The Role of Dynamics in Cloud Feedbacks

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September 8, 2009

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4th IPCC: Key Uncertainties

- “Cloud feedbacks (particularly from low clouds) remain the largest source of uncertainty [to climate sensitivity].”
- “… processes leading to modification of cloud properties by aerosols [are] not well understood and … indirect radiative effects are poorly determined.”
- “Surface and satellite observations disagree on total and low-level cloud changes over the ocean.”
- “Large uncertainties remain about how clouds might respond to global climate change.”
- “Cloud feedbacks are the primary source of intermodel differences in equilibrium climate sensitivity…”

Why the Cloud Uncertainty?

- We have no stable system to monitor global cloudiness and radiation on multidecadal time scales
- Models incorrectly and inconsistently simulate cloudiness

Alternative strategy

- Estimate cloud feedbacks from high-frequency observations

Calculating Feedbacks from Observations

- Detailed and comprehensive cloud measurements are not enough!
- It is absolutely essential to integrate meteorological and cloud observations
- Calculation methods to estimate feedbacks must be relevant to climate change problem
- Observed cloud-meteorological relationships are the best basis for model evaluation

Simple Equilibrium Climate Framework

What is the change in the temperature of Earth's climate (ΔT_c) produced by external radiative forcing (ΔR)?

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

$$\frac{1}{\lambda_{BB}} =$$ *rate of increase of blackbody emission*

$$\frac{\partial F}{\partial I_k}\frac{dI_k}{dT_c} =$$ *radiative effect of change in internal parameter I_k in response to temperature*

Cloud Response to Temperature

$\frac{\partial F}{\partial C}$ radiative effect of a change in cloud properties is relatively straightforward to calculate

$\frac{dC}{dT_c}$ change in cloud properties in response to temperature is much more difficult to calculate

$$\frac{dC}{dT_c} = \frac{\partial C}{\partial T_c} + \sum_i \frac{\partial C}{\partial M_i} \frac{dM_i}{dT_c}$$

direct response to temperature change

indirect response through modification of dynamics by temperature change

Difficulties with Observational Calculations

Observations provide $\frac{dC}{dT}$, not $\frac{\partial C}{\partial T}$

$$\frac{\partial C}{\partial M_i}\frac{dM_i}{dT}$$

is based on meteorological variability, not equilibrium climate change
– *dynamical relationships may differ*

Example: El Nino causes global temperature to increase, but atmospheric circulation and cloud changes do not correspond to those expected for global warming from increasing greenhouse gases

Dynamical Compositing (Bony et al. 2004)

C = cloud property
ω = vertical velocity

Aggregate
C change

Covariation Term

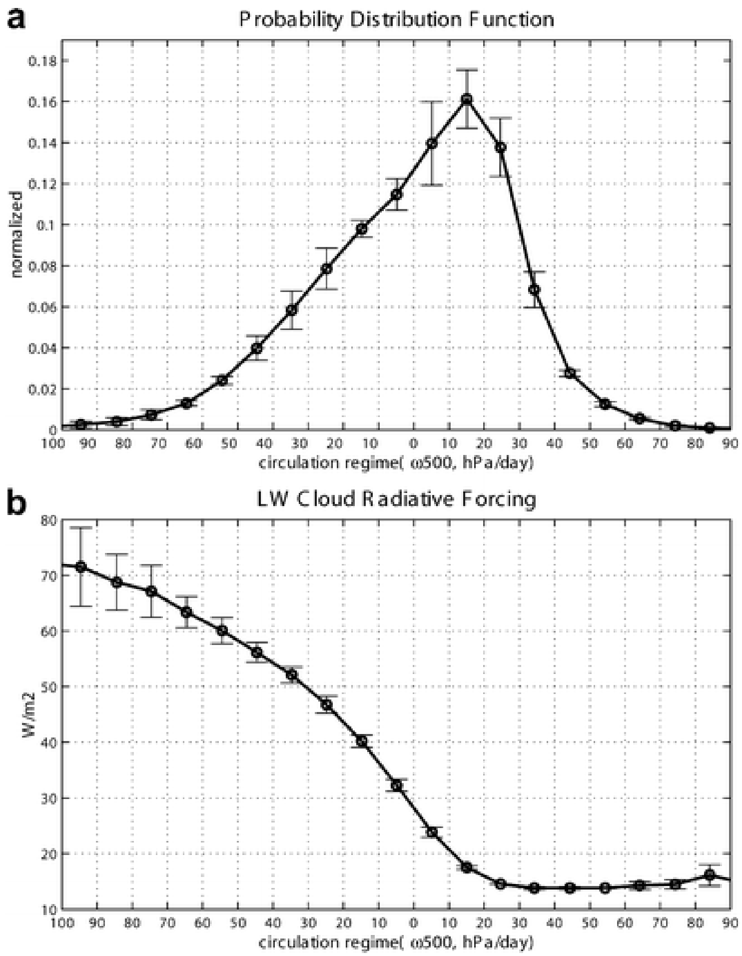
$$\overline{\delta c} = \int_{-\infty}^{+\infty} C_\omega \delta P_\omega \mathrm{d}\omega + \int_{-\infty}^{+\infty} P_\omega \delta C_\omega \mathrm{d}\omega + \int_{-\infty}^{+\infty} \delta P_\omega \delta C_\omega \mathrm{d}\omega \ .$$

Dynamic Component
no C change for same ω,
ω distribution changes

Thermodynamic Component
C does change for same ω,
no ω distribution change

Dynamical Compositing (Bony et al. 2004)

Freq



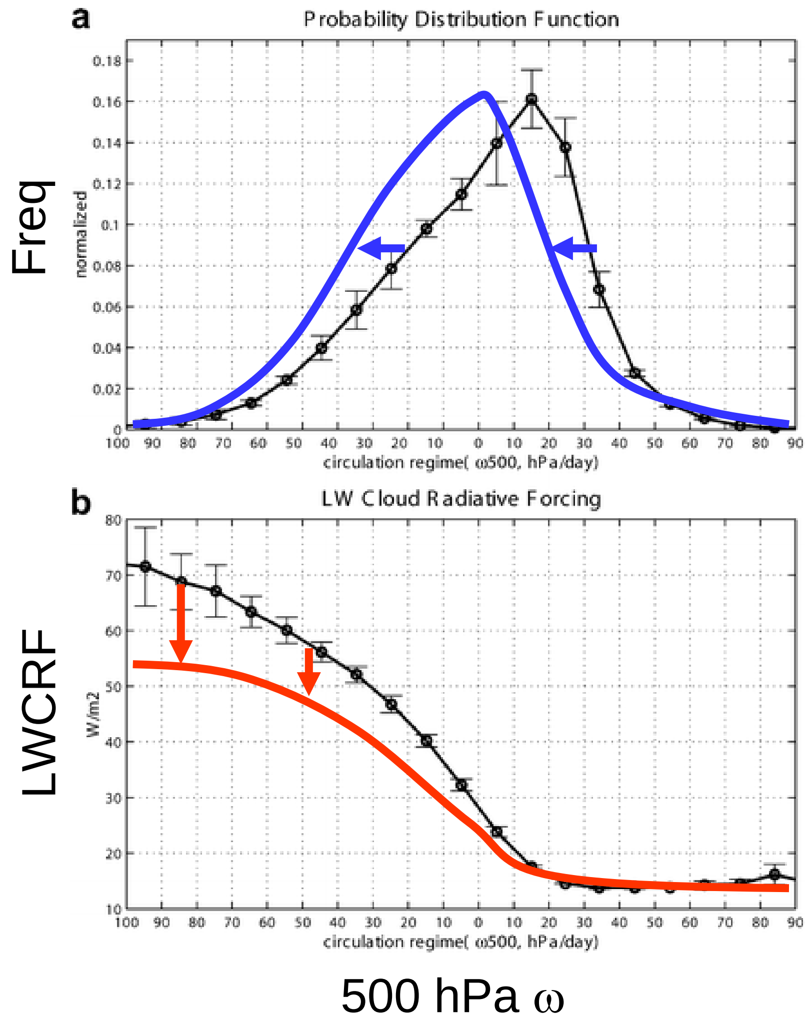
LWCRF

500 hPa ω

Distribution of monthly mean vertical velocity in the tropics

Longwave cloud radiative forcing as a function of vertical velocity in the tropics

Dynamical Compositing (Bony et al. 2004)



Hypothetical Example

Shift in ω distribution produces net cloud change, i.e., $\dfrac{\partial C}{\partial M_i}\dfrac{dM_i}{dT}$

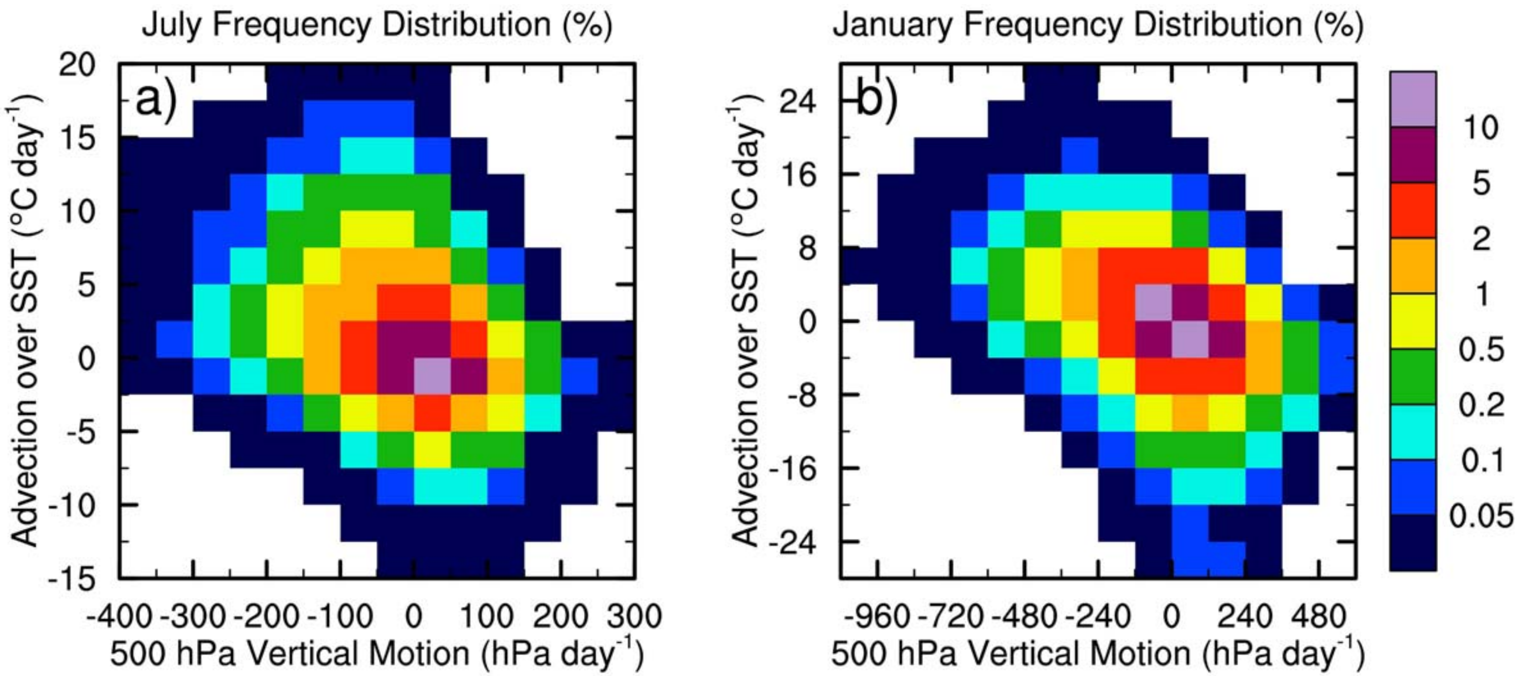
Hypothetical Example

Cloud change with temperature not associated with change in ω, i.e. $\dfrac{\partial C}{\partial T}$

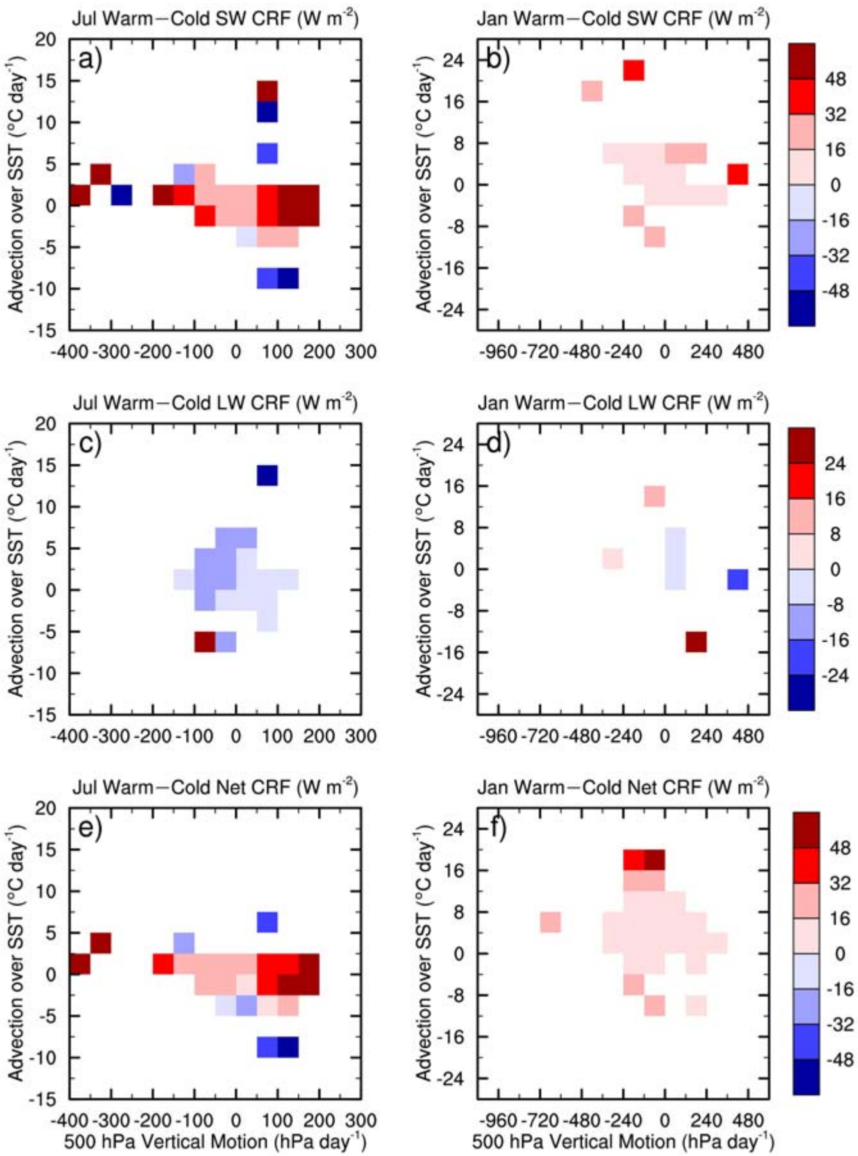
Cloud, SST, and Advection

- Synoptic variability causes atmospheric flow over the North Pacific SST gradient to frequently change.
- Horizontal advection and vertical motion have large impacts on cloud and temperature
- Bin daily cloud and CRF on according to ω_{500} and SST advection (defined as $-\mathbf{V}_{1000}\cdot\nabla SST$)
- Examine composite difference in cloud and CRF between warm and cold temperature for each bin

SST Advection-ω_{500} Histograms (Freq)



Adv-ω Histograms (Warm–Cold CRF)



SW CRF more positive (weaker negative) for warm conditions under most dynamical states

LW CRF more negative (weaker positive) for warm conditions under most dynamical states

net CRF more positive (weaker negative) for warm conditions under most dynamical states

Average Warm-Cold Cloud Properties

ω_{500}, $-\boldsymbol{V}_{1000} \cdot \nabla SST$, *and vertical stratification held constant (as much as possible)*

Cloud Amount (%-cover K^{-1})	–1.4
Cloud Optical Thickness (K^{-1})	–0.1
Cloud Top Pressure (hPa K^{-1})	–1.5
SW CRF (W m^{-2} K^{-1})	+6.9
LW CRF (W m^{-2} K^{-1})	–1.8
Net CRF (W m^{-2} K^{-1})	+5.2

Cloud response to temperature suggests a positive cloud feedback for North Pacific $\partial C/\partial T$

One Nagging Question…

Does compositing on one or two single-level parameters truly constrain the dynamical influence on cloudiness?

- The composite parameters may not represent all possible dynamical effects on temperature and clouds
- The Bony et al. approach provides only a lower limit for the impact of dynamics on clouds
- The “thermodynamic component” may actually be mostly composed of “hidden” dynamics

Stronger Dynamical Constraints

- Cluster ISCCP daily gridbox values over midlatitude oceans into seven cloud regimes

- Only use daily values in the middle quartiles (25%-75%) of both vertical and horizontal temperature advection in each of three layers of the troposphere

- Also require daily values to be in the middle quartiles of lapse rate in both the upper and lower troposphere

- What is the difference in cloud properties between the warm half and cold half of each cloud regime?

Average Warm-Cold Cloud Properties

Horizontal and vertical temperature advection and vertical stratification held constant in three layers

Cloud Amount (%-cover K^{-1})	–0.9
Cloud Optical Thickness (K^{-1})	+0.1
Cloud Top Pressure (hPa K^{-1})	+3.6
SW CRF (W m^{-2} K^{-1})	+0.1
LW CRF (W m^{-2} K^{-1})	–0.6
Net CRF (W m^{-2} K^{-1})	–0.5

Cloud response to temperature suggests a small negative cloud feedback for midlatitude ocean $\partial C/\partial T$

Influence of Meteorological History on Cloud

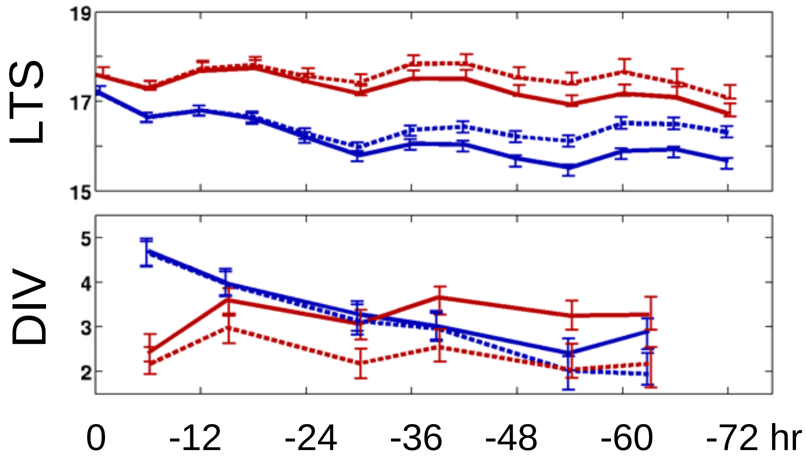
- Select MODIS daily gridbox values of small and large cloud amount

- Calculate back trajectories using ECMWF analysis

- Interpolate cloud and meteorological data to back trajectory locations

- How are cloud properties at t = 0 related to meteorological conditions at prior times?

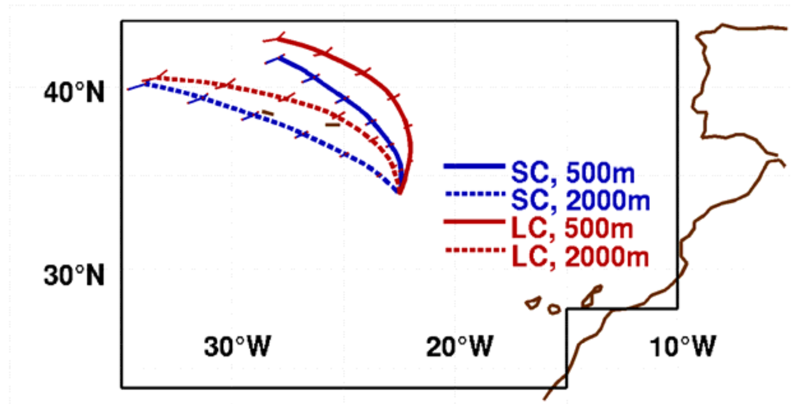
Influence of Meteorological History on Cloud

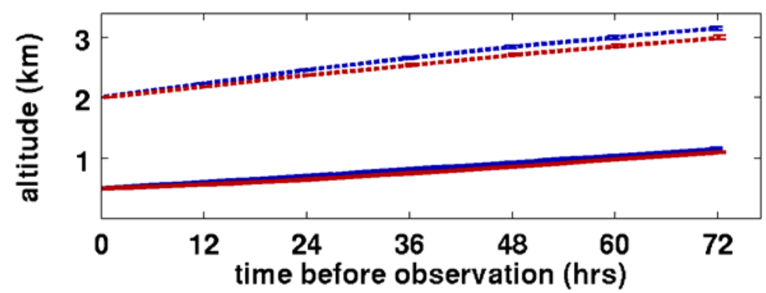


LC = red   SC = blue

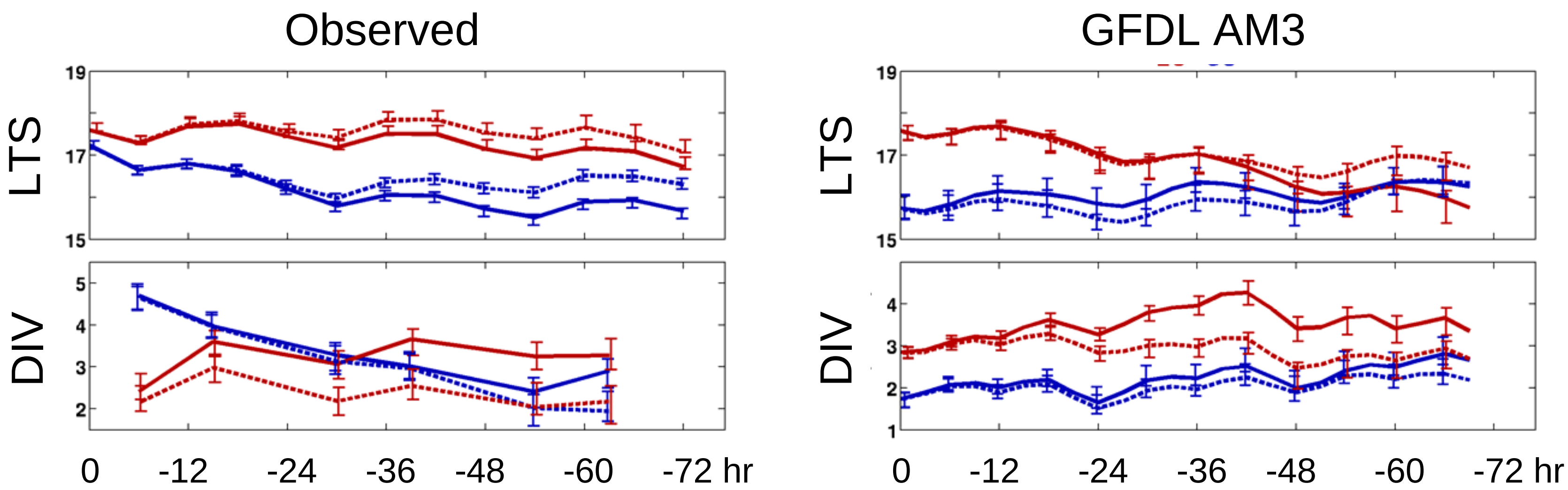
Observed LC has strongest LTS at *t* = -36 hr

Observed SC has strongest DIV_{sfc} at *t* = -6 hr





Evaluation of GFDL AM3



LC = red SC = blue

Observed LC has strongest LTS at t = -36 hr
Model LC has strongest LTS at t = 0 hr

Observed LC has weak DIV_{sfc} at t = -6 hr
Model LC has strong DIV_{sfc} at t = 0 hr and t = -36 hr

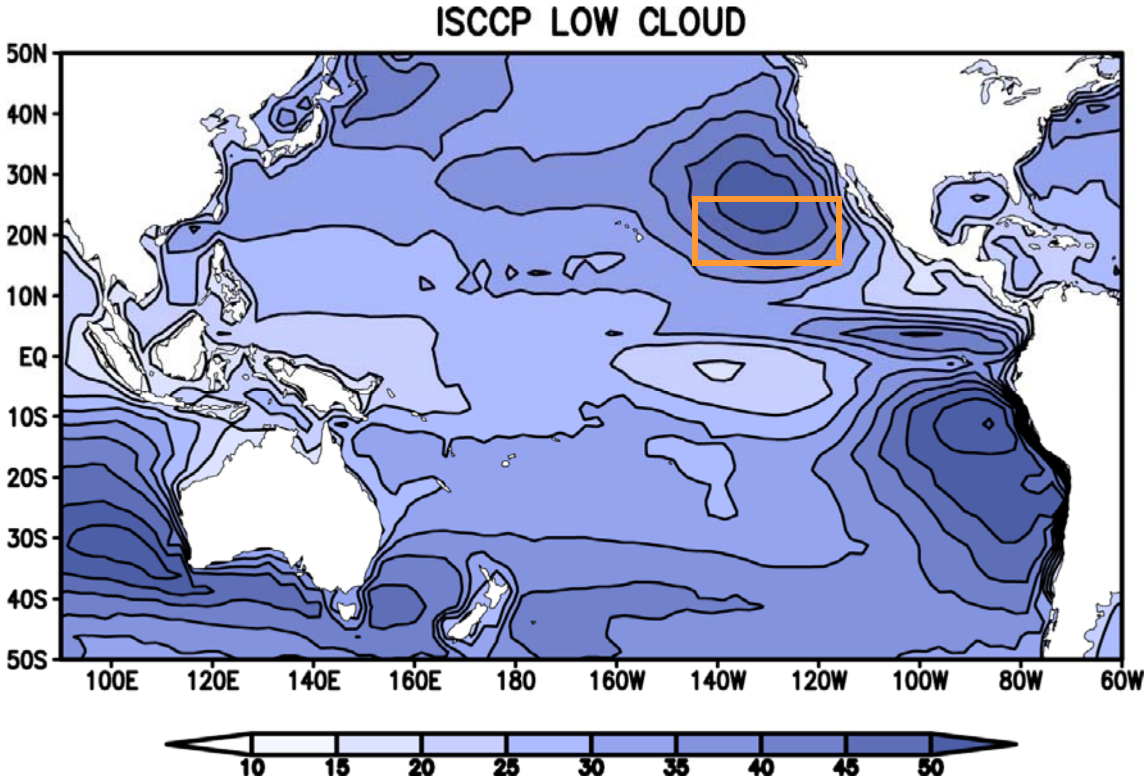
Circulation and Cloud Feedbacks

What is the primary direct driver of cloud feedbacks in climate change?

- Previous work has likely overestimated the impact of "thermodynamics" (temperature and lapse rate change)
- Atmospheric circulation change associated with global warming may instead play a leading role

NE Pacific Decadal Variability

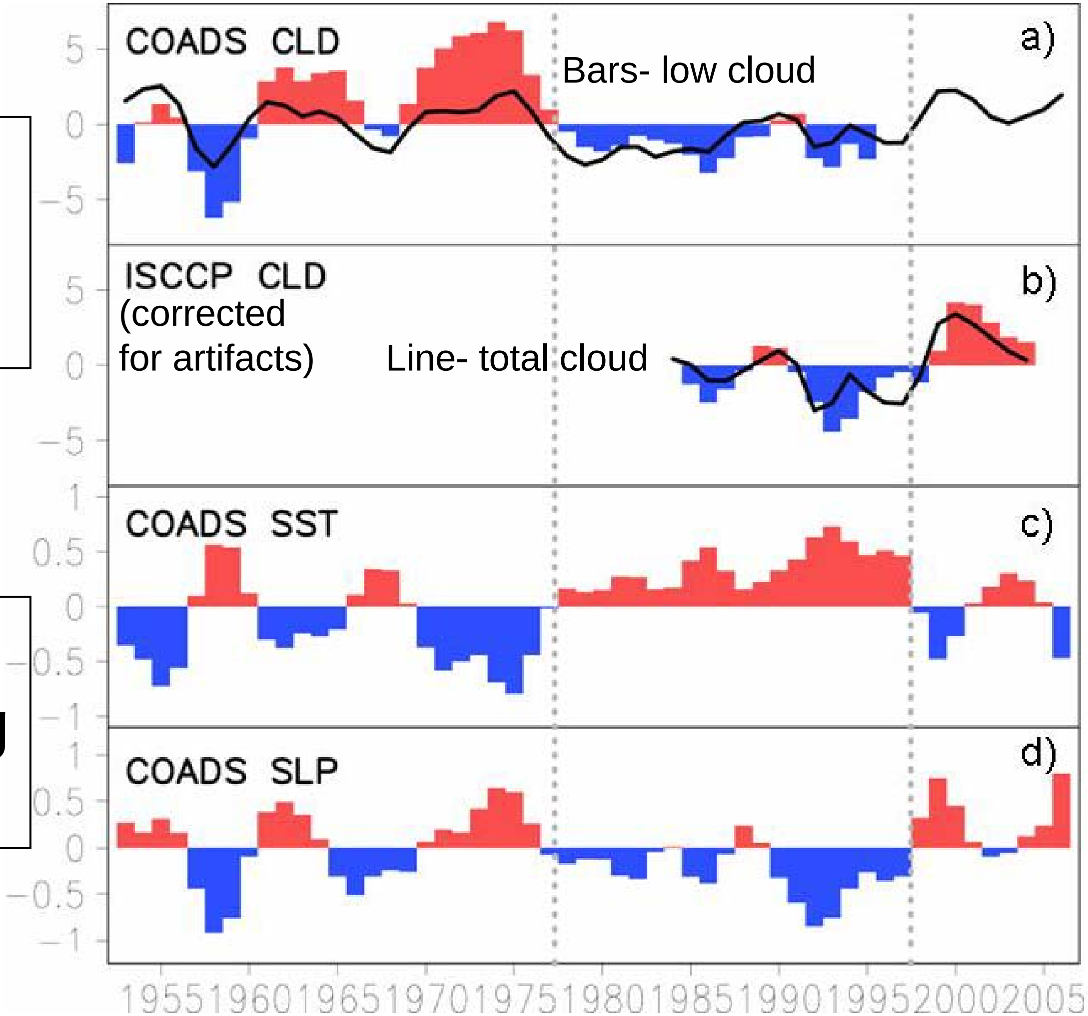
Does a cloud feedback promote decadal variability in SST and circulation?



NE Pacific Decadal Variability

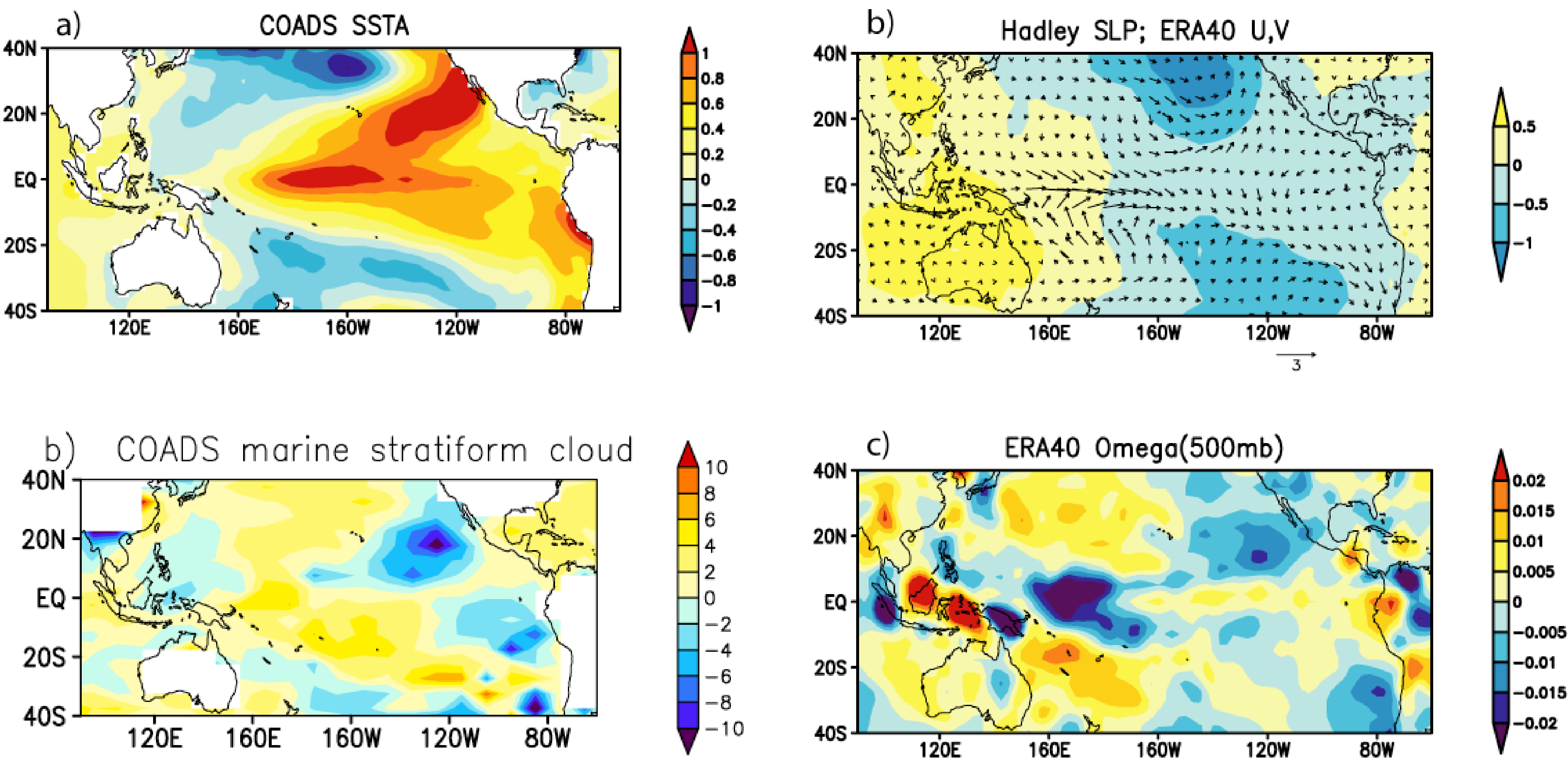
warm SST
weak SLP
weak wind

less stratocumulus
more ocean heating
less BL cooling



NE Pacific Decadal Variability

Basin-wide regression on NE Pacific SST time series



Is this feedback present in IPCC AR4 models?

Observed r NE Pacific cloud and meteorology

Correct sign r and robust simulation

wrong sign $r(\text{cloud},\omega_{500})$

wrong sign $r(\text{cloud},\text{SLP})$

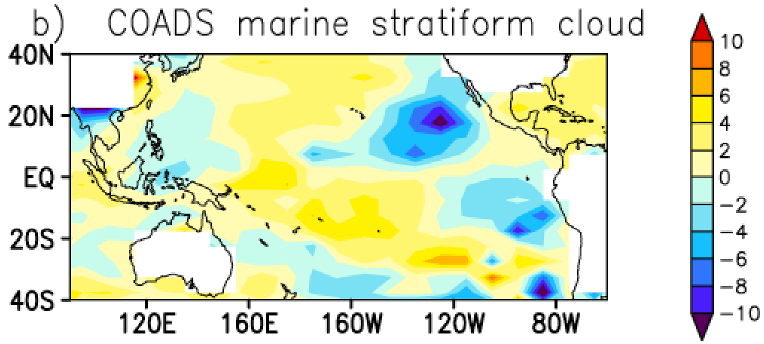
models with wrong sign $r(\text{cloud},\text{LTS})$

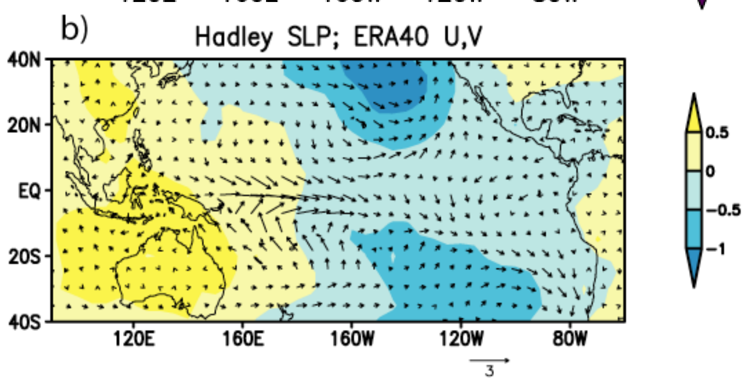
models with wrong sign $r(\text{cloud},\text{SST})$

	SST	LTS	SLP	Vs	ω 500
ISCCP low	-0.78	0.51	0.64	-0.56	0.50
COADS msc	-0.92	0.43	0.80	-0.63	0.62
ukmo_hadgem1	-0.81	0.84	0.65	-0.55	0.39
inmcm3_0	-0.77	0.37	0.58	-0.57	0.14
bccr_bcm2_0	-0.60	0.43	0.44	-0.58	NA
mri_cgcm2_3_2a	-0.59	0.14	0.32	-0.31	-0.60
miroc3_2_hires	-0.91	0.54	-0.03	0.71	-0.10
cccma_cgcm3_1_t63	-0.86	0.01	0.52	-0.44	0.20
gfdl_cm2_0	-0.69	0.06	0.52	-0.73	-0.42
cccma_cgcm3_1	-0.80	-0.08	0.35	-0.51	-0.14
ncar_ccsm3_0	-0.76	-0.22	0.69	NA	-0.23
cnrm_cm3	-0.73	-0.24	0.54	-0.45	-0.54
ipsl_cm4	-0.53	-0.16	0.25	-0.40	-0.32
csiro_mk3_5	-0.48	-0.47	.20	-0.56	NA
ukmo_hadcm3	-0.44	-0.17	0.33	-0.29	-0.43
miub_echo_g	-0.35	NA	0.13	-0.24	NA
gfdl_cm2_1	-0.31	-0.38	0.05	-0.19	-0.56
mpi_echam5	-0.23	-0.44	-0.06	-0.15	-0.70
ingv_echam4	-0.22	-0.12	-0.16	NA	NA
miroc3_2_medres	-0.13	-0.08	-0.04	-0.28	-0.67
csiro_mk3_0	-0.12	-0.12	-0.23	NA	NA
giss_aom	0.12	-0.63	-0.39	0.32	-0.67
iap_fgoals1_0_g	0.22	-0.43	-0.24	0.47	-0.89
giss_model_e_h	0.34	0.10	0.10	0.27	-0.81
giss_model_e_r	0.39	-0.04	0.003	0.22	-0.58
ncar_pcm1	0.45	-0.61	-0.51	NA	-0.76

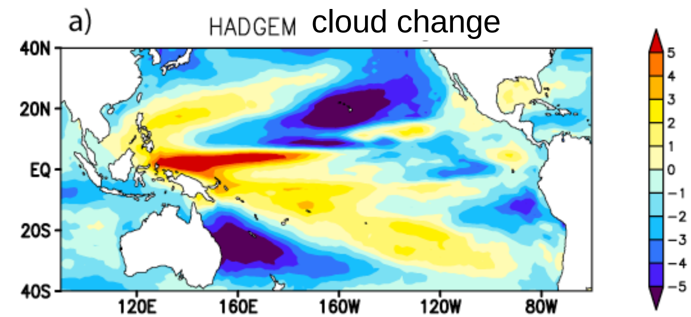
HadGEM1 2×CO_2 Change

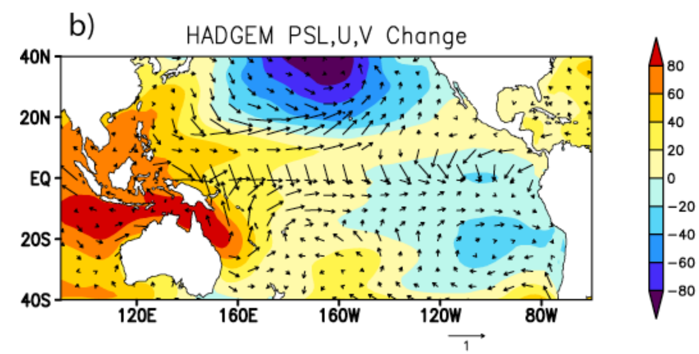
Observed Decadal

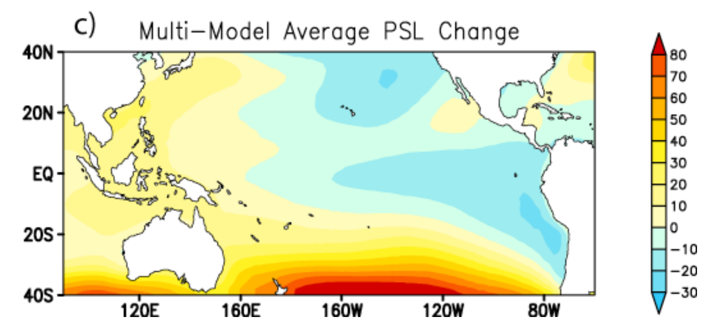




2×CO_2 Simulation







2×CO_2 cloud and circulation changes
resemble observed decadal
cloud and circulation changes

Circulation and Cloud Feedbacks

- On decadal time scales, decreased stratocumulus associated with warmer SST and weaker circulation
- Likely positive cloud feedback due to solar warming of ocean and reduced cooling of atmospheric BL
- Only one robust IPCC AR4 model reproduces correct sign for all 5 cloud-meteorological correlations
- This model exhibits stratocumulus decrease and weaker circulation for $2 \times CO_2$ that resembles observed pattern

Recommendations (1)

- Integrate meteorological conditions with cloud and radiation measurements

  – detailed information of cloud properties is not sufficient to characterize processes and feedbacks

- Understand that the instantaneous cloud and radiation state results from a history of meteorological processes

  – coincident cloud and meteorological correlations may not show true relationships

Recommendations (2)

- Assimilate cloud and radiation measurements into global models for best integration

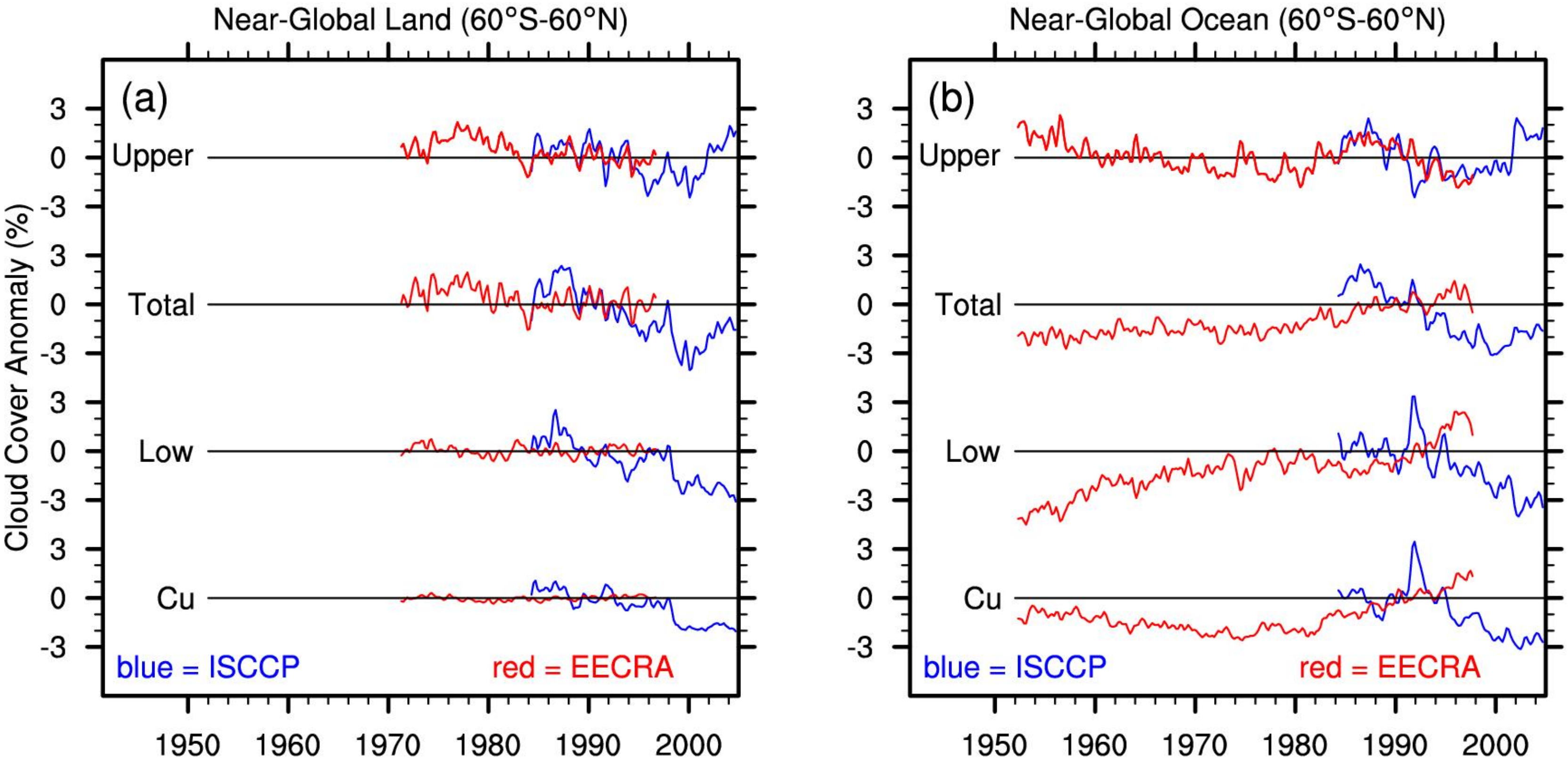
  – this is a very difficult task due to model cloud biases

- Focus on essential cloud, convection, and turbulence parameterization development

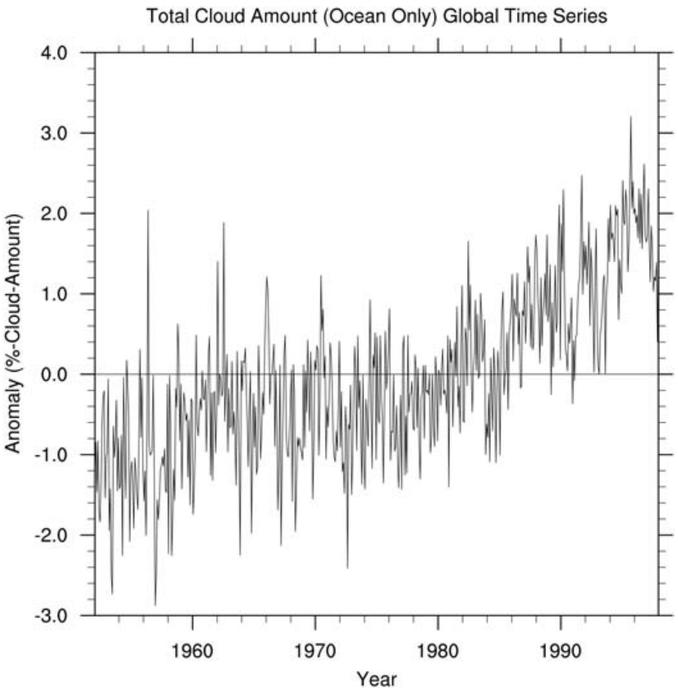
  – it doesn’t make sense to add aerosol indirect effects when basic cloud processes are not credible

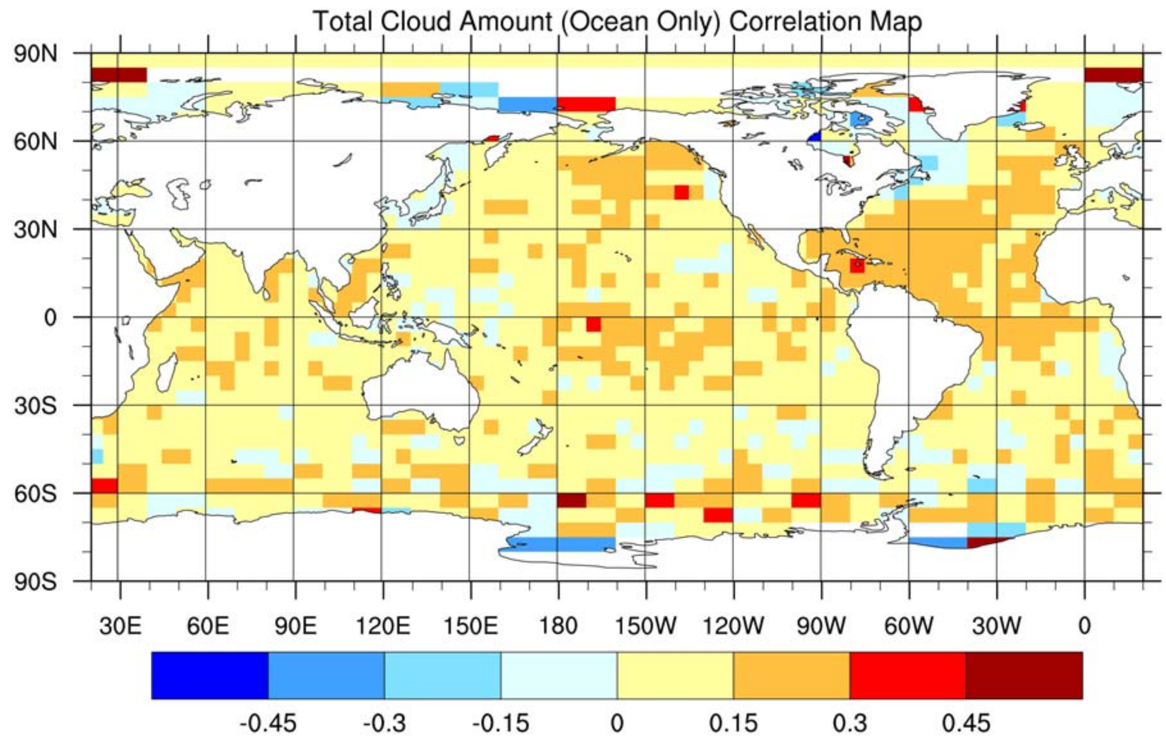
Additional Slides

Surface and Satellite Cloud



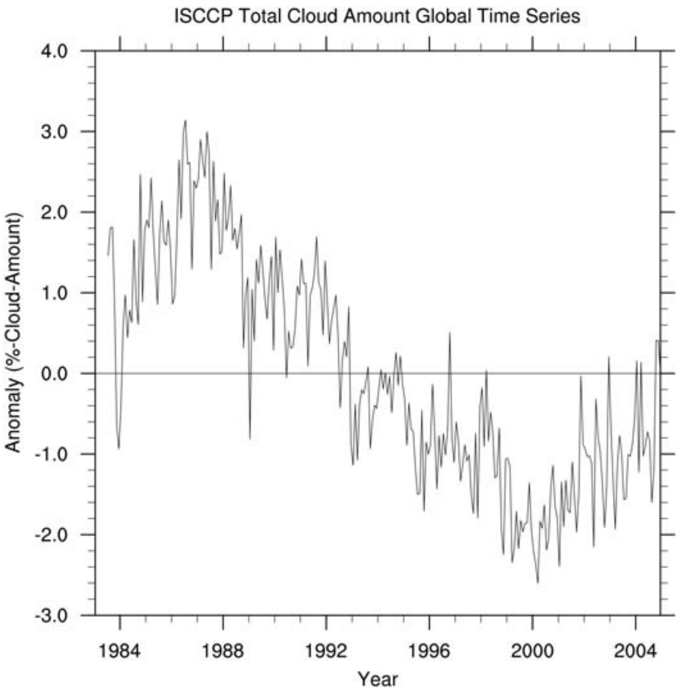
Surface Cloud Record

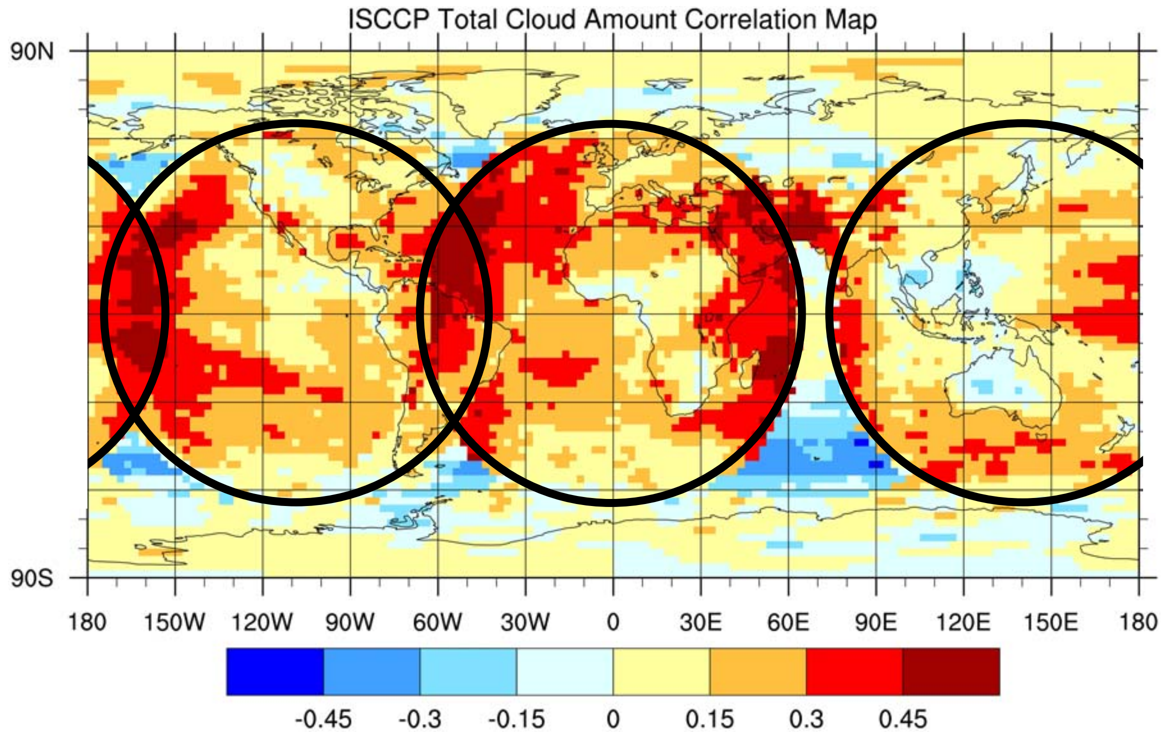




Low-level and especially cumulus cloud types are the greatest contributors to the upward trend in total cloud cover.

Satellite Cloud Record





Low-level cloudiness is the largest contributor to the apparent artifact in total amount (not shown).