

# Inter-model Spread in CMIP5/CMIP6 ECS, Feedbacks, and Feedback Kinkiness

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**University of Washington**

Kyle Armour (UW)

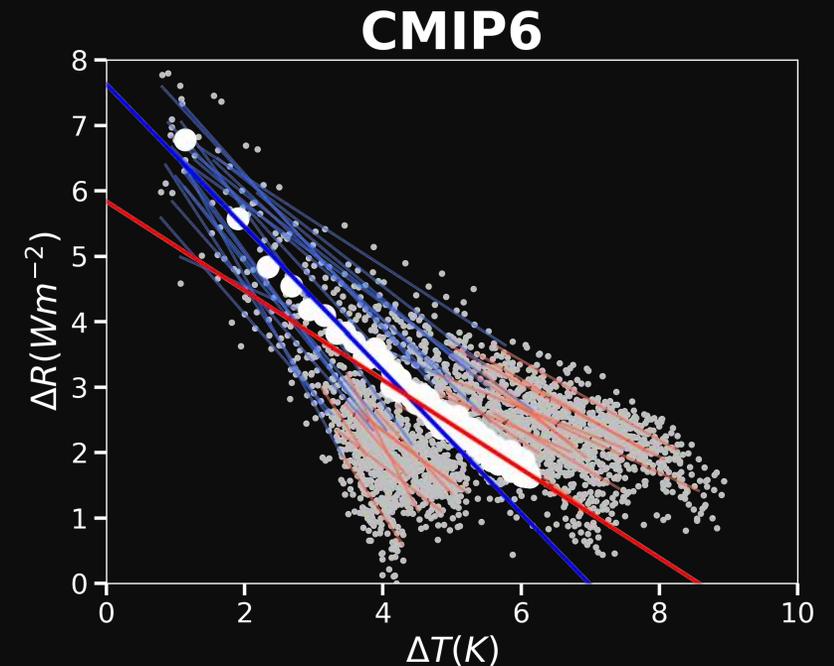
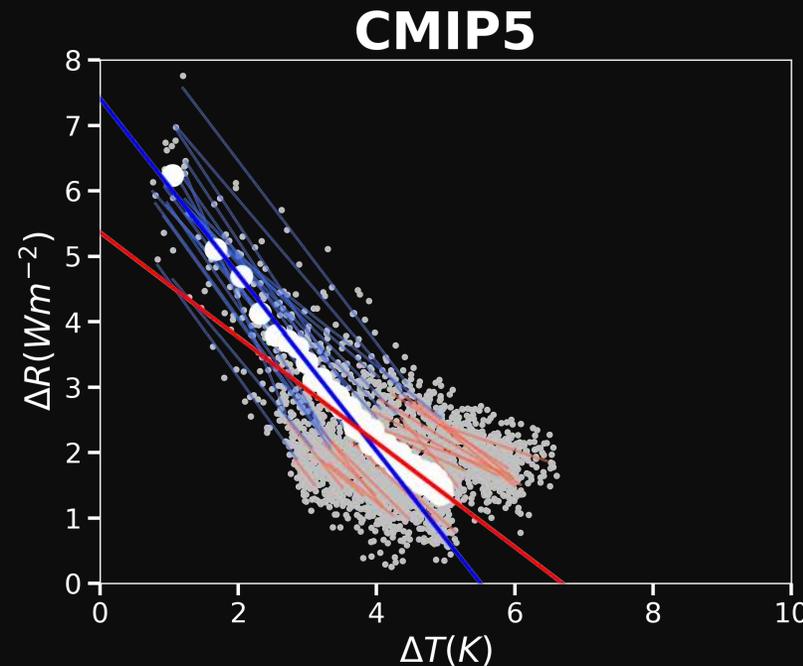
David Battisti (UW)

Cristian Proistosescu (UW)

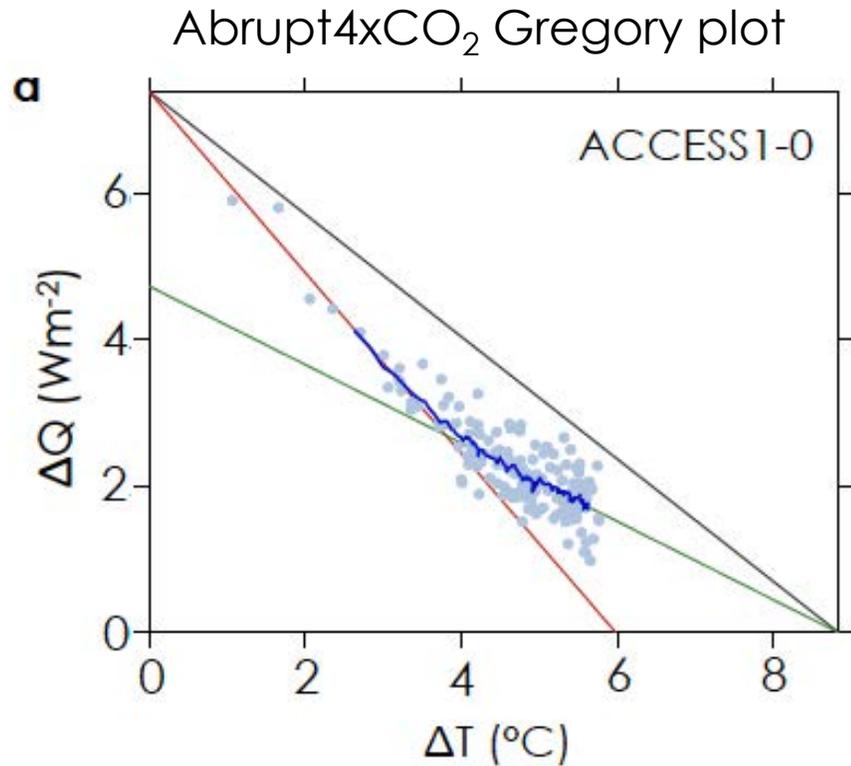
Mark Zelinka (LLNL)

Chen Zhou (NanJing Univeristy)

Steve Klein (LLNL)



# Time-varying feedbacks in CMIP5



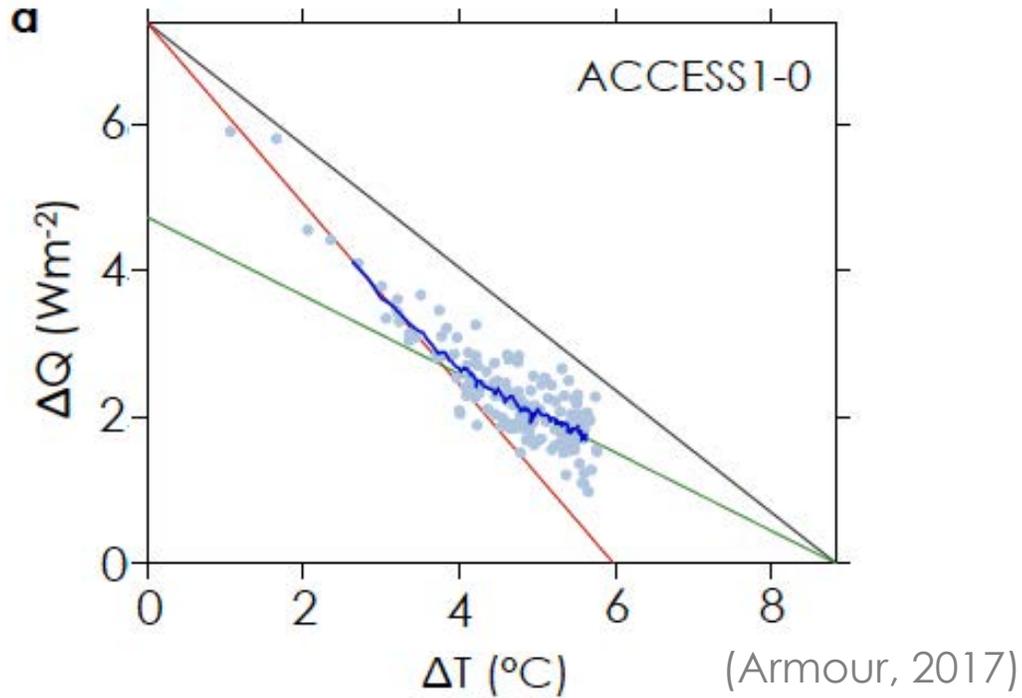
## “kinky” (time-varying) feedbacks

- Higher equilibrium climate sensitivity on longer time-scales
- Dependence on SST patterns

(Armour et al. 2013; Andrews et al. 2015; Zhou et al. 2016; Andrews and Webb 2017; Dong et al. 2019)

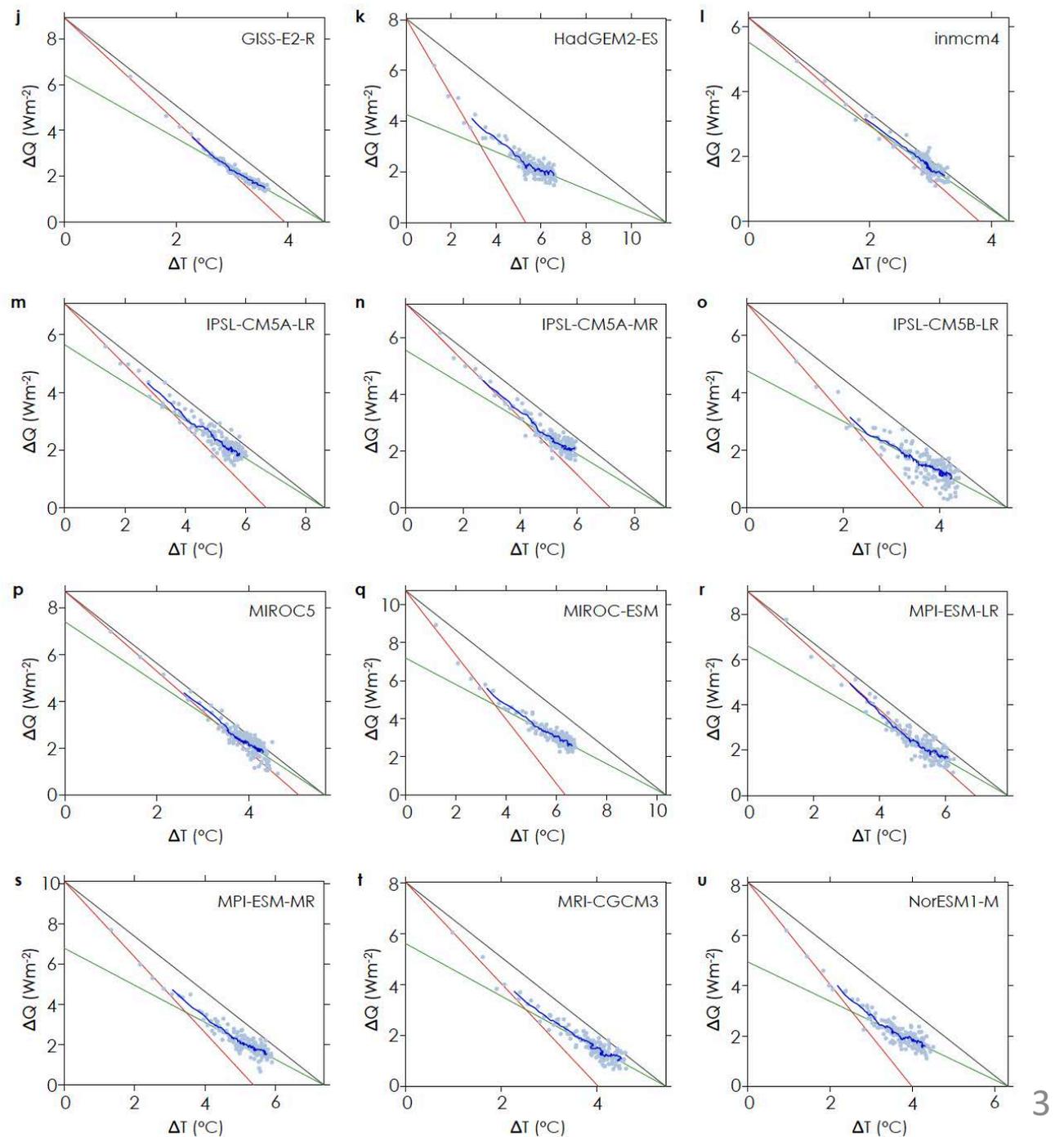
# Time-varying feedback

Abrupt4xCO<sub>2</sub> Gregory plot

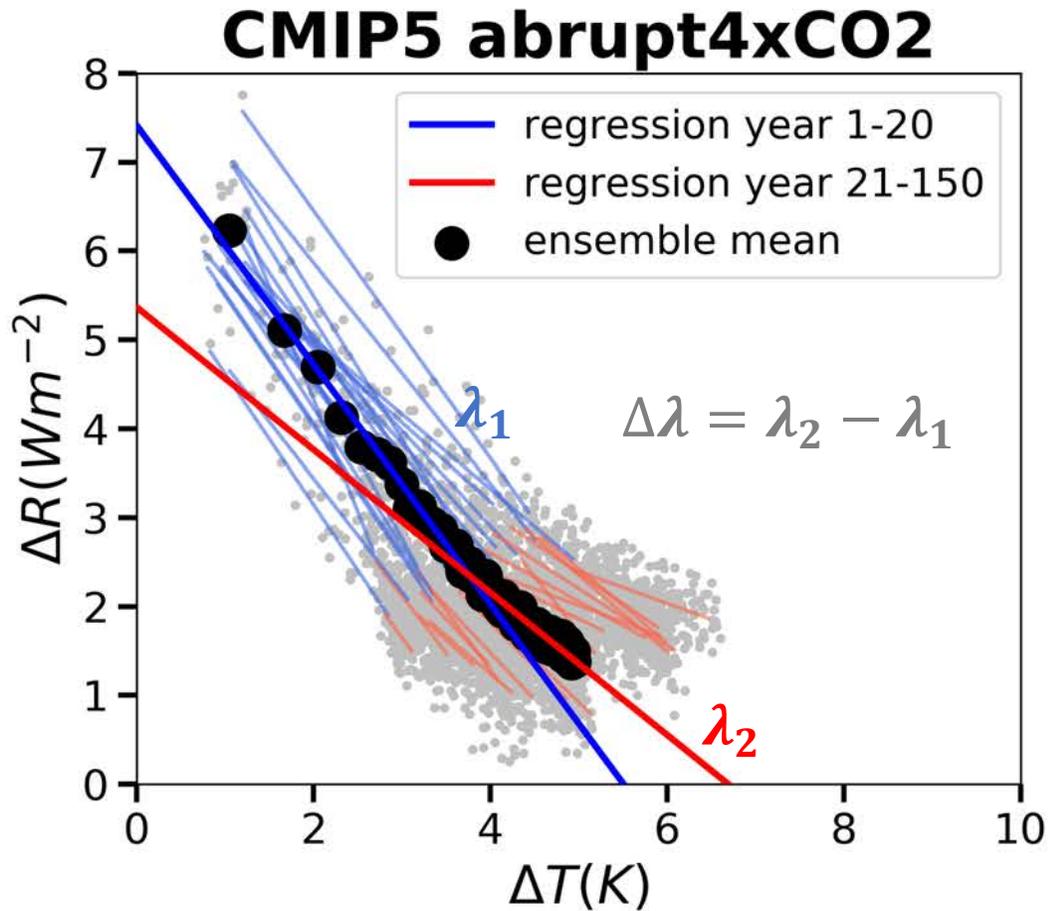


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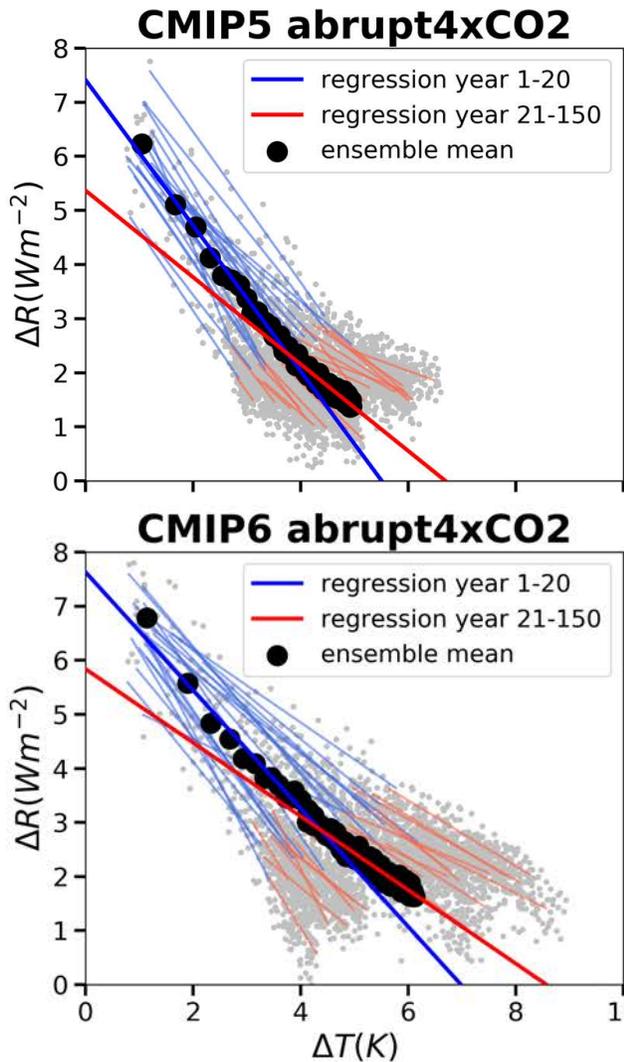
**The degree of kinkiness (time-variation) varies across models... but why?**



# Overview of CMIP5 and CMIP6 Feedbacks



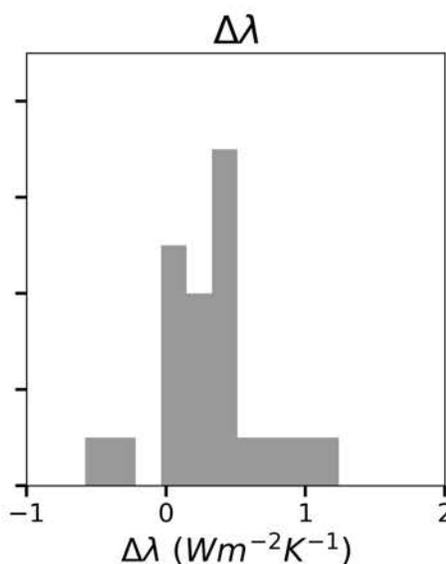
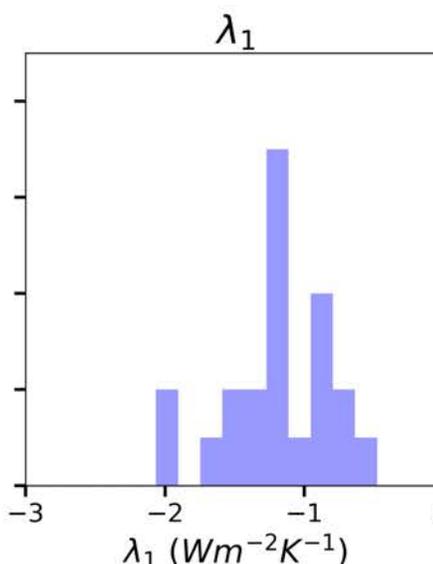
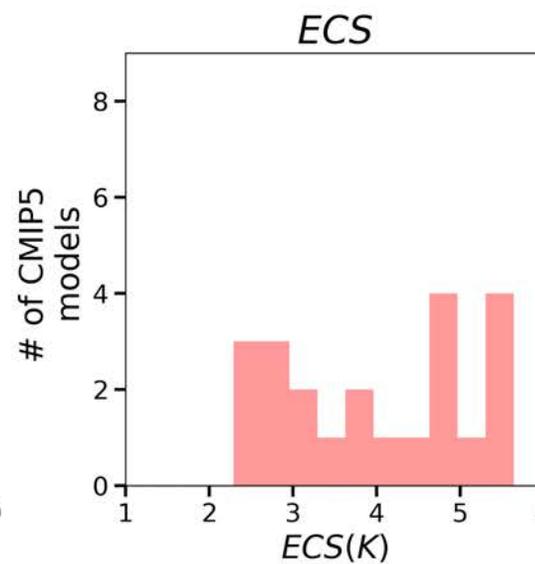
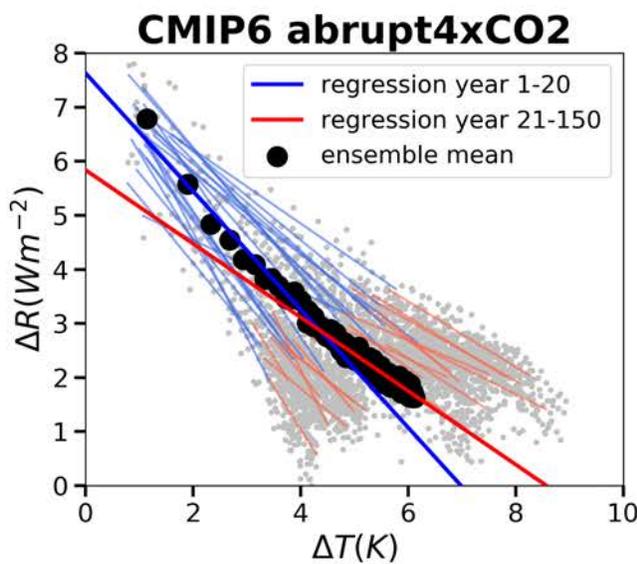
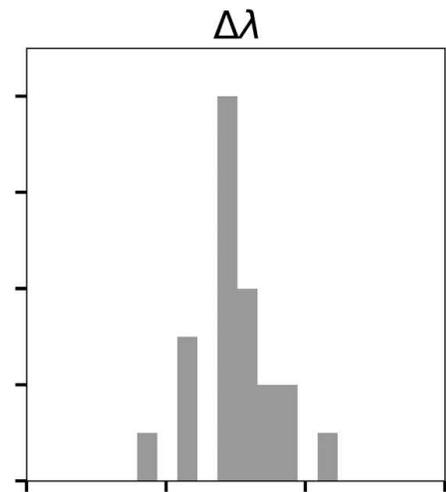
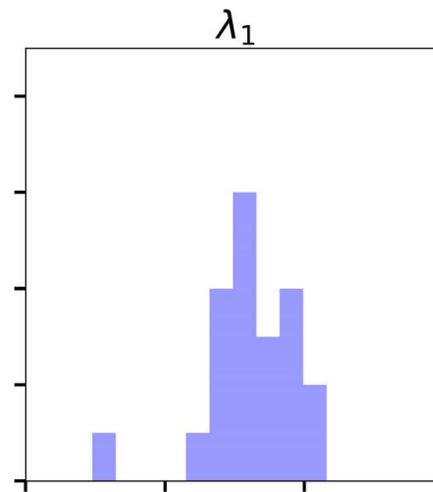
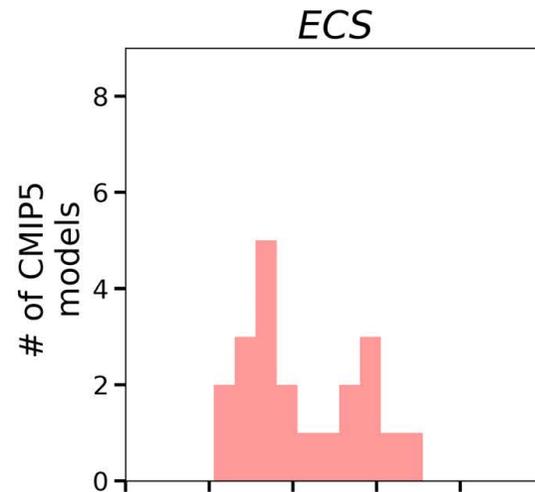
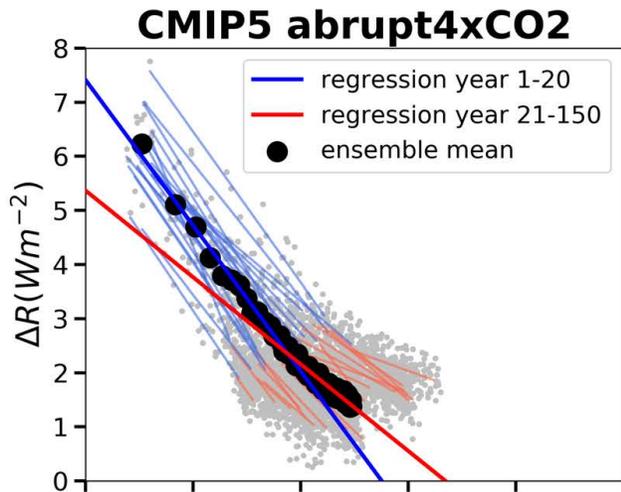
# Overview of CMIP5 and CMIP6 Feedbacks



Does curvature contribute to higher ECS in CMIP6?

CMIP6: Higher *Inferred* climate sensitivity

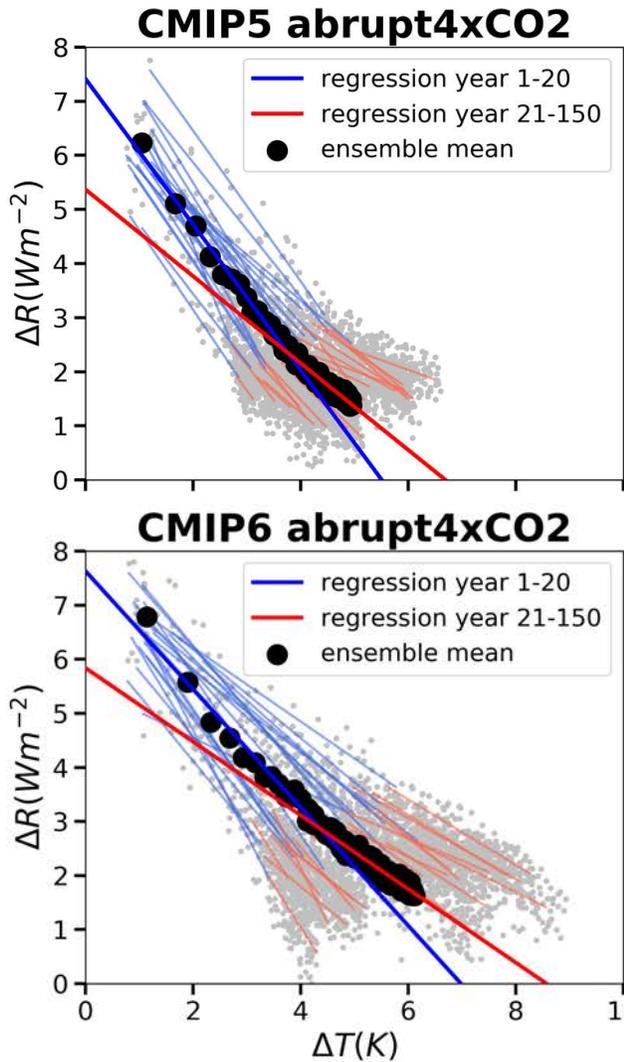
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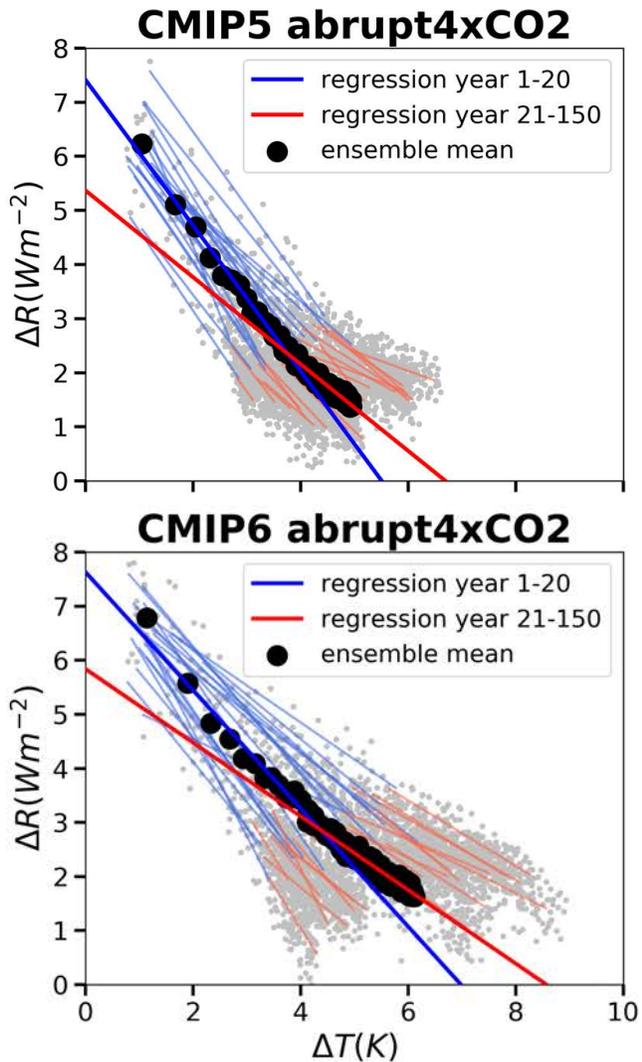
CMIP6: Higher *Inferred* climate sensitivity

Less-negative  $\lambda_1$  + Smaller  $\Delta\lambda$

# Overview of CMIP5 and CMIP6 Feedbacks



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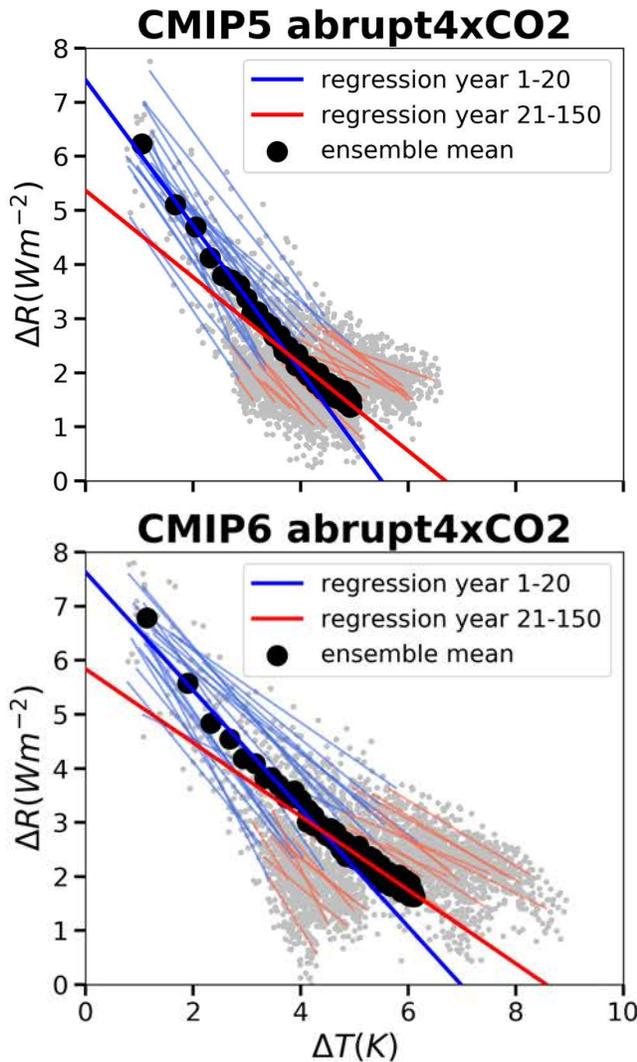
## 1. Dependence of $\Delta\lambda$ on SST patterns in individual GCMs or multi-model mean

Gregory and Andrews 2016 (HadGEM2/HadCM3)

Zhou et al. 2016 (CAM5); Dong et al. 2019 (CAM4)

Silvers et al. 2018 (GFDL); Ceppi and Gregory 2017 (Multi-model Mean)

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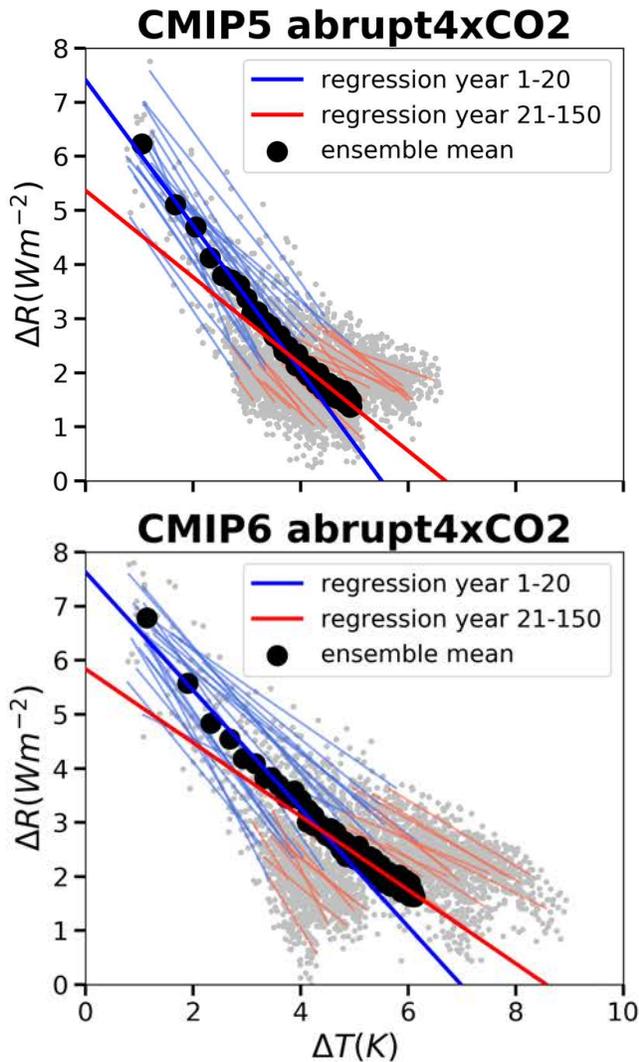
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Q: What drives the **inter-model spread in  $\Delta\lambda$** ?

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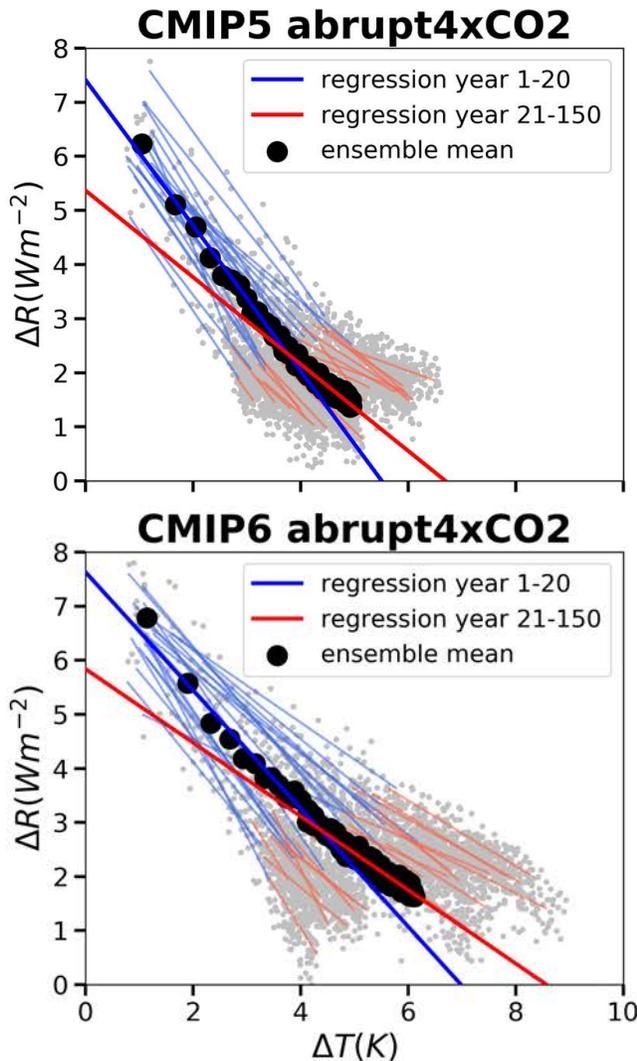
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## 2. Major source of ECS spread -> cloud feedback -> Model radiative-physics (low cloud response)

Soden and Held 2006; Dufresne and Bony 2008; Webb et al. 2013;

Caldwell et al 2016

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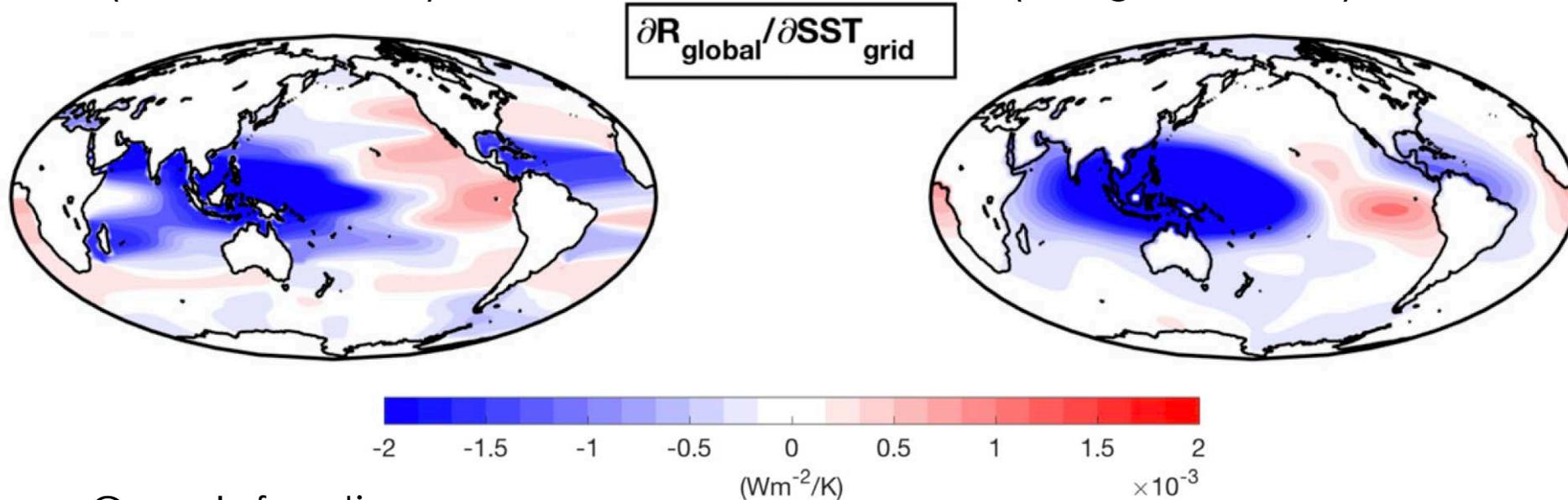
Caldwell et al 2016

Q: To what degree  $\Delta\lambda$  differences **contribute to ECS spread** (How much do SST pattern differences contribute to ECS)?

# Using Green's functions to isolate pattern effect

CAM5 Green's function  
(Zhou et al. 2017)

CAM4 Green's function  
(Dong et al. 2019)

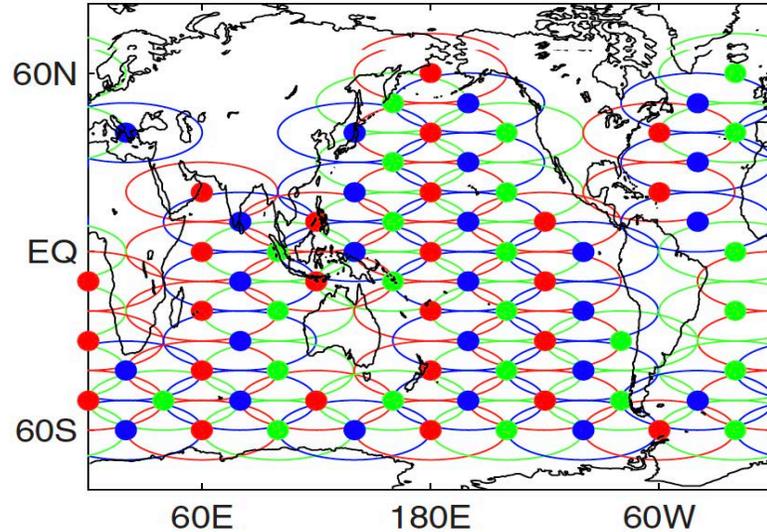


Green's functions:

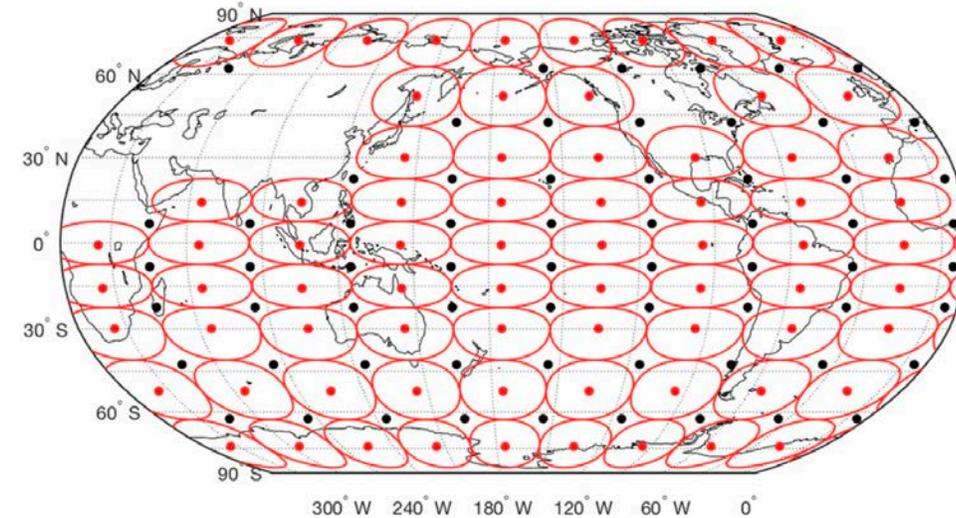
- Sensitivity of global-averaged TOA radiation response to unit change in local SSTs of individual grids

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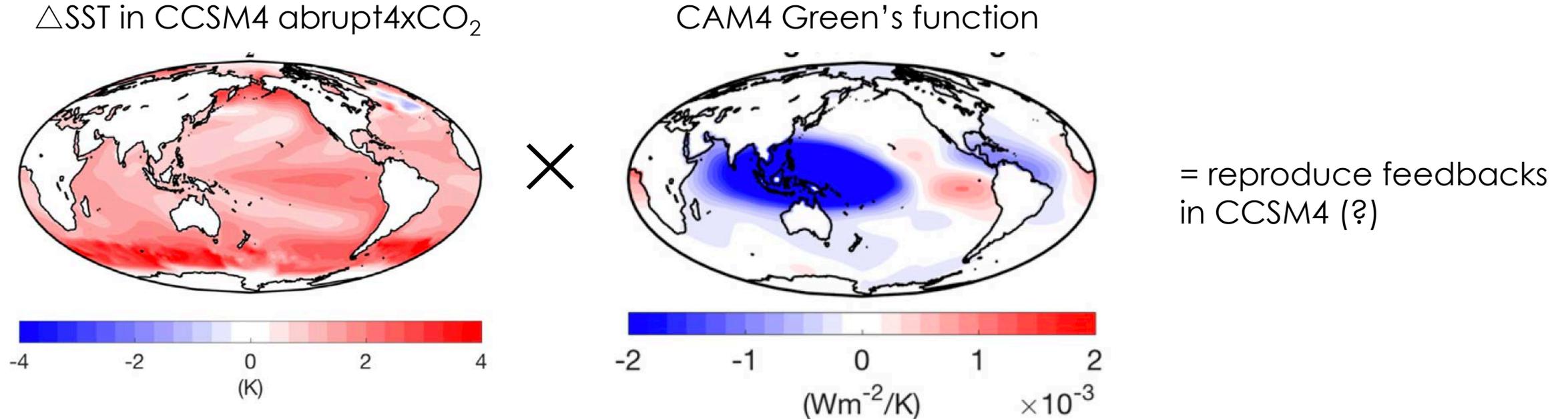
CAM4 Green's function  
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Green's functions:

- Sensitivity of global-averaged TOA radiation response to unit change in local SSTs of individual grids
- Derived from a suite of prescribed-SST simulations each with a localized patch of SST anomalies

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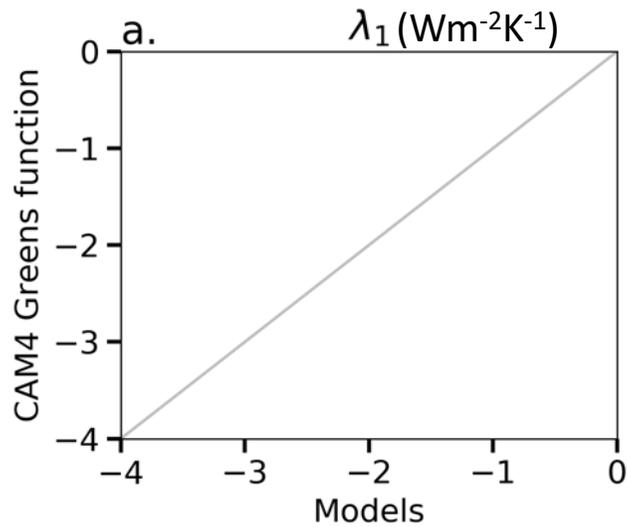


Green's functions:

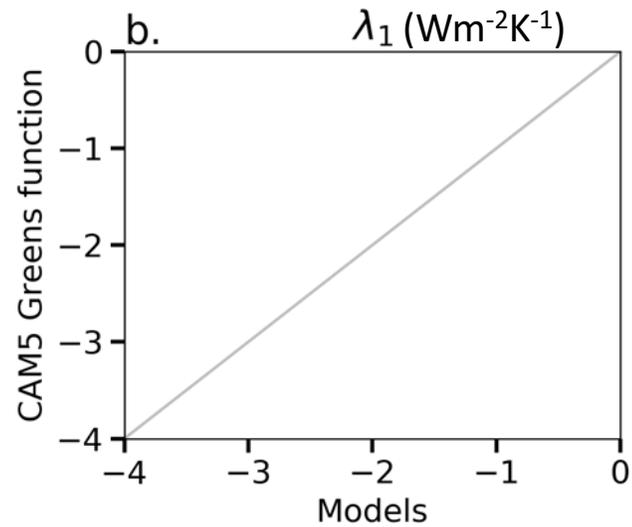
- Sensitivity of global-averaged TOA radiation response to unit change in local SSTs of individual grids (model-physics dependent)
- Derived from a suite of prescribed-SST simulations each with a localized patch of SST anomalies
- Convolution with any patterns of SST anomalies provides an estimate of the global response to that particular SST pattern

# Applying Green's functions to CMIP5 models

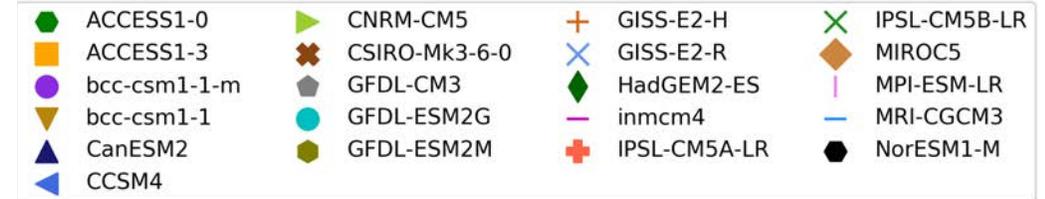
CAM4 reconstruction



CAM5 reconstruction

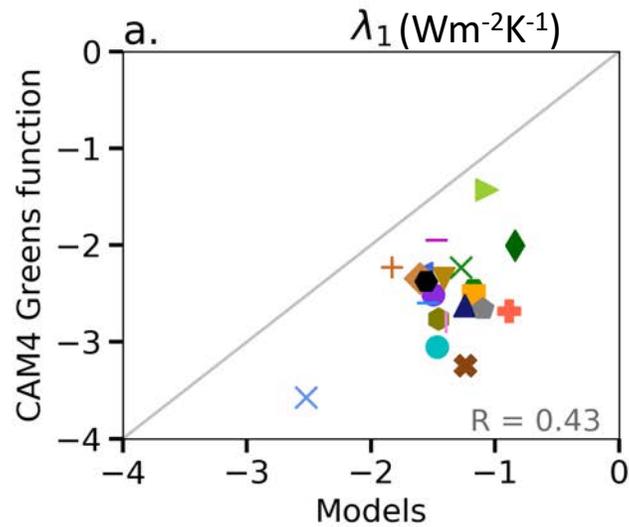


21 CMIP5 models

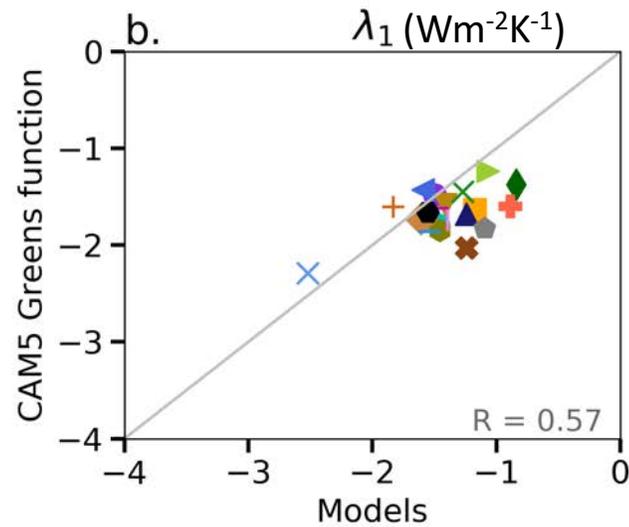


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CAM4 reconstruction



CAM5 reconstruction

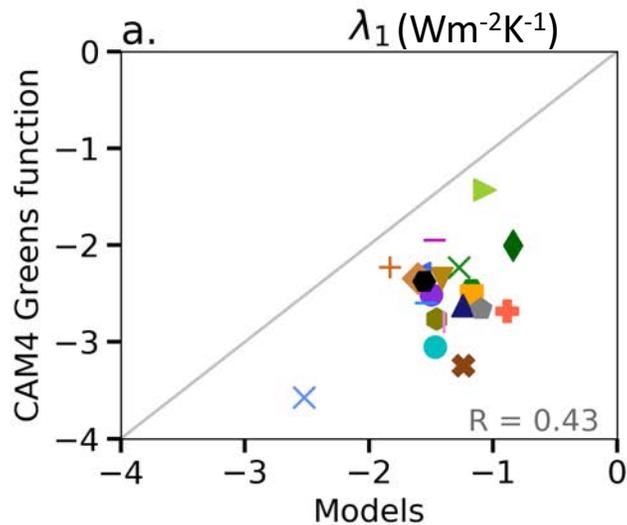


21 CMIP5 models

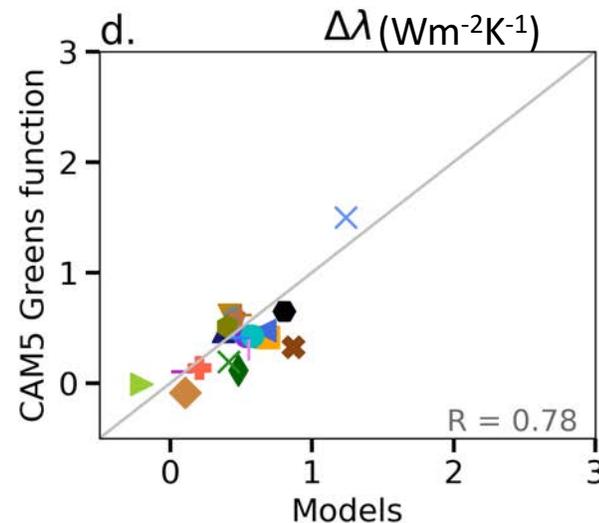
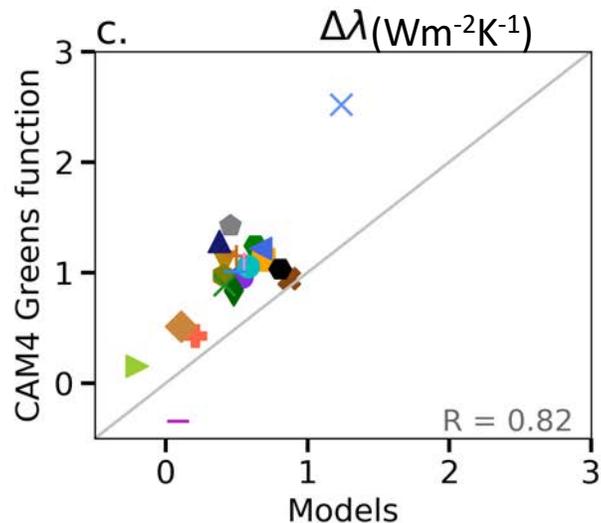
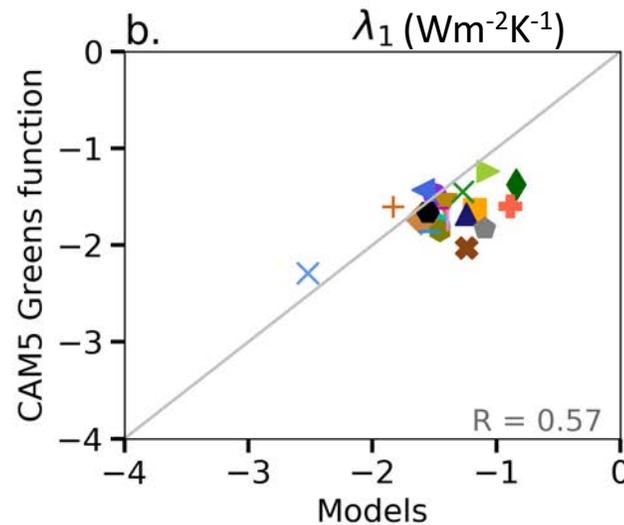


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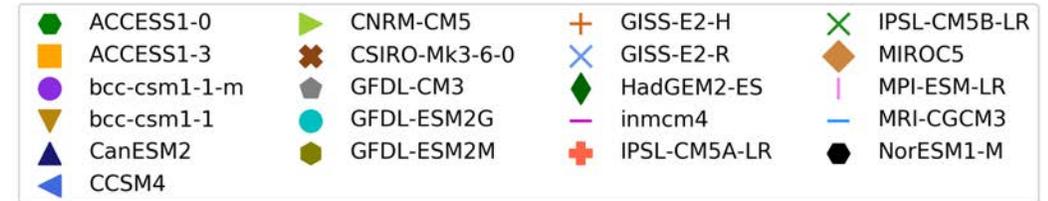
## CAM4 reconstruction



## CAM5 reconstruction



## 21 CMIP5 models



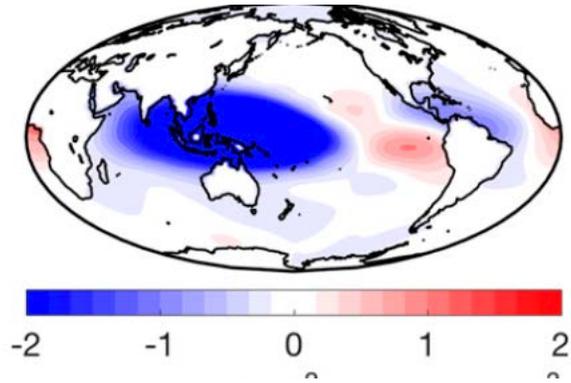
## Take-Home 1

$\lambda_1$  spread is primarily determined by each model's physics

$\Delta\lambda$  spread depends primarily on differences in SST patterns

# CMIP5 $\Delta\lambda$ traced to surface warming patterns

$dR_{\text{global}}/dSST_{\text{grid}}$  (CAM4)



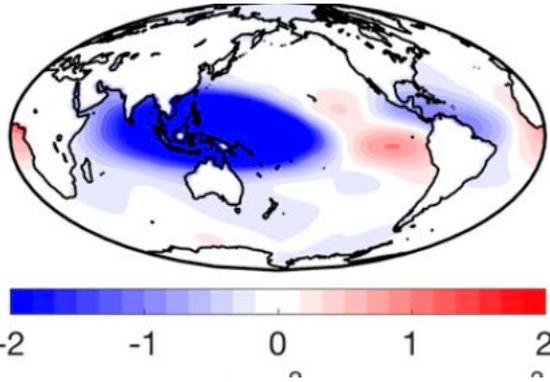
Dong et al. 2019

$\Delta\lambda$  is driven by  $\gamma(t) = \frac{\Delta SST_{WP}}{\Delta T}$  Warm-Pool warming ratio

for both historical patterns and abrupt4xCO2 patterns within CAM4

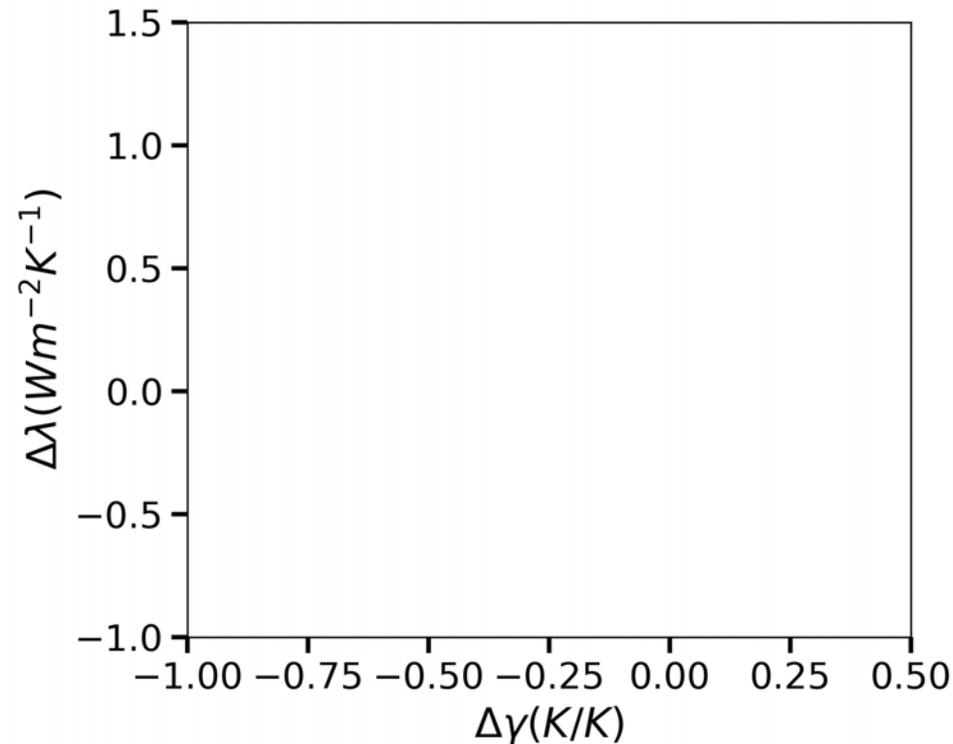
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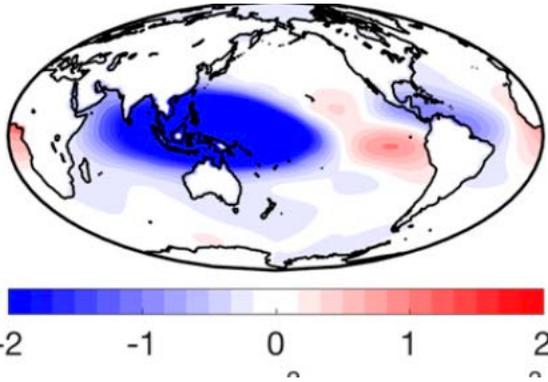


21 CMIP5 models

- |                 |                |
|-----------------|----------------|
| ● ACCESS1-0     | + GISS-E2-H    |
| ■ ACCESS1-3     | × GISS-E2-R    |
| ● bcc-csm1-1-m  | ◆ HadGEM2-ES   |
| ▼ bcc-csm1-1    | — inmcm4       |
| ▲ CanESM2       | + IPSL-CM5A-LR |
| ▲ CCSM4         | × IPSL-CM5B-LR |
| ▲ CNRM-CM5      | ◆ MIROC5       |
| × CSIRO-Mk3-6-0 | — MPI-ESM-LR   |
| ■ GFDL-CM3      | — MRI-CGCM3    |
| ● GFDL-ESM2G    | ● NorESM1-M    |
| ● GFDL-ESM2M    |                |

# CMIP5 $\Delta\lambda$ traced to surface warming patterns

$dR_{\text{global}}/dSST_{\text{grid}}$  (CAM4)

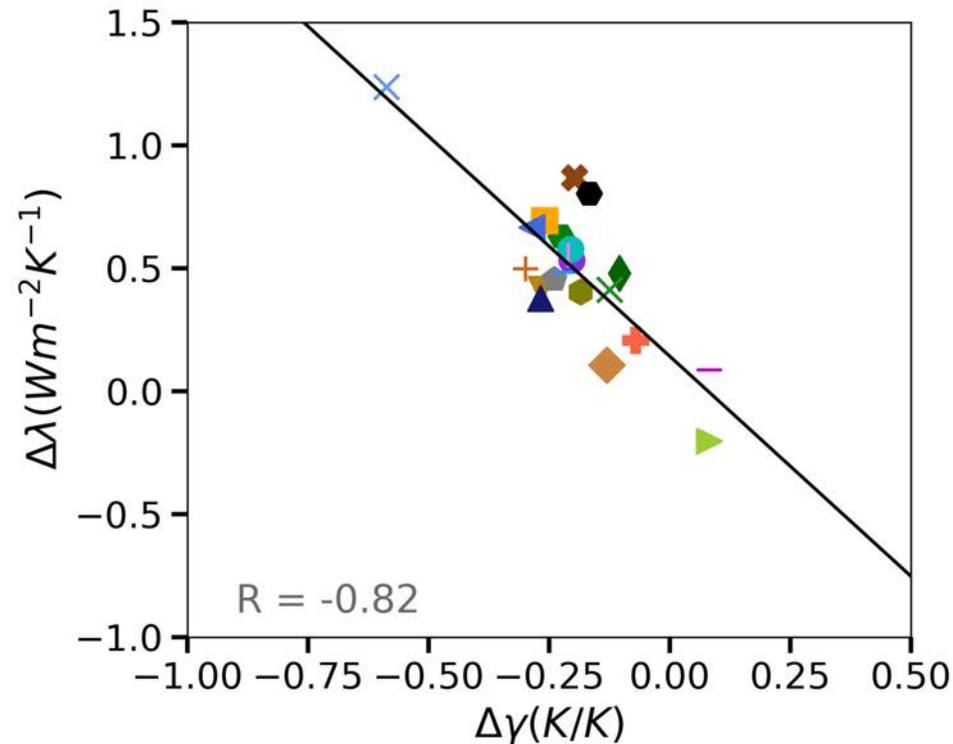


Dong et al. 2019

$\Delta\lambda$  is driven by  $\gamma(t) = \frac{\Delta SST_{WP}}{\Delta T}$  Warm-Pool warming ratio

## Take-Home 2

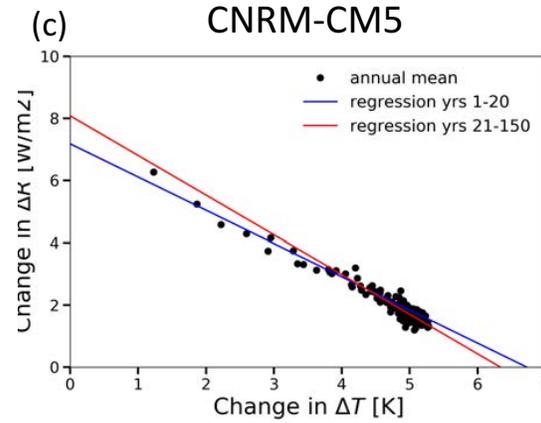
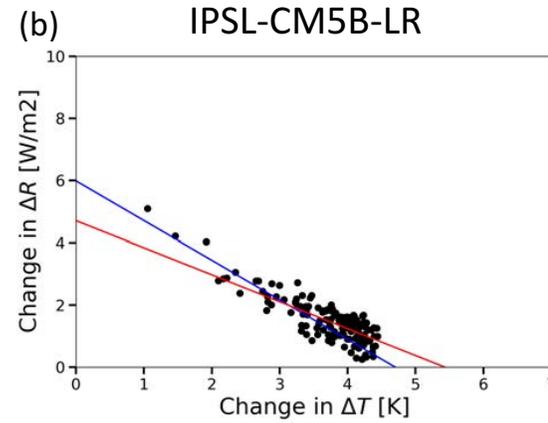
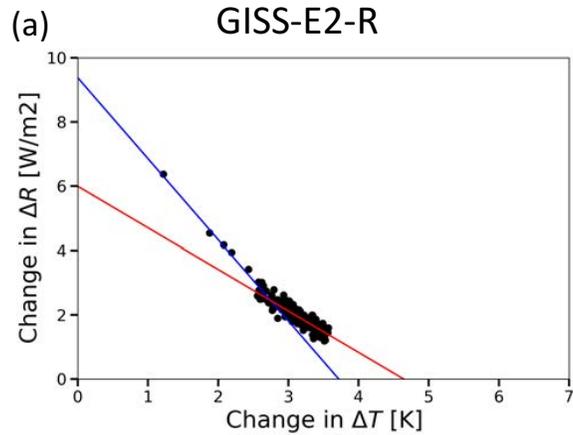
$\Delta\lambda$  tracks the ratio of changes in Warm-pool SSTs over changes in global-mean T, for all CMIP5 models



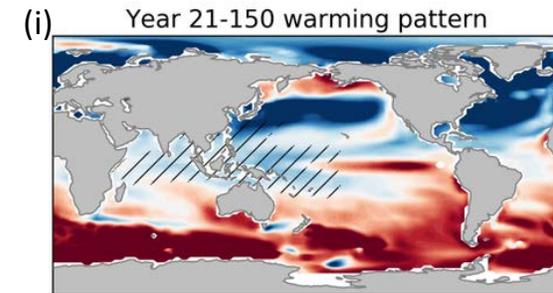
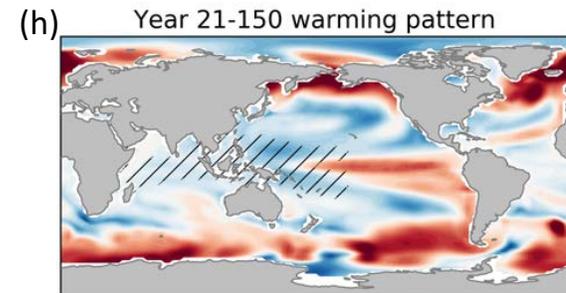
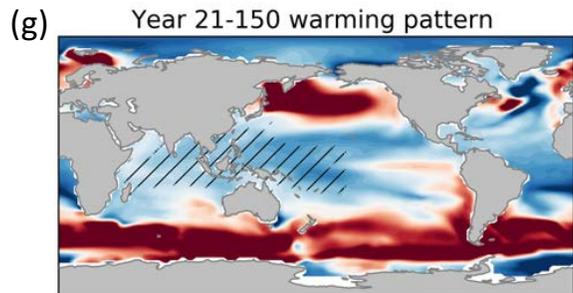
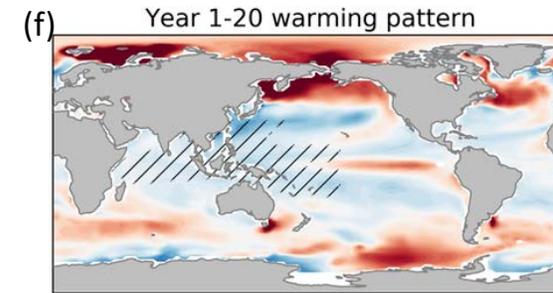
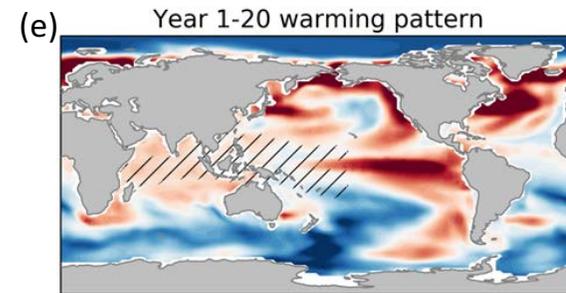
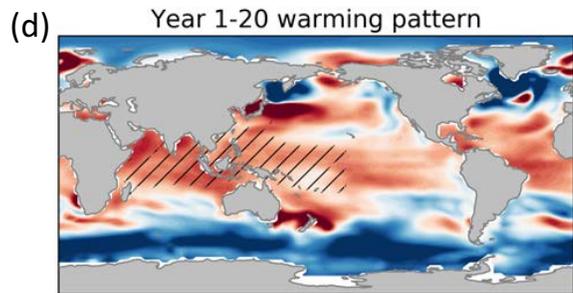
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| × CSIRO-Mk3-6-0 | — MPI-ESM-LR   |
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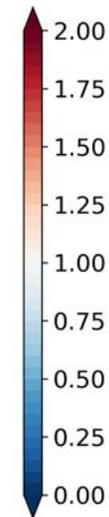
# CMIP5 $\Delta\lambda$ traced to surface warming patterns



- annual mean
- regression yrs 1-20
- regression yrs 21-150



**Faster than global-mean**



Local  $\Delta$ SST regressed against global-mean  $\Delta$ SST [K/K]

**Slower than global-mean**

# Implications for CMIP5 ECS

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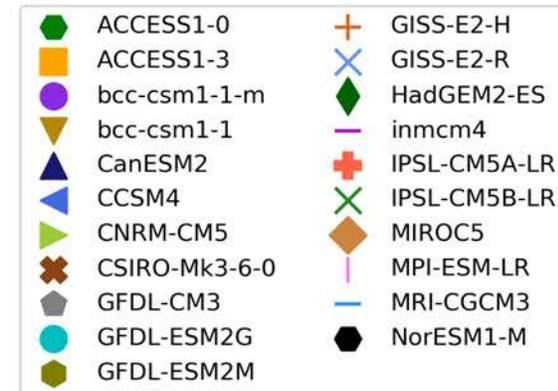
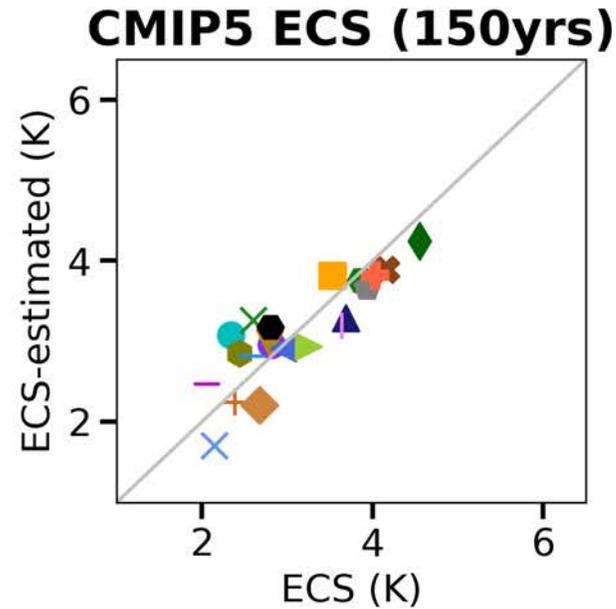
ECS decomposition  
(multi-regression)

Model physics    Pattern effect  
$$\text{ECS} = a\lambda_1 + b\Delta\lambda + res$$

# Implications for CMIP5 ECS

ECS decomposition  
(multi-regression)

Model physics    Pattern effect  
$$\text{ECS} = a\lambda_1 + b\Delta\lambda + \text{res}$$



$$R^2 = 0.74$$

$$R^2(\lambda_1) = 0.55$$

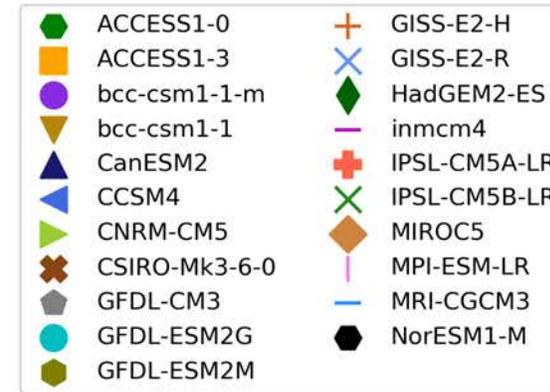
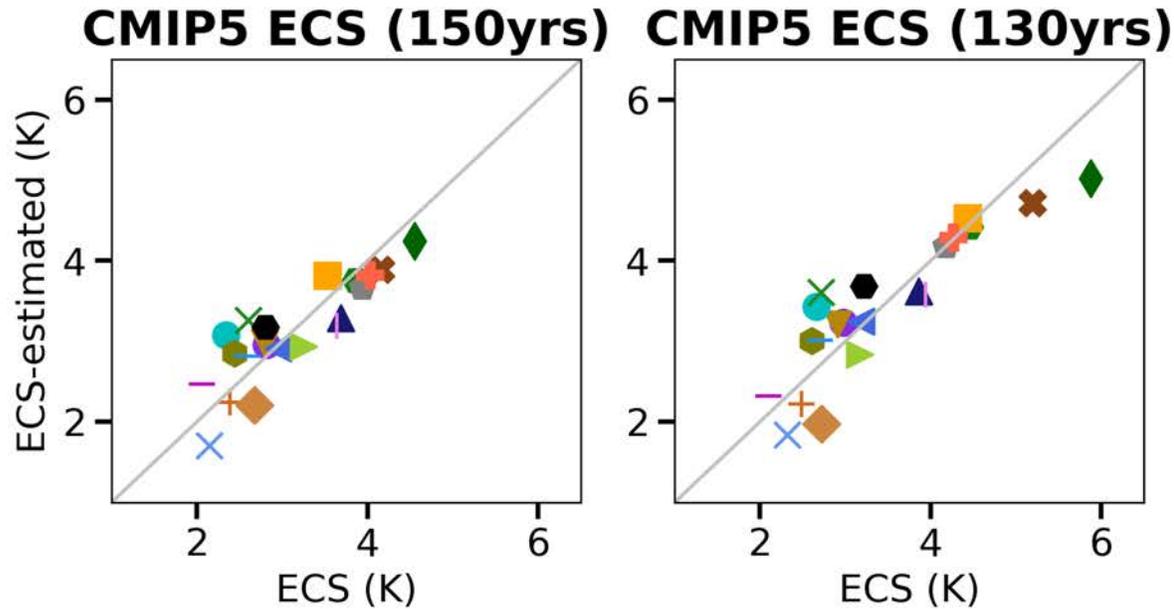
$$R^2(\Delta\lambda) = 0$$

# Implications for CMIP5 ECS

ECS decomposition  
(multi-regression)

Model physics    Pattern effect  

$$\text{ECS} = a\lambda_1 + b\Delta\lambda + \text{res}$$



$$R^2 = 0.74$$

$$R^2(\lambda_1) = 0.55$$

$$R^2(\Delta\lambda) = 0$$

$$R^2 = 0.79$$

$$R^2(\lambda_1) = 0.46$$

$$R^2(\Delta\lambda) = 0.02$$

Take-Home 3

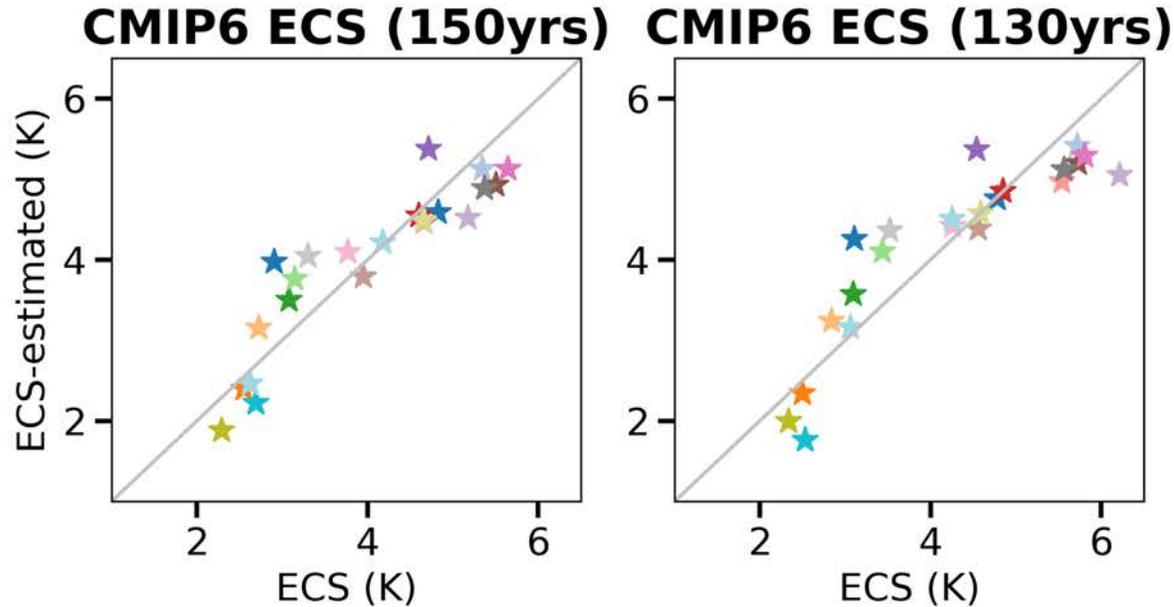
Major source of the ECS spread is  $\lambda_1$  (model physics), rather than warming patterns.

# Implications for CMIP6 ECS

ECS decomposition  
(multi-regression)

Model physics    Pattern effect  

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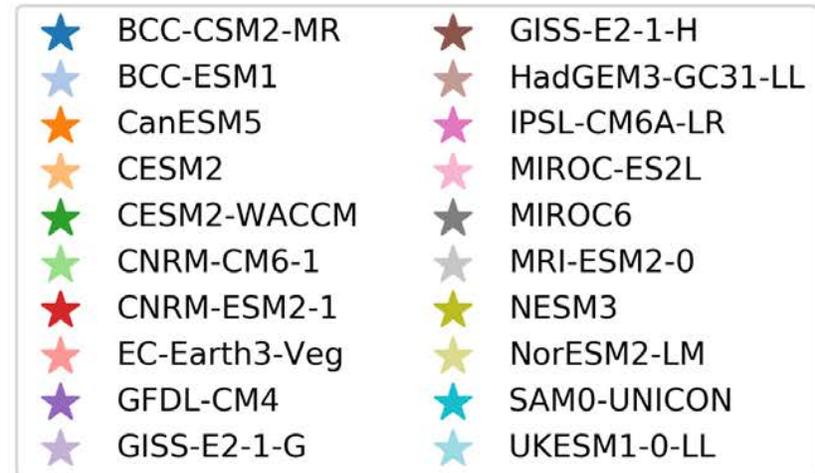


$R^2 = 0.81$

$R^2(\lambda_1) = 0.7$   
 $R^2(\Delta\lambda) = 0$

$R^2 = 0.78$

$R^2(\lambda_1) = 0.53$   
 $R^2(\Delta\lambda) = 0.02$

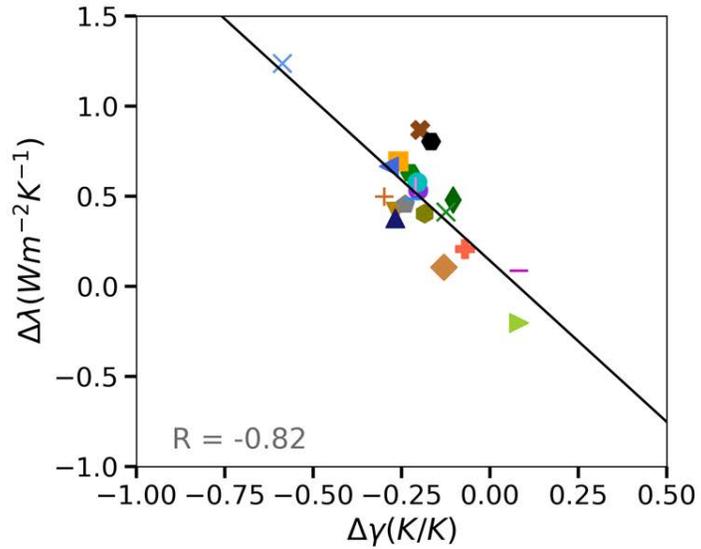


Take-Home 3

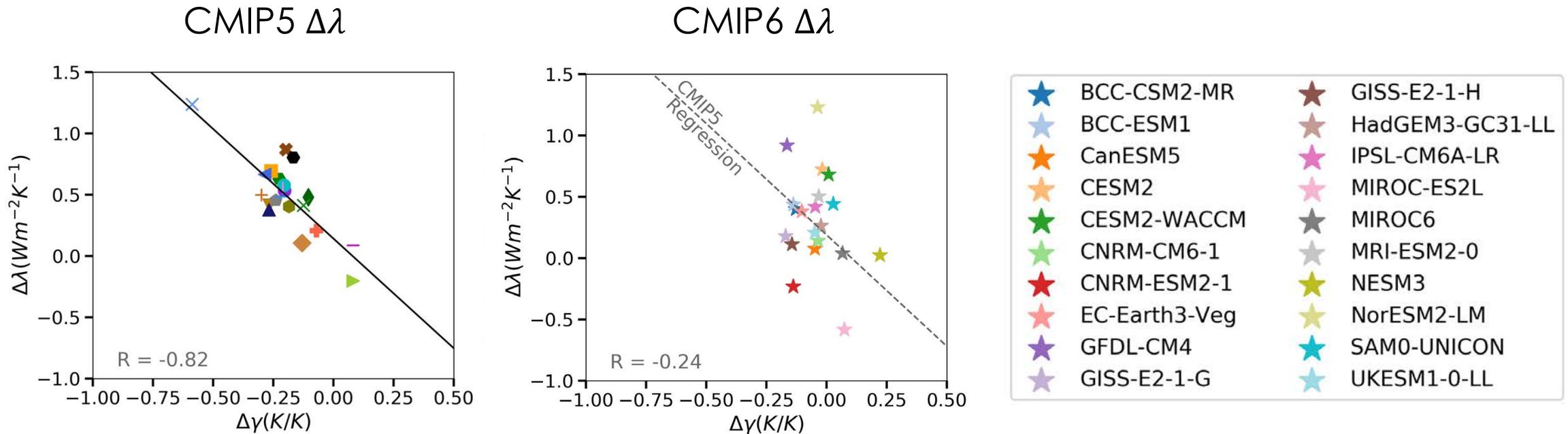
Major source of the ECS spread is  $\lambda_1$  (model physics), rather than warming patterns  
 ... True for both CMIP5 and CMIP6

# Inter-model spread in CMIP6 feedbacks

CMIP5  $\Delta\lambda$

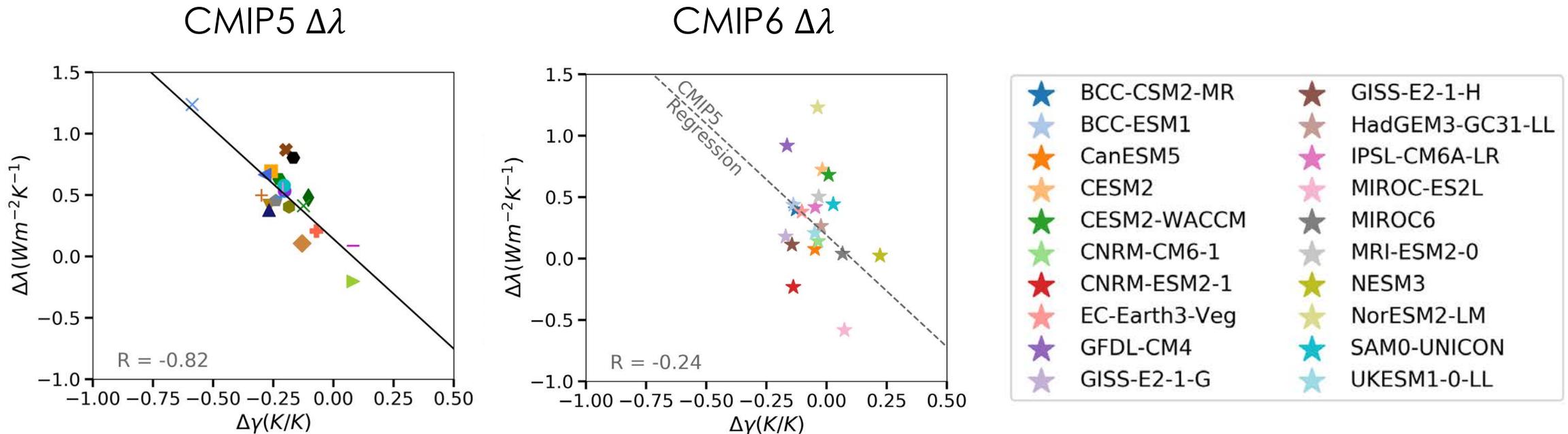


# Inter-model spread in CMIP6 feedbacks



CMIP6  $\Delta\lambda$  do not track warm-pool warming ratio ( $\Delta\gamma$ )

# Inter-model spread in CMIP6 feedbacks



CMIP6  $\Delta\lambda$  do not track warm-pool warming ratio ( $\Delta\gamma$ )

Speculation:

**Stronger or Nonlinear** global TOA/CRE radiation dependence out of tropics, e.g. Southern Ocean mixed-phase clouds ?

Bodas-Salcedo et al. 2019 (new mixed-phase scheme in HadGEM3)

# Summary

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## CMIP5

## CMIP6

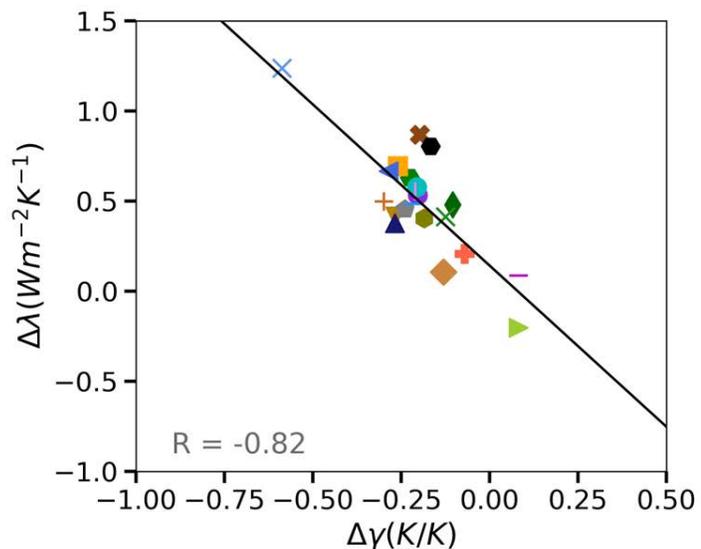
- Inter-model spread in ECS is mainly from  $\lambda_1$  (initial slope), rather than  $\Delta\lambda$  (curvature)
- $\lambda_1$  spread is primarily governed by model physics
- $\Delta\lambda$  spread is primarily governed by surface warming patterns

# Summary

## CMIP5

- Inter-model spread in ECS is mainly from  $\lambda_1$  (initial slope), rather than  $\Delta\lambda$  (curvature)
- $\lambda_1$  spread is primarily governed by model physics
- $\Delta\lambda$  spread is primarily governed by surface warming patterns

➤  $\Delta\lambda$  is well explained by warm-pool warming ratio



## CMIP6

➤ No clear relation between  $\Delta\lambda$  and  $\Delta\gamma$

