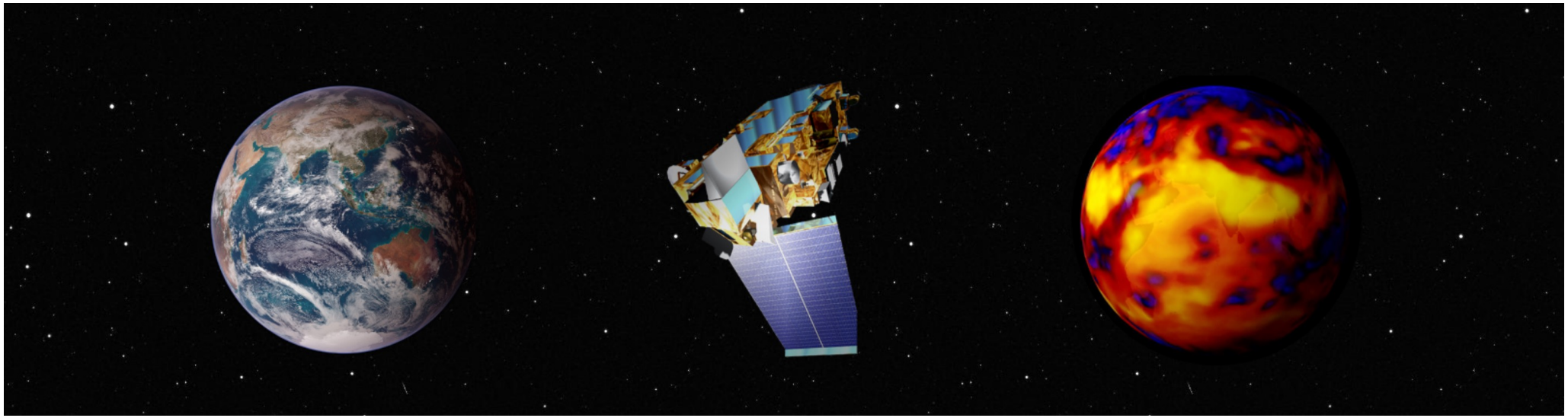
Forcing, Cloud Feedbacks, Cloud Masking, and Internal Variability in the Cloud Radiative Effect Satellite Record



NASA Langley CERES Science Team Meeting

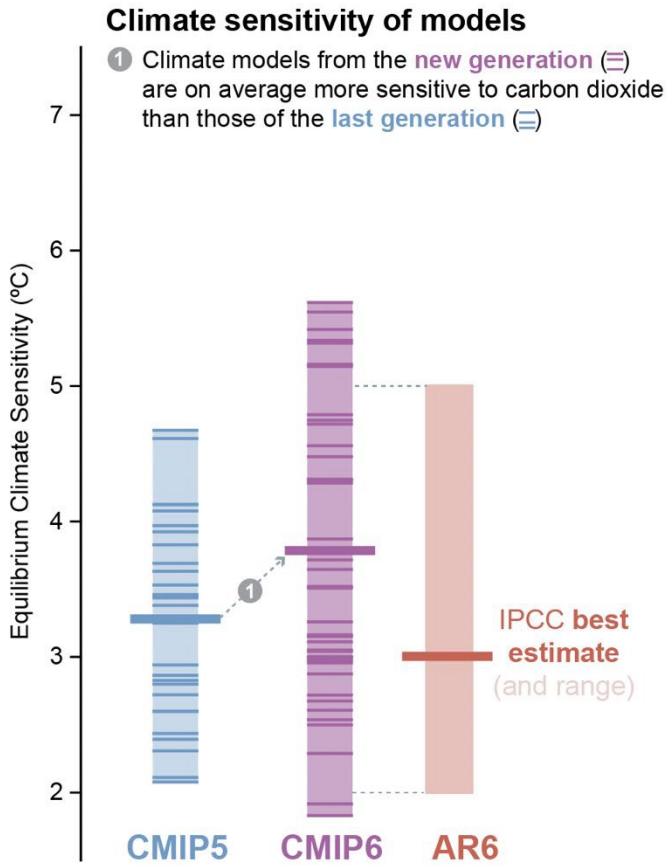
May 10th, 2023

Shiv Priyam Raghuraman (NCAR, formerly Princeton University), David Paynter (GFDL), Raymond Menzel (UCAR, GFDL), V. Ramaswamy (GFDL)

Outline

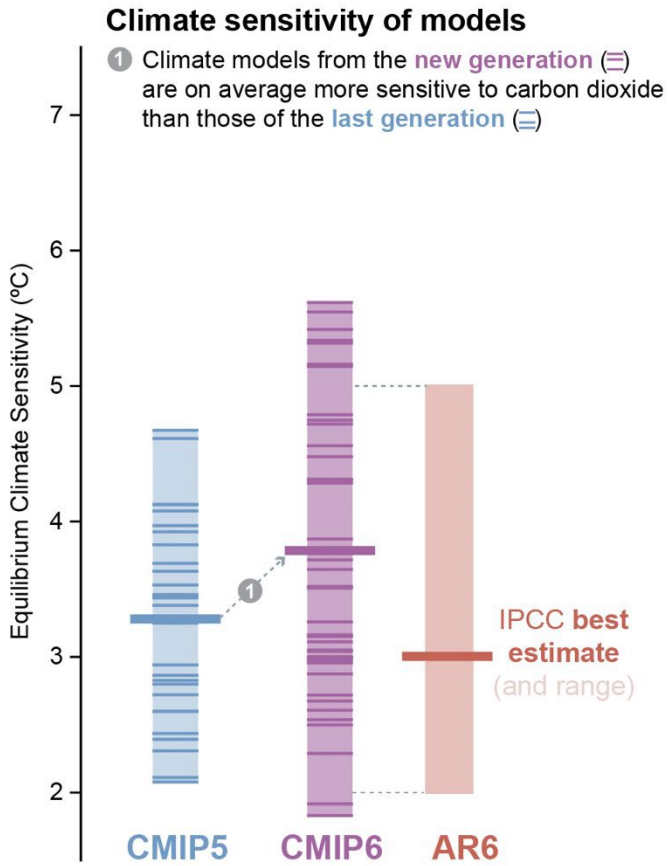
1. Motivation and methodology
2. Internal variability
3. Forcing
4. Cloud masking
5. Cloud feedbacks
6. Summary and broader conclusions

Uncertainty in estimating future global warming remains large



IPCC AR6

Uncertainty in estimating future global warming remains large



IPCC AR6

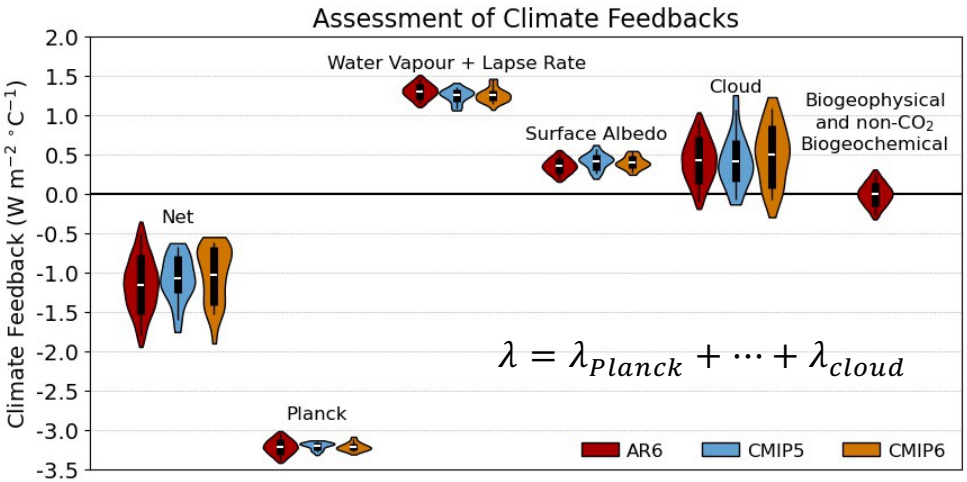
$$\Delta N = \Delta \mathrm{F} + \lambda \Delta T_s$$

N – Net radiative imbalance
F – Radiative forcing
λ – Climate Feedback
T_s - Global-mean surface temperature

Global warming due to doubling of carbon dioxide once planet has reached equilibrium ($\Delta N = 0$):

$$\Delta T_s = -\frac{F_{2x}}{\lambda}$$

Much of the uncertainty in future warming arises from cloud feedback



IPCC AR6

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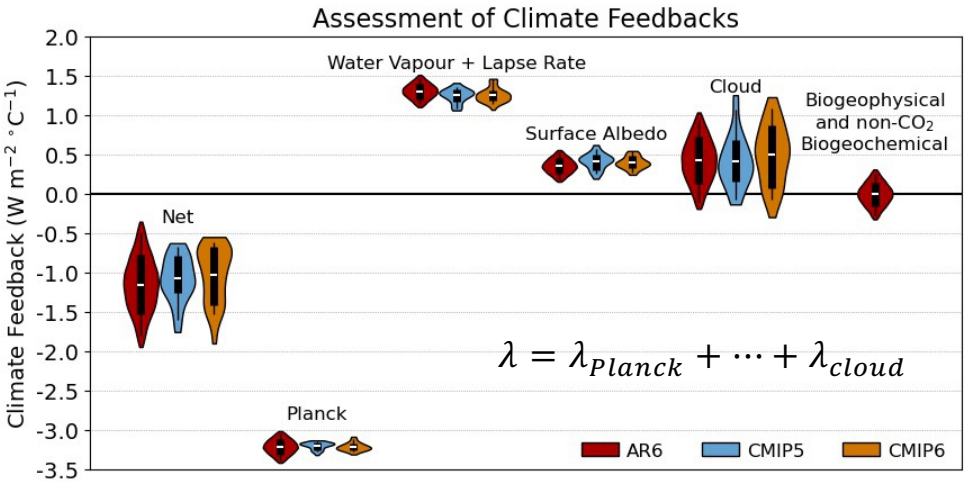
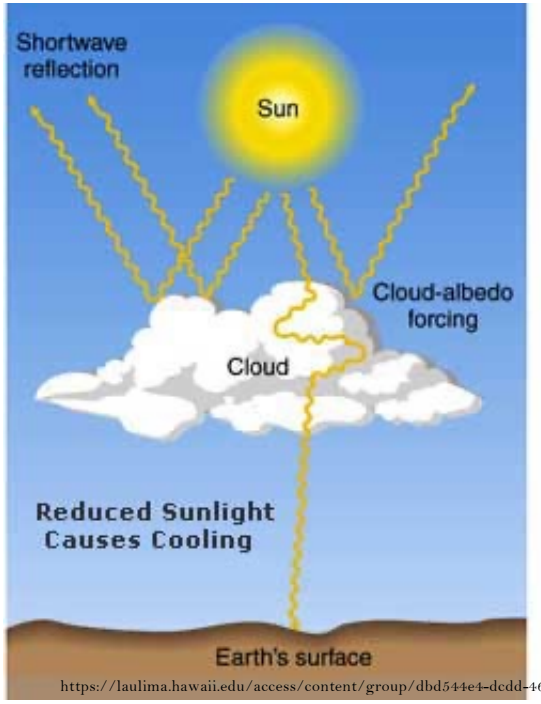
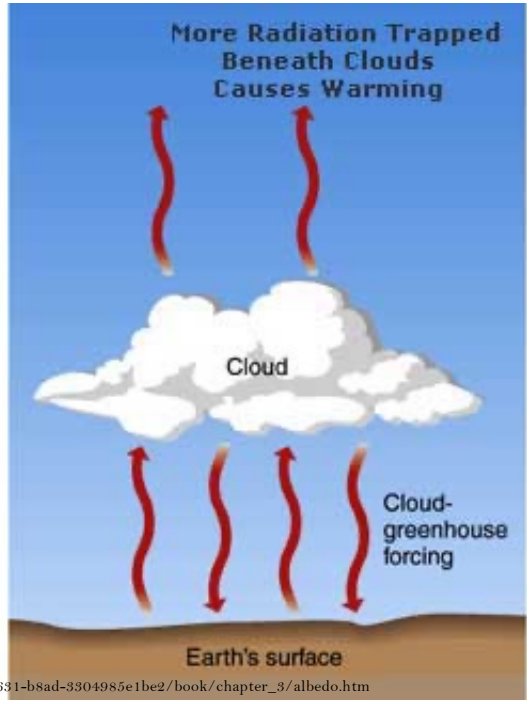


Clouds are bright



Clouds reflect $\sim -45\ Wm^{-2}$ of sunlight, cooling the planet

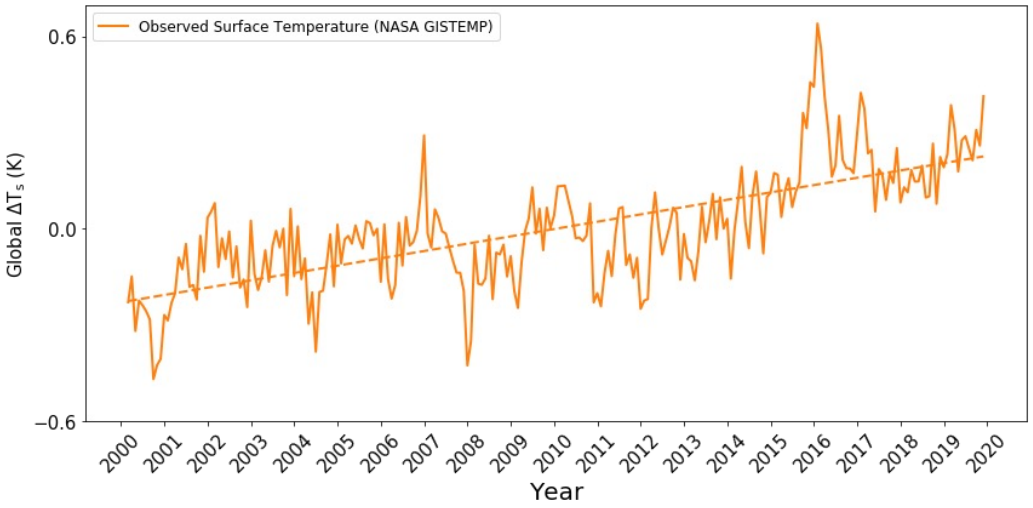
Clouds are cold



Clouds trap infrared radiation $\sim 25\ Wm^{-2}$, heating the planet

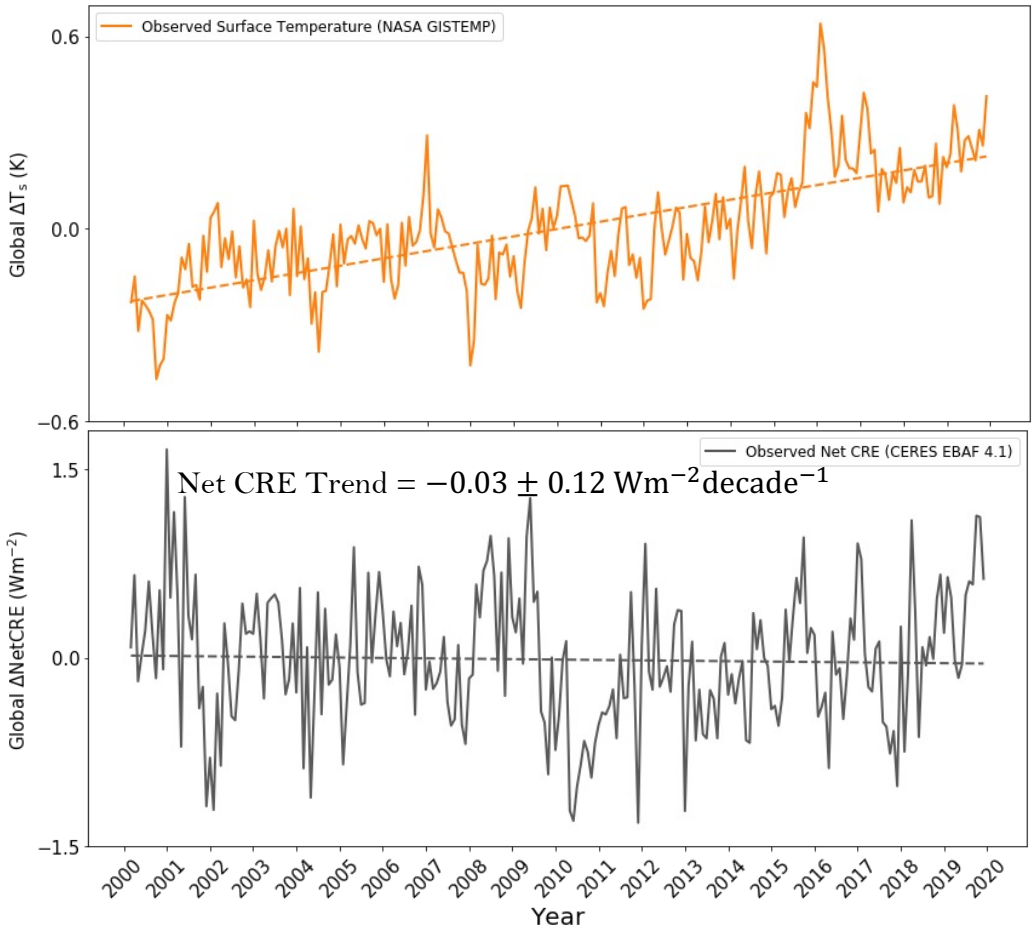
- Together, clouds have a net cooling effect of $\sim -20\ Wm^{-2}$ on the planet.
- How much this will increase or decrease in response to global warming, thereby amplifying or diminishing it, is a key challenge.

Global warming trend



- Given the strong surface warming trend ($0.23\ \mathrm{K\ decade^{-1}}$), can we see its impact on the TOA cloud-radiation budget?
- Numerous studies have indicated a positive cloud feedback with warming; can we see evidence of this in the satellite record?

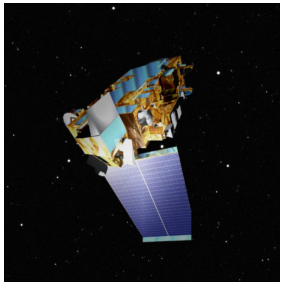
Global warming trend yet no cloud radiative effect change?



- Given the strong surface warming trend ($0.23\ \mathrm{K\ decade^{-1}}$), can we see its impact on the TOA cloud-radiation budget?
- Numerous studies have indicated a positive cloud feedback with warming; can we see evidence of this in the satellite record?

- CRE = Cloud Radiative Effect
- Global Net CRE $\sim -20\ \mathrm{Wm^{-2}}$, i.e., clouds cool the planet
- This cooling effect has not changed over the last 2 decades (flat trend)
- Forcing? Feedbacks? Cloud-masking? Internal variability?

Decomposition of cloud radiative effect trends into forcing, cloud feedbacks, cloud masking, and internal variability

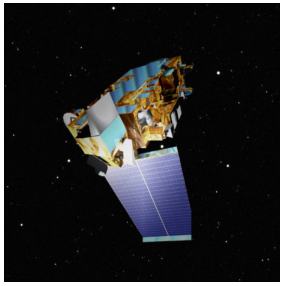


$$\Delta CRE = \Delta ERF_{CRE} + \Delta W_{CRE} + \epsilon$$

CERES EBAF Ed4.1 satellite observations

- Cloud radiative effect = Clear-sky – All-sky fluxes
- NetCRE = Longwave (LW) CRE + Shortwave (SW) CRE

Decomposition of cloud radiative effect trends into forcing, cloud feedbacks, cloud masking, and internal variability



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Effective Radiative Forcing

- GFDL AM4 and CMIP6 RFMIP
- 2001-2020 Forcing
- 7 models, 38 realizations

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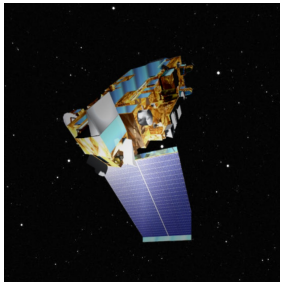

$$\leftarrow \Delta CRE = \Delta ERF_{CRE} + \overbrace{\Delta W_{CRE}}^{\lambda_{CRE}\Delta T_S} + \epsilon$$

$$\Delta W_{cloud-masking} + \Delta W_{cloud}$$

CERES EBAF satellite observations

- Cloud radiative effect = Clear-sky – All-sky fluxes
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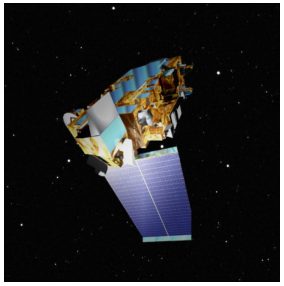
Warming-induced CRE (Response)

- Cloud masking and cloud feedback
- ERA5 reanalysis meteorological profiles + radiation model RRTMGP; PRP experiments

Decomposition of cloud radiative effect trends into forcing, cloud feedbacks, cloud masking, and internal variability



$$\leftarrow \Delta CRE = \Delta ERF_{CRE} + \Delta W_{CRE} + \epsilon$$

$\lambda_{CRE}\Delta T_S$

$\Delta W_{cloud-masking} + \Delta W_{cloud}$

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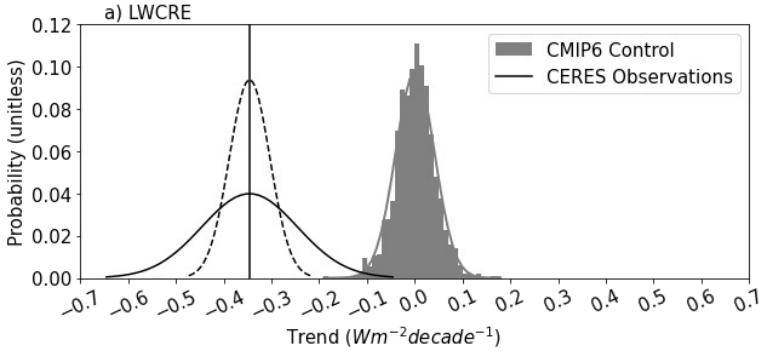
Internal Variability

- CMIP6 Control
- Pre-industrial Forcing
- 40 models, 1,144 realizations

Internal Variability Trends

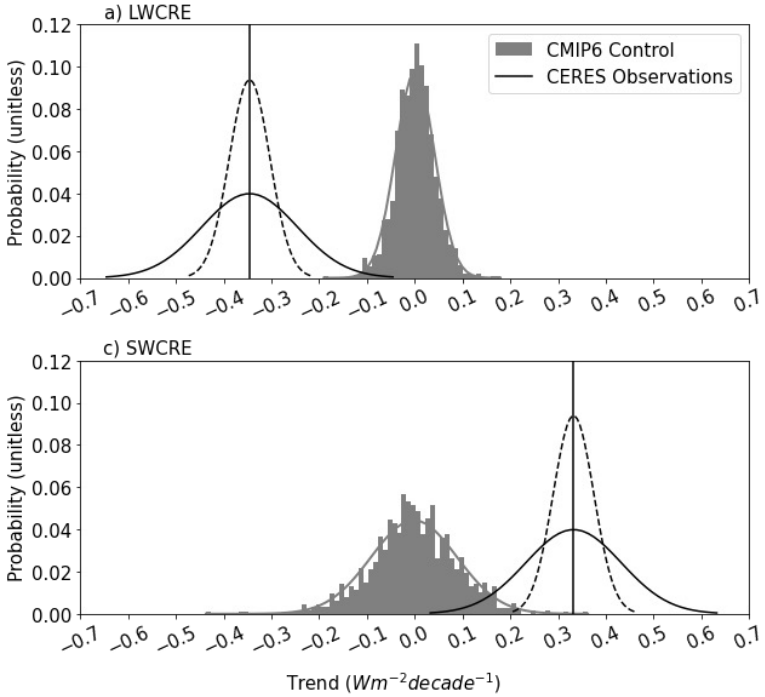


$$\boldsymbol{\Delta CRE} = \Delta ERF_{CRE} + \Delta W_{CRE} + \epsilon$$

- CERES shows trends detectable above internal variability and observational uncertainty in LWCRE.

(2001-2020 global-mean trends)

Internal Variability Trends



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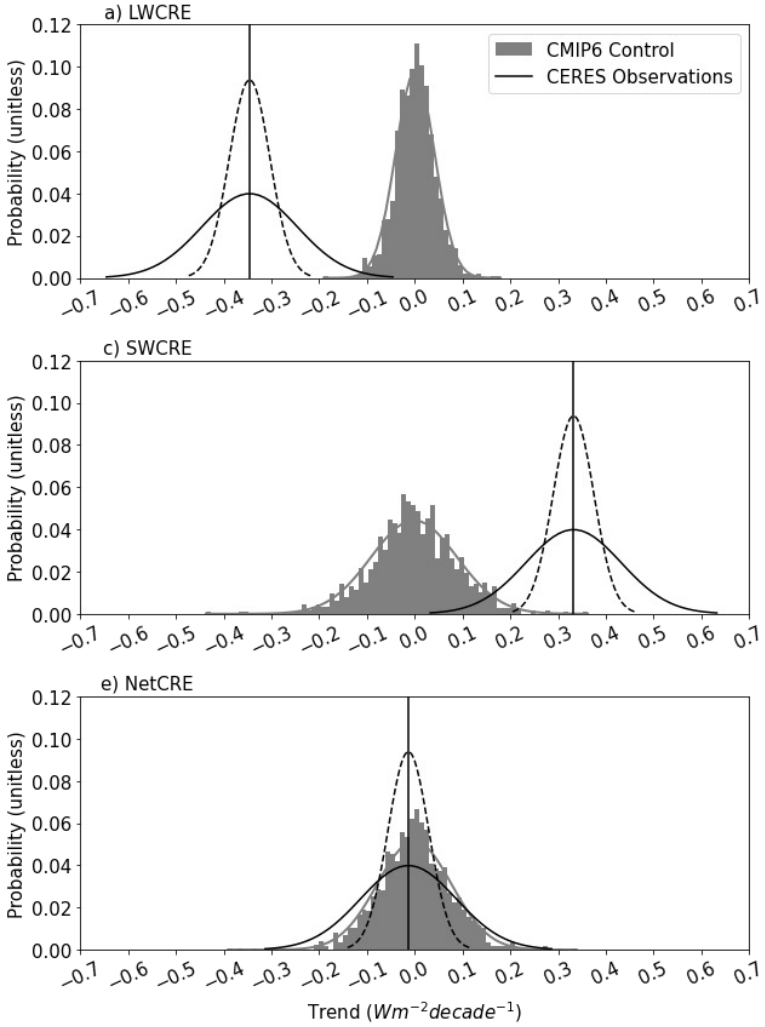
- CERES shows trends detectable above internal variability and observational uncertainty in LWCRE.

- CERES shows trends detectable above internal variability and observational uncertainty in SWCRE.

(2001-2020 global-mean trends)

Internal Variability Trends



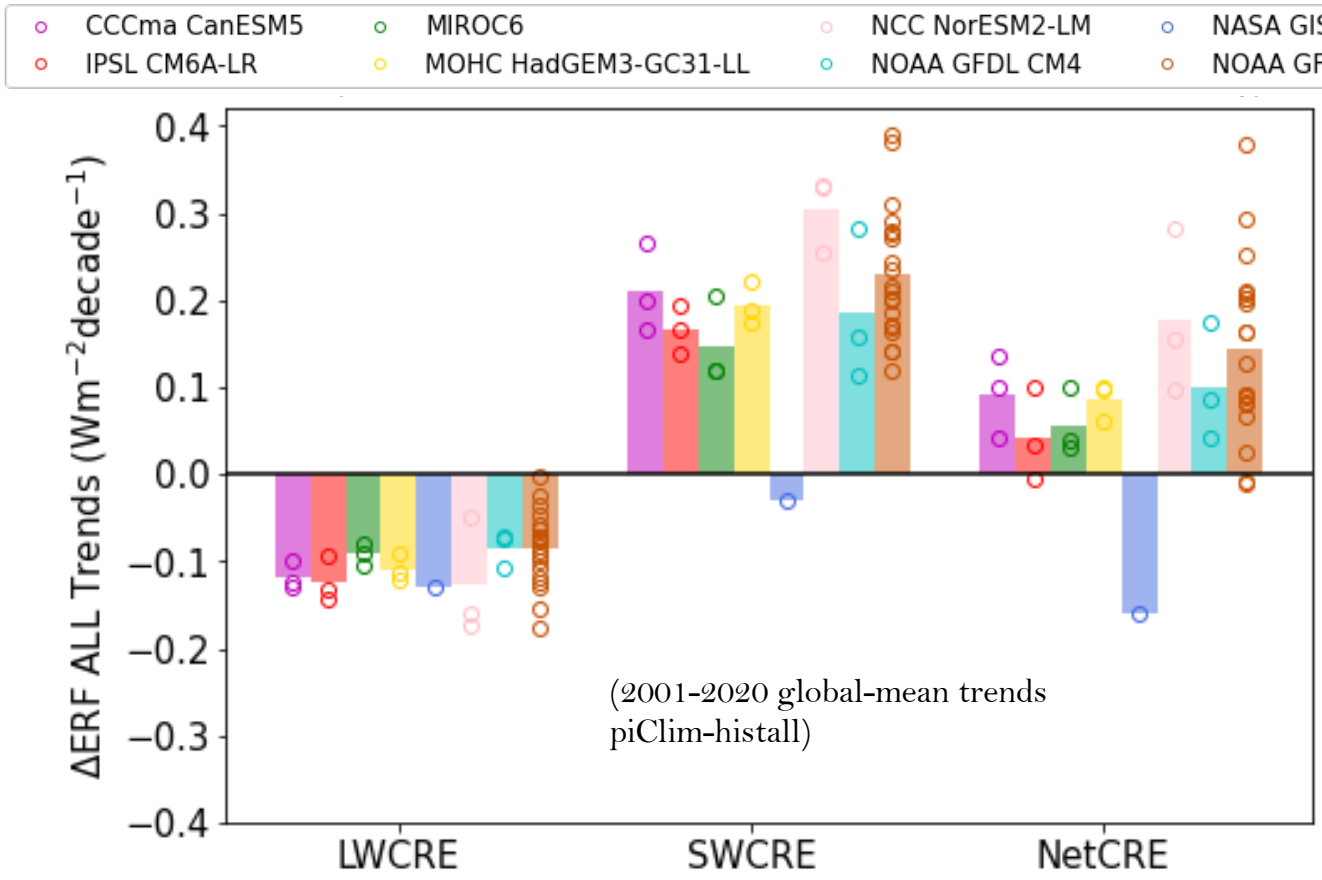
$$\boldsymbol{\Delta CRE} = \Delta ERF_{CRE} + \Delta W_{CRE} + \epsilon$$

- CERES shows trends detectable above internal variability and observational uncertainty in LWCRE.
- CERES shows trends detectable above internal variability and observational uncertainty in SWCRE.
- These large LWCRE and SWCRE trends cancel yielding NetCRE as undetectable.

(2001-2020 global-mean trends)

Effective Radiative Forcing Trends

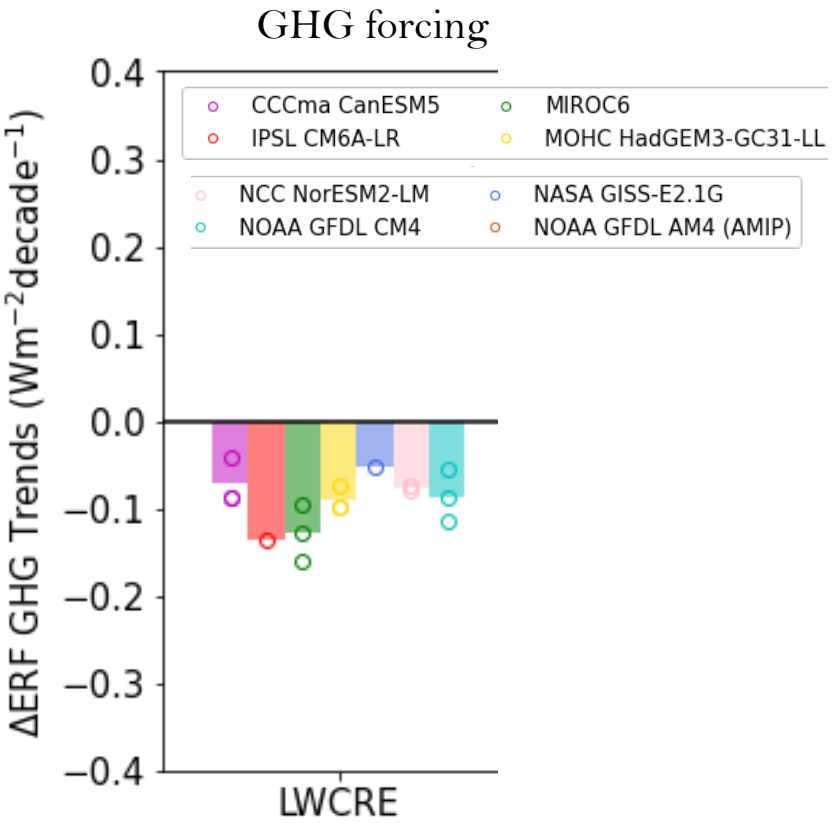
$$\Delta CRE = \boldsymbol{\Delta ERF_{CRE}} + \Delta W_{CRE} + \epsilon$$



- Multi-model mean LWCRE ERF: $-0.11 \pm 0.01\ Wm^{-2}decade^{-1}$
- Multi-model mean SWCRE ERF: $0.19 \pm 0.04\ Wm^{-2}decade^{-1}$
- Robustness across models is encouraging and can help explain the CERES-observed negative LWCRE trend and positive SWCRE trend

Effective Radiative Forcing Trends – LWCRE breakdown

$$\Delta CRE = \boxed{\boldsymbol{\Delta ERF_{CRE}}} + \Delta W_{CRE} + \epsilon$$



Effective Radiative Forcing Trends – LWCRE breakdown

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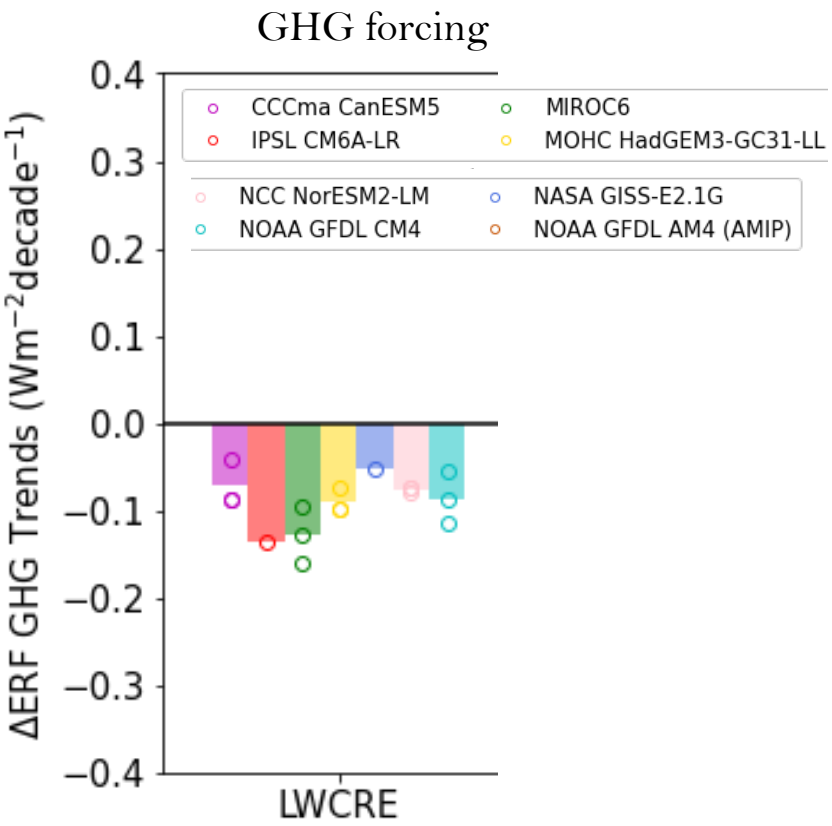
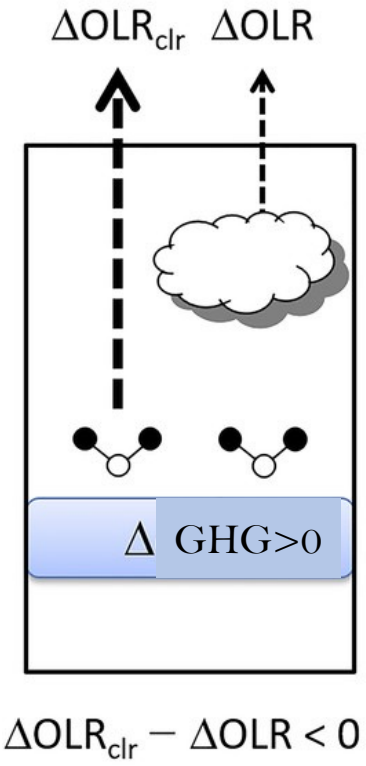


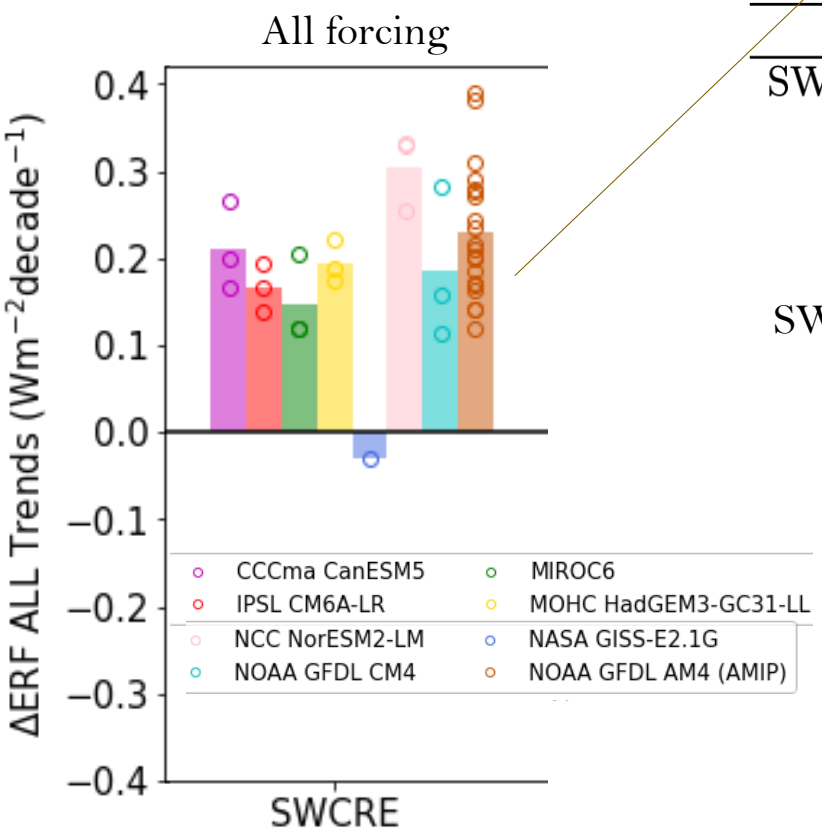


Schematic adapted from Yoshimori et al., 2020

- LWCRE forcing trend is dominated by the greenhouse gas forcing.
- Cloud masking of well-mixed greenhouse gases.

Effective Radiative Forcing Trends – SWCRE Breakdown

$$\Delta CRE = \boxed{\boldsymbol{\Delta ERF_{CRE}}} + \Delta W_{CRE} + \epsilon$$



GFDL AM4 ERF Trends; 2001-2020 Global-mean; Units: $Wm^{-2}decade^{-1}$

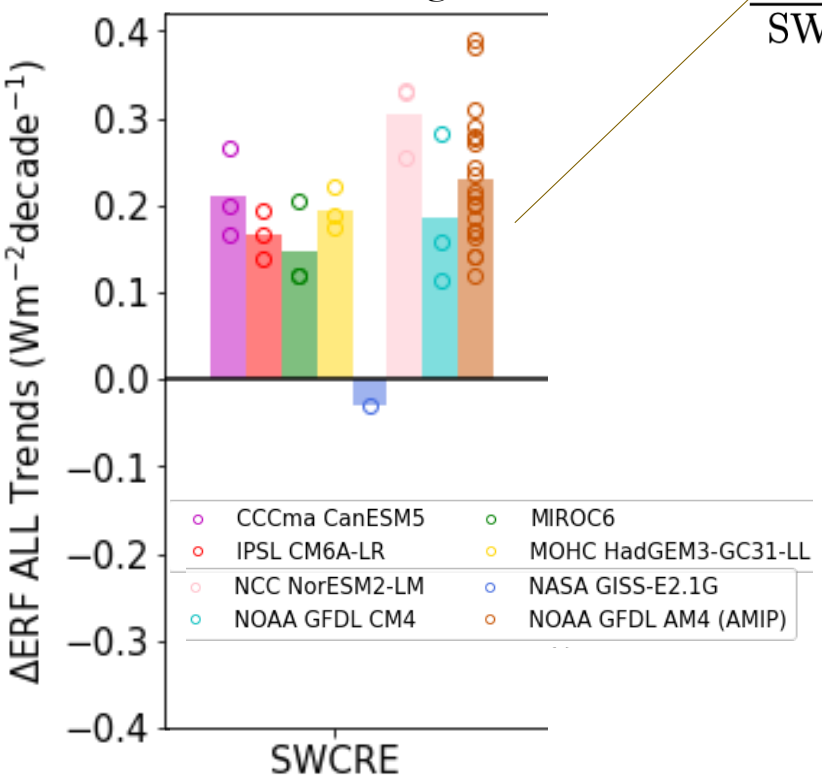
	All forcing	**GHG only**	**AER only**	**NAT only**
SWCRE	0.19 ± 0.03	0.09 ± 0.05	0.08 ± 0.07	-0.01 ± 0.01

SWCRE forcing trend is half GHG-driven and half aerosol-driven.

Effective Radiative Forcing Trends – SWCRE Breakdown

$$\Delta CRE = \boxed{\Delta ERF_{CRE}} + \Delta W_{CRE} + \epsilon$$

All forcing



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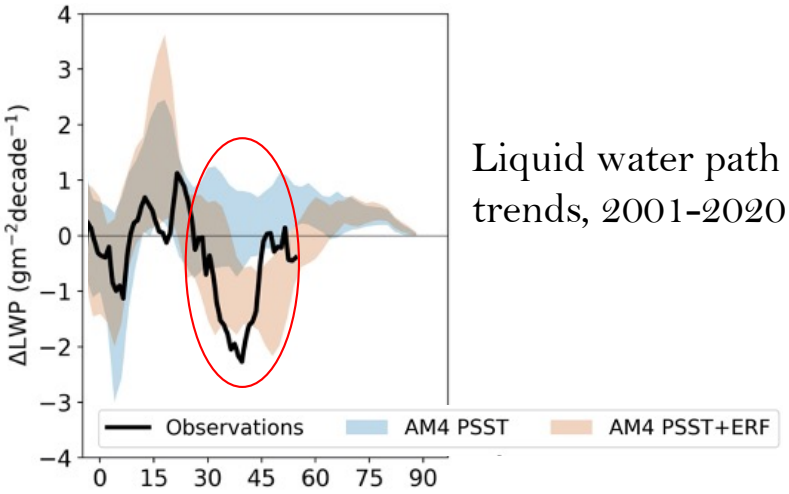
Aerosol indirect effect



Liquid water path trends, 2001-2020

Latitude

Raghuraman et al., 2021, *Nature Communications*

Effective Radiative Forcing Trends – SWCRE Breakdown

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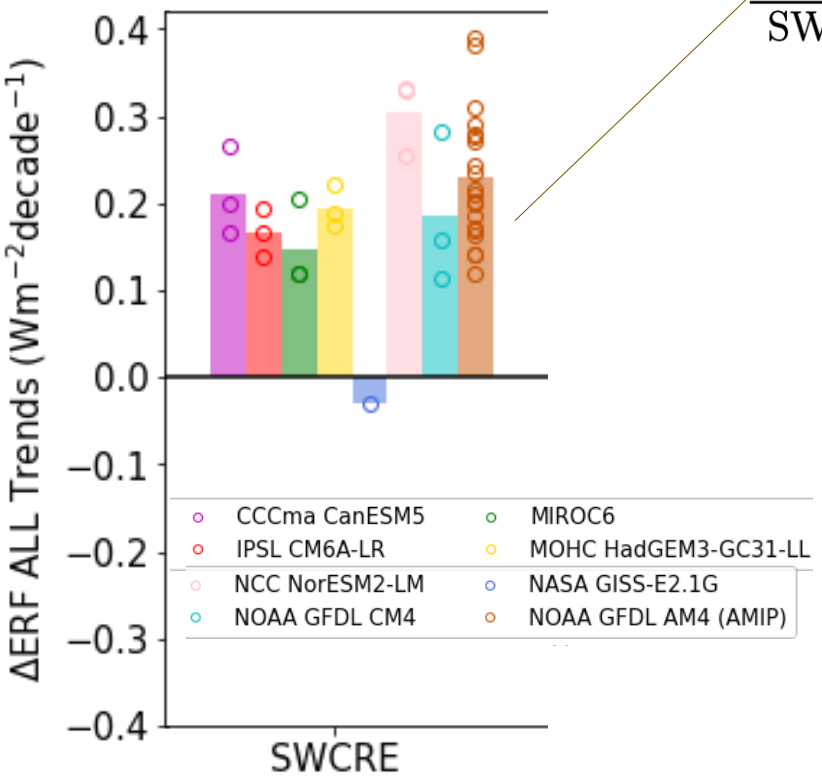
All forcing



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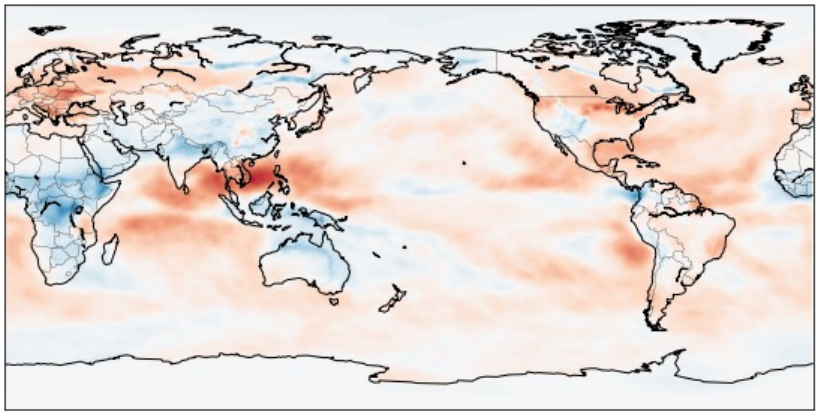
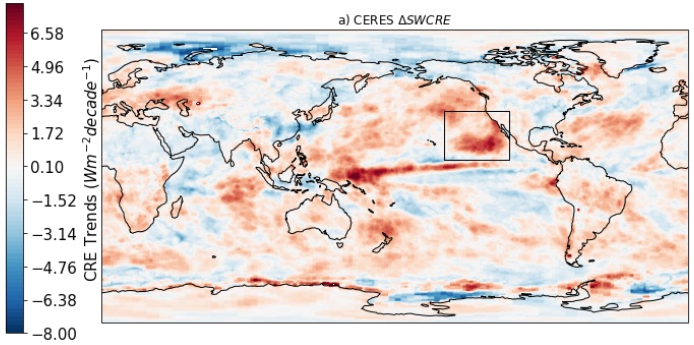
Rapid cloud adjustments



$\Delta GHG\ ERF_{SWCRE}$ 2080-2100

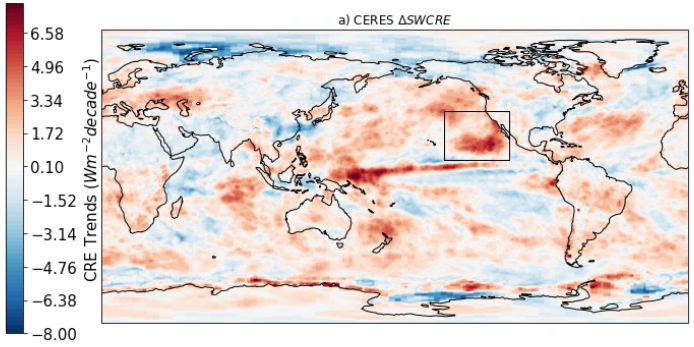
Effective Radiative Forcing Trends – Northeast Pacific

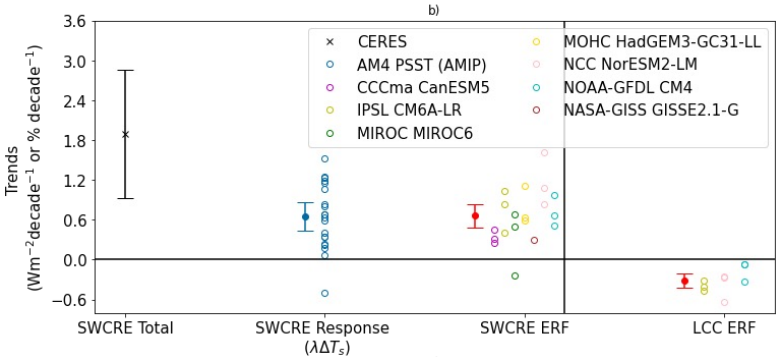


$$\boldsymbol{\Delta CRE} = \boldsymbol{\Delta ERF_{CRE}} + \Delta W_{CRE} + \epsilon$$

- CERES shows a large decrease in reflection over the boxed region. Previous studies indicate it is due to SST changes.

Effective Radiative Forcing Trends – Northeast Pacific





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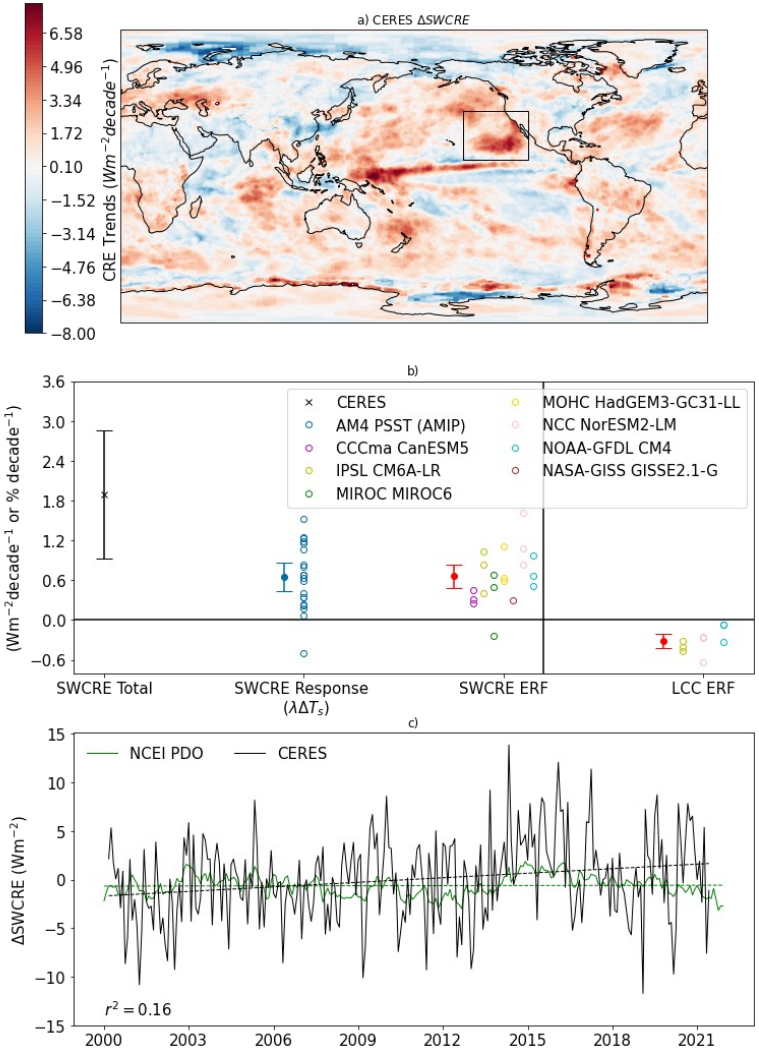
- CERES shows a large decrease in reflection over the boxed region. Previous studies indicate it is due to SST changes.

- Here we show that SST changes are only half the story (blue). Forcing (red) makes up the other half of the observed SWCRE trend. This is due to a forcing-induced decrease in low cloud cover.

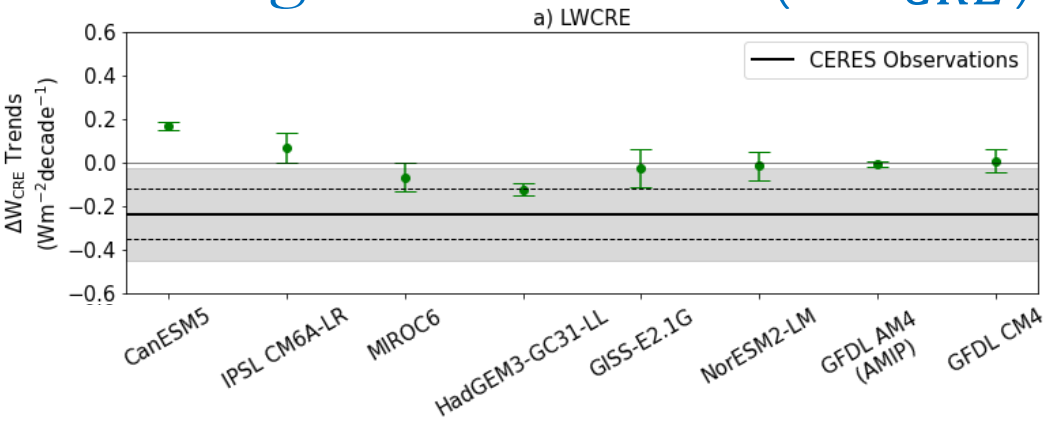
Effective Radiative Forcing Trends – Northeast Pacific



$$\boxed{\Delta CRE} = \Delta ERF_{CRE} + \Delta W_{CRE} + \boxed{\epsilon}$$

- CERES shows a large decrease in reflection over the boxed region. Previous studies indicate it is due to SST changes.
- Here we show that SST changes are only half the story (blue). Forcing (red) makes up the other half of the observed SWCRE trend. This is due to a forcing-induced decrease in low cloud cover.
- Pacific Decadal Oscillation (PDO) poorly correlated with NE Pacific SWCRE changes.

Warming-induced CRE (ΔW_{CRE}) – Observed & modeled trends



$$\boxed{\Delta W_{CRE}} = \Delta CRE - \Delta ERF_{CRE}$$

- Observationally-derived LW ΔW_{CRE} is negative (cooling the climate) after accounting for observational and internal variability uncertainties. Models are not negative enough.

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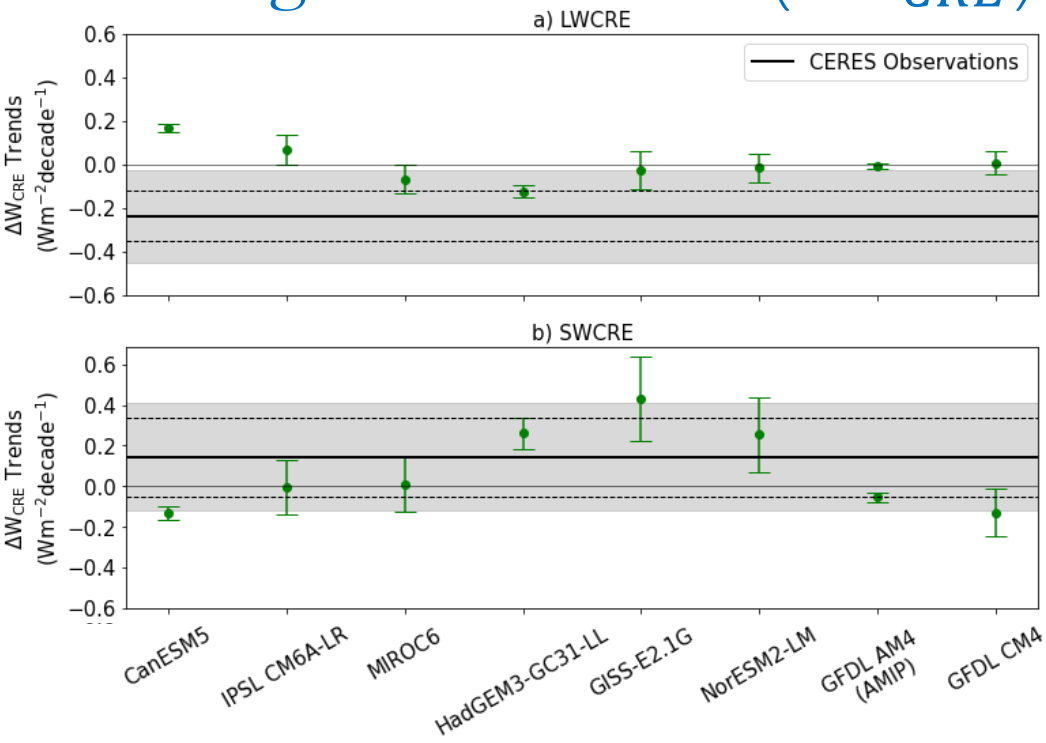

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- Observationally-derived SW ΔW_{CRE} could be positive or negative. Models fall into the observed range but are all over the place.

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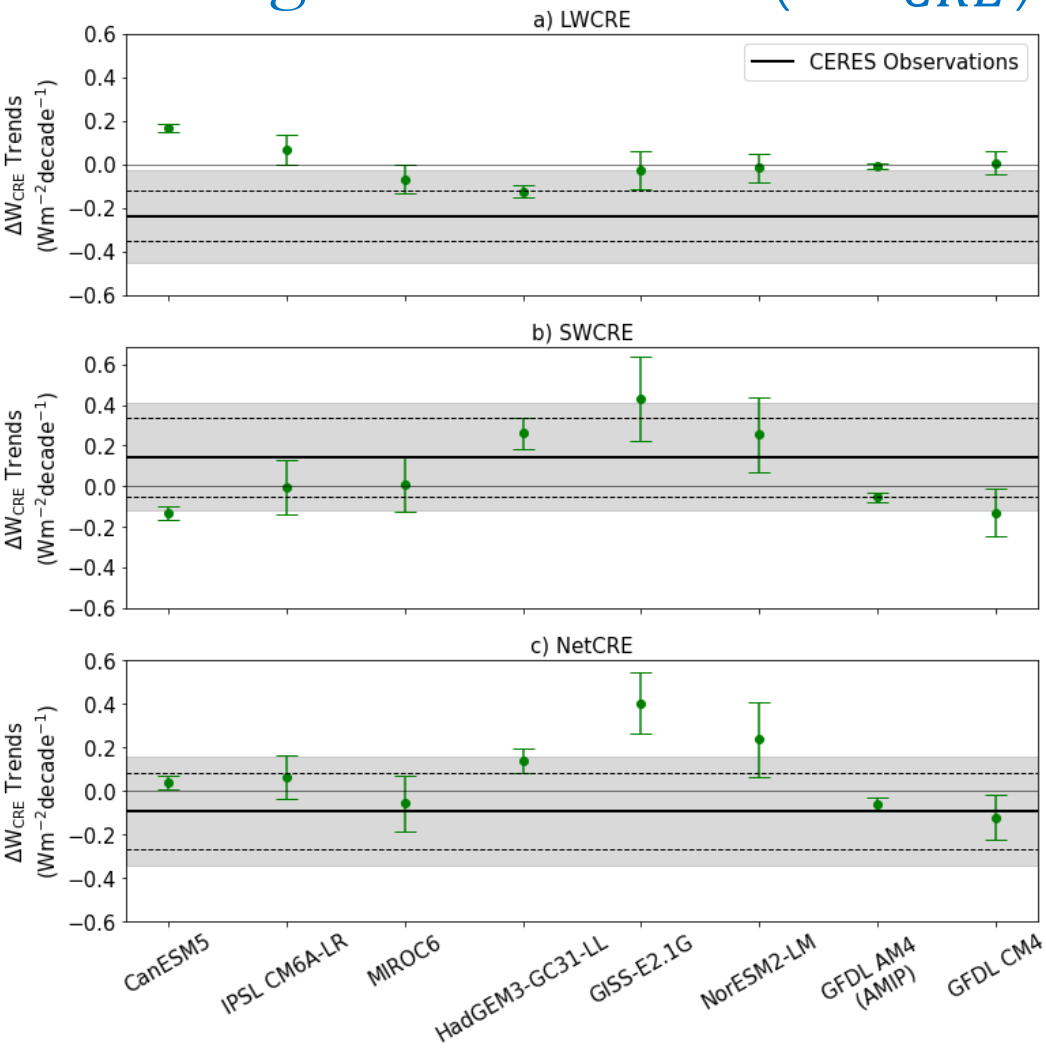

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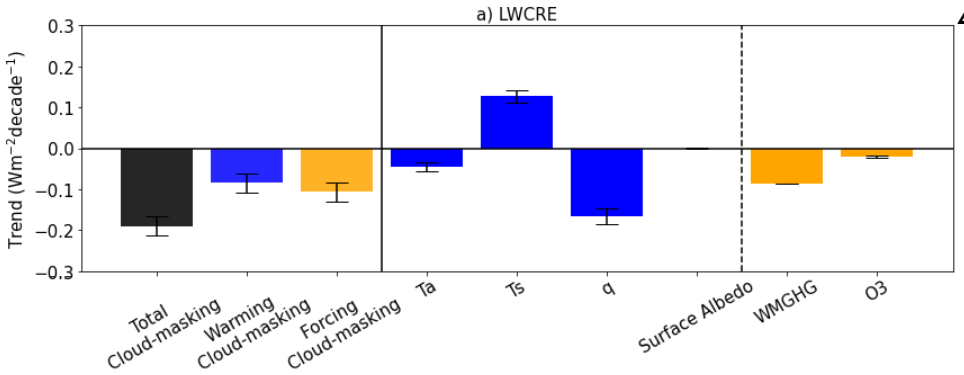
- Observationally-derived LW ΔW_{CRE} is negative (cooling the climate) after accounting for observational and internal variability uncertainties. Models are not negative enough.
- Observationally-derived SW ΔW_{CRE} could be positive or negative. Models fall into the observed range but are all over the place.
- Only MIROC6 (coupled) falls into the stricter observed range for LW, SW, and Net CRE trends.

Warming-induced Cloud-Masking Trends

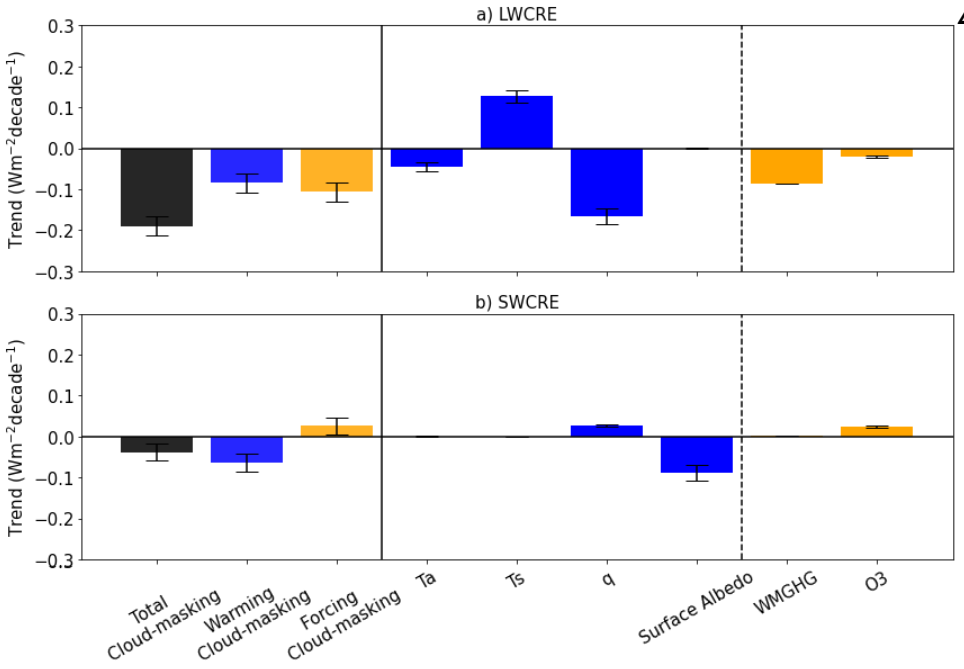


$$\Delta CRE = \Delta ERF_{CRE} + \boxed{\Delta W_{cloud-masking}} + \Delta W_{cloud} + \epsilon$$

- LWCRE's $\Delta W_{cloud-masking}$ trend is negative due to H_2O cloud-masking.

(2001-2020 global-mean trends)

Warming-induced Cloud-Masking Trends

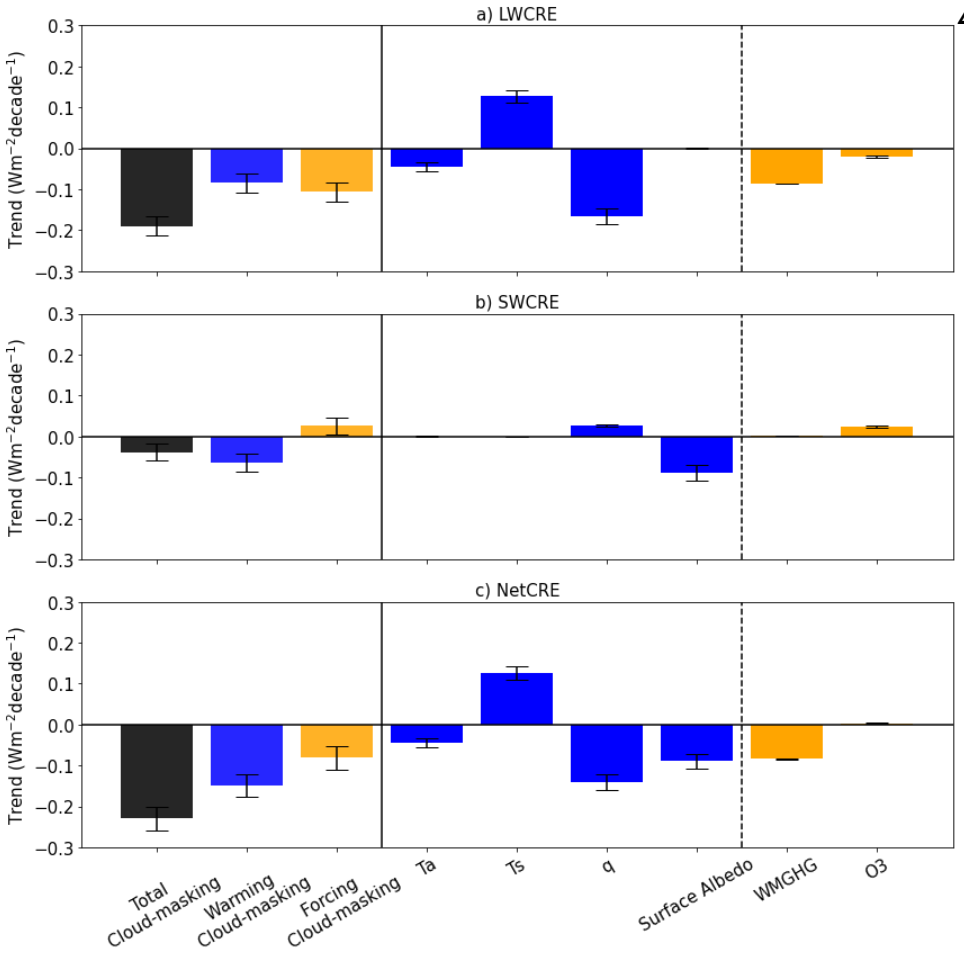


$$\Delta CRE = \Delta ERF_{CRE} + \boxed{\Delta W_{cloud-masking}} + \Delta W_{cloud} + \epsilon$$

- LWCRE's $\Delta W_{cloud-masking}$ trend is negative due to H_2O cloud-masking.
- SWCRE's $\Delta W_{cloud-masking}$ trend is slightly negative due to ice-albedo masking.

(2001-2020 global-mean trends)

Warming-induced Cloud-Masking Trends



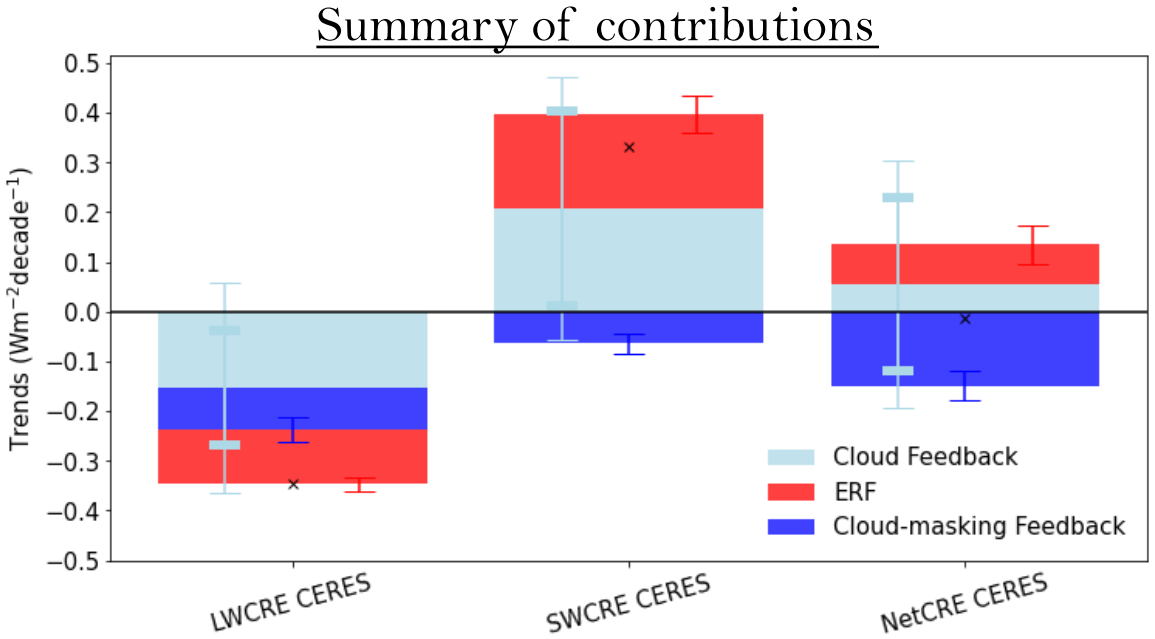
$$\Delta CRE = \Delta ERF_{CRE} + \boldsymbol{\Delta W_{cloud-masking}} + \Delta W_{cloud} + \epsilon$$

- LWCRE's $\Delta W_{cloud-masking}$ trend is negative due to H_2O cloud-masking.
- SWCRE's $\Delta W_{cloud-masking}$ trend is slightly negative due to ice-albedo masking.
- As a result, NetCRE's $\Delta W_{cloud-masking}$ trend is strongly negative.

(2001-2020 global-mean trends)

Observed Cloud Feedback Trends

$$\boxed{\Delta W_{cloud}} = \Delta CRE - (\Delta ERF_{CRE} + \Delta W_{cloud-masking})$$



- LW cloud feedback trend is negative and significant at 80-95% confidence
- SW cloud feedback trend is positive and significant at 85-95% confidence
- Net cloud feedback could be positive or negative, i.e., it could amplify or diminish global warming
- Thus, flat NetCRE trend due to cancellations in LW & SW CRE forcing, feedbacks, masking

2001-2020 global-mean trends

CRE and cloud feedback are not interchangeable

Quantity (Units: $Wm^{-2}K^{-1}$)	Cloud Feedback (λ_{cloud})	CRE Feedback (λ_{CRE})
LW CERES	-0.38 ± 0.18	-0.72 ± 0.18
SW CERES	0.58 ± 0.44	0.83 ± 0.44
Net CERES	0.20 ± 0.34	0.11 ± 0.34

- Using CRE as a proxy for cloud feedback is a poor approximation since CRE is a combination of various factors

Summary

- Cloud-masking trends from well-mixed greenhouse gases and water vapor cause a majority of the observed negative trend in LWCRE.

- Forcing from rapid cloud adjustments and aerosol indirect effect trends cause a majority of the observed positive trend in SWCRE.

- Significant negative LW and positive SW cloud feedbacks yield a small and non-significant net cloud feedback, implying that clouds could amplify or diminish global warming.

Broader conclusions on how Earth is accumulating heat

- Earth's Energy Imbalance (EEI) is increasing (~0.4 $Wm^{-2}decade^{-1}$)
- LW cooling the planet (~-0.3 $Wm^{-2}decade^{-1}$):
  - Planck response and LW cloud feedback overwhelm the greenhouse gas increases
- SW heating the planet (~0.7 $Wm^{-2}decade^{-1}$):
  - A tale of two theories
    - Clouds alone matter (e.g., Clement and Soden, 2005, Trenberth and Fasullo, 2009)
    - Clouds don't matter (e.g., Donohoe et al., 2014)
  - In reality, it's between these two:
    - Effective radiative forcing (40%) – aerosol direct and indirect effects and GHG adjustments
    - SW cloud feedback (30%)
    - Surface albedo (20%)
    - Water vapor (10%)

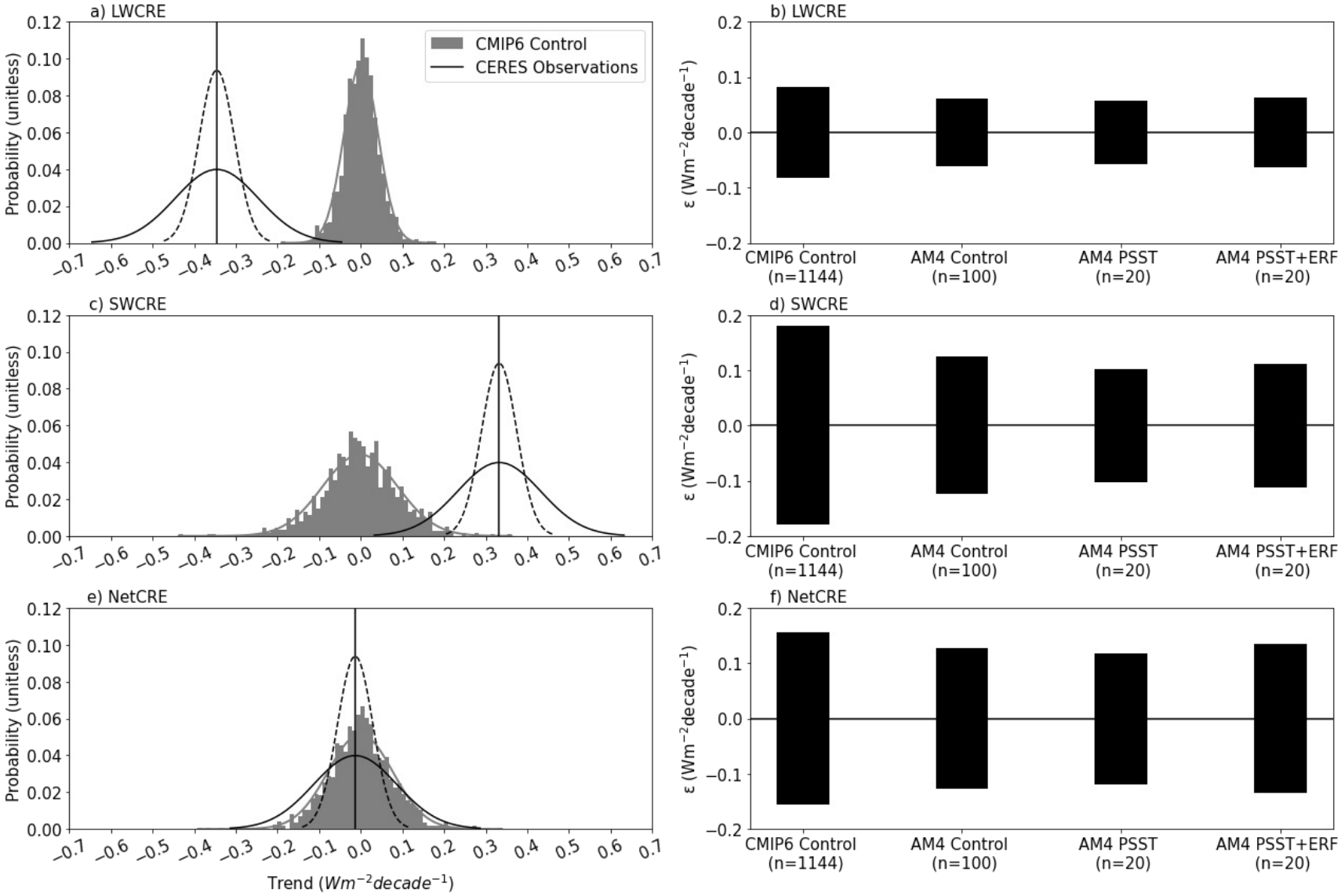
Thank you! Questions?

References:

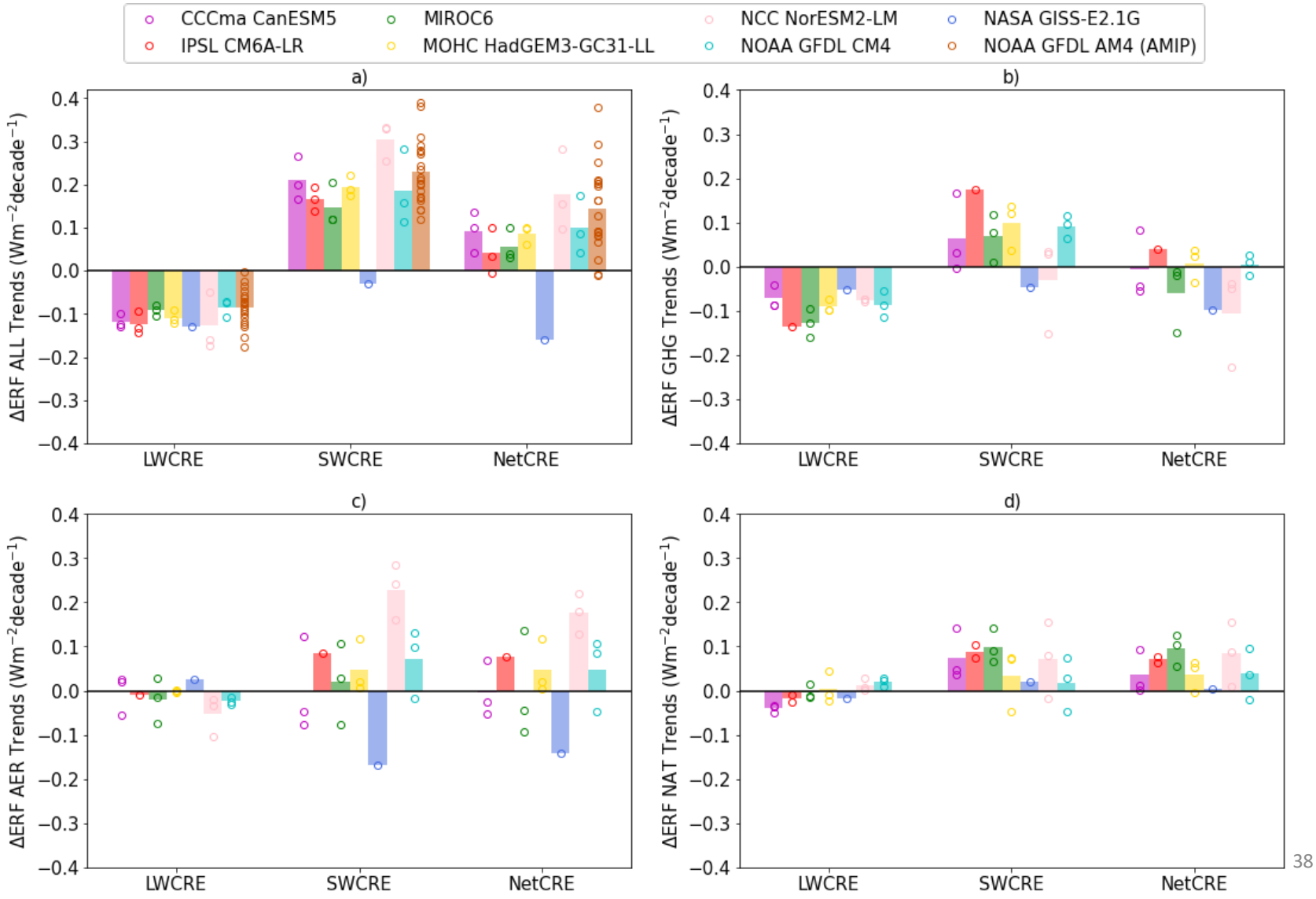
Raghuraman, SP., Paynter, D., Menzel, R., & Ramaswamy, V. (2023). Forcing, cloud feedbacks, cloud masking, and internal variability in the cloud radiative effect satellite record. *Journal of Climate*, 1-38.

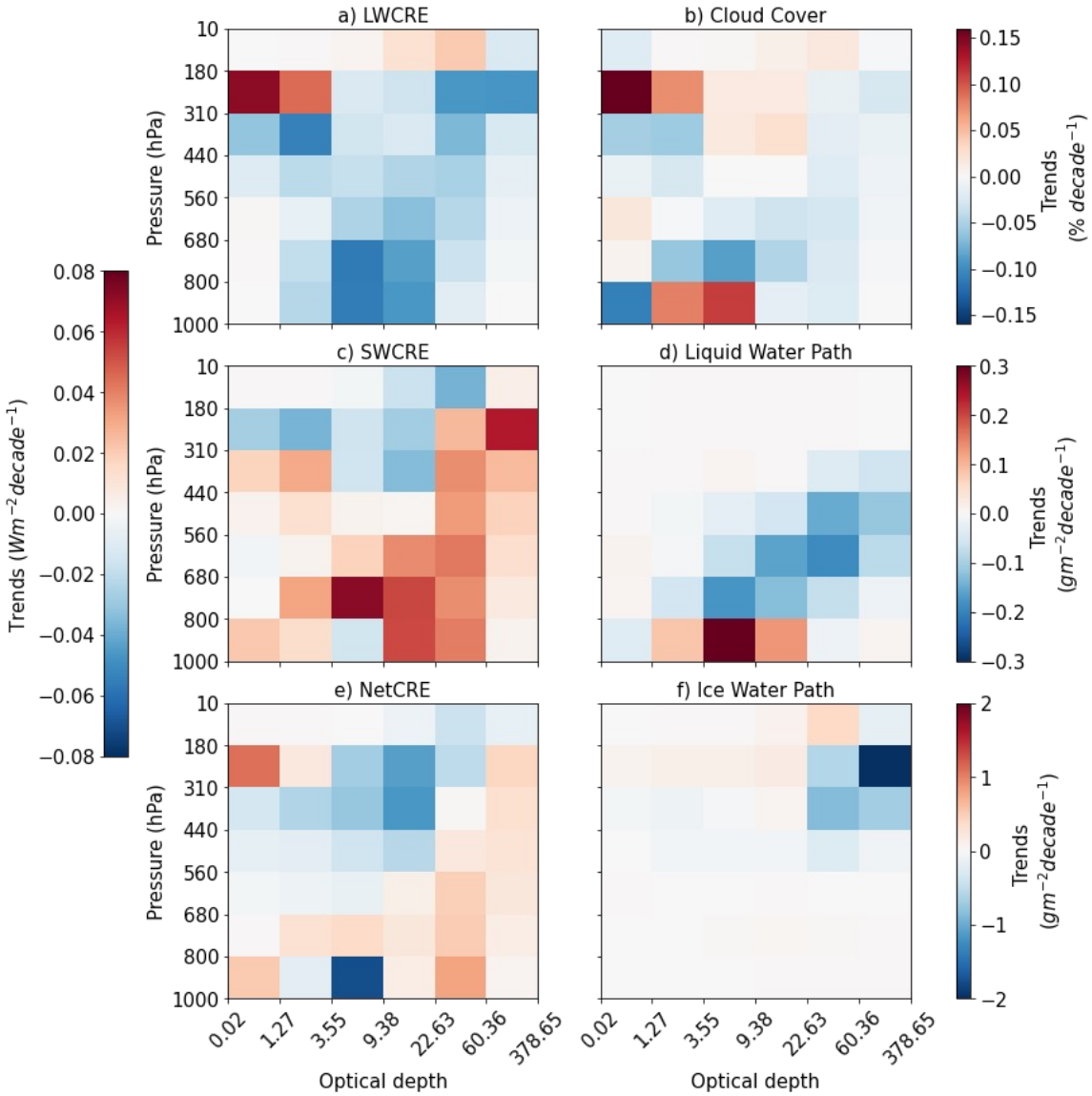
Raghuraman, SP., Paynter, D., & Ramaswamy, V. (2021). Anthropogenic forcing and response yield observed positive trend in Earth's energy imbalance. *Nature Communications*, *12*(1), 4577.

Backup


a) LWCRE
b) LWCRE
c) SWCRE
d) SWCRE
e) NetCRE
f) NetCRE
CMIP6 Control
CERES Observations
Probability (unitless)
Trend ($Wm^{-2}decade^{-1}$)
ε ($Wm^{-2}decade^{-1}$)
CMIP6 Control (n=1144)
AM4 Control (n=100)
AM4 PSST (n=20)
AM4 PSST+ERF (n=20)

Rest of plot


CCCma CanESM5
IPSL CM6A-LR
MIROC6
MOHC HadGEM3-GC31-LL
NCC NorESM2-LM
NOAA GFDL CM4
NASA GISS-E2.1G
NOAA GFDL AM4 (AMIP)
a)
b)
c)
d)
ΔERF ALL Trends (Wm^{-2}decade^{-1})
ΔERF GHG Trends (Wm^{-2}decade^{-1})
ΔERF AER Trends (Wm^{-2}decade^{-1})
ΔERF NAT Trends (Wm^{-2}decade^{-1})
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
LWCRE
SWCRE
NetCRE


a) LWCRE
b) Cloud Cover
c) SWCRE
d) Liquid Water Path
e) NetCRE
f) Ice Water Path
Pressure (hPa)
10
180
310
440
560
680
800
1000
Optical depth
0.02
1.27
3.55
9.38
22.63
60.36
378.65
Trends ($Wm^{-2}decade^{-1}$)
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.08
Trends (% $decade^{-1}$)
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
Trends ($gm^{-2}decade^{-1}$)
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
2
1
0
−1
−2