The Role of Cloud Radiative Effects on the Large-Scale Atmospheric Circulation

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CSU, Mar 14, 2019

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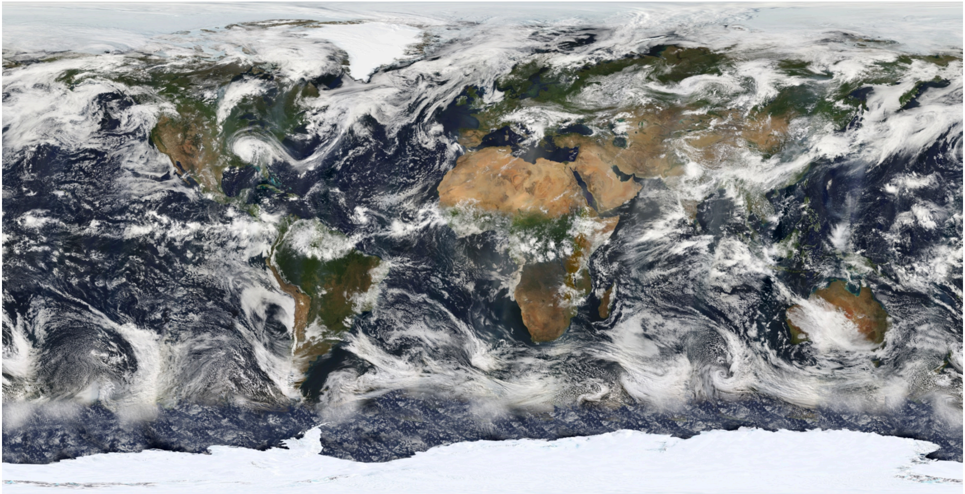
Clouds are crucially important.

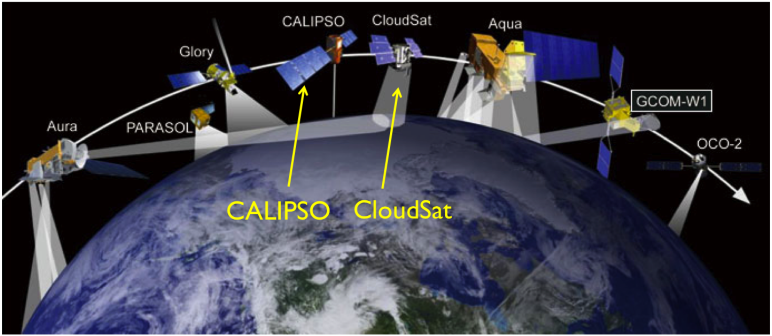


The importance of cloud radiative effects has been recognized for a long time.

" ... the modeling of time dependent clouds is perhaps the weakest aspect of the existing general circulation models and may be the most difficult task in constructing any reliable climate model."

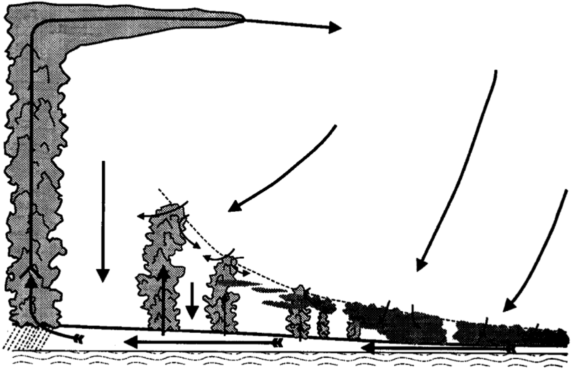
—— Arakawa (WMO, 1975).

A golden age of Earth observations



For the first time, a thorough evaluation of clouds and cloud-radiation interactions in GCMs will be possible.

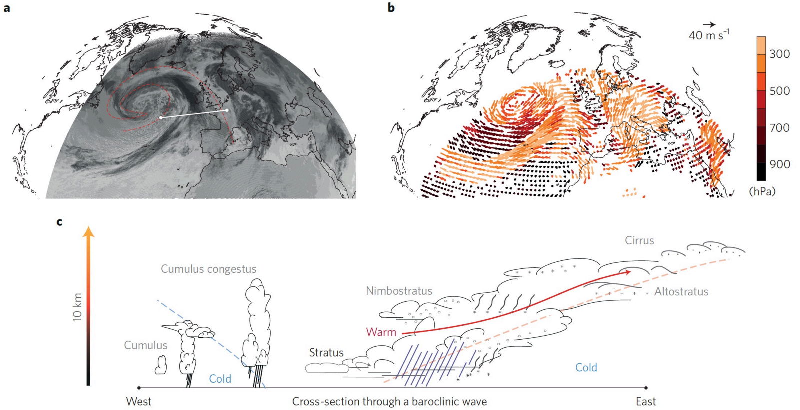
How do clouds interact with large-scale atmospheric circulation?



(Emanuel, 1994)

But over many decades, efforts to understand cloud process and large-scale general circulation have developed in parallel.

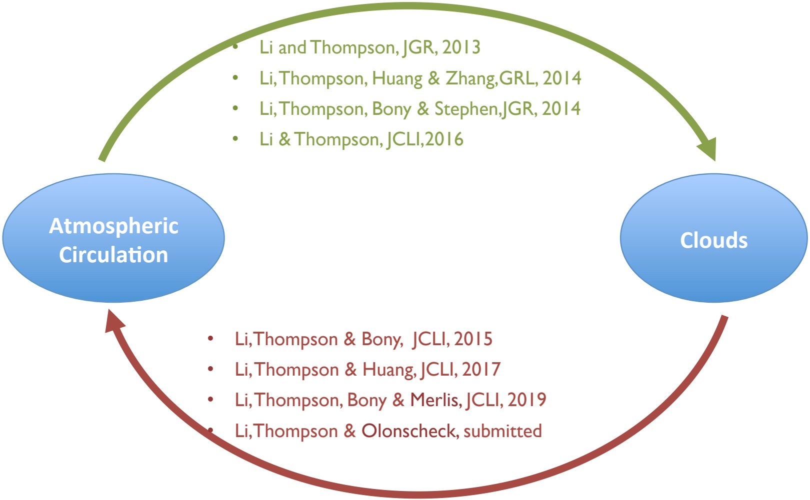
Improving our understanding of the coupling between clouds, circulation and climate



From *Bony et al. Nature Geosci., (2015)*

"Clouds, Circulation, and Climate Sensitivity" has been identified as one (out of six) "WCRP Grand Challenge" (Bony et al. 2015)

Understand coupling between clouds and the large-scale atmospheric circulation



Model and technique hierarchies of assessing the influence of CREs on the atmospheric circulation

Null CRE
Non-interactive SST

- CRE are turned off in every call to the radiation code
- "Clouds On-Off Klima Intercomparison Experiments" (COOKIE)

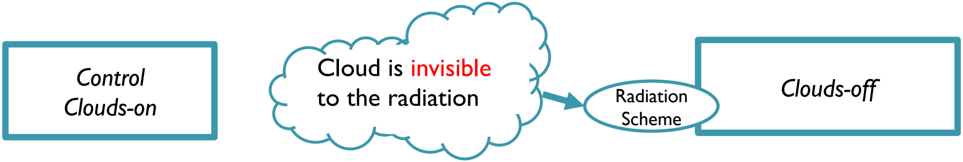
Non-interactive CRE
Non-interactive SST

- CRE are prescribed or locked to the value in the control simulation in every call to the radiation code
- "Cloud-locking"

Non-interactive CRE
Interactive SST

Role of clouds on the long-term mean circulation

COOKIE-type of simulations have been sued in studying the CRE on the long-term mean circulation



- Forced with fixed SST
- Focus on how clouds impact the circulation by directly affecting the atmospheric heating without change SSTs, mostly via LW radiation

- Slingo and Slingo (1988, 1991)
- Randall et al. (1989)
- Sherwood et al. (1994)
- Fermephin and Bony (2014)
- Crueger and Steven et al. (2015)
- Harrop and Hartmann (2016)
- Li et al. (2015, 2017)

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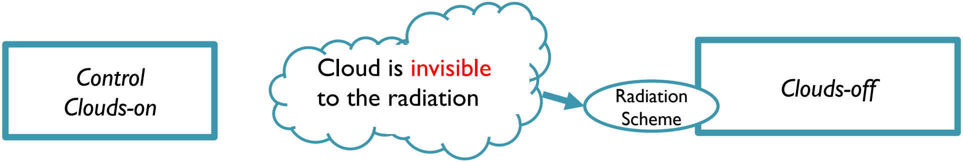

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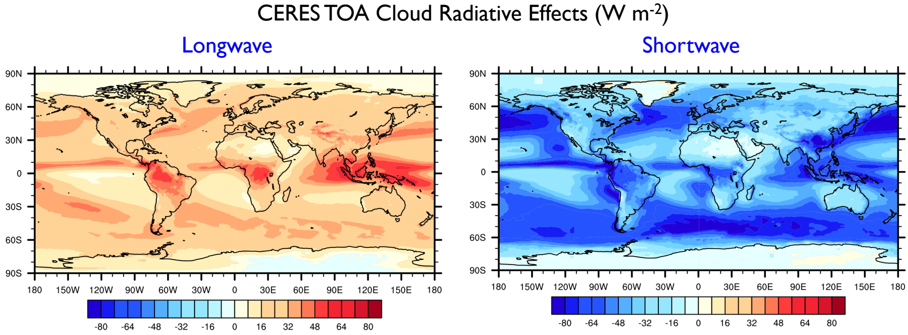
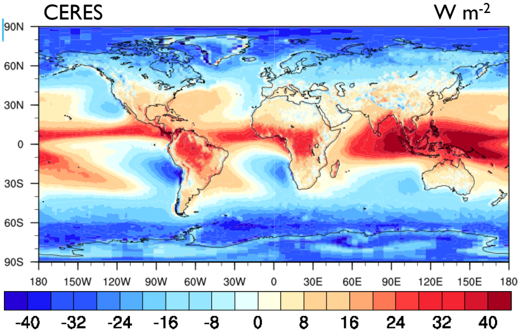
Why are atmospheric CRE (ACRE) important? Net CRE on the Earth's radiation budget is near zero



ACRE show strong equator-to-pole gradients



- $ACRE = CRE_{TOA} - CRE_{SFC}$
- Dominated by LW component

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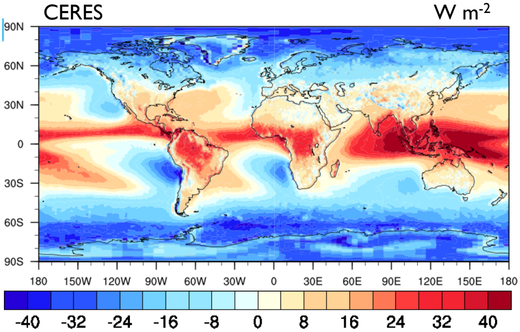


imum at the equator and minima at the poles. The outgoing infrared radiation, however, is only weakly latitude dependent. Thus, there is a net radiation surplus in the equatorial region and a deficit in the polar region. This differential heating warms the equatorial atmosphere relative to higher latitudes and creates a pole-to-equator temperature gradient. Hence it produces a growing store of zonal-mean available potential energy. At some point the westerly thermal wind (which must

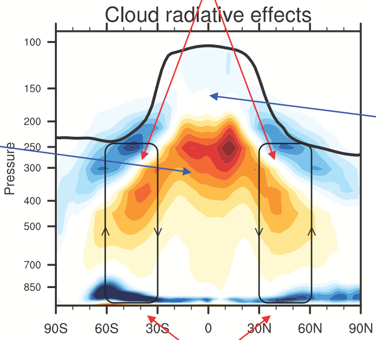
From *Holton* (2014) P. 315

- $ACRE = CRE_{TOA} - CRE_{SFC}$
- Dominated by LW component

Impacts of ACRE on the zonal-mean tropospheric circulation

Increases in baroclinicity in the extratropical upper troposphere lead to enhanced eddy kinetic energy, larger poleward eddy heat fluxes, and larger eastward eddy momentum forcing.

Radiative warming in the tropics is primarily balanced by less latent heating and thus reductions in precipitation.

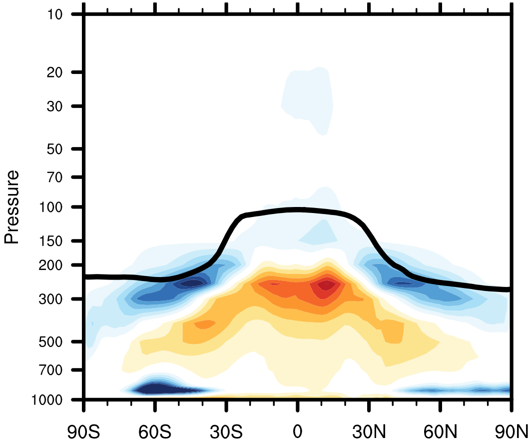


Zonally asymmetric heating in the upper tropical troposphere leads to larger amplitude equatorial waves and eastward flow centered about the Equator.

Changes in eddy momentum forcing aloft lead to decreases in subtropical precipitation juxtaposed against increases in midlatitude precipitation.

From *Li, Thompson & Bony JCLI, (2015)*

Impacts of ACRE on the zonal-mean stratospheric circulation



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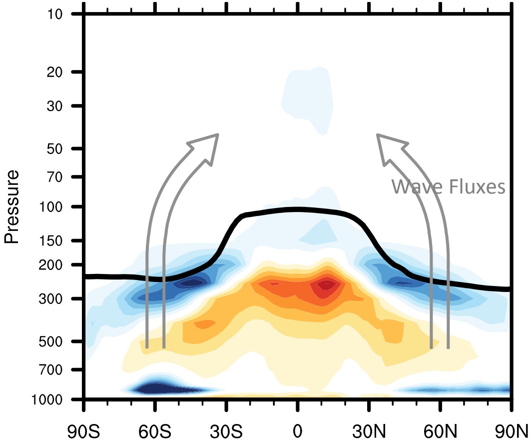

Increased wave fluxes in extratropical stratosphere

From *Li, Thompson & Huang JCLI, (2017)*

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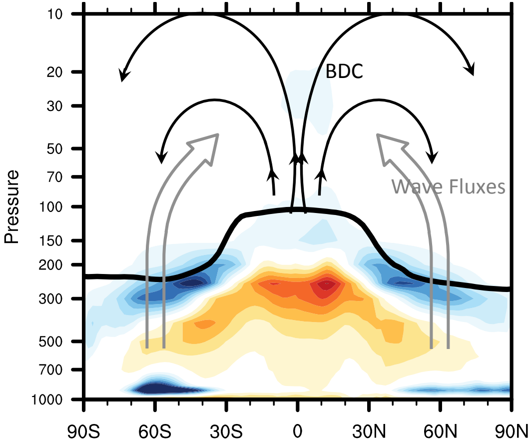

Increased wave fluxes in extratropical stratosphere

↓

Strengthening of BDC

From *Li, Thompson & Huang JCLI, (2017)*

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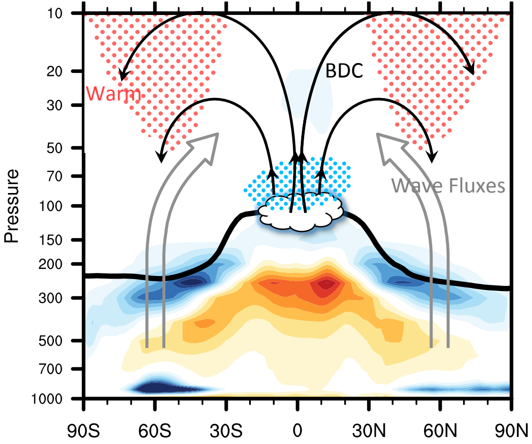

Increased wave fluxes in extratropical stratosphere

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Strengthening of BDC

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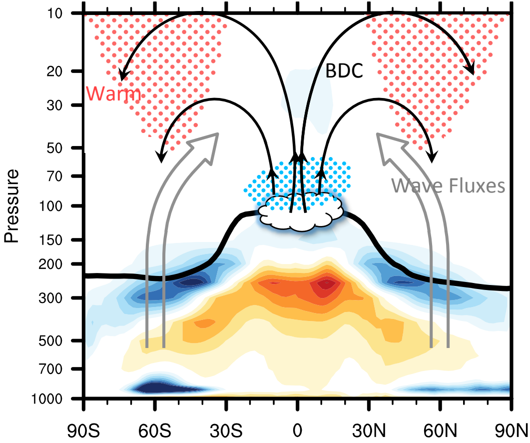
Cooling of the tropical lower stratosphere

Weakening and warming of the polar vortex

From *Li, Thompson & Huang JCLI, (2017)*

Impacts of ACRE on the zonal-mean stratospheric circulation



Increased wave fluxes in extratropical stratosphere

↓

Strengthening of BDC

↓

Cooling of the tropical lower stratosphere

Weakening and warming of the polar vortex

More disturbed stratosphere polar vortex

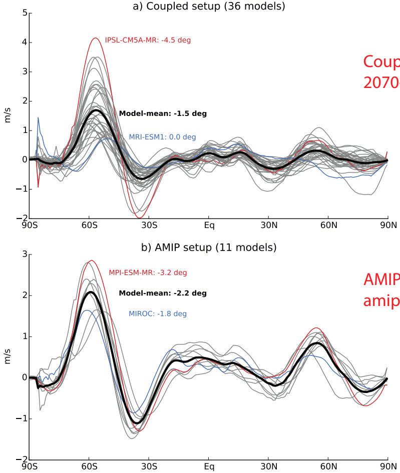
↓

Shorter persistence of stratosphere flow

From *Li, Thompson & Huang JCLI, (2017)*

Role of clouds on the circulation responses to climate change

Considerable spread in the magnitude of future jet shifts in CMIP5 models across a hierarchy of setups



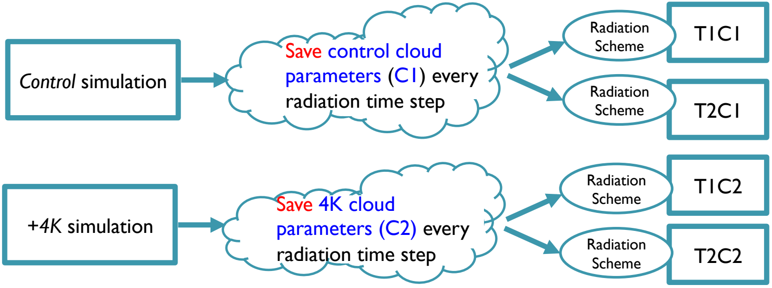
Coupled set-up
2070-2099 (RCP8.5) – 1979-2005(historical)

AMIP set-up
amip4K – amip

From *Voigt and Shaw JCLI, (2016)*

- Recent studies suggest that a substantial part of these uncertainties are caused by CRE.

Cloud-locking simulations are used in studying the role of clouds on the circulation responses to global warming



$$\Delta X = X_{+4K} - X_{CTL} \approx X_{T2C2} - X_{T1C1}$$

$$\boxed{\Delta X = \Delta X_{SST} + \Delta X_{Clouds}}$$

$$\Delta X_{SST} = 0.5x[(X_{T2C2} - X_{T1C2}) + (X_{T2C1} - X_{T1C1})]$$

$$\Delta X_{Clouds} = 0.5x[(X_{T1C2} - X_{T1C1}) + (X_{T2C2} - X_{T2C1})]$$

- interactive-SST: via modulating *SST* and surface baroclinicity through SW cloud feedbacks (Ceppi and Hartmann 2016, Ceppi and Hartmann 2017)
- non-interactive-SST: via modulating *Ta* through LW cloud feedbacks (Voigt and Shaw 2015; Voigt and Shaw 2016)

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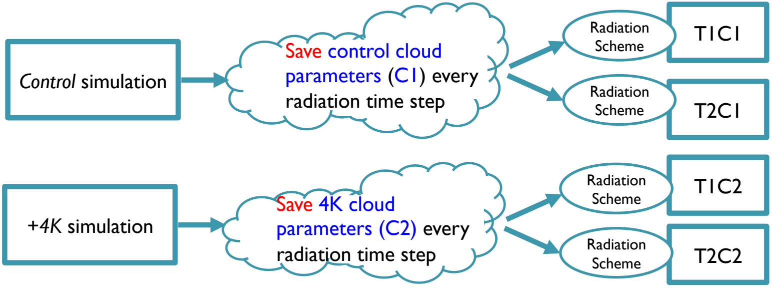

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COOKIE simulations are used in studying the role of clouds on the circulation responses to global warming

"clouds-on"		"clouds-off"
4K "T2A2"		4K "T2A0"
−		−
Control "T1A1"		Control "T1A0"
=		=
4K–Control with ACRE "T2A2 − T1A1"	−	4K–Control without ACRE "T2A0 − T1A0"

Δ = 4K–Control with ACRE "T2A2 − T1A1" − 4K–Control without ACRE "T2A0 − T1A0"

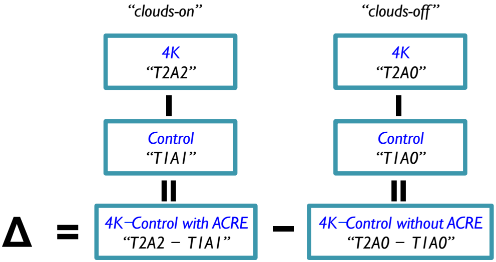
$$\boxed{\Delta = \Delta ACRE + \Delta ACRE*}$$

$$\Delta ACRE = \frac{1}{2}[(T2A2 - T2A1) + (T1A2 - T1A1)]$$

$$\Delta ACRE* = \frac{1}{2}[(T2A2 - T1A2) + (T2A1 - T1A1)] - (T2A0 - T1A0)$$

- $\Delta ACRE$: due to the effects of warming-induced changes in ACRE on the circulation responses to warming.
- $\Delta ACRE*$: due to the effect of ACRE on base state climatology which, in turn influences the response to warming.

COOKIE simulations are used in studying the role of clouds on the circulation responses to global warming



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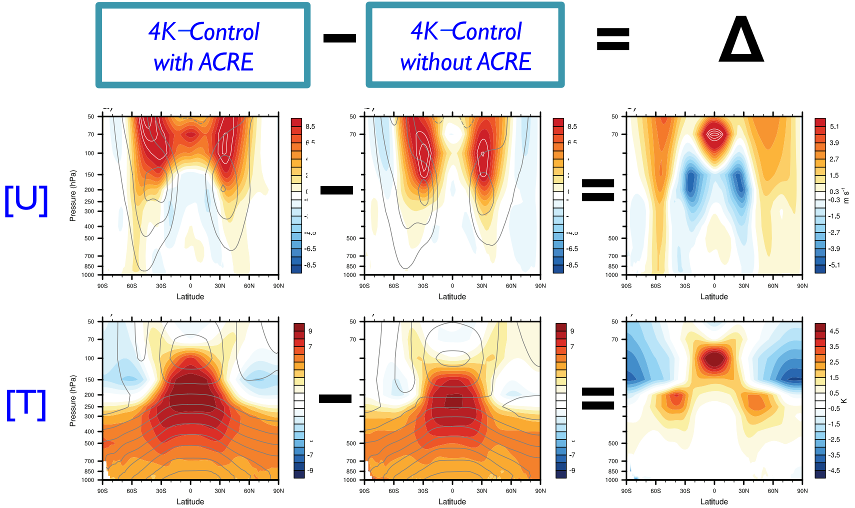
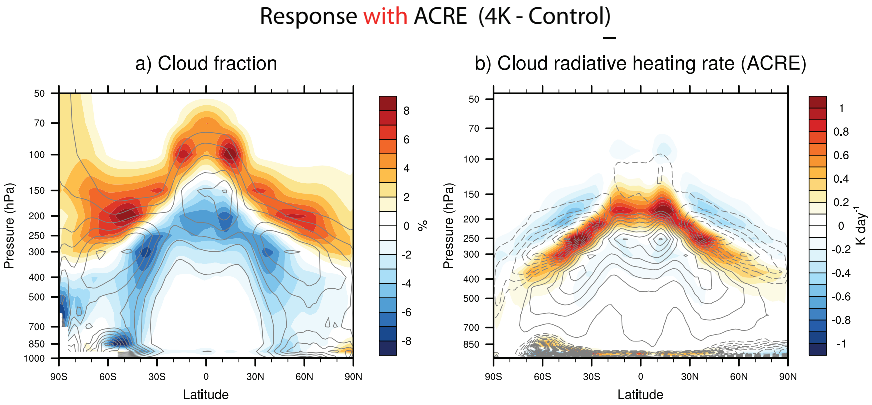


From *Li, Thompson, Bony & Merlis, JCLI 2019*

With ACRE,

- the magnitude of the poleward jet shift in response +4K is larger.
- dT/dy in the upper troposphere is also much larger.

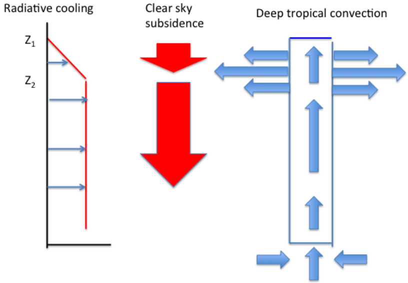
Changes in clouds and ACRE under warming mainly consist of systematic global lifting



From *Li, Thompson, Bony & Merlis, JCLI 2019*

- The vertical shifts in both fields are evidenced as vertical dipoles in the differences.

The vertical shift of clouds is consistent with the Fixed Anvil Temperature (FAT)



courtesy Issac Held

FAT has been applied specifically to the case of tropical anvil cloud height and amount

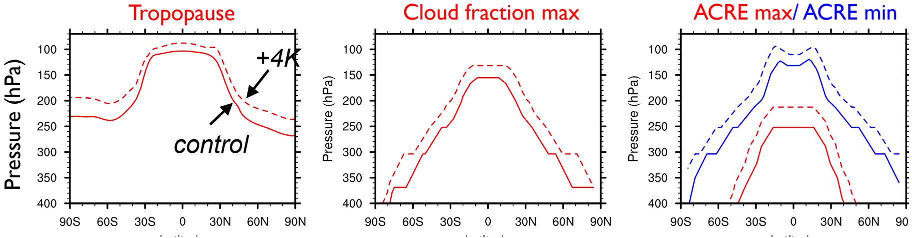
Hartmann & Larson 2002
Zelinka & Hartmann 2010

But ... FAT-physics should hold globally

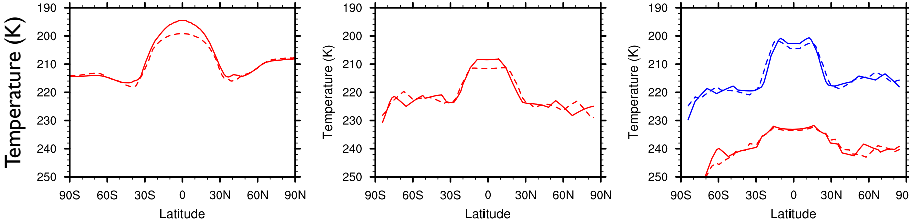
Thompson, Bony & Li, PNAS 2017
Thompson, Ceppi & Li, JCLI 2019

Vertical shifting of various fields

moves to lower pressure,

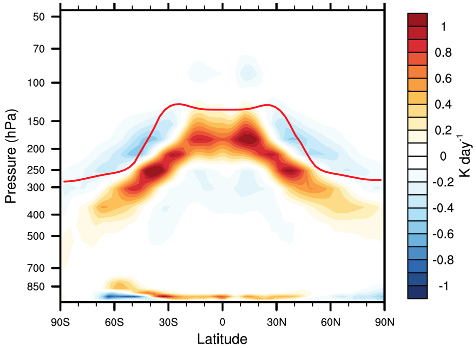


, but stay at roughly the same temperature



From *Li, Thompson, Bony & Merlis, JCLI 2019*

Hypothesis of how warming-induced changes in ACRE can affect poleward jet shift



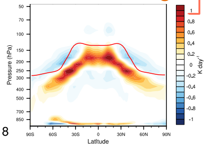
From *Li, Thompson, Bony & Merlis, JCLI 2019*

meridional slope of tropopause
$\rightarrow$ meridional slope of radiative warming from the rising clouds
$\rightarrow$ 1) increase in the upper tropospheric temperature gradient
2) weaken (enhance) the static stability in the extratropics (tropics).
$\rightarrow$ enhanced poleward jet shift

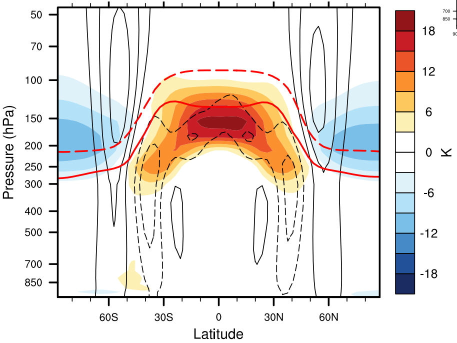
Hypothesis is tested in idealized dry GCM simulations

$$\frac{\partial T}{\partial t} = dry\ dynamics - K_T[T - T_{eq}(\phi, p)] + \frac{\partial T(\phi, p)}{\partial t}$$

Thermal forcing



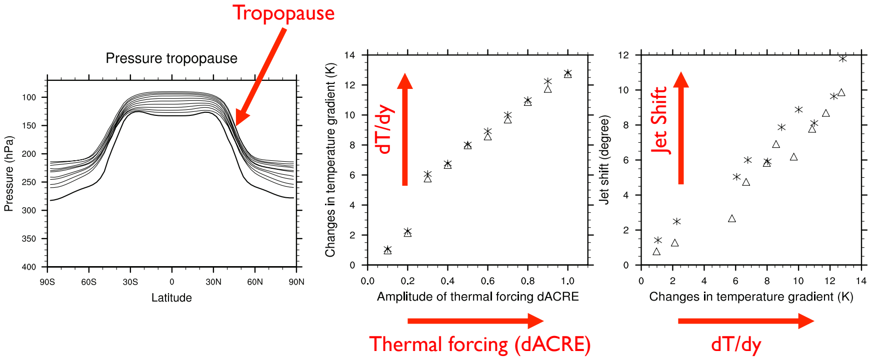
Circulation response [U] and [T]



From *Li, Thompson, Bony & Merlis, JCLI 2019*

Linear relationship is found between the amplitude of radiative forcing and the jet shift

The amplitude of the radiative forcing is multiplied by 0.1, 0.2, ... 0.9.



From *Li, Thompson, Bony & Merlis, JCLI 2019*

The larger the amplitude of the radiative forcing,
→ the larger the increases in the tropopause height,
→ the larger dT/dy in the upper troposphere, and
→ the larger the poleward shift of the jet.

Key message so far ...

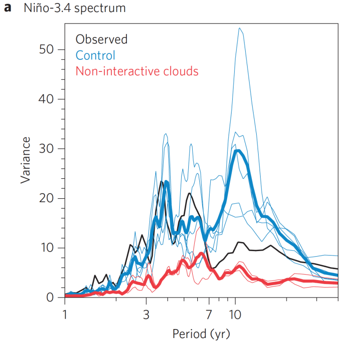
- Magnitude of the jet shift under climate change is substantially increased in simulations run with ACRE.

- Poleward jet shift can be viewed as another robust thermodynamically constrained response to climate change.

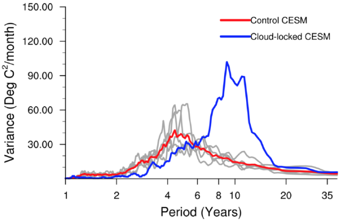
Li, Thompson, Bony & Merlis, J. Climate, 2019

Role of clouds on the tropical climate variability

Cloud radiative feedbacks on the ENSO amplitude – different results in two recent studies



- From *Radel et al., Nat. Geo, 2016*
- ENSO variability is enhanced across all timescales



- From *Middlemas et al., JCLI 2019*
- ENSO variability is enhanced on timescales shorter than 6 years, but reduced on timescales longer than that

Cloud-locking simulations

Control
"*interactive-clouds*" run
(250-yr)

Save various cloud parameters every 2 hours for 250 years

Scramble cloud fields by randoming the year but not the hour or day

"*locked-clouds*" run
(250-yr)

Every 2 hour radiation call

1. Clouds are prescribed and thus are decoupled from the circulation.
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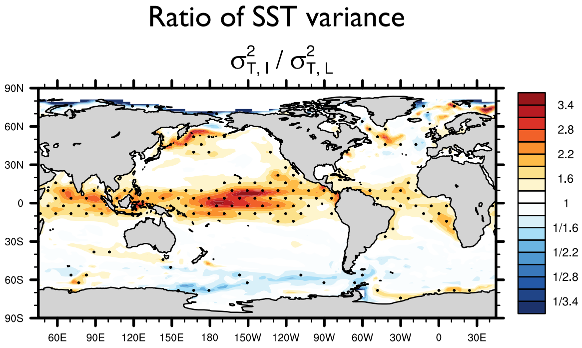
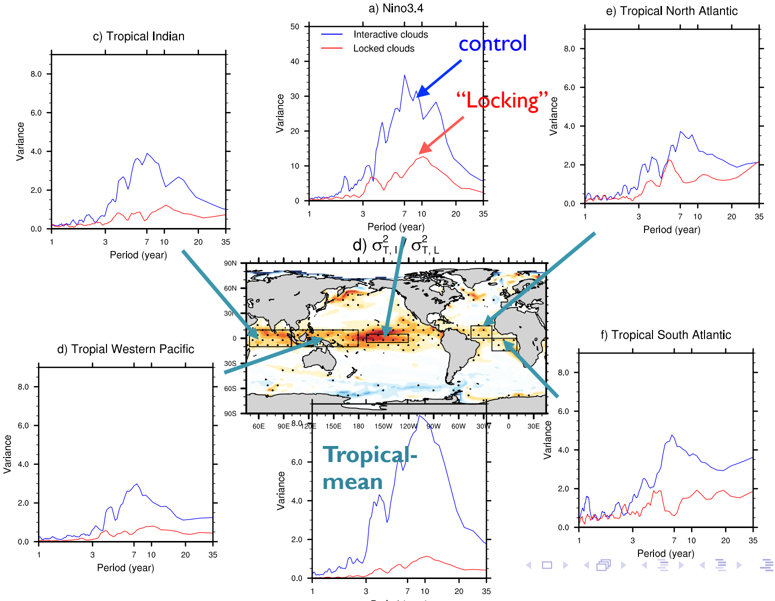
The influence of CRE on tropical SST variability

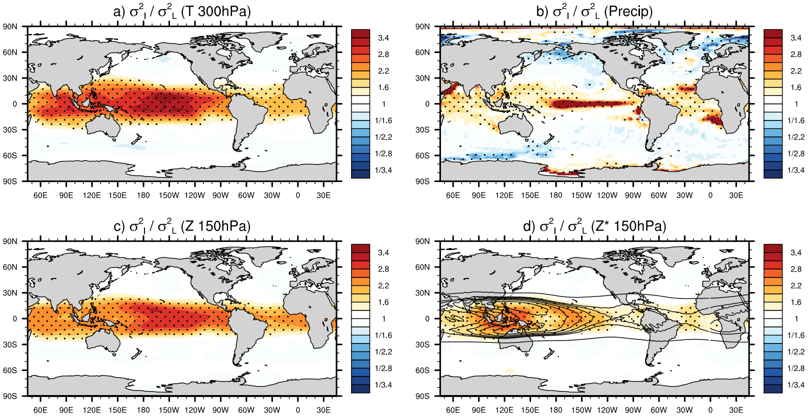


The variance in SST anomalies is increased not only over the eastern tropical Pacific, but throughout the tropical oceans.

Systematic wakening of the spectral power at all timescales for SST averaged over different tropical oceans



… and more general and widespread effect on the tropical climate variability



Role of CRE in driving SST (surface energy balance)

- The energy budget for the surface mixed layer of the ocean (in monthly-mean anomaly):

$$C_o \frac{\partial T'}{\partial t} = Q'_{SW} + Q'_{LW} + Q'_{LH} + Q'_{SH} + Q'_{EK} + Q'_{geo}, \tag{1}$$

- Taking the centered difference, square, and then time-mean of Eq. (1) yields:

$$\sigma_T^2 = \sigma_\Sigma^2 \cdot e \cdot G \tag{2}$$

  - $\sigma_\Sigma^2 = \sigma_{SW}^2 + \sigma_{LW}^2 + \sigma_{LH}^2 + \sigma_{SH}^2 + \sigma_{EK}^2 + \sigma_{geo}^2$ ("the variances factor")
  - $e = 1 + \frac{2\Sigma(cov(Q_i, Q_j))}{\sigma_\Sigma^2}$ ("the efficiency factor")
  - $G = \frac{2(\Delta t)^2}{C_o^2(1-r_1)}$ ("the persistence factor")

- The ratio of temperature variance between interactive and locking run:

$$\boxed{\frac{\sigma^2_{T\ \ interactive}}{\sigma^2_{T\ \ locked}} = \frac{\sigma^2_{\Sigma\ \ interactive}}{\sigma^2_{\Sigma\ \ locked}} \cdot \frac{e_{interactive}}{e_{locked}} \cdot \frac{G_{interactive}}{G_{locked}}}$$

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$$\boxed{\frac{\sigma_{T\ interactive}^2}{\sigma_{T\ locked}^2} = \frac{\sigma_{\Sigma\ interactive}^2}{\sigma_{\Sigma\ locked}^2} \cdot \frac{e_{interactive}}{e_{locked}} \cdot \frac{G_{interactive}}{G_{locked}}}$$

Role of CRE in driving SST (surface energy balance)

- The energy budget for the surface mixed layer of the ocean (in monthly-mean anomaly):

$$C_o \frac{\partial T'}{\partial t} = Q'_{SW} + Q'_{LW} + Q'_{LH} + Q'_{SH} + Q'_{EK} + Q'_{geo}, \tag{1}$$

- Taking the centered difference, square, and then time-mean of Eq. (1) yields:

$$\sigma_T^2 = \sigma_\Sigma^2 \cdot e \cdot G \tag{2}$$

  - $\sigma_\Sigma^2 = \sigma_{SW}^2 + \sigma_{LW}^2 + \sigma_{LH}^2 + \sigma_{SH}^2 + \sigma_{EK}^2 + \sigma_{geo}^2$ ("the variances factor")
  - $e = 1 + \frac{2\Sigma(cov(Q_i, Q_j))}{\sigma_\Sigma^2}$ ("the efficiency factor")
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$$\boxed{\frac{\sigma^2_{T\ \ interactive}}{\sigma^2_{T\ \ locked}} = \frac{\sigma^2_{\Sigma\ \ interactive}}{\sigma^2_{\Sigma\ \ locked}} \cdot \frac{e_{interactive}}{e_{locked}} \cdot \frac{G_{interactive}}{G_{locked}}}$$

Scaling the changes of SST variance $\frac{\sigma^2_{T\ interactive}}{\sigma^2_{T\ locked}}$

$$
\begin{aligned}
\frac{\sigma^2_{T\ interactive}}{\sigma^2_{T\ locked}} &= \frac{\sigma^2_{\Sigma\ interactive}}{\sigma^2_{\Sigma\ locked}} \cdot \cancel{\frac{e_{interactive}}{e_{locked}}} \cdot \cancel{\frac{G_{interactive}}{G_{locked}}} \\
&\approx \frac{\sigma^2_{\Sigma\ interactive}}{\sigma^2_{\Sigma\ locked}} \\
&\approx \frac{\sigma^2_{\Sigma\ interactive}}{(\cancel{\sigma^2_{SW}} + \cancel{\sigma^2_{LW}} + \sigma^2_{LH} + \sigma^2_{SH} + \sigma^2_{EK} + \sigma^2_{geo})_{locked}} \\
&\approx \frac{\sigma^2_{\Sigma\ interactive}}{(\sigma^2_{LH} + \sigma^2_{SH} + \sigma^2_{EK} + \sigma^2_{geo})_{interactive}} \\
&\approx \frac{1}{1 - (\frac{\sigma^2_{SW}}{\sigma^2_{\Sigma}} + \cancel{\frac{\sigma^2_{LW}}{\sigma^2_{\Sigma}}})_{interactive}} \\
&\approx \frac{1}{1 - (\frac{\sigma^2_{SW}}{\sigma^2_{\Sigma}})_{interactive}}
\end{aligned}
$$

- The changes in σ^2_T is related to the changes in σ^2_{Σ} between the interactive and locked simulations.
- The changes in σ^2_{Σ} should peak over regions where $\frac{\sigma^2_{SW}}{\sigma^2_{\Sigma}}$ is largest in the interactive simulation.

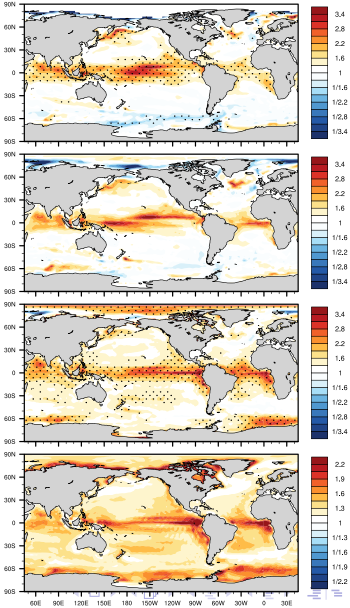
Quantify the contributions to $\frac{\sigma^2_{T\ \ interactive}}{\sigma^2_{T\ \ locked}}$

$$\frac{\sigma^2_{T\ \ interactive}}{\sigma^2_{T\ \ locked}}$$

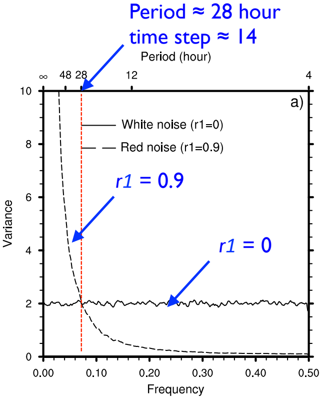
$$= \frac{\sigma^2_{\Sigma\ \ interactive}}{\sigma^2_{\Sigma\ \ locked}} \cdot \frac{e_{interactive}}{e_{locked}} \cdot \frac{G_{interactive}}{G_{locked}}$$

$$\approx \frac{\sigma^2_{\Sigma\ \ interactive}}{\sigma^2_{\Sigma\ \ locked}}$$

$$\approx \frac{1}{1 - \left(\frac{\sigma^2_{SW}}{\sigma^2_{\Sigma}}\right)_{interactive}}$$

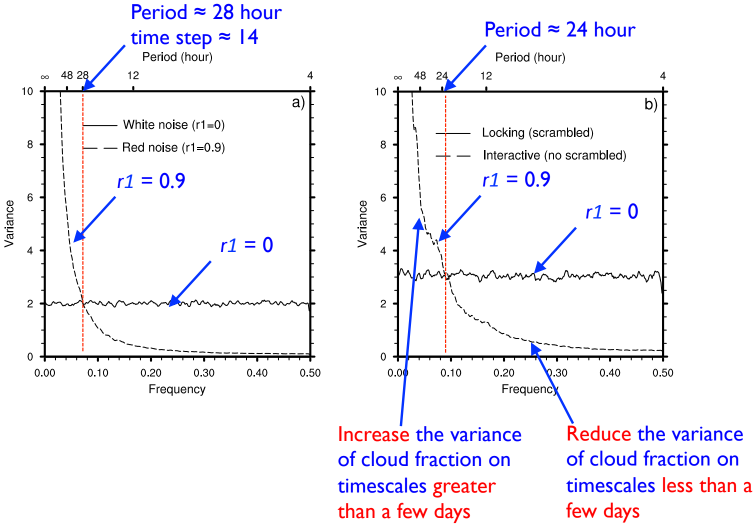


The effect of autocorrelation on the power spectra



- The basic effect of two-way coupling between clouds and the atmospheric circulation is to increase the variance of CRE on timescales longer than a few days

The effect of autocorrelation on the power spectra



- The basic effect of two-way coupling between clouds and the atmospheric circulation is to increase the variance of CRE on timescales longer than a few days

Key message so far ...

- CREs play a much more basic role in governing the variance of SSTs and climate variability throughout the tropics than that indicated in previous studies.

Li, Thompson & Olonscheck, submitted

What have we learned? Where should we go from here?

- Cloud-Radiative effects are critical not only for climate sensitivity, but also for :
  - the mean circulation in the tropics, extratropics, and stratosphere
  - the circulation response to climate change
  - the tropical climate variability
- Continue efforts are needed:
  - understanding the role of clouds in atmosphere-ocean interaction
  - understanding the role of clouds in extratropical subseasonal-to-seasonal variability

Thanks for your attention!

Questions?

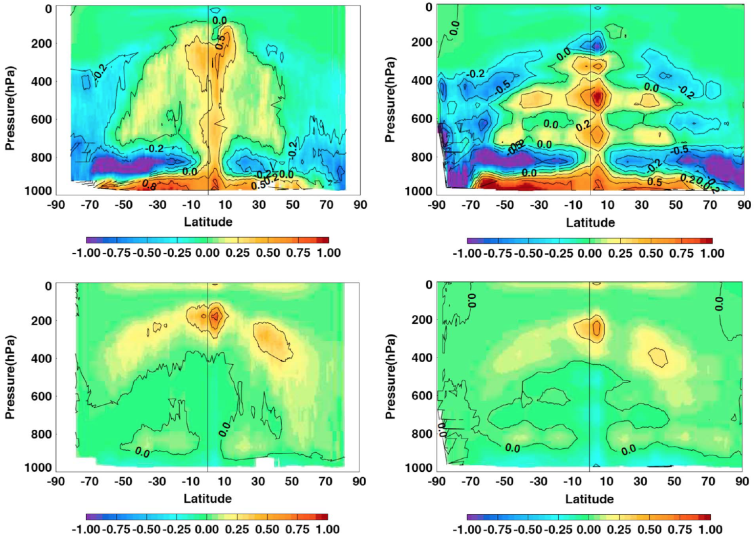
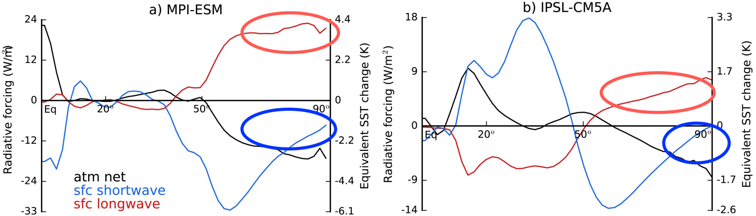


Figure 8. Profile of cloud radiative effect (all-sky values minus clear-sky values) due to (top) longwave and (bottom) shortwave irradiances in K day^{-1}. The heating rate is computed in 24 layers in the atmosphere. Left plots are computed with CALIPSO, CloudSat, and Moderate Resolution Imaging Spectroradiometer (CCCM), and right plots are computed using passive sensor only (SYN1deg-Month). April 2010 data are used for the plots.

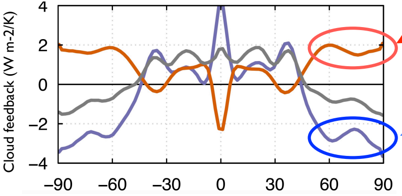
From *Kato et al., JGR 2019*

Competition between SW and LW radiative forcing at the surface

Voigt and Shaw JCLI,2016



Ceppi and Hartmann JCLI,2016



Surface LW
Due to increase in cloud fraction
(enhanced DW LW radiation cools the lower atmosphere but warms the surface

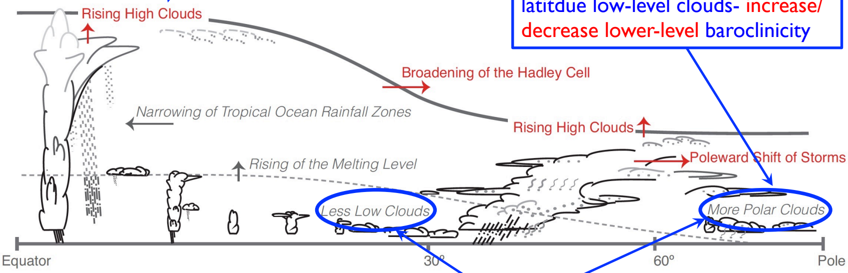
Surface SW
Due to cloud phase from ice to liquid
(increased albedo)

The outcome of net effect may be model and seasonal dependent.

So the amplitude of jet shift to warming is uncertain and probably model-dependent

longwave atmospheric cloud radiative changes due to rising high clouds - increase upper-level baroclinicity

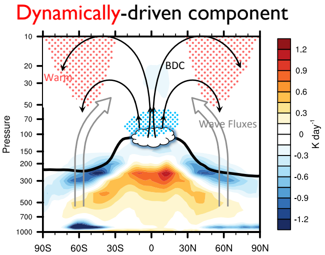
longwave atmospheric cloud radiative changes due to high-latitdue low-level clouds- increase/ decrease lower-level baroclinicity



shortwave surface cloud radiative changes →increase surface baroclinicity

longwave surface cloud radiative changes →decrease surface baroclinicity

Impact of ACRE on the stratospheric circulation - dynamically driven



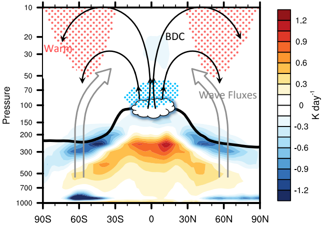
By modulating the fluxes of wave activity both into the lower stratosphere and within the stratosphere, inclusion of ACRE leads to

- strengthening of the BDC
- cooling of the tropical lower stratosphere
- weakening and warming of the polar vortex

From *Li, Thompson and Huang, JCLI, 2017*

Impact of ACRE on the stratospheric circulation - dynamically driven

Dynamically-driven component



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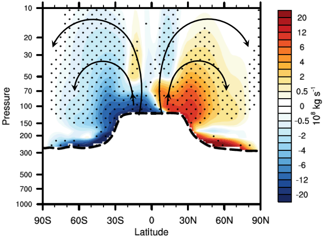
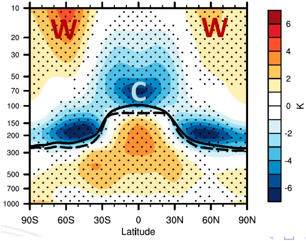
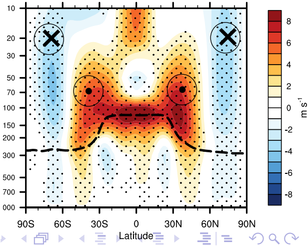
Impact of atmospheric cloud radiative effect on residual mass circulation



Impact of atmospheric cloud radiative effect on temperature

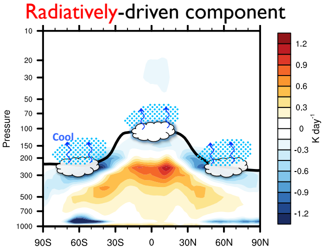


Impact of atmospheric cloud radiative effect on zonal wind



From *Li, Thompson and Huang, JCLI, 2017*

Impact of atmospheric cloud-radiative effects (ACRE) on the stratospheric circulation - radiatively driven

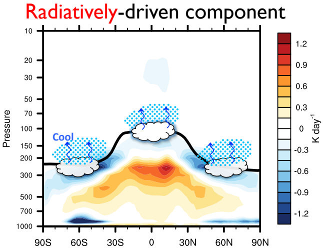


By modulating the flux of longwave radiation into the lower stratosphere, inclusion of ACRE leads to

- cooling of the extratropical lower stratosphere
- changes in the static stability
- increases in cloud fraction near the extratropical tropopause

From Li, Thompson and Huang, JCLI, 2017

Impact of atmospheric cloud-radiative effects (ACRE) on the stratospheric circulation - radiatively driven



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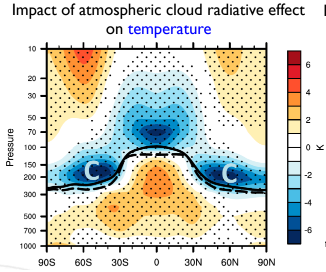
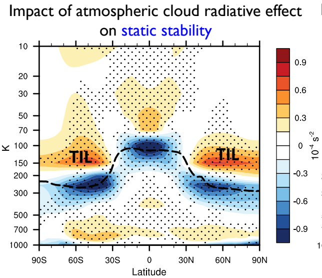
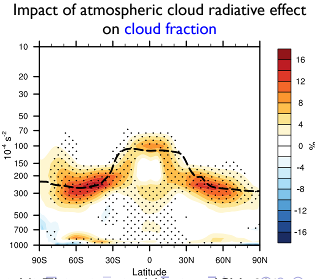


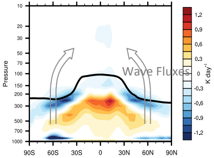




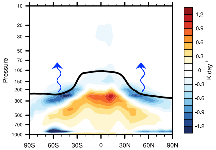
From *Li, Thompson and Huang, JCLI, 2017*

The shorter time scale of the extratropical stratospheric circulation in the clouds-on experiment are consistent with both the **dynamic** and **radiative** components of the responses

Dynamically - driven



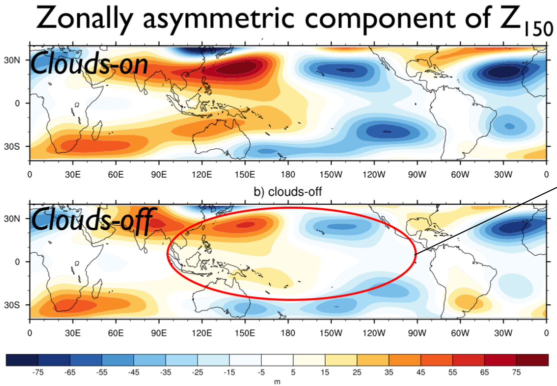
Increases in the flux of wave activity → More disturbed stratospheric polar vortex → Shorter persistence of stratospheric flow



Increases in upward LW emission → Enhance the local radiative cooling rate → Shorter local radiative damping timescales → Shorter persistence of stratospheric flow

Radiatively - driven

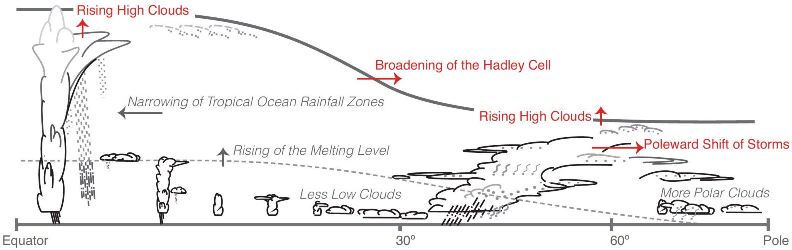
Influence of ACRE on EPW and tropical circulation



weaker off-equatorial ridges and troughs

From *Li, Thompson and Bony, JCLI 2015*

Observations and climate models suggest extratropical eddy driven jet and storm tracks shift poleward in a warmer climate



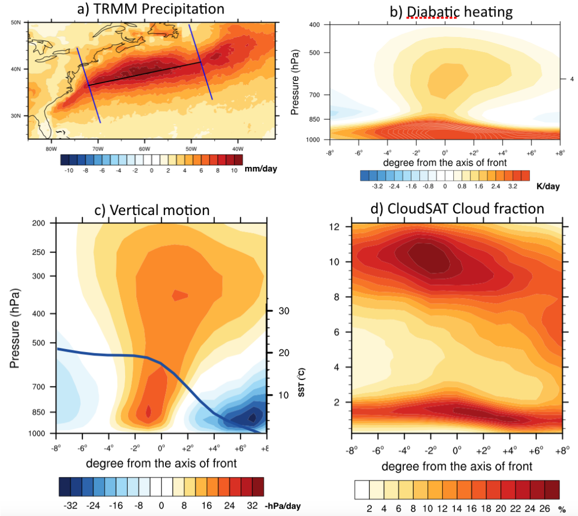
"Observations and most models suggest storm tracks shift poleward in a warmer climate ... which causes further positive feedback via a net shift in cloud cover to latitudes that receive less sunshine."

"The true amount of positive feedback coming from poleward shifts therefore remains highly uncertain ..."

From *Chapter 7, IPCC AR5*

Possibly due to the uncertainty in the amplitude of jet shift to warming.
Possibly due to the role of cloud-radiative processes.

Understanding the role of clouds in atmosphere-ocean interaction



Li and Thompson, in prepration

Quantify the contributions to $\frac{\sigma^2_{T\ interactive}}{\sigma^2_{T\ locked}}$

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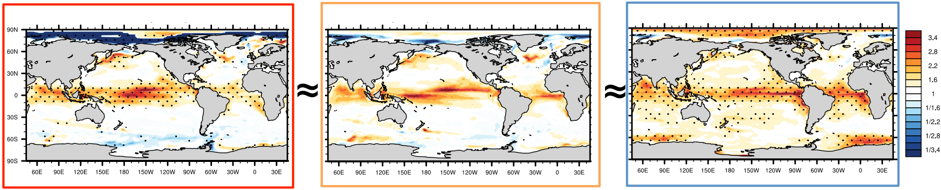
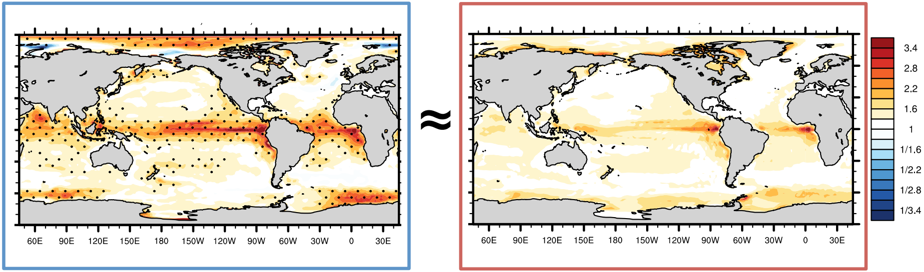


The simple scaling of $\frac{\sigma^2_{\Sigma\ \ interactive}}{\sigma^2_{\Sigma\ \ locked}}$

$$\frac{\sigma^2_{\Sigma\ \ interactive}}{\sigma^2_{\Sigma\ \ locked}} \approx \frac{\sigma^2_{\Sigma\ \ interactive}}{(\sigma^2_{LH}+\sigma^2_{SH}+\sigma^2_{EK}+\sigma^2_{geo})_{interactive}} \approx \frac{1}{1-(\frac{\sigma^2_{SW}}{\sigma^2_{\Sigma}})_{interactive}}.$$



1. Cloud-locking acts to substantially reduce the σ^2_{SW} and σ^2_{LW} (see next slide)
2. σ^2_{SW} accounts for a relatively large fraction of total energy flux variance, and thus matter most for SSTs in the deep tropics

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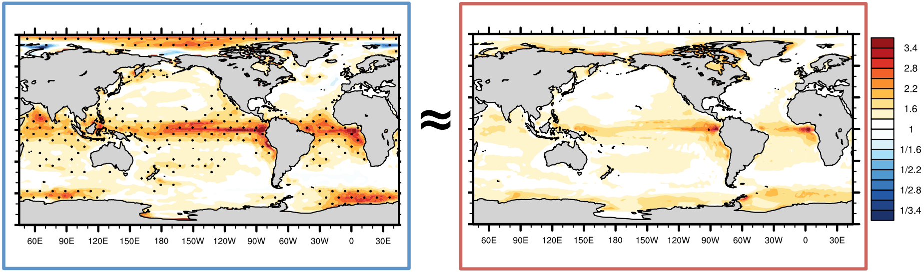

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