Cloud Feedbacks:
The Peculiar Trajectory of Global Warming

Stephan Fueglistaler

Princeton University

CERES Science Team Meeting, April 28-30, 2020

The problem (apart from COVID-19): Global warming

Anthropogenic modifications of land surface and atmospheric composition (leading to oceanic changes) **do change climate**.

How much?

Model results diverge: Between models, and methods.
IPCC AR5: 1.5K to 4.5K global average temperature increase for doubling CO_2. (CMIP6: high).
Uncertainty in timescale for transition to carbon-neutral economy … $$$$.

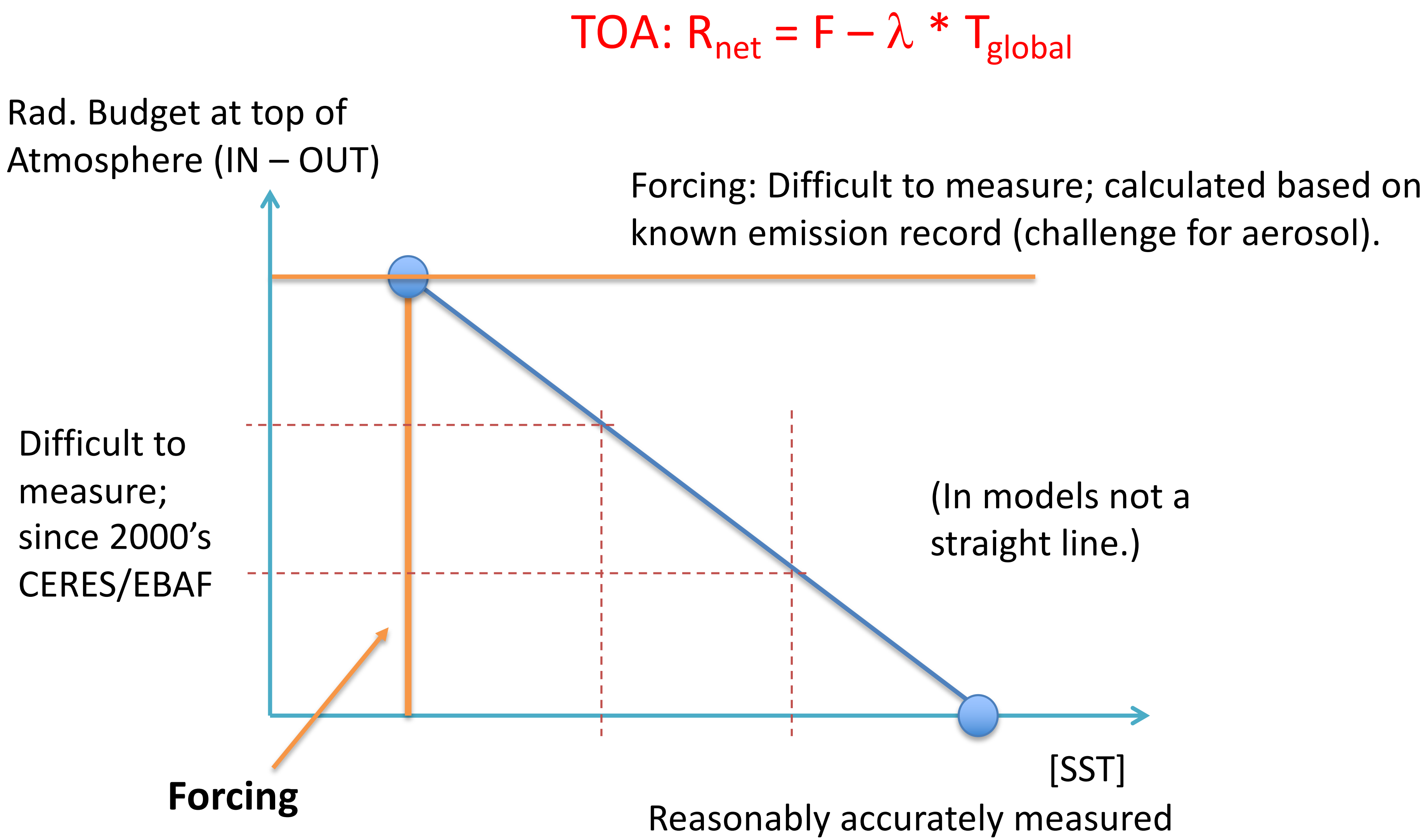
=> Need observational constraints.

This talk:

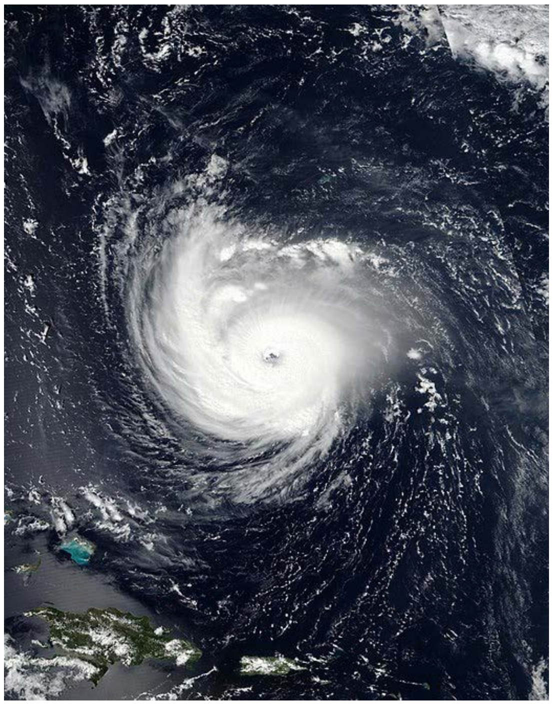
Context: Clouds remain large(st) uncertainty – the “pattern effect” is a challenge; is a pure modeling result – but is it real?

(1) CERES/EBAF tropical average SWCRE 2000 – present can be understood with just two variables: **mean SST**, and **difference to SST in regions of deep convection (SST#).**
(2) Tropical temperature profile shows the same two modes, confirms and explains the mechanism controlling SWCRE.
(3) SST# is important to understand ENSO control on SWCRE.
(4) SST# also explains the “pattern effect” noted in AMIP piForcing simulations.
(5) The strong negative cloud feedback seen in these simulations since the 1970’s is **due to a change in SST# unparalleled in reconstructed SST over historical period, and in coupled ocean-atmosphere models**.

Forcing and climate sensitivity



Linearity is key …



+

=

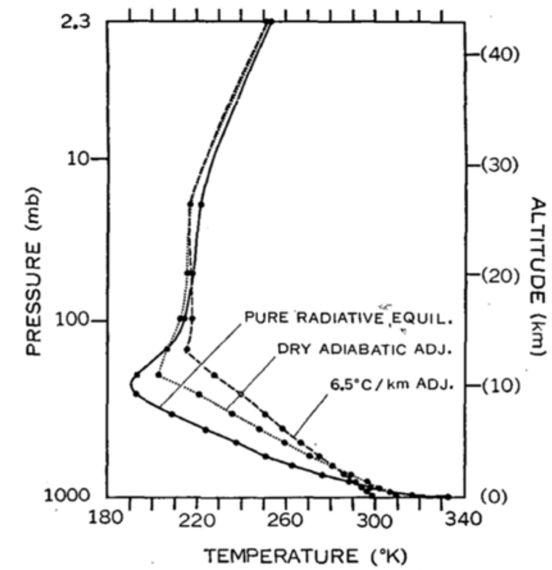
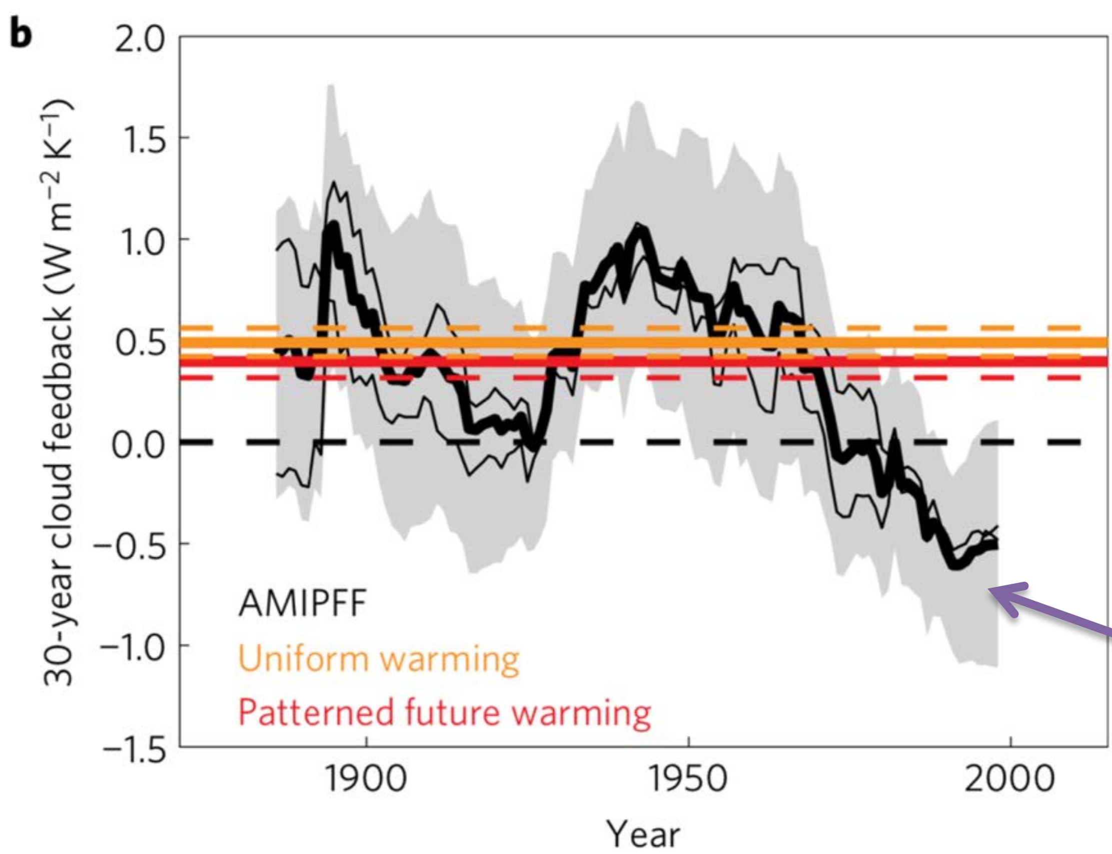


FIG. 4. The dashed, dotted, and solid lines show the thermal equilibrium with a critical lapse rate of 6.5 deg km^{-1}, a dry-adiabatic critical lapse rate (10 deg km^{-1}), and pure radiative equilibrium.

Indicative of **linearity**.

-> Global Climate System a **compact function of global average temperature** (! / ?)

Evolution of observation-informed cloud feedback



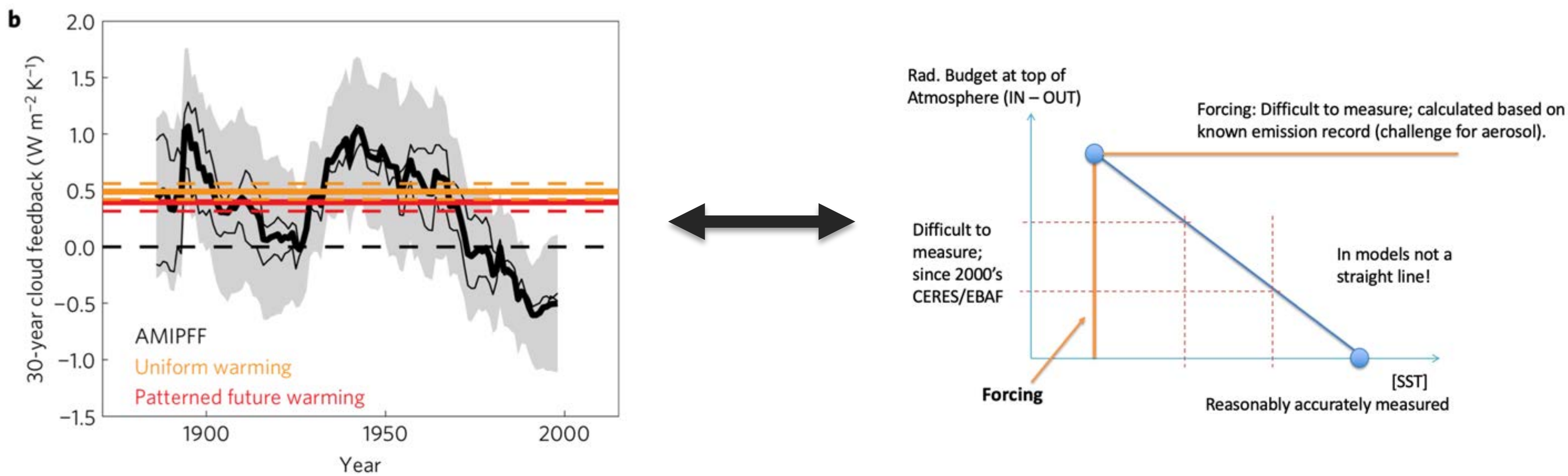
[Zhou/Zelinka/Klein, 2016]

Experiment: ”Observed” global SST field as lower boundary condition for atmospheric GCM, and diagnose the model’s top-of-atmosphere radiative imbalance.

Extract the cloud radiative feedback from 30 year periods.

Result: Varies substantially, and becomes **negative**! (Canonical coupled ocean-atmosphere result: positive; see orange line.)

Houston, we've got a problem: Time-varying cloud feedback



-> SWCRE is NOT a function (only) of global average temperature.

-> Challenges the concept of "climate sensitivity" as used in the community.

How to fix?

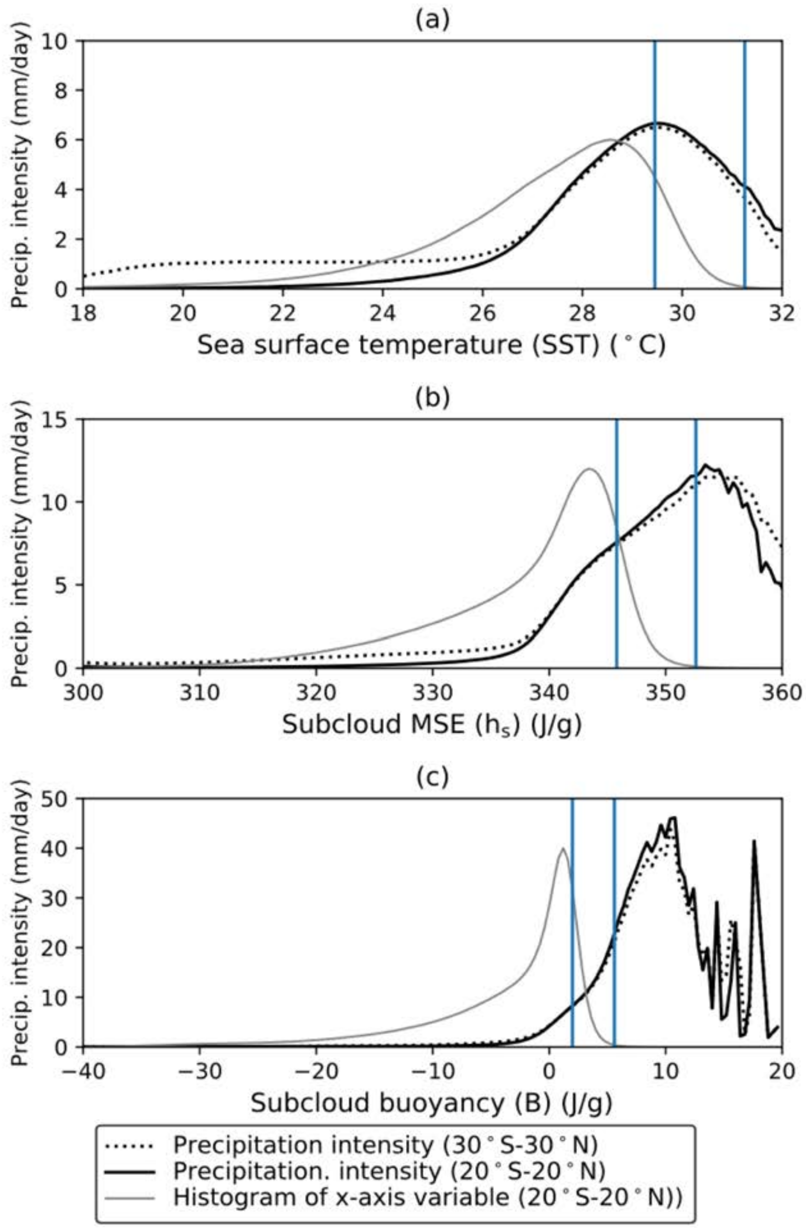
Here: Retain **low dimensionality, physically** based.

Low dimensionality: each location special? How many patterns? What's wrong with linearity?

Physically based: As opposed to data mining (EOFs).

PRINCETON UNIVERSITY

What's wrong with linearity?



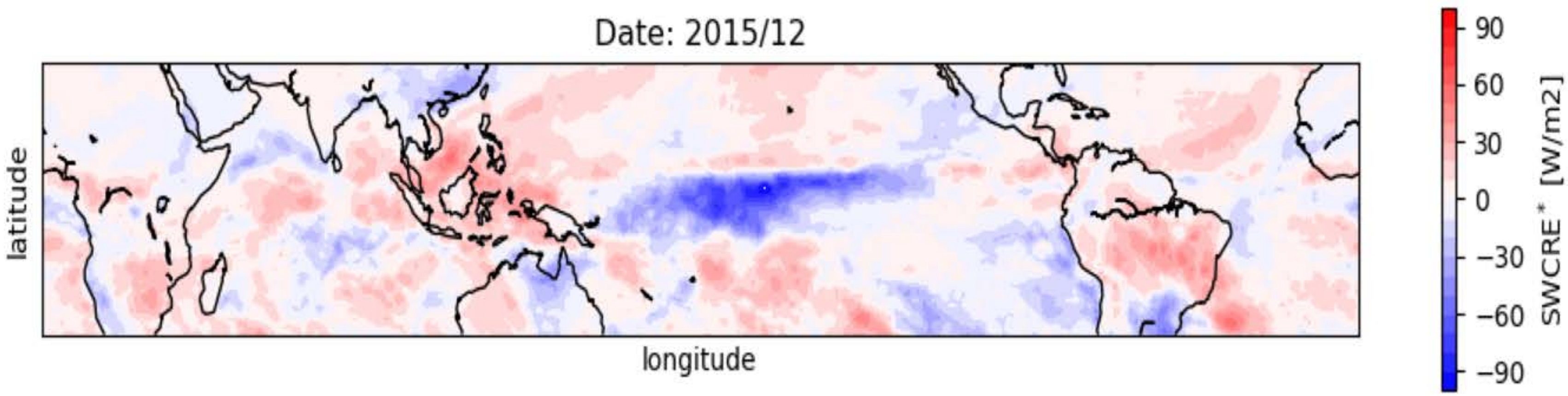
Focus on tropics:
Weak temperature gradient (WTG) leads to strong non-linearity of deep convection (and other aspects) as function of surface temperature.

(More accurately: subcloud MSE.)

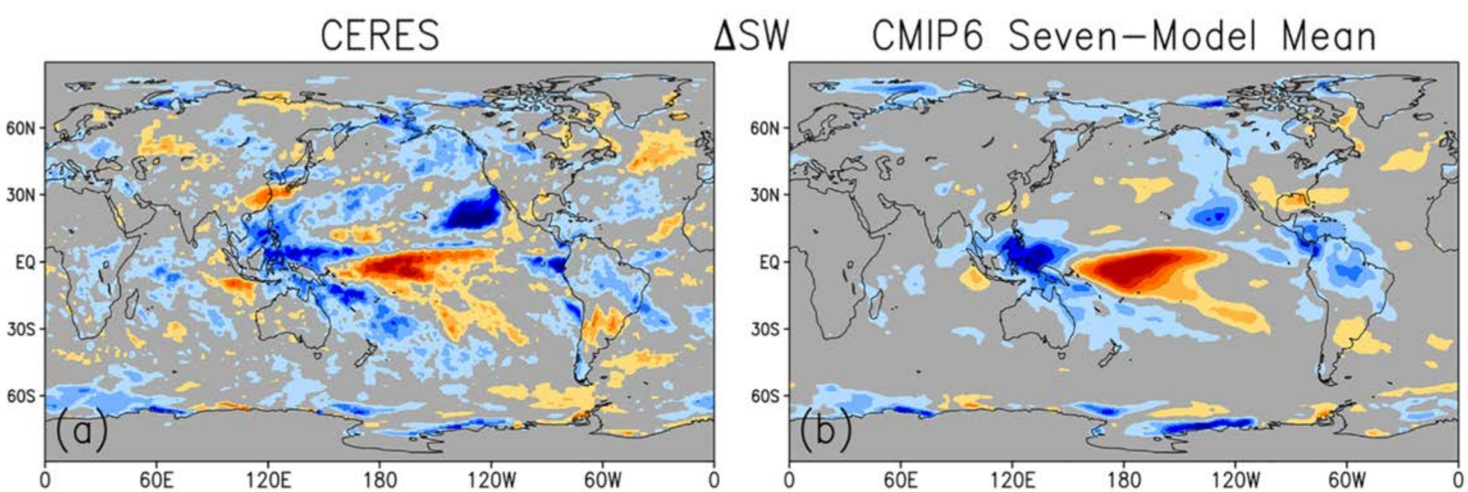
Figures:
Zhang and Fueglistaler, in review.

Do we need Geography?

The ”net” is generally the small residual of **large local antagonistic changes**.
Example: SWCRE = clearsky - allsky solar radiation;
negative anomaly = more reflection/clouds



(see also Radley et al., 2014)



[Loeb et al. 2020]

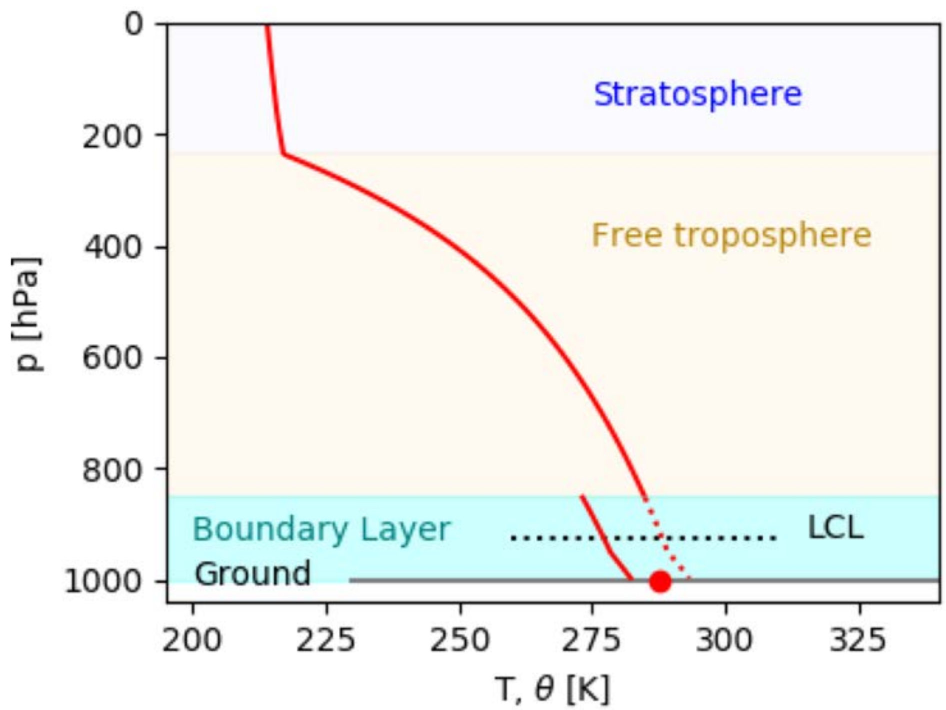
Do we need Geography?

For many problems: yes.

For understanding the mechanisms controlling the mean state – not necessarily.

-> Abandon Geography.

The physical argument for **2** modes

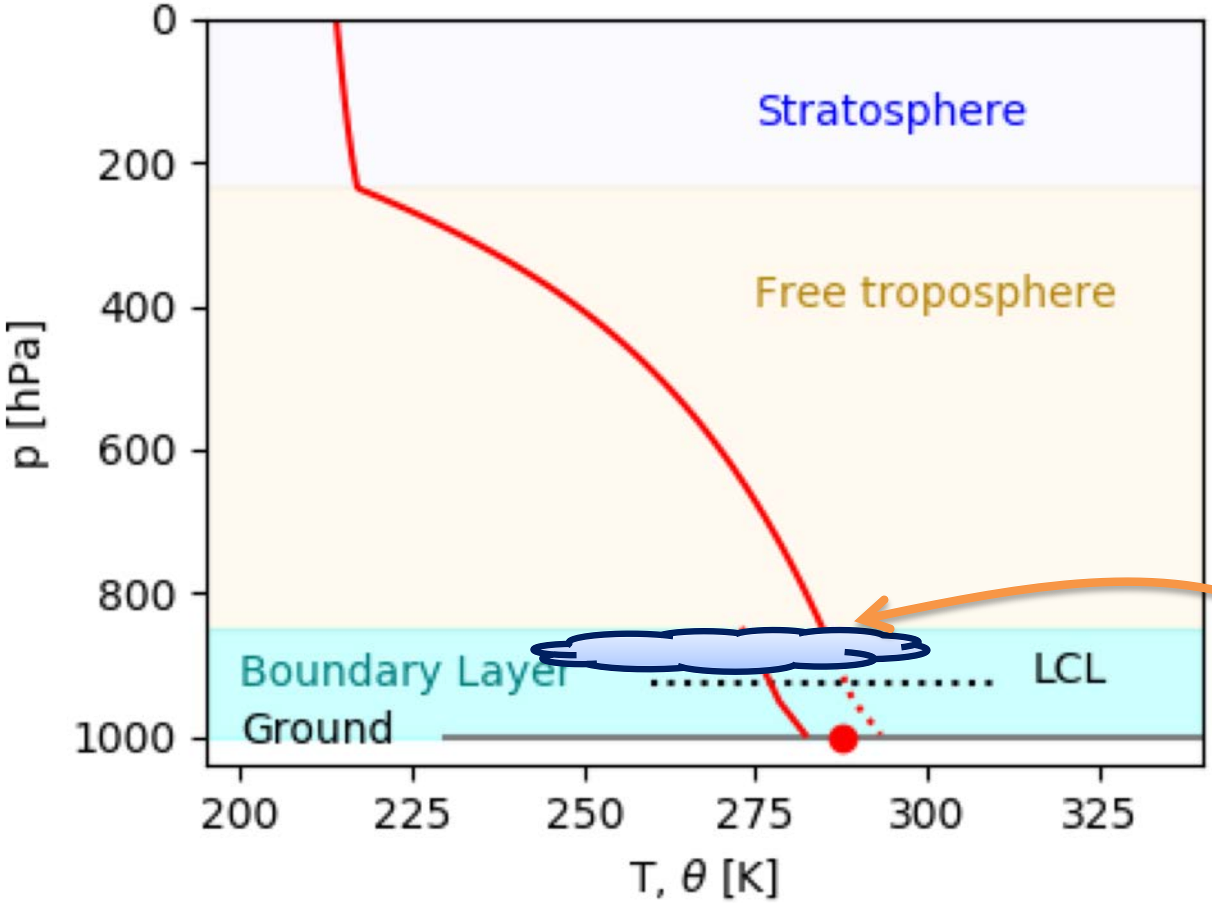


Full domain average free troposphere = function of surface **only** in regions of air export (tropics: deep convection).

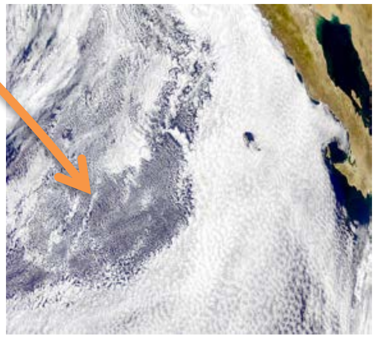
Full domain average boundary layer = function of full domain average surface.

If, and only if, the average surface temperature in the “export/convective” region is a function of the average temperature, we can reduce the problem to a single variable (global average).

Low cloud cover over oceans



Klein&Hartmann (1993) + many more:
Cloudiness controlled by (absolute) SST, and inversion strength (refined later to EIS).
Warmer = less clouds.
Stronger inversion= more clouds.

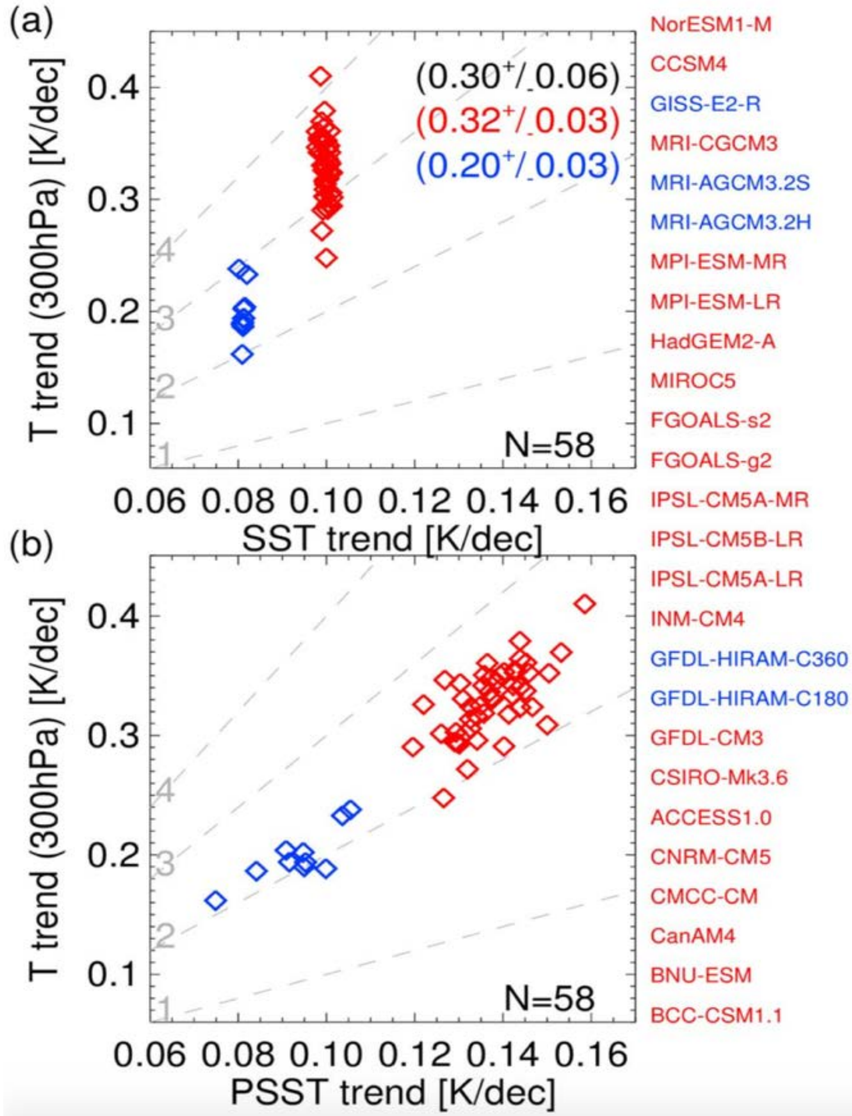


Pattern effect -> “thermodynamic variance effect”

Argue: key is **not** the **geographic** location of temperature trends, but whether the trends lead to an **increase in variance** (warming the warmest more) or **decrease in variance** (more even world).

In tropics, Weak Temperature Gradient (WTG) limit is sound theoretical basis for decoupling from mean (extratropics tbd).

Temperature trends,
“hot spot controversy”
[Flannaghan et al., 2014; Fueglistaler et al., 2015]



The 2nd Mode

Metric for difference between average surface temperature (1st mode), and temperature in convecting regions.

(α) Δ^{conv} == PSST – $\overline{SST}$

(b) $SST^{\#}$ == SST^{top30} – $\overline{SST}$

$SST^{\#}$ is just a gradient /variance metric; builds on the fact that convection occurs primarily over warmest waters.

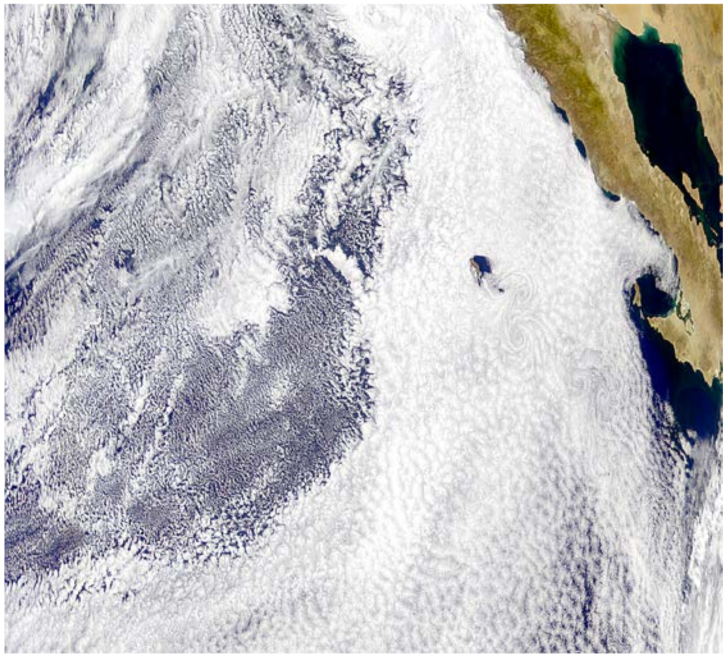
Advantage over Δ^{conv} (or ω-500 etc.): No rainfall or atmospheric model needed (i.e. can understand what happens from "forcing" in AMIP simulations).

Observational evidence for 2 modes ($\overline{SST}$, $SST^{\#}$)

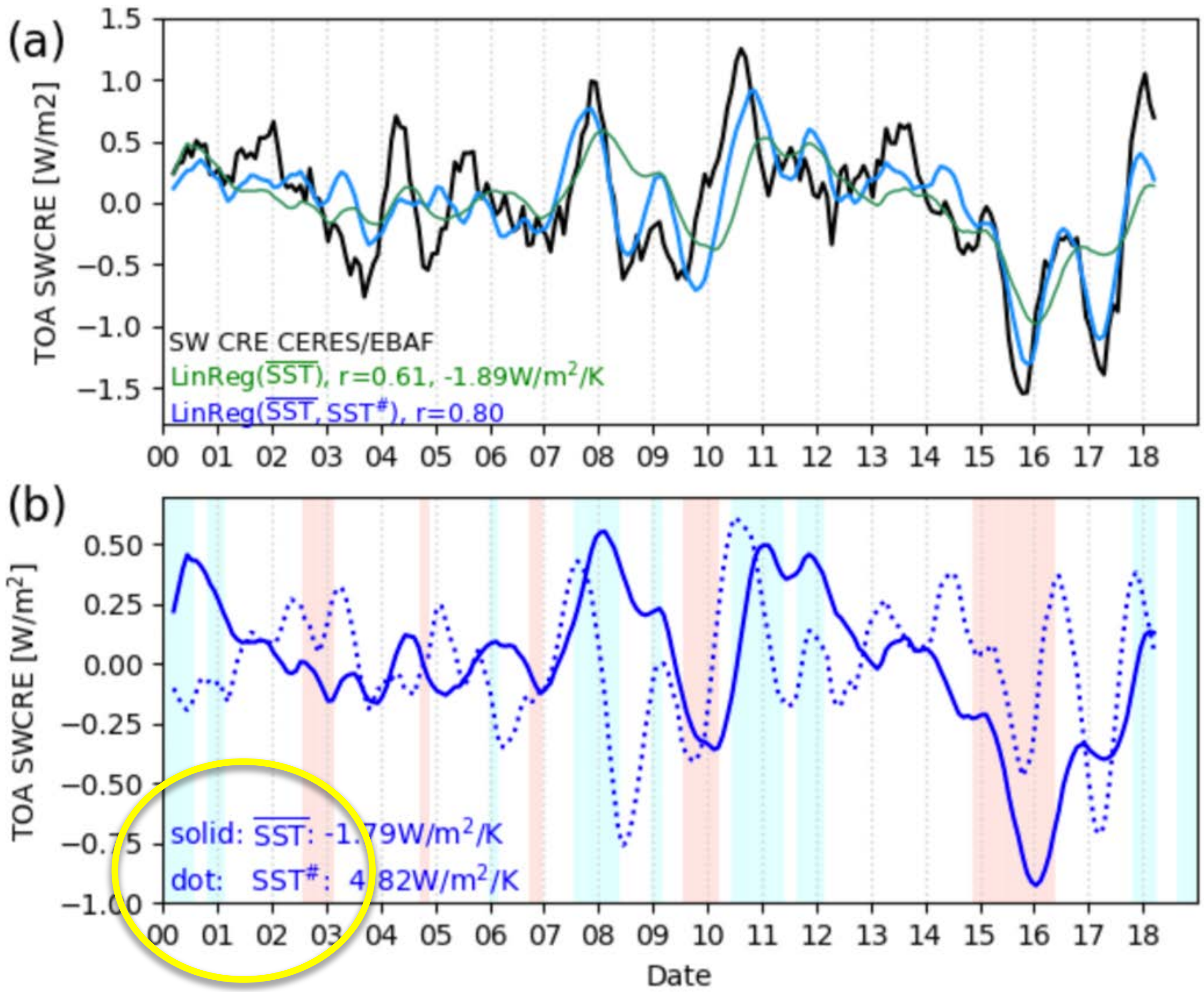
Data:

SWCRE: CERES/EBAF
Atmospheric temperature: ERA-Interim
SST: HadISST1

[Fueglistaler, GRL, 2019]



Observational evidence for 2 modes ($\overline{SST}$, $SST^{\#}$) [Fueglistaler, 2019]



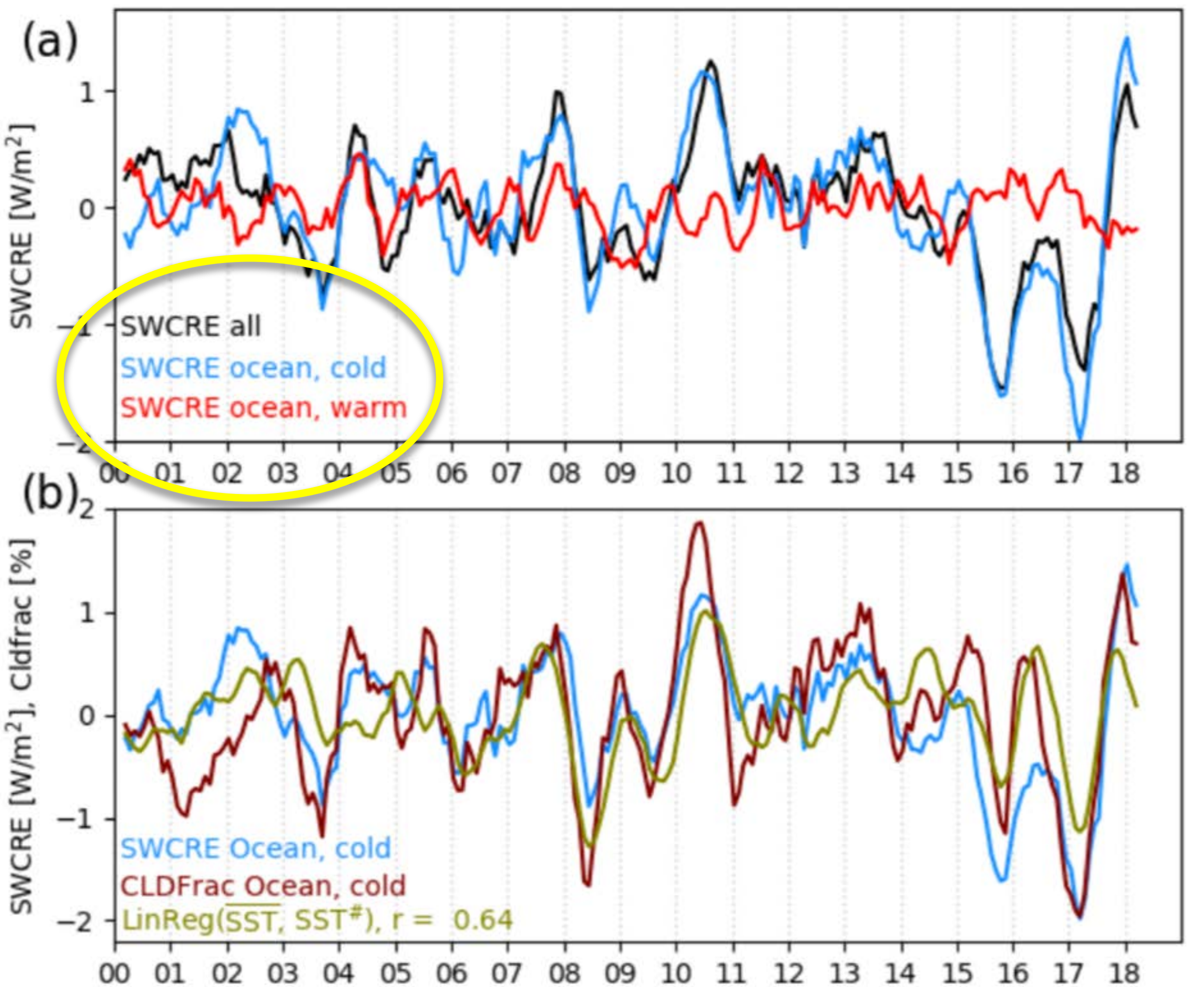
[Fueglistaler, 2019]

Best observed (CERES/EBAF) tropical average SWCRE explained by **$\overline{SST}$ and SST#.**

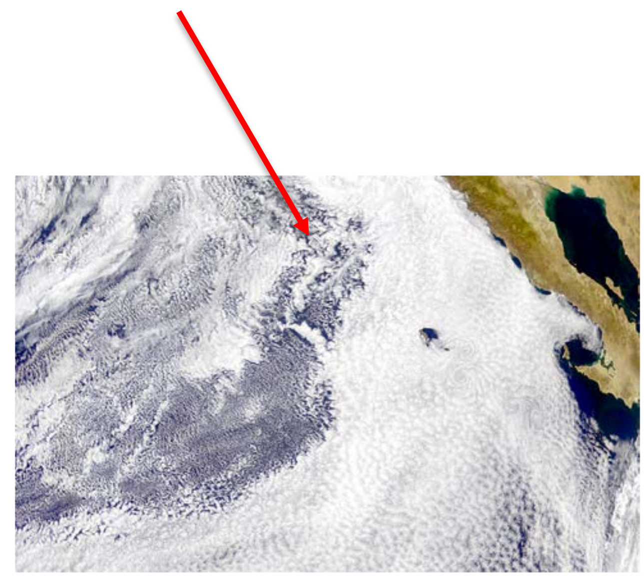
ENSO (El Nino, La Nina): important over the observed period.

Both modes explain similar amount of variance; **little correlation between modes**.

Tropical cloud albedo variations

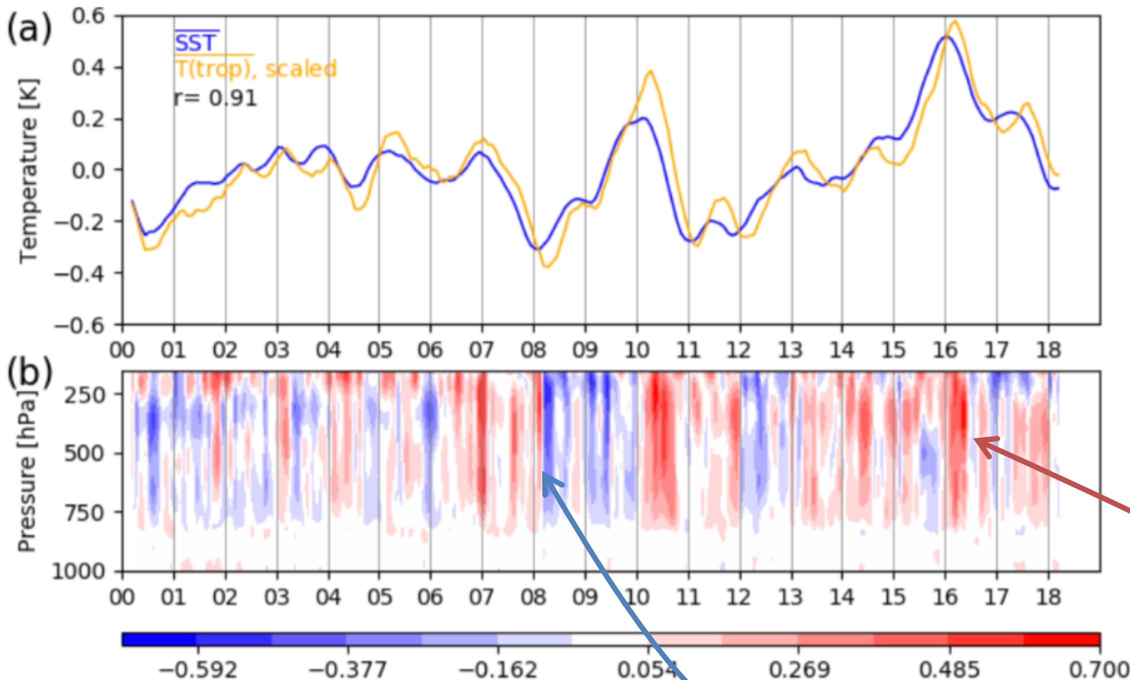


It's the oceanic low cloud amount (vs deep convection, cloud albedo etc.)



[Fueglistaler, 2019]

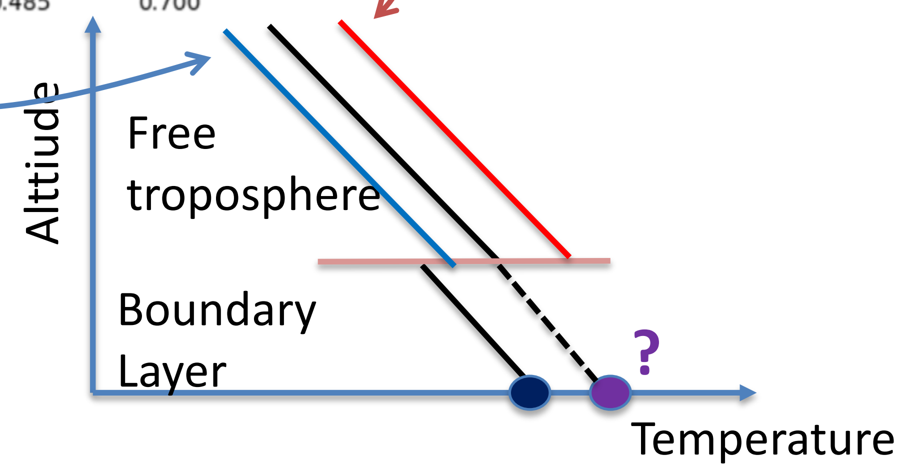
The two modes in tropical tropospheric temperature



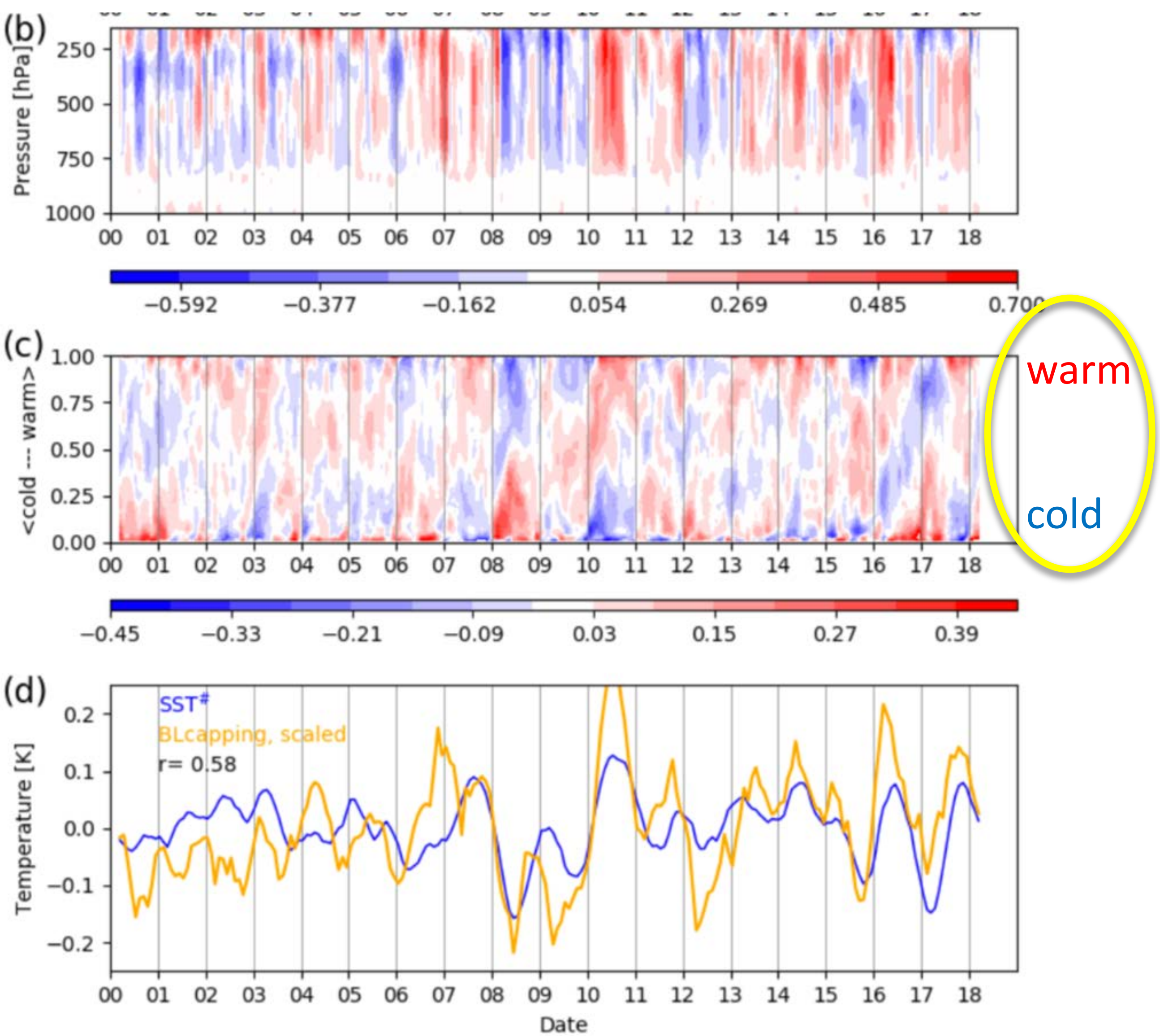
Temperature [K]

Average

Departure from climatological scaling with average boundary layer temperature (moist adiabat).



Impact of SST# on boundary layer capping strength



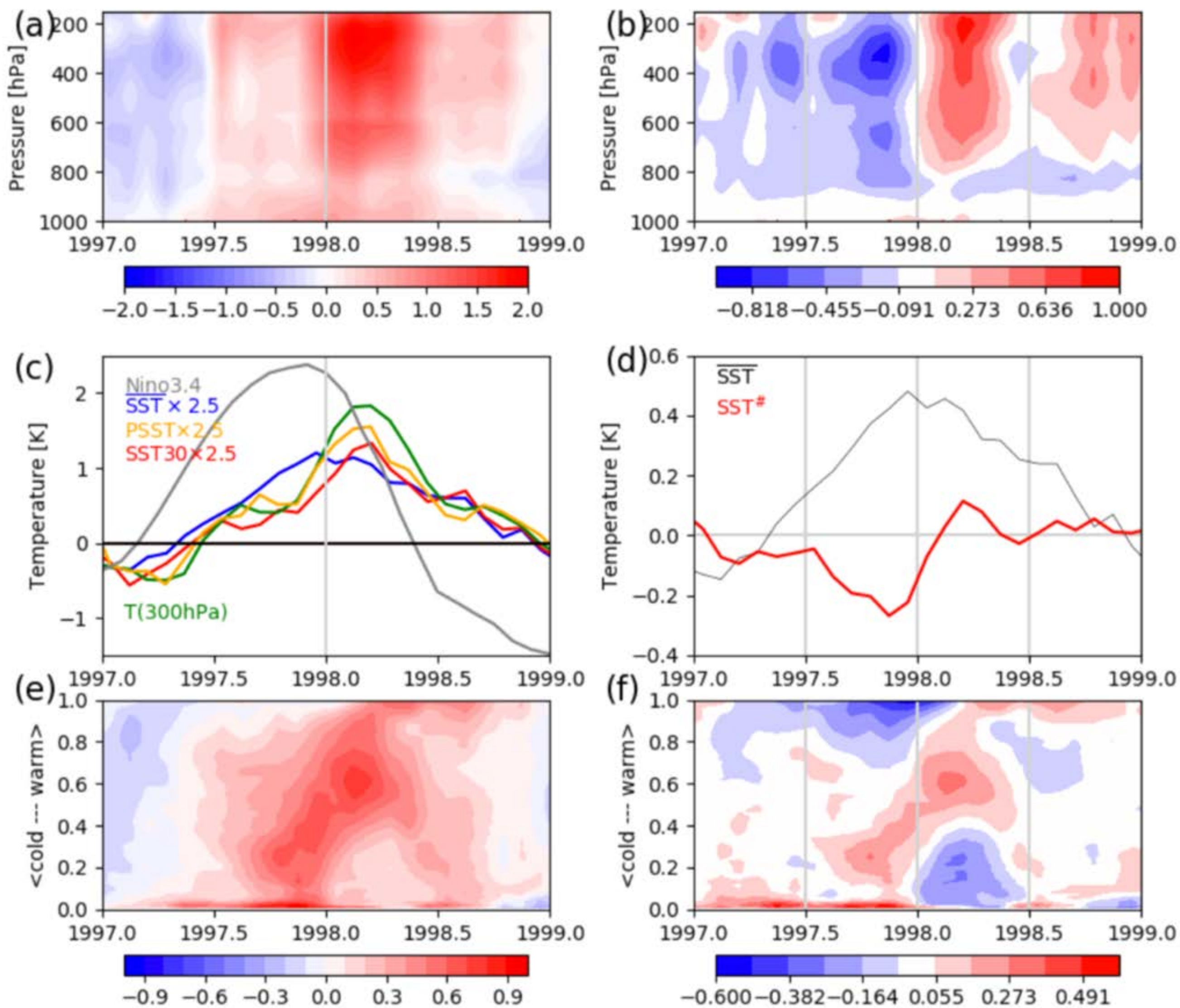
Atmosphere: Departure from climatological scaling (moist adiabat) with Boundary Layer temperature.

SST area percentile distribution, monthly mean subtracted.

SST# and "BL capping index"; simply panel (b) integrated from 800-400hPa.

[Fueglistaler, 2019]

Phasing of average SST and SST$^{\#}$ during El-Nino

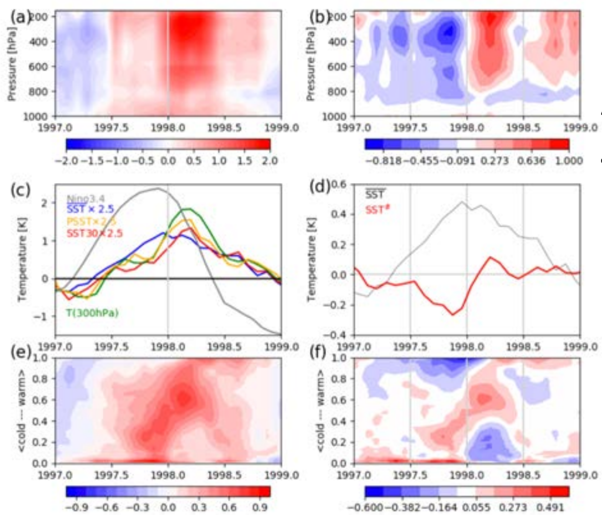


Tropical average atmospheric temperature

Averages (to be explained)

Sea Surface Temperatures

Phasing of average SST and $SST^{\#}$ during El-Nino



In words:

At the **onset of El-Nino**, the cold waters warm first -> SST# decreases.

Implication: Low clouds decrease with warming, and they decrease with decreasing SST# => **a strong positive feedback** (more solar absorbed).

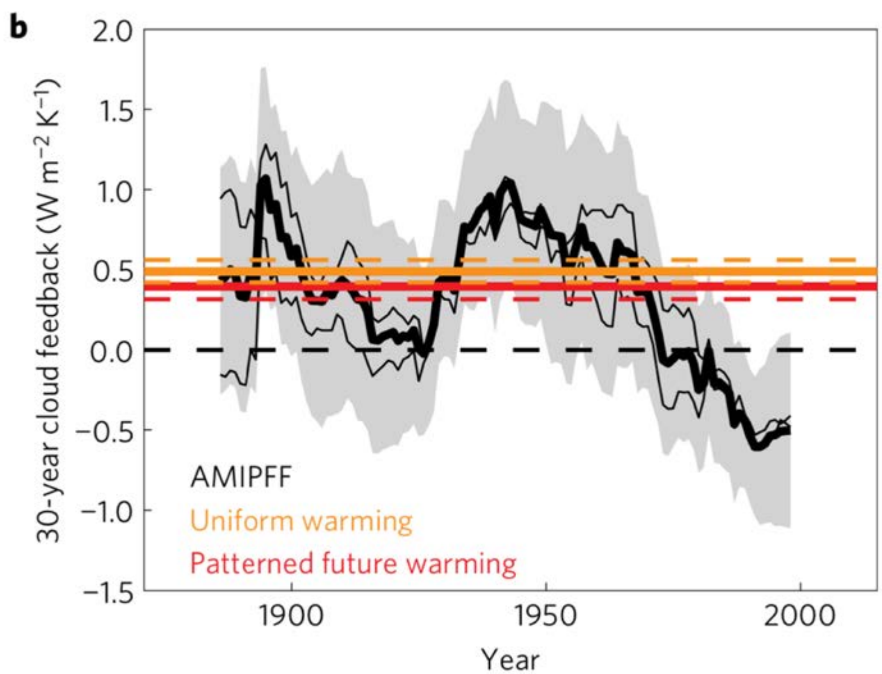
From **January onwards**, the cold water are still warm (implying less cloud amount), but now also the warm regions warm -> SST# increases -> forces an increase in cloud amount.

$\Rightarrow$ **For the same average SST we get two different SWCRE values**.

(Side note: “removal” of ENSO with regression against Nino-index problematic.)

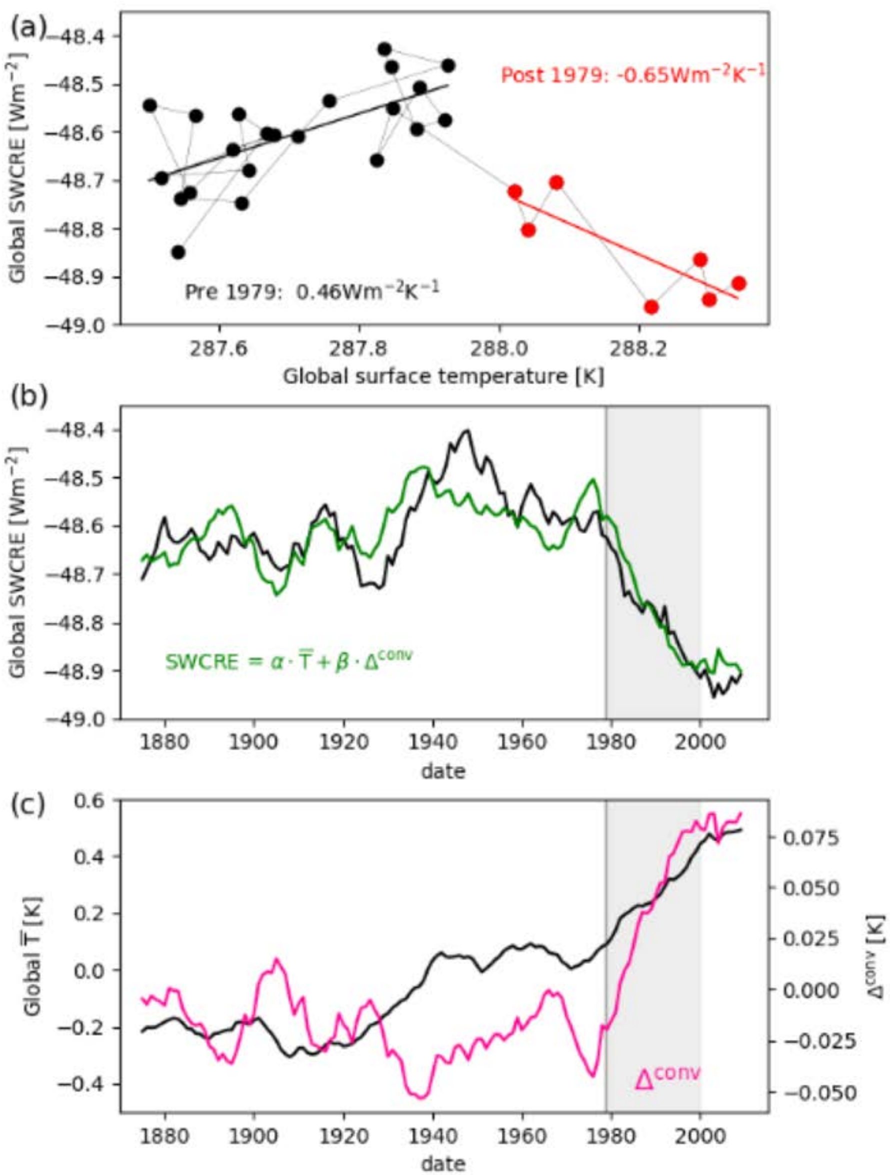
Why "peculiar"?

Recall AMIP piForcing results (Zhou et al., 2015; Silvers et al. 2018):



PRINCETON UNIVERSITY

Why peculiar?



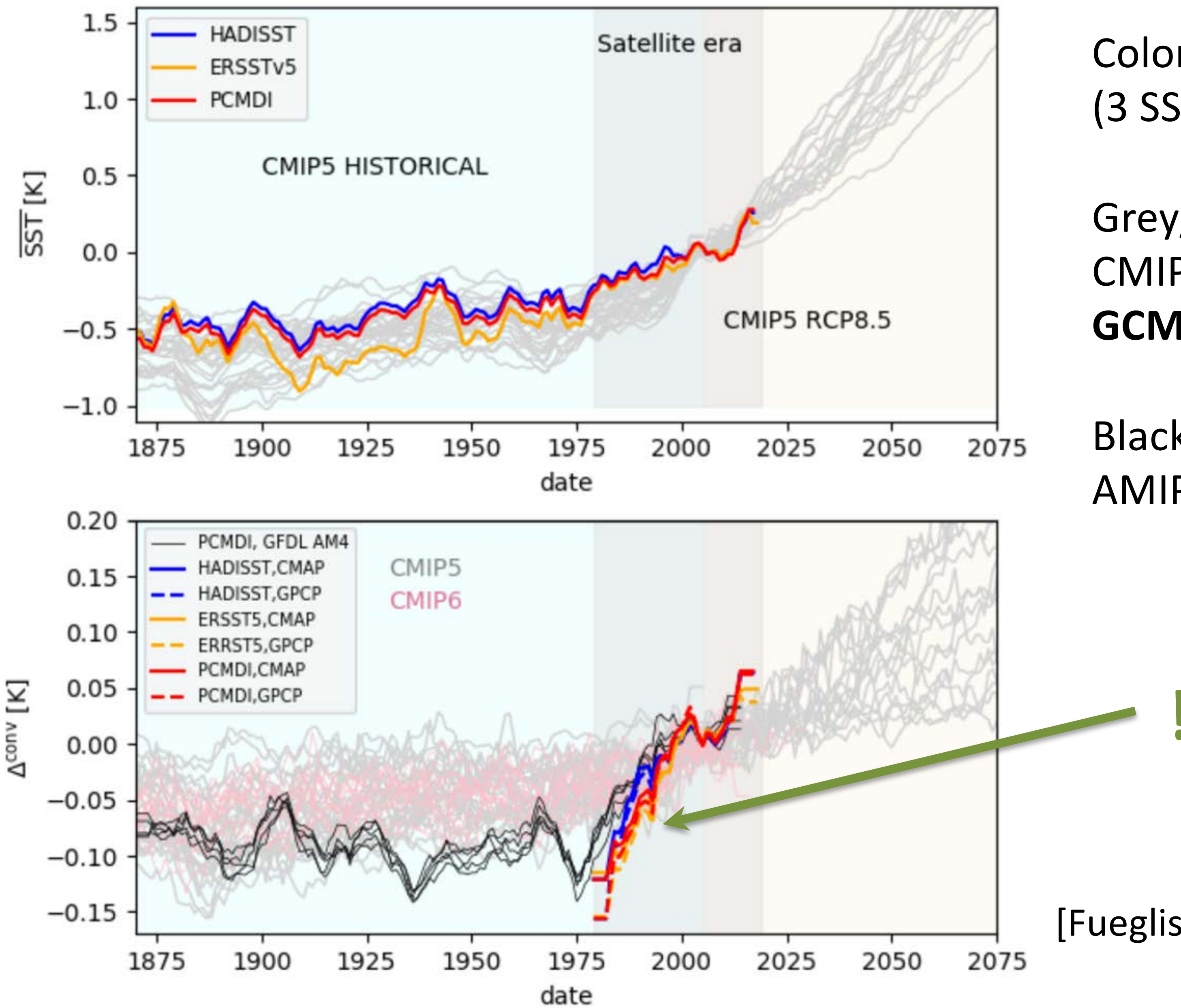
Breakpoint in relation SWCRE versus average SST in late 1970s.

AMIP piForcing SWCRE well explained by SST and Δ^{conv}.

It's Δ^{conv} that has a break point in the late 1970s.

[Fueglistaler & Silvers, in prep.]

Why peculiar? Compare with coupled GCMs



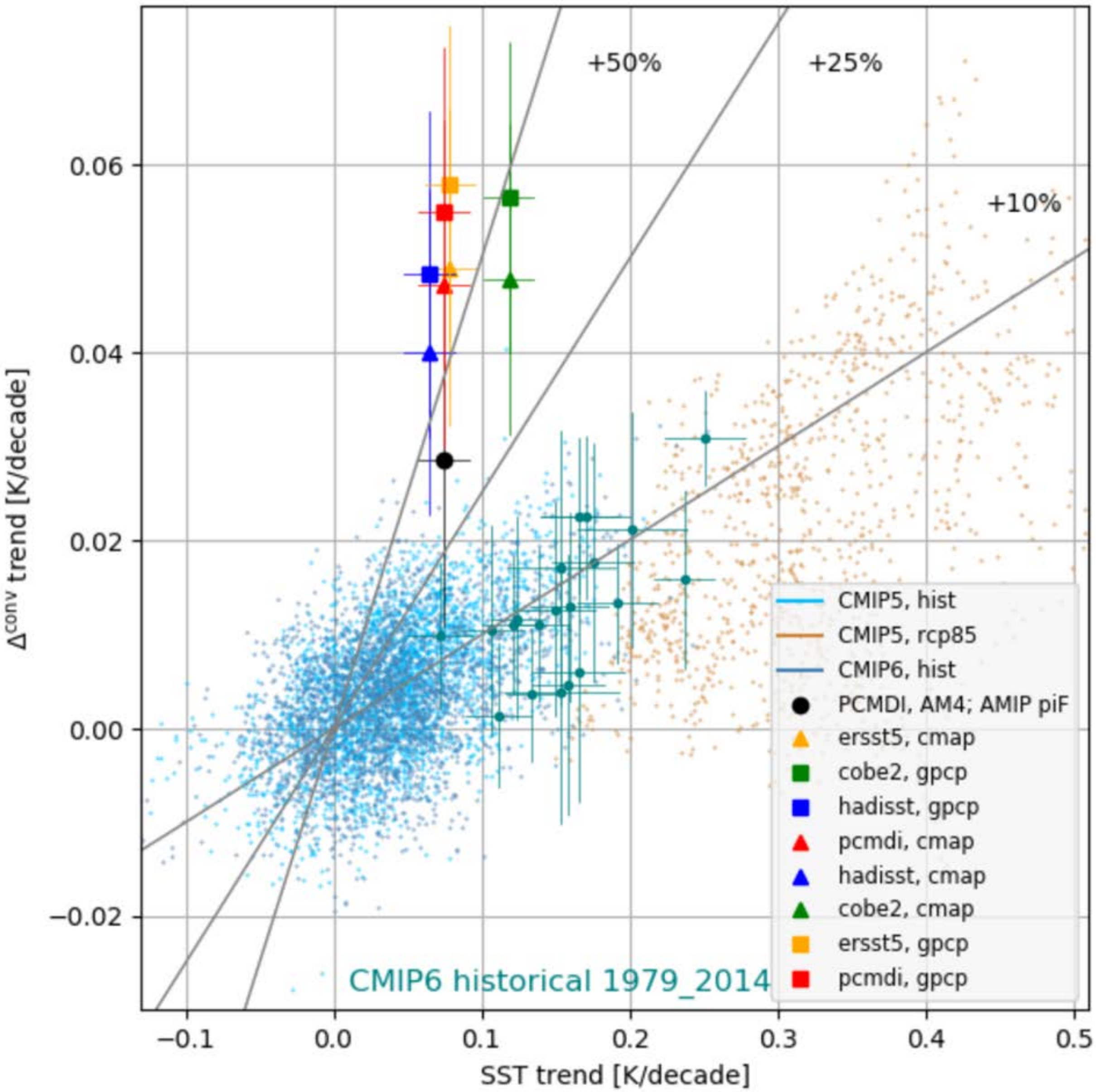
Colors: Observations (3 SSTs, 2 rainfall data)

Grey/pink: CMIP5/CMIP6 **coupled GCMs**.

Black: GFDL AM4 AMIP-piForcing.

[Fueglistaler & Silvers, in prep.]

Why peculiar? Compare with coupled GCMs

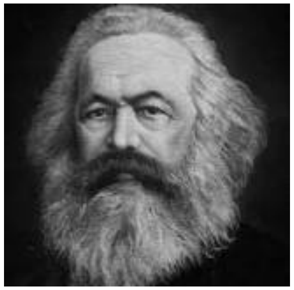


[Fueglistaler & Silvers, in prep.]

Take-home

(1) Evenness (variance) is important (2nd mode).

(2) An even world is a warm world.
(Any association … is far-fetched.)



(3) Since the late 1970's, the world has become increasingly uneven.
(Any association … is far-fetched. Really!)

The peculiar trajectory - summary

Satellite period 1979 – present: best observed, but out of norm (norm = previous 100+ years; coupled GCMs).

Observational evidence for SST# -> atmos BL capping -> cloud feedback.

SWCRE trend only in models (not good enough observations prior 2000).

Large impact on climate sensitivity – very low when estimated 1980-present.

SST#/cloud and Hiatus/Pacific dynamics don't add up – unclear how SWCRE and disequilibrium perspective align.

(How trustworthy are SSTs? Prior to 1980's?)

Interesting times – much work to be done!

Thank you!

PRINCETON UNIVERSITY

Geophysical Research Letters

RESEARCH LETTER

10.1029/2019GL083990

Key Points:
- Average SST and difference between the warmest waters and the average ($SST^{\#}$) control tropical tropospheric temperature profile and SWCRE
- Observational evidence for pattern effect (encapsulated by $SST^{\#}$) on climate sensitivity as previously noted in GCM simulations
- Observations driven by ENSO have

Observational Evidence for Two Modes of Coupling Between Sea Surface Temperatures, Tropospheric Temperature Profile, and Shortwave Cloud Radiative Effect in the Tropics

S. Fueglistaler[1,2]

[1]Department of Geosciences, Guyot Hall, Princeton University, Princeton, NJ, USA , [2]Program in Atmospheric and Oceanic Sciences, Sayre Hall, Princeton University, Princeton, NJ, USA

Geophysical Research Letters

RESEARCH LETTER

10.1029/2019GL086387

Key Points:
- The utility of quasi-equilibrium and weak temperature gradient theories (QE-WTG) can be demonstrated by a rainfall-weighting method

How Tropical Convection Couples High Moist Static Energy Over Land and Ocean

Yi Zhang[1] **and Stephan Fueglistaler**[1,2]

[1]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA, [2]Department of Geosciences, Princeton University, Princeton, NJ, USA

Geophysical Research Letters

RESEARCH LETTER

10.1029/2019GL086058

Key Points:
- The unevenness of tropical rainfall increases with warming because of Clausius-Clapeyron scaling of subcloud moist static energy

Mechanism for Increasing Tropical Rainfall Unevenness With Global Warming

Yi Zhang[1] **and Stephan Fueglistaler**[1,2]

[1]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA, [2]Department of Geosciences, Princeton University, Princeton, NJ, USA

Additional slides

Stratus clouds and lower tropospheric stability

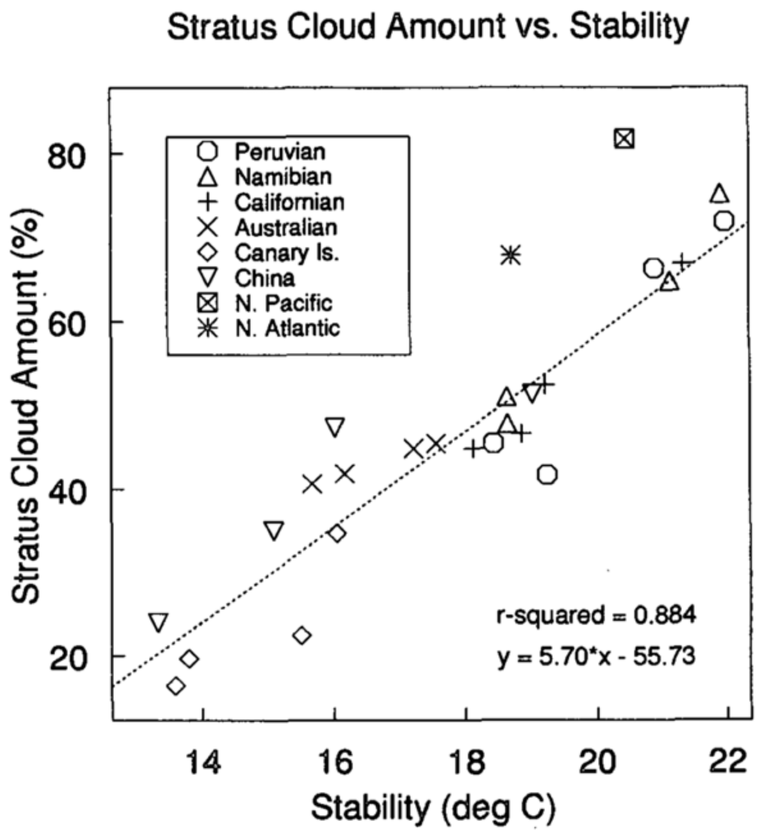


FIG. 13. Scatterplot of seasonally averaged stratocumulus cloud amount with seasonally averaged lower-tropospheric stability for the five subtropical oceanic regions and the Chinese stratus region. In addition, the June, July, and August seasonally averaged quantities are plotted for the North Pacific and North Atlantic but are not included in the regression.

Klein and Hartmann, 1993: Stability – here defined as potential temperature difference between 700hPa and surface air – has a strong impact on cloud cover.

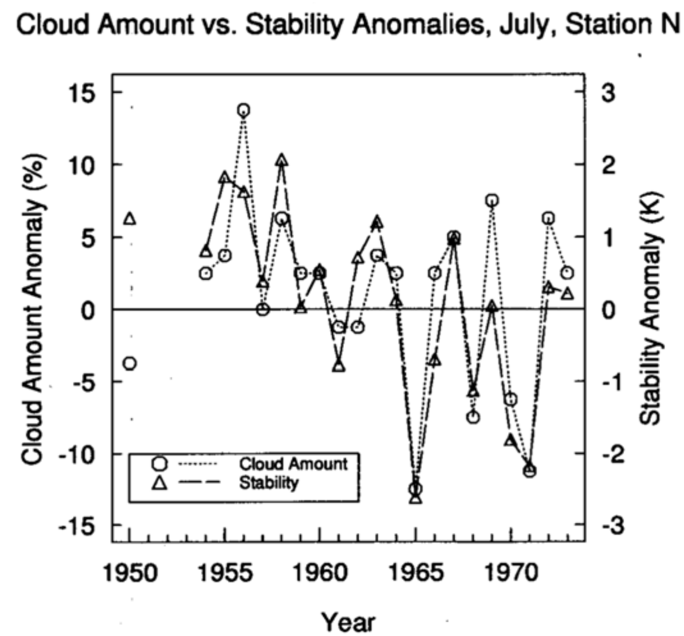


FIG. 15. Time series of the July anomalies in total cloud amount and lower-tropospheric stability at weather ship N (30°N, 140°W).

CMIP5 climate sensitivity

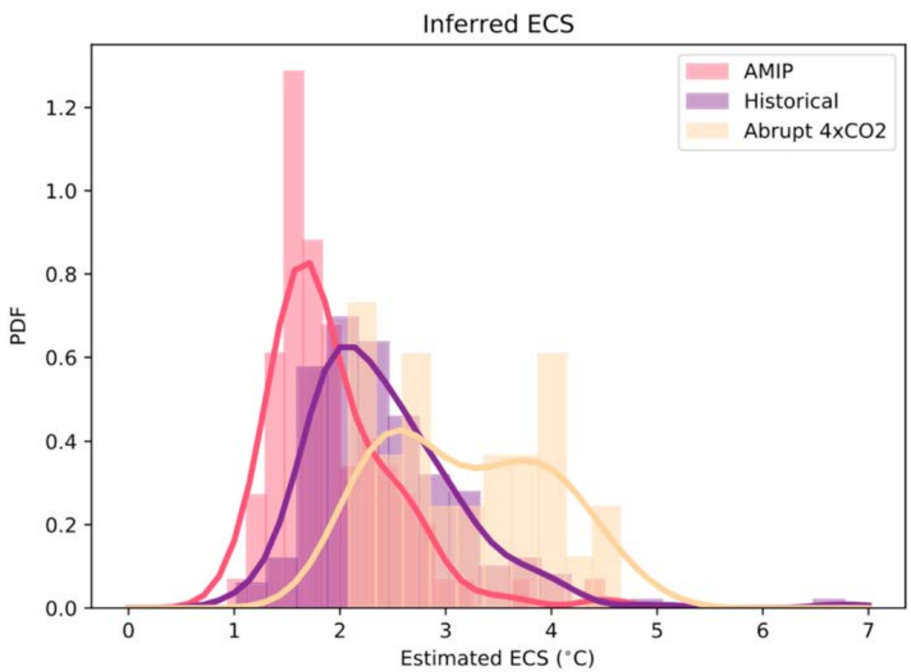


Figure 1. Equilibrium climate sensitivities inferred from amip (pink), historical (purple), and long-term (yellow) simulations, with kernel density estimates overplotted for visual clarity.

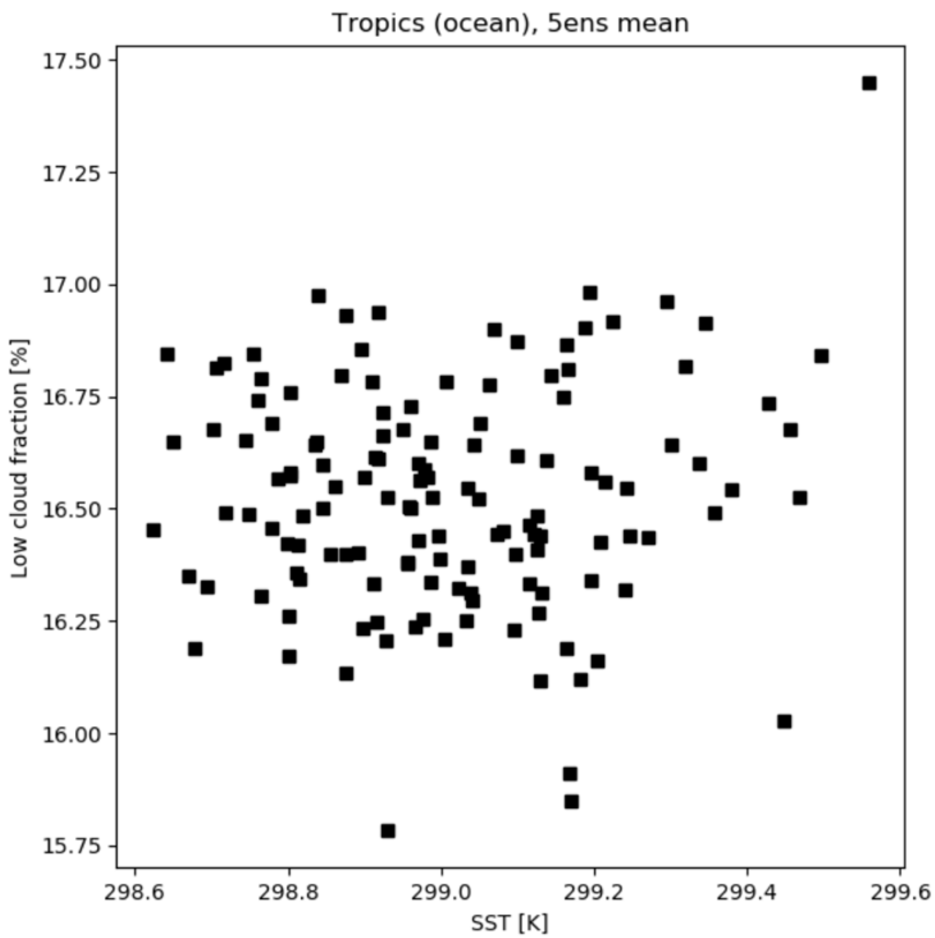
E.g. Marvel et al. [2018]:

Equilibrium climate sensitivity estimated from:

- AMIP (prescribed SST, 1870-2005): **1.8K**
- Historical (coupled ocean/atmos GCM): **2.3K**
- Abrupt 4xCO2: **3.1K**

-> Climate feedbacks become more positive in the future. Why?
And why is AMIP lowest?

Low cloud fraction and average SST

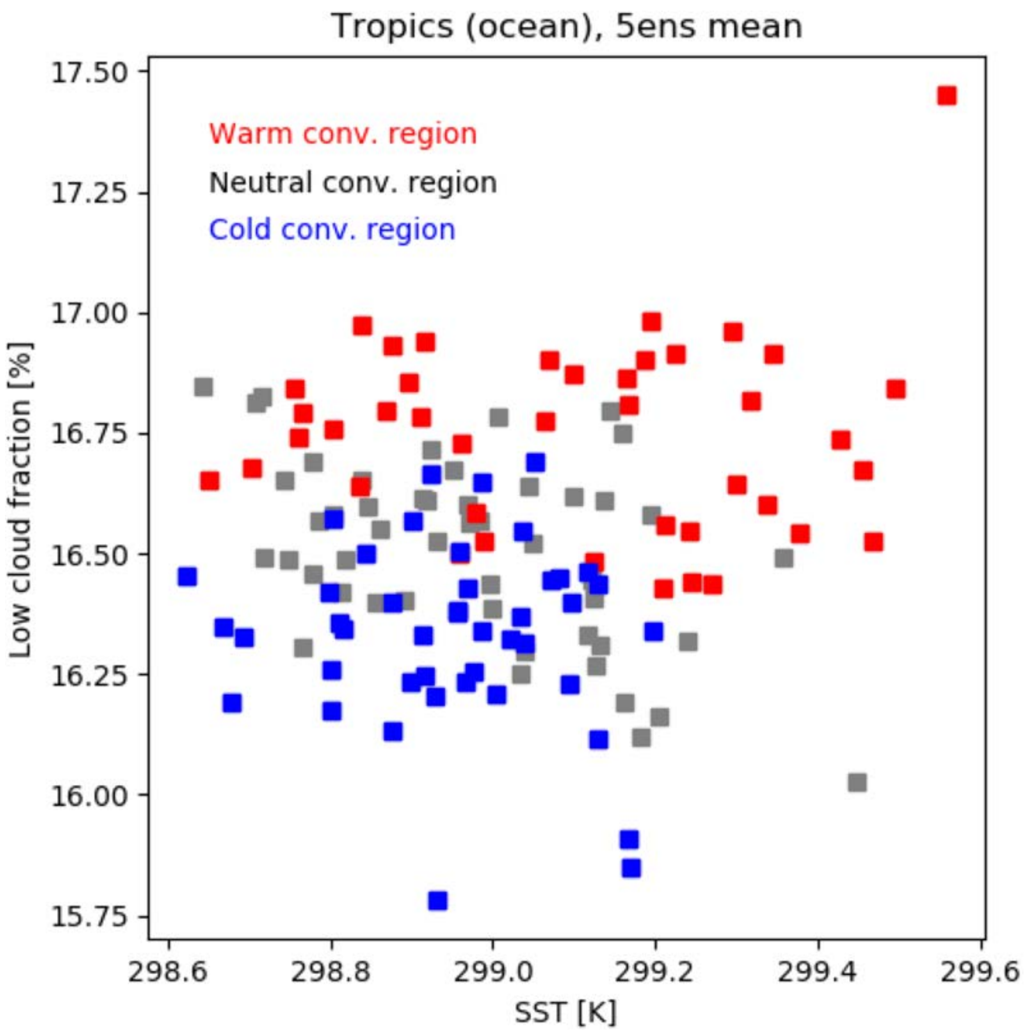


GFDL AM4, forced with prescribed Sea Surface Temperatures 1870-2014. Annual averages, averaged over 5 ensemble members.

Data courtesy Levi Silvers.

For reference:
1% low cloud fraction ~ 1W/m2 shortwave cloud radiative effect; [Klein & Hartmann, 1993].

Variations in SST# explain historical period GCM result



AM4 data: GFDL/Levi Silvers

SST# := warmest 30% minus tropical average

SST# high (=strong BL capping)

SST# average

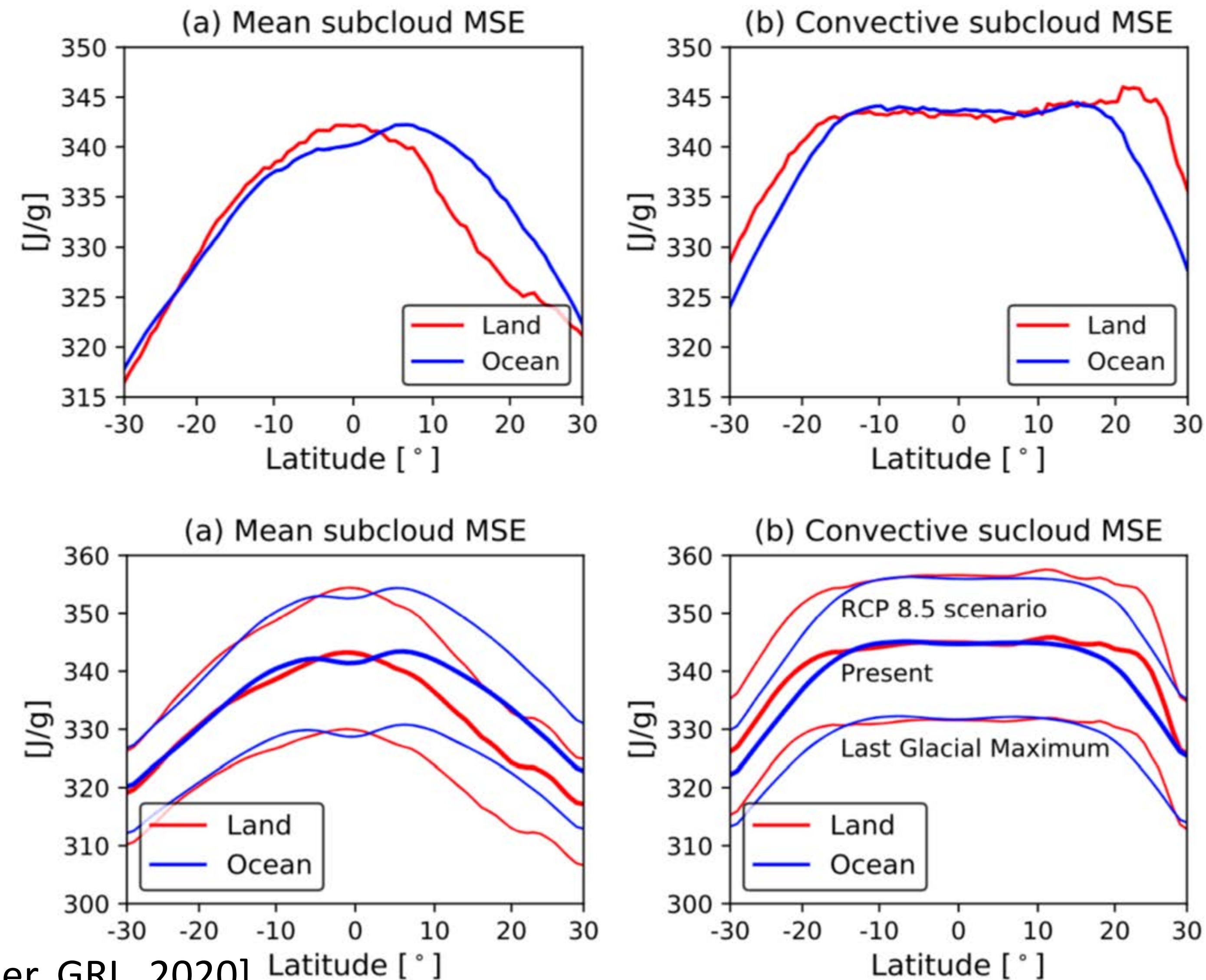
SST# low (=weak BL capping)

Consistent with emphasis on "ascent regions", and Western Pacific using Green's function approach (Zhou et al., 2017; Dong et al., 2019).

Observational evidence for WTG (+QQ)

Observations

CMIP5



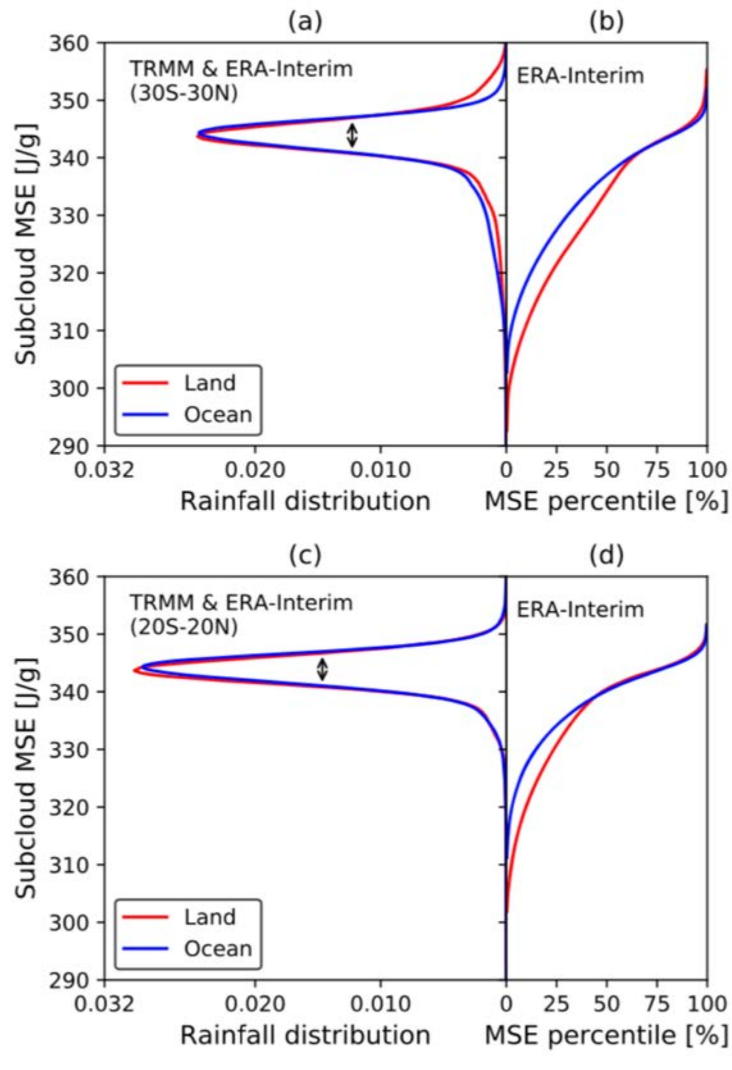
[Zhang and Fueglistaler, GRL, 2020]

Rainfall amount in subcloud MSE space

WTG: subcloud MSE in convective regions (NOT on average) are similar.
Fair enough.

But who'd thought that rainfall amount distribution in subcloud MSE-space is almost identical over land and ocean?

Something to think about!

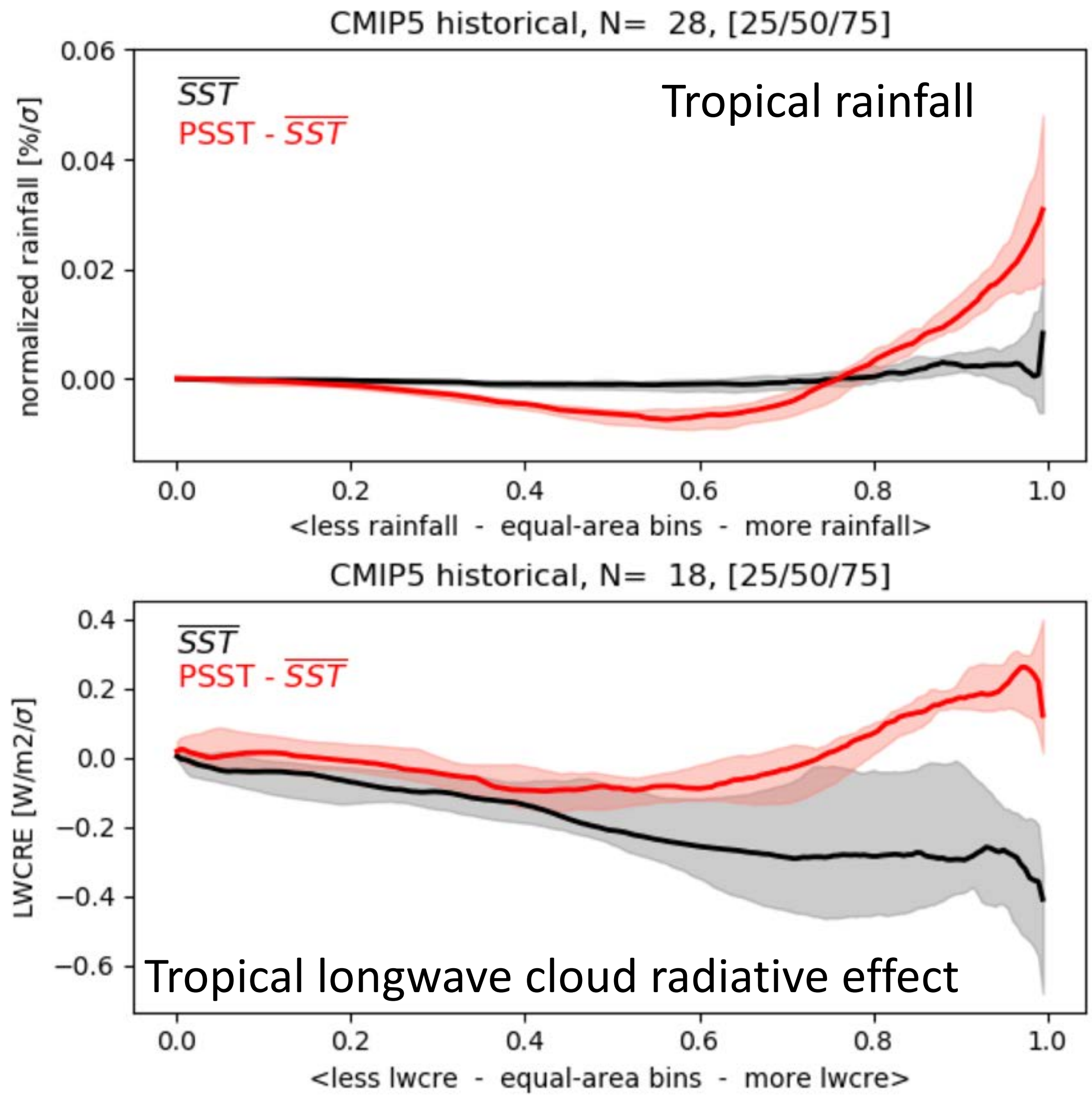


[Zhang and Fueglistaler, GRL, 2020]

Additional effects of warming the warmest

The “2nd mode” – excess warming of the warmest regions - is not only affecting BL capping strength, but is also a **contraction mode.**

CMIP5 model data show this effect clearly in interannual variability – but little trend because they have little PSST-SSTavg trend.



[Fueglistaler et al., in prep.]

Causality and implications for past and future climates

CO_2 ↗ -> SSTavg ↗ -> cloud albedo ↘ Positive cloud feedback

CO_2 ↗ -> SST#? -> cloud albedo? Positive or negative impact on SSTavg.

-> SST# = f(SSTavg)?

Alternative:

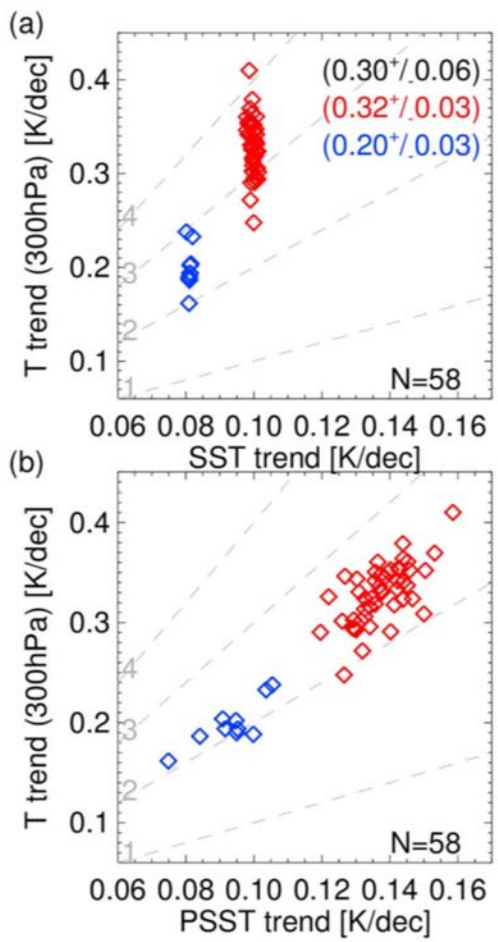
Forcing -> SST# -> Radiative forcing from cloud albedo

-> SSTavg -> cloud albedo positive feedback

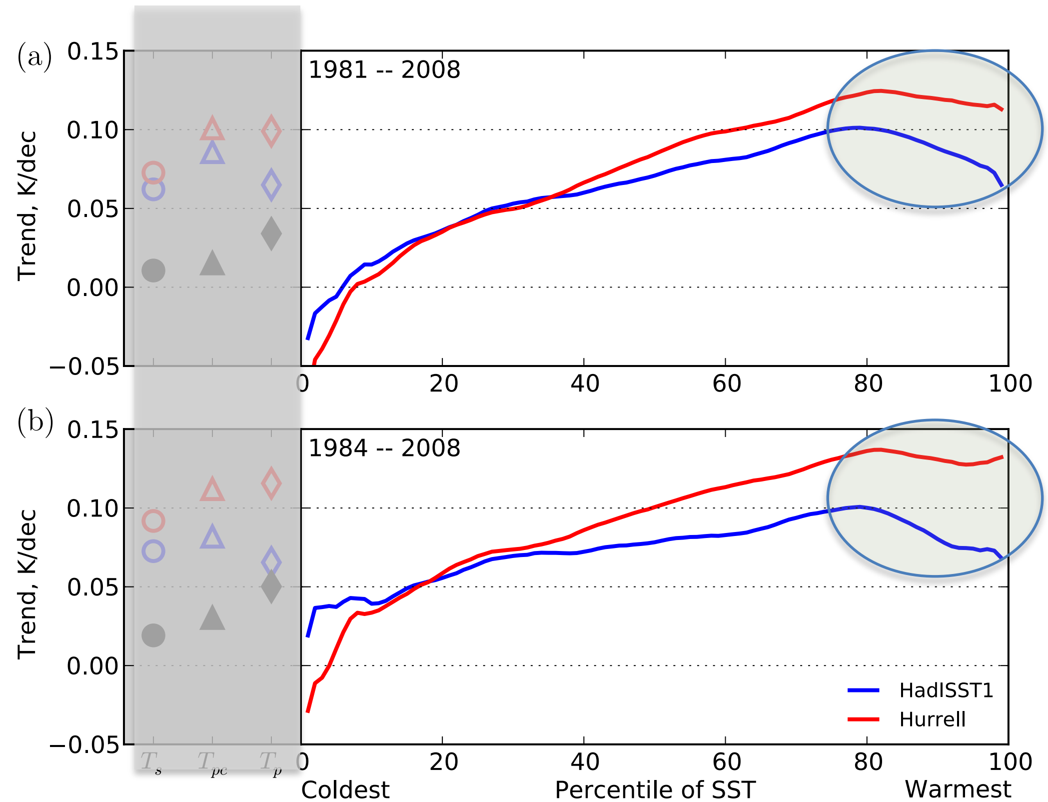
-> "Warm climates" without elevated CO_2?

The hot spot controversy

Do observations show moist adiabatic scaling?



[Fueglistaler et al., 2015]



[Flannaghan et al., 2014]