"Indirect Effect"

- aerosol particles act as nuclei for cloud droplets (depending on composition)
- more anthropogenic aerosol particles likely means more cloud condensation nuclei
- more cloud condensation nuclei likely means more but smaller droplets
- cloud reflectivity is enhanced

Indirect Aerosol Radiative Forcing

Natural State

small number of cloud
condensation nuclei

small number of
large cloud droplets

low reflectivity

Indirect Aerosol Radiative Forcing

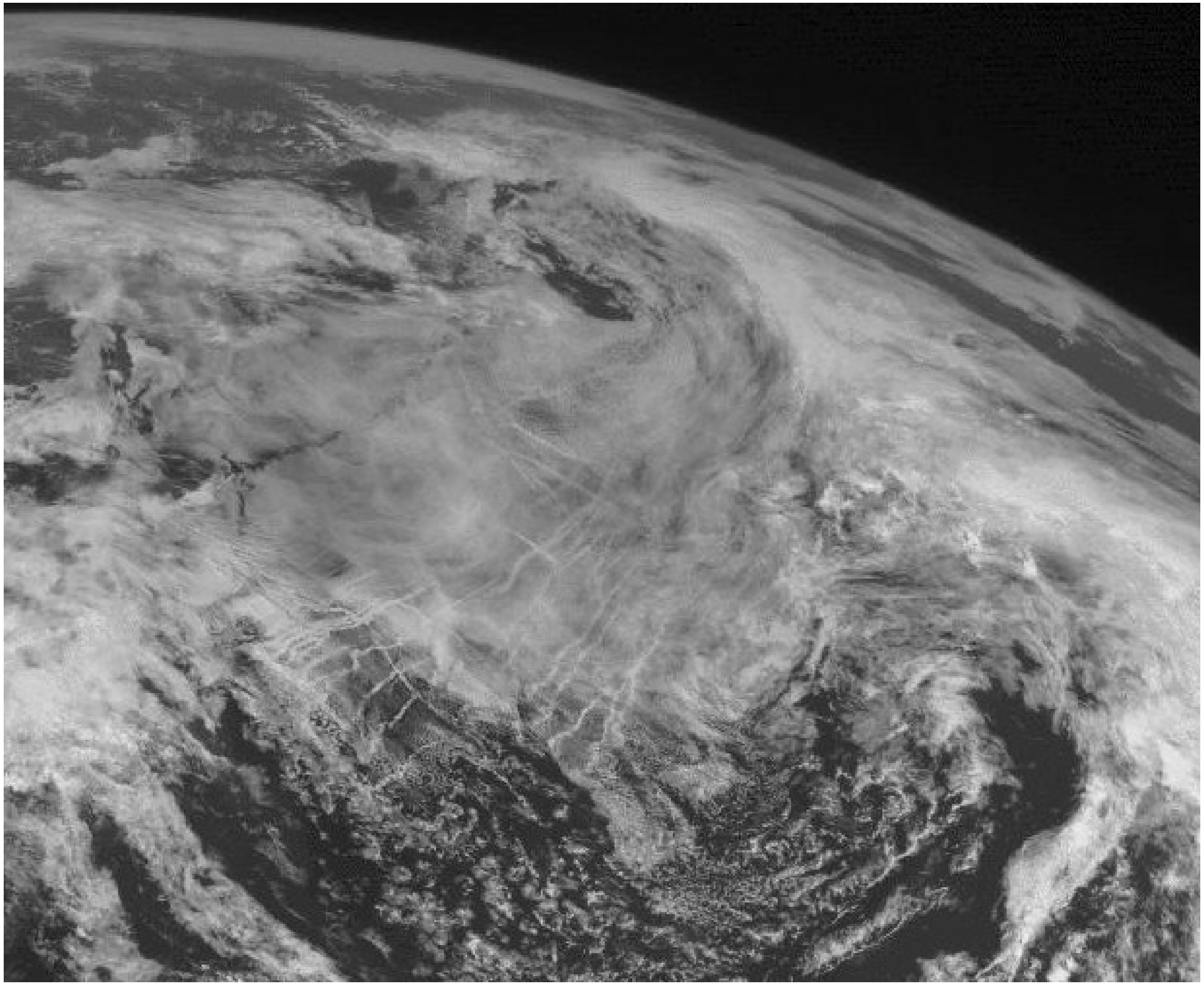
Anthropogenic Effect

large number of cloud condensation nuclei

large number of small cloud droplets

high reflectivity

Ship Tracks



Uncertainties in Feedbacks

- general theories do not exist for quantifying most individual climate feedbacks
- observations lack sufficient detail and comprehensiveness
- competing climate processes cannot be distinguished using observations
- global climate models have insufficient spatial resolution to simulate climate processes

Global Climate Model Intercomparison

Cess et al. (1990) compared 19 atmospheric global climate models (GCMs)

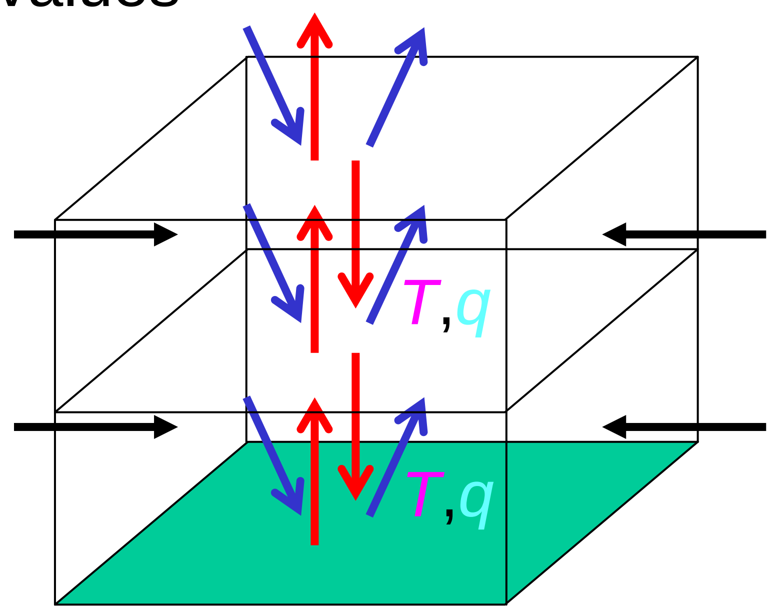
- climate sensitivity *without clouds* ranged from 0.4 to 0.57 K $(Wm^{-2})^{-1}$
- climate sensitivity *with clouds* ranged from 0.4 to 1.22 K $(Wm^{-2})^{-1}$
- models did not even agree on whether the net cloud feedback was positive or negative

the uncertainty range for projected global warming has not narrowed since 30 years ago

Global Climate Models

- the global atmosphere is divided into grid boxes
- equations relating wind, radiation, temperature, moisture, etc. are solved to get new values for the next time step
- adjacent grid boxes exchange radiation, mass, heat, moisture, etc.
- coupled to models of ocean, ice, land surface, chemistry, ecosystem, …

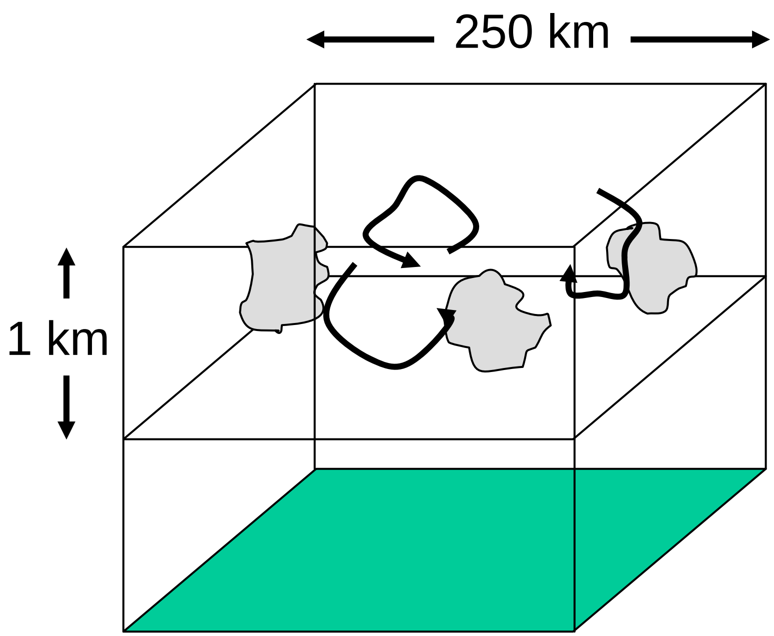
winds
SW radiation
LW radiation
temperature
moisture



GCM Resolution Difficulties

- grid boxes are typically 250 km wide and 1 km high
- processes important for cloud formation happen at much smaller scales
- it is very difficult to represent effects of clouds and small scale processes only in terms of grid box mean properties

clouds and small-scale circulations



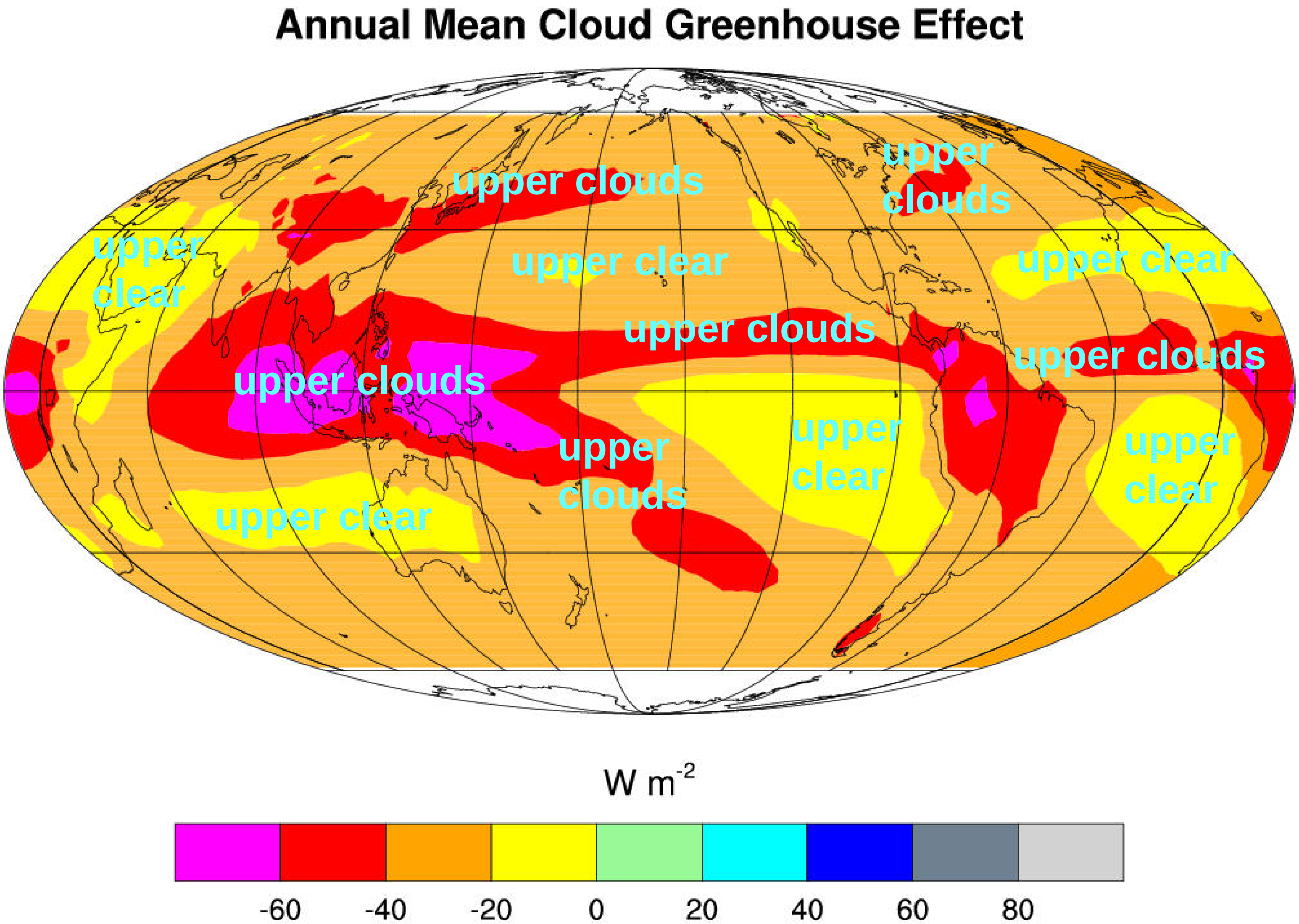
Strategy for the Cloud Feedback Problem

- use reliable satellite measurements to document radiation variability since 1985
- use surface observations of clouds to estimate radiation variability back to 1952
- verify estimated cloud-related radiation variability with satellite measurements
- compare cloud and radiation output from GCMs run with historical external forcing
- use GCM to explore cause of cloud variability
- determine climate sensitivity from GCMs with correct historical cloud variability

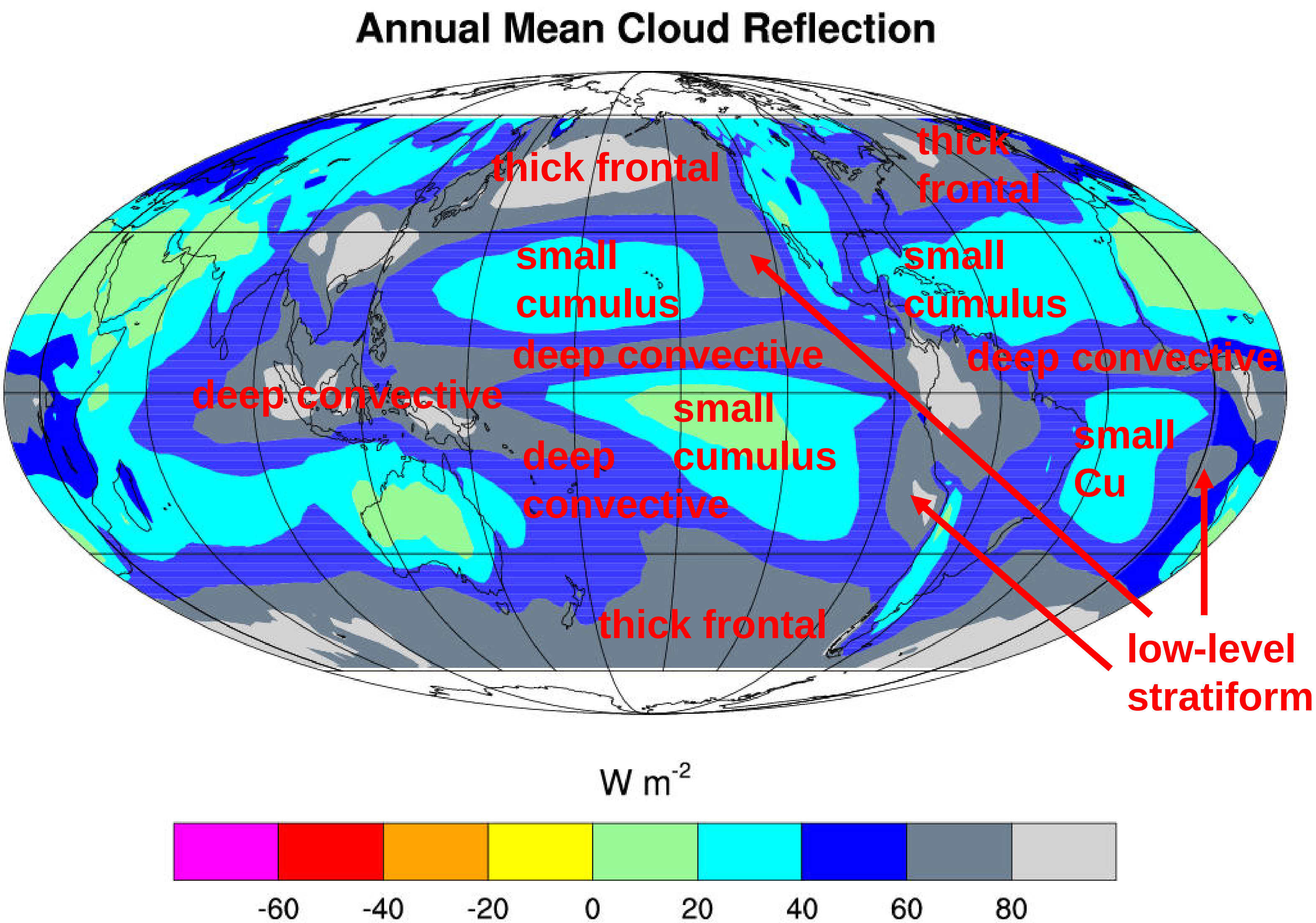
Satellite Radiation Observations

- it is difficult to accurately measure long-term radiation variability by satellite
- only the Earth Radiation Budget Experiment (ERBE) provides reliable data
- ERBE data distinguishing clear and cloudy conditions are available for 1985-1989
- ERBE data for mixed clear and cloudy conditions are available for 1985-1999
- 1985-1999 data are not available poleward of 60° and are best sampled equatorward of 40°

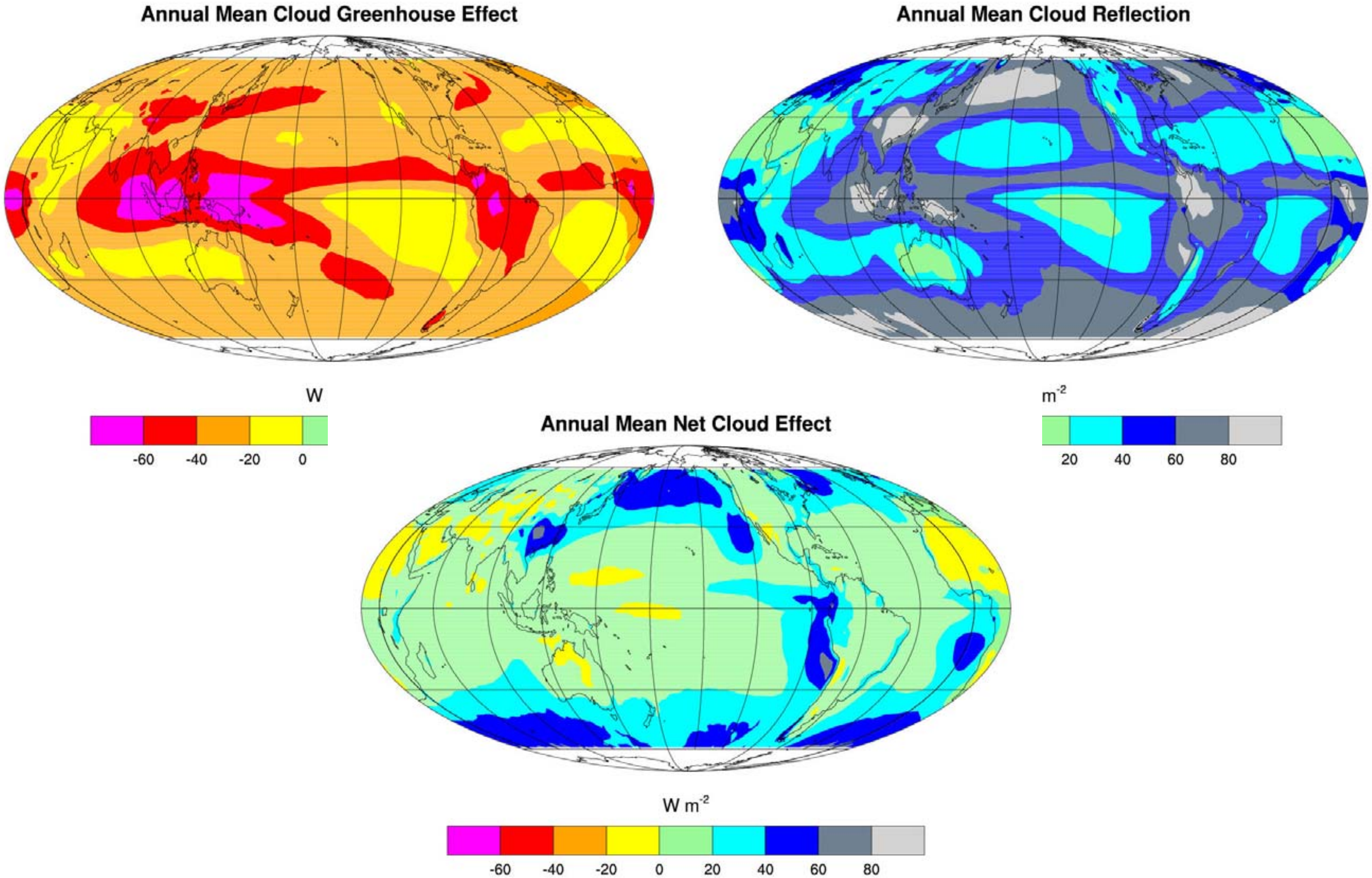
Outgoing LW Radiation



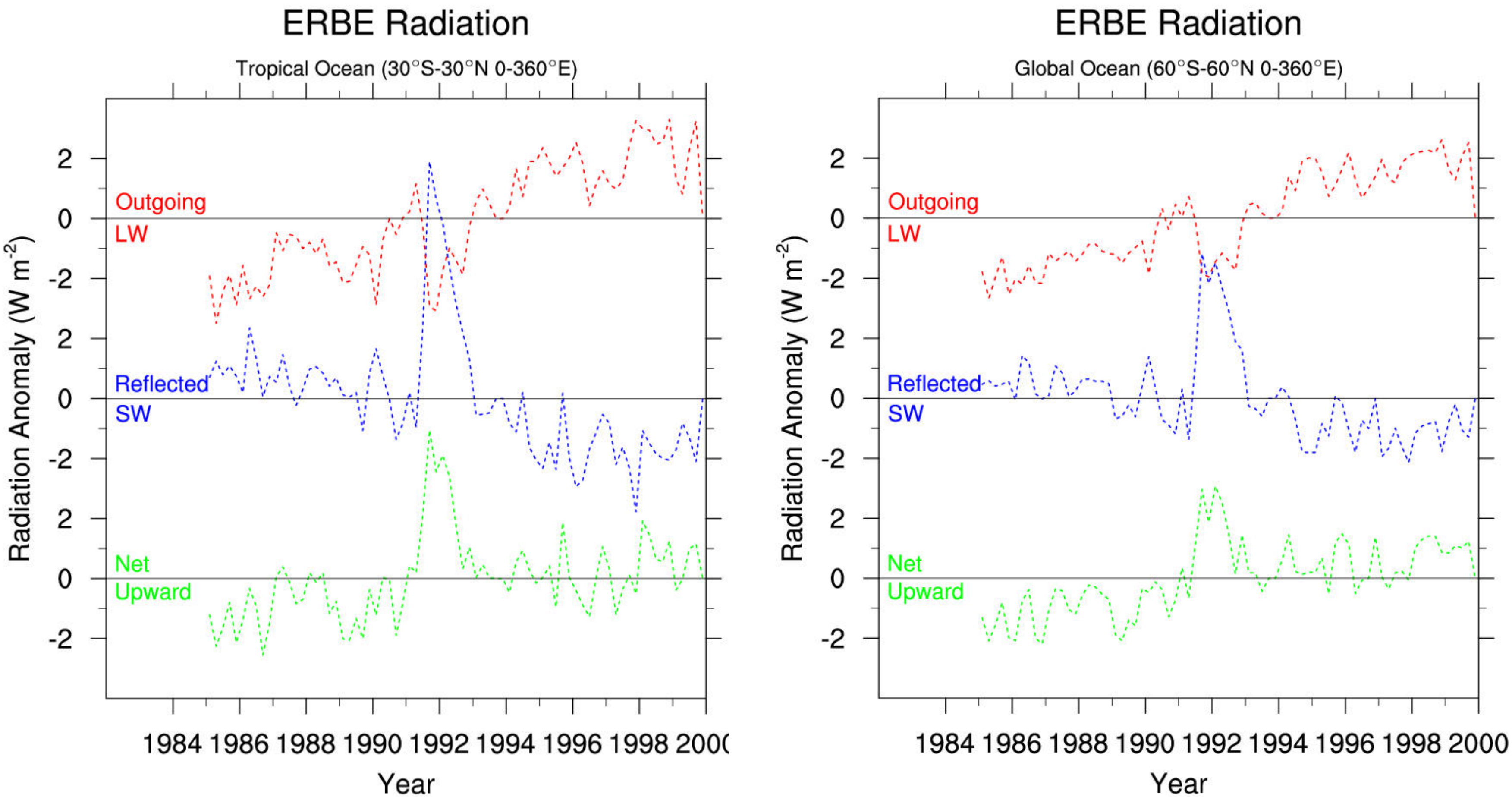
Reflected SW Radiation



SW and LW Cloud Effects



Measured Radiation Variability

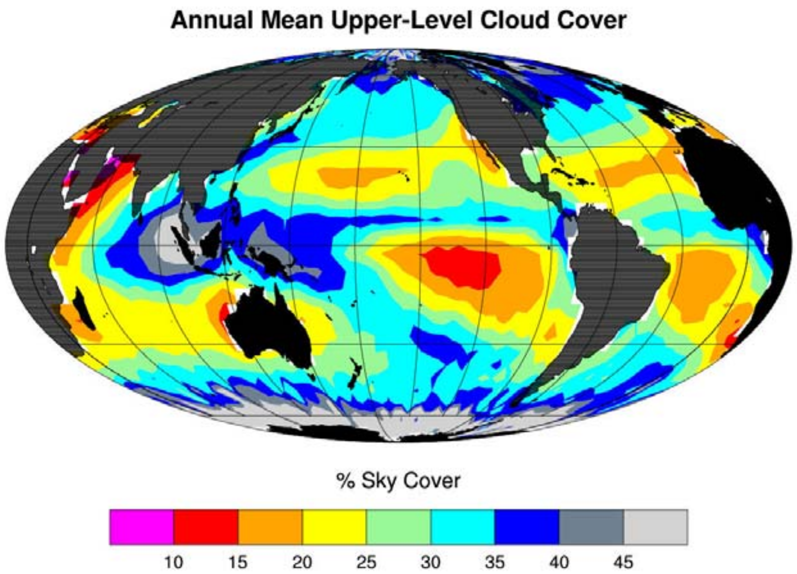


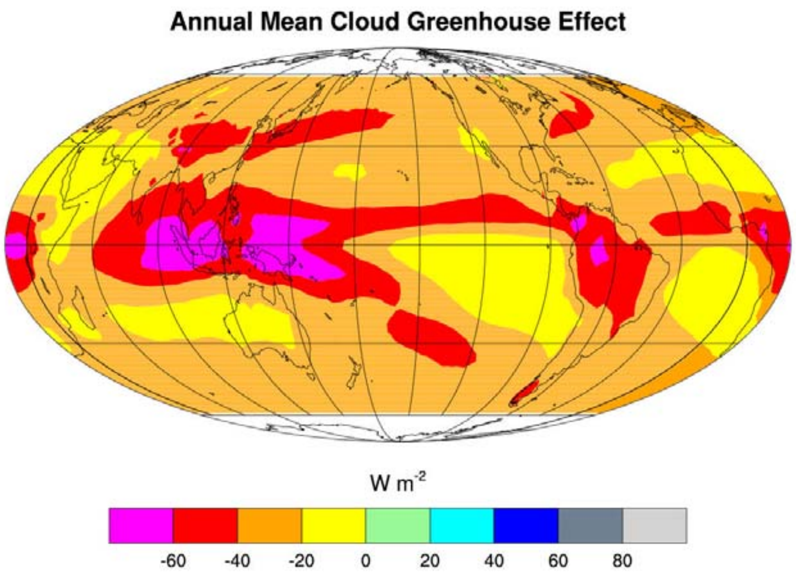
based on Wielicki et al. 2002 (*Science*)

Surface Observations of Cloud Cover

- surface observers on ships routinely report weather and cloud conditions
- an (almost) homogeneous reporting procedure has existed since 1952
- observers report coverage of the sky dome by all clouds and by low-level clouds
- observers report cloud type at low, middle, and high levels
- individual observations are averaged over $10° \times 10°$ grid boxes and 72-day time intervals

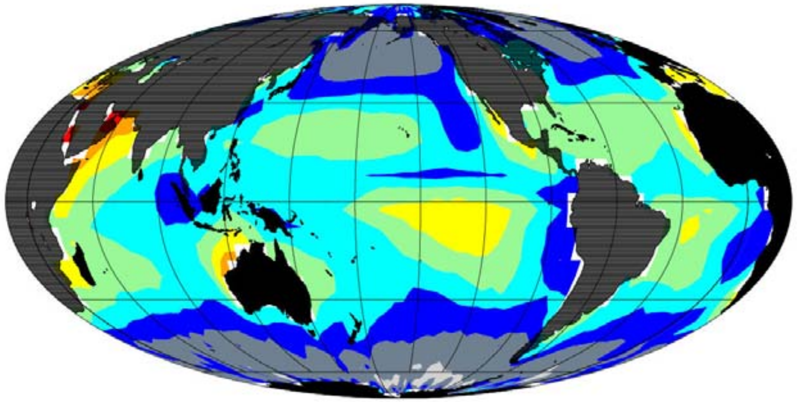
Upper-Level Cloud Cover



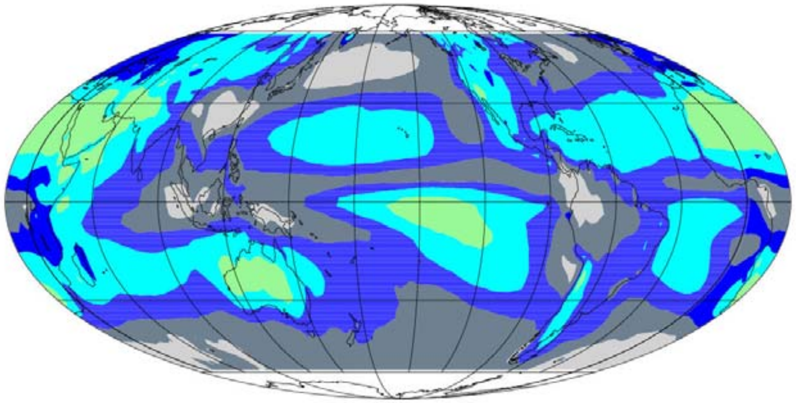


Total Cloud Cover

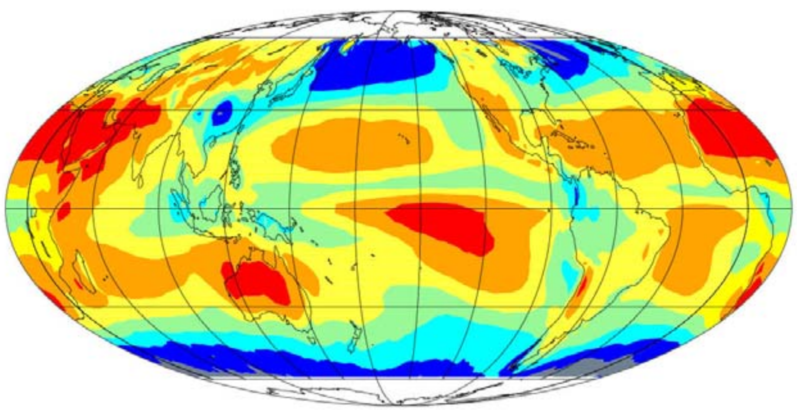
Annual Mean Total Cloud Cover



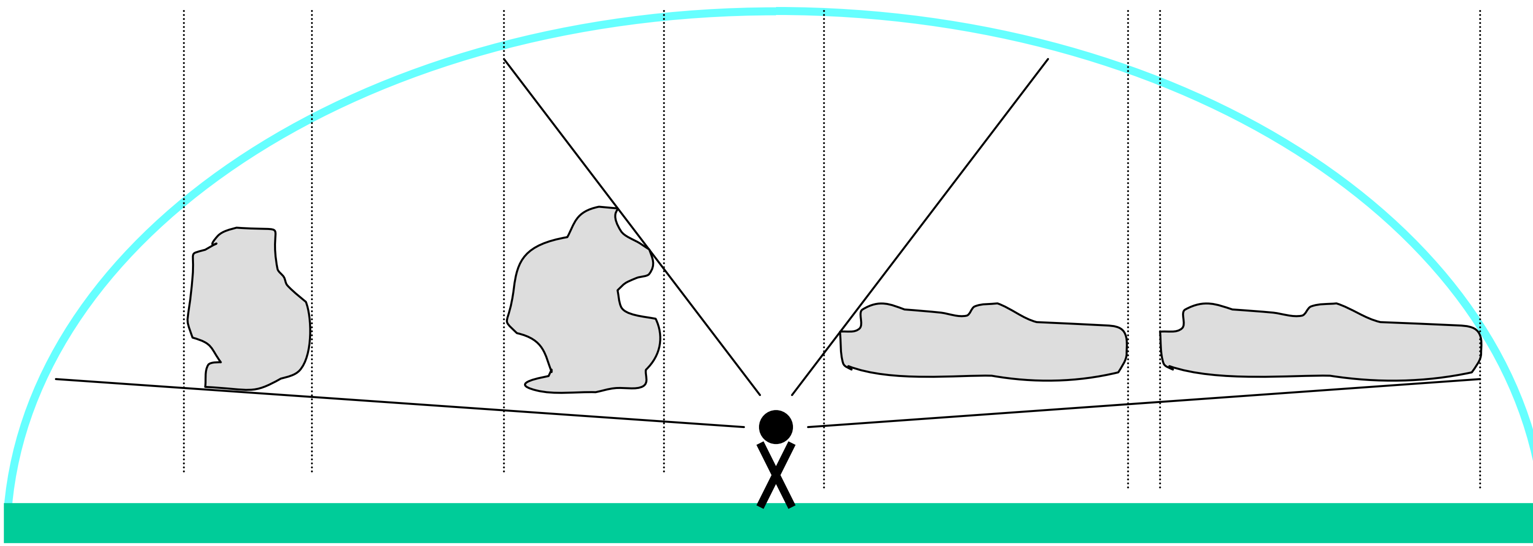
Annual Mean Cloud Reflection



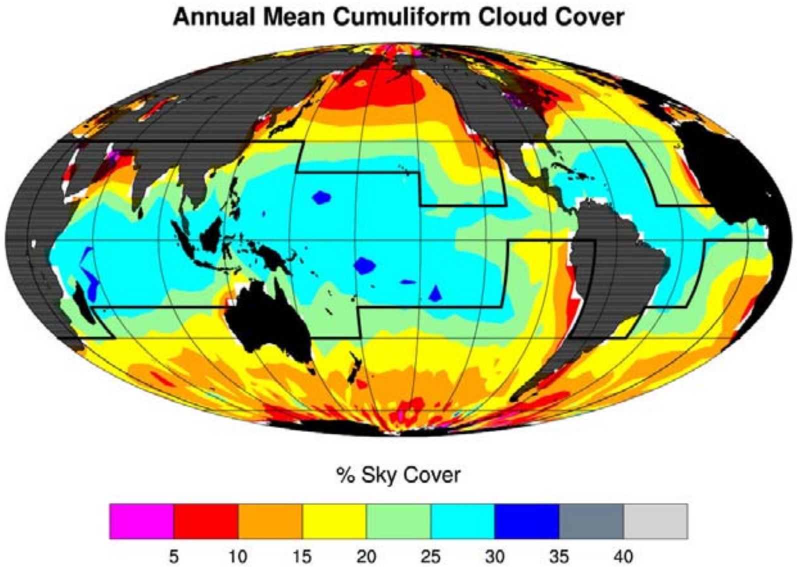
Annual Mean Cloud Albedo

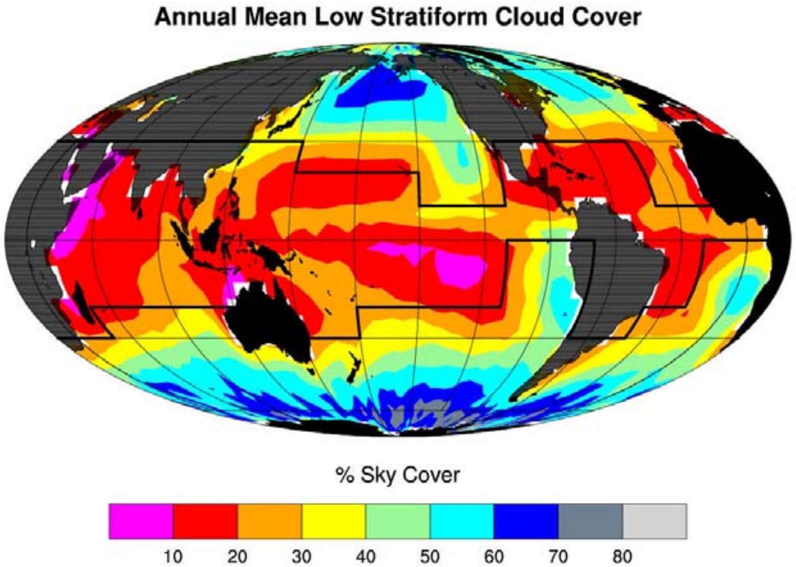


Cumulus Sides and Sky Cover



Cumuliform and Low Stratiform Cover





lines distinguish where cumuliform cloud is prevalent and where low-level stratiform cloud is prevalent

LW Cloud Cover and Albedo Cloud Cover

- assume only upper-level cover affects outgoing LW radiation variability
- assume total cover affects albedo variability for midlatitude and eastern subtropical oceans
- assume only upper-level cover affects albedo variability for tropical ocean
- multiply tropical cloud albedo coefficient by 1.4 to correct for cumuliform cover overestimate

Estimation of Radiation Flux

$$\text{estimated LW radiation anomaly}(\theta, \phi, t) = \frac{\text{cloud greenhouse}(\theta, \phi, \bar{t})}{\text{upper cloud cover}(\theta, \phi, \bar{t})} \times \text{upper cloud anomaly}(\theta, \phi, t)$$

$$\text{estimated SW radiation anomaly}(\theta, \phi, t) = S(\theta, \phi, t) \times \frac{\text{cloud albedo}(\theta, \phi, \bar{t})}{\text{total cloud cover}(\theta, \phi, \bar{t})} \times \text{albedo cloud anomaly}(\theta, \phi, t)$$

θ = longitude

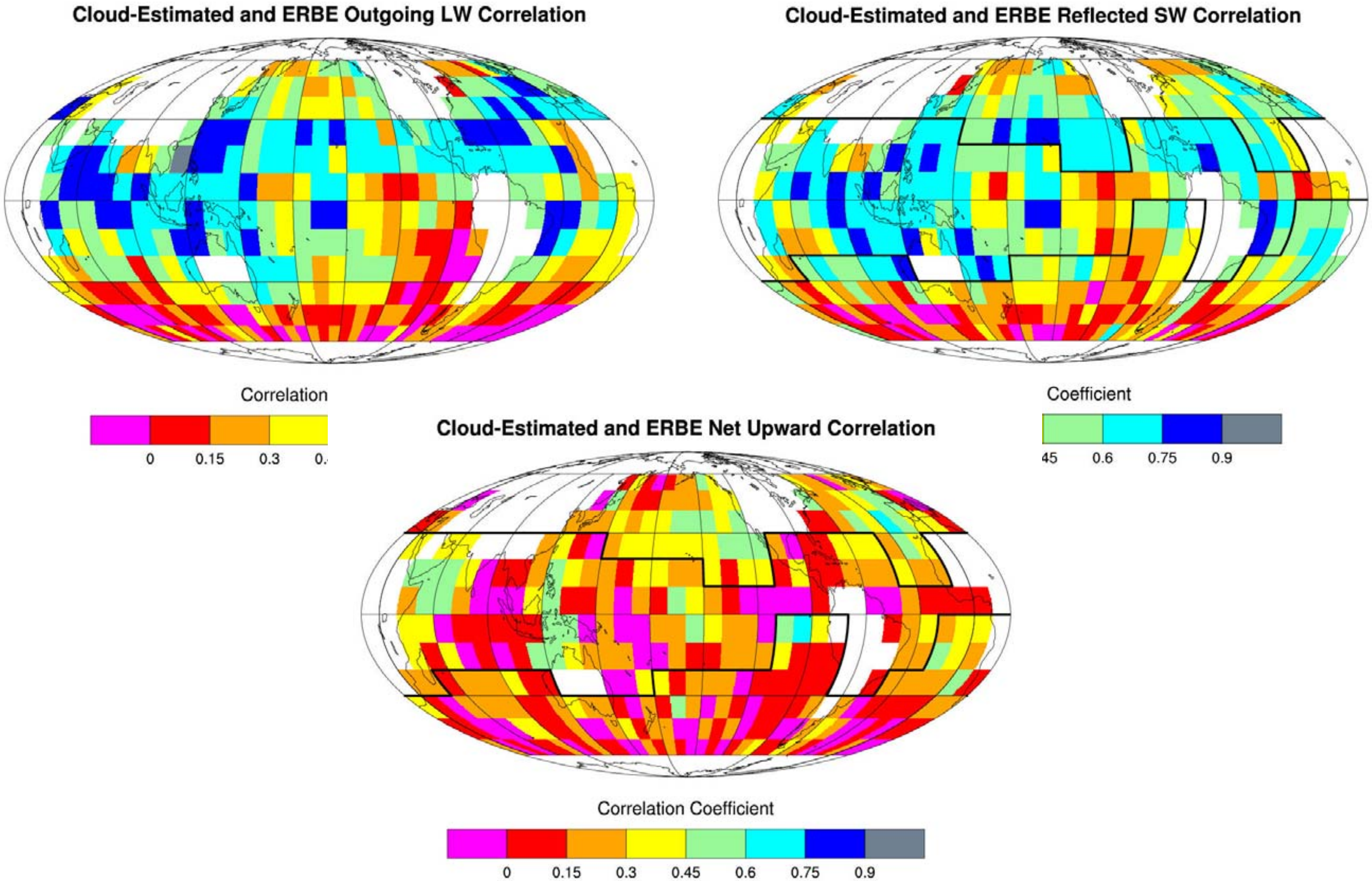
ϕ = latitude

t = time

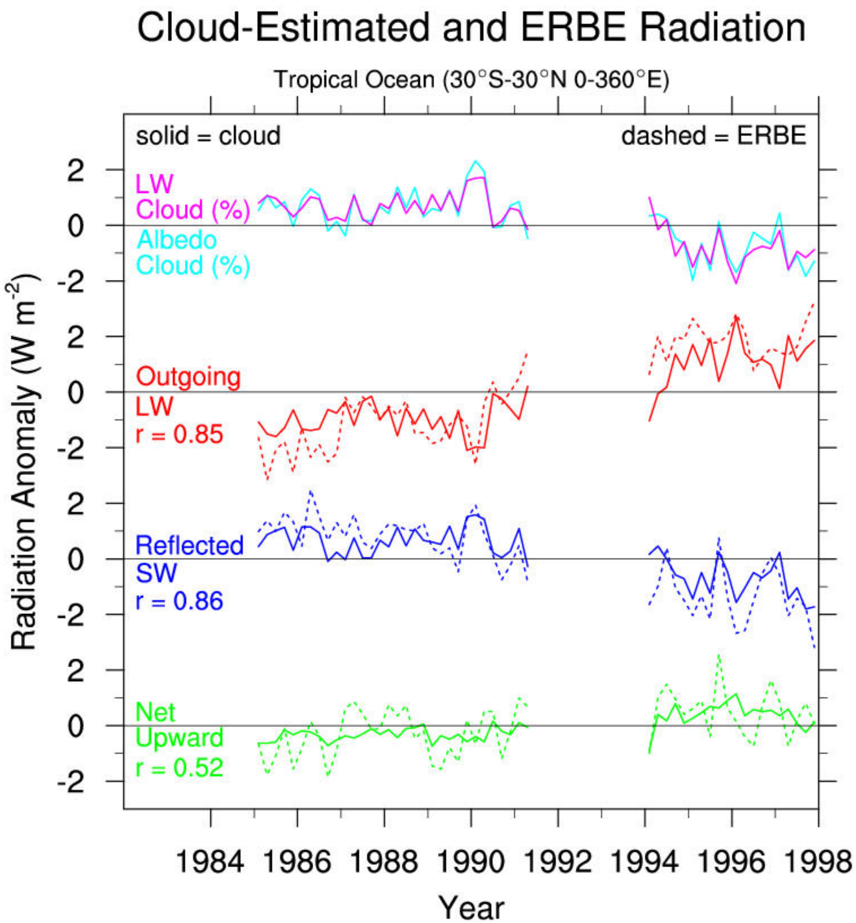
$\bar{t}$ = time in seasonal cycle

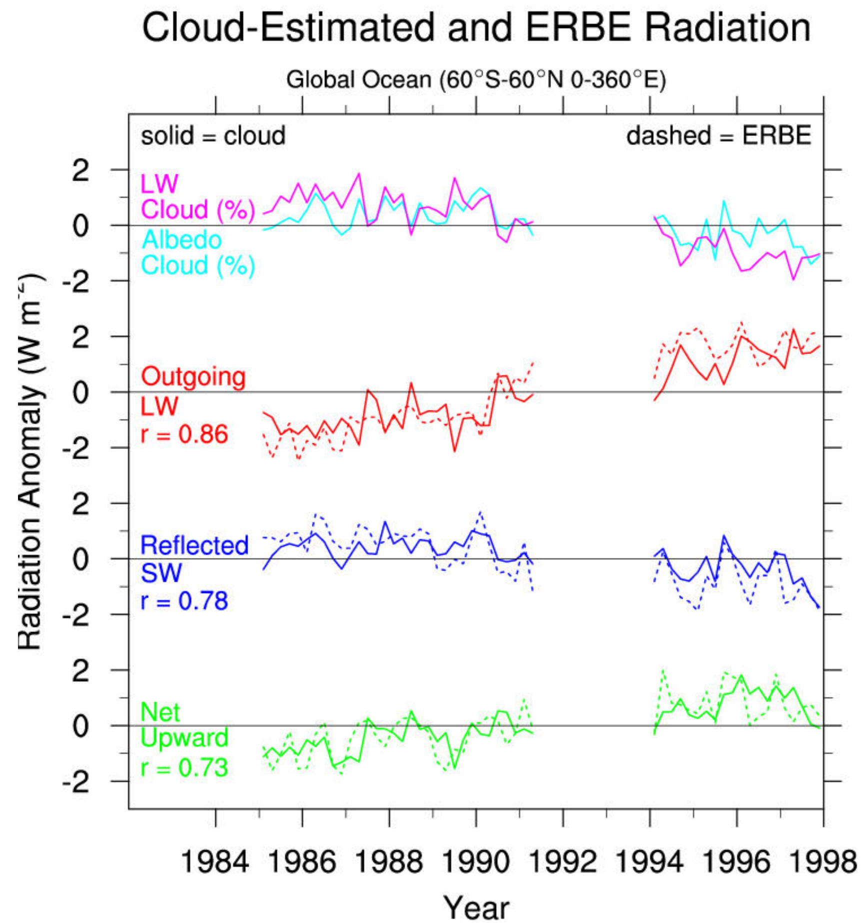
S = insolation

Correlation of Estimated with Measured

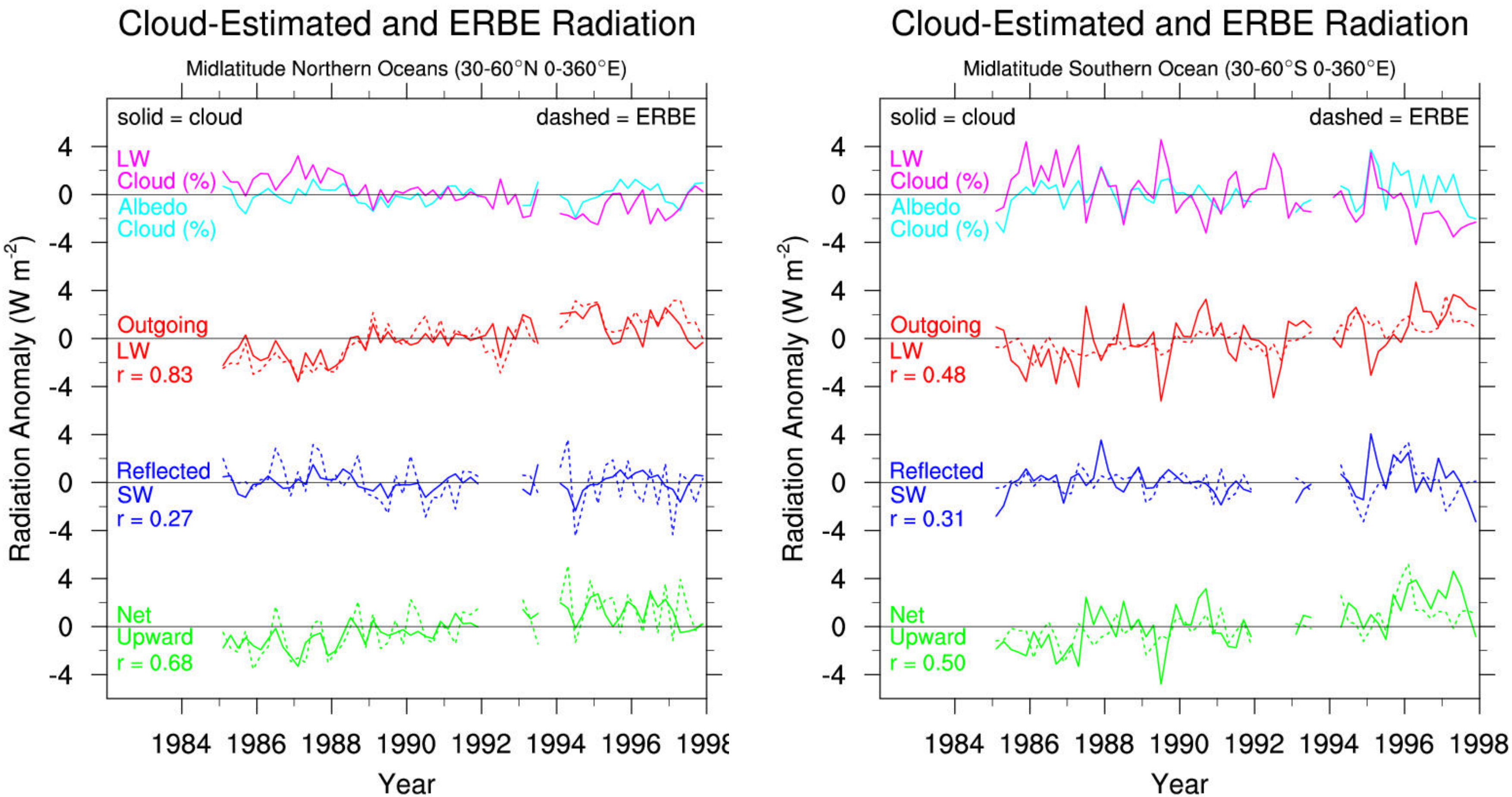


Estimated and Measured Variability





Estimated and Measured Variability

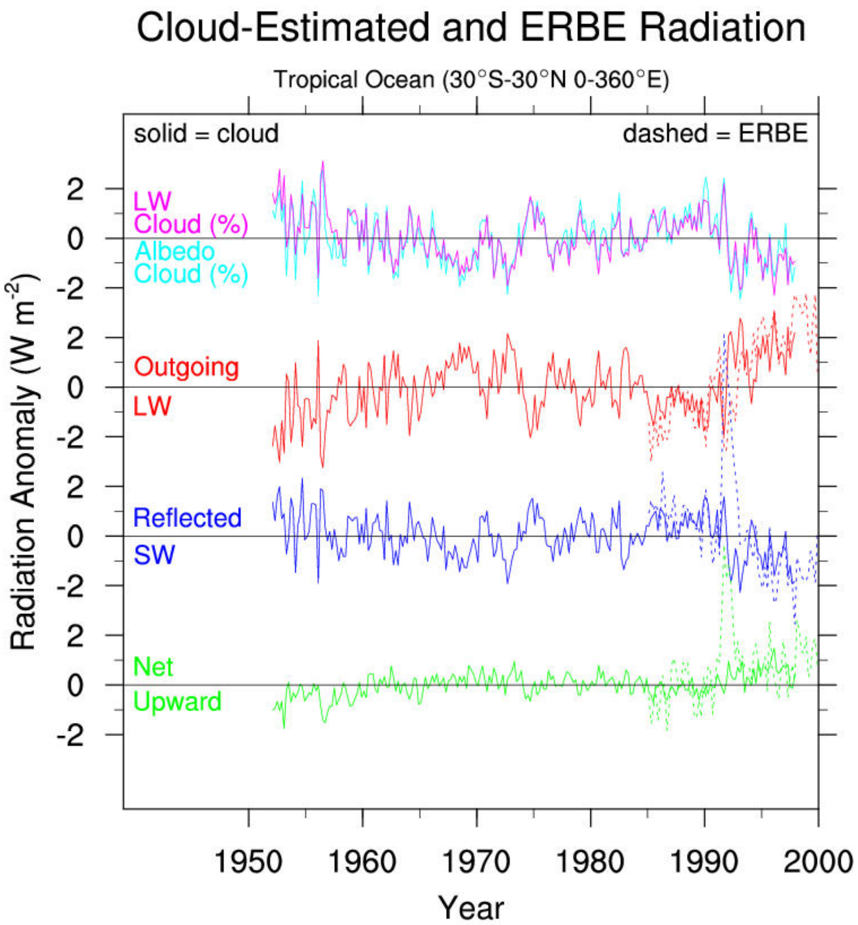


Uncertainty of Estimated Radiation

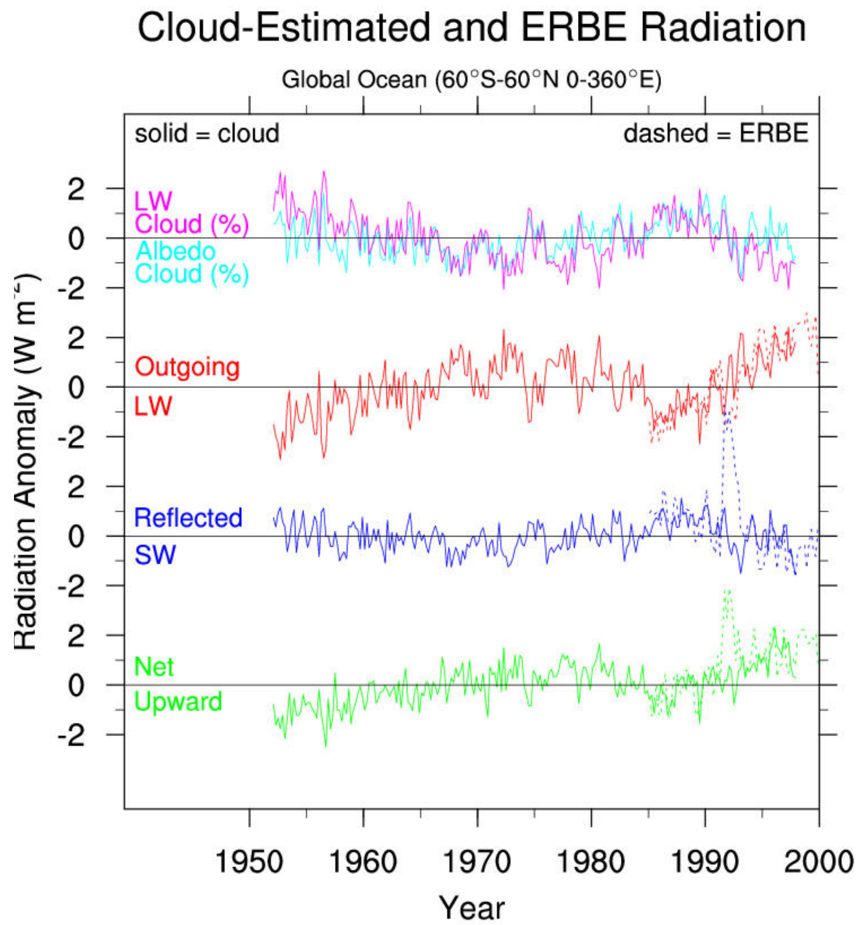
95% confidence interval for 1 Wm^{-2}

	outgoing LW	reflected SW	net upward
northern ocean	±0.2	±1.2	±0.5
tropical ocean	±0.3	±0.2	±0.6
southern ocean	±0.5	±0.5	±0.6
global ocean	±0.2	±0.2	±0.2

Estimated Variability Since 1952

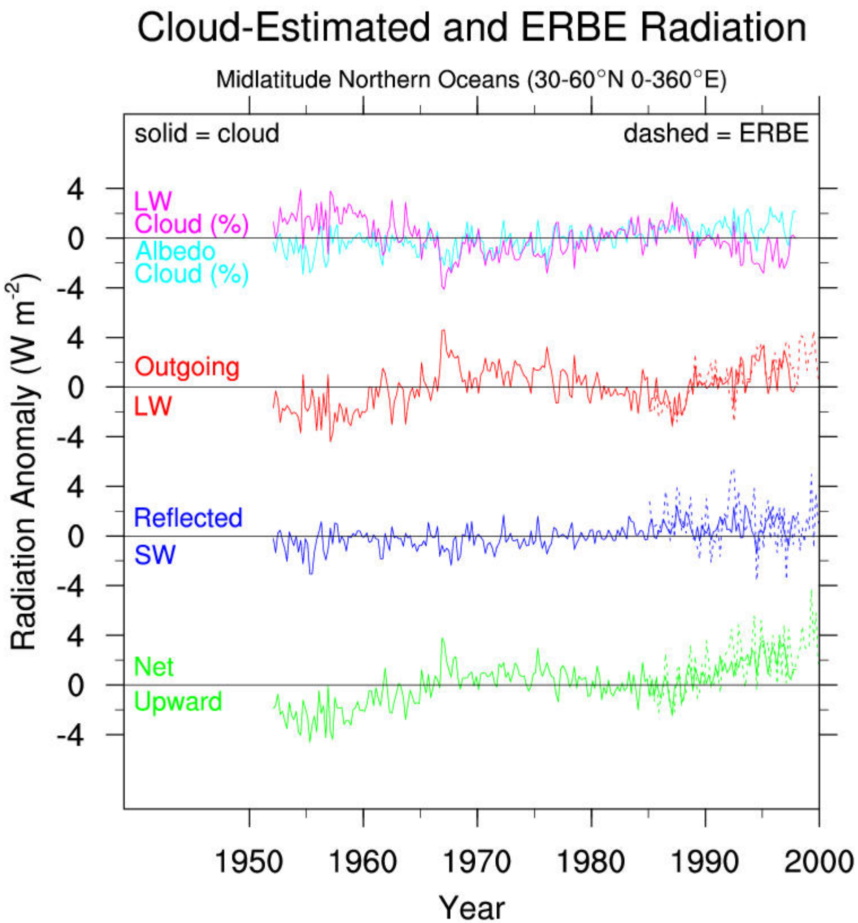


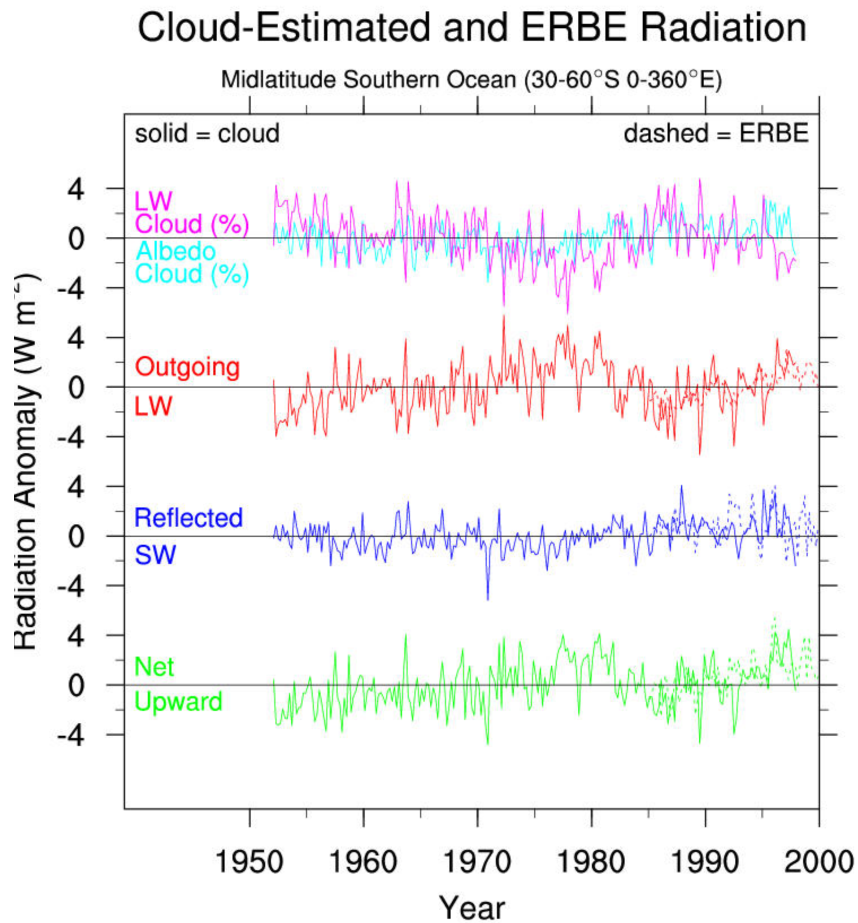
tropical ocean = 41% area of globe



global ocean = 70% area of globe

Estimated Variability Since 1952





northern ocean = 11% area of globe

southern ocean = 18% area of globe

Linear Trends Since 1952

change from 1952 to 1997 (Wm^{-2})

	outgoing LW	reflected SW	net upward
northern ocean	**+2.1±1.7**	+1.7±2.5	**+3.8±2.8**
tropical ocean	**+1.4±1.3**	–0.6±1.0	+0.7±1.0
southern ocean	+1.4±2.2	+1.1±1.5	**+2.5±2.3**
global ocean	**+1.5±1.2**	+0.2±0.7	**+1.7±1.1**

Potential Impact on Temperature

assume energy for change in TOA net upward radiation comes out of top layer *h* of the ocean

$$\Delta T_o = \frac{-\Delta F_C \Delta t}{c \rho h}$$

c = specific heat of water ρ = density of water

some numbers…

for $\Delta F_C = 0.5 \times 1.7$ Wm^{-2}, $\Delta t = 46$ yr, and $h = 200$ m,

$\Delta T_o = -1.5$ K

Potential Climate Feedback

what if the observed cloud trend is solely an internal climate response to externally forced global warming?

then $f_C = f_{CLW} + f_{C\alpha}$ = net cloud cover feedback is

$$f_C = -\frac{\lambda_{BB}}{\lambda_C} = -\frac{1}{4\sigma T_s^3}\frac{\partial F}{\partial C}\frac{dC}{dT_s} \approx -\frac{1}{4\sigma T_s^3}\frac{\Delta F_C}{\Delta T_s}$$

some numbers…

for $\Delta F_C = 1.7\ \mathrm{Wm^{-2}}$, $\Delta T_s = 0.4$ K, $4\sigma T_s^3 = 5.4\ \mathrm{Wm^{-2}K^{-1}}$,

$f_C = –0.8$ *a strong negative feedback*

Attribution of Cloud Trends

(my opinions)

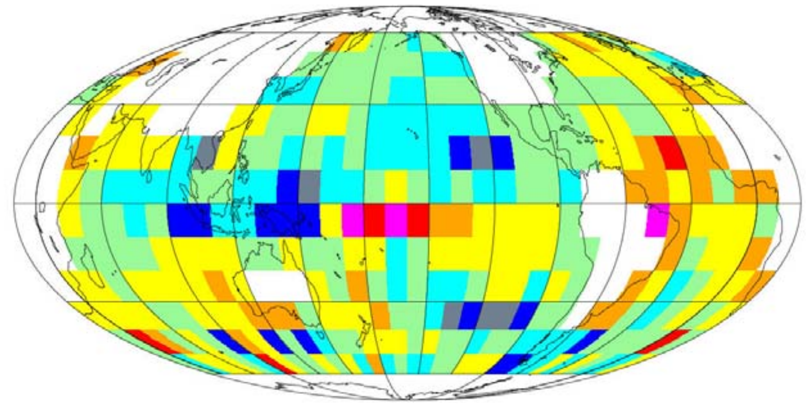
- internal climate variability is unlikely to produce cloud trends occurring over the length of 46 years
- anthropogenic or natural external forcing is unlikely to directly produce the observed cloud trends
- an internal response of the climate system to external forcing could produce the cloud trends
- there is not yet enough information to attribute the cloud trends to anthropogenic global warming

Investigation of Causes of Cloud Changes

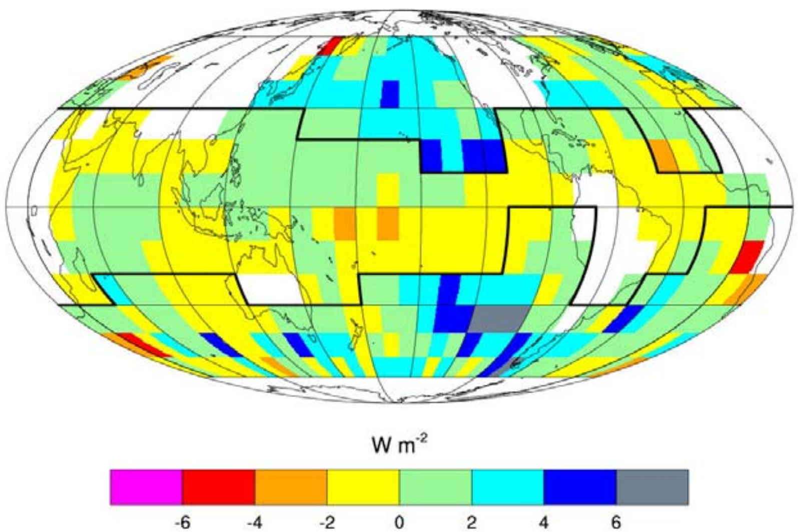
- multidecadal reliable observations of the upper atmosphere over the ocean are not available
- the limited surface data available might suggest possible mechanisms for observed cloud changes
- GCMs will likely be needed to explore possible mechanisms and the response of the climate system to external forcing

Spatial Distribution of Cloud Change

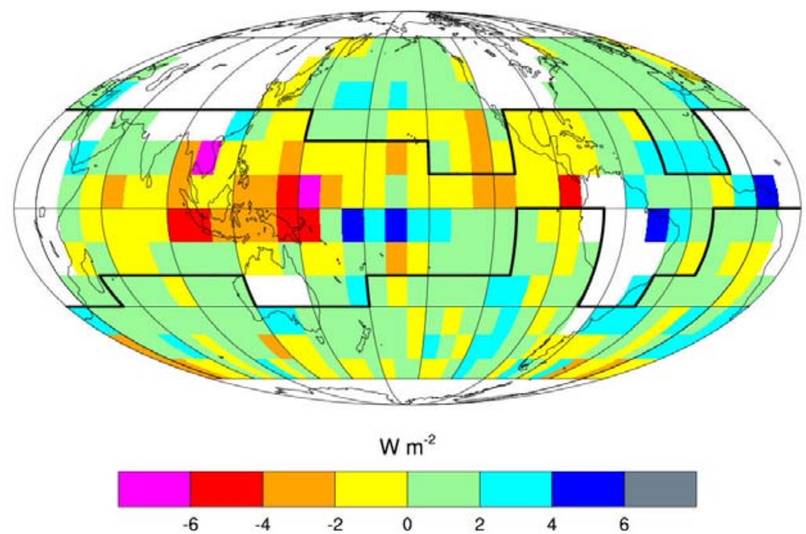
Outgoing LW Change from 1952-74 to 1975-97



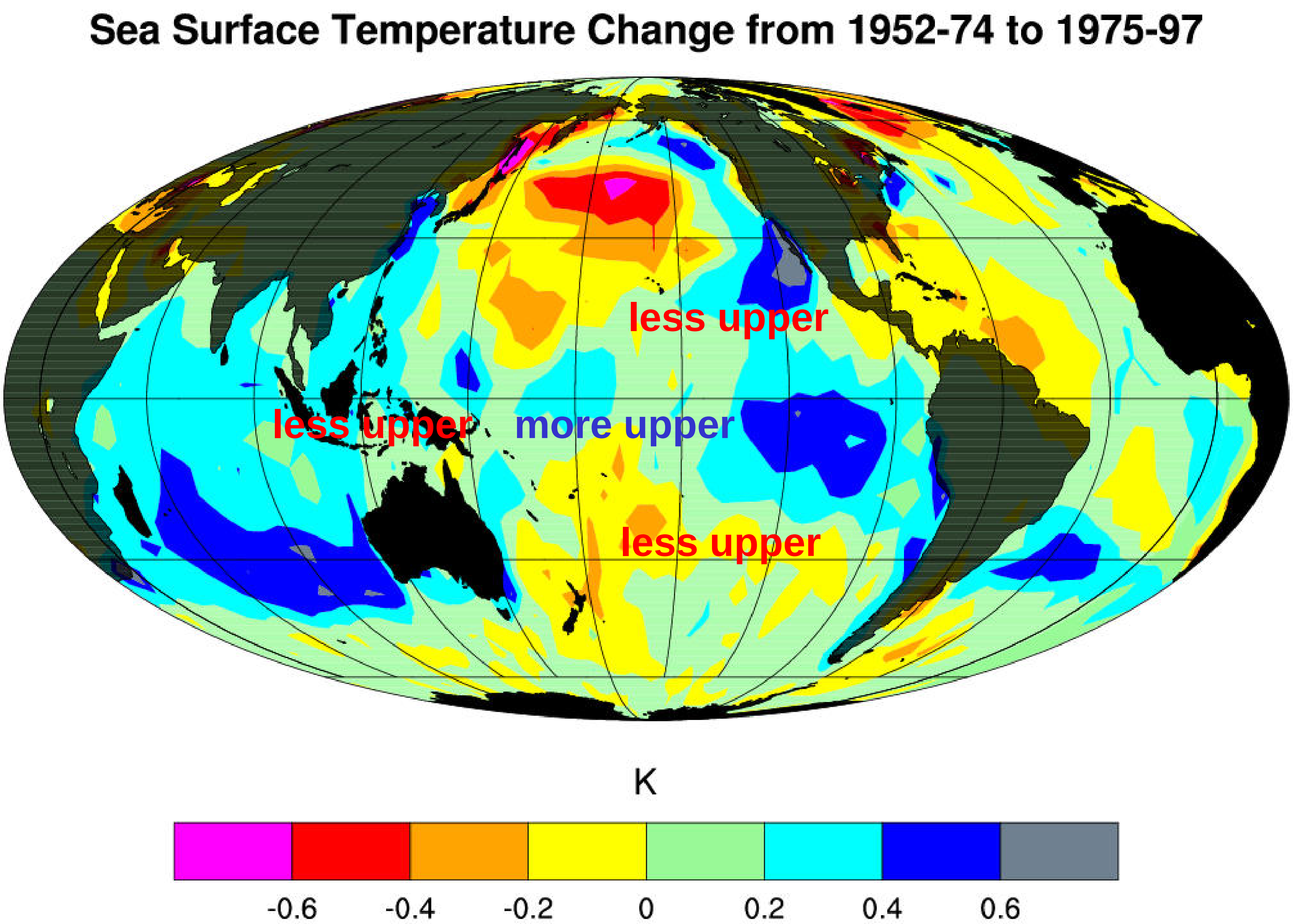
Net Upward Change from 1952-74 to 1975-97



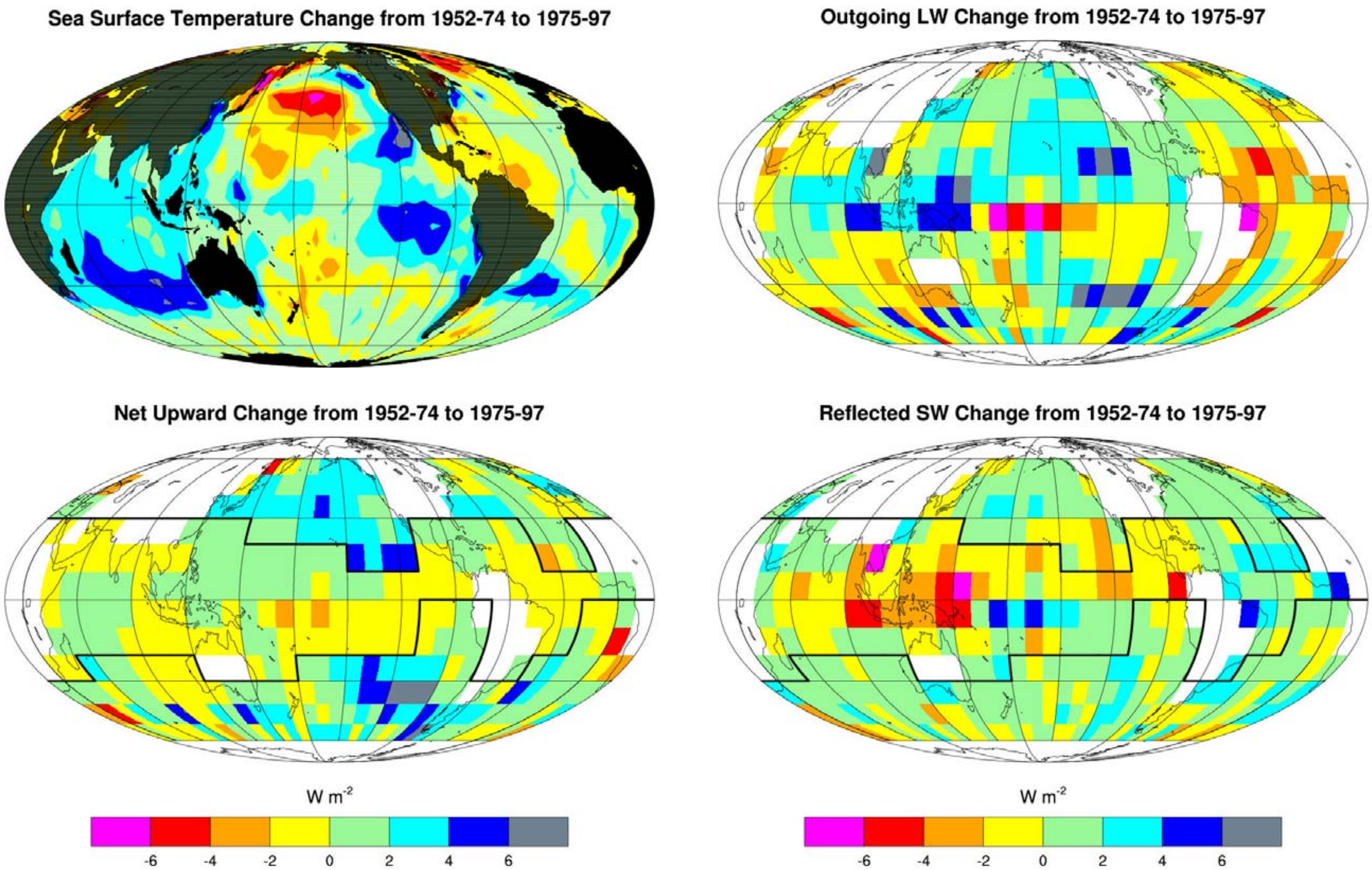
Reflected SW Change from 1952-74 to 1975-97



Sea Surface Temperature Change



Sea Surface Temperature and Cloud



Summary

- low-level stratiform cloud cover and reflected SW radiation have increased over midlatitude oceans
- low-level stratiform cloud cover and reflected SW radiation have decreased over eastern subtropical oceans
- cloud changes since 1952 have had a net cooling effect on the Earth

More Information

- these results are currently being prepared for publication
- many more figures and detailed descriptions of methods are available at

  meteora.ucsd.edu/~jnorris/cloud_trend.html