Clouds in the Climate System:

Why is this such a difficult problem, and where do we go from here?

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4^{th} 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 is this a difficult problem?

- We have no stable system to monitor global cloudiness and radiation on multidecadal time scales
- Cloud and radiation measurements are insufficiently integrated with associated meteorological processes
- Wrong priorities in climate modeling efforts

Why is *dCloud/dT* so uncertain?

Unlike other climate feedbacks, temperature does not exert a direct influence on cloud feedbacks

- Ice/snow albedo feedback → ice/snow melts for T > 0°C
- Water vapor feedback → saturation humidity strongly varies with temperature
- Cloud feedback → relative humidity > 100% is under dynamical control

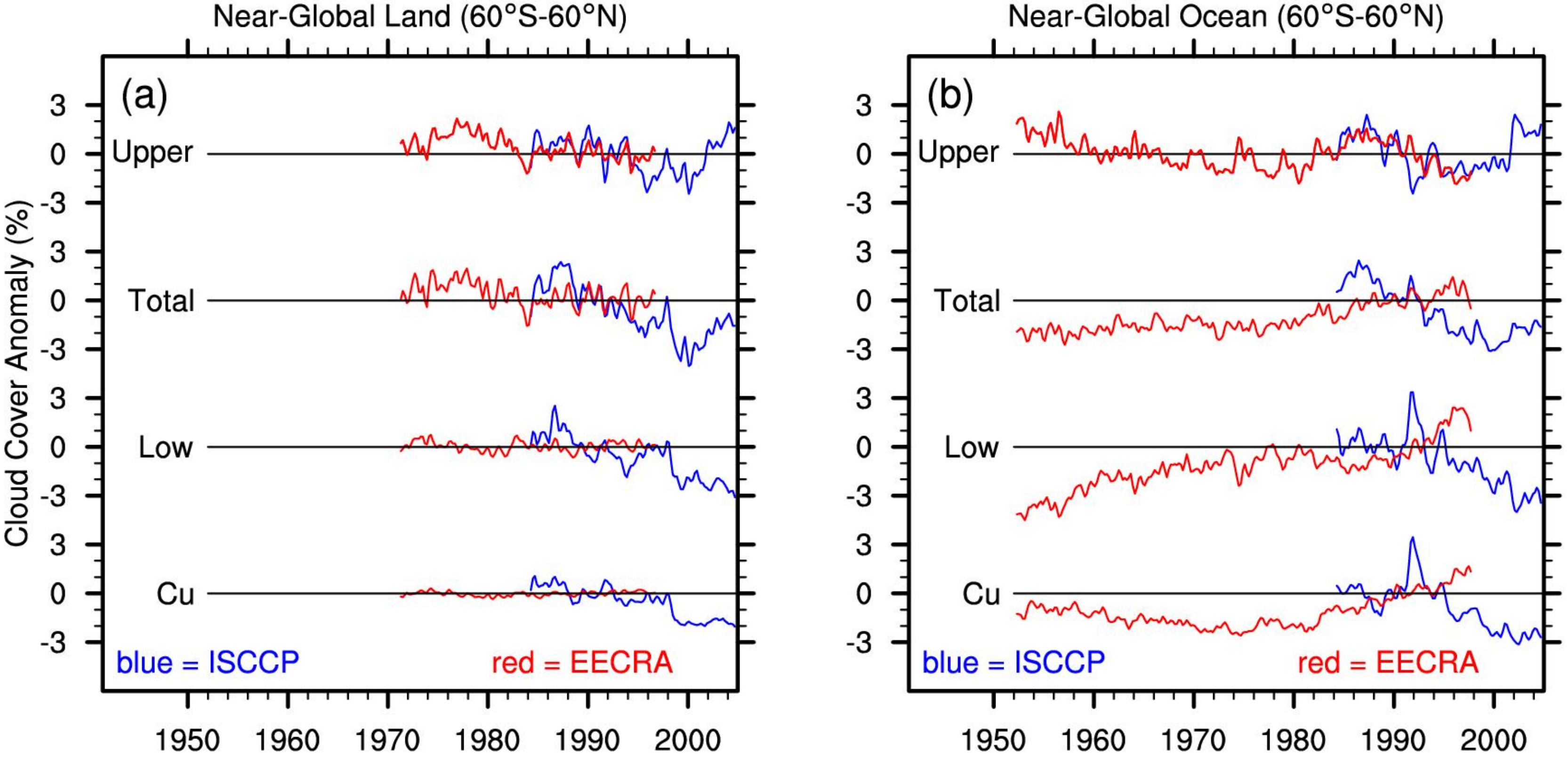
How to determine *dCloud/dT*?

Approximate as change in cloud during recent decades of rapid warming

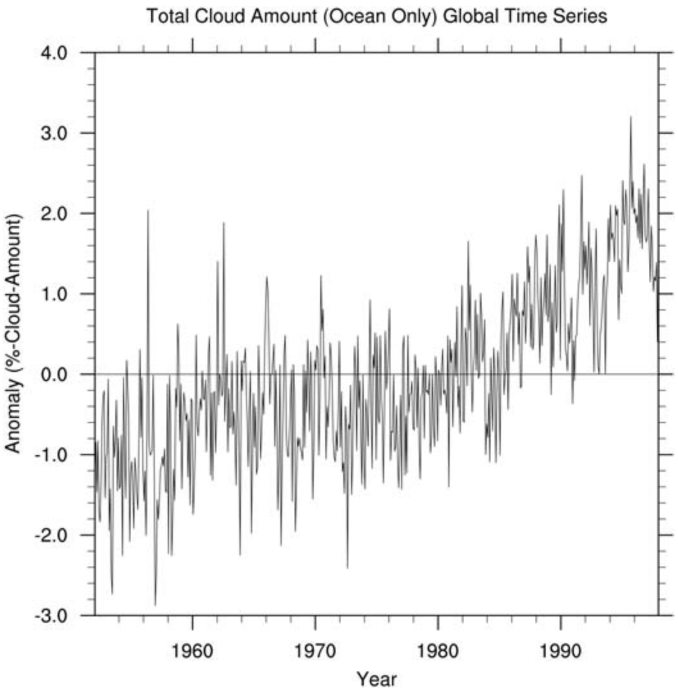
Some weaknesses…

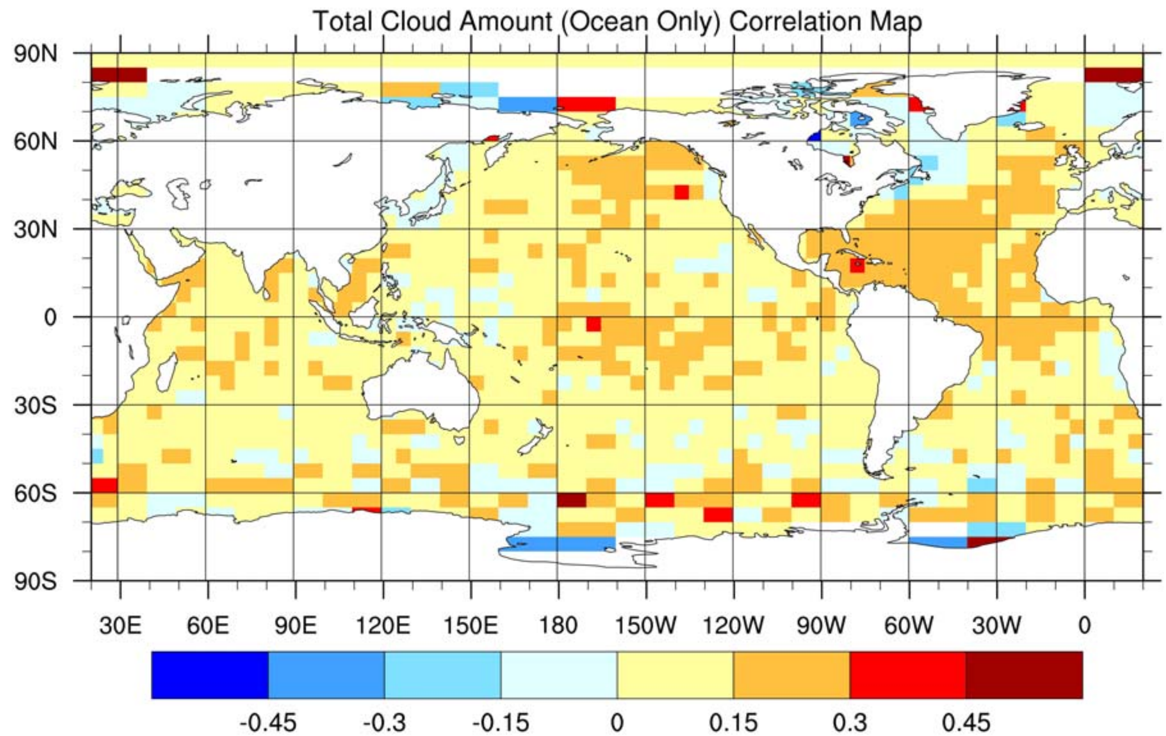
- Not an equilibrium response
- Cloud changes may be influenced by unforced dynamical variability instead of solely temperature
- Lack of a homogeneous observational record

Surface and Satellite Cloud



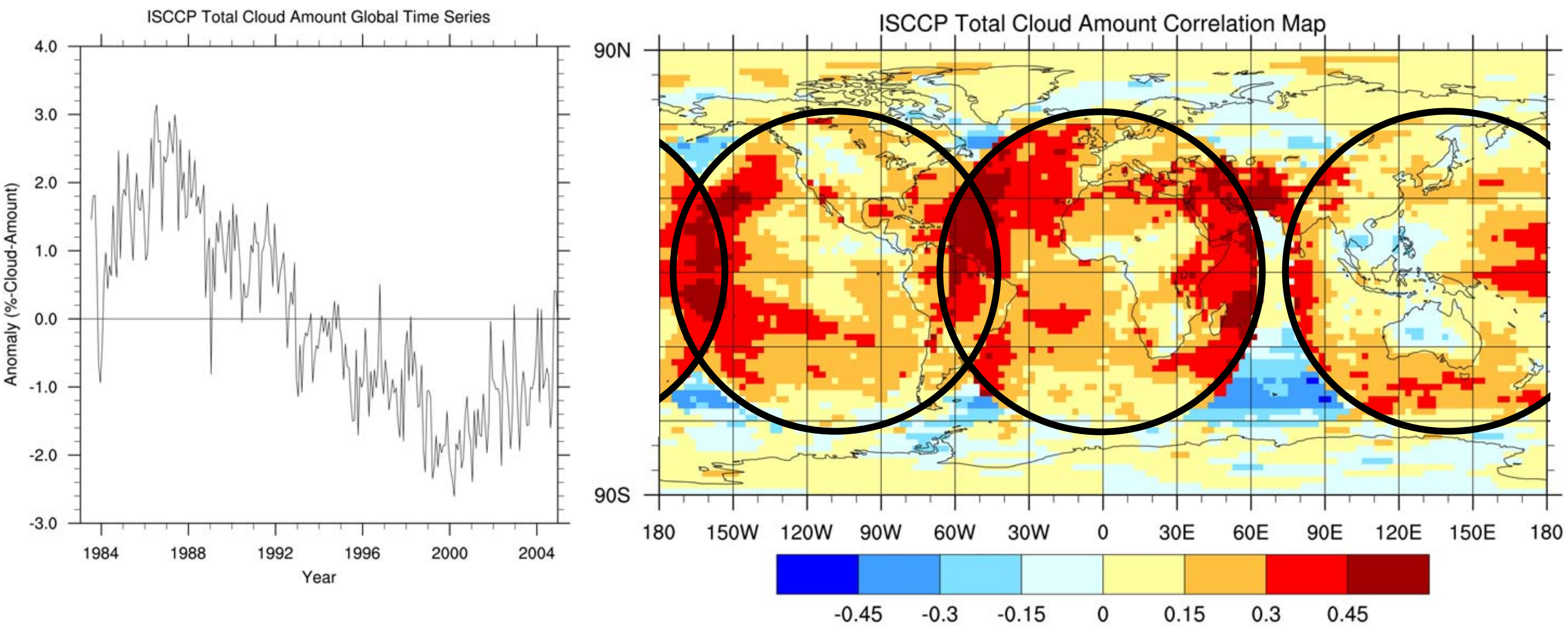
Surface Cloud Record





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).

Another method for *dCloud/dT*

Cloud change associated with temperature change on short time scales (daily to monthly)

Some weaknesses…

- Not an equilibrium response
- Processes dominant on short time scales may not be dominant on long time scales
- Cloudiness and temperature are strongly and jointly influenced by dynamical variability

Conceptual Model

Simple Cloud-Temperature-Meteorology System

Rate of change of cloud anomaly

Cloud anomaly dissipation

$$\frac{dC}{dt} = \alpha_C T + \alpha_D C + M'$$

Temperature forcing of cloud

Meteorological forcing of cloud (uncorrelated with temperature)

Rate of change of temperature anomaly

temperature anomaly dissipation

$$\frac{dT}{dt} = \alpha_T C + \alpha_E T + N'$$

cloud forcing of temperature

meteorological forcing of temperature (uncorrelated with cloud)

Conceptual Model

Discretize…

Set Δt to $-\alpha_D^{-1}$ (cloud anomaly damping time scale)

$$C_{t+\Delta t} = \beta_C T_t + M_t$$

$$T_{t+\Delta t} = (1 + \beta_E) T_t + \beta_T C_t + N_t$$

β_C cloud response factor ($\beta_C < 0$ for Sc)

β_T cloud radiative forcing factor ($\beta_T < 0$ for Sc)

β_E temperature damping factor ($-1 < \beta_E < 0$)

Cloud-Temperature Regression

Calculate regression of C_t on T_t …

For simplicity, set $\beta_E = 0$ and $\mathrm{cov}(T,N) = 0$

Term 1 *Term 2*

$$\frac{\mathrm{cov}(C,T)}{\mathrm{var}(T)} = \frac{\beta_C}{1-\beta_C\beta_T} + \frac{\beta_T}{1-\beta_C\beta_T}\frac{\mathrm{cov}(C,M)}{\mathrm{var}(T)}$$

$$+ \frac{1}{1-\beta_C\beta_T}\frac{\mathrm{cov}(M,N)}{\mathrm{var}(T)}$$

Term 3

Cloud-Temperature Regression

Term 1 $$\frac{\beta_C}{1-\beta_C\beta_T}$$

If $\beta_T = 0$ no cloud radiative forcing

→ Regression of C on $T = \beta_C$

If $\beta_T \neq 0$ yes cloud radiative forcing

→ $|$Regression of C on $T| > |\beta_C|$

Overestimation of cloud response factor magnitude

Overestimation of cloud feedback

Cloud-Temperature Regression

Term 2 $$\frac{\beta_T}{1-\beta_C\beta_T}\frac{\mathrm{cov}(C,M)}{\mathrm{var}(T)}$$

If $\mathrm{cov}(C,M) \neq 0$ — $C_{t+\Delta t}$ and C_t are autocorrelated through long M timescale

→ Even if $\beta_C = 0$, coincident C-T relationship because previous cloud radiatively forced current temperature

→ Regression of C on T has additional negative factor

Cloud response factor appears more negative

Cloud feedback appears more positive

Cloud-Temperature Regression

Term 3 $$\frac{1}{1-\beta_C\beta_T}\frac{\mathrm{cov}(M,N)}{\mathrm{var}(T)}$$

If $\mathrm{cov}(M,N) \neq 0$ meteorology influencing cloud is correlated with meteorology influencing temperature

→ Even if $\beta_C = 0$ and $\beta_T = 0$, coincident *C*-*T* relationship due to joint forcing by meteorology

Effect on apparent cloud response factor and cloud feedback depends on nature of meteorological forcing

Observed Cloud Feedback

- Meteorological memory can mix cloud radiative impact on temperature with cloud response to temperature
- Averaging over time (e.g., monthly means) will exacerbate the above effect
- Is the above effect important? Need better quantification
- *It is essential to consider joint meteorological forcing of cloud and temperature*

Bias due to Meteorology

For simplicity, set $\beta_T = 0$ and cov(C,M) = 0
(no cloud radiative forcing of temperature, no memory)

$$\beta_C = \frac{\mathrm{cov}(C,T)}{\mathrm{var}(T)} - \frac{\mathrm{cov}(M,N)}{\mathrm{var}(T)}$$

what we want

what we measure

what we don't know

Bias due to Meteorology

How can the impact of cov(M,N) be reduced?

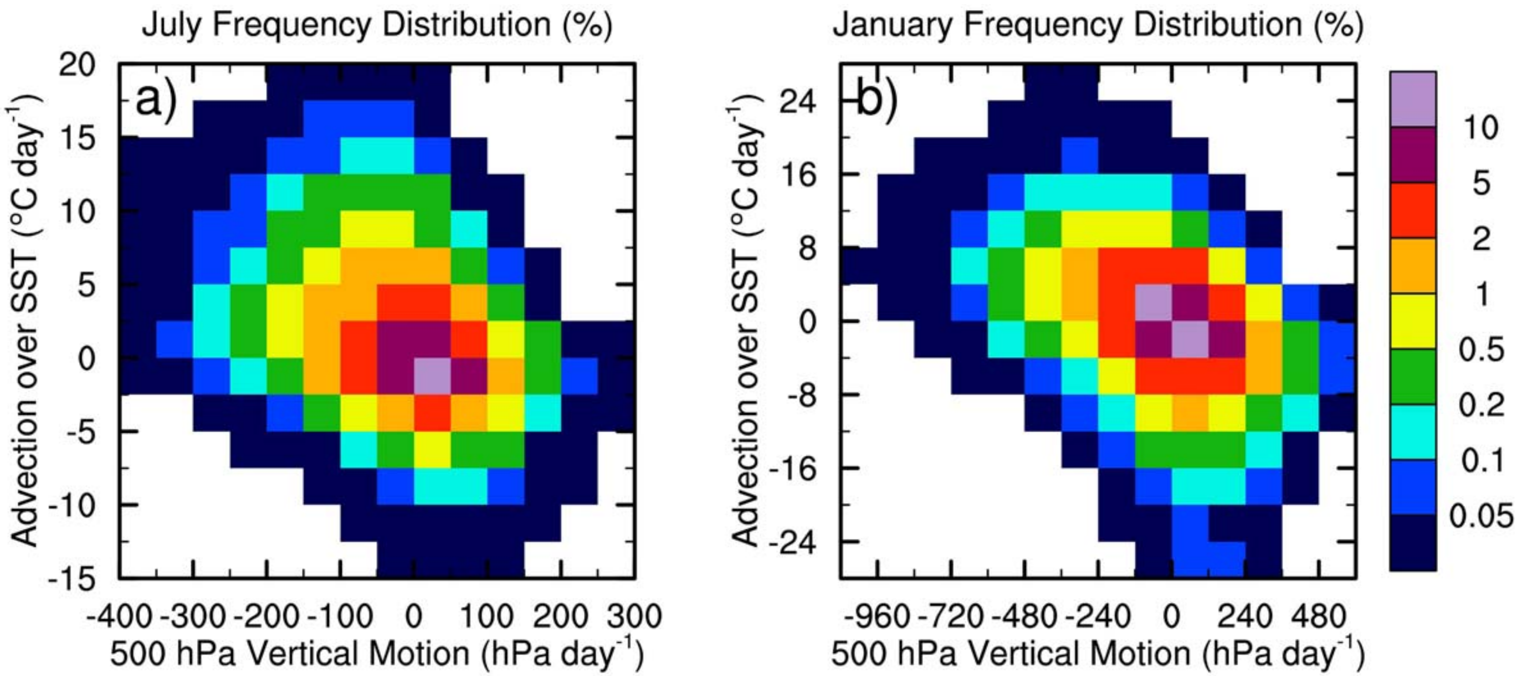
- Select relevant parameters to represent influential meteorological processes
- Bin cloud and temperature data into small intervals of the parameters (e.g., hold meteorology "constant")
- Examine cov(C,T) separately for each bin
- *What if an important parameter is left out?*
- *What if a process cannot be fully represented by a simple parameter?*

Meteorological influence will always be underestimated!

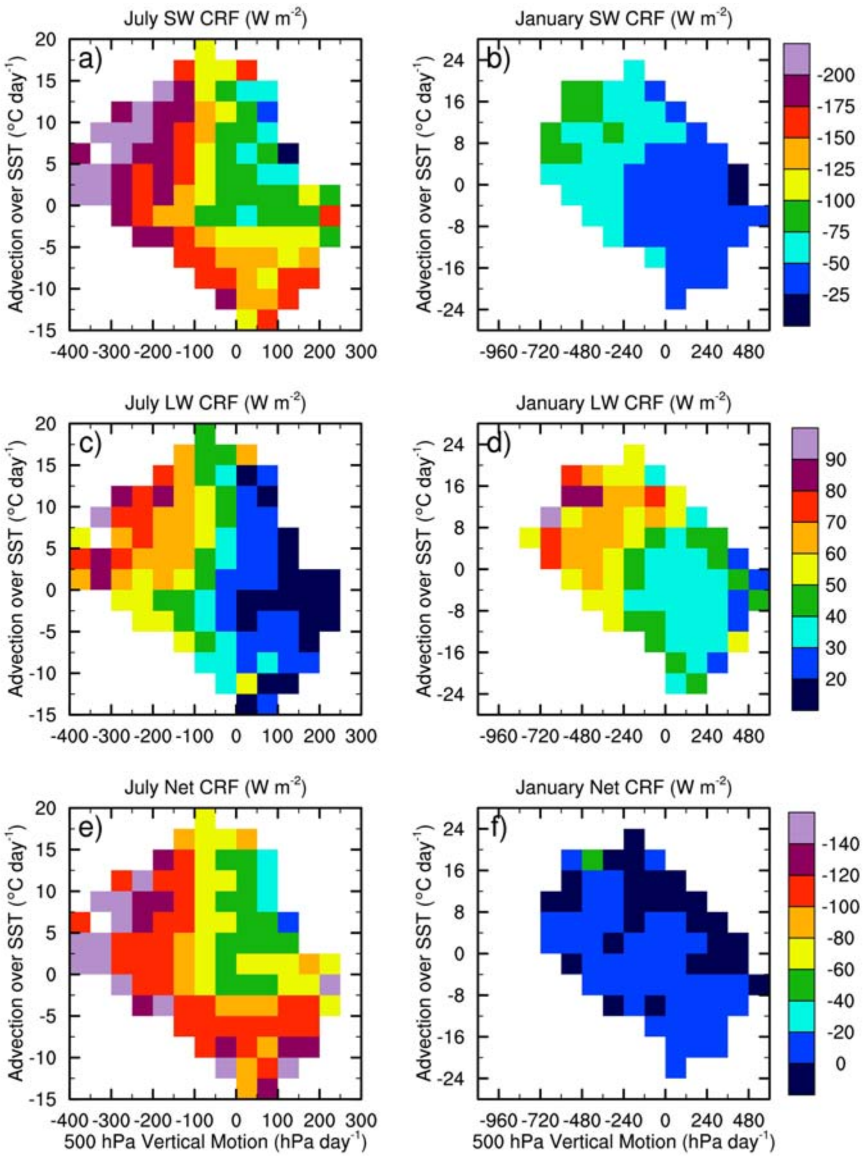
Cloud, SST, and Advection

- 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)



SST Advection-ω_{500} Histograms (CRF)

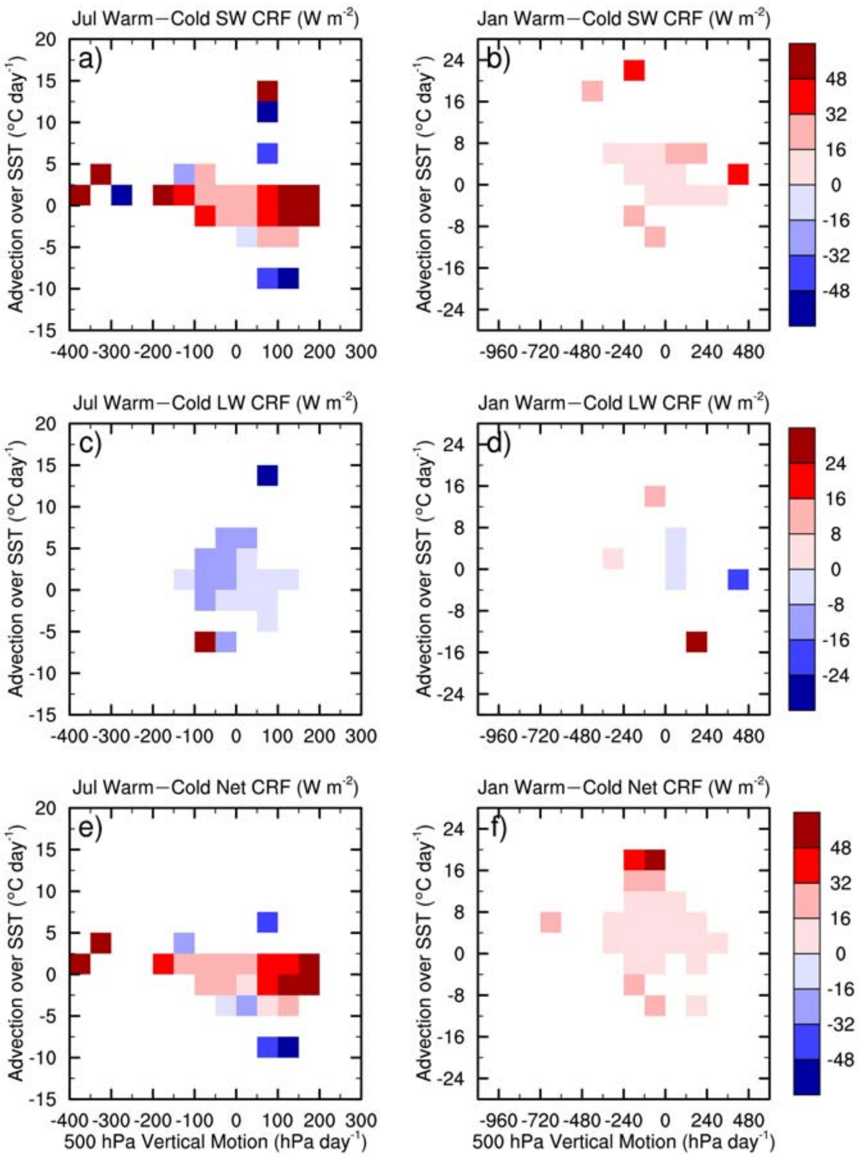


large SW CRF for upward and cold/down quadrants (latter only for July)

Large LW CRF for upward motion

large net CRF for upward and cold/down quadrants in July

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 CRF

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

Month	SW CRF	LW CRF	Net CRF
	(W m^{-2} per K)		
January	**+4.4**	**-1.0**	**+3.4**
July	**+9.4**	**-2.5**	**+6.9**

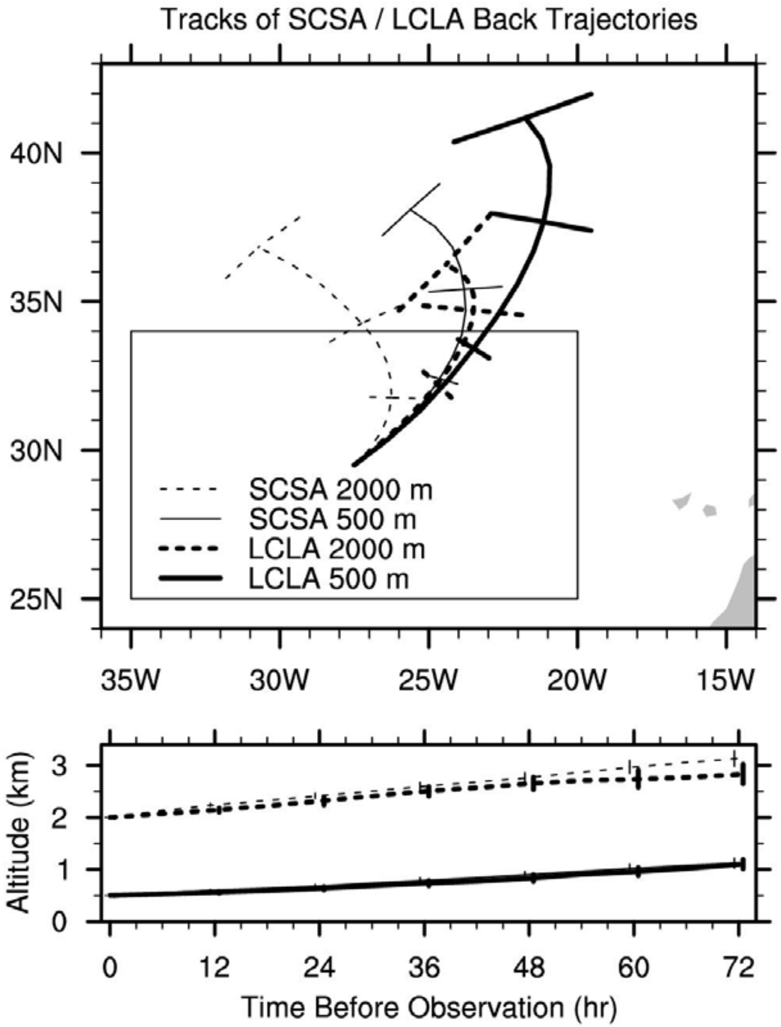
Cloud response to temperature suggests a positive cloud feedback

But are there any additional meteorological processes that produce less cloud and warmer temperature?

Aerosol Influence on Cloud?

- Previous studies have reported a positive correlation between satellite-retrieved AOD and cloud fraction
- Does greater AOD mean more CCN, smaller cloud droplets, less precipitation loss, and more cloud?
- Or is greater AOD associated with greater cloud fraction due to meteorological conditions?
- Since clouds have a non-instantaneous response time, it is essential to consider *meteorological history*

Aerosol Influence on Cloud?

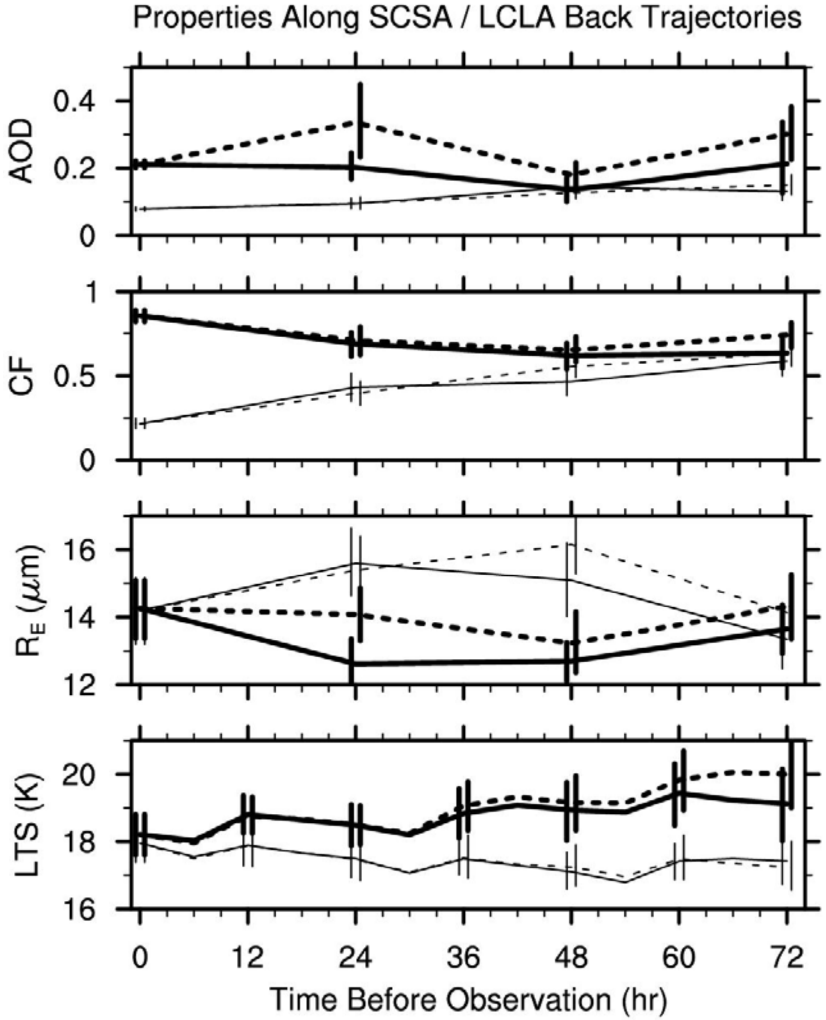


SCSA – Small Cloud, Small Aerosol

LCLA – Large Cloud, Large Aerosol

LCLA trajectories come from locations that are systematically closer to Europe

Aerosol Influence on Cloud?



SCSA – thin lines

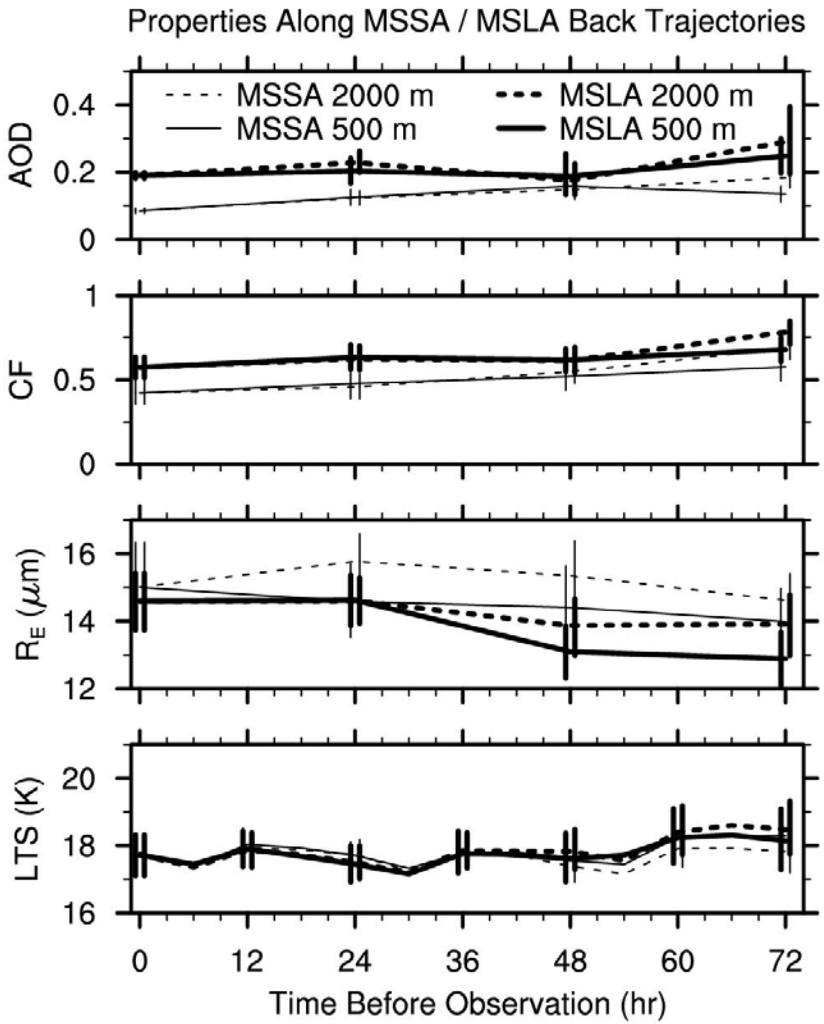
LCLA – thick lines

LTS – lower tropospheric static stability (θ_{700}–θ_{sfc})

Previous studies show larger LTS promotes more cloud fraction

LCLA has larger LTS at –72 hours but not 0 hours

Aerosol Influence on Cloud?



MSSA – Median Stability, Small Aerosol

MSLA – Median Stability, Large Aerosol

When LTS history is the same, much smaller cloud difference between small and large aerosol

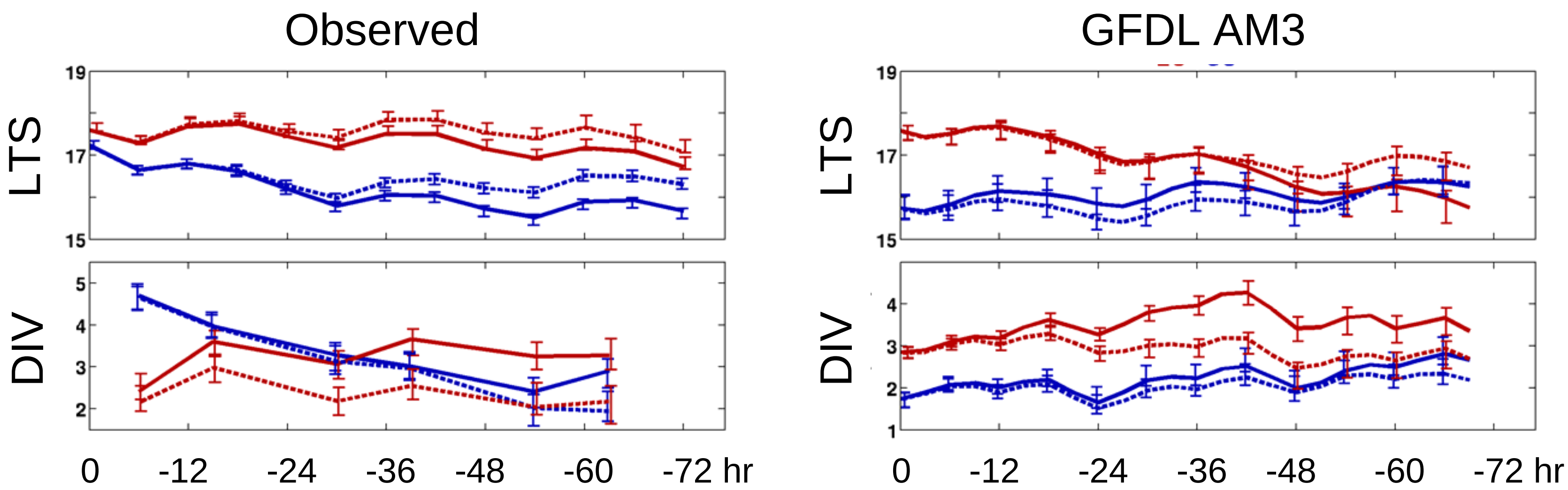
Aerosol Influence on Cloud?

- Air mass source region is related to history of meteorological conditions experienced by a parcel
- This creates an apparent correlation between aerosol (from source region) and cloud (from meteorological history)
- The correlation between meteorological influence and cloud may be near-zero at $t = 0$
- The preceding results are a lower limit for the confounding impact of meteorology and an upper limit for the influence of aerosol

Evaluation of GCM Cloud

- Calculate trajectories for observed and model large cloud fraction (LC) and small cloud fraction (SC)
- Compare observed and model meteorological history for LC and SC composites
- Substantial differences are seen in the sign and timing of observed and simulated cloud relationships for the GFDL AM3

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

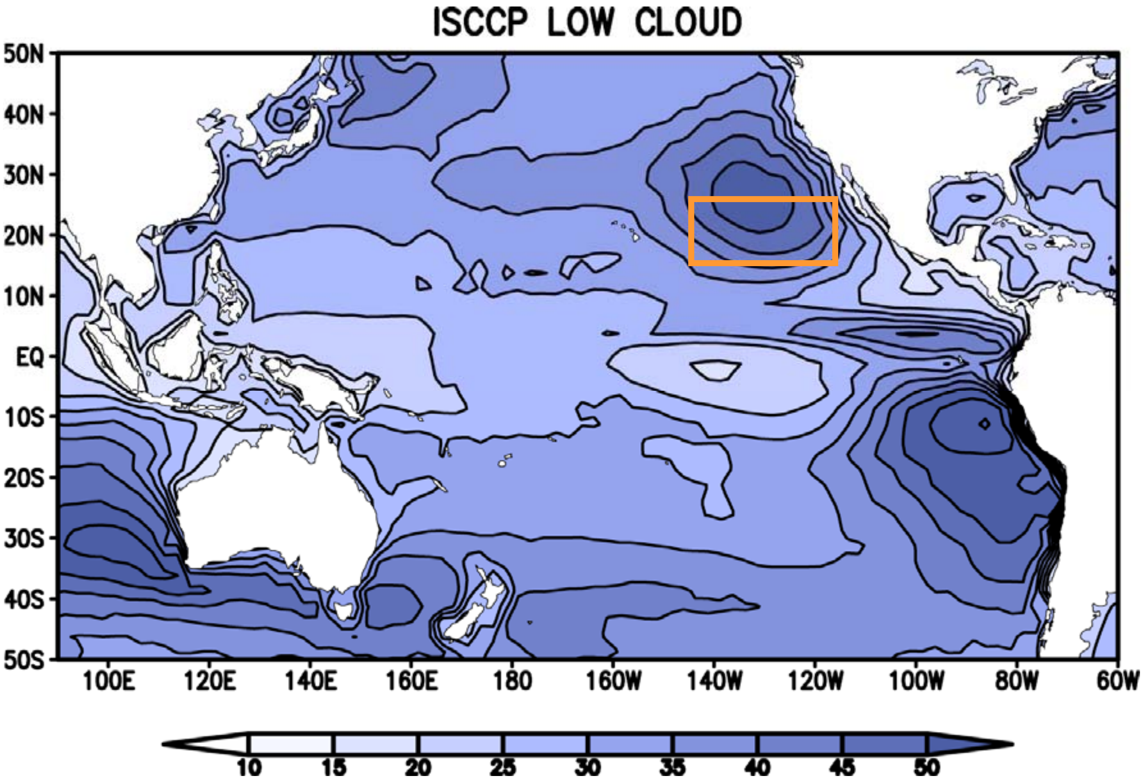
Circulation and Cloud Feedbacks

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

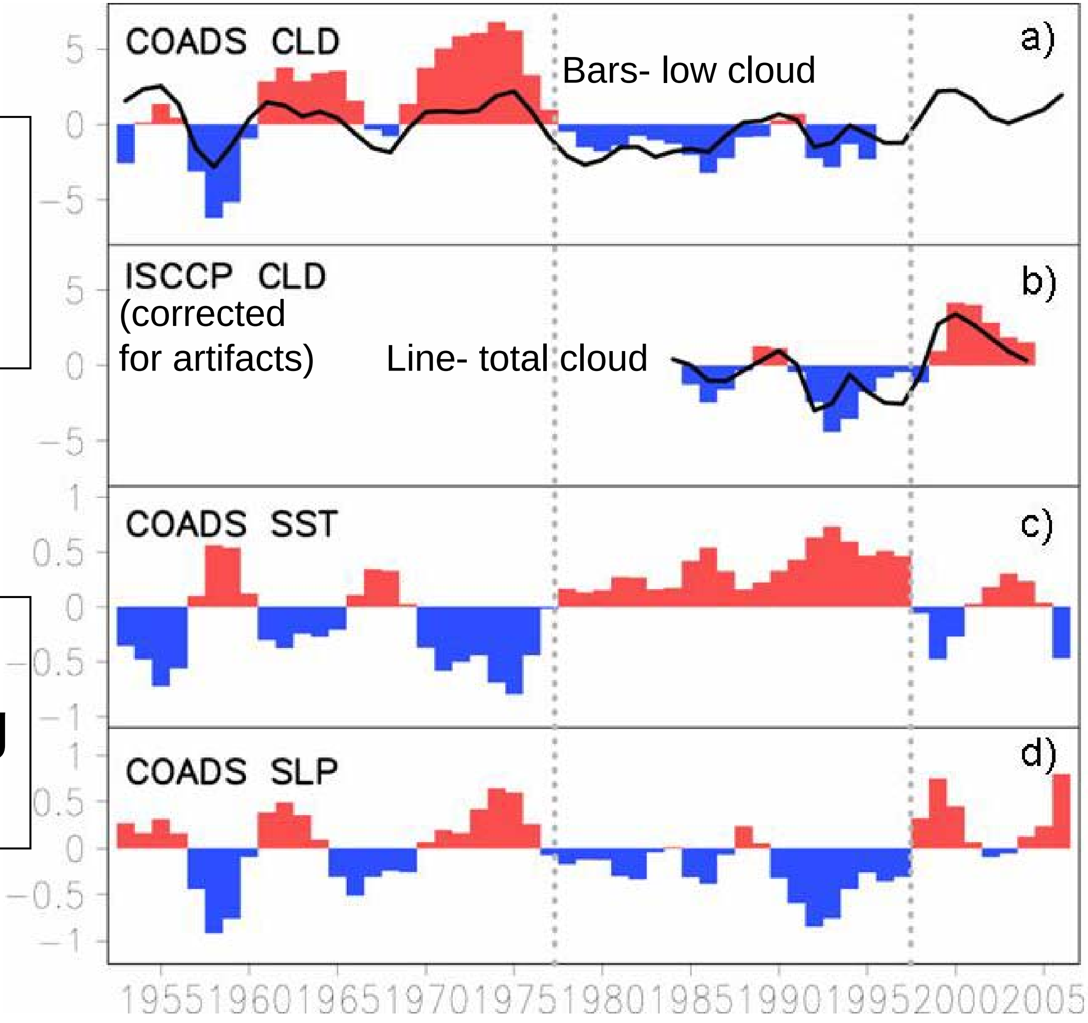
Does a cloud feedback promote decadal variability in SST and circulation?



NE Pacific Decadal Variability

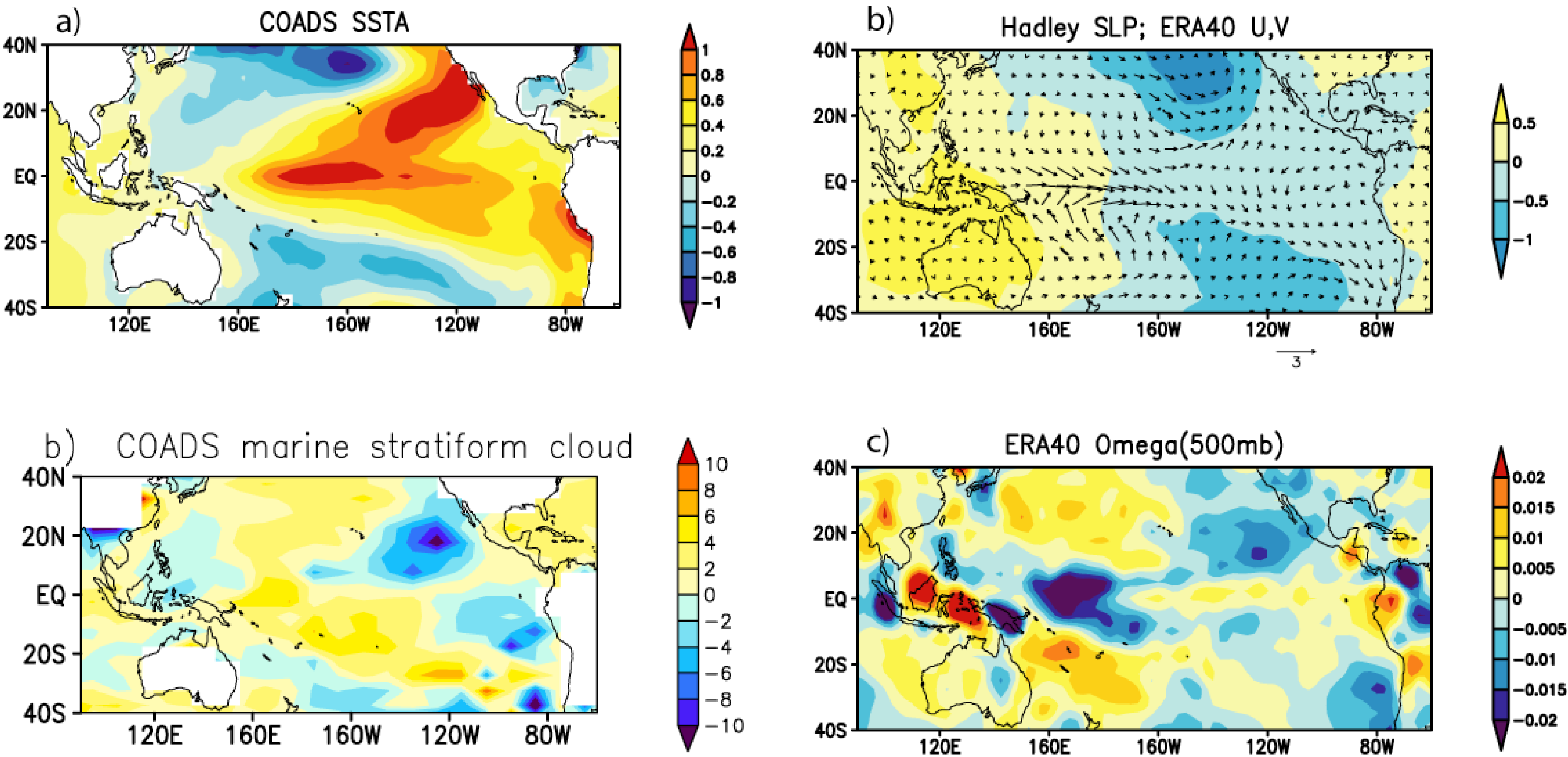
warm SST
weak SLP
weak wind

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

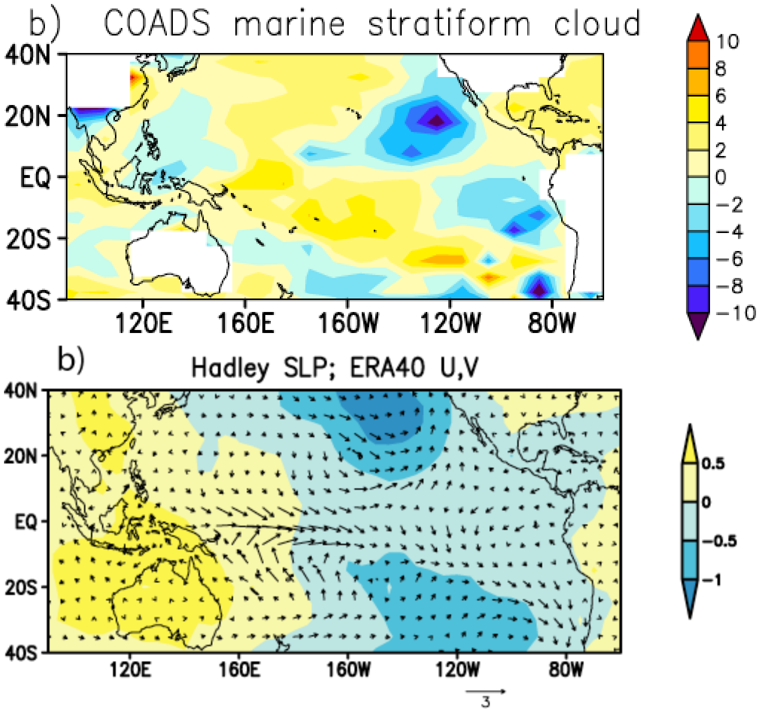
models with wrong sign $r(\text{cloud},\text{LTS})$

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

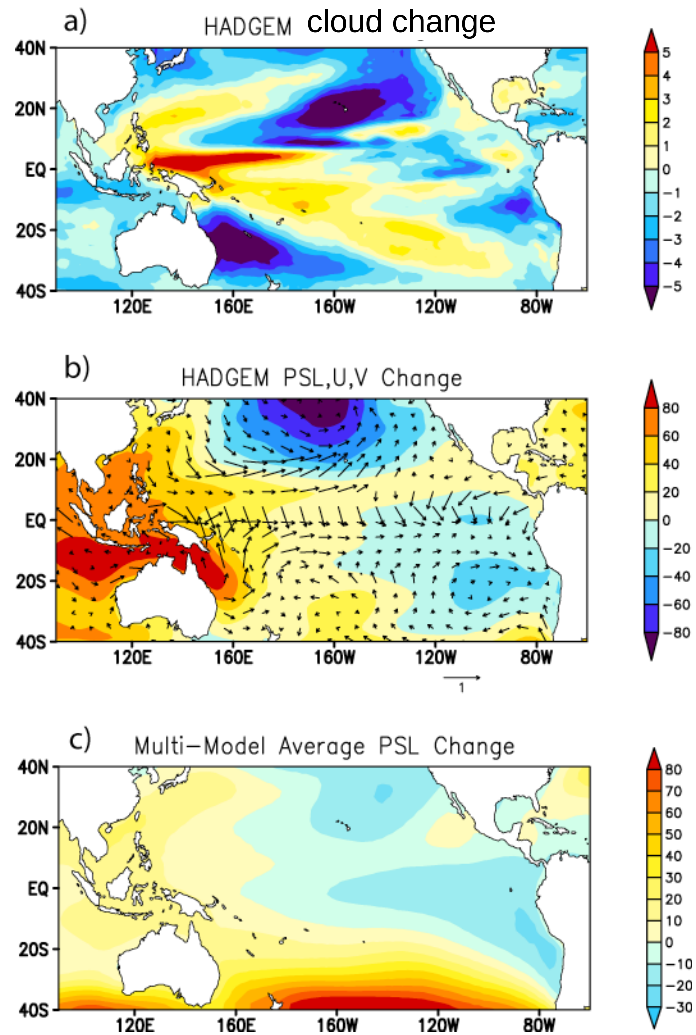
	SST	LTS	SLP	Vs	ω 500
ISCCP low	-0.78	0.51	0.64	-0.56	0.50
COADS msc	-0.92	0.43	0.80	-0.63	0.62
ukmo_hadgem1	-0.81	0.84	0.65	-0.55	0.39
inmcm3_0	-0.77	0.37	0.58	-0.57	0.14
bccr_bcm2_0	-0.60	0.43	0.44	-0.58	NA
mri_cgcm2_3_2a	-0.59	0.14	0.32	-0.31	-0.60
miroc3_2_hires	-0.91	0.54	-0.03	-0.71	-0.10
cccma_cgcm3_1_t63	-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

Where do we go from here? (1)

- Develop a stable observational system to monitor global cloudiness and radiation on decadal time scales
- Correct (to the extent possible) the historical cloud and radiation record

  – this includes reprocessing data long after a mission has ended

  – integrate satellite and non-satellite datasets (surface observations, ocean heat content, reanalysis meteorology)

Where do we go from here? (2)

- Integrate meteorological conditions with cloud and radiation measurements

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

  – *daily rather than monthly data is fundamental*

- 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*

Where do we go from here? (3)

- 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*

Thank You!

Additional Slides

Conceptual Model for Climate

Equilibrium climate response to external radiative forcing

$$0 = \Delta R + \frac{1}{\lambda_{BB}} \Delta T_s + \sum_k \frac{\partial F}{\partial I_k} \frac{dI_k}{dT_s} \Delta T_s$$

ΔR	external radiative forcing change
ΔT_s	surface temperature change
$1/\lambda_{BB}$	increase of blackbody emission
F_k	radiation flux from internal parameter I_k

Conceptual Model for Climate

Equilibrium climate response to external radiative forcing

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

$$\Delta T_s = -\Delta R\,\lambda_{clim} \qquad \text{where} \qquad \frac{1}{\lambda_{clim}} = \frac{1}{\lambda_{BB}} + \sum_k \frac{1}{\lambda_k}$$

λ_{clim} climate sensitivity

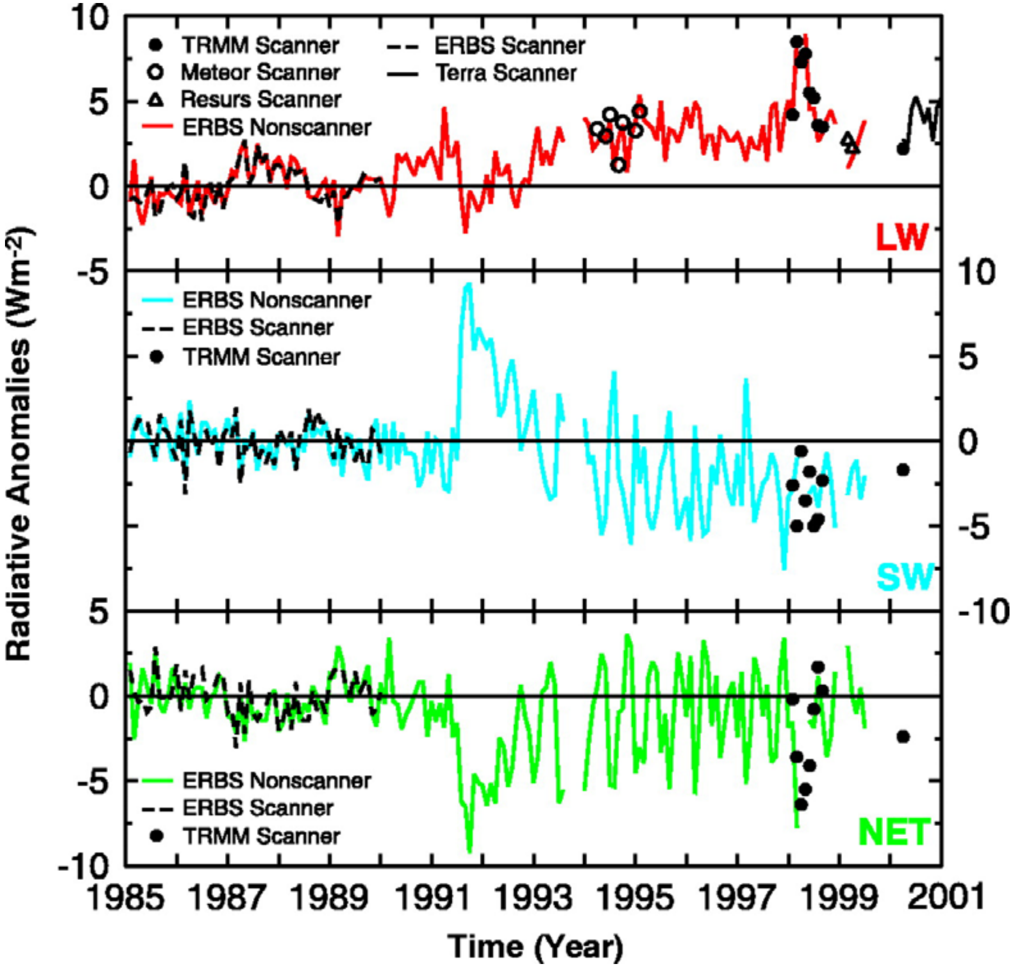
What is λ_{cloud}?

$$\frac{1}{\lambda_{cloud}} = \frac{\partial F}{\partial I_{cloud}} \frac{dI_{cloud}}{dT_s}$$

$\dfrac{\partial F}{\partial I_{cloud}}$ straightforward for specified cloud properties

$\dfrac{dI_{cloud}}{dT_s}$ very uncertain, many different cloud types

Tropical Mean Radiation Flux (Satellite)



1985-1999 tropical mean time series of all-sky SW, LW, and net radiation flux from the Earth Radiation Budget Satellite (ERBS)

Created by
B. Wielicki group

from Wielicki et al. (2002)

Cloud-Temperature Regression

Calculate regression of cloud on coincident temperature…

Term 1 *Term 2*

$$\frac{\mathrm{cov}(C,T)}{\mathrm{var}(T)} = \frac{(1+\beta_E)\beta_C}{1-\beta_C\beta_T} + \frac{\beta_T}{1-\beta_C\beta_T}\frac{\mathrm{cov}(C,M)}{\mathrm{var}(T)}$$

$$+ \frac{\beta_C}{1-\beta_C\beta_T}\frac{\mathrm{cov}(T,N)}{\mathrm{var}(T)} + \frac{1}{1-\beta_C\beta_T}\frac{\mathrm{cov}(M,N)}{\mathrm{var}(T)}$$

Term 4 *Term 3*

Cloud-Temperature Regression

Term 1 $$\frac{(1+\beta_E)\beta_C}{1-\beta_C\beta_T}$$

If $\beta_E \neq 0$ temperature damping

$\beta_T = 0$ no cloud radiative forcing

$\rightarrow$ |Regression of C on T| < $|\beta_C|$

Underestimation of cloud response factor magnitude

Underestimation of cloud feedback

Cloud-Temperature Regression

Term 4 $$\frac{\beta_C}{1-\beta_C\beta_T}\frac{\text{cov}(T,N)}{\text{var}(T)}$$

If $\text{cov}(T,N) \neq 0$ $T_{t+\Delta t}$ and T_t are autocorrelated through long N timescale

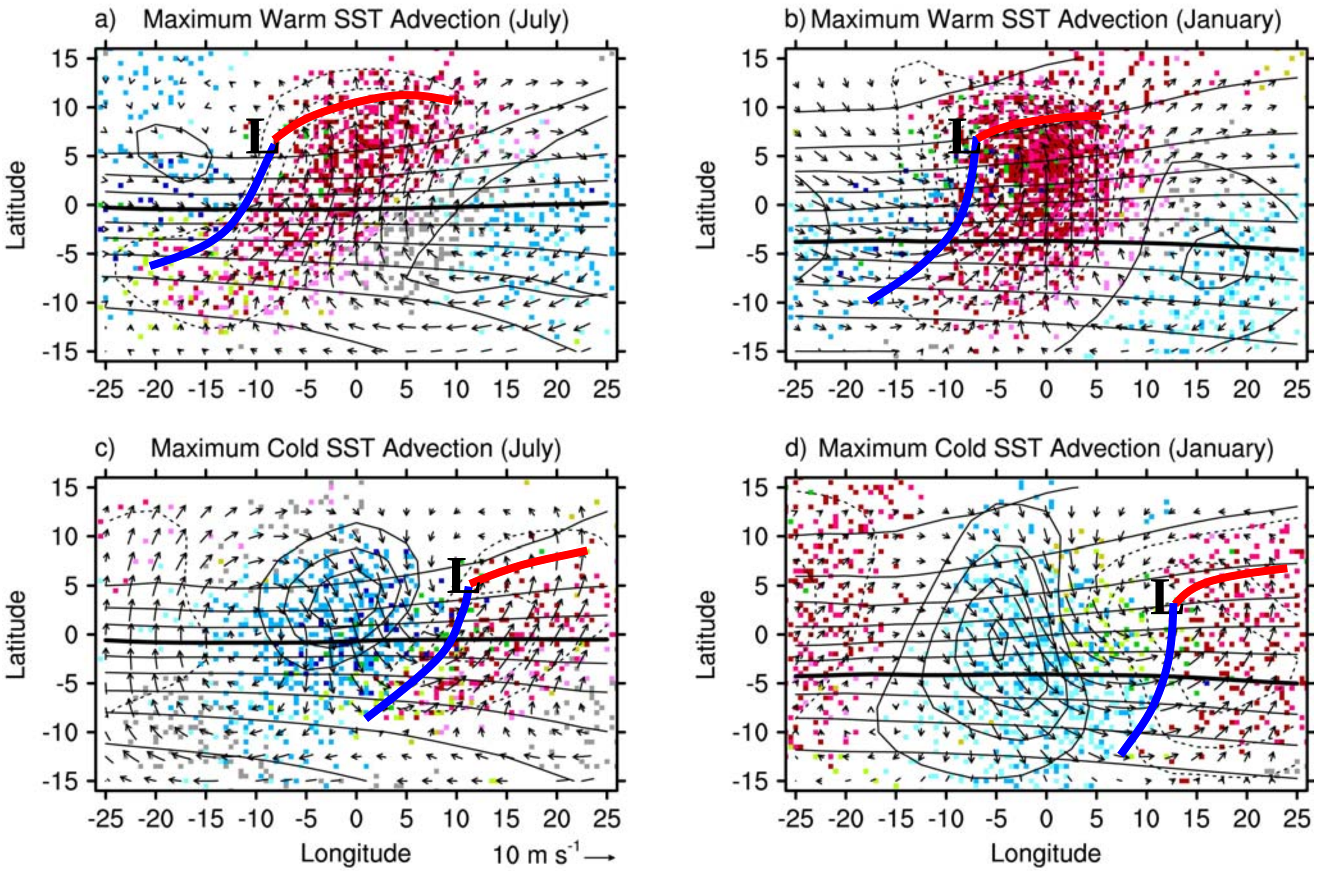
→ Coincident *C*-*T* relationship because current temperature related to previous forcing of cloud

→ Regression of *C* on *T* has additional negative factor

Cloud response factor appears more negative

Cloud feedback appears more positive

Advection over SST Gradient



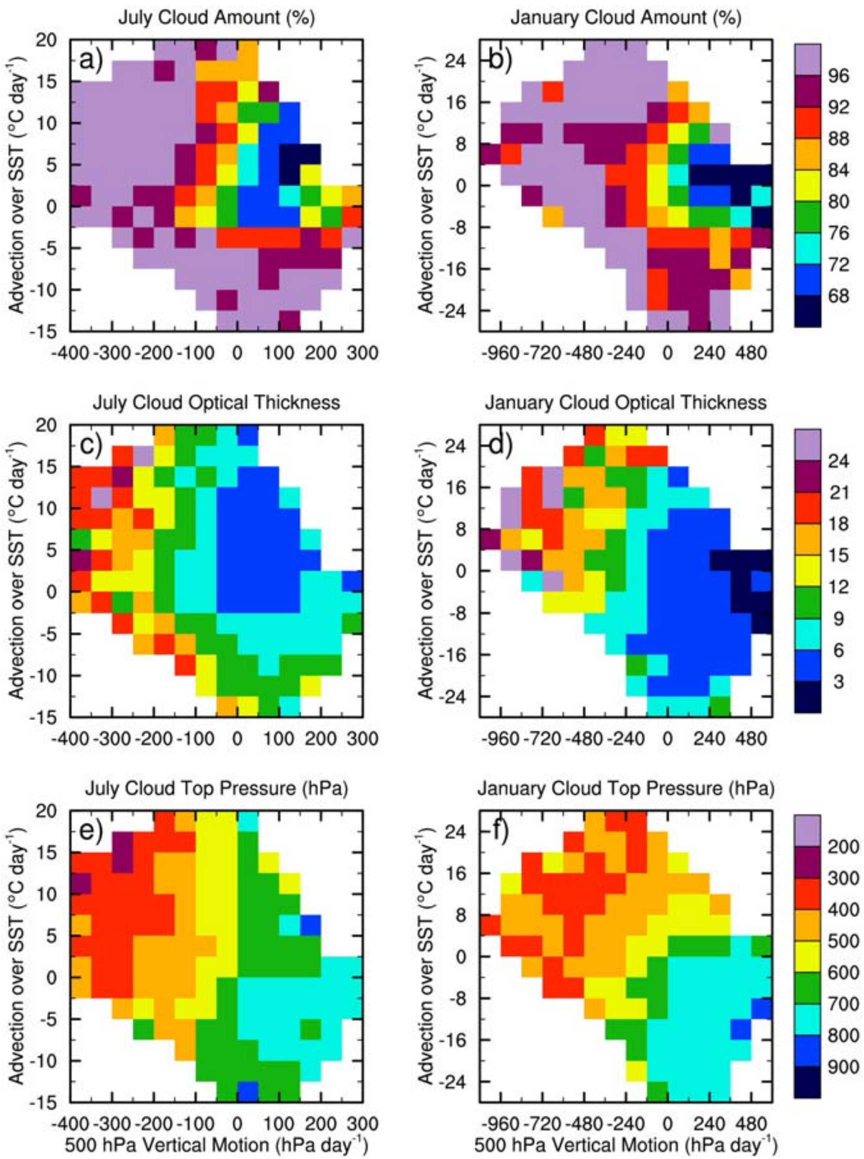
color: ISCCP cloud types

black straight lines: SST

black curved lines: ω_{500}

black arrows: $\mathbf{V}_{1000}$

SST Advection-ω_{500} Histograms (Cloud)



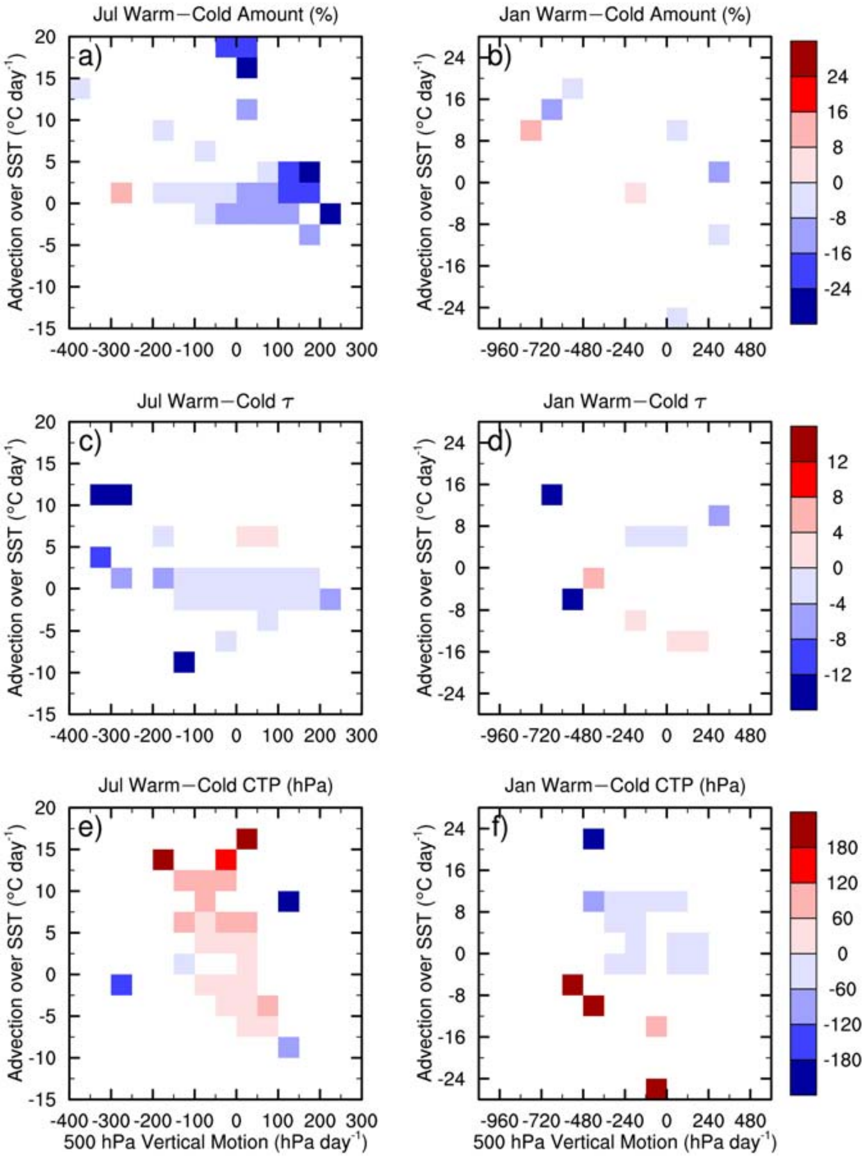
large cloud amount except for warm/down quadrant

largest optical thickness for upward and cold/down quadrants (latter only for July)

lowest cloud top pressure for upward motion

some cirrus clouds occur in warm/down quadrant

Adv-ω Histograms (Warm–Cold Cloud)



less cloud amount for warm conditions under most dynamical states

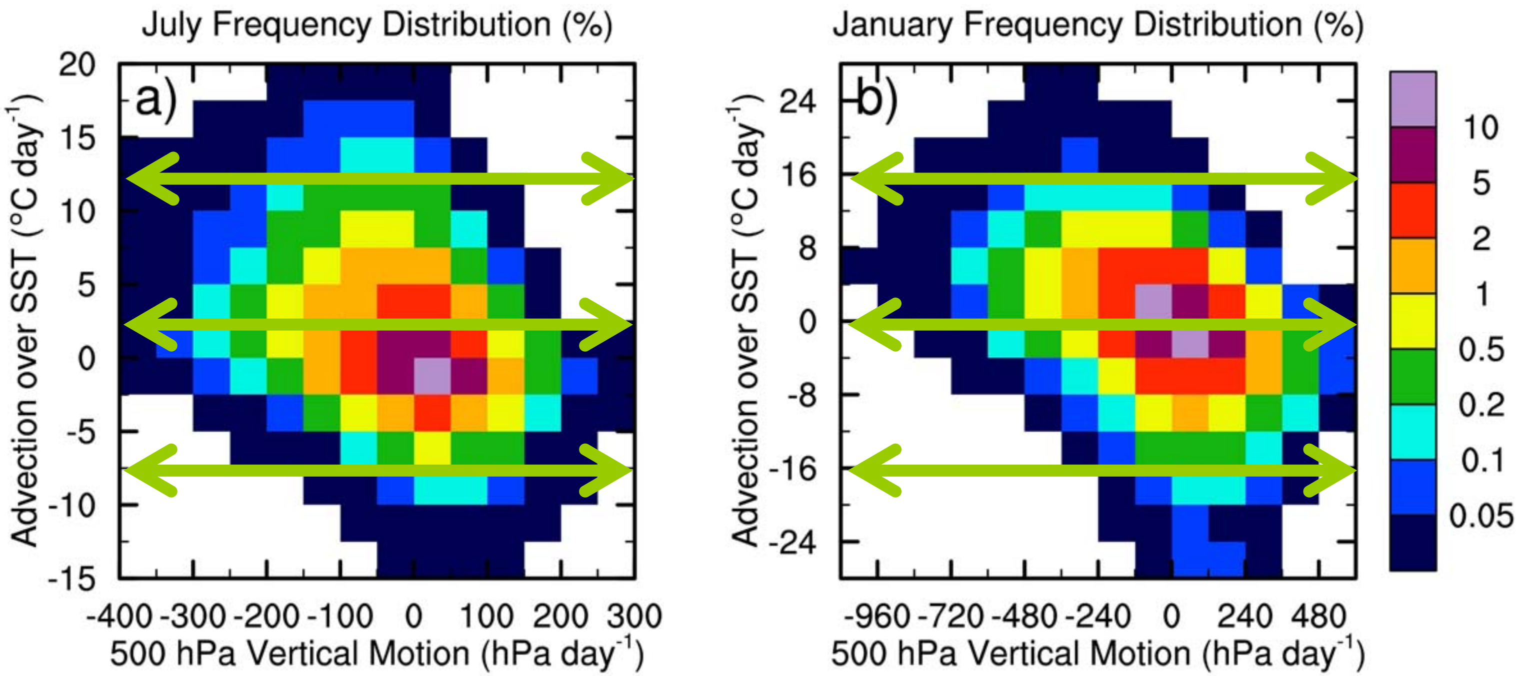
less cloud optical thickness for warm conditions under most dynamical states

mixed cloud top pressure response for warming across seasons and dynamical states

Average Warm–Cold Cloud

Month	Cloud Amount (% per K)	Optical Thickness (per K)	Cloud Top Pressure (hPa per K)
January	-0.1	0.0	**-6**
April	**-1.1**	**-0.1**	**-4**
July	**-2.6**	**-0.3**	**+6**
October	**-1.6**	0.0	**-2**

Cloud Response to Dynamical Changes



Increase standard deviation of vertical motion and average cloud properties and CRF with new frequency distribution.

20% Decrease in ω_{500} Variability

Month	SW CRF (W m^{-2} per K)	LW CRF	Net CRF
January	+0.7	-0.8	-0.1
July	**+3.6**	**-1.2**	**+2.3**

20% Decrease in SST Advection Variability

Month	SW CRF	LW CRF	Net CRF
	(W m^{-2} per K)		
January	+0.4	-0.3	-0.1
July	**+1.2**	**-0.3**	**+1.0**