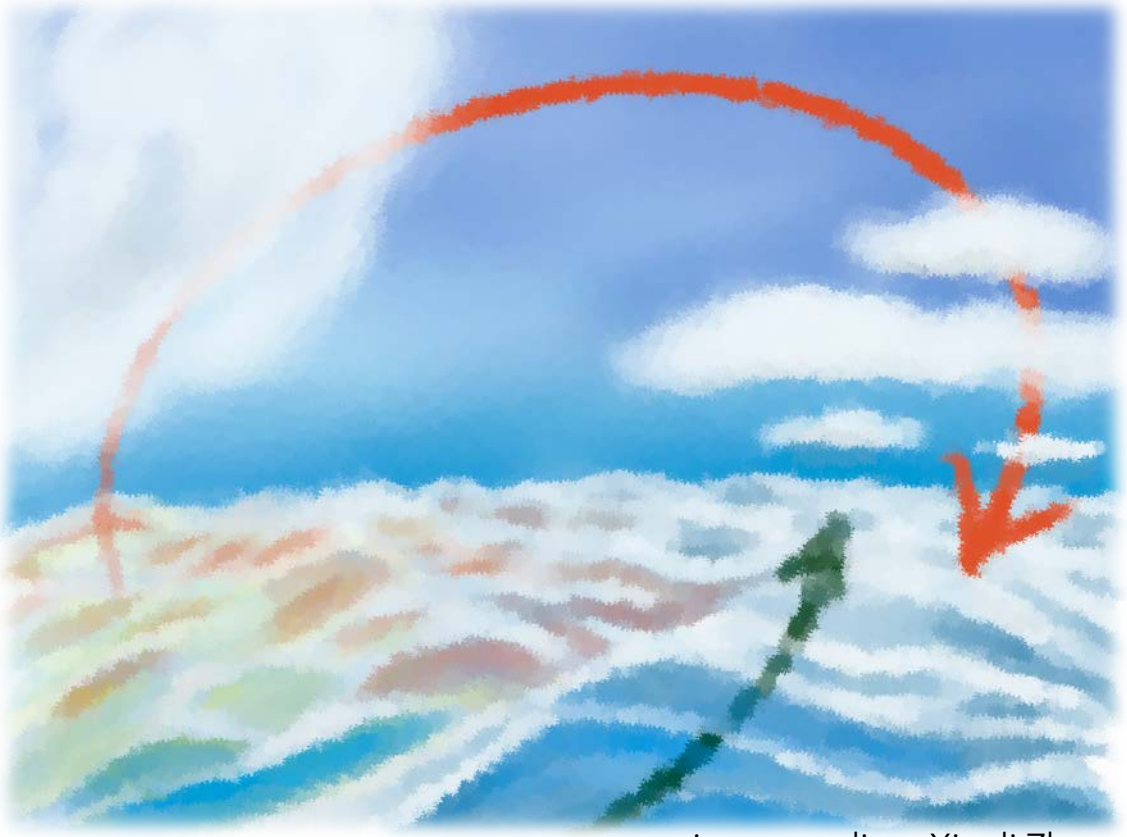
Mechanisms of the non-constancy of radiative feedbacks

Yue Dong
Columbia University

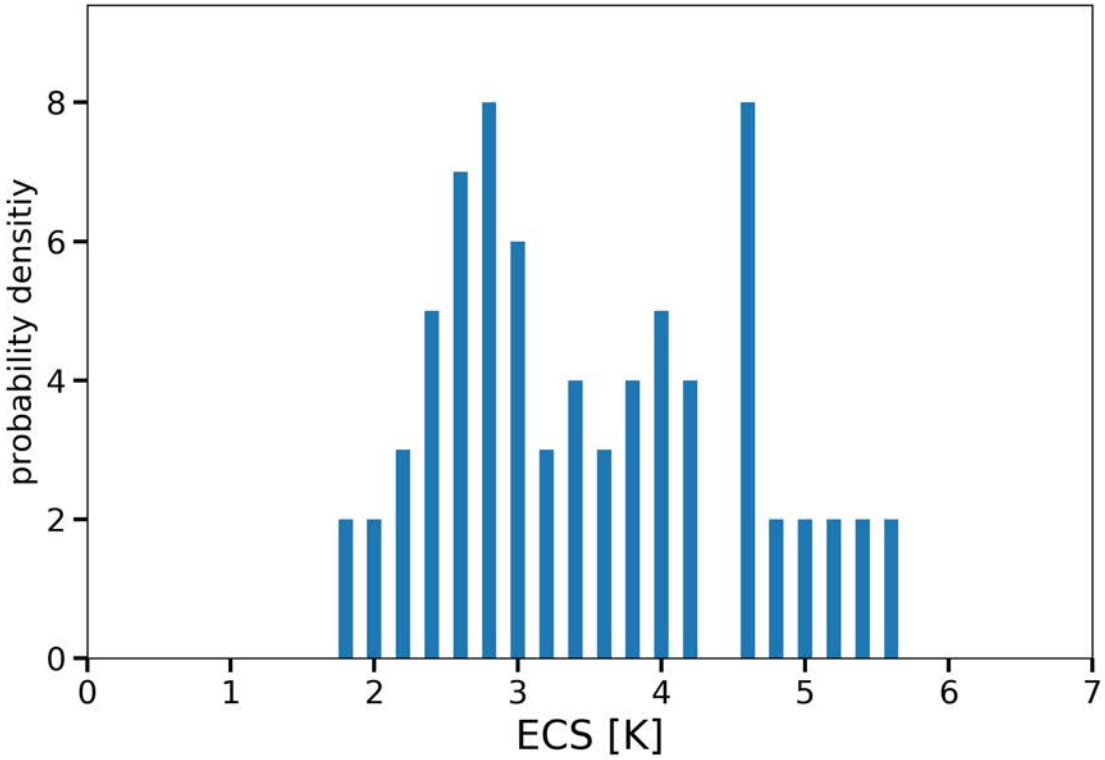


picture credit to Xiaoli Zhou

With input from
Kyle Armour (UW), Timothy Andrews (Met office),
Mark Zelinka (LLNL), Chen Zhou (Nanjing U),
Jonah Bloch-Johnson (U Reading), Yuan-Jen Lin (NTU)

The Pattern Effect Workshop
May 2022

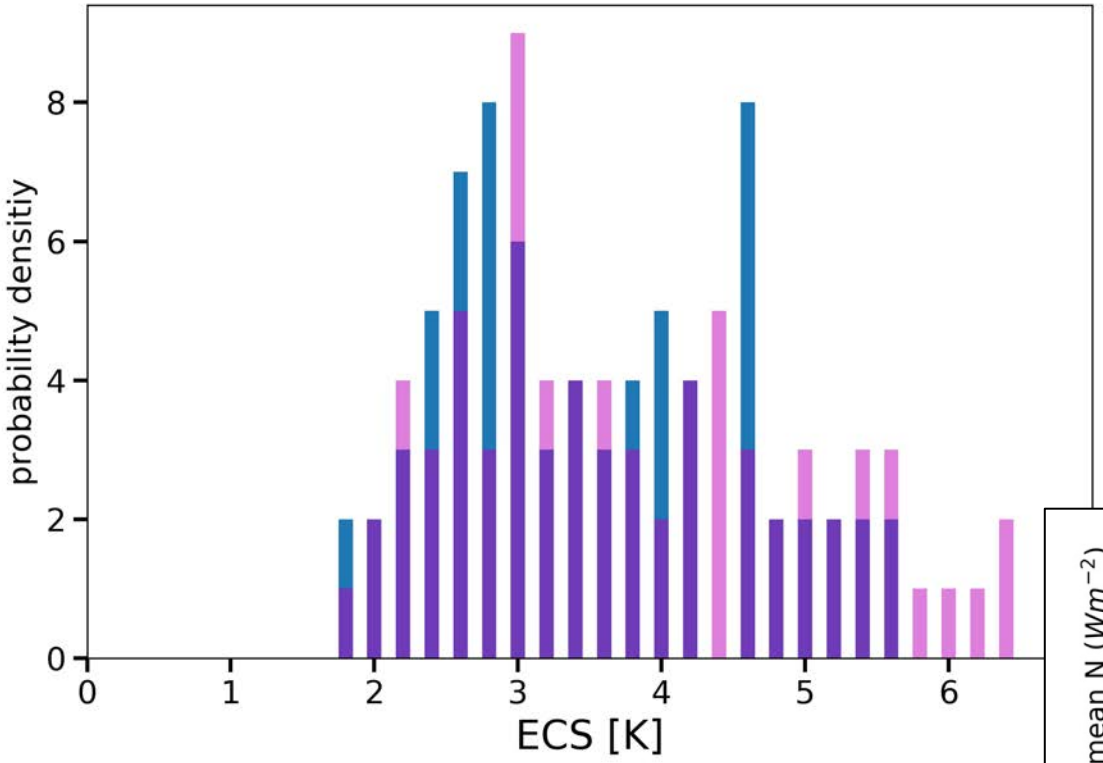
Discrepancies in ECS estimates due to the pattern effect



CMIP5+6 abrupt4xCO2
150yr-regression

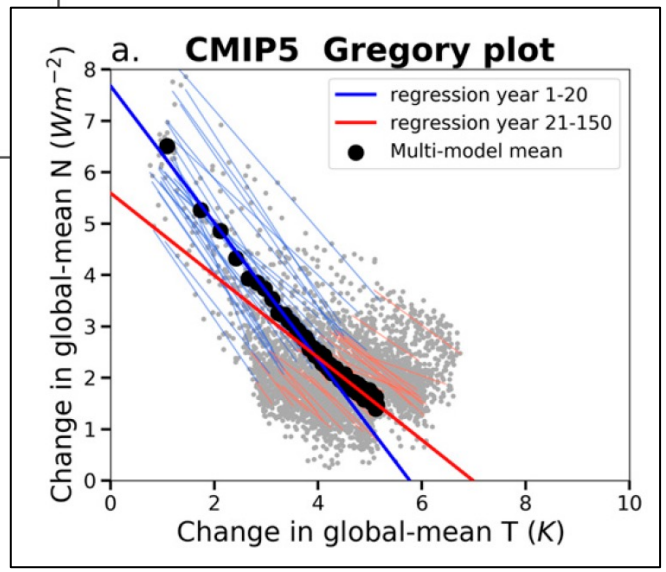
CMIP5+6 ECS (150yr): Zelinka et al. 2020

Discrepancies in ECS estimates due to the pattern effect



CMIP5+6 abrupt4xCO2 150yr-regression

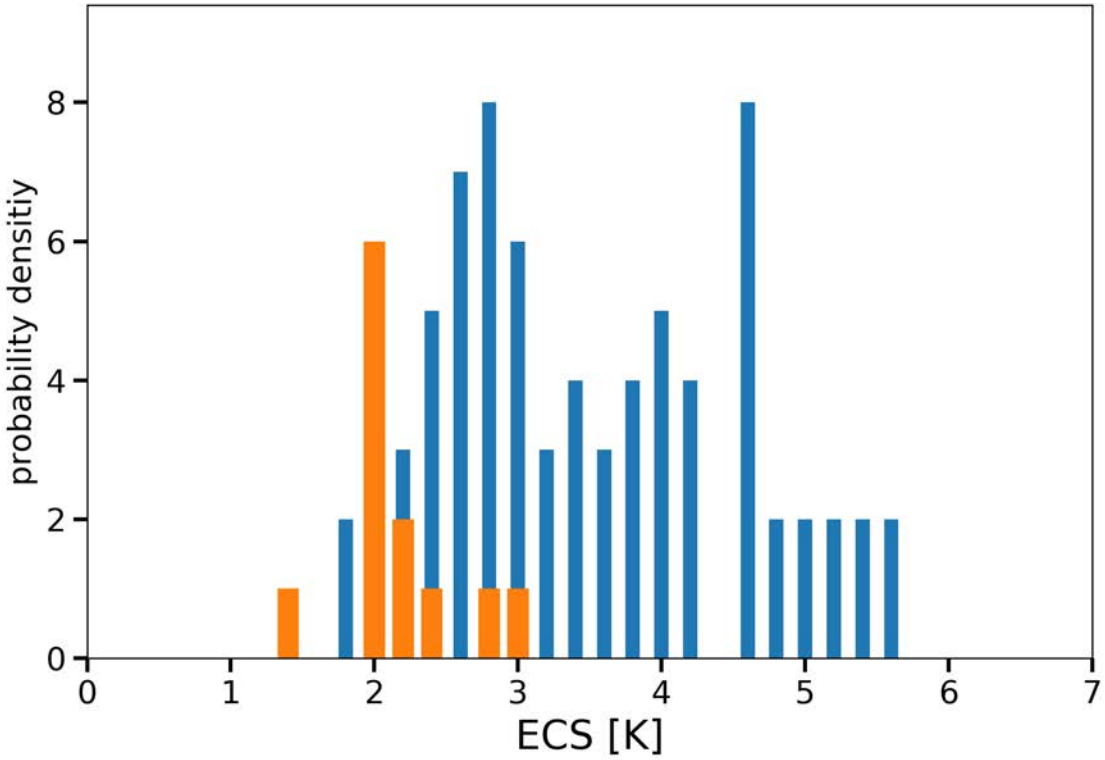
CMIP5+6 abrupt4xCO2 last130yr regression



Dong et al. 2020

CMIP5+6 ECS (130yr): Dong et al. 2020
CMIP5+6 ECS (150yr): Zelinka et al. 2020

Discrepancies in ECS estimates due to the pattern effect

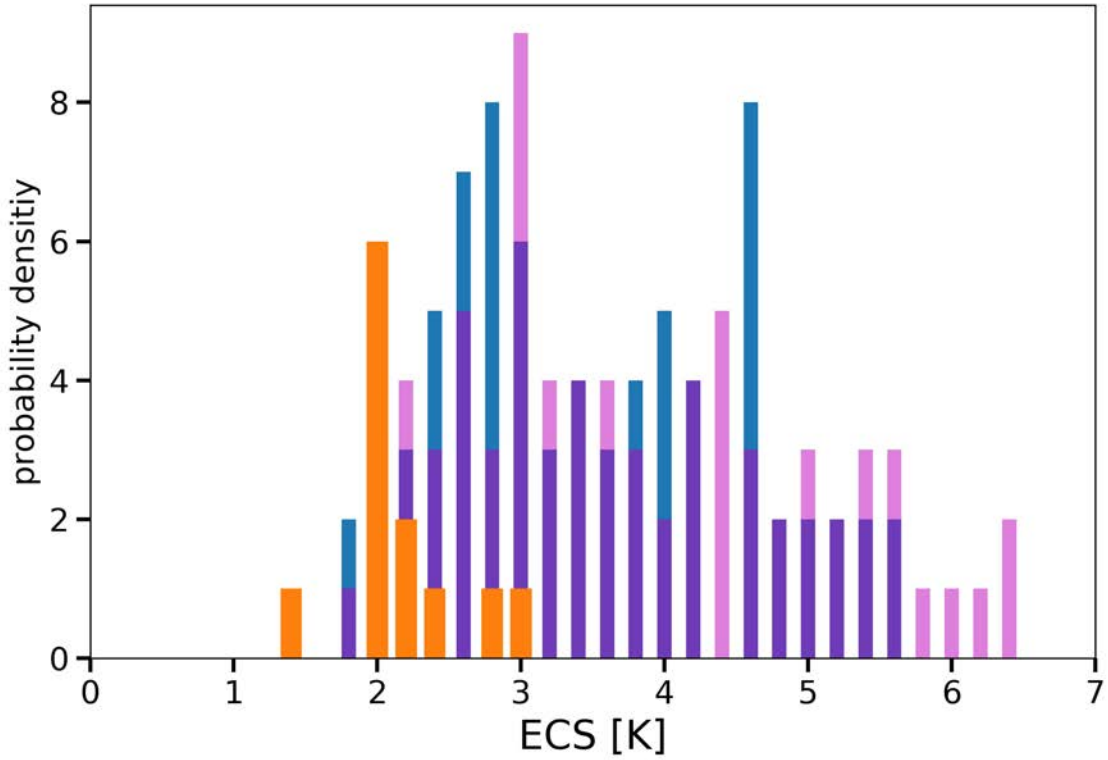


CMIP5+6 abrupt4xCO2
150yr-regression

AGCM forced observed SST/SIC
(amip-piForcing)

CMIP5+6 ECS (amipPF): Andrews et al. 2018; Dong et al. 2021
CMIP5+6 ECS (130yr): Dong et al. 2020
CMIP5+6 ECS (150yr): Zelinka et al. 2020

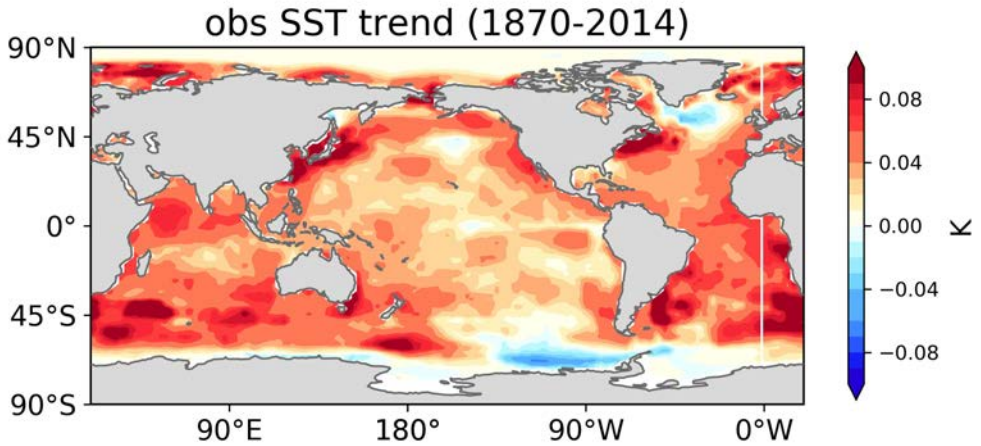
Discrepancies in ECS estimates due to the pattern effect

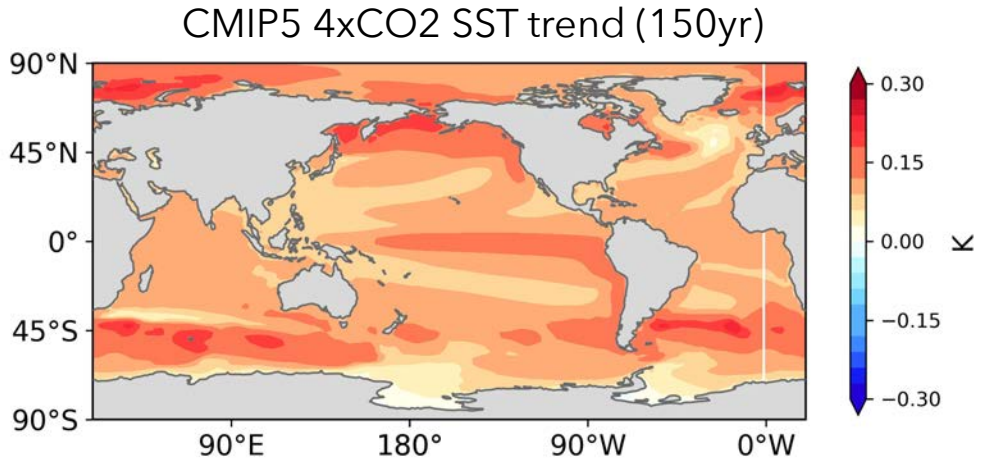


CMIP5+6 abrupt4xCO2 150yr-regression

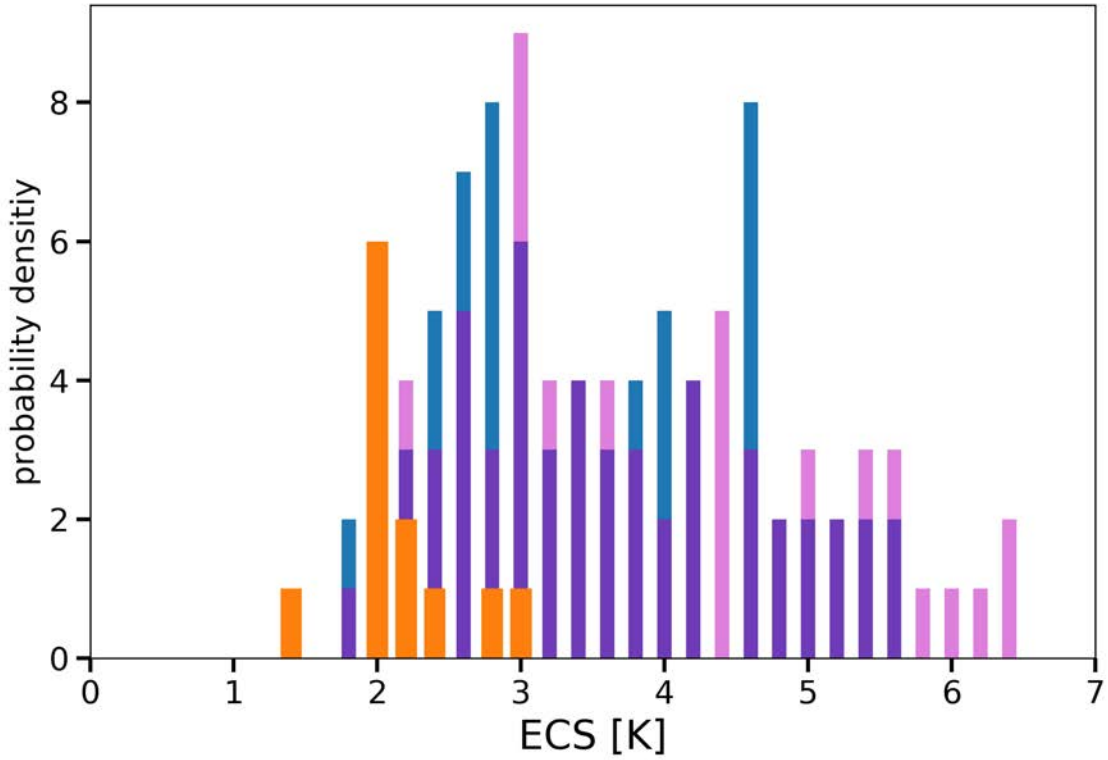
CMIP5+6 abrupt4xCO2 last130yr regression

AGCM forced observed SST/SIC (amip-piForcing)





Discrepancies in ECS estimates due to the pattern effect

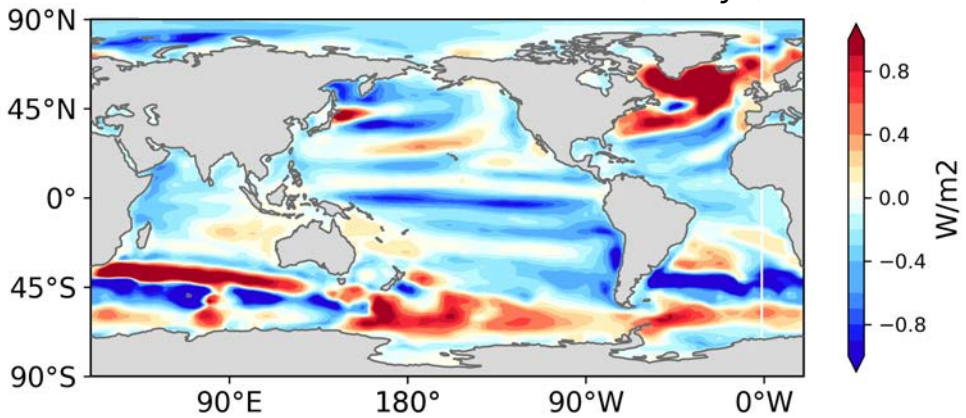


CMIP5+6 abrupt4xCO2 150yr-regression

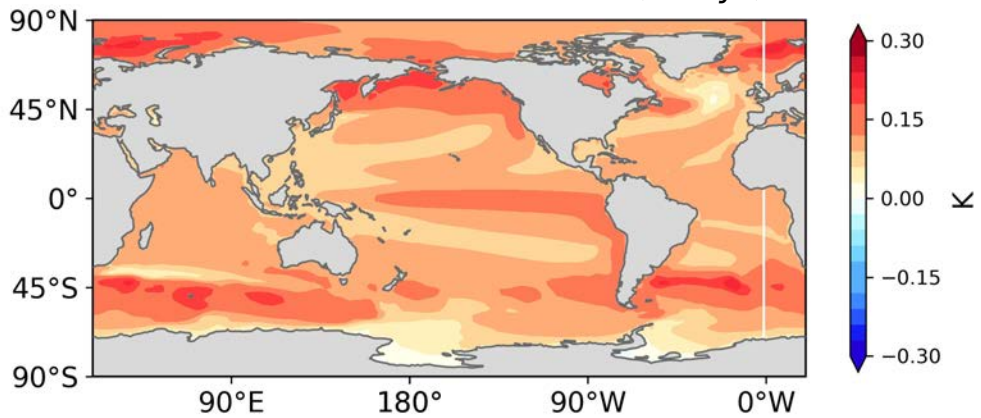
CMIP5+6 abrupt4xCO2 last130yr regression

AGCM forced observed SST/SIC (amip-piForcing)

CMIP5 4xCO2 OHU trend (150yr)



CMIP5 4xCO2 SST trend (150yr)



Outline

Non-constant λ

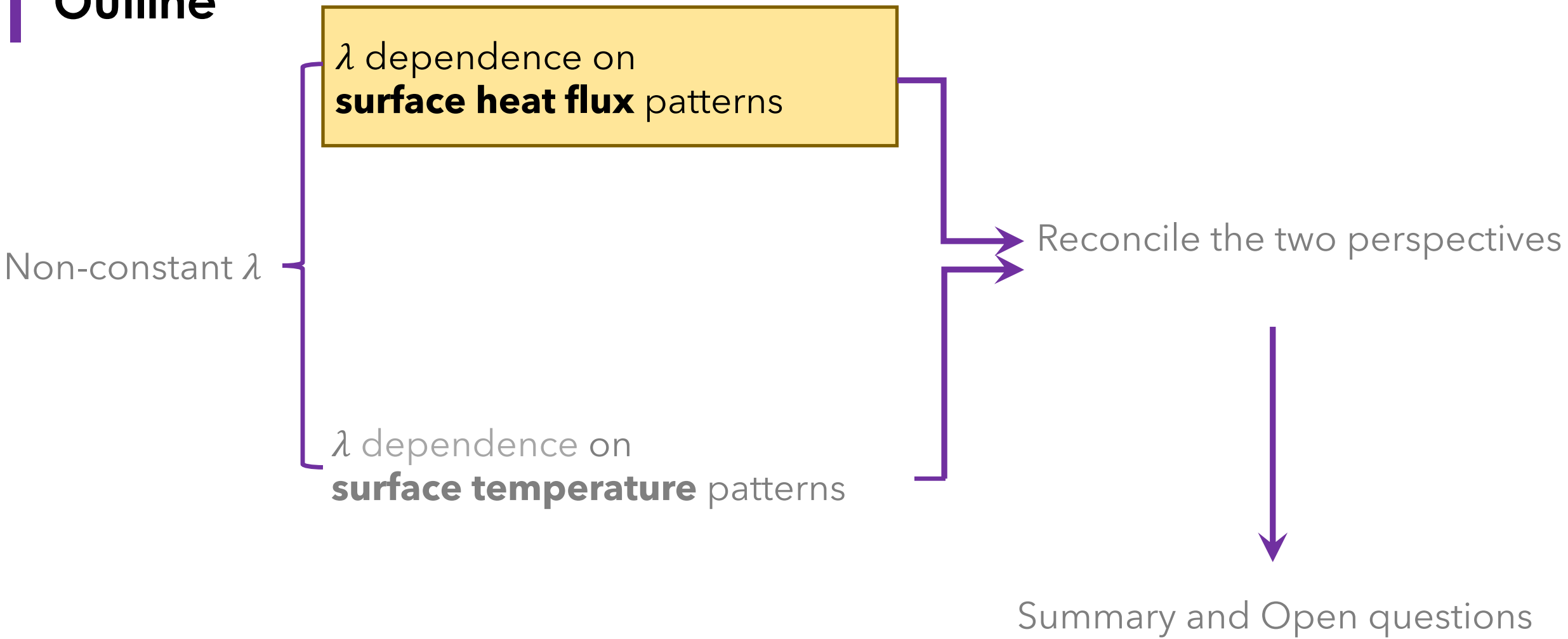
- λ dependence on **surface heat flux** patterns
- λ dependence on **surface temperature** patterns

→ Reconcile the two perspectives

↓

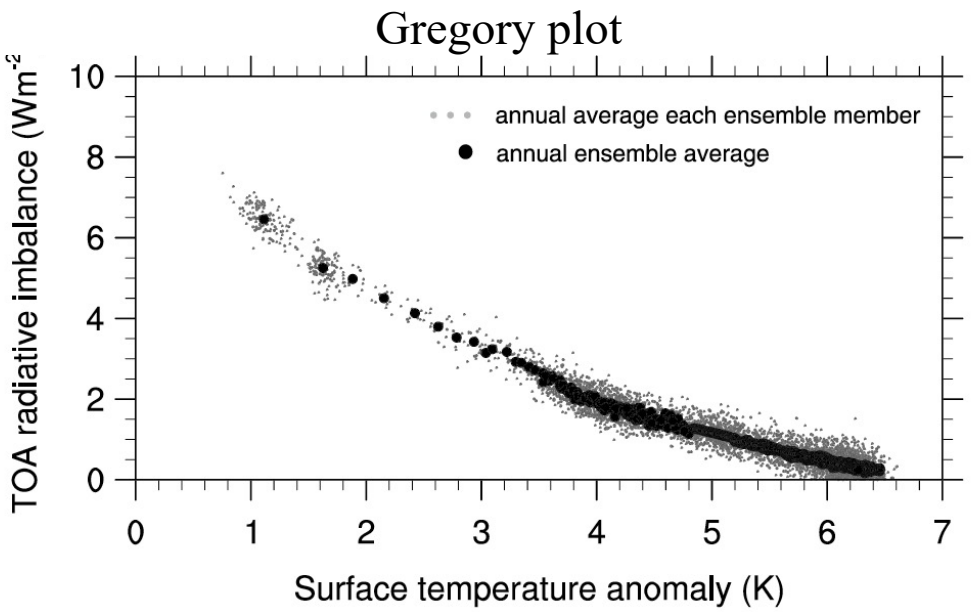
Summary and Open questions

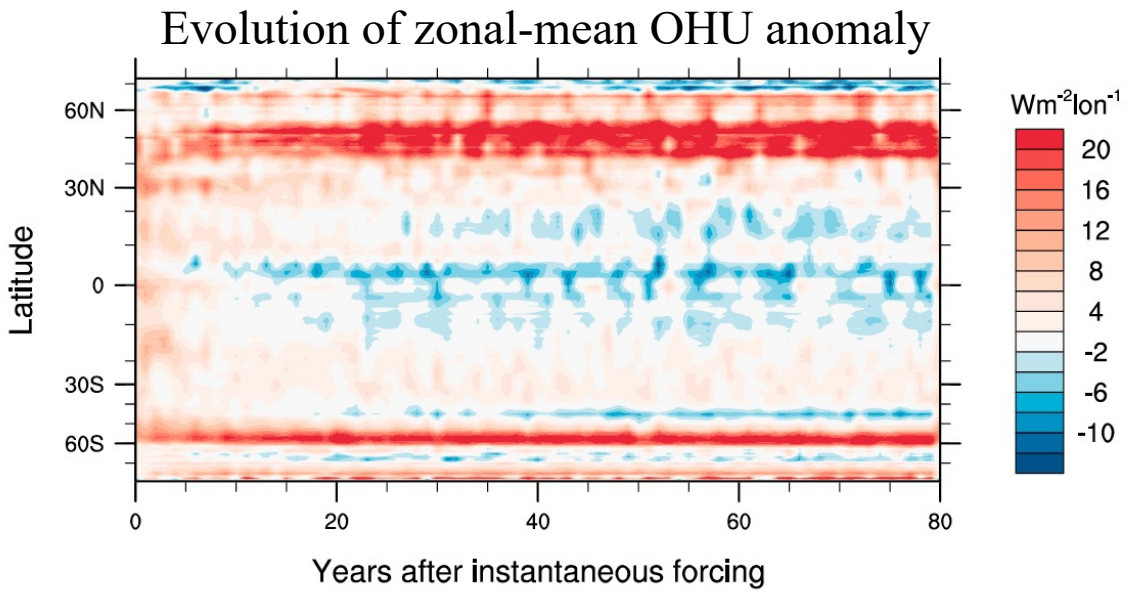
Outline


λ dependence on
surface heat flux patterns
Non-constant λ
λ dependence on
surface temperature patterns
Reconcile the two perspectives
Summary and Open questions

The OHU pattern effect: tropics vs. extratropics

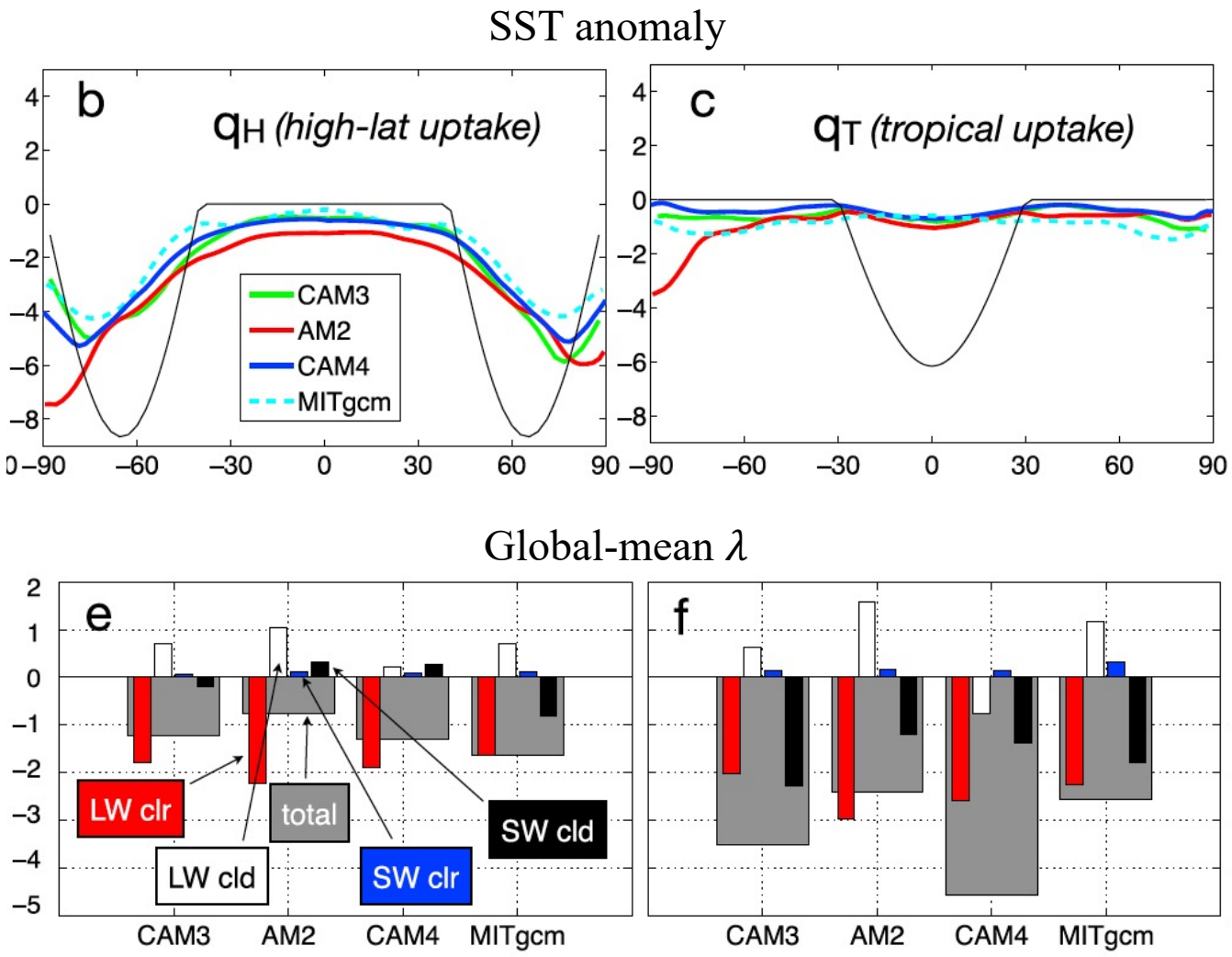
Fully-coupled CESM1 abrupt4xCO2
(Rugenstein et al. 2016)





Transition of OHU from a tropics-centered pattern to an extratropics-centered pattern

The OHU pattern effect: tropics vs. extratropics



Rose et al. 2014 (*GRL*)

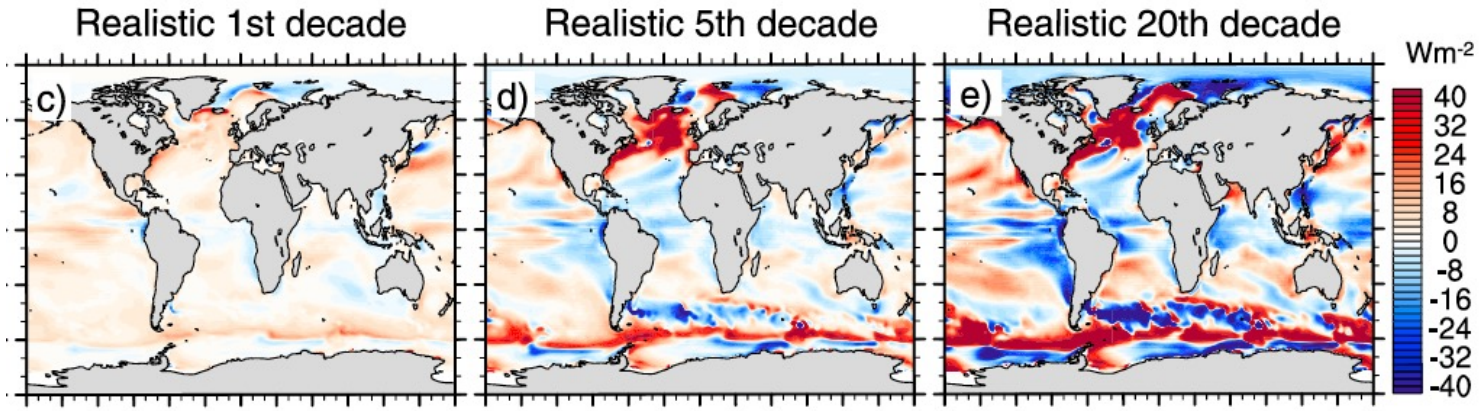
Various slab-ocean simulations with distinct zonal bands of qflux forcing

With the same global mean OHU, more cooling in response to extratropical OHU than to tropical OHU

- Extratropical OHU: less-stabilizing λ
- tropical OHU: more-stabilizing λ
- Mostly from SW cloud λ

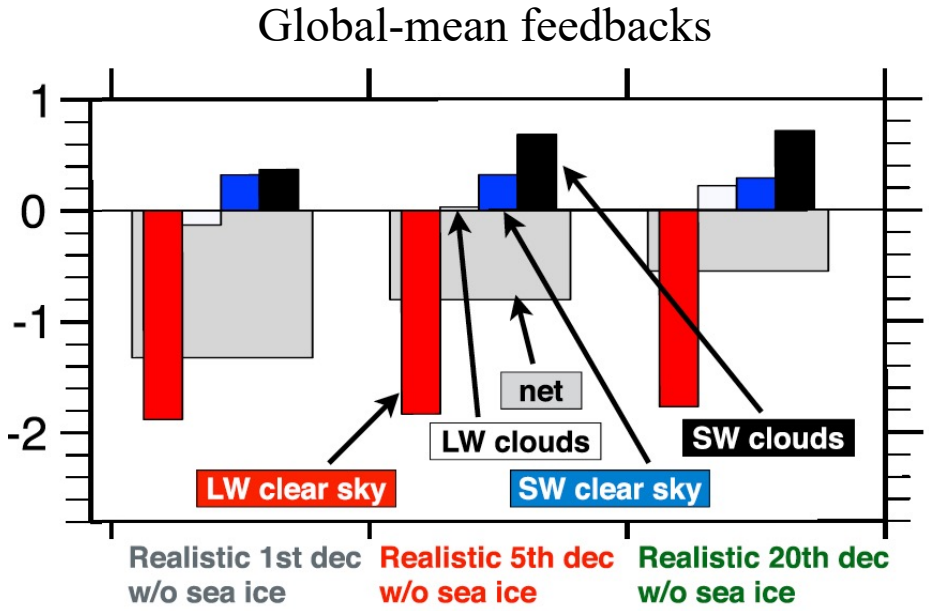
Also see: Winton et al. 2010; Kang and Xie 2014; Rose and Rayborn 2016

The OHU pattern effect: tropics vs. extratropics



Rugenstein et al. 2016 (*GRL*)

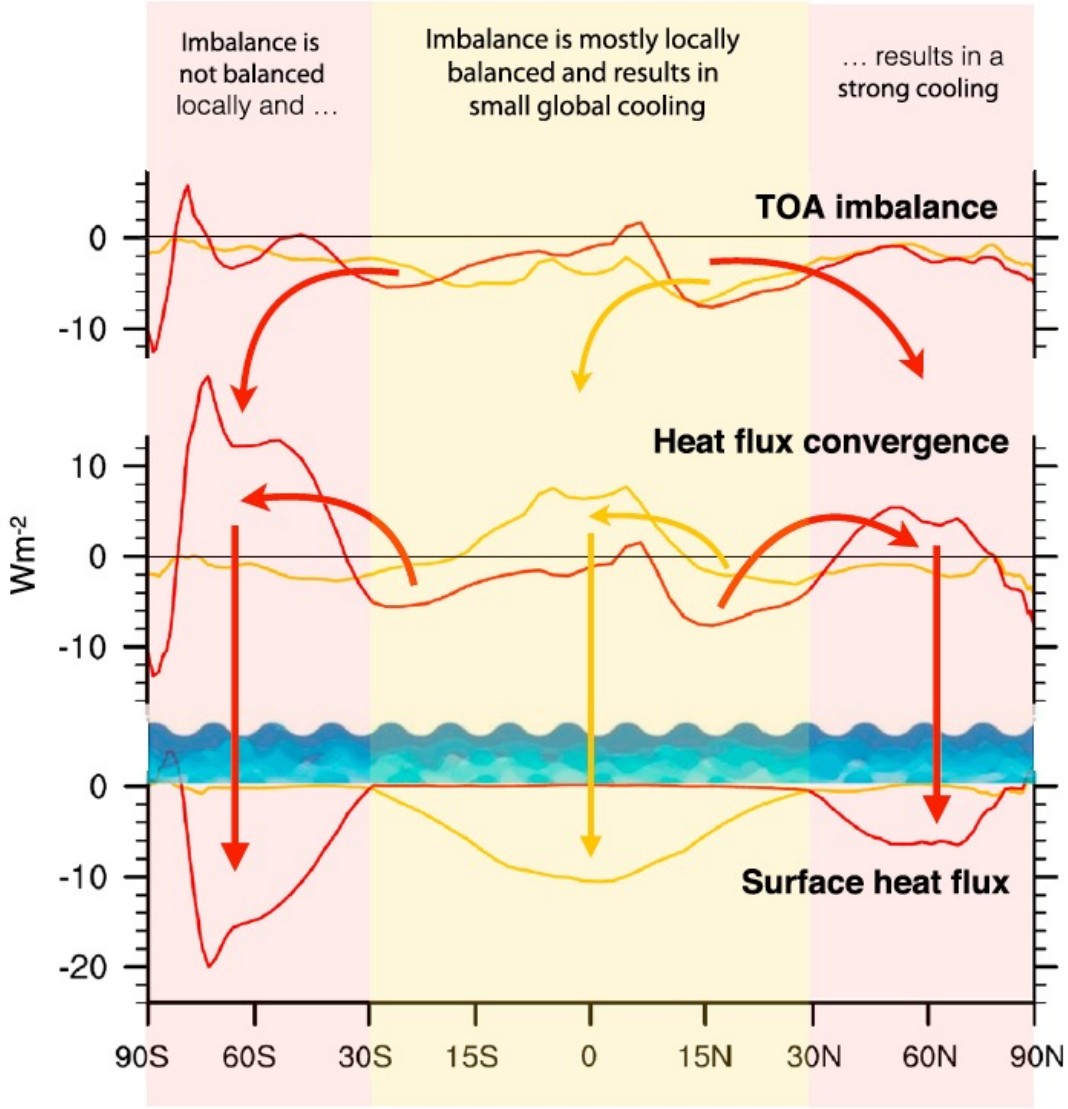
Slab-ocean runs with full patterns of OHU derived from the fully-coupled model under 4xCO2



- As OHU evolves towards a "polar-amplified" pattern, λ becomes less negative
- Mostly due to enhanced positive SW cloud λ

Also see: Winton et al. 2010; Kang and Xie 2014; Rose and Rayborn 2016

The OHU pattern effect: tropics vs. extratropics



Rugenstein et al. 2016 (*GRL*)

Tropical OHU is mostly balanced by local TOA fluxes due to to unstable atmosphere

Extratropical OHU is not balanced locally due to atmospheric stability, thus requires large heat transport into extratropic

Also see: Rose et al. 2014; Kang and Xie 2014

Outline

Non-constant λ

λ dependence on **surface heat flux** patterns

Differences in temperature and cloud response to tropical/extratropical OHU

λ dependence on **surface temperature** patterns

Reconcile the two perspectives

Open questions and future work

Outline

Non-constant λ

λ dependence on **surface heat flux** patterns

Differences in temperature and cloud response to tropical/extratropical OHU

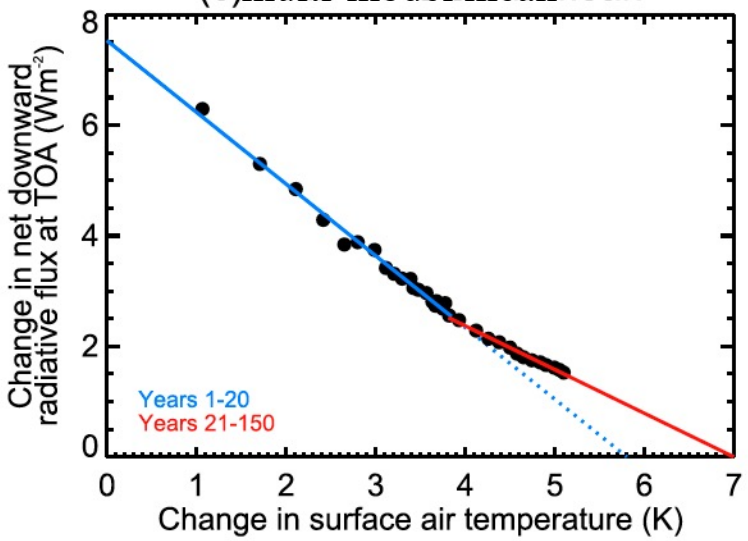
λ dependence on **surface temperature** patterns

Reconcile the two perspectives

Open questions and future work

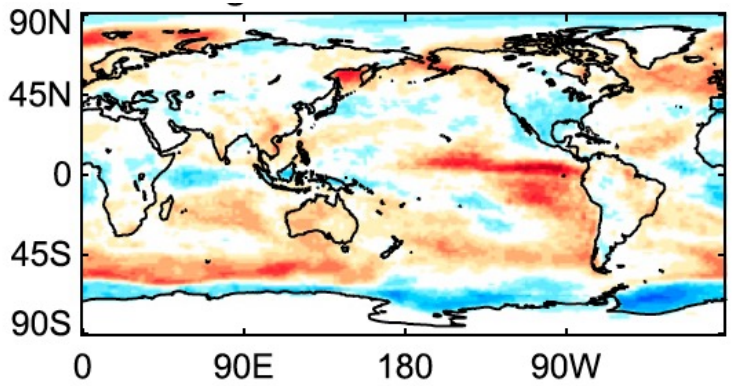
Projected changes in λ and tropical SST pattern

CMIP5 abrupt4xCO2
multi-model mean

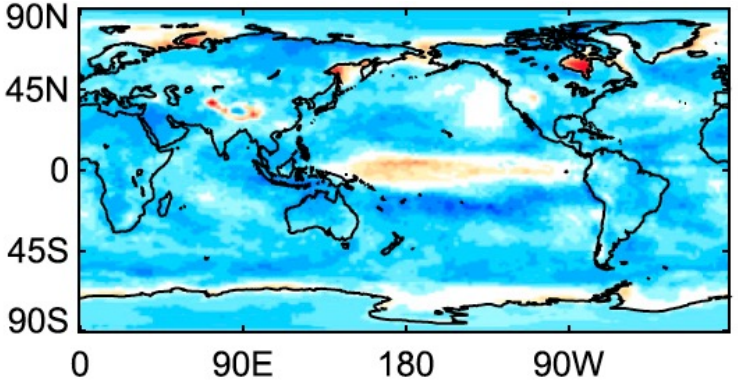


Andrews et al. 2015 (*J. Climate*)

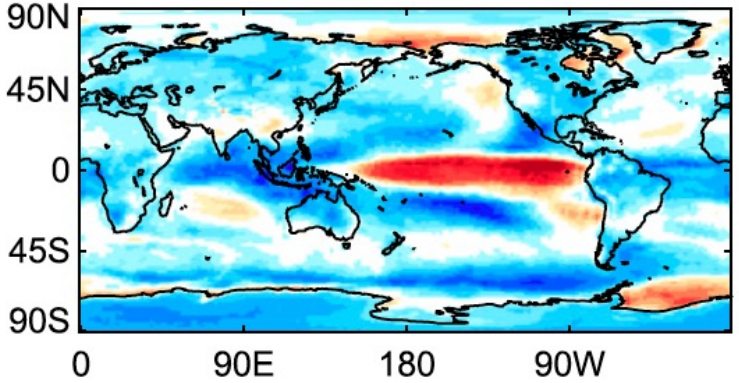
Change in net Cloud feedback



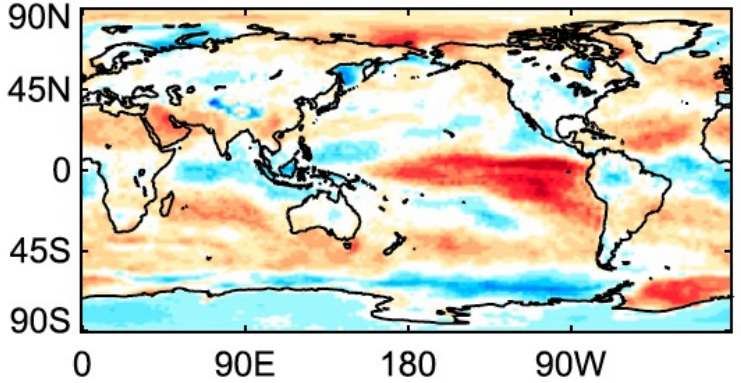
Net λ (yr1 – 20)



Net λ (yr21 – 150)

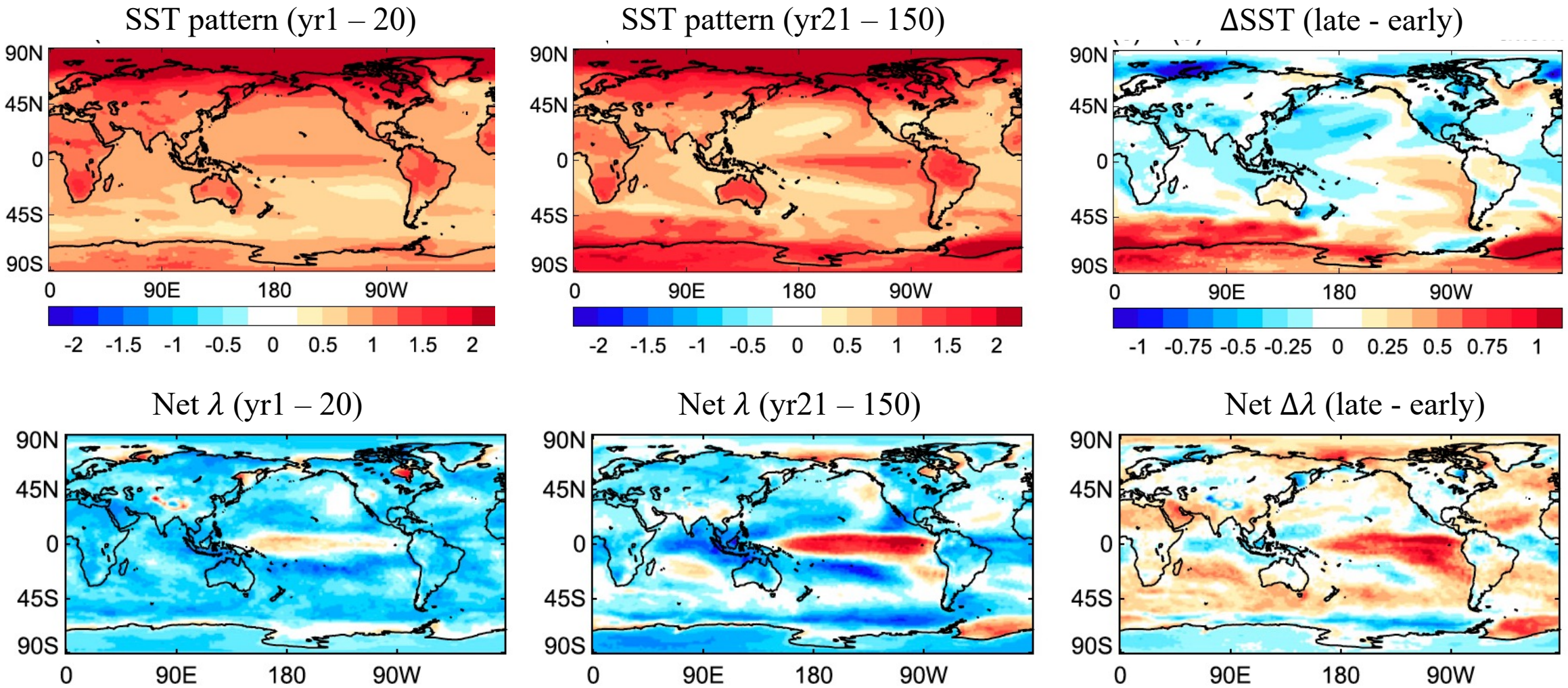


Net $\Delta\lambda$ (late - early)



Projected changes in λ and tropical SST pattern

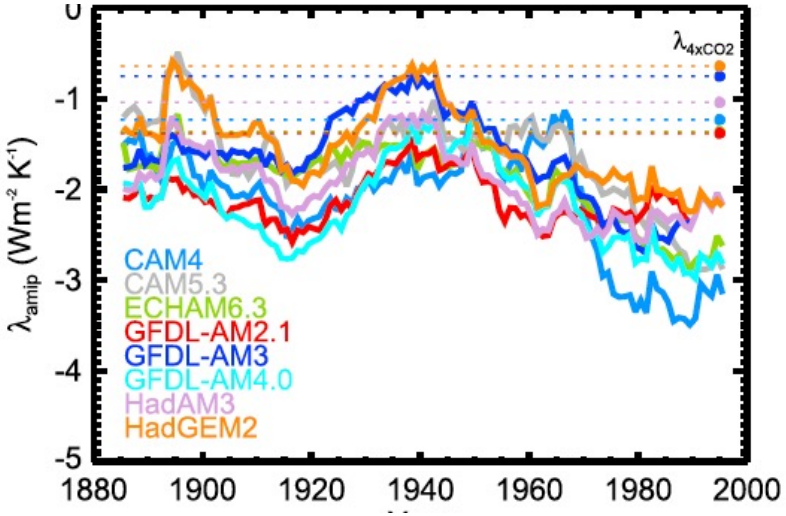
Dominant role of tropical cloud $\Delta\lambda$ associated with changes in tropical SSTs



Andrews et al. 2015 (*J. Climate*)

Historical changes in λ and tropical SST pattern

$\Delta\lambda$ over historical period in CMIP5 amip-piForcing runs (w/ observed SST)



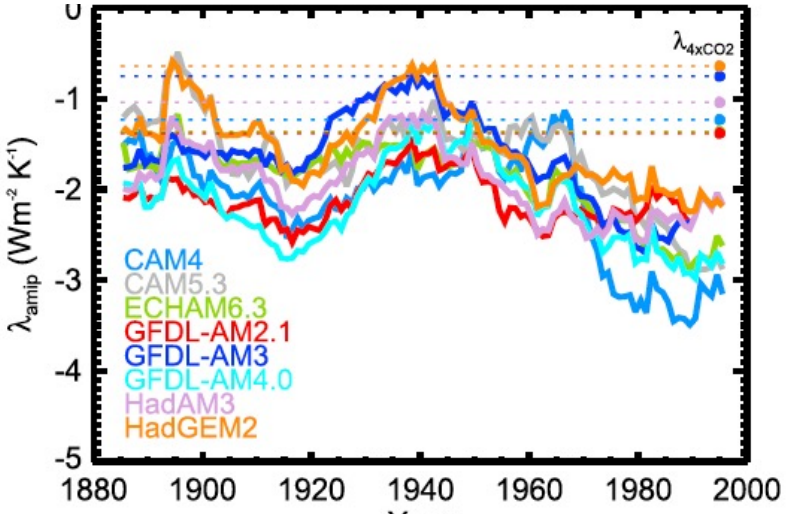
(Andrews et al. 2018)

Also see:

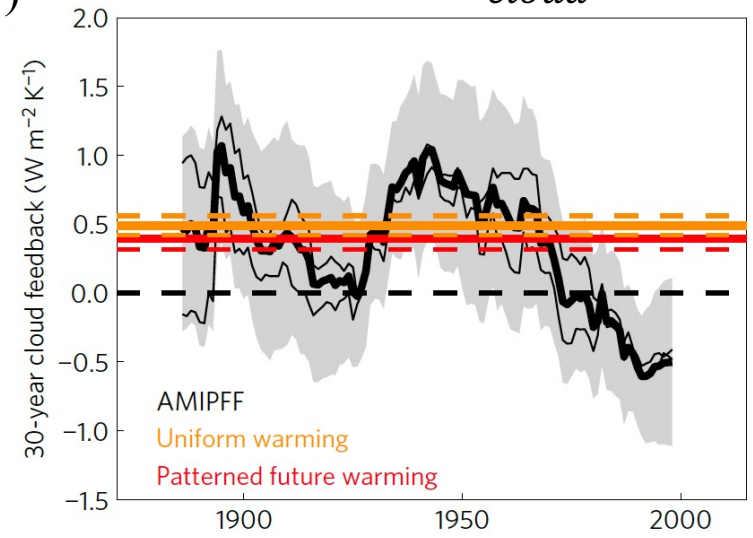
- For CMIP6 models
  - Dong et al. 2021
- For other individual models
  - Gregory and Andrews 2016
  - Zhou et al. 2016
  - Silvers et al. 2018
  - Gregory et al. 2020

Historical changes in λ and tropical SST pattern

$\Delta\lambda$ over historical period in CMIP5 amip-piForcing runs (w/ observed SST)



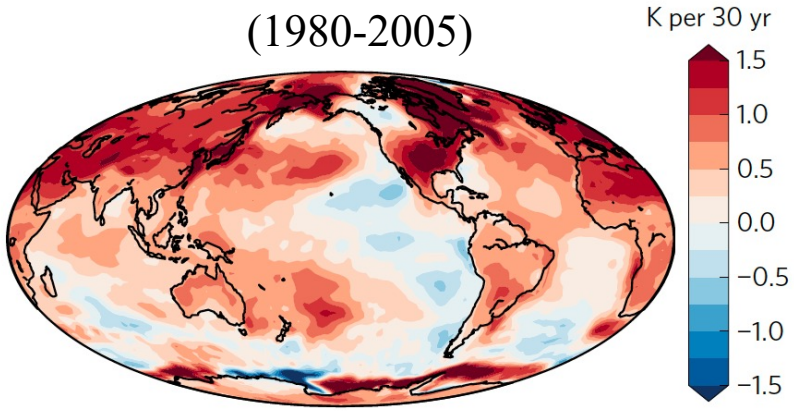
CAM5 $\Delta\lambda_{cloud}$



Zhou et al. 2016 (*Nat. Geo.*)

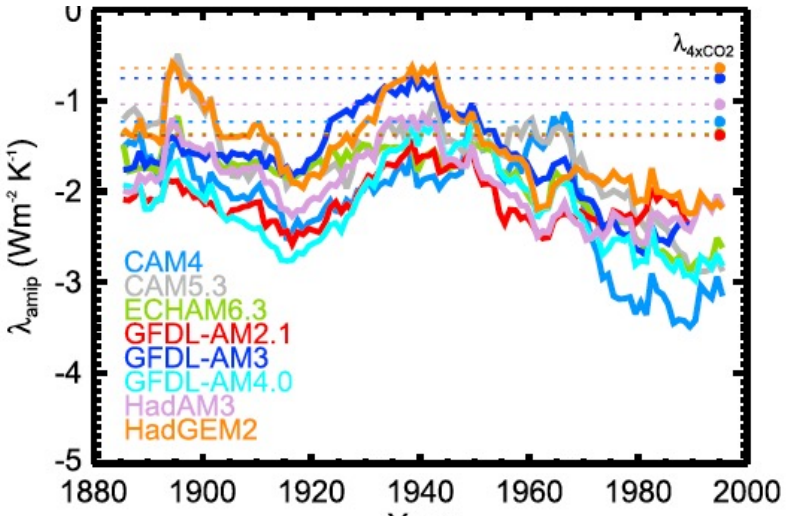
$\Delta\lambda_{cloud}$ arises due to changes in SST patterns

AMIP TS trend (1980-2005)

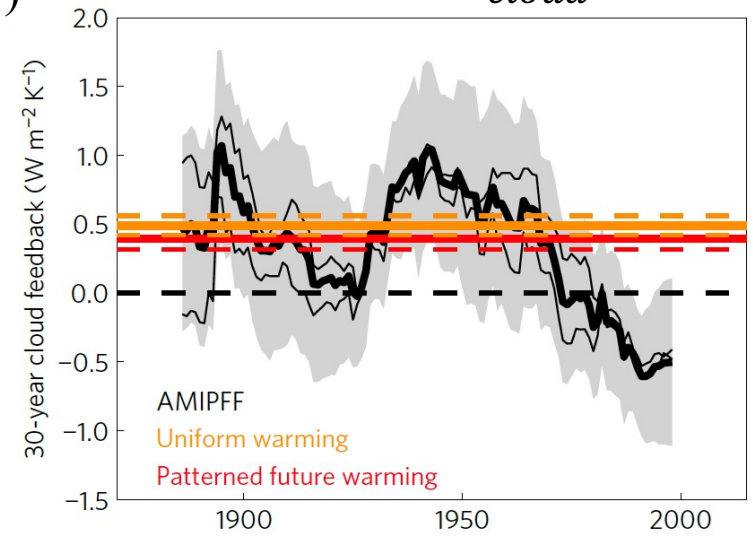


Historical changes in λ and tropical SST pattern

$\Delta\lambda$ over historical period in CMIP5 amip-piForcing runs (w/ observed SST)



CAM5 $\Delta\lambda_{cloud}$

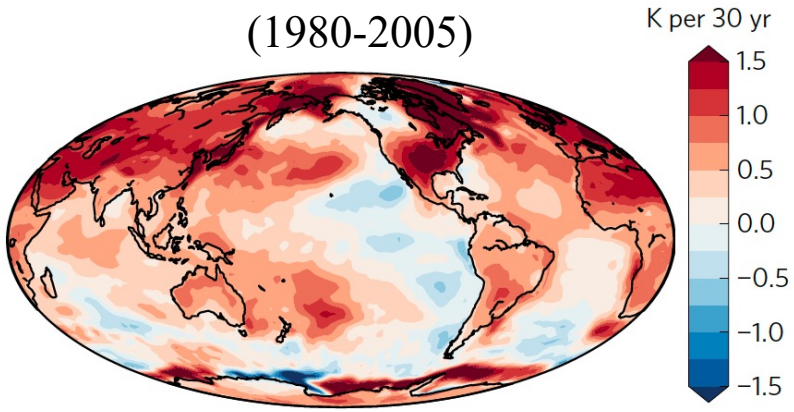


Zhou et al. 2016 (*Nat. Geo.*)

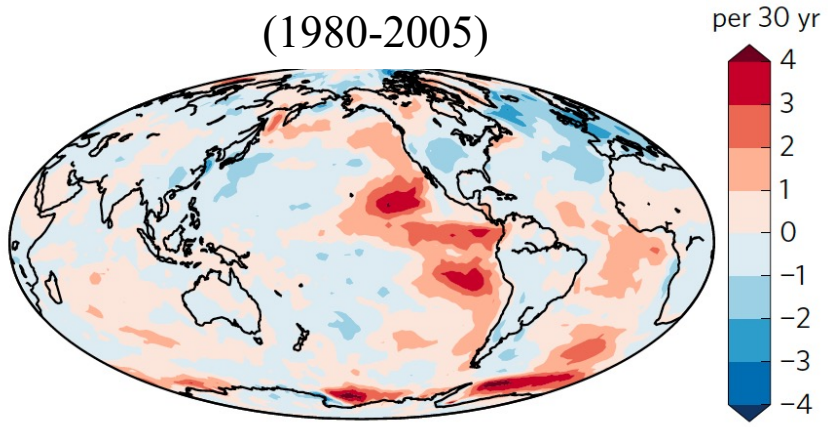
$\Delta\lambda_{cloud}$ arises due to changes in SST patterns

mostly associated with tropical marine low clouds that are sensitive to lower tropospheric stability

AMIP TS trend (1980-2005)

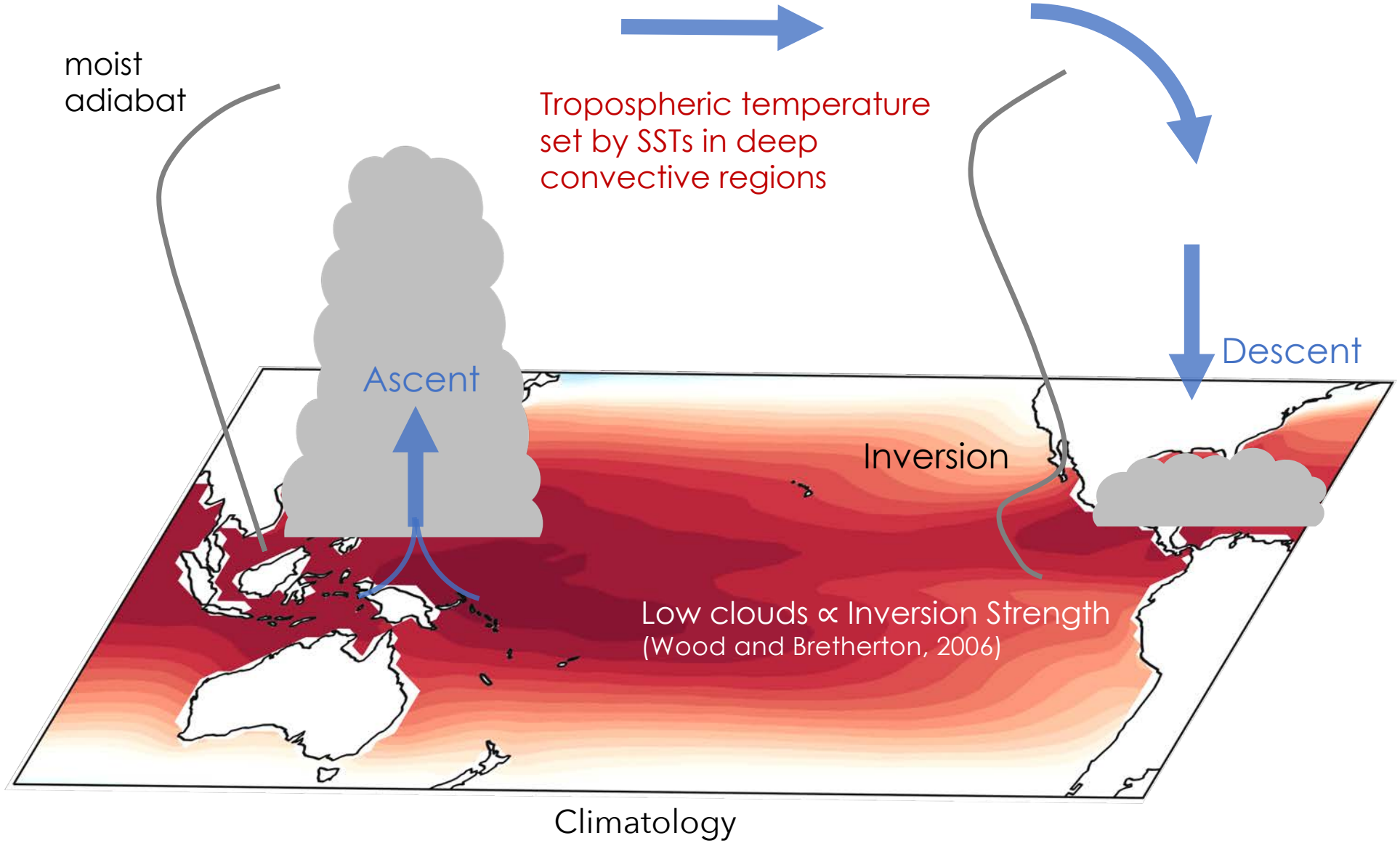


AMIP Low cloud cover trend (1980-2005)

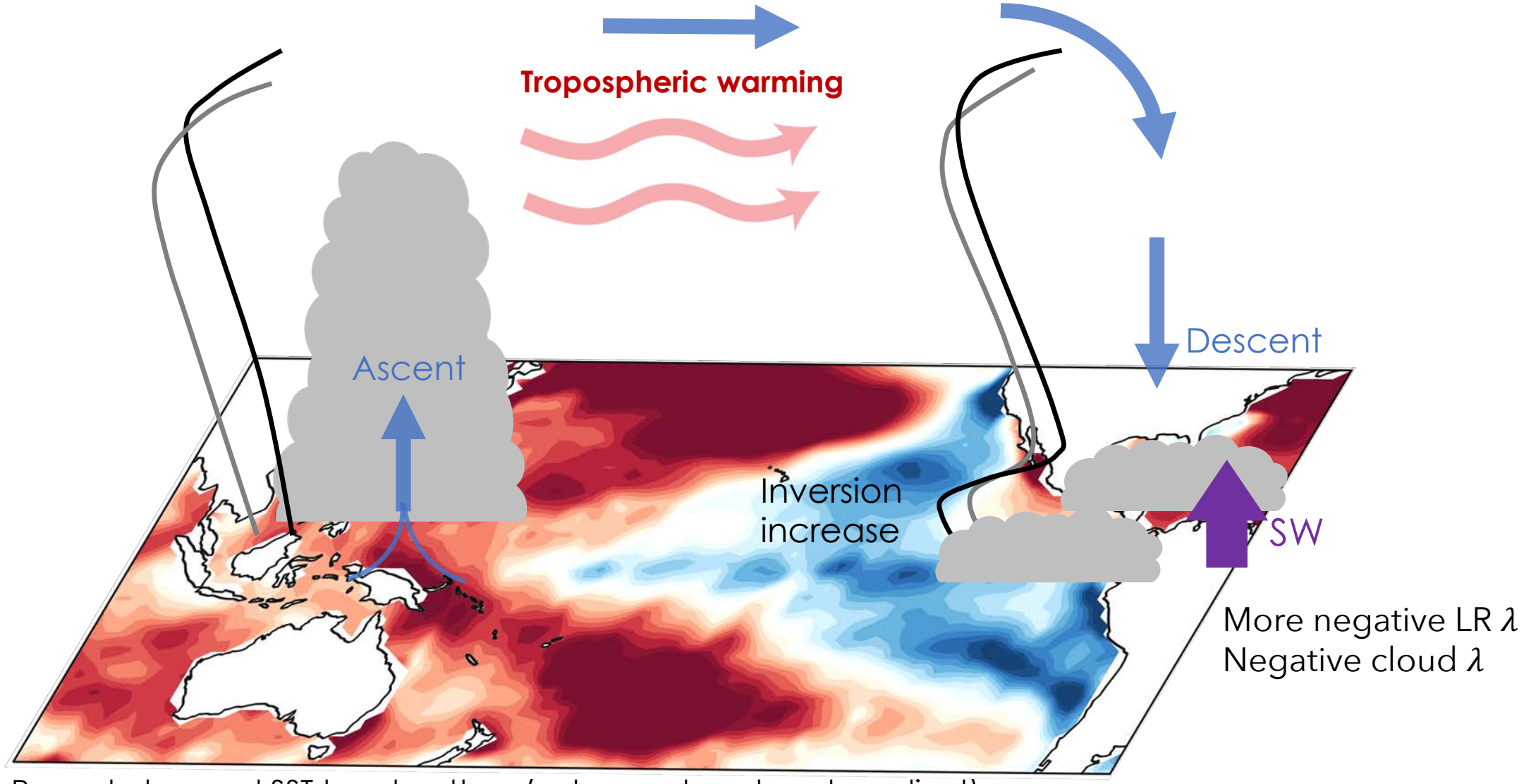


Andrews & Webb 2017 (*J. Climate*)
and lapse-rate feedback!

Tropical mean circulation



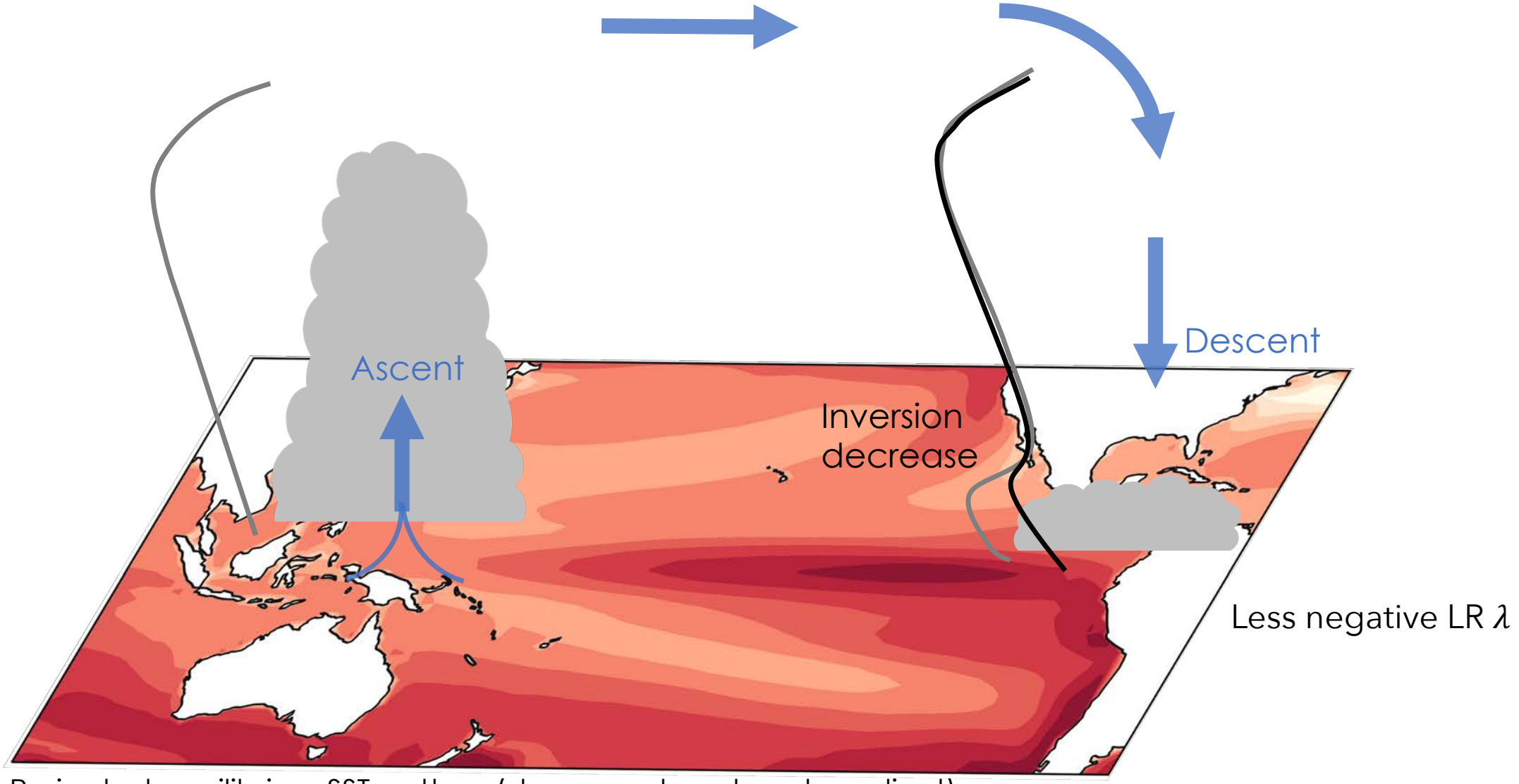
More-negative λ response to enhanced tropical SST W-E SST gradient



Recent observed SST trend pattern (enhanced west-east gradient)

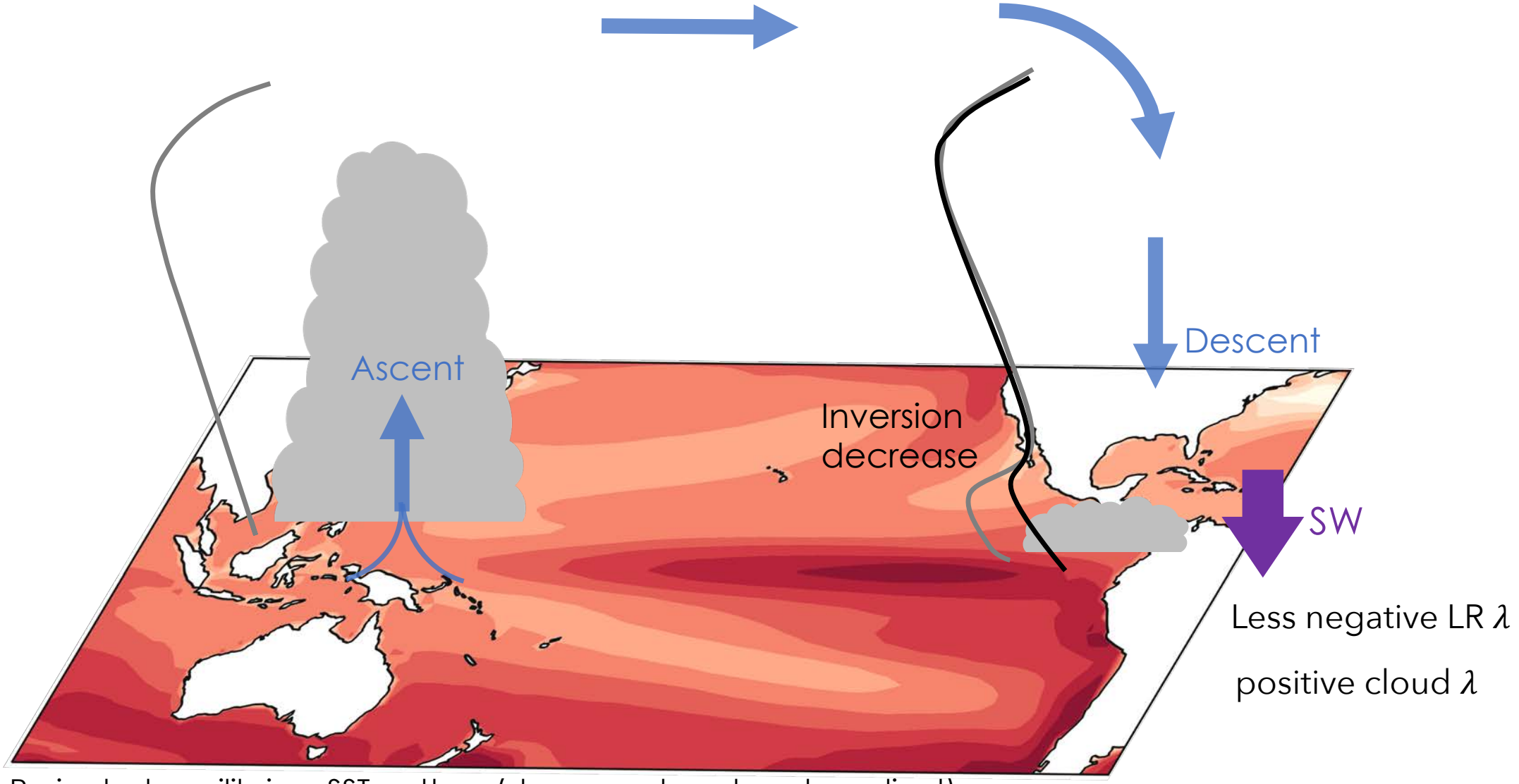
Zhou et al. 2016; Andrews and Webb 2017

Less-negative λ response to decreased tropical SST W-E SST gradient



Zhou et al. 2016; Andrews and Webb 2017

Less-negative λ response to decreased tropical SST W-E SST gradient



Zhou et al. 2016; Andrews and Webb 2017

Radiative feedback Green's functions

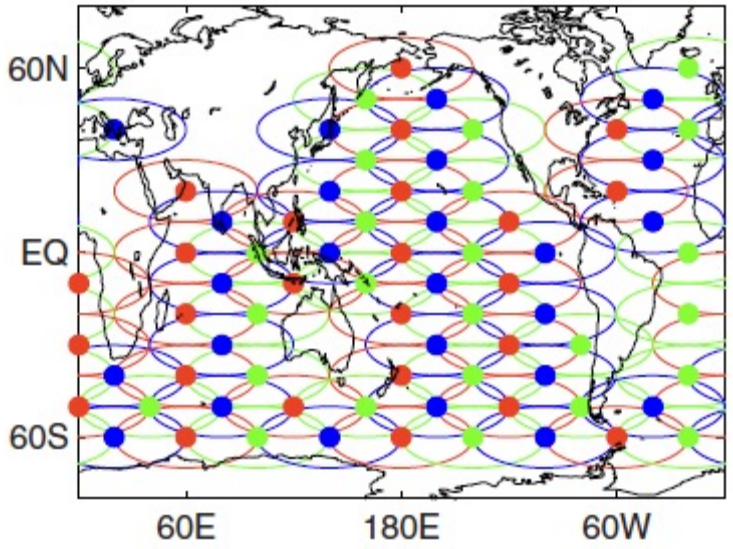
Green's function approach

- A suite of prescribed SST simulations within an AGCM
- Each simulation is forced by a localized patch of SST anomalies

- Useful to quantify local and remote impacts of regional SST changes on TOA radiation /clouds/precipitation/circulation/etc.
- Assuming climate responses remain linear

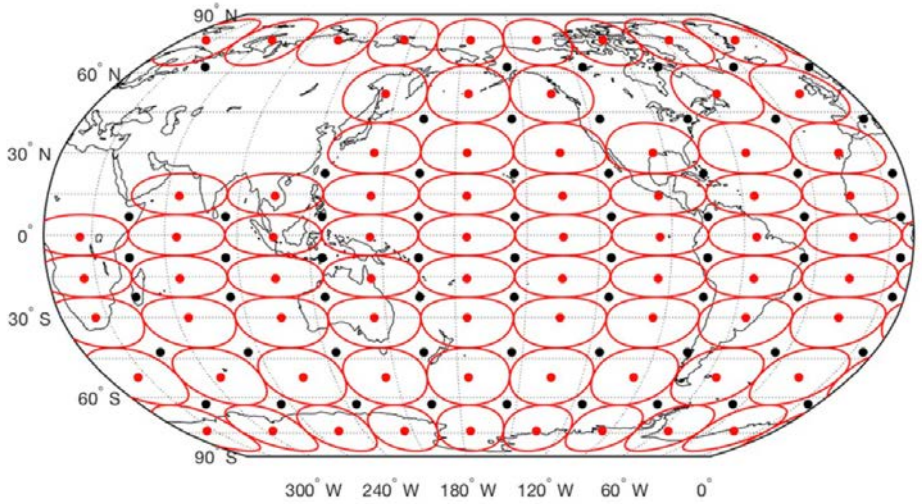
Zhou et al. 2017 (*JAMES*)

CAM5

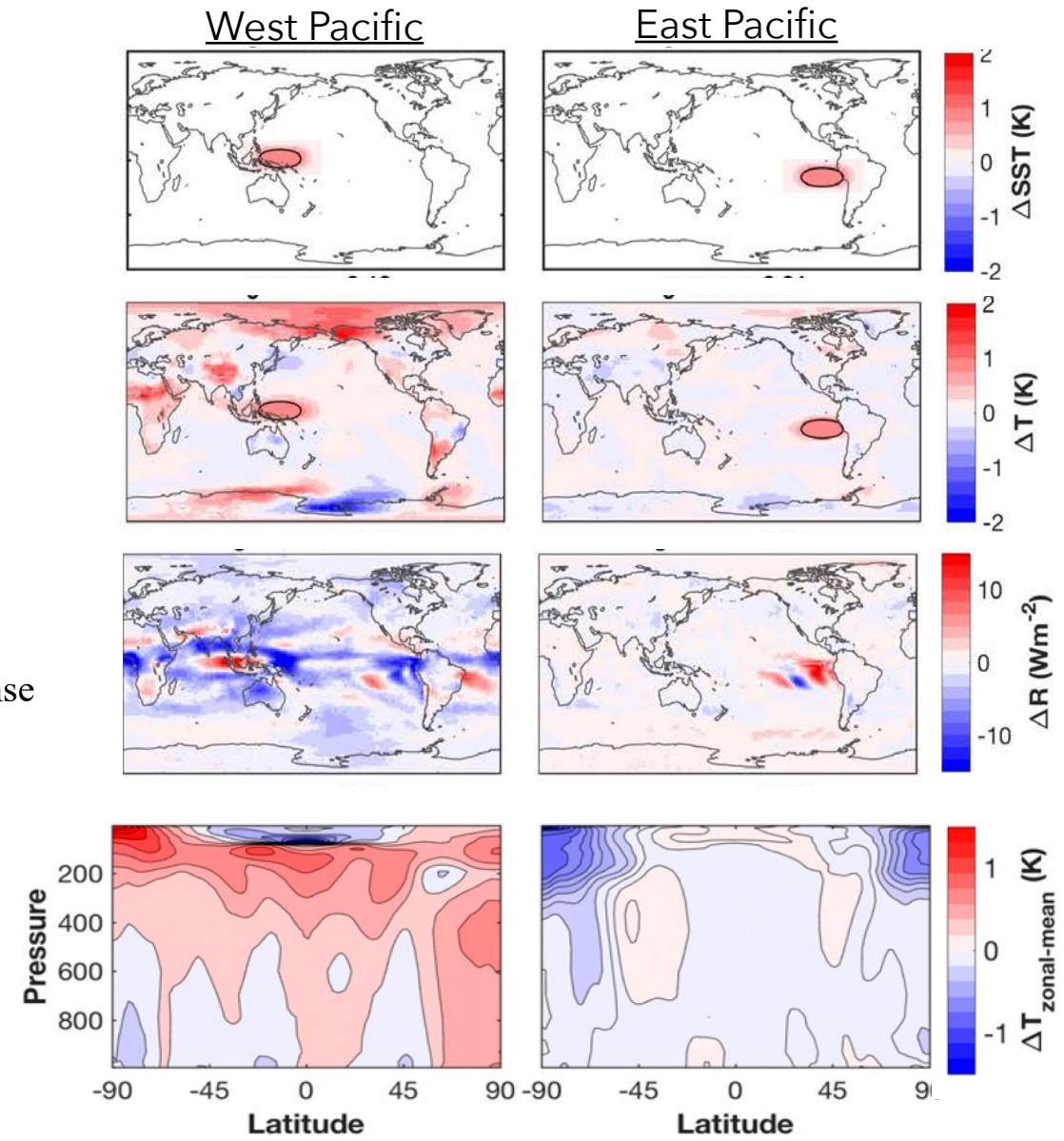


Dong et al. 2019 (*J. Climate*)

CAM4



Radiative feedback Green's functions



(+): down to surface (positive feedback)

(-): Out to space (negative feedback)

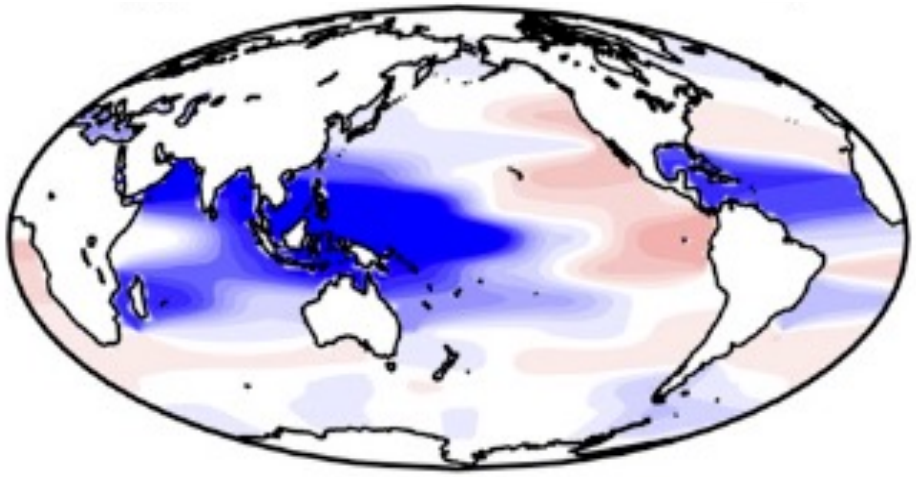
Dong et al. 2019 (*J. Climate*)

Radiative feedback Green's functions

Global λ response to local ΔSST

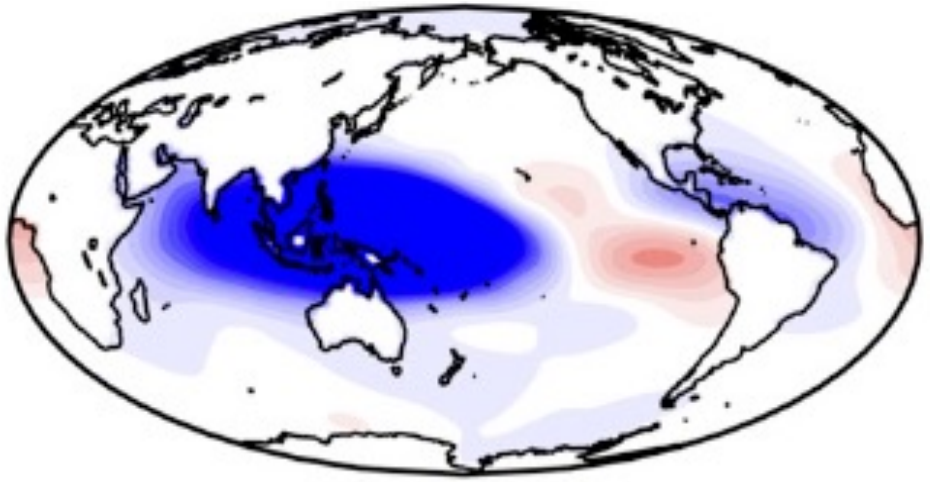
$$\frac{\partial \lambda}{\partial SST}$$

CAM5

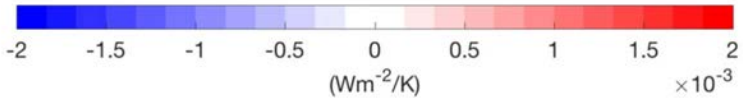


Zhou et al. 2017

CAM4

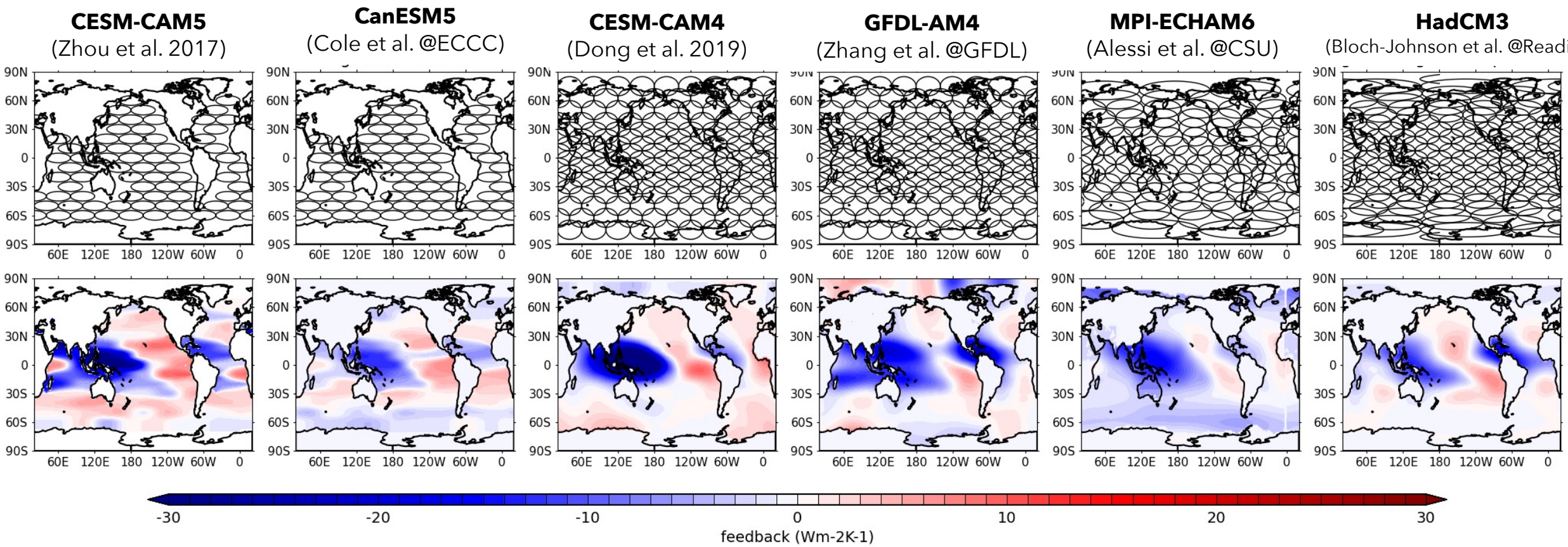


Dong et al. 2019



Changes in λ primarily determined by relative warming in the west Pacific Warm Pool region with respect to global mean (or tropical mean) warming

GFMIP: inter-model comparison of Green's functions

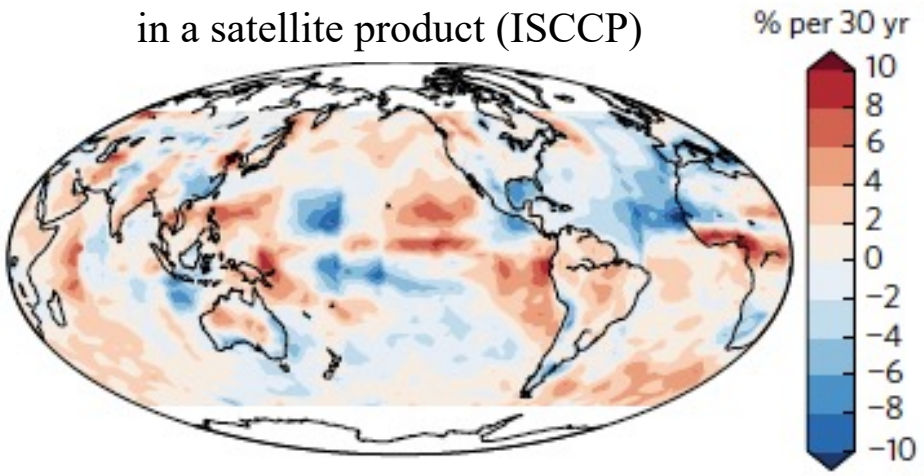


GFMIP: Bloch-Johnson et al. (in prep)

Stay tuned for the GFMIP discussion on Friday and individual GF posters on Wednesday!

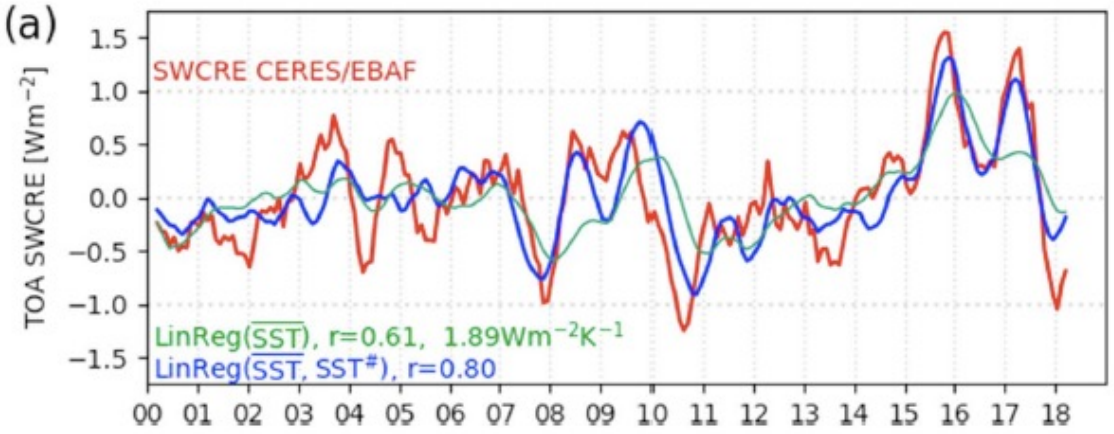
The tropical SST pattern effect in observations

Low-cloud cover trend (1983-2005)
in a satellite product (ISCCP)



Zhou et al. 2016 (*Nat. Geo.)*

CERES SW CRE times series



Fueglistaler. 2019 (*GRL*)

Observed SW cloud feedback tracks the ratio between tropical-mean warming and warming over the warmest 30% convective regions

Outline

Non-constant λ

- λ dependence on **surface heat flux** patterns
  - Differences in temperature and cloud response to tropical/extratropical OHU
- λ dependence on **surface temperature** patterns
  - Tropical low-cloud feedback and lapse-rate feedback sensitive to the tropical Pacific zonal SST gradient

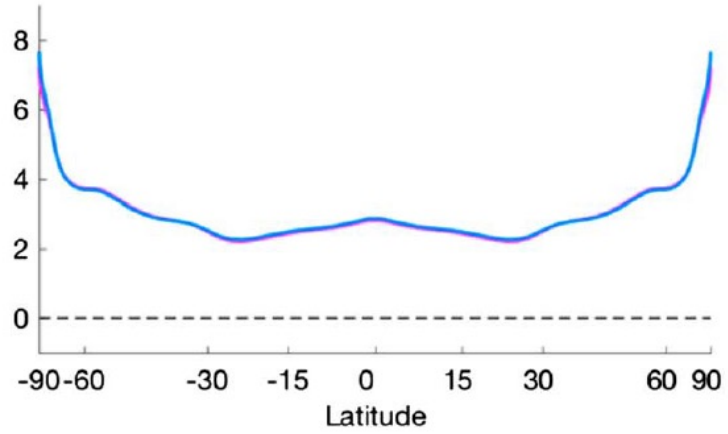
→ Reconcile the two perspectives

↓

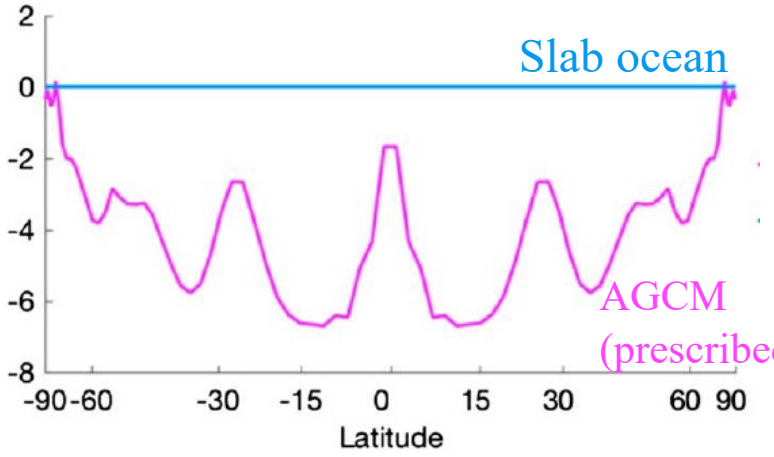
Summary and Open questions

Is λ more sensitive to OHU pattern or SST pattern?

SST anomaly

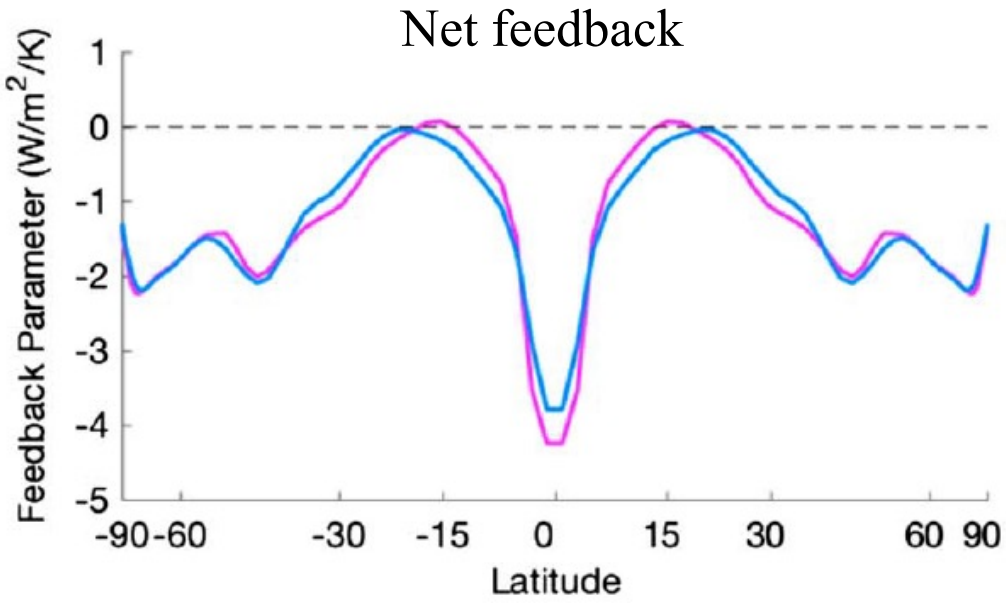


Surface flux anomaly



Haugstad et al. 2017 (*GRL*)

- one slab-ocean run: forced by 2xCO2 and qflux climatology
- one AGCM prescribed-SST run: SST anomaly taken from the coupled slab ocean
- The two have the same SSTs but different surface heat fluxes

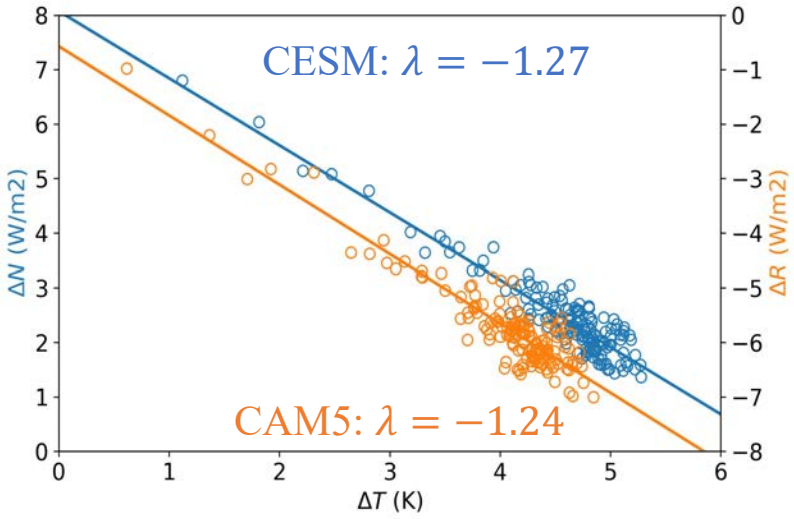


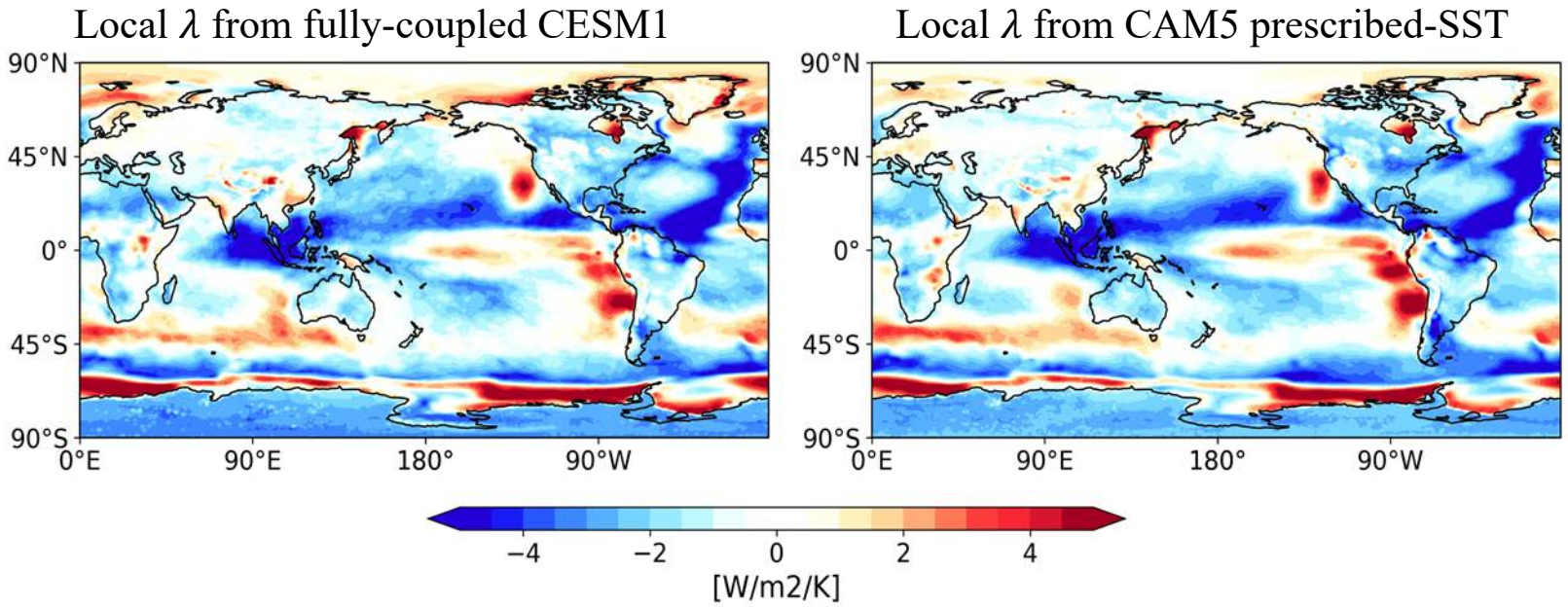
Same feedbacks arise from a given SST pattern, regardless the SST pattern is generated by coupled models or prescribed

Is λ more sensitive to OHU pattern or SST pattern?

Mitevski et al. *in prep (poster!)*

1. Fully-coupled CESM1 runs: forced by 4xCO_2 (2x, 3x,… 8x CO_2), run for 150yrs
2. CAM5 runs: prescribe SSTs generated from CESM1

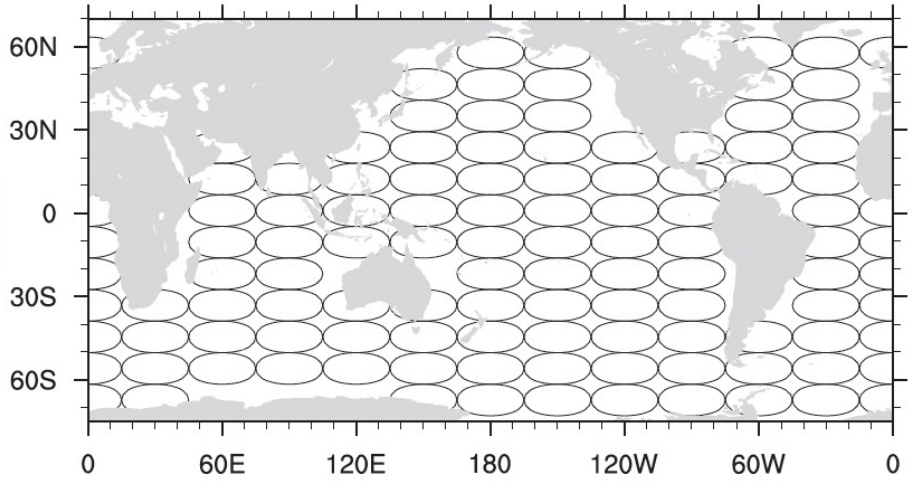




Same feedbacks arise from a given SST pattern, regardless the SST pattern is generated by coupled models or prescribed

Tropical-extratropical OHU vs. tropical West-east SST

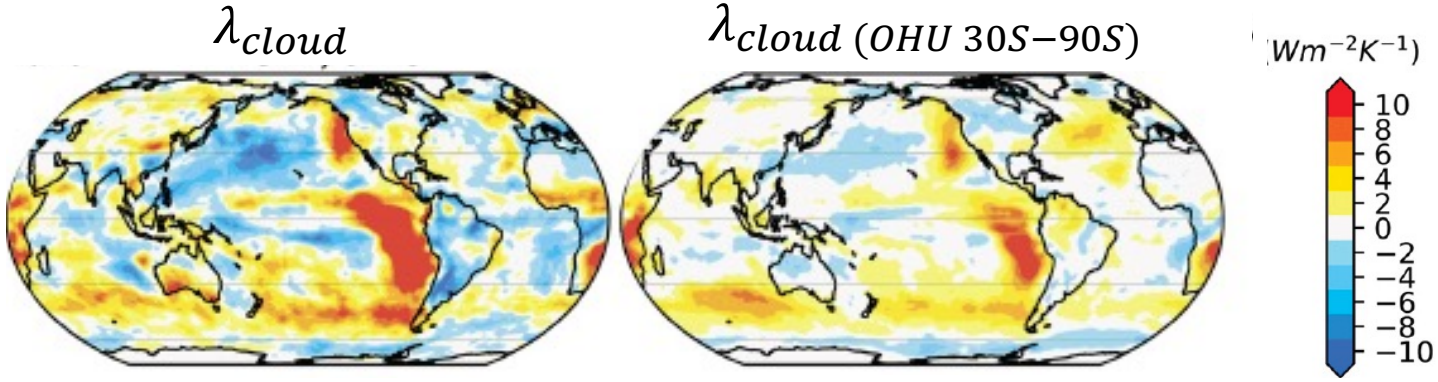
Qflux Green's function (CAM5-SOM)



Liu et al. 2018 (*J. Climate*)

Lin et al. 2021 (*GRL*)

CESM abrupt4xCO2 reconstruction using Qflux Green's function



Southern Ocean OHU mostly responsible for changes in λ_{cloud}

Tropical-extratropical OHU vs. tropical West-east SST

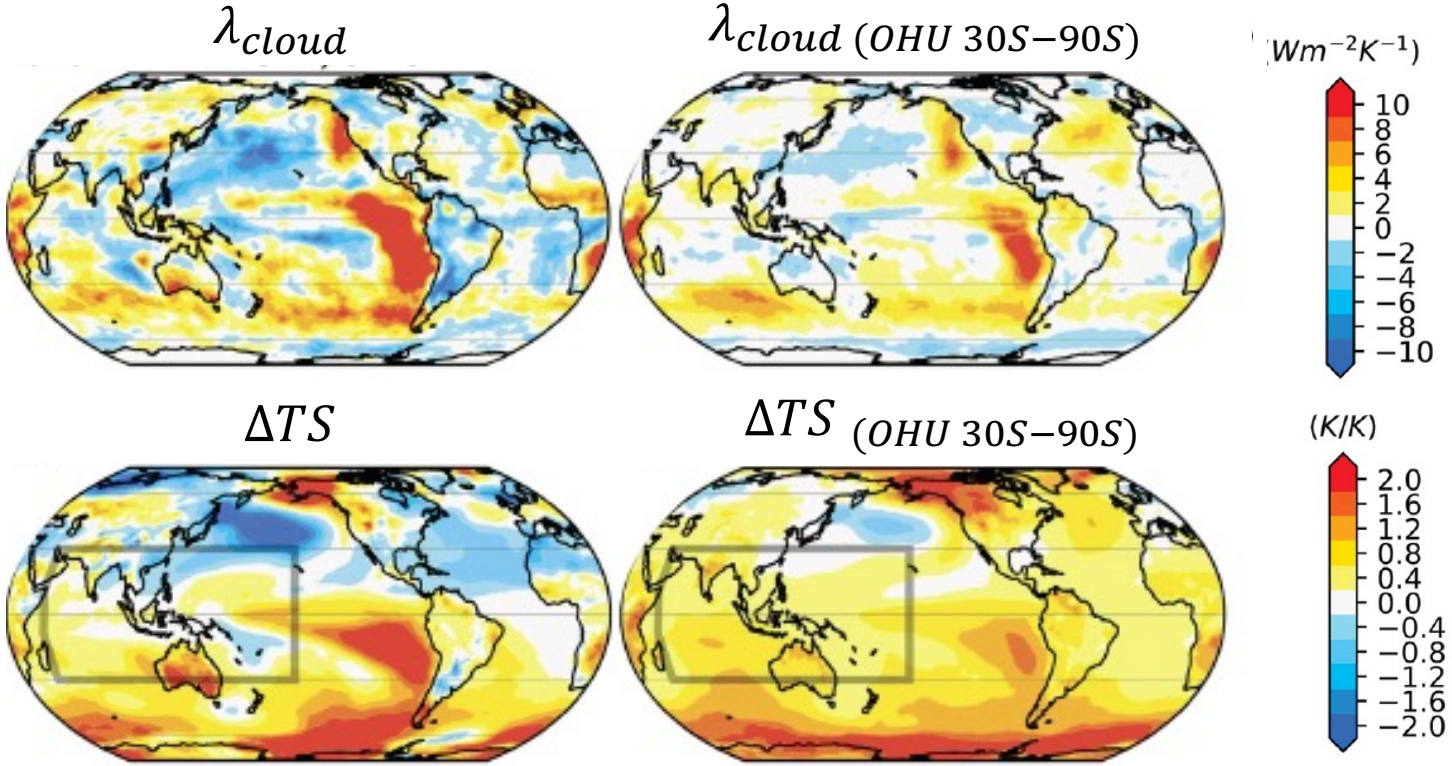
λ is governed by tropical SST pattern, which itself can be influenced by extratropical OHU

Southern Ocean OHU mostly responsible for changes in λ_{cloud}

through changing tropical SSTs via teleconnections

Lin et al. 2021 (*GRL*)

CESM abrupt4xCO2 reconstruction using Qflux Green's function



Outline

Non-constant λ

- λ dependence on **surface heat flux** patterns
  - Differences in temperature and cloud response to tropical/extratropical OHU
- λ dependence on **surface temperature** patterns
  - Tropical low-cloud feedback and lapse-rate feedback sensitive to the tropical Pacific zonal SST gradient

→ Reconcile the two perspectives

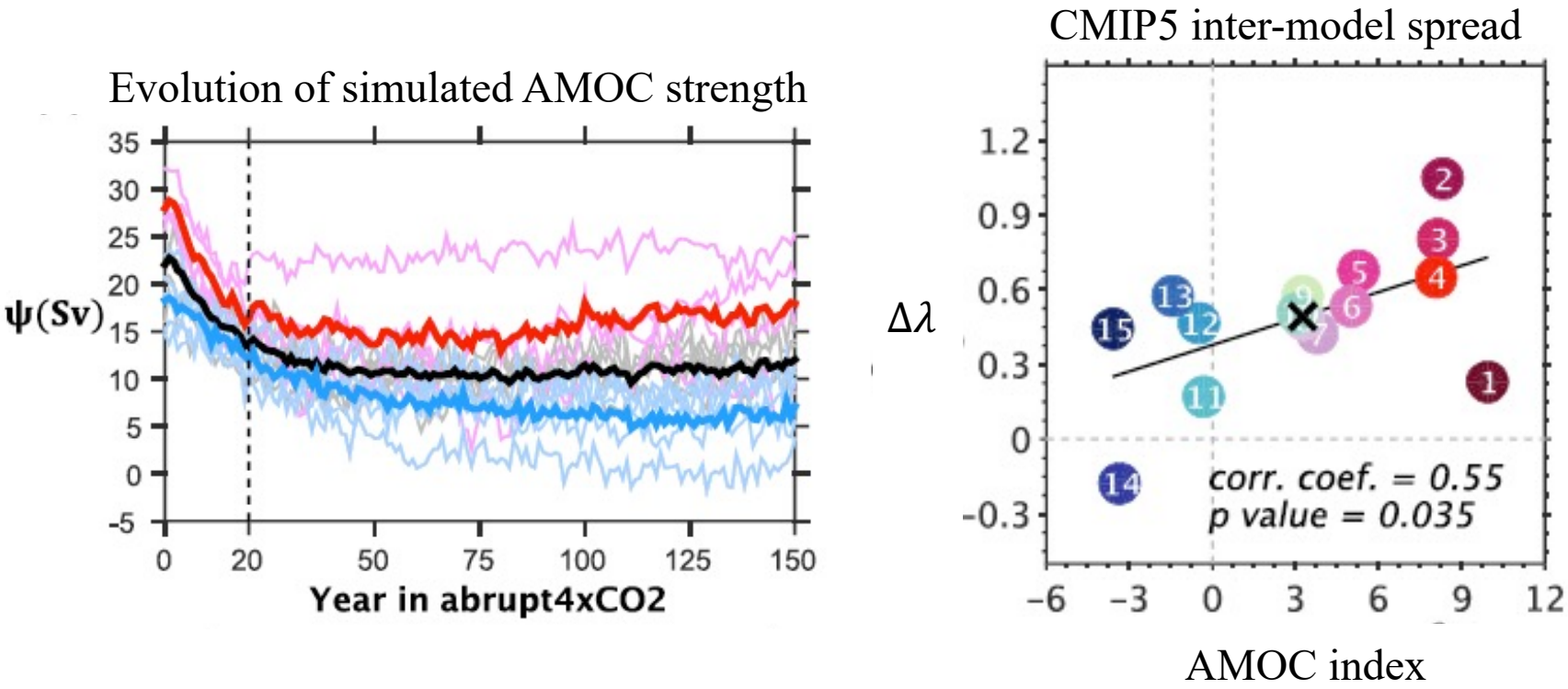
- λ more sensitive to the pattern of SST, though it can be modulated by OHU

→ Summary and Open questions

Summary and outlook

Attribution: What regions/feedbacks are most responsible for the pattern effect?

- The relative role of **different regions** (aside from the tropical Pacific)?
  - Other tropical basins (Silvers et al. 2018)
  - Southern Ocean (Senior & Mitchell 2011; Armour et al. 2013)
  - North Atlantic (Trossman et al. 2016; Lin et al. 2019; Mitevski et al. in prep)



Lin et al. 2019 (*GRL*)

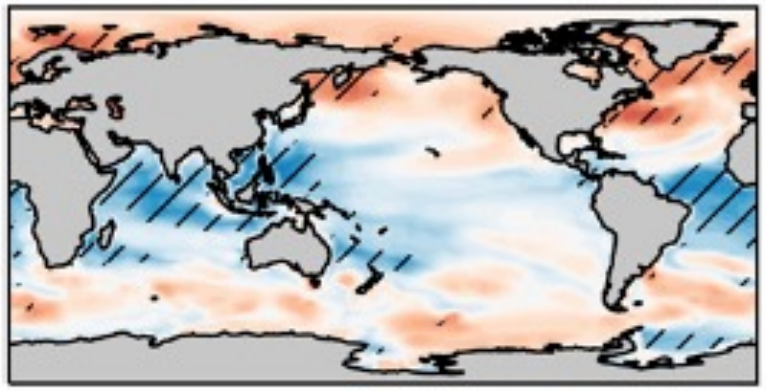
Summary and outlook

Attribution: What regions/feedbacks are most responsible for the pattern effect?

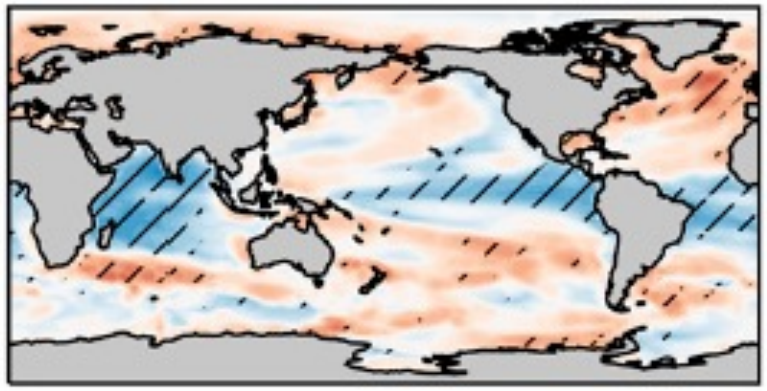
- The relative role of different regions (aside from the tropical Pacific)?
- The relative role of **different feedbacks** (aside from the tropical low-cloud feedback)?
  - Lapse-rate feedback (Andrews and Webb 2017; Ceppi and Gregory 2017)
  - Extratropical cloud feedbacks (Zelinka et al. 2020)

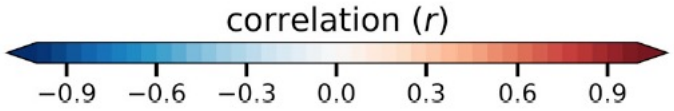
- Do the findings from CMIP5 hold in CMIP6?

Correlation between $\Delta\lambda$ and local ΔSST across **CMIP5** models



Correlation between $\Delta\lambda$ and local ΔSST across **CMIP6** models



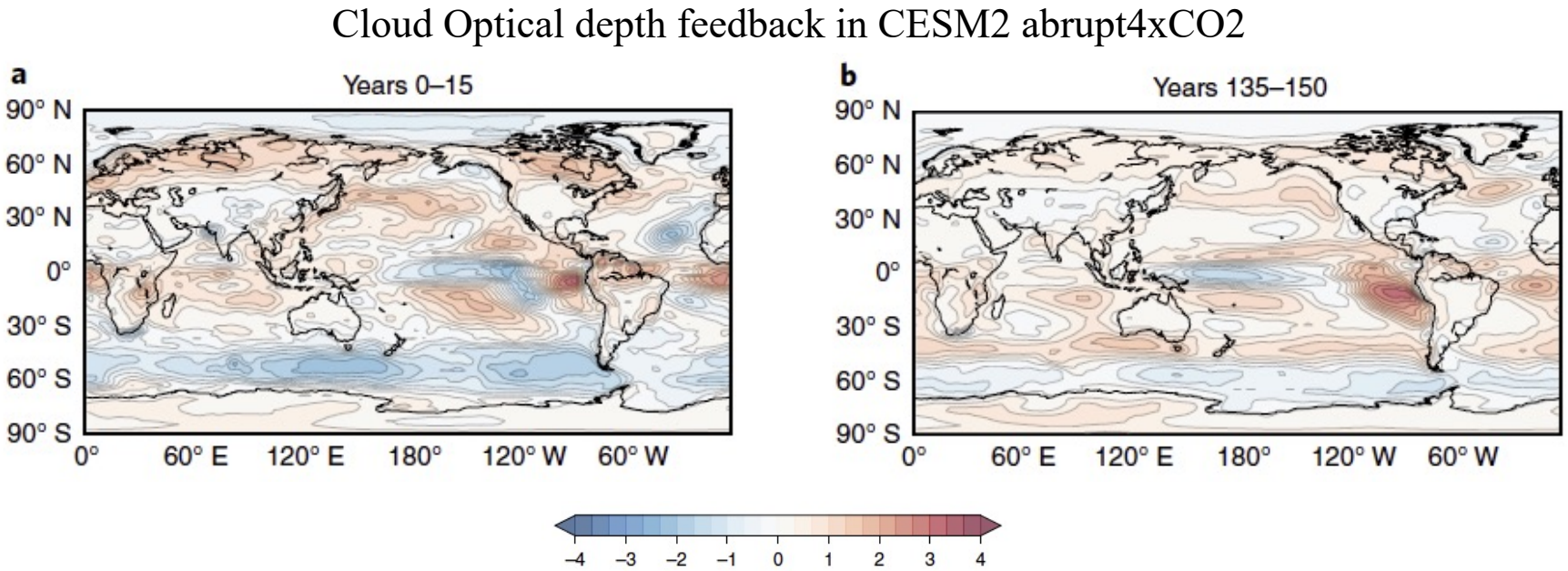


Dong et al. 2020 (*J. Climate*)

Summary and outlook

Methodology: How useful are the Green's functions for understanding the pattern effect?

- To what extent the key feedback processes are linear/nonlinear w/t to local or global warming?
  - Nonlinearity of feedbacks (Bloch-Johnson 2015; 2021; Meraner et al. 2013)



Nonlinear state-dependence of Southern Ocean mixed-phase clouds in a CMIP6 model

Bjordal et al. 2021 (*Nat. Geo.*)

Non-constant λ

λ dependence on surface heat flux patterns

Differences in temperature and cloud response to tropical/extratropical OHU

λ dependence on surface temperature patterns

Tropical low-cloud feedback and lapse-rate feedback sensitive to the tropical Pacific zonal SST gradient

Reconcile the two perspectives

The OHU pattern effect comes about through changing SST pattern

Yue Dong
(yd2644@columbia.edu)