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

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CMIP5

CMIP6
“kinky” (time-varying) feedbacks

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

“kinky” (time-varying) feedbacks

The degree of kinkiness (time-variation) varies across models... but why?
Overview of CMIP5 and CMIP6 Feedbacks

\[ \Delta \lambda = \lambda_2 - \lambda_1 \]
Overview of CMIP5 and CMIP6 Feedbacks

CMIP6: Higher inferred climate sensitivity

Does curvature contribute to higher ECS in CMIP6?
Overview of CMIP5 and CMIP6 Feedbacks

CMIP6: Higher inferred climate sensitivity
Less-negative $\lambda_1$ + Smaller $\Delta \lambda$
Overview of CMIP5 and CMIP6 Feedbacks
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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Q: What drives the inter-model spread in $\Delta \lambda$?
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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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   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
Using Green’s functions to isolate pattern effect

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
Using Green’s functions to isolate pattern effect

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
- Convolving with any patterns of SST anomalies provides an estimate of the global response to that particular SST pattern

\[ \Delta \text{SST in CCSM4 abrupt4xCO}_2 \times \text{CAM4 Green's function} = \text{reproduce feedbacks in CCSM4 (\?)} \]
Applying Green’s functions to CMIP5 models

CAM4 reconstruction

CAM5 reconstruction

21 CMIP5 models

ACCESS1-0
ACCESS1-3
CSIRO-Mk3-6-0
GISS-E2-H
GISS-E2-R
MIROC5
MIROCS
MPI-ESM-LR
MRI-CGCM3
NorESM1-M

ACCESS1-0
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Applying Green’s functions to CMIP5 models

CAM4 reconstruction

\[ \lambda_1 \text{ (Wm}^{-2}\text{K}^{-1}) \]

CAM5 reconstruction

\[ \lambda_1 \text{ (Wm}^{-2}\text{K}^{-1}) \]

21 CMIP5 models

- ACCESS1-0
- ACCESS1-3
- bcc-csm1-1-m
- bcc-csm1-1
- CanESM2
- CNRM-CM5
- CSIRO-Mk3-6-0
- GFDL-CM3
- GFDL-ESM2G
- GFDL-ESM2M
- HadGEM2-ES
- IPSL-CM5A-LR
- IPSL-CM5B-LR
- INM-CM4-8
- IPSL-CM5A-LR
- IPSL-CM5B-LR
- MIRCA
- MPI-ESM-LR
- NorESM1-M

R = 0.43
R = 0.57
Applying Green’s functions to 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

$\frac{dR_{\text{global}}}{dSST_{\text{grid}}}$ (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
CMIP5 $\Delta \lambda$ traced to surface warming patterns

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

$\Delta SST_{WP}$

Dong et al. 2019

21 CMIP5 models

- ACCESS1-0
- ACCESS1-3
- bcc-csm1-1-m
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- CanESM2
- CCSM4
- CNRM-CM5
- CSIRO-Mk3-6-0
- GFDL-CM3
- GFDL-ESM2G
- GFDL-ESM2M
- GISS-E2-H
- GISS-E2-R
- HadGEM2-ES
- inmcm4
- IPSL-CM5A-LR
- IPSL-CM5B-LR
- MIROC5
- MPI-ESM-LR
- MRI-CGCM3
- NorESM1-M
CMIP5 $\Delta \lambda$ traced to surface warming patterns

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

$\Delta \lambda$ is driven by $\gamma(t) = \frac{\Delta SST_{WP}}{\Delta T}$  

Warm-Pool warming ratio  

Dong et al. 2019

Take-Home 2

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

21 CMIP5 models

$\Delta \lambda (W/m^{-2}K^{-1})$  

$R = -0.82$  

$\Delta \lambda$ tracks the ratio of changes in Warm-pool SSTs over changes in global-mean T, for all CMIP5 models.
CMIP5 $\Delta \lambda$ traced to surface warming patterns

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

- Faster than global-mean
- Slower than global-mean

Local $\Delta$SST regressed against global-mean $\Delta$SST [K/K]
### Implications for CMIP5 ECS

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ECS decomposition (multi-regression)

Model physics  
Pattern effect

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

**CMIP5 ECS (150yrs)**

\[ R^2 = 0.74 \]

\[ R^2(\lambda_1) = 0.55 \]

\[ R^2(\Delta\lambda) = 0 \]

Implications for CMIP5 ECS
Implications for CMIP5 ECS

**ECS decomposition (multi-regression)**

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

**Model physics**

- \( R^2 = 0.74 \)
- \( R^2(\lambda_1) = 0.55 \)
- \( R^2(\Delta\lambda) = 0 \)

**Pattern effect**

- \( R^2 = 0.79 \)
- \( R^2(\lambda_1) = 0.46 \)
- \( R^2(\Delta\lambda) = 0.02 \)

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

$ECS = a\lambda_1 + b\Delta\lambda + res$

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 Δλ

R = -0.82
Inter-model spread in CMIP6 feedbacks

CMIP5 $\Delta \lambda$

CMIP6 $\Delta \lambda$

CMIP6 $\Delta \lambda$ do not track warm-pool warming ratio ($\Delta \gamma$)
Inter-model spread in CMIP6 feedbacks

CMIP5 $\Delta \lambda$

CMIP6 $\Delta \lambda$

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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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.

**CMIP6**

- $\Delta \lambda$ is well explained by warm-pool warming ratio.
- No clear relation between $\Delta \lambda$ and $\Delta \gamma$.

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