IMPERIAL

Observed cloud sensitivities and implications for Earth energy imbalance

CERES meeting

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(with S. Wilson Kemsley, H. Andersen, T. Andrews, R. J. Kramer, P. Nowack, C. J. Wall, M. D. Zelinka)
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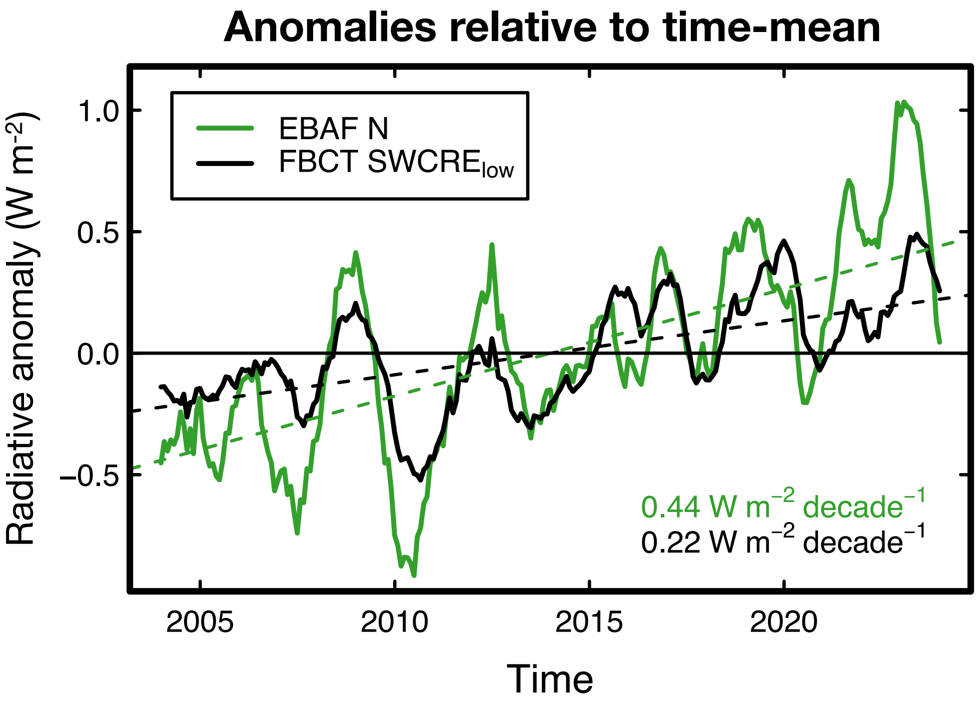
Contribution of low clouds to EEI

- CERES-EBAF anomalies in energy imbalance (N)
- CERES-FBCT SW low-cloud radiative anomalies ($SWCRE_{low}$)

- **Low cloud contribution is ~50% of the trend in EEI**



Ceppi et al. 2026

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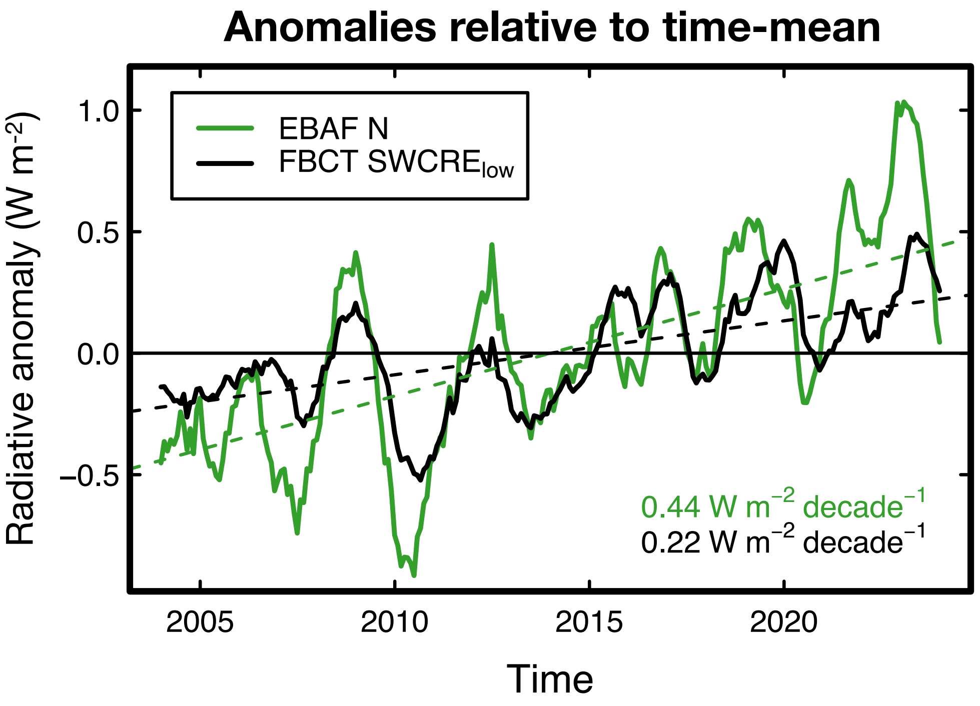

What's causing the low-cloud reduction?

- Low-cloud feedback?
- Cloud adjustment to aerosol? (cf. 2020 shipping emissions reduction)
- Cloud adjustment to GHG?
- Natural variability?

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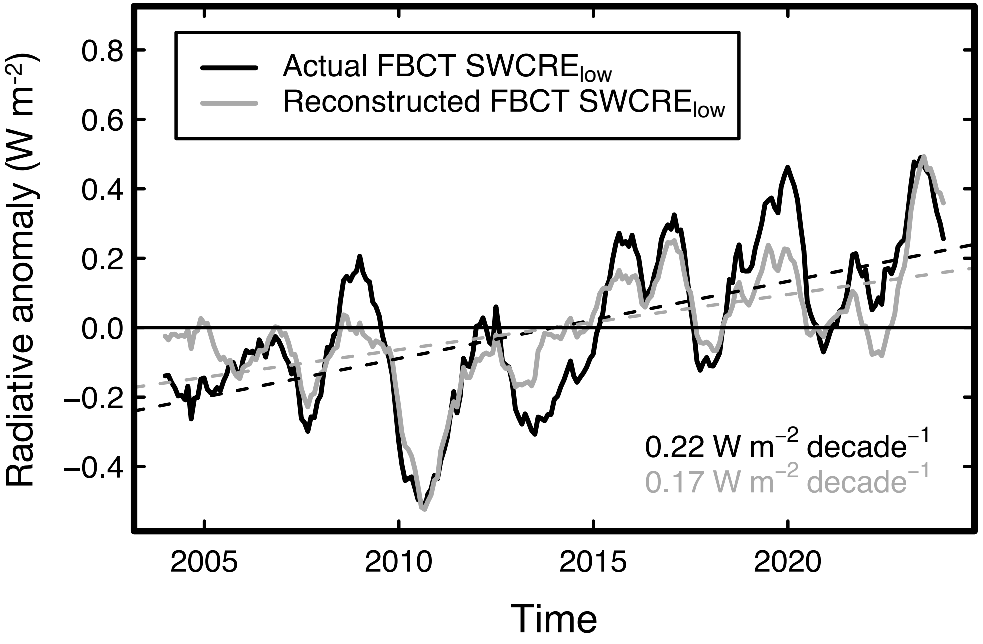
Interpreting the cloud-radiative trend
Forced & unforced trend contributions

Can use cloud-controlling factor (CCF) analysis to interpret the $SWCRE_{low}$ trend:

$$\frac{\mathrm{d}C(r)}{\mathrm{d}t} \approx \sum_{i=1}^{M} \mathbf{\Theta}_i(r) \cdot \frac{\mathrm{d}\boldsymbol{X}_i(r)}{\mathrm{d}t}$$



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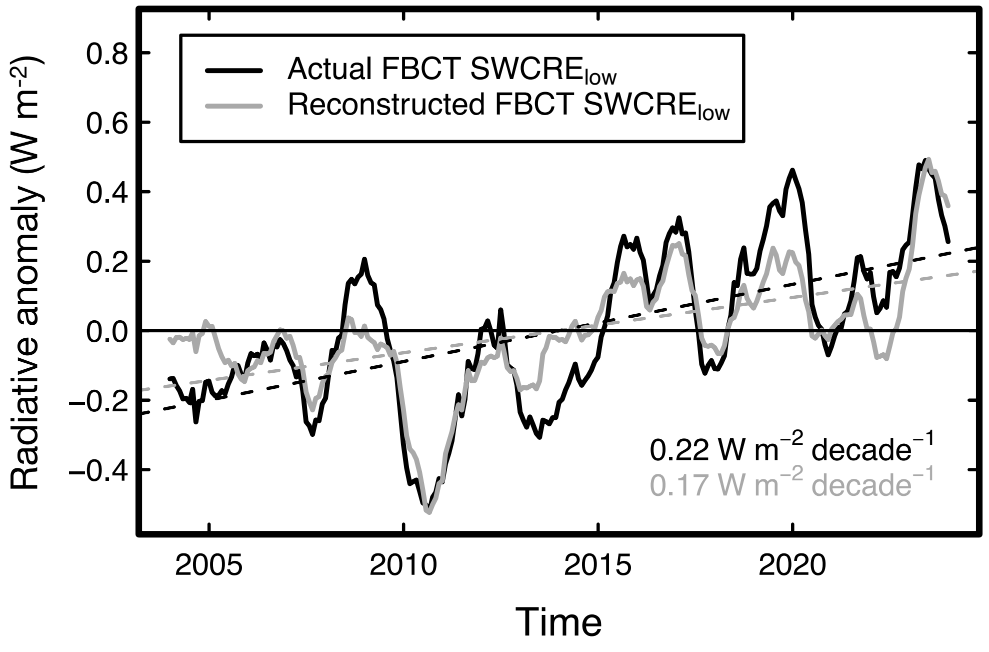
Decompose trends into:

Forced	+	Unforced
CMIP6-mean CCF trends		Residual CCF trend (observed minus CMIP6-mean)



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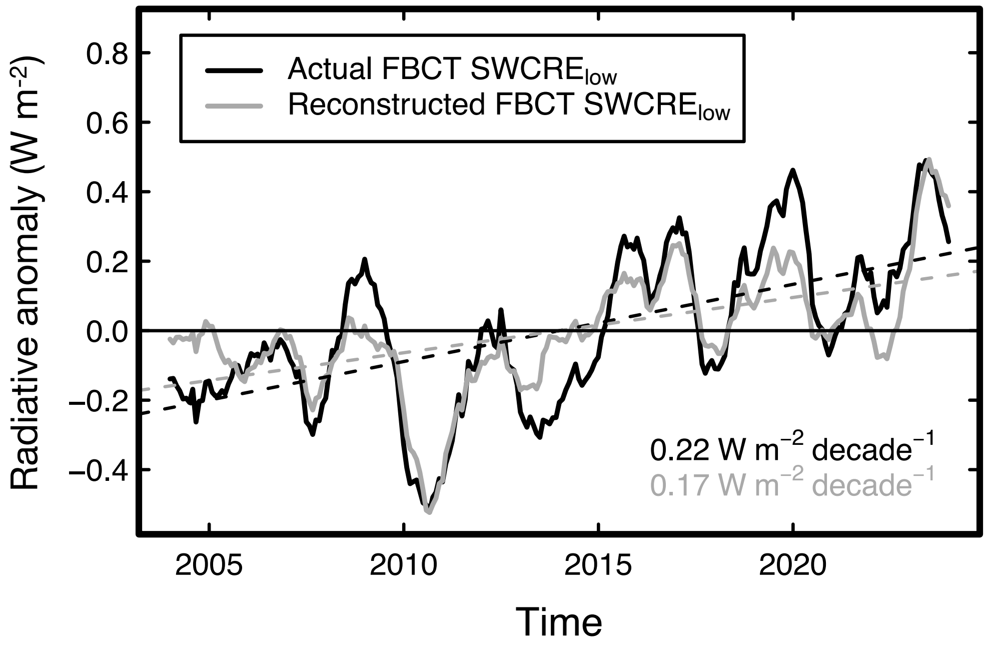

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Feedback	=	SST-mediated trend of 6 meteorological CCFs
+		
Aerosol adjustment	=	Trend of aerosol CCF
+		
GHG adjustment	=	From CMIP6 models

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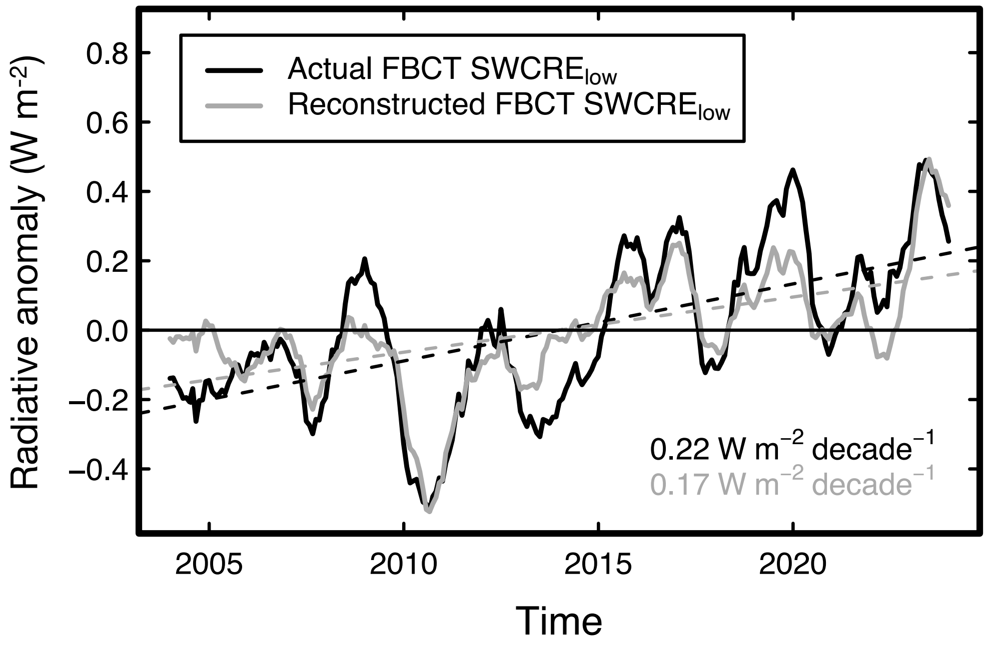

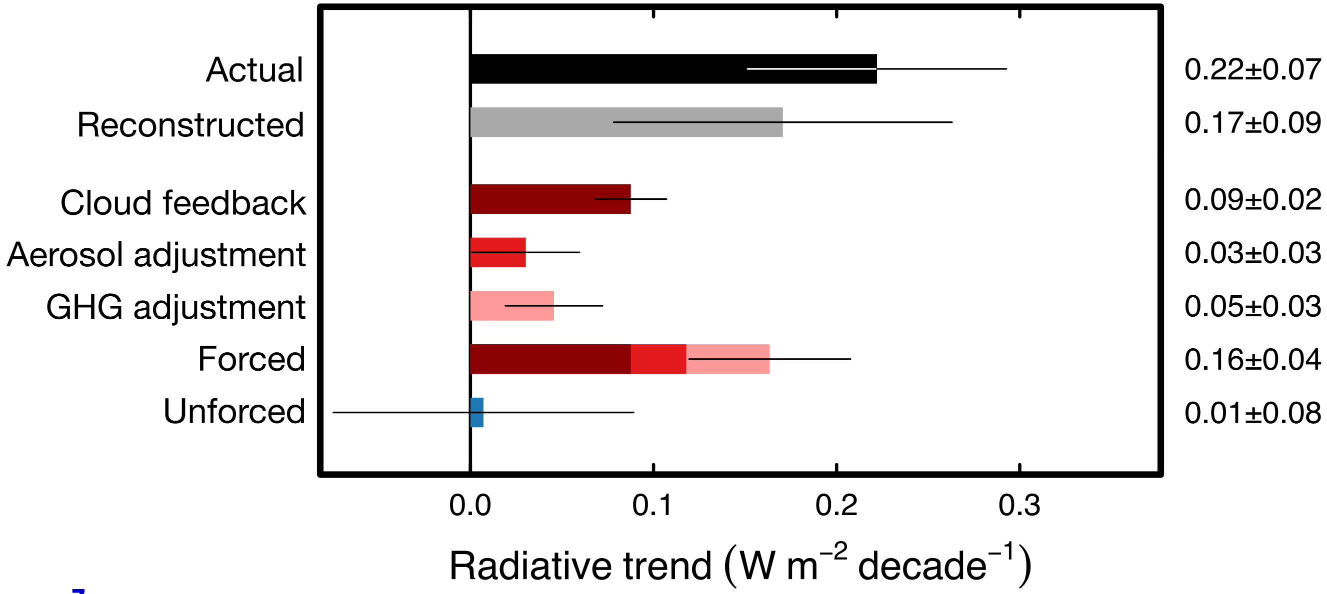

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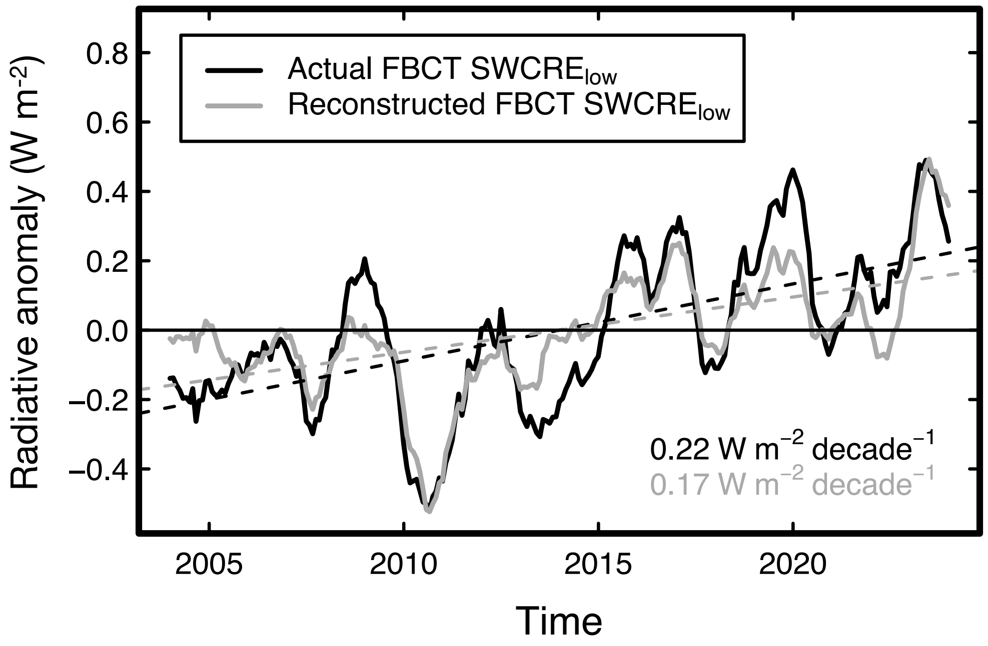
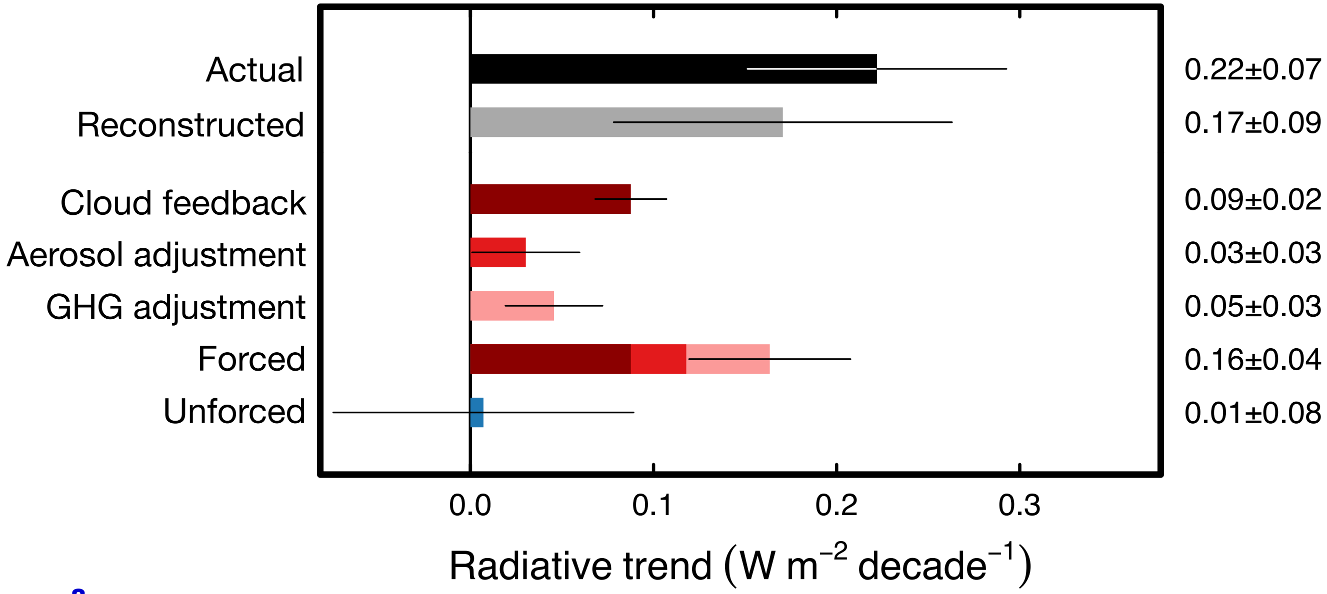
Cloud feedback explains ~40% of trend

Adjustments to GHG and aerosols also contribute

Forced component explains ~74%





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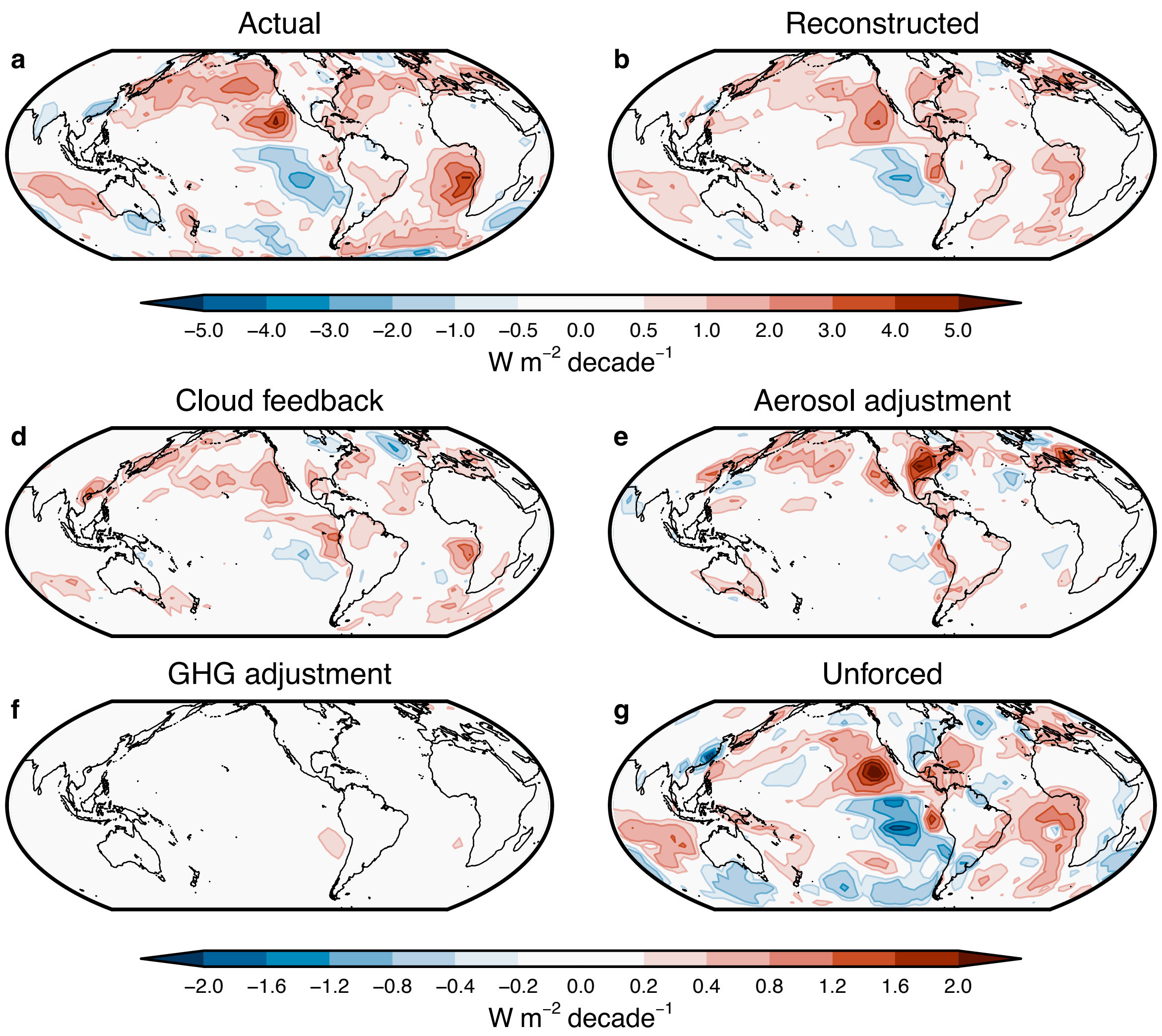
Interpreting the cloud-radiative trend
Forced & unforced trend contributions

- Low-cloud trend mainly from NH oceans, SE Atlantic, Indian Ocean
- CCF reconstruction reproduces this well
- Unforced variability dominates regionally
- Aerosols dominate in some NH regions

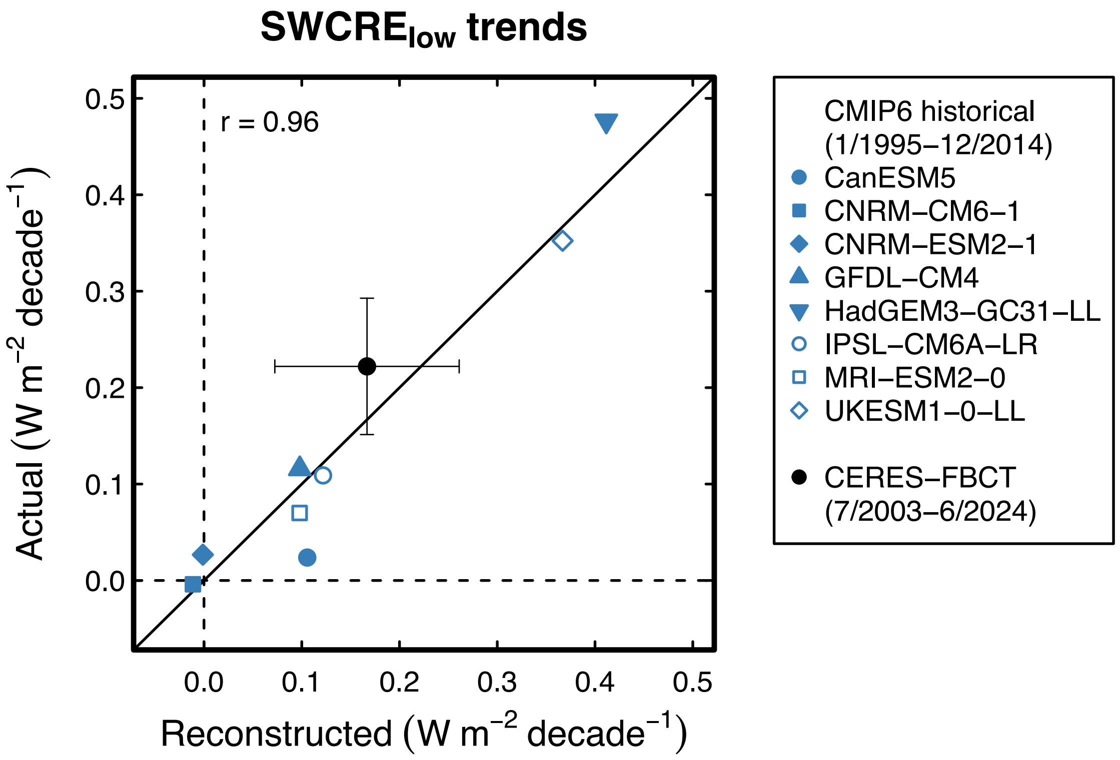


Validating the method with CMIP6 simulations

- Can apply the method to CMIP6 models as a test

- Used historical simulations, 1995–2014
- Trained on detrended data, predict trend

- Works very well across models
- **Observed trend within CMIP6 range** (though higher than most models)



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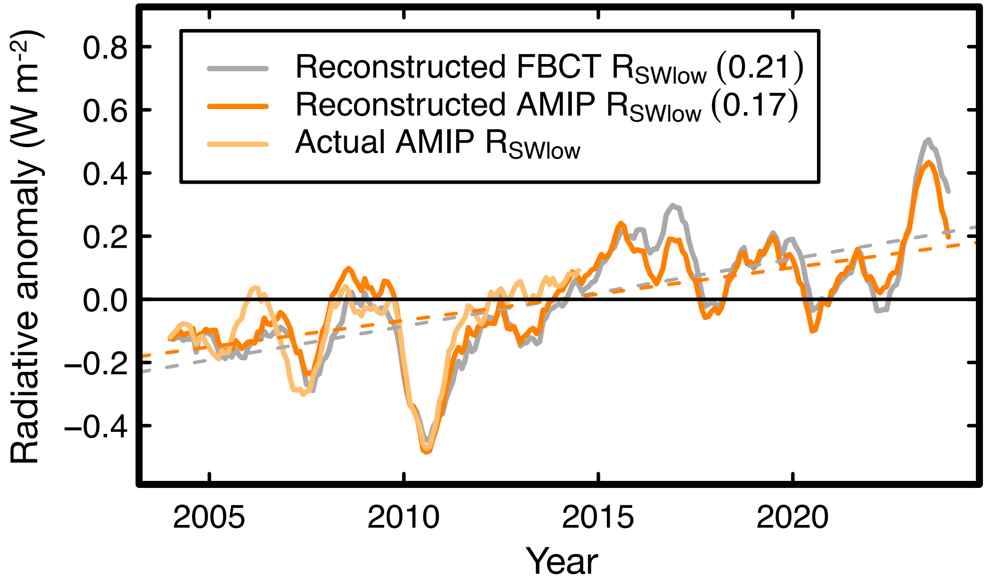
What would CMIP6 models simulate?

- CMIP6 AMIP simulations end in 2014
- What would CMIP6 models simulate for the 2003–2024 period, given observed controlling factor trends?

CMIP6 models simulate a similar trend to that observed

(Caveat – this is a small CMIP6 sample)



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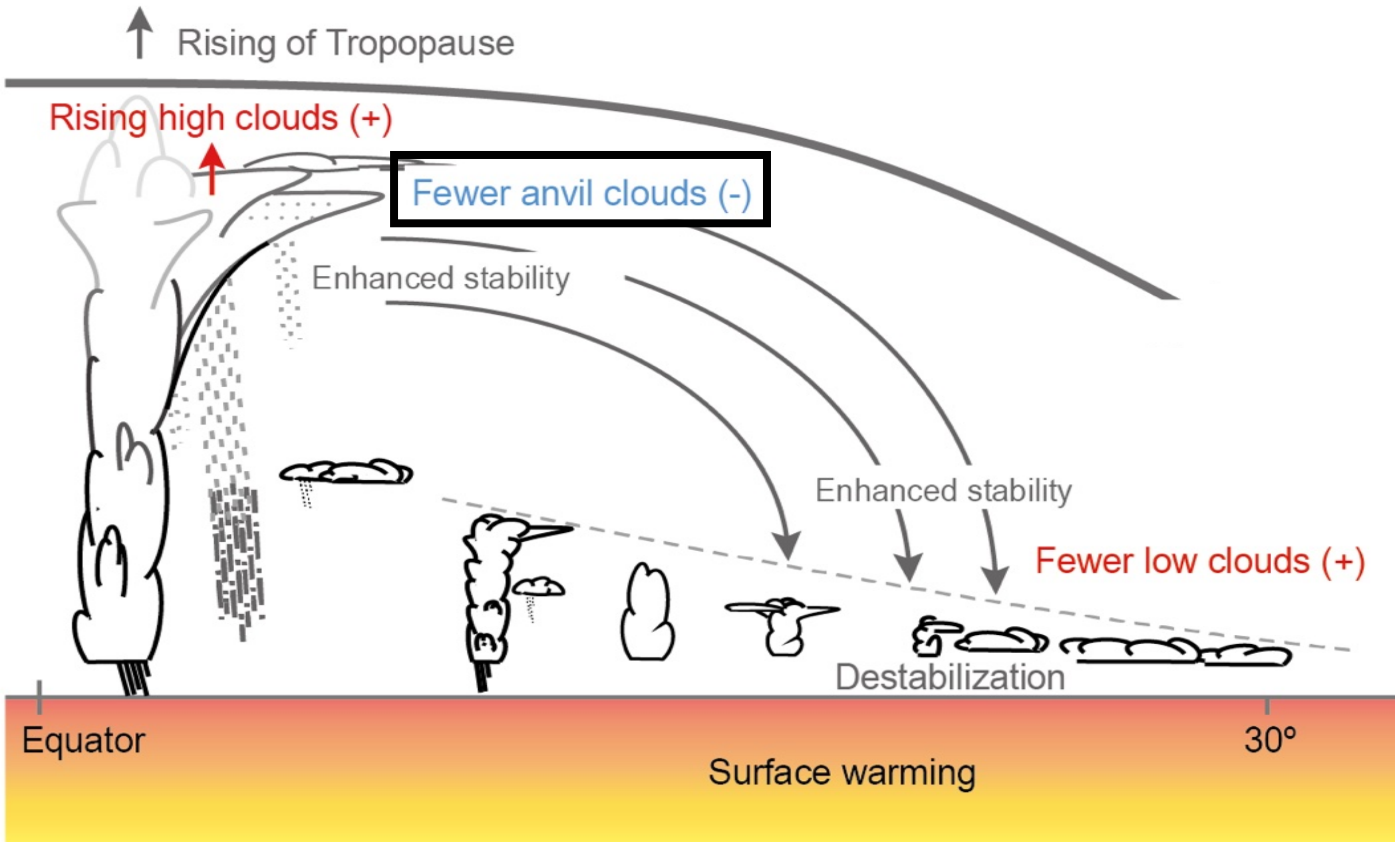
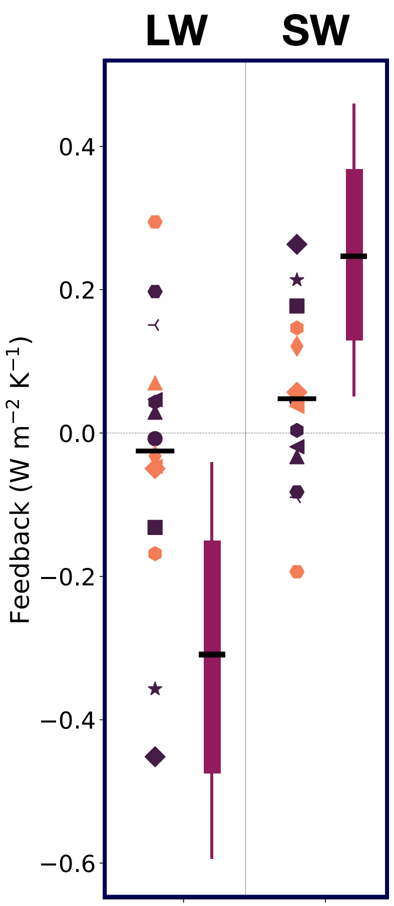
What about high clouds?

- There is a theory predicting a high-cloud amount reduction with warming: the **“stability iris”** feedback (Bony et al. 2016)
- Links **increasing upper-tropospheric static stability** to **less anvil cloud** from detrained convection
- Less high cloud → expect **negative LW feedback** and **positive SW feedback**

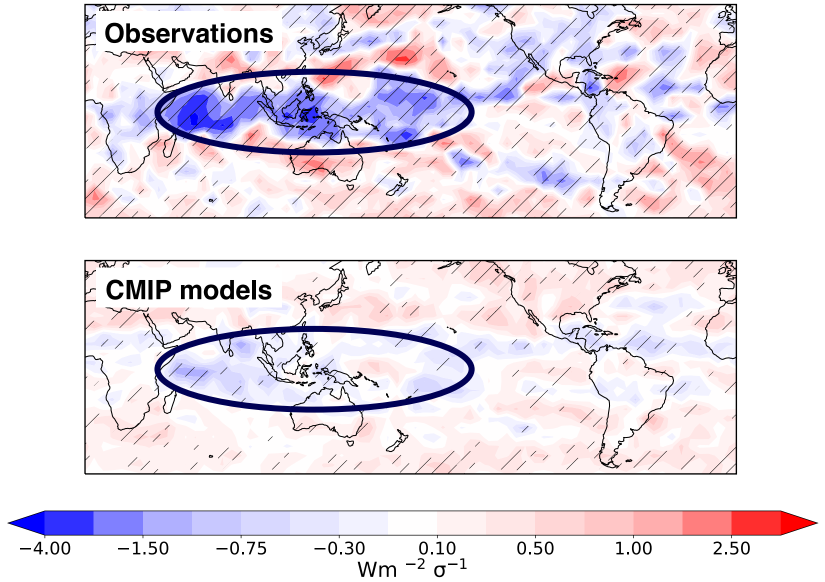


Constraints on high-cloud amount feedback

- Analysis of radiative anomalies due to **high-cloud amount**
- Observations point to more negative LW high-cloud amount feedback; more positive SW feedback



LW high-cloud radiative sensitivity to upper-tropospheric stability

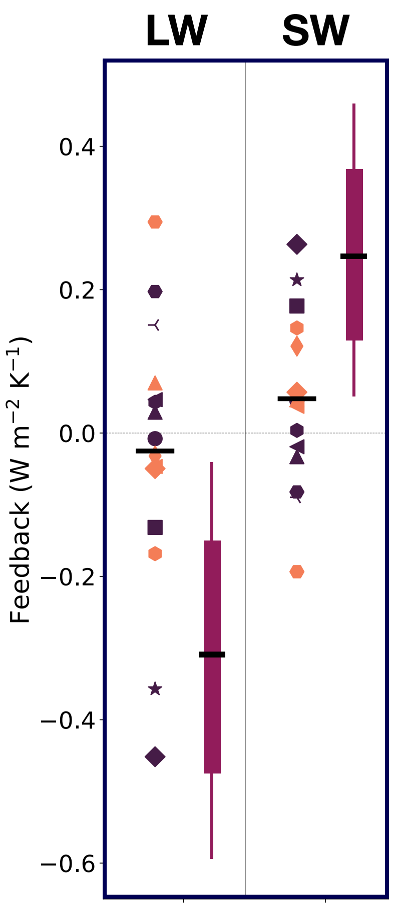


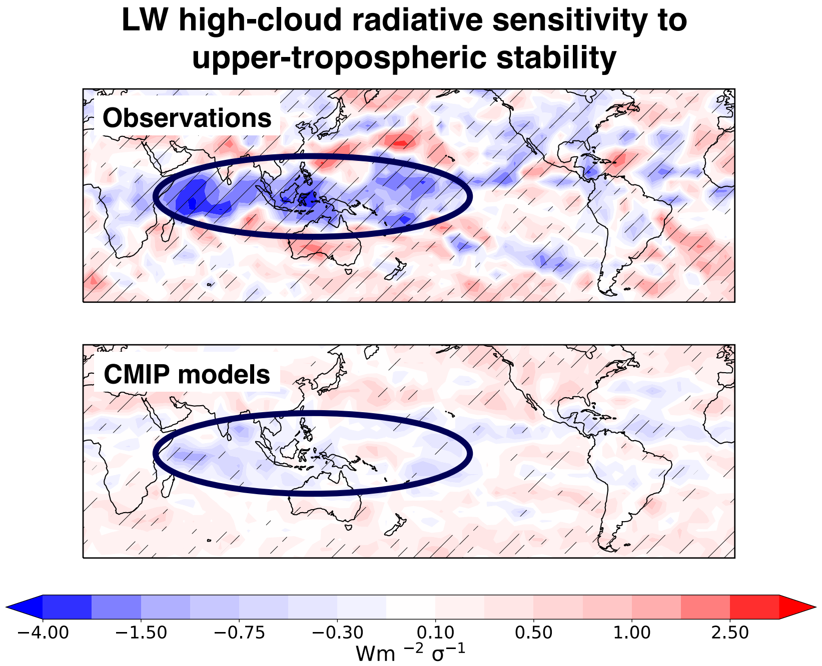
Take-home: models underestimate "stability iris" feedback; hence compensating LW/SW biases

Wilson-Kemsley et al. 2025

Constraints on high-cloud amount feedback

- Analysis of radiative anomalies due to **high-cloud amount**
- Observations point to more negative LW high-cloud amount feedback; more positive SW feedback
- **Might explain large opposing LW/SW CERES trends?**





Take-home: models underestimate "stability iris" feedback; hence compensating LW/SW biases

Wilson-Kemsley et al. 2025

Conclusions

Low clouds:

- Observed low-cloud reduction is ~50% of the EEI trend

- This trend is mostly forced: mainly cloud feedback, but also adjustments to sulphate aerosols and greenhouse gases

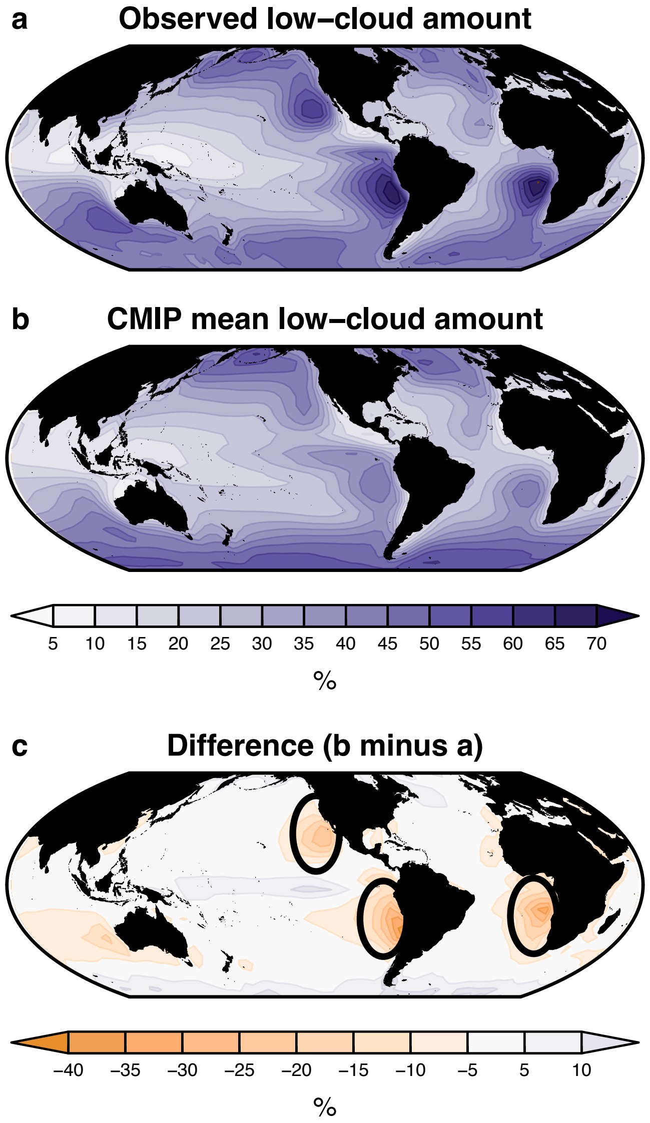
- Models can simulate similar low-cloud trends
  - Low clouds cannot account for models underestimating EEI

High clouds:

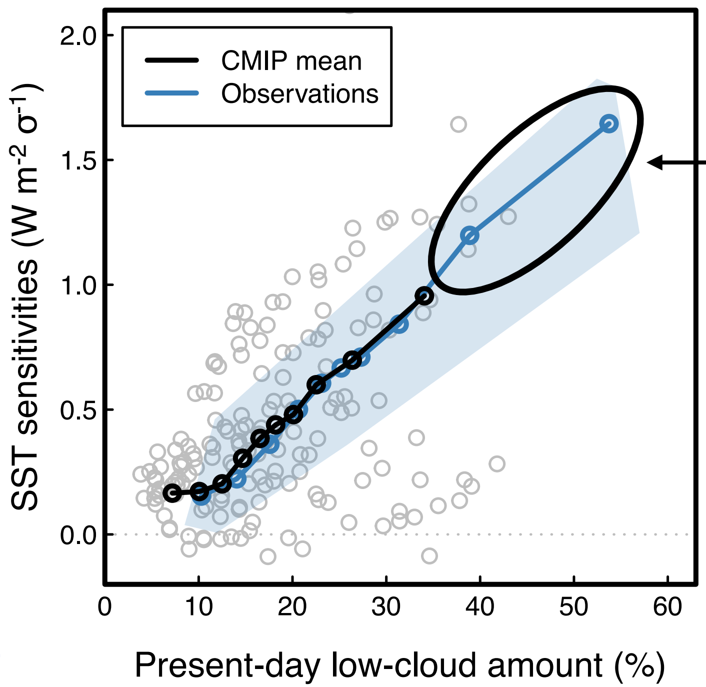
- Observations suggest large reduction in high-cloud amount as the upper troposphere stabilises
  - Large opposing LW and SW signals
  - How does this contribute to EEI trends?

Extra slides

Mean-state bias affects low-cloud feedback



- Low-cloud sensitivity to SST is proportional to baseline low-cloud amount
- **More low cloud → greater sensitivity to SST → more positive feedback**



Not enough present-day clouds → underestimated feedback

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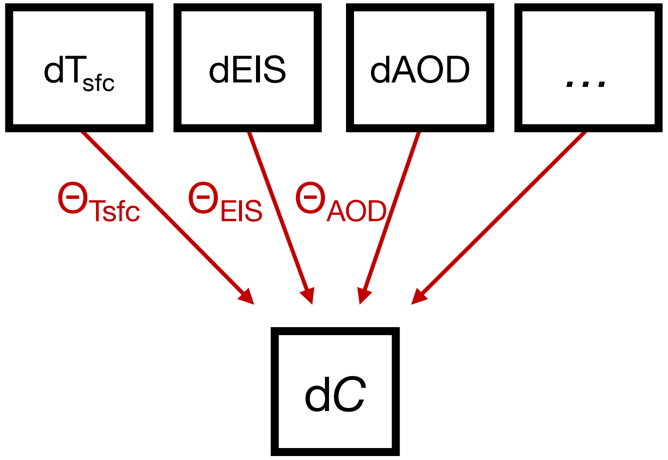
Cloud-controlling factor (CCF) analysis

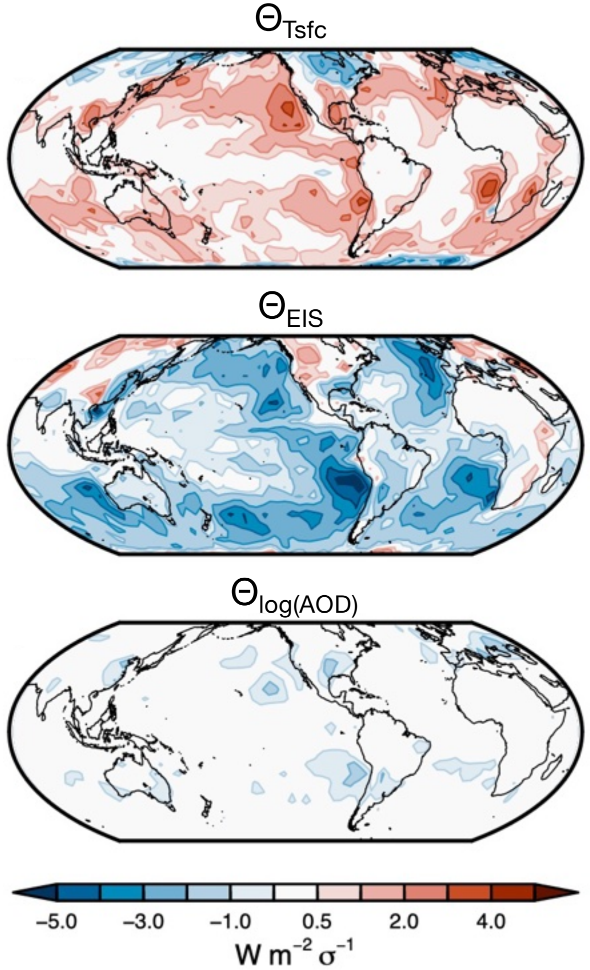
7 cloud-controlling factors (CCFs)



Cloud-radiative anomalies

- Use **ridge regression** to learn the **sensitivities Θ_i** at each location r (Ceppi et al. 2024, GRL)
- Train on detrended data (20 years = 240 months), predict trend

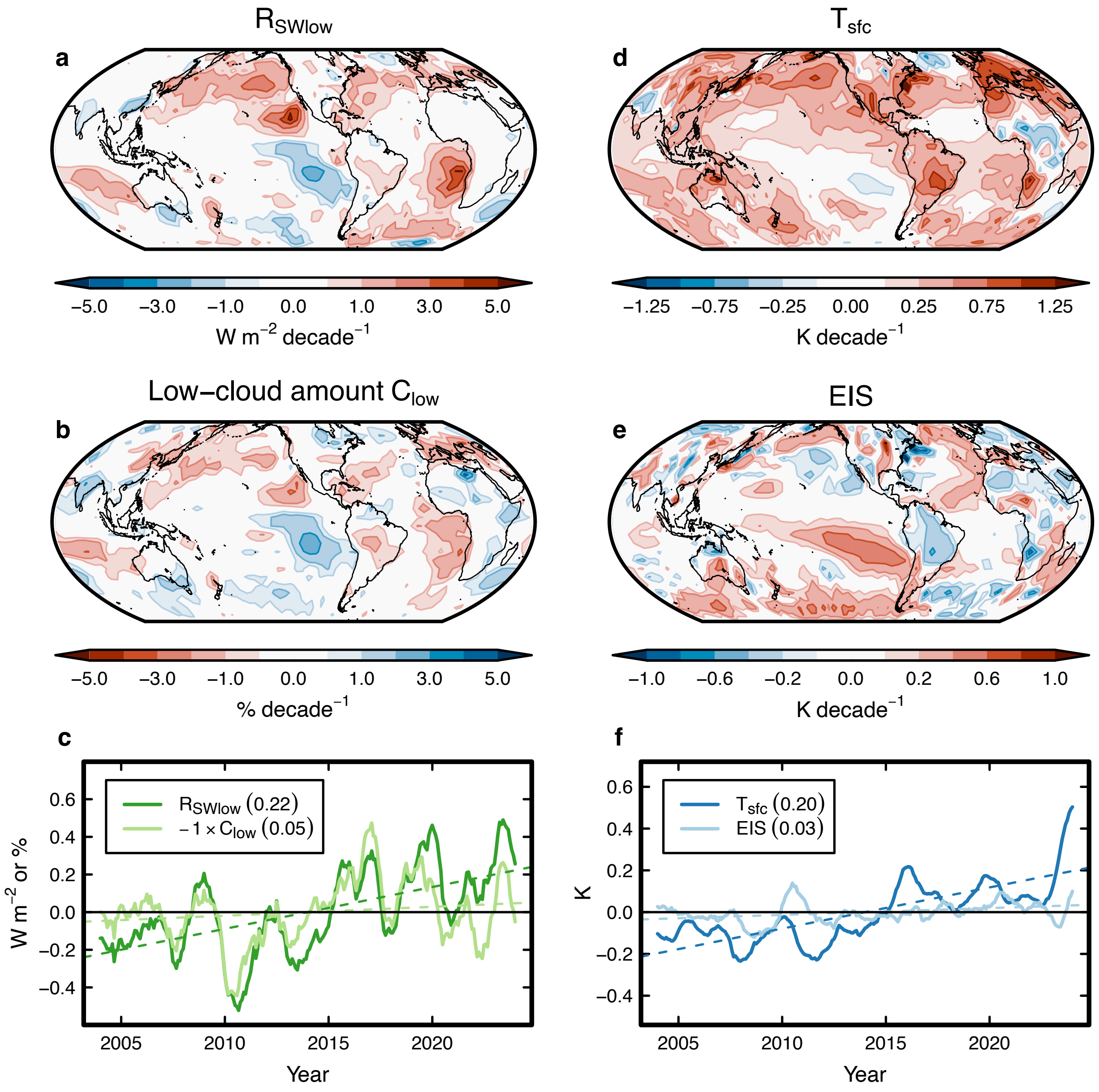
Maps of the sensitivities Θ

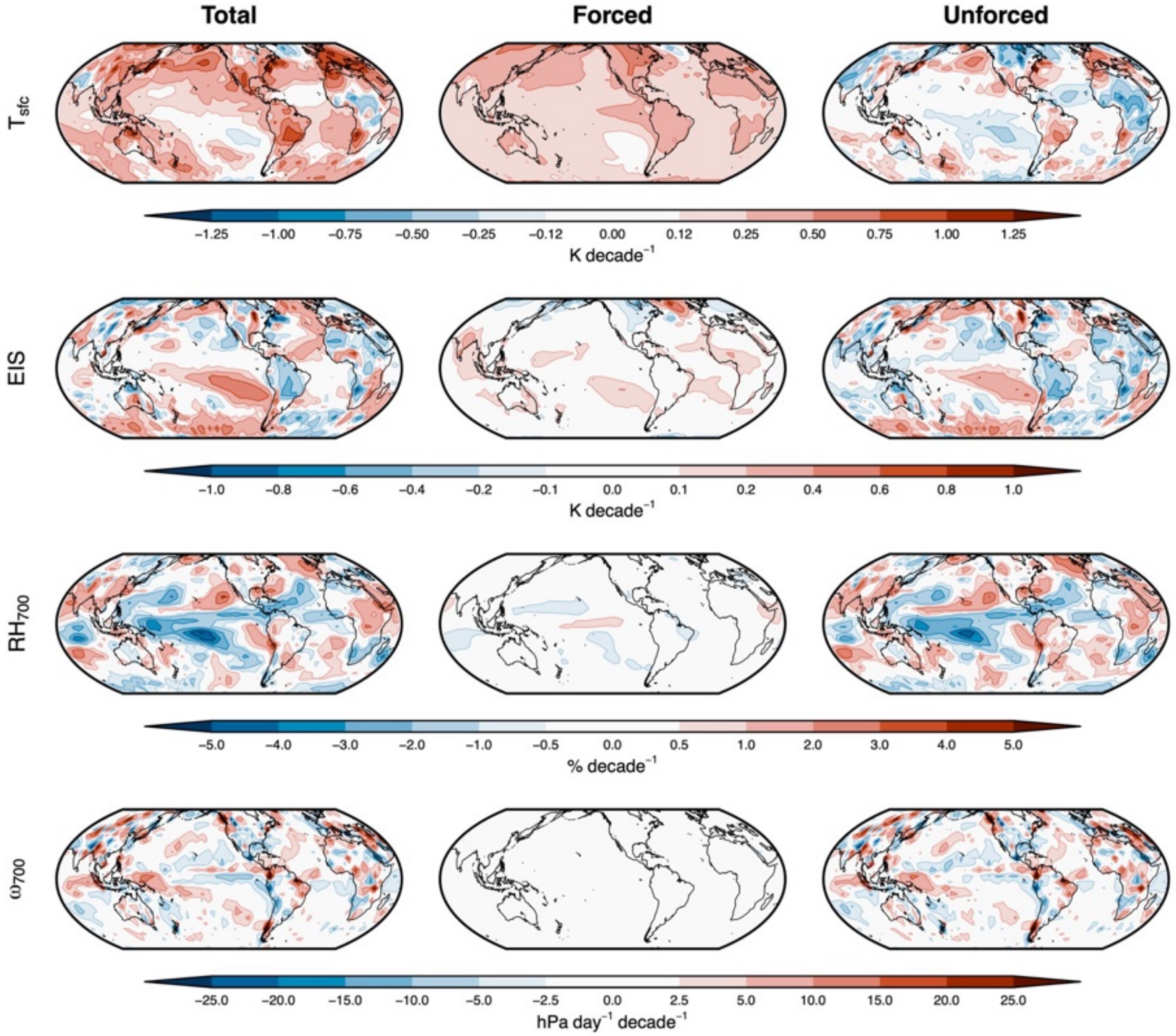


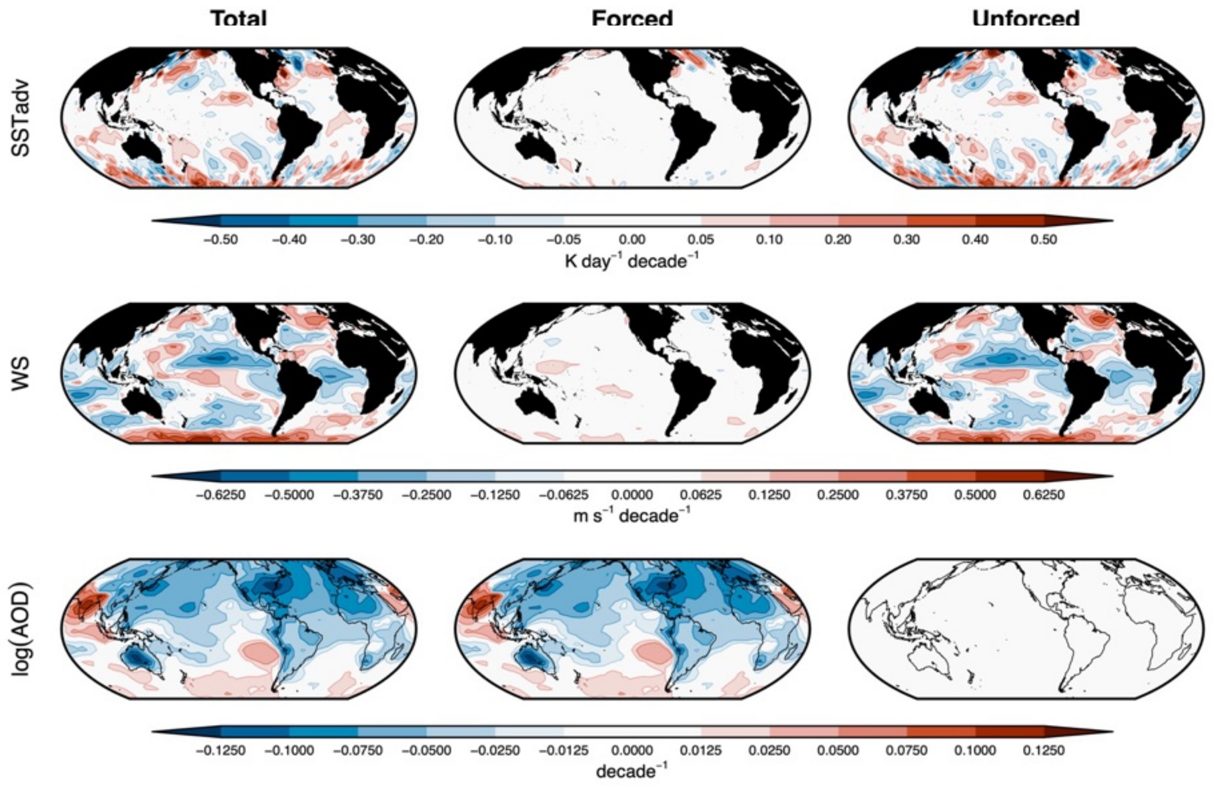
Prediction model for cloud-radiative trends

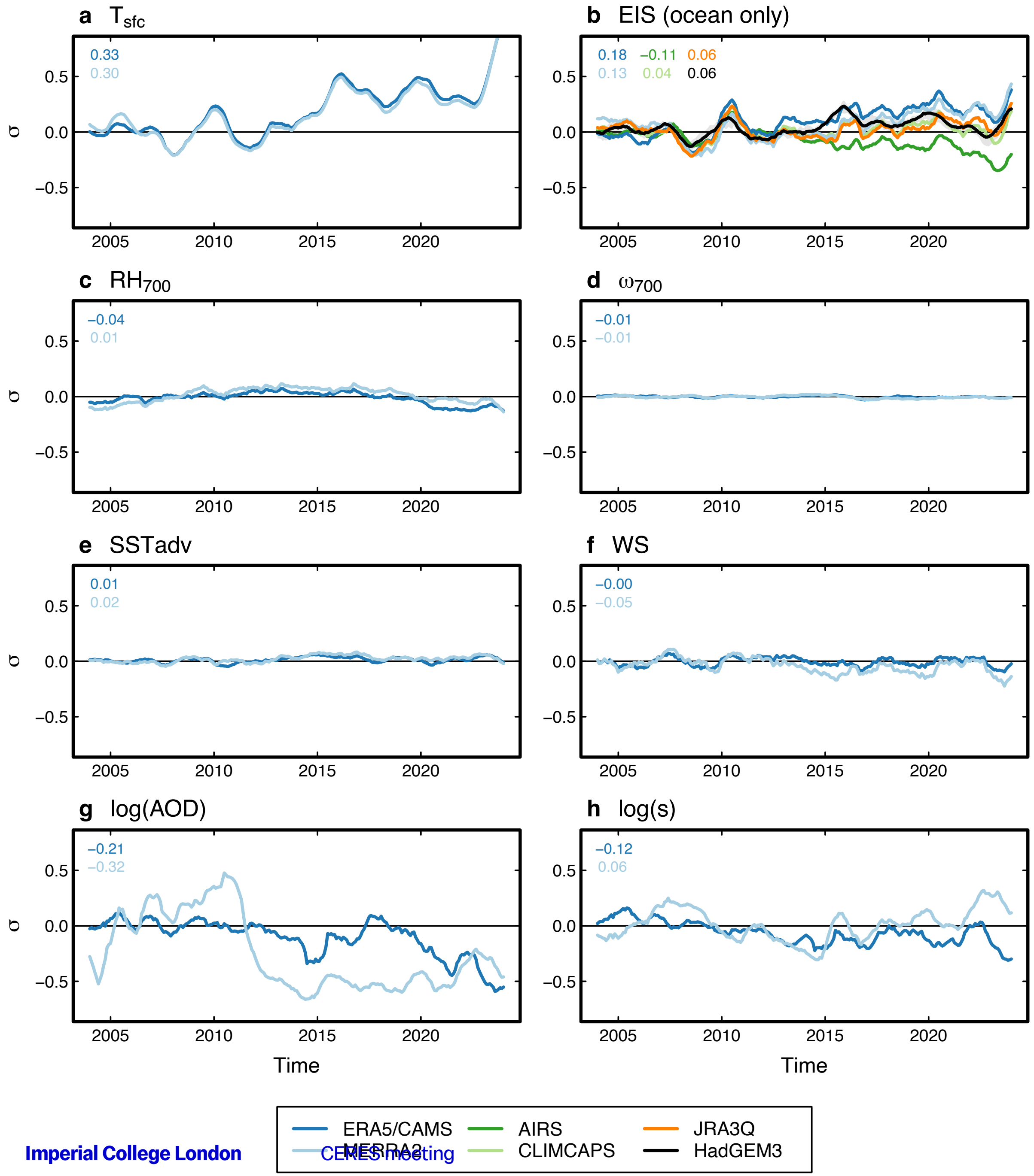
$$\frac{\mathrm{d}C(r)}{\mathrm{d}t} \approx \sum_{i=1}^{M} \boldsymbol{\Theta}_i(r) \cdot \frac{\mathrm{d}\boldsymbol{X}_i(r)}{\mathrm{d}t}$$

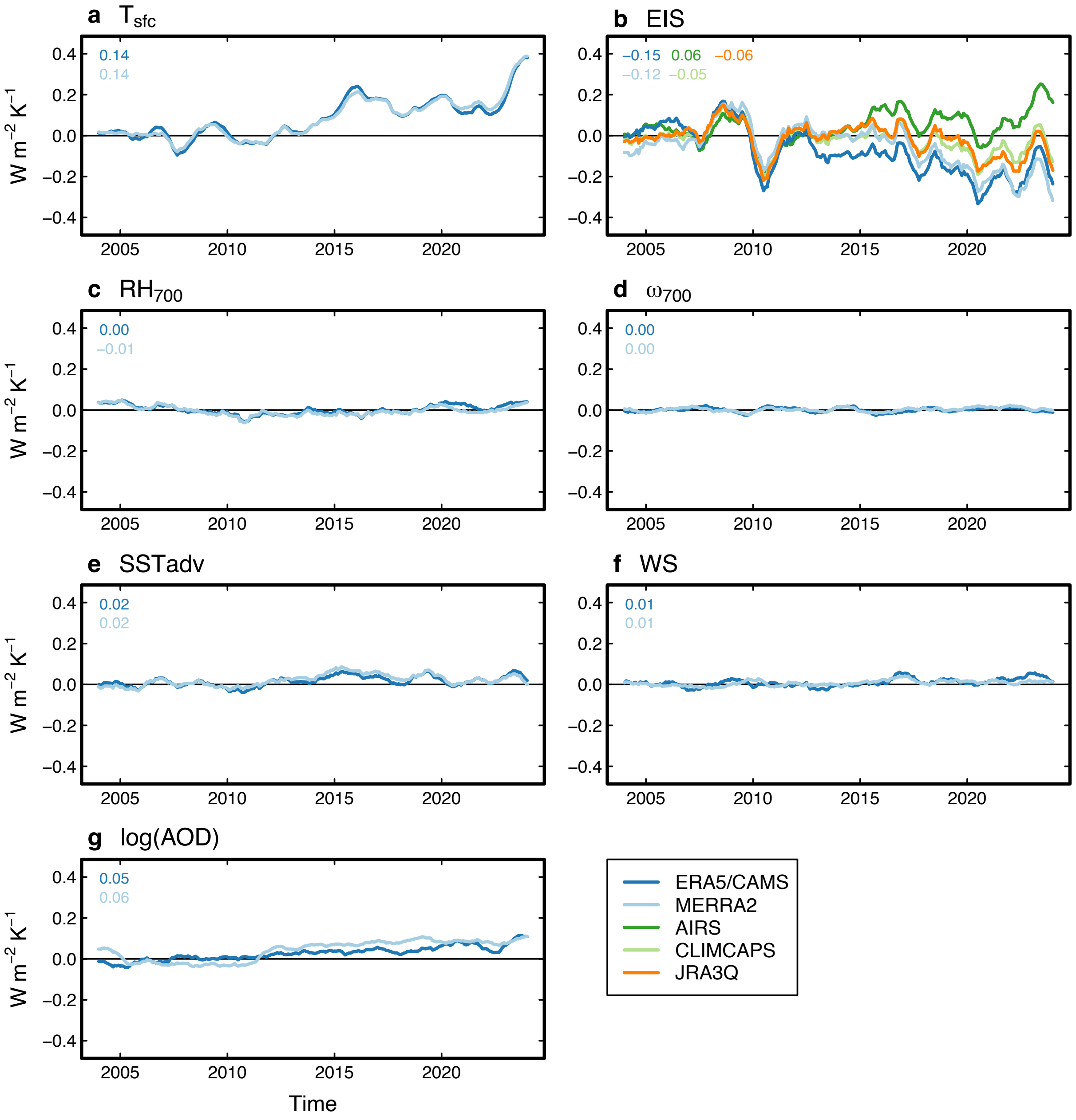
Decadal trends, July 2003 to June 2024




Total
Forced
Unforced
Tsfc
−1.25 −1.00 −0.75 −0.50 −0.25 −0.12 0.00 0.12 0.25 0.50 0.75 1.00 1.25
K decade⁻¹
EIS
−1.0 −0.8 −0.6 −0.4 −0.2 −0.1 0.0 0.1 0.2 0.4 0.6 0.8 1.0
K decade⁻¹
RH700
−5.0 −4.0 −3.0 −2.0 −1.0 −0.5 0.0 0.5 1.0 2.0 3.0 4.0 5.0
% decade⁻¹
ω700
−25.0 −20.0 −15.0 −10.0 −5.0 −2.5 0.0 2.5 5.0 10.0 15.0 20.0 25.0
hPa day⁻¹ decade⁻¹


Total
Forced
Unforced
SSTadv
−0.50 −0.40 −0.30 −0.20 −0.10 −0.05 0.00 0.05 0.10 0.20 0.30 0.40 0.50
K day⁻¹ decade⁻¹
WS
−0.6250 −0.5000 −0.3750 −0.2500 −0.1250 −0.0625 0.0000 0.0625 0.1250 0.2500 0.3750 0.5000 0.6250
m s⁻¹ decade⁻¹
log(AOD)
−0.1250 −0.1000 −0.0750 −0.0500 −0.0250 −0.0125 0.0000 0.0125 0.0250 0.0500 0.0750 0.1000 0.1250
decade⁻¹


a T_sfc
0.33
0.30
b EIS (ocean only)
0.18 −0.11 0.06
0.13 0.04 0.06
c RH700
−0.04
0.01
d ω700
−0.01
−0.01
e SSTadv
0.01
0.02
f WS
−0.00
−0.05
g log(AOD)
−0.21
−0.32
h log(s)
−0.12
0.06
σ
Time
ERA5/CAMS
MERRA2
AIRS
CLIMCAPS
JRA3Q
HadGEM3


a T_sfc
0.14
0.14
b EIS
−0.15 0.06 −0.06
−0.12 −0.05
c RH700
0.00
−0.01
d ω700
0.00
0.00
e SSTadv
0.02
0.02
f WS
0.01
0.01
g log(AOD)
0.05
0.06
W m−2 K−1
Time
ERA5/CAMS
MERRA2
AIRS
CLIMCAPS
JRA3Q