Recent cloud trends and extremes reaffirm moderate climate sensitivity

Mark Zelinka[1], Tim Myers[2,3], Yi Qin[4], Li-Wei Chao[1], Steve Klein[1], Steve Po-Chedley[1], Po-Lun Ma[4], Casey Wall[5], Paulo Ceppi[6], & Andrew Gettelman[4]

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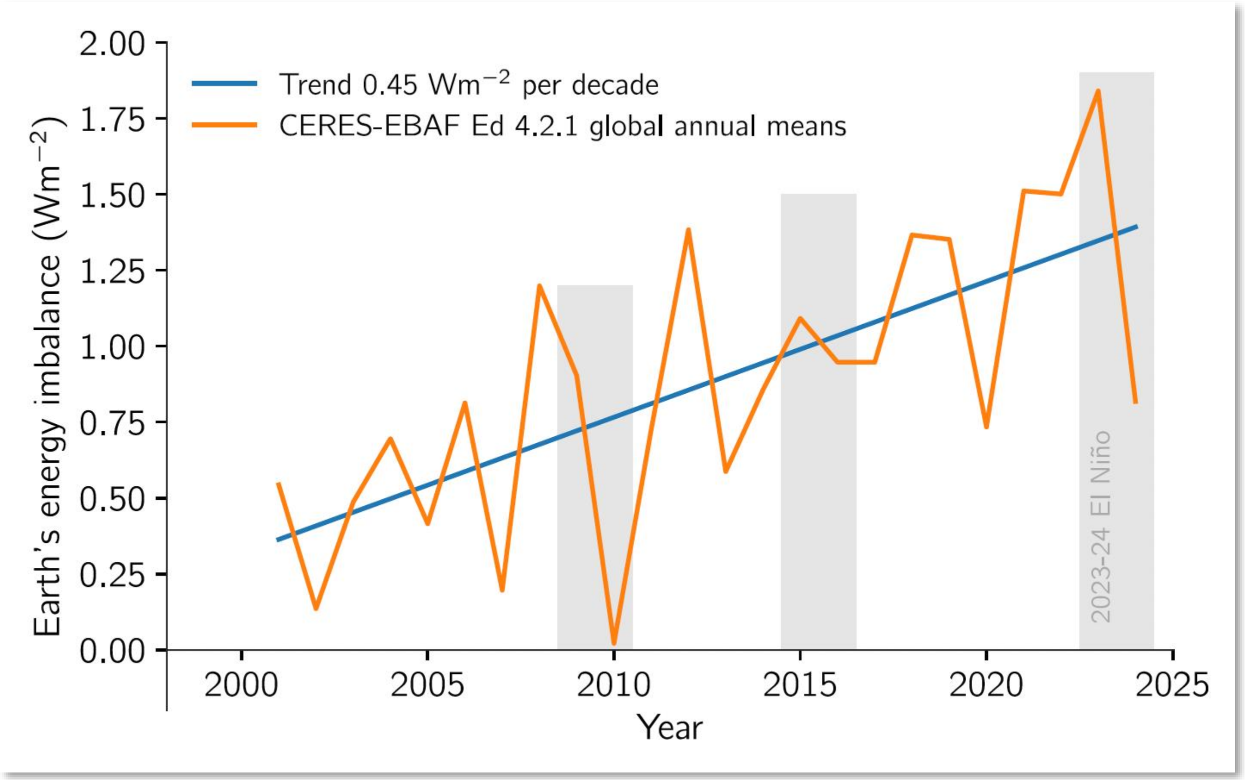
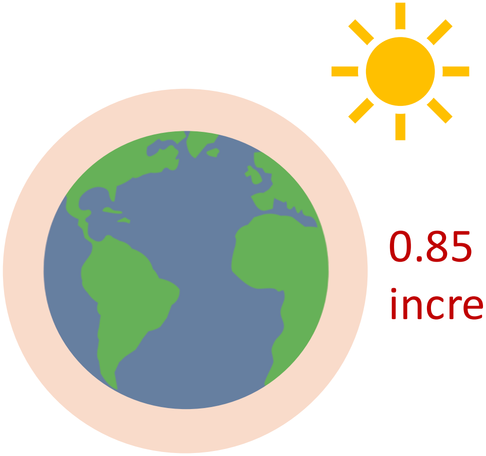
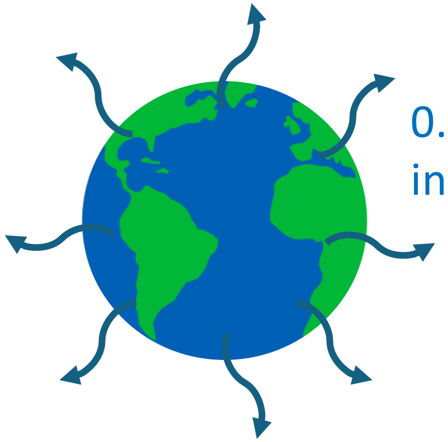
Earth’s Growing Energy Surplus



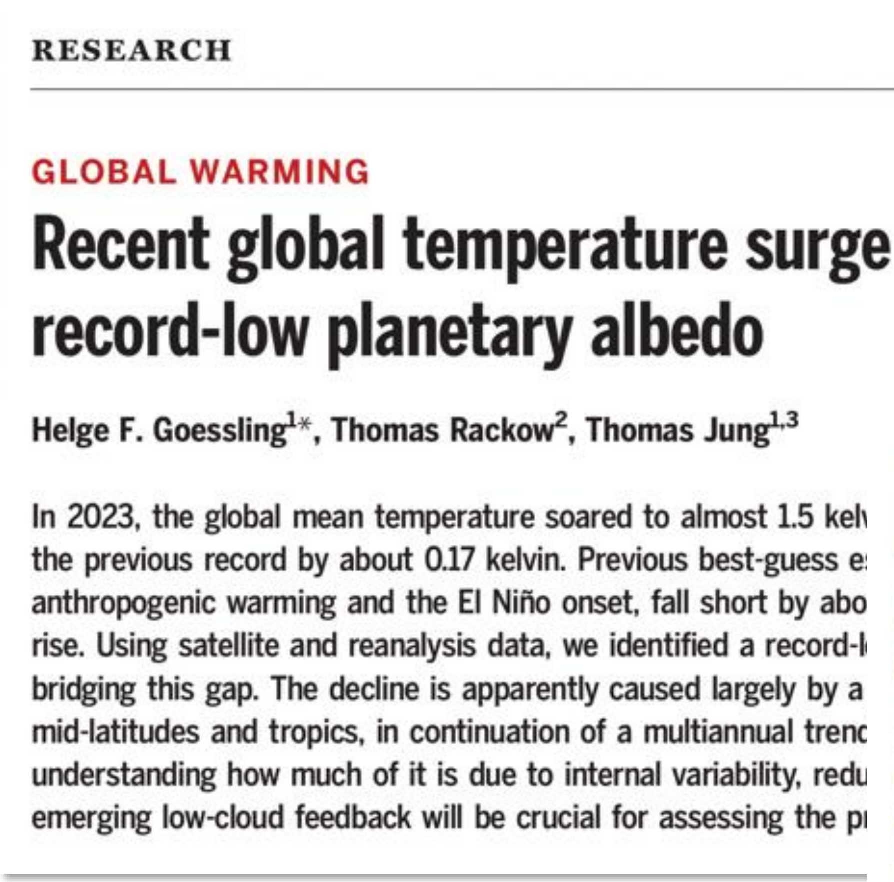
Mauritsen et al (2025)



0.85 ± 0.22 W/m^2/dec increased solar heating



0.41 ± 0.23 W/m^2/dec increased outgoing LW radiation



RESEARCH

GLOBAL WARMING

Recent global temperature surge intensified by record-low planetary albedo

Helge F. Goessling[1]*, Thomas Rackow[2], Thomas Jung[1,3]

In 2023, the global mean temperature soared to almost 1.5 kel
the previous record by about 0.17 kelvin. Previous best-guess e
anthropogenic warming and the El Niño onset, fall short by abo
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bridging this gap. The decline is apparently caused largely by a
mid-latitudes and tropics, in continuation of a multiannual tren
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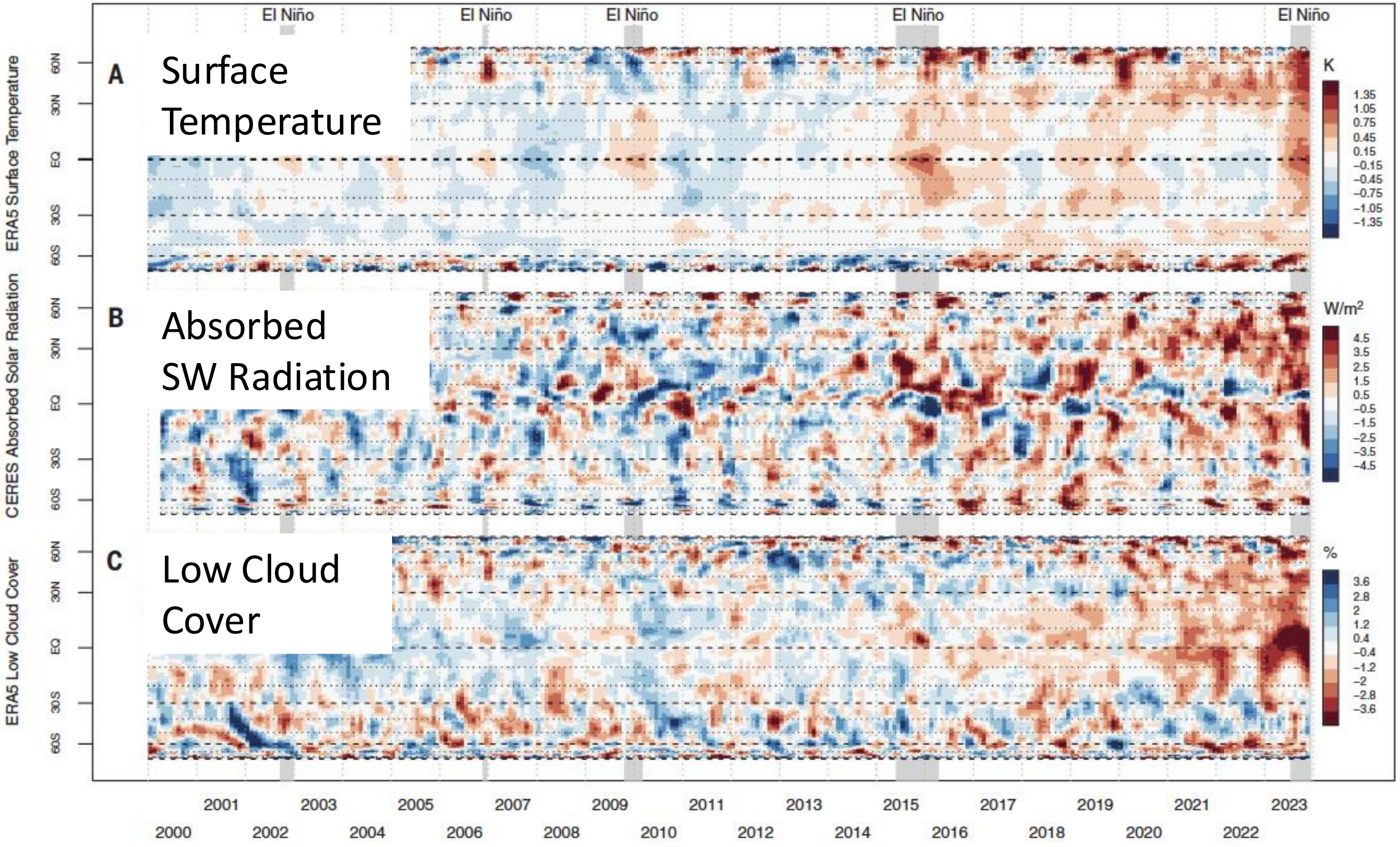


Surface Temperature

Absorbed SW Radiation

Low Cloud Cover

Questions

- Can anomalies in cloud controlling factors (CCFs) explain recent extremes in cloud-radiative effects?
- Can trends in CCFs explain trends in cloud-radiative effects?
- What does this mean for cloud feedback, aerosol forcing, and climate sensitivity?

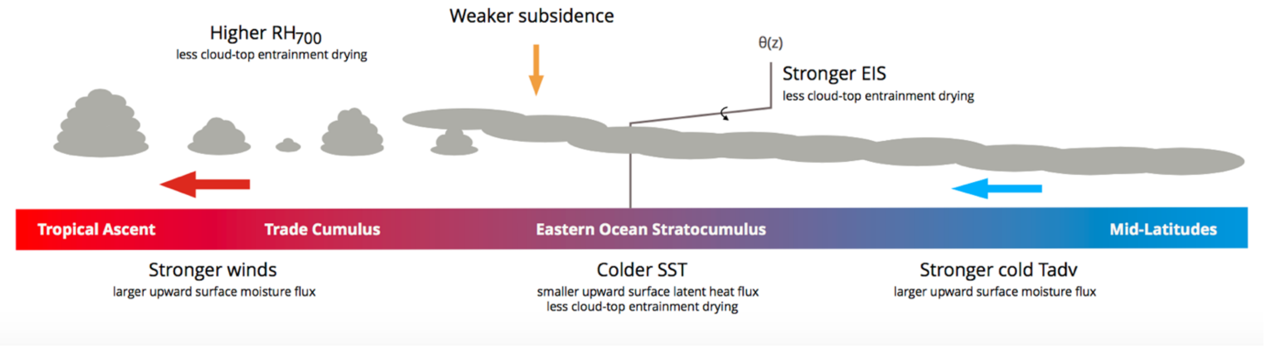
Looking at low-cloud changes through the lens of their controlling factors

Derive from satellite observations

$$\Delta R_{cld} \approx \sum_i \frac{\partial R_{cld}}{\partial x_i} \Delta x_i$$

The change in radiation due to low-clouds

Interannual anomalies or trends in CCFs



$$x_i \in \{\mathrm{SST}, \text{inversion strength}, \text{advection}, \ldots\}$$

“low-cloud controlling factors”

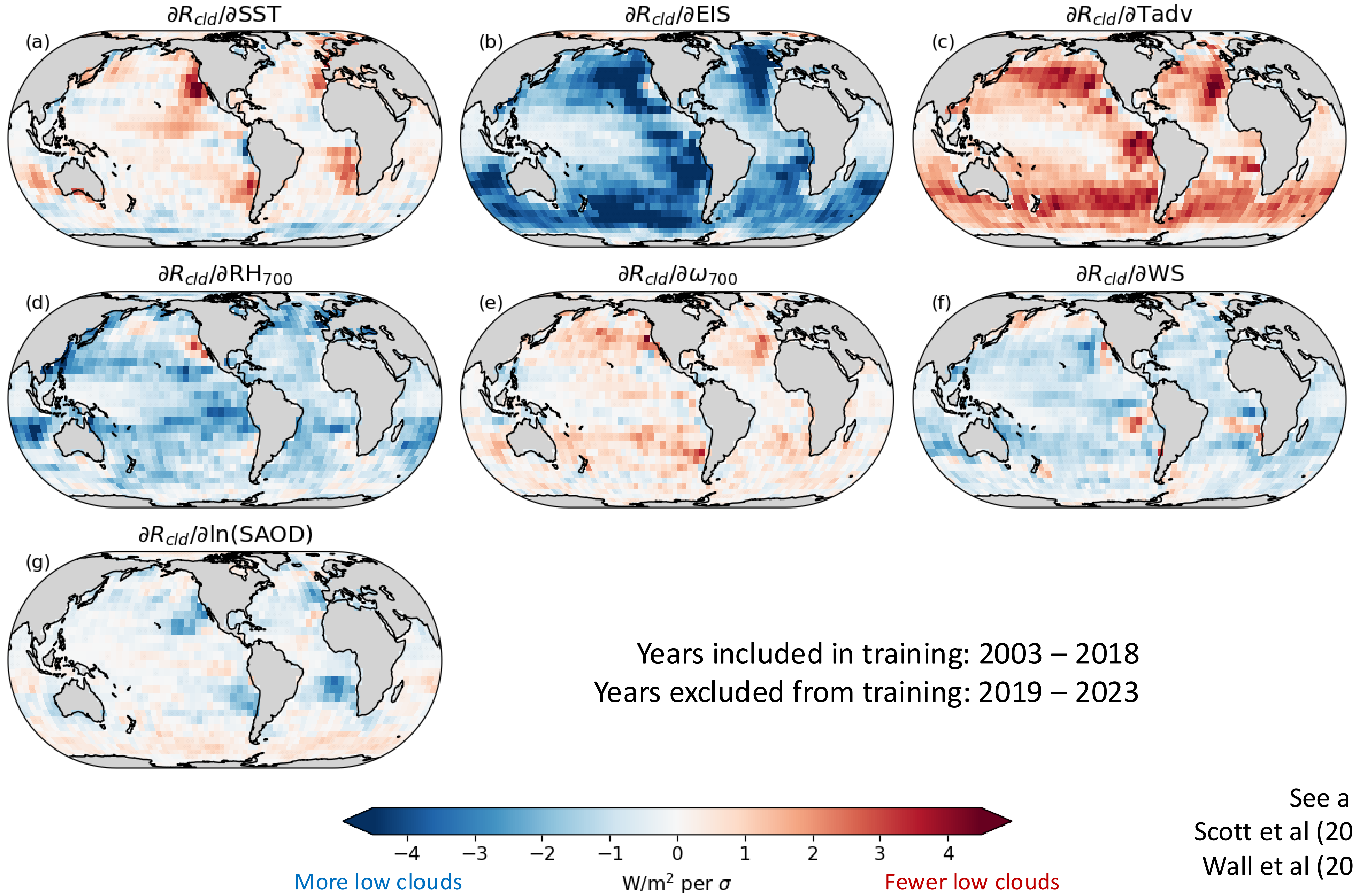
Calculating CCF Sensitivities

- R_{cld}: Monthly-resolved low-cloud induced SW anomalies
- x_i: Standardized monthly-resolved anomalies in 7 CCFs
- Detrend x_i and R_{cld}
- For a given target year, remove it and 2 years on either side of it from training (5 years total left out)
- Calculate $\partial R_{cld} / \partial x_i$ at each 5˚x5˚ grid box via multilinear regression
- Loop over target years, from 2003 to 2024 (full years with MODIS)

CCF Coefficients; Target Year = 2023

Meteo CCFs
from ERA5

Aerosol CCF:
Sulfate AOD at
550nm from CAMS
global reanalysis
(EAC4)



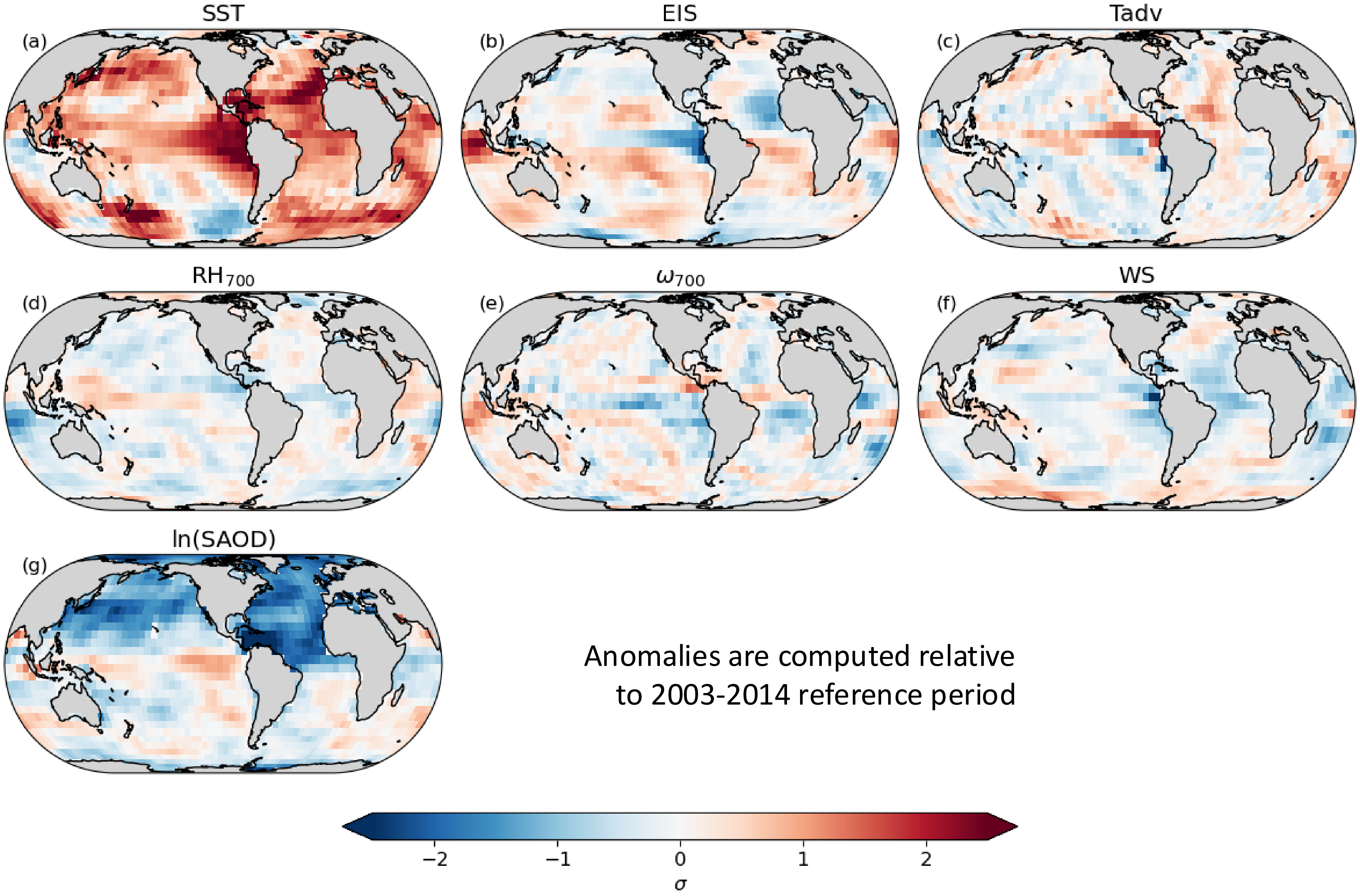
Years included in training: 2003 – 2018
Years excluded from training: 2019 – 2023

See also:
Scott et al (2020)
Wall et al (2022)

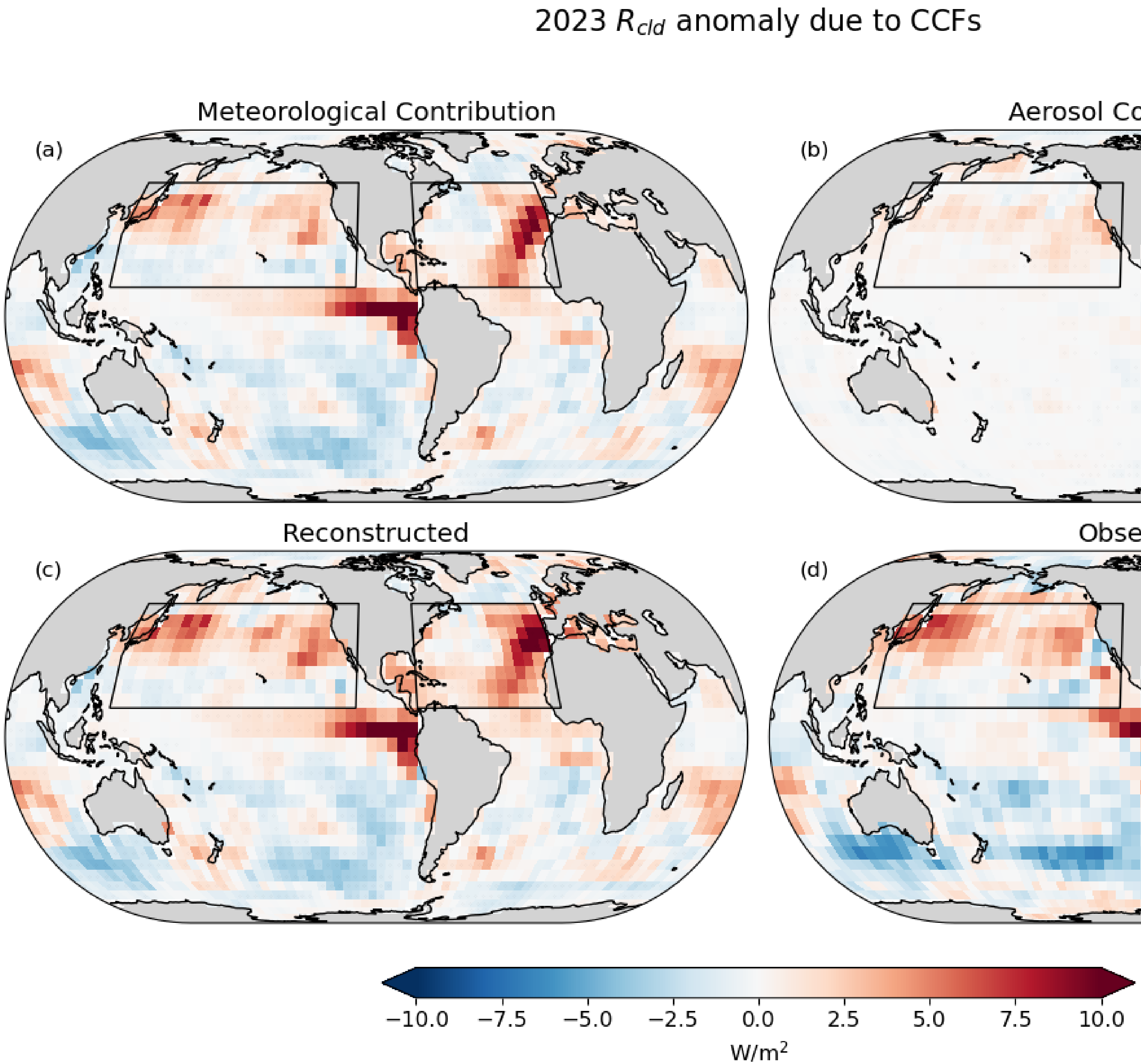
CCF Anomalies in 2023

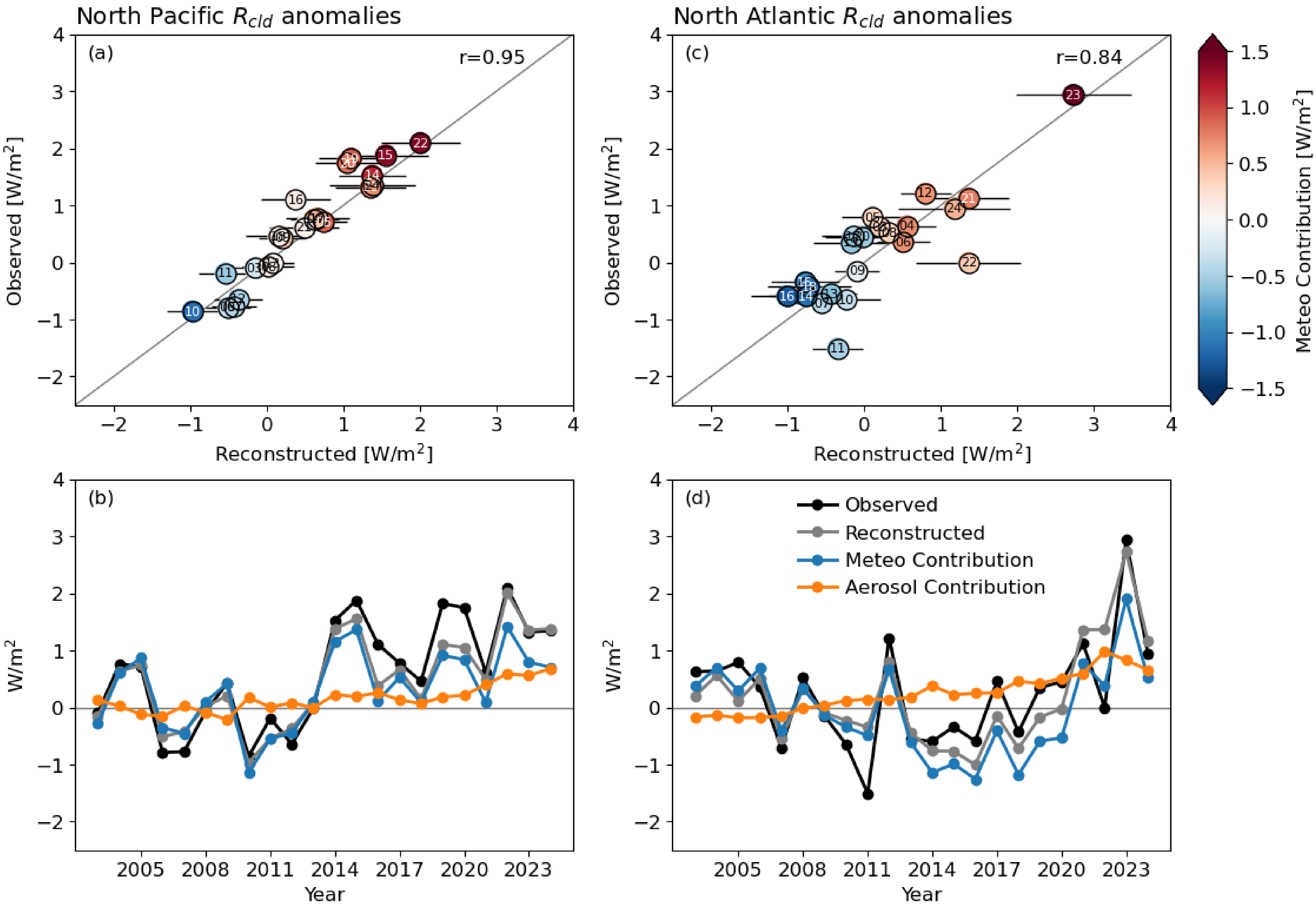
Meteo CCFs
from ERA5

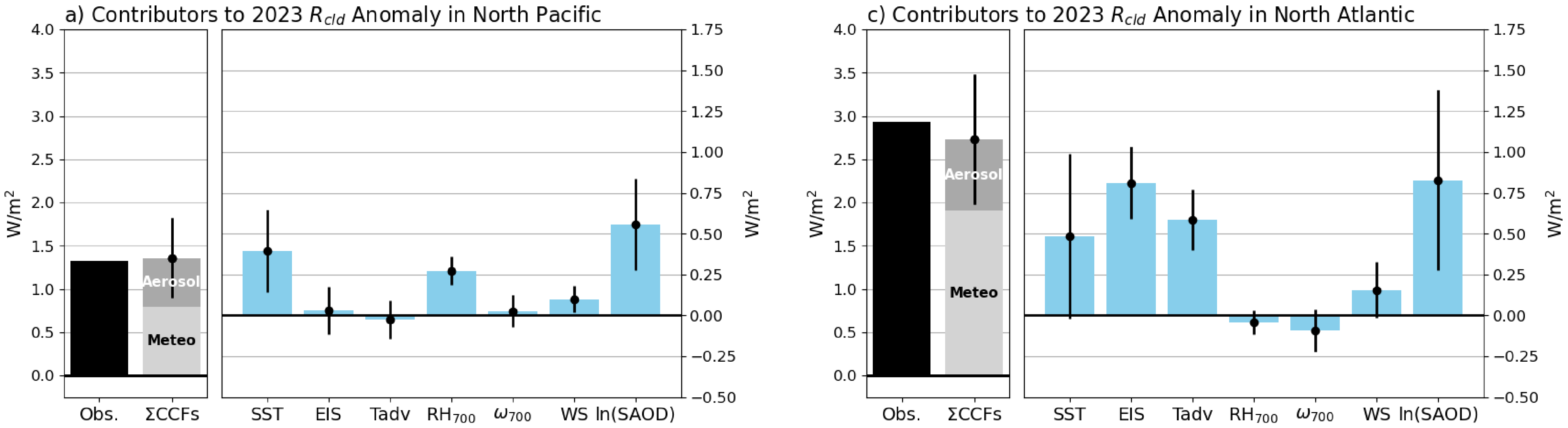
Aerosol CCF:
Sulfate AOD at
550nm from CAMS
global reanalysis
(EAC4)

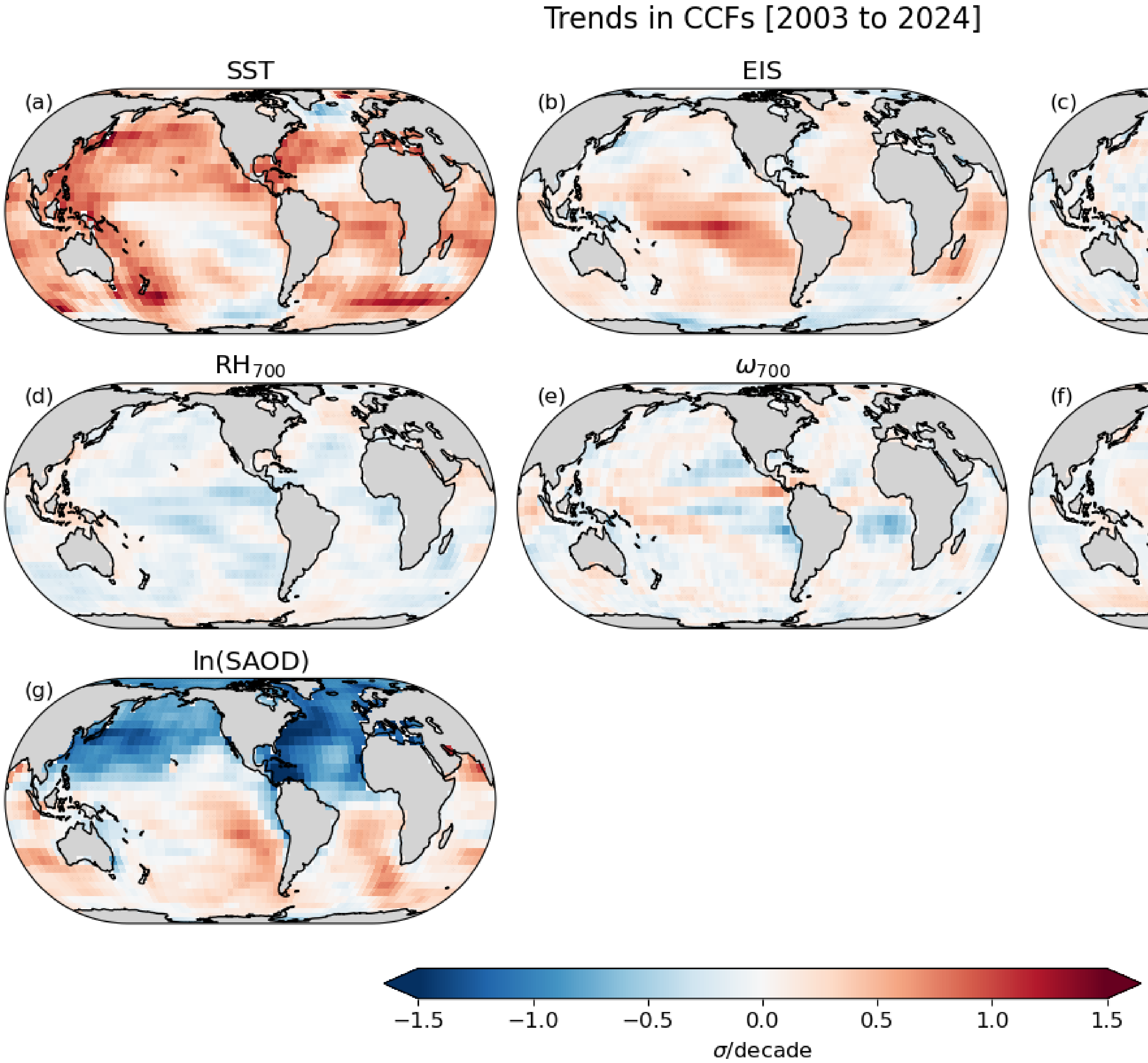


Anomalies are computed relative
to 2003-2014 reference period

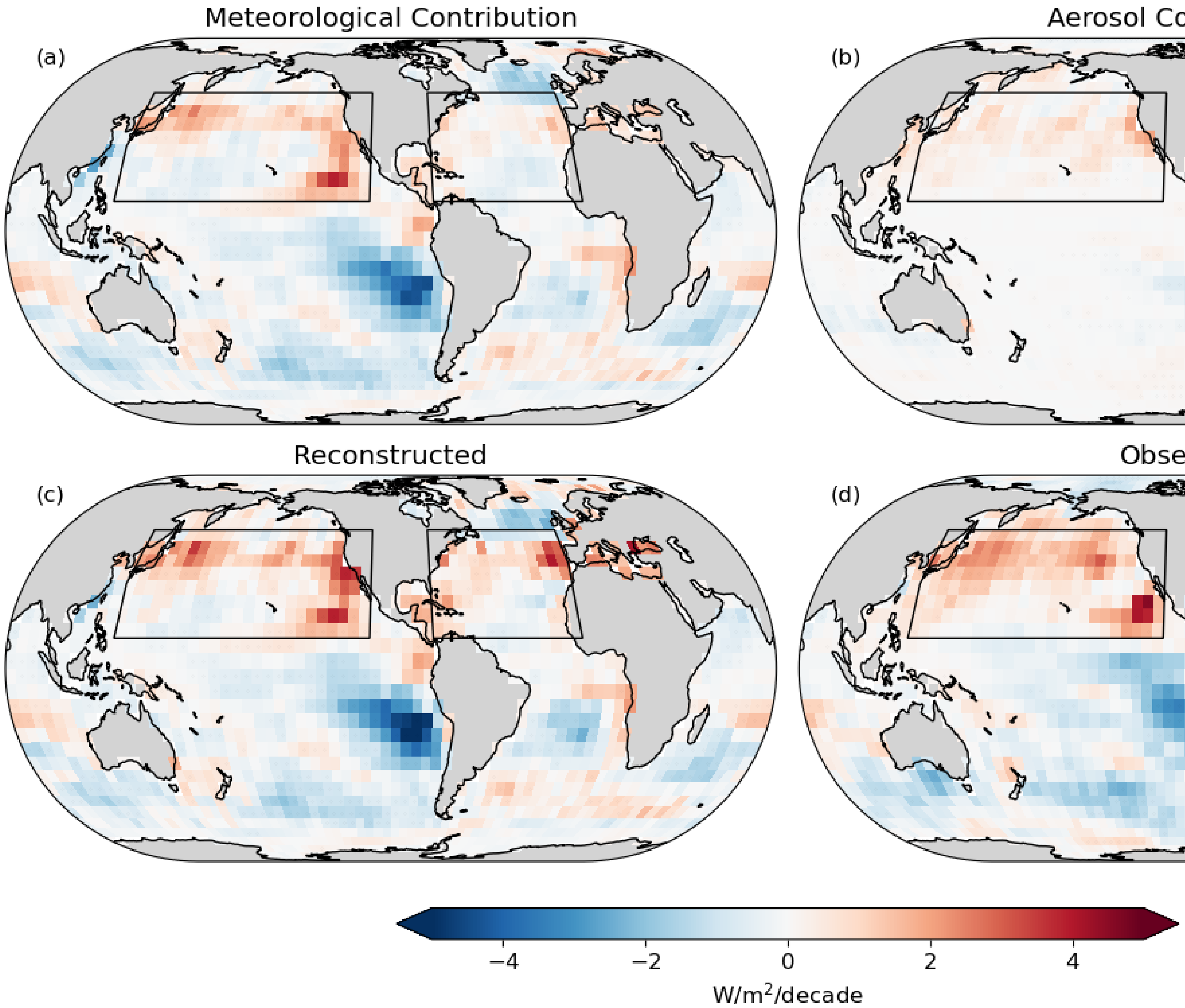

2023 R_{cld} anomaly due to CCFs
Meteorological Contribution
(a)
Aerosol Contribution
(b)
Reconstructed
(c)
Observed
(d)
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
W/m^2


North Pacific R_{cld} anomalies
North Atlantic R_{cld} anomalies
(a)
r=0.95
(c)
r=0.84
(b)
(d)
Observed [W/m^2]
Reconstructed [W/m^2]
W/m^2
Year
Meteo Contribution [W/m^2]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
4
3
2
1
0
−1
−2
2005
2008
2011
2014
2017
2020
2023
Observed
Reconstructed
Meteo Contribution
Aerosol Contribution


a) Contributors to 2023 R_{cld} Anomaly in North Pacific
W/m^2
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Aerosol
Meteo
Obs.
ΣCCFs
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
SST
EIS
Tadv
RH$_{700}$
ω_{700}
WS
ln(SAOD)
c) Contributors to 2023 R_{cld} Anomaly in North Atlantic
W/m^2
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Aerosol
Meteo
Obs.
ΣCCFs
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
SST
EIS
Tadv
RH$_{700}$
ω_{700}
WS
ln(SAOD)


Trends in CCFs [2003 to 2024]
SST
(a)
EIS
(b)
Tadv
(c)
RH_{700}
(d)
ω_{700}
(e)
WS
(f)
ln(SAOD)
(g)
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
σ/decade

R_{cld} trend due to CCFs

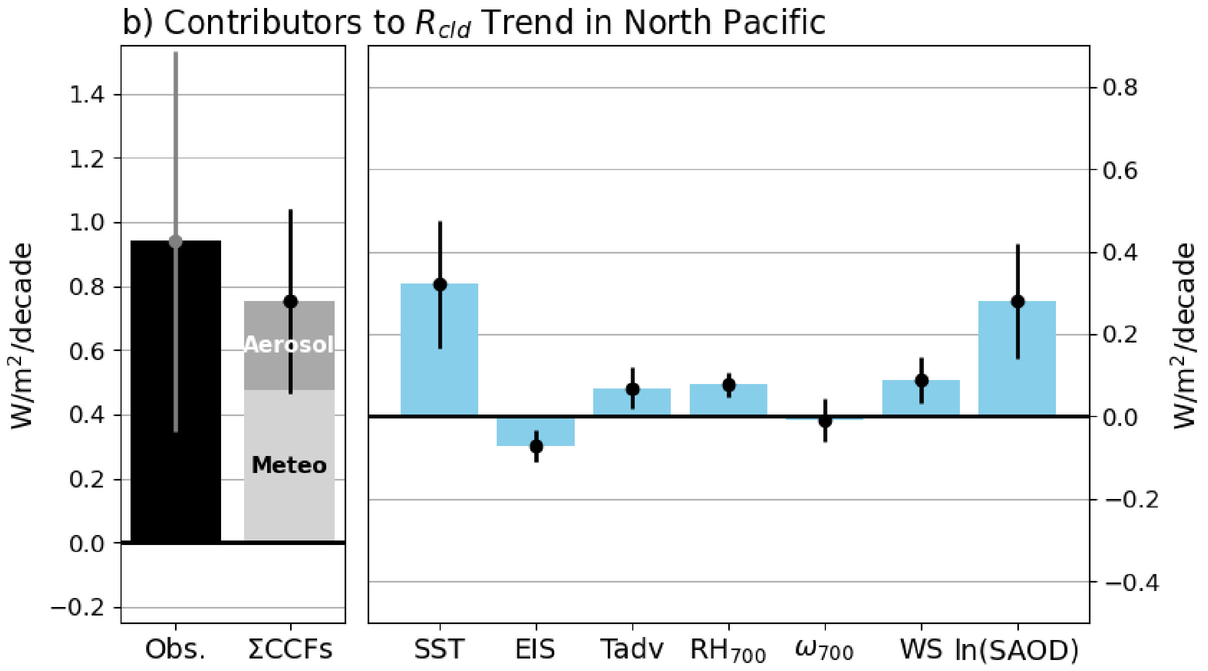

Meteorological Contribution

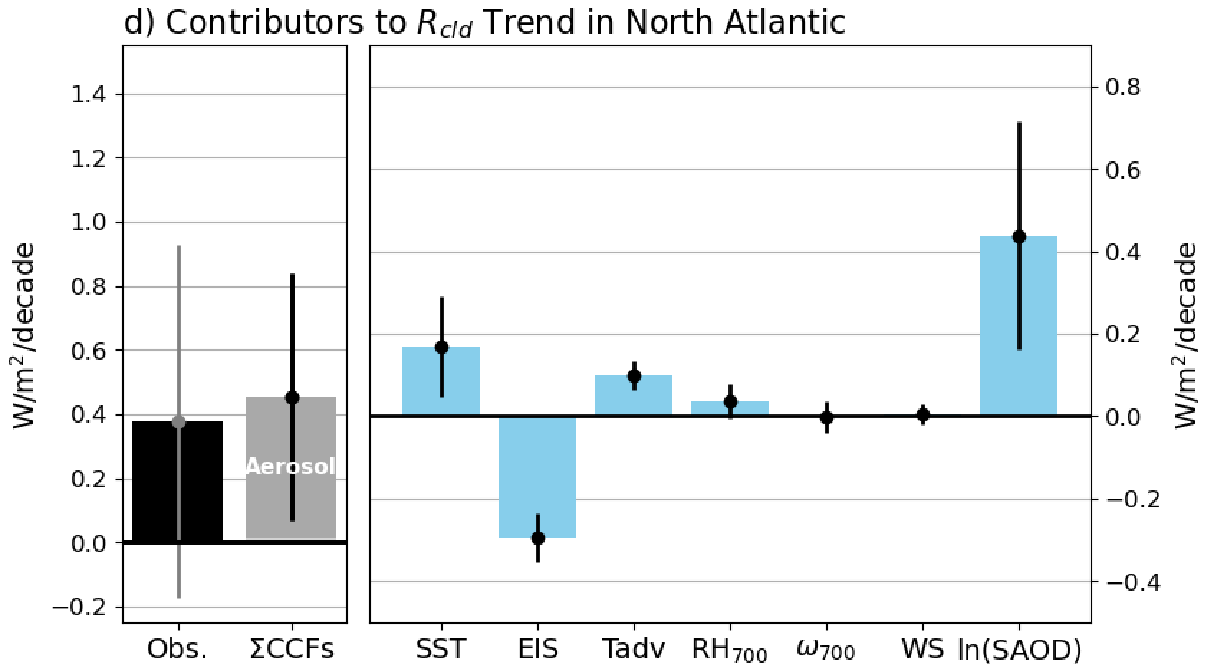
Aerosol Contribution

Reconstructed

Observed

See also G. Tselioudis's
talk on Monday


b) Contributors to R_{cld} Trend in North Pacific


d) Contributors to R_{cld} Trend in North Atlantic

See also G. Tselioudis's
talk on Monday

Summary so far

- Both the extreme regional R_{cld} anomalies in 2023 and the 22-year R_{cld} trend over the MODIS record are well-predicted using observed sensitivities of R_{cld} to CCFs.
- These sensitivities are very similar to those used previously to observationally constrain cloud feedback and aerosol forcing.
- Therefore, it seems unlikely that recent observed R_{cld} extremes and trends imply that an upward adjustment of climate sensitivity is necessary.
- **Let’s verify this quantitatively…**

Observational constraints on λ_{cld} & $\mathrm{ERF}_{\mathrm{aci}}$

Climate Change in CCFs

[from abrupt-4xCO$_2$ exps]

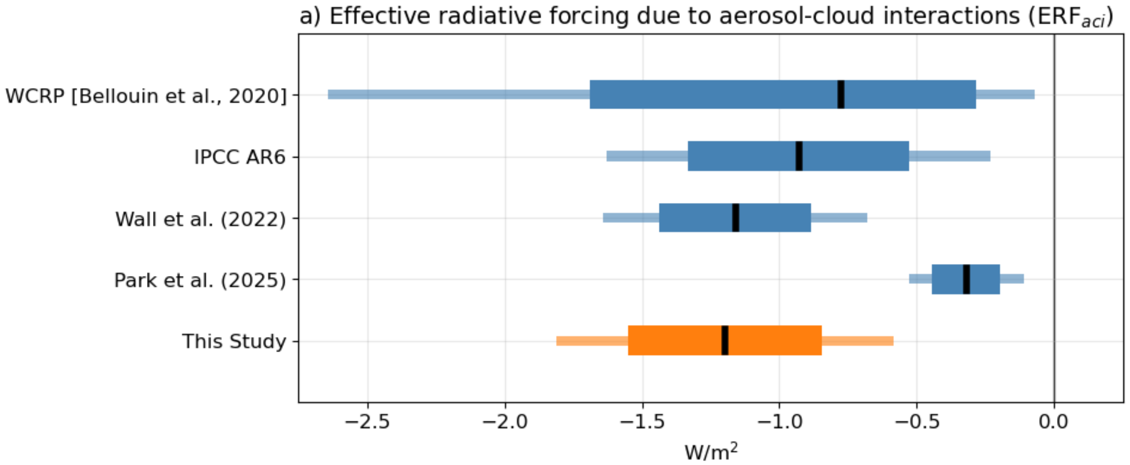
$$\lambda_{cld} = \sum_i \frac{\partial R_{cld}}{\partial x_i}\frac{dx_i}{dT_g} \qquad x_i \in \{\mathrm{SST}, \text{inversion strength}, \text{advection}, \ldots\}$$

[from satellite observations]

$$ERF_{aci} \approx \frac{\partial R_{cld}}{\partial ln(SAOD)} \Delta ln(SAOD)$$

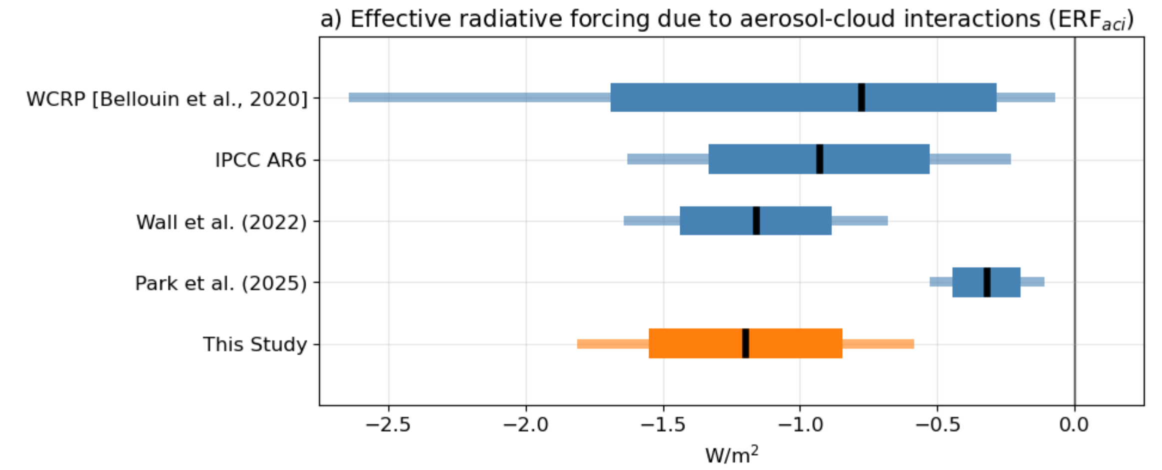
Historical Change in SAOD

[from historical exps]

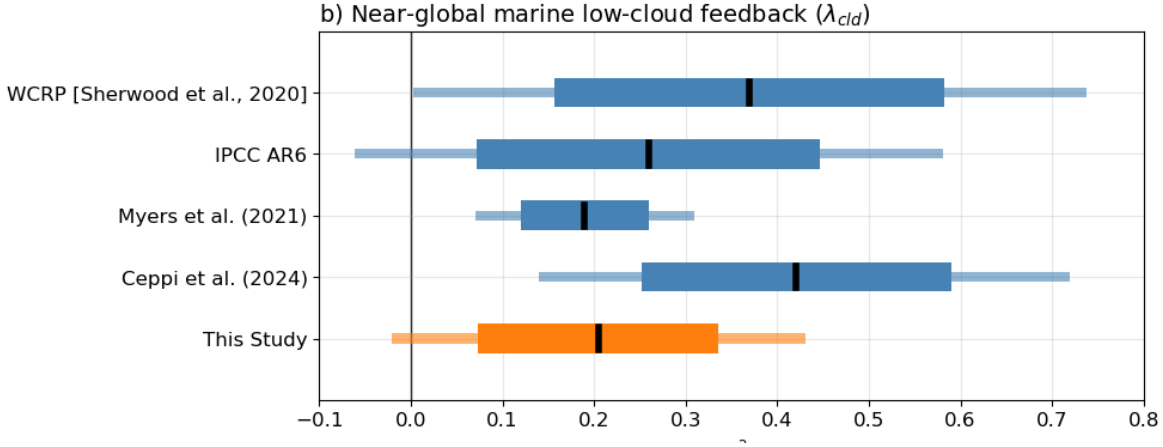


ERF$_{aci}$

This study: **-1.20 ± 0.61 W/m^2** (90% CI)



a) Effective radiative forcing due to aerosol-cloud interactions (ERF_{aci})



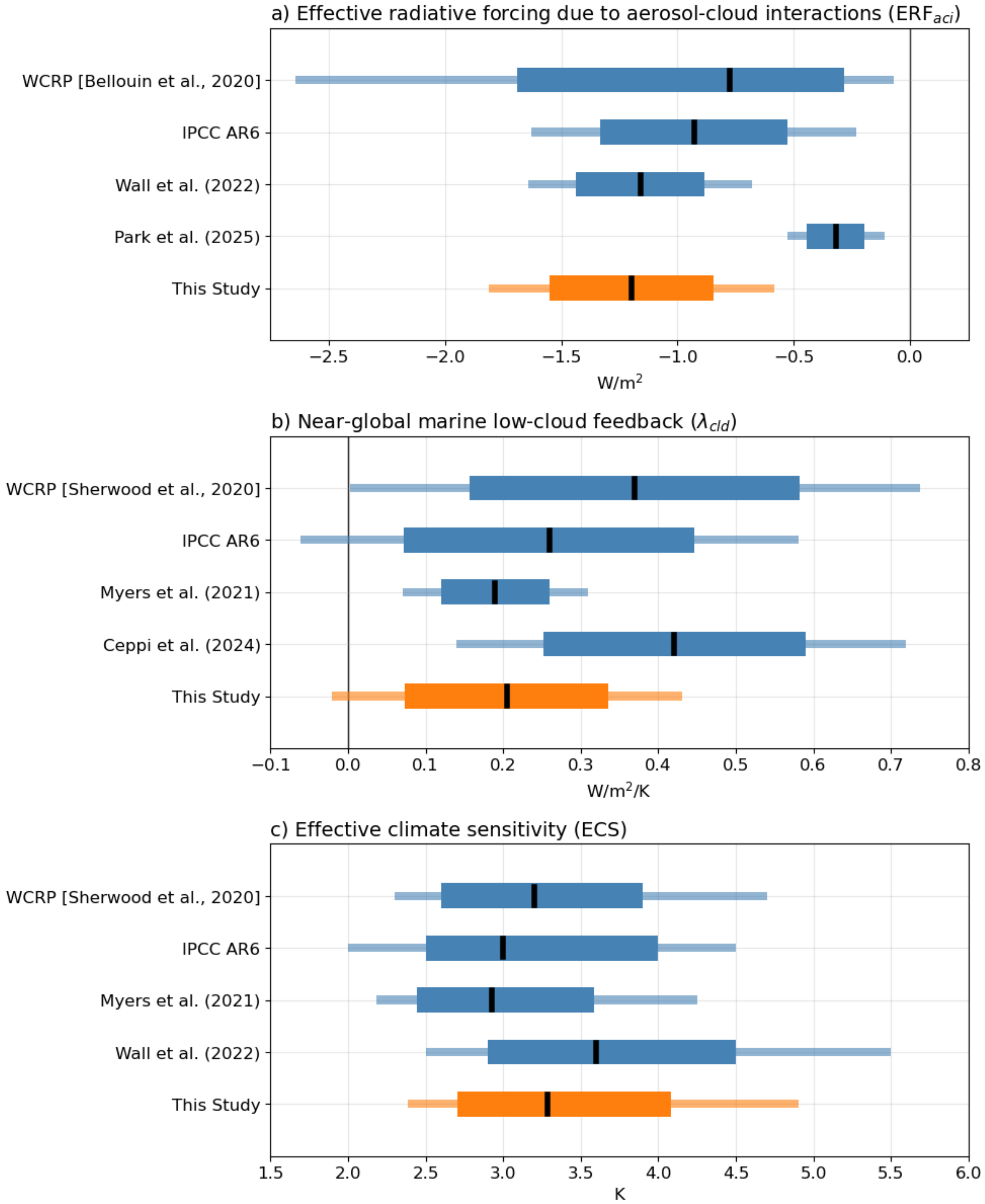
b) Near-global marine low-cloud feedback (λ_{cld})

ERF_{aci}

This study: **-1.20 ± 0.61 W/m^2** (90% CI)

Low-Cloud Feedback

This study: **0.21 ± 0.23 W/m^2/K** (90% CI)



ERF$_{aci}$

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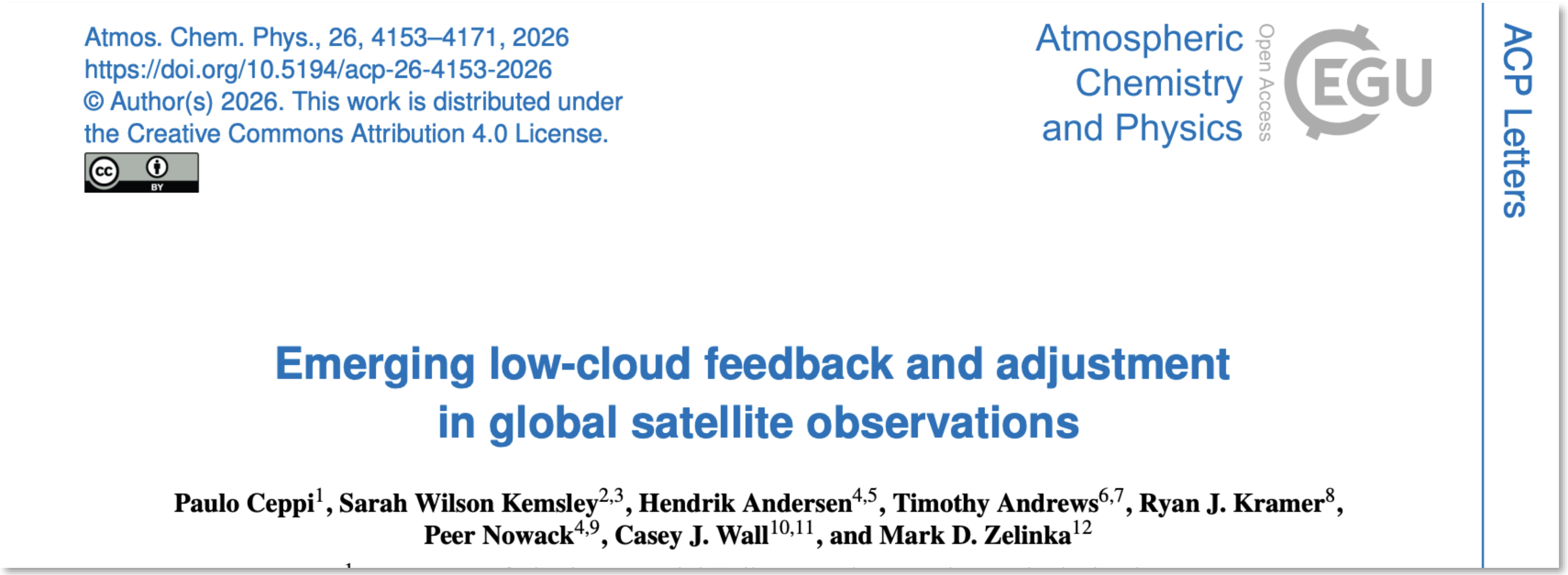
Low-Cloud Feedback

This study: **0.21 ± 0.23 W/m^2/K** (90% CI)

ECS

Slight increase in ECS likely range from 2.6–3.9K to **2.7–4.1K**



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Atmospheric
Chemistry
and Physics

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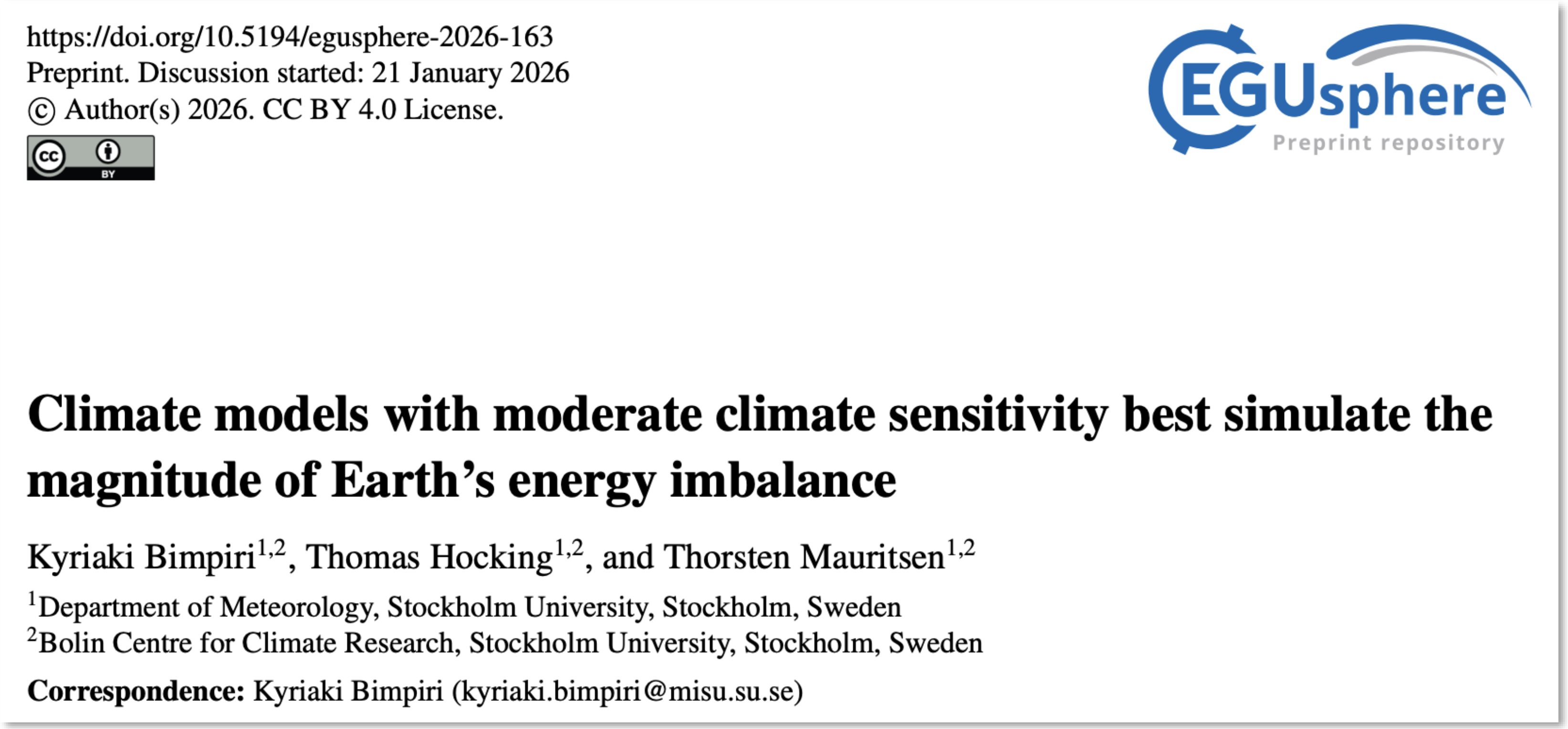
EGU

ACP Letters

Emerging low-cloud feedback and adjustment in global satellite observations

Paulo Ceppi[1], **Sarah Wilson Kemsley**[2,3], **Hendrik Andersen**[4,5], **Timothy Andrews**[6,7], **Ryan J. Kramer**[8],
Peer Nowack[4,9], **Casey J. Wall**[10,11], and **Mark D. Zelinka**[12]

←"Any systematic model error in the representation of present-day global energy imbalance trends is thus likely to originate in processes ***unrelated*** to low clouds."



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Preprint. Discussion started: 21 January 2026
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Climate models with moderate climate sensitivity best simulate the magnitude of Earth's energy imbalance

Kyriaki Bimpiri[1,2], Thomas Hocking[1,2], and Thorsten Mauritsen[1,2]
[1]Department of Meteorology, Stockholm University, Stockholm, Sweden
[2]Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden
Correspondence: Kyriaki Bimpiri (kyriaki.bimpiri@misu.su.se)

Questions

- Can anomalies in CCFs explain recent extremes in cloud-radiative effects? **Yes.**
- Can trends in CCFs explain trends in cloud-radiative effects? **Yes.**
  - ✓ Sensitivities of clouds to their controlling factors determined from detrended climate variability do well in predicting out-of-sample events.

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- What does this mean for cloud feedback, aerosol forcing, and climate sensitivity?
  - We do not need to invoke some emergence of a stronger-than-expected cloud feedback to understand what is happening in nature.
    (In fact, we infer a slightly weaker feedback than in the WCRP Assessment.)

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- Can trends in CCFs explain trends in cloud-radiative effects? **Yes.**
  - ✓ Sensitivities of clouds to their controlling factors determined from detrended climate variability do well in predicting out-of-sample events.
- What does this mean for cloud feedback, aerosol forcing, and climate sensitivity?
  - We do not need to invoke some emergence of a stronger-than-expected cloud feedback to understand what is happening in nature.
    (In fact, we infer a slightly weaker feedback than in the WCRP Assessment.)
  - However, our inferred (negative) $\mathrm{ERF}_{\mathrm{aci}}$ is a bit stronger than recent assessments.
  - This moves the posterior ECS likely range upward slightly from 2.6–3.9K to 2.7–4.1K

Final Thoughts

- What is causing the CCF extremes / trends in the first place?
  - Forced by GHGs?
  - Forced by aerosols?
  - Internal climate oscillations?

- How much do clouds amplify vs simply respond to the underlying SST anomalies?

- What is the likelihood of compound cloud-hostile factors like what was seen in 2023? And how might that likelihood change into the future?

- *While cloud-radiative anomalies and trends over the past 22 years are within expectations, continued global monitoring of clouds and radiation remains crucial to assess how Earth's energy budget is impacted by the likely larger warming, continued aerosol reductions, and evolving surface temperature patterns of future years.*

communications earth & environment

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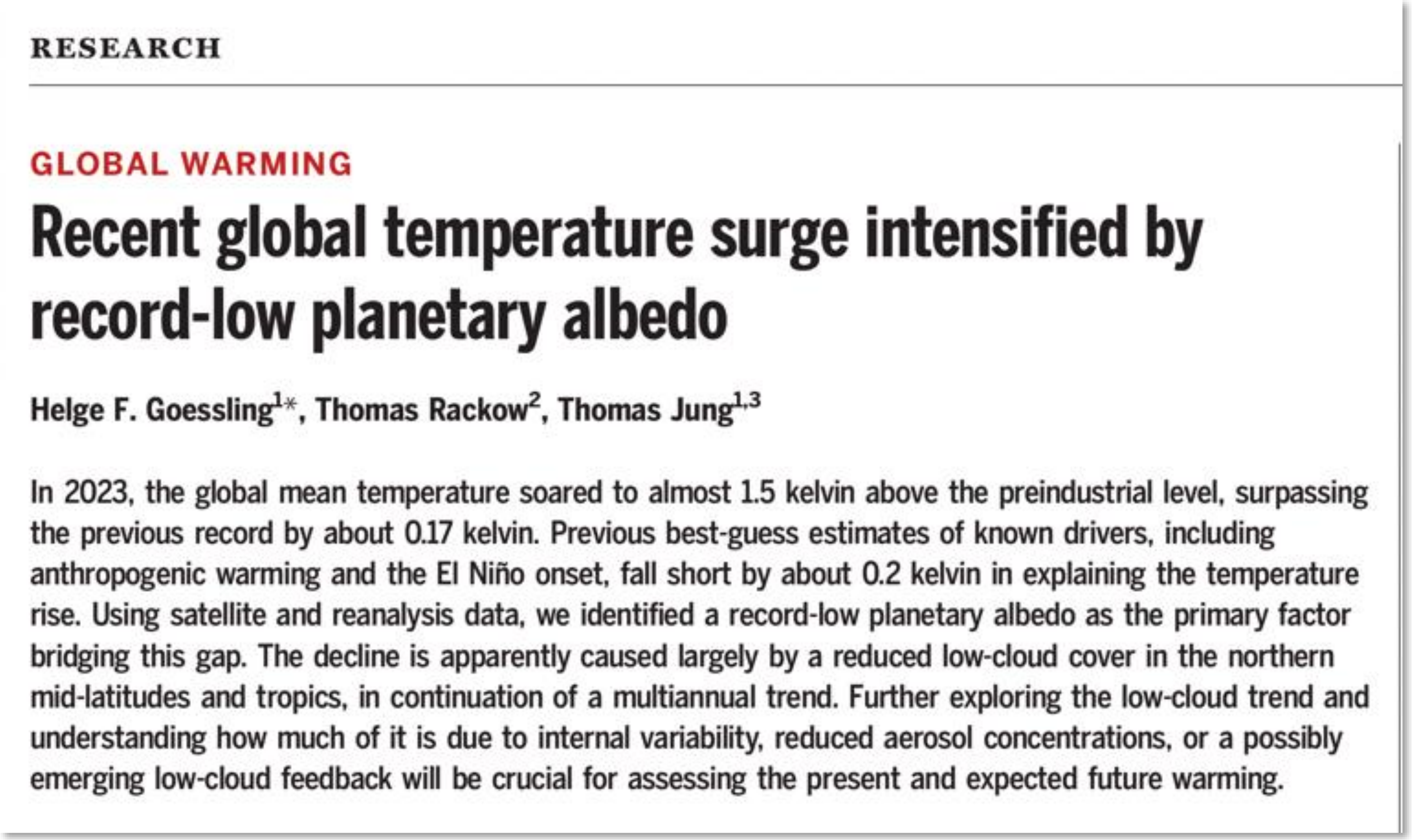
Recent cloud trends and extremes reaffirm established bounds on cloud feedback and aerosol-cloud interactions

Mark D. Zelinka, Timothy A. Myers, Yi Qin, Li-Wei Chao, Stephen A. Klein, Stephen Po-Chedley, Po-Lun Ma, Casey J. Wall, Paulo Ceppi & Andrew Gettelman

Communications Earth & Environment (2026) | Cite this article

SCAN ME

Extras



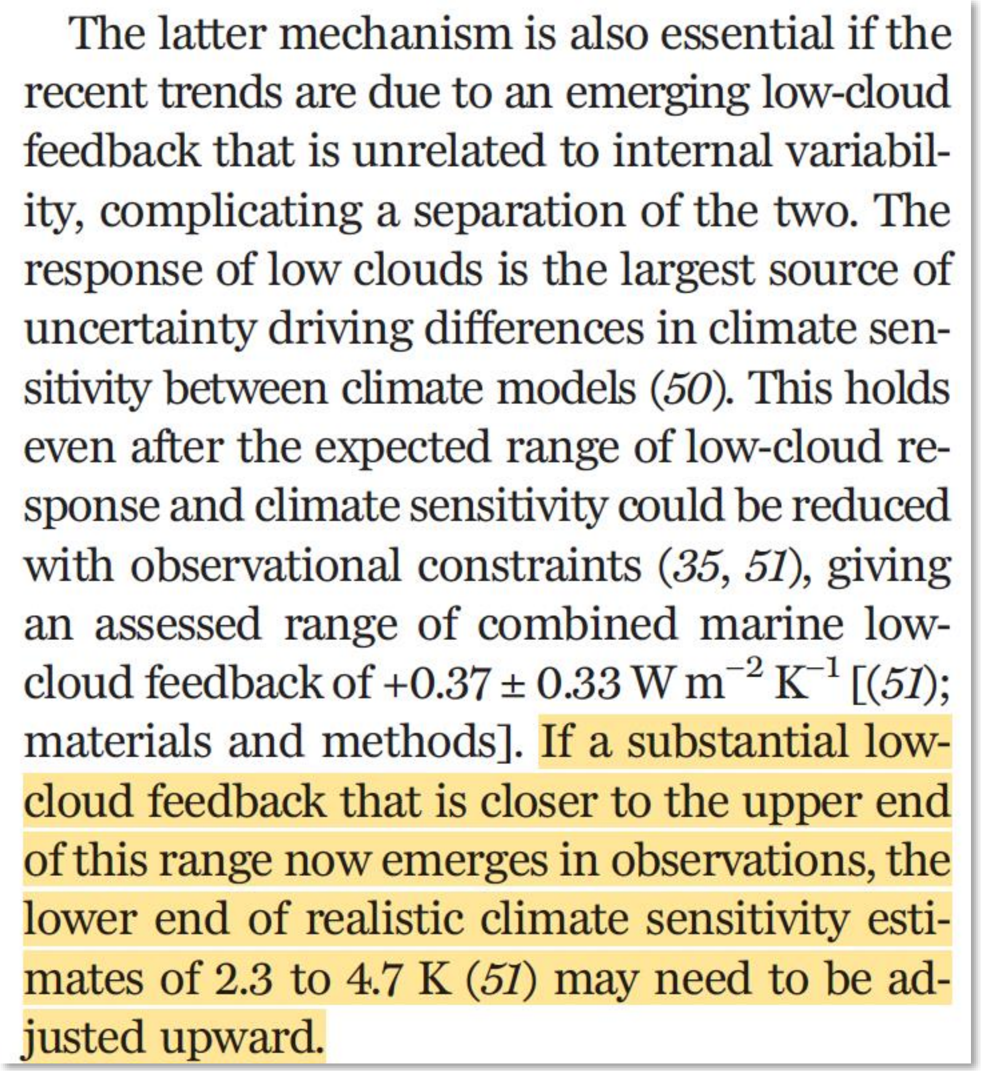
RESEARCH

GLOBAL WARMING

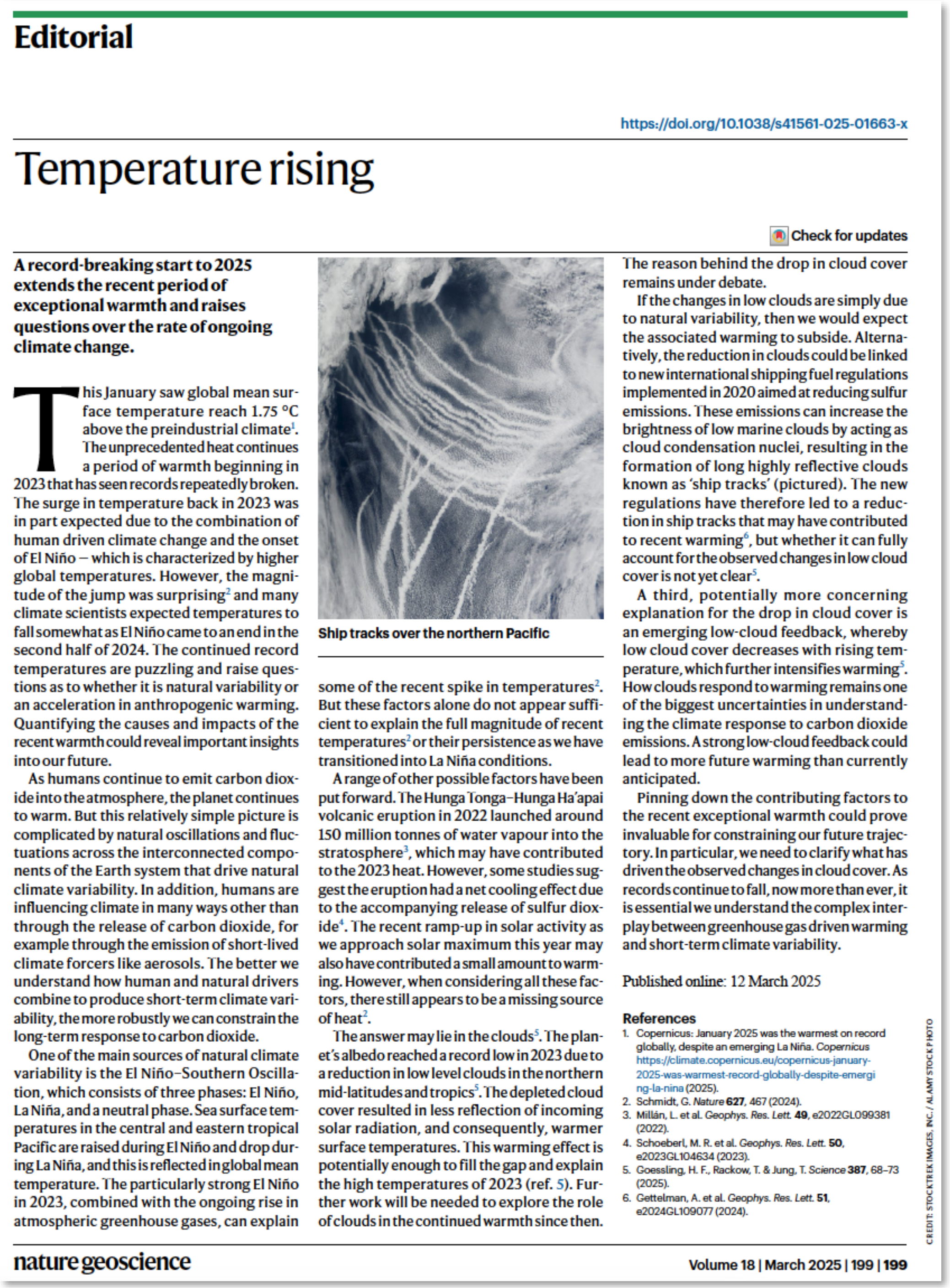
Recent global temperature surge intensified by record-low planetary albedo

Helge F. Goessling[1*], Thomas Rackow[2], Thomas Jung[1,3]

In 2023, the global mean temperature soared to almost 1.5 kelvin above the preindustrial level, surpassing the previous record by about 0.17 kelvin. Previous best-guess estimates of known drivers, including anthropogenic warming and the El Niño onset, fall short by about 0.2 kelvin in explaining the temperature rise. Using satellite and reanalysis data, we identified a record-low planetary albedo as the primary factor bridging this gap. The decline is apparently caused largely by a reduced low-cloud cover in the northern mid-latitudes and tropics, in continuation of a multiannual trend. Further exploring the low-cloud trend and understanding how much of it is due to internal variability, reduced aerosol concentrations, or a possibly emerging low-cloud feedback will be crucial for assessing the present and expected future warming.



The latter mechanism is also essential if the recent trends are due to an emerging low-cloud feedback that is unrelated to internal variability, complicating a separation of the two. The response of low clouds is the largest source of uncertainty driving differences in climate sensitivity between climate models (*50*). This holds even after the expected range of low-cloud response and climate sensitivity could be reduced with observational constraints (*35*, *51*), giving an assessed range of combined marine low-cloud feedback of $+0.37 \pm 0.33\ \mathrm{W\ m^{-2}\ K^{-1}}$ [(*51*); materials and methods]. If a substantial low-cloud feedback that is closer to the upper end of this range now emerges in observations, the lower end of realistic climate sensitivity estimates of 2.3 to 4.7 K (*51*) may need to be adjusted upward.



https://doi.org/10.1038/s41561-025-01663-x

Temperature rising

Check for updates

A record-breaking start to 2025 extends the recent period of exceptional warmth and raises questions over the rate of ongoing climate change.

This January saw global mean surface temperature reach 1.75 °C above the preindustrial climate[1]. The unprecedented heat continues a period of warmth beginning in 2023 that has seen records repeatedly broken. The surge in temperature back in 2023 was in part expected due to the combination of human driven climate change and the onset of El Niño – which is characterized by higher global temperatures. However, the magnitude of the jump was surprising[2] and many climate scientists expected temperatures to fall somewhat as El Niño came to an end in the second half of 2024. The continued record temperatures are puzzling and raise questions as to whether it is natural variability or an acceleration in anthropogenic warming. Quantifying the causes and impacts of the recent warmth could reveal important insights into our future.

As humans continue to emit carbon dioxide into the atmosphere, the planet continues to warm. But this relatively simple picture is complicated by natural oscillations and fluctuations across the interconnected components of the Earth system that drive natural climate variability. In addition, humans are influencing climate in many ways other than through the release of carbon dioxide, for example through the emission of short-lived climate forcers like aerosols. The better we understand how human and natural drivers combine to produce short-term climate variability, the more robustly we can constrain the long-term response to carbon dioxide.

Ship tracks over the northern Pacific

One of the main sources of natural climate variability is the El Niño–Southern Oscillation, which consists of three phases: El Niño, La Niña, and a neutral phase. Sea surface temperatures in the central and eastern tropical Pacific are raised during El Niño and drop during La Niña, and this is reflected in global mean temperature. The particularly strong El Niño in 2023, combined with the ongoing rise in atmospheric greenhouse gases, can explain some of the recent spike in temperatures[2]. But these factors alone do not appear sufficient to explain the full magnitude of recent temperatures[2] or their persistence as we have transitioned into La Niña conditions.

A range of other possible factors have been put forward. The Hunga Tonga–Hunga Ha'apai volcanic eruption in 2022 launched around 150 million tonnes of water vapour into the stratosphere[3], which may have contributed to the 2023 heat. However, some studies suggest the eruption had a net cooling effect due to the accompanying release of sulfur dioxide[4]. The recent ramp-up in solar activity as we approach solar maximum this year may also have contributed a small amount to warming. However, when considering all these factors, there still appears to be a missing source of heat[2].

The answer may lie in the clouds[5]. The planet's albedo reached a record low in 2023 due to a reduction in low level clouds in the northern mid-latitudes and tropics[5]. The depleted cloud cover resulted in less reflection of incoming solar radiation, and consequently, warmer surface temperatures. This warming effect is potentially enough to fill the gap and explain the high temperatures of 2023 (ref. 5). Further work will be needed to explore the role of clouds in the continued warmth since then. The reason behind the drop in cloud cover remains under debate.

If the changes in low clouds are simply due to natural variability, then we would expect the associated warming to subside. Alternatively, the reduction in clouds could be linked to new international shipping fuel regulations implemented in 2020 aimed at reducing sulfur emissions. These emissions can increase the brightness of low marine clouds by acting as cloud condensation nuclei, resulting in the formation of long highly reflective clouds known as 'ship tracks' (pictured). The new regulations have therefore led to a reduction in ship tracks that may have contributed to recent warming[6], but whether it can fully account for the observed changes in low cloud cover is not yet clear[5].

A third, potentially more concerning explanation for the drop in cloud cover is an emerging low-cloud feedback, whereby low cloud cover decreases with rising temperature, which further intensifies warming[5]. How clouds respond to warming remains one of the biggest uncertainties in understanding the climate response to carbon dioxide emissions. A strong low-cloud feedback could lead to more future warming than currently anticipated.

Pinning down the contributing factors to the recent exceptional warmth could prove invaluable for constraining our future trajectory. In particular, we need to clarify what has driven the observed changes in cloud cover. As records continue to fall, now more than ever, it is essential we understand the complex interplay between greenhouse gas driven warming and short-term climate variability.

References

1. Copernicus: January 2025 was the warmest on record globally, despite an emerging La Niña. *Copernicus* https://climate.copernicus.eu/copernicus-january-2025-was-warmest-record-globally-despite-emerging-la-nina (2025).
2. Schmidt, G. *Nature* **627**, 467 (2024).
3. Millán, L. et al. *Geophys. Res. Lett.* **49**, e2022GL099381 (2022).
4. Schoeberl, M. R. et al. *Geophys. Res. Lett.* **50**, e2023GL104634 (2023).
5. Goessling, H. F., Rackow, T. & Jung, T. *Science* **387**, 68–73 (2025).
6. Gettelman, A. et al. *Geophys. Res. Lett.* **51**, e2024GL109077 (2024).

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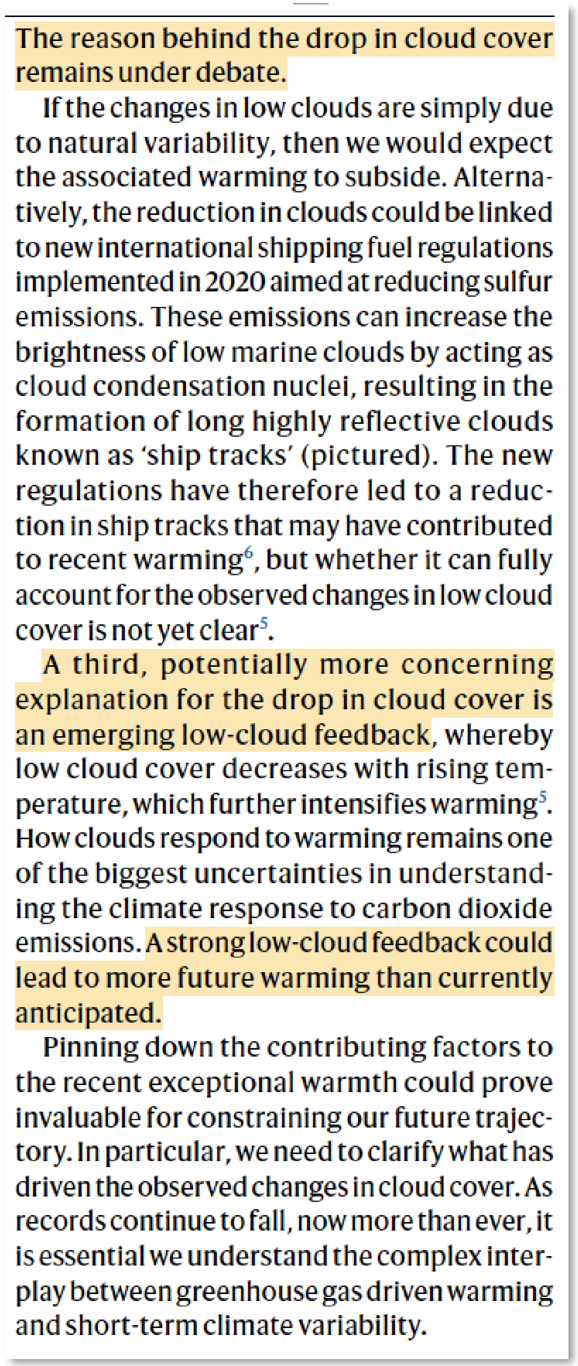

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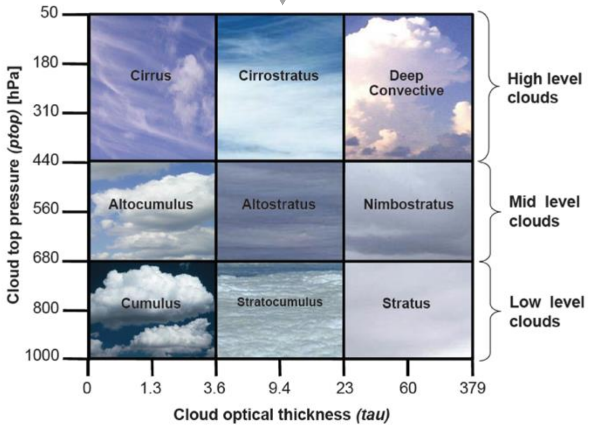
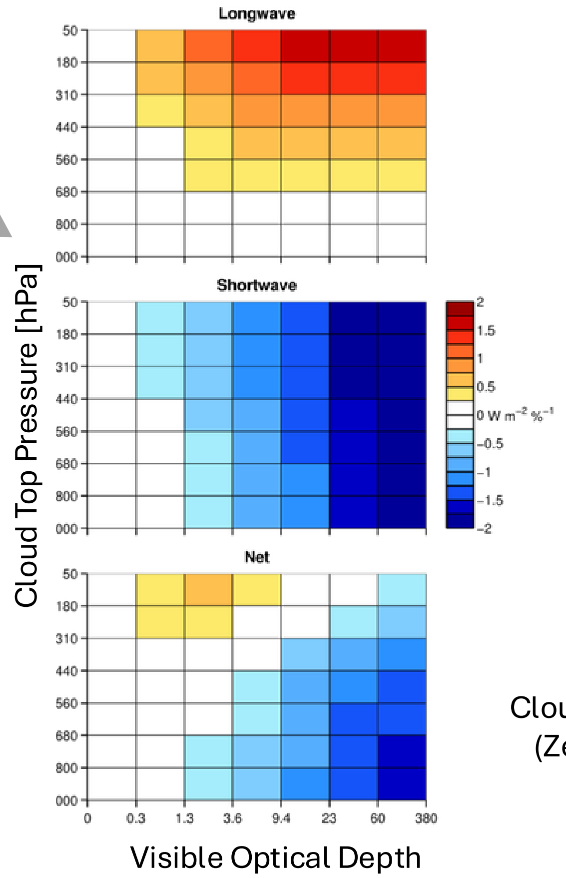
Calculating CCF Sensitivities

- R_{cld}: Monthly-resolved low-cloud induced SW anomalies

$$\Delta R_{cld} = \sum_{p} \sum_{\tau} \Delta C_{p,\tau} \frac{\partial R}{\partial C_{p,\tau}}$$



(Cloud Fraction from MODIS)



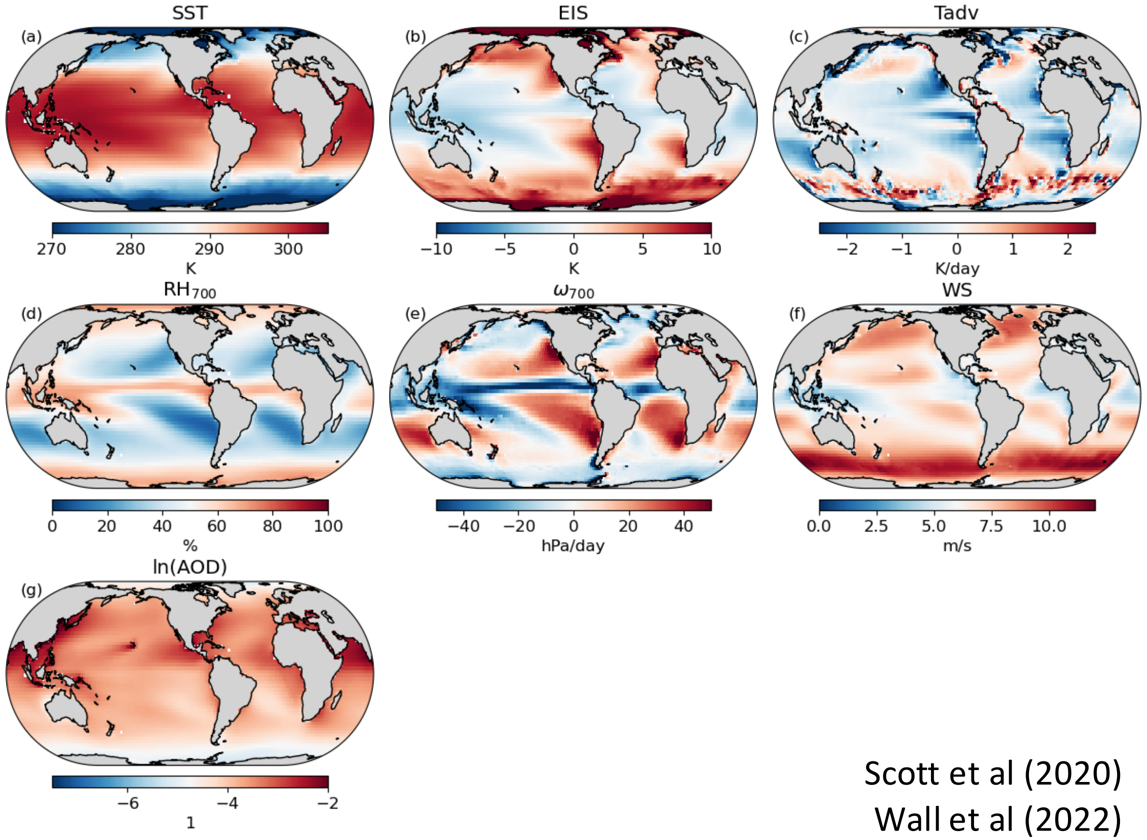
Cloud radiative kernels
(Zelinka et al. 2012)

Calculating CCF Sensitivities

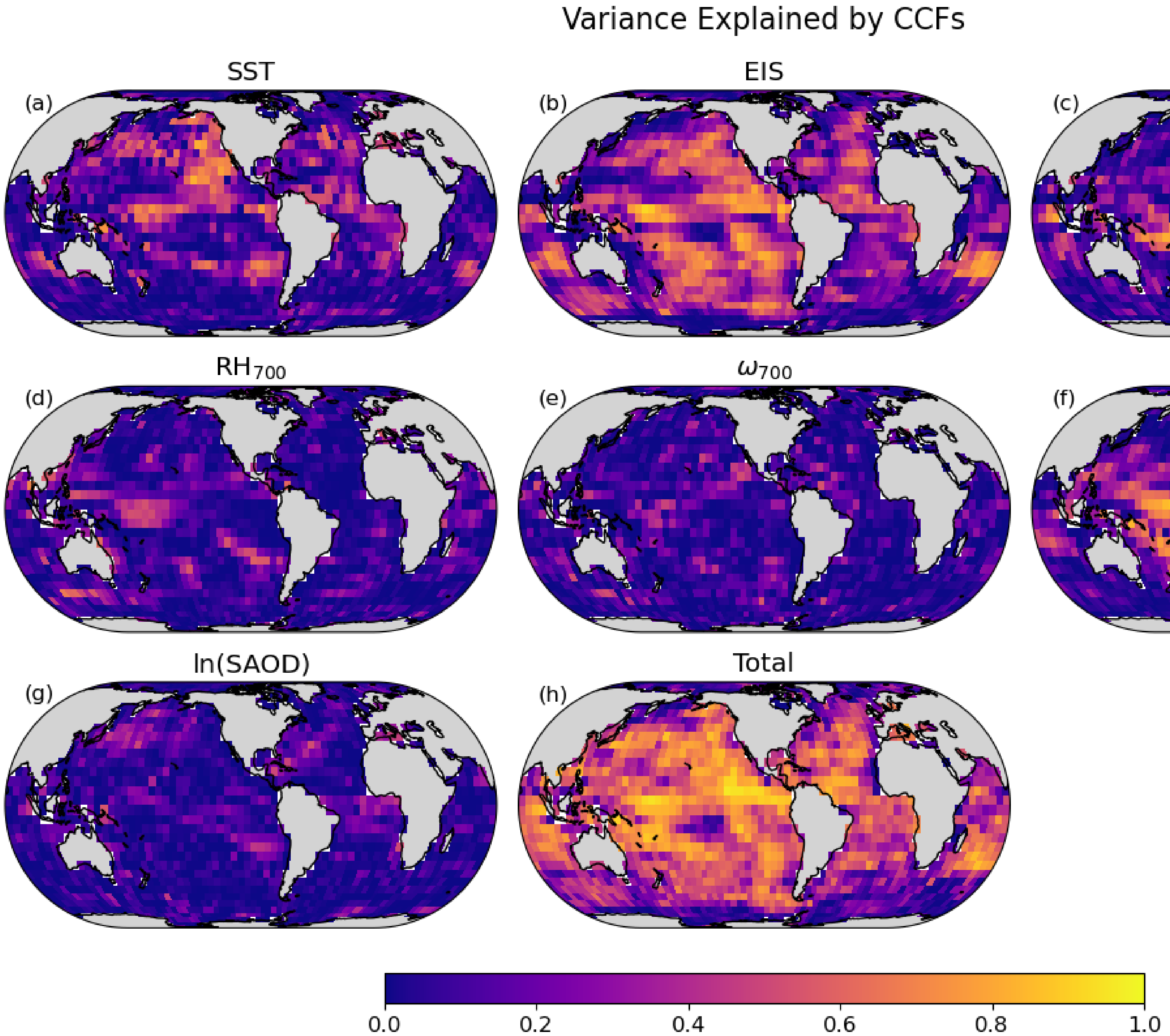
- R_{cld}: Monthly-resolved low-cloud induced SW anomalies
- x_i: Standardized monthly-resolved anomalies in 7 CCFs

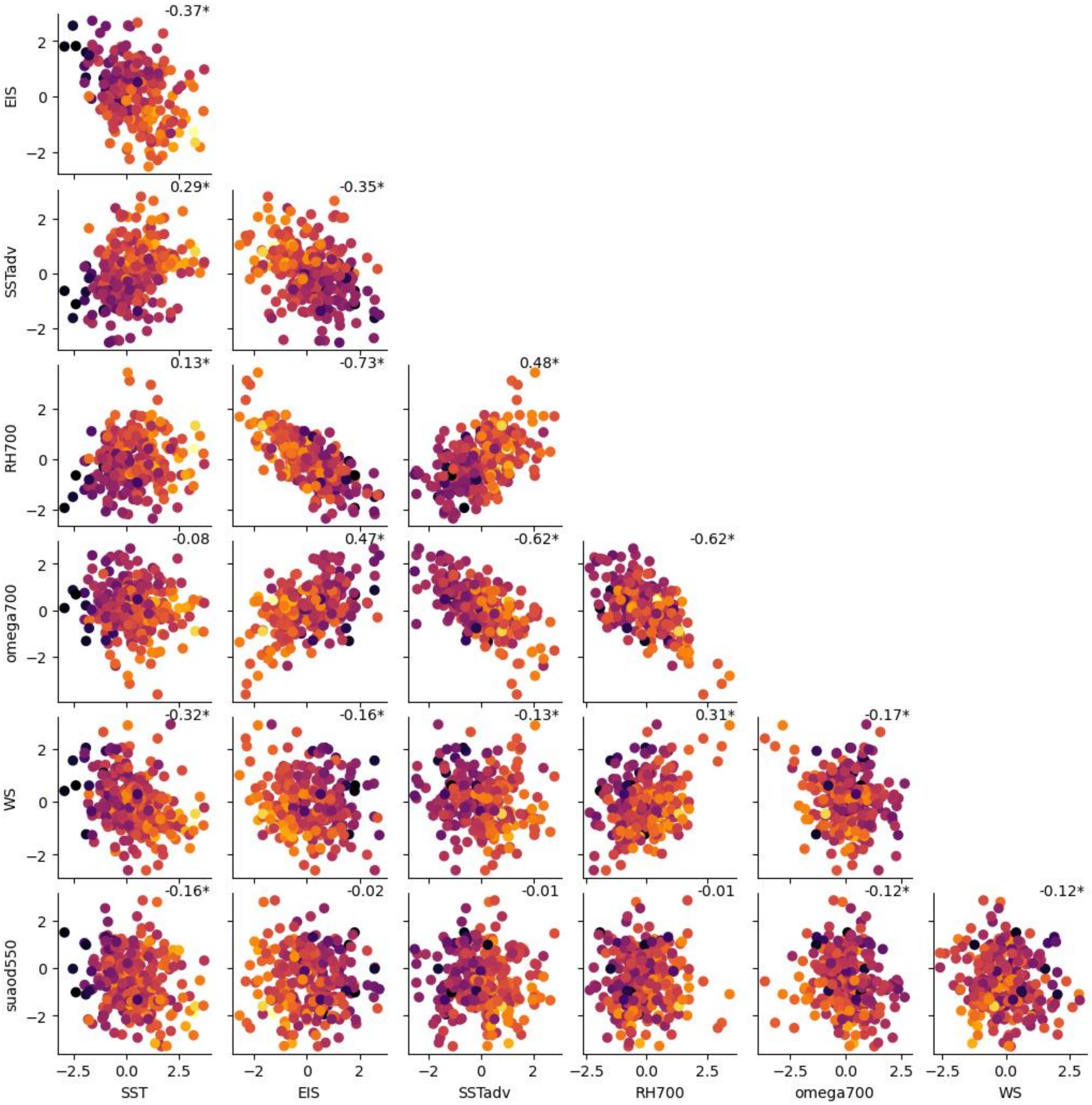
Meteo CCFs
from ERA5

Aerosol CCF:
Sulfate AOD at
550nm from CAMS
global reanalysis
(EAC4)

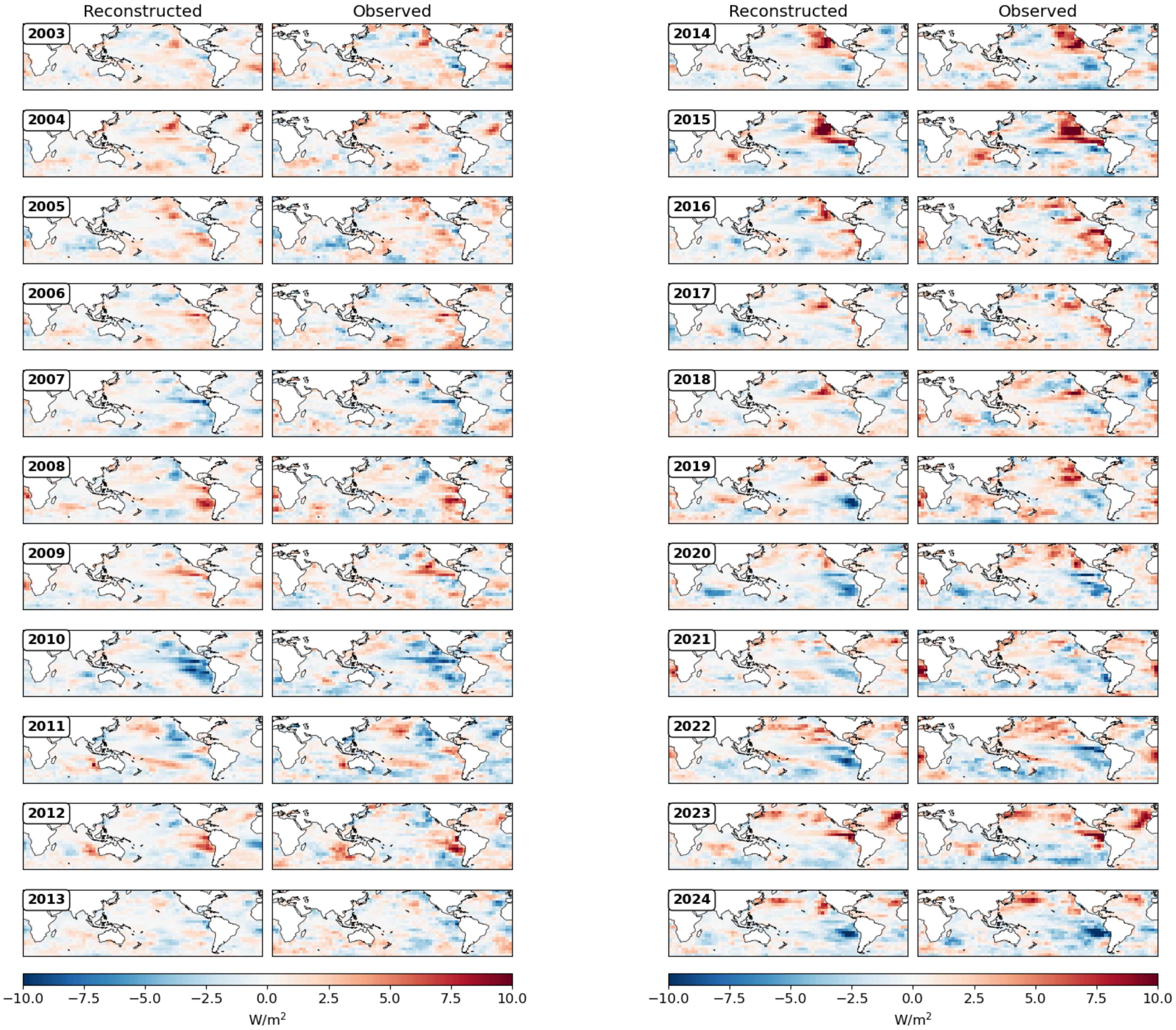


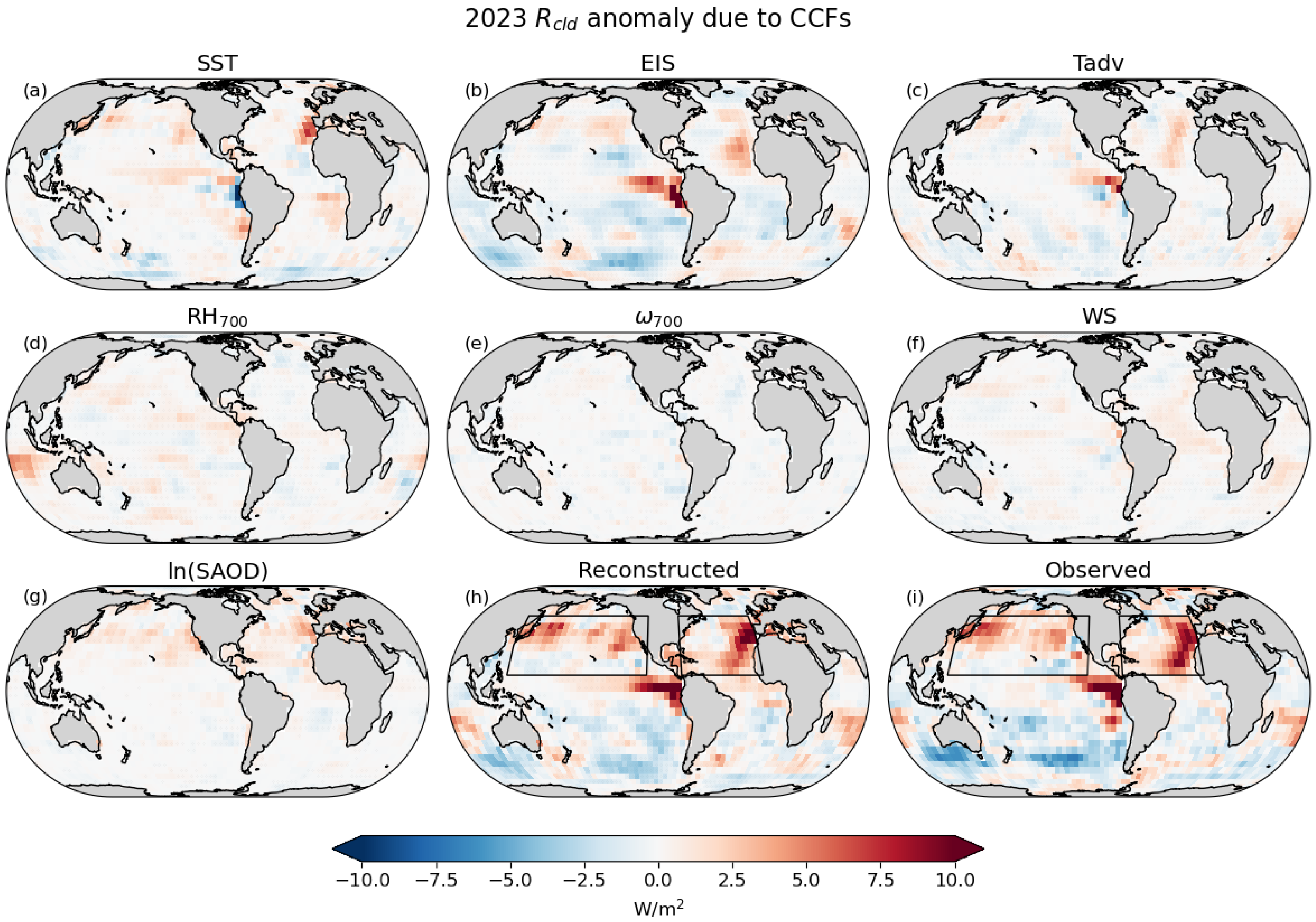
Scott et al (2020)
Wall et al (2022)

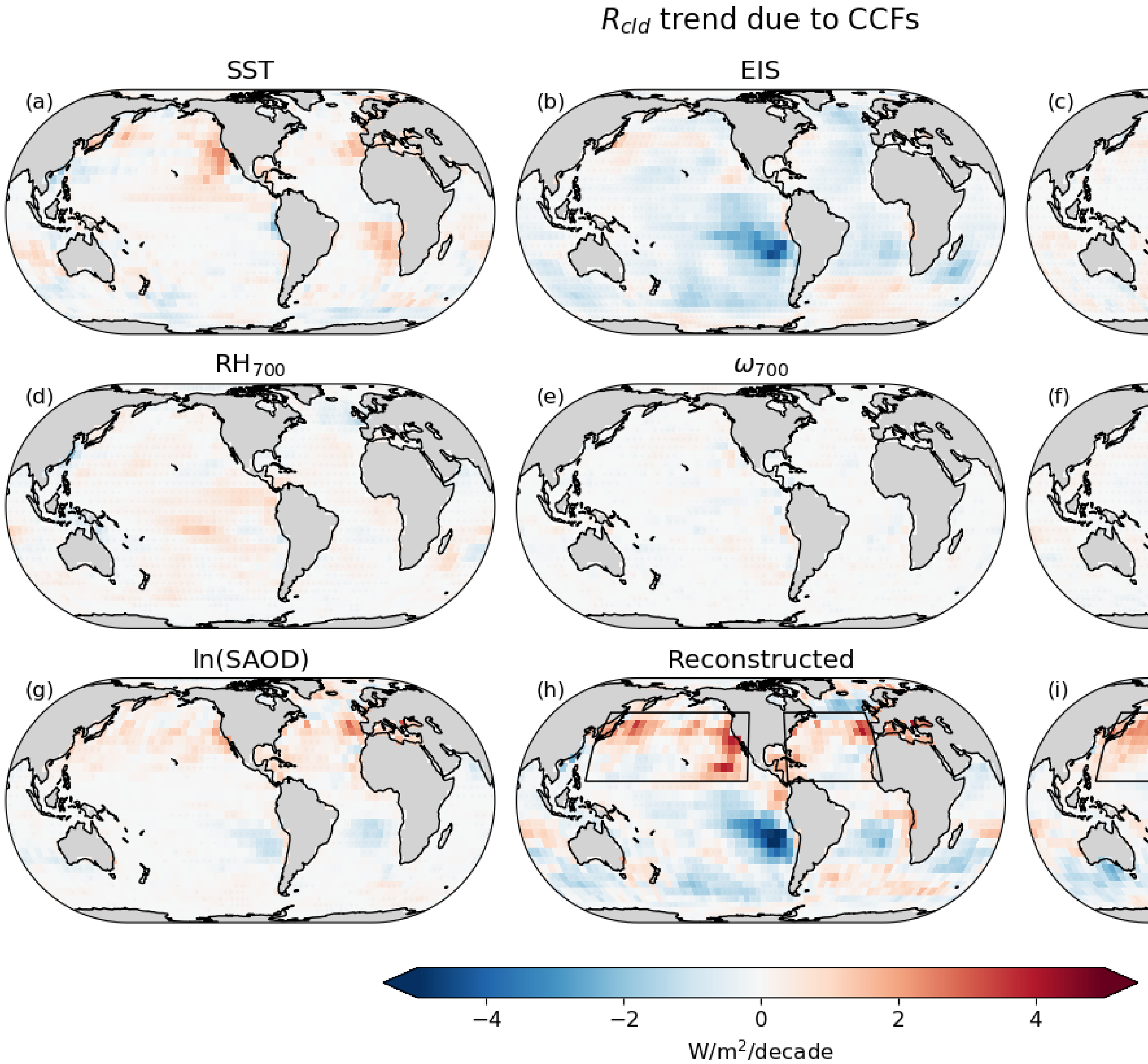

Variance Explained by CCFs
SST
(a)
EIS
(b)
Tadv
(c)
RH$_{700}$
(d)
ω_{700}
(e)
WS
(f)
ln(SAOD)
(g)
Total
(h)
0.0
0.2
0.4
0.6
0.8
1.0



N. Atlantic box
37.5˚N, 17.5˚W

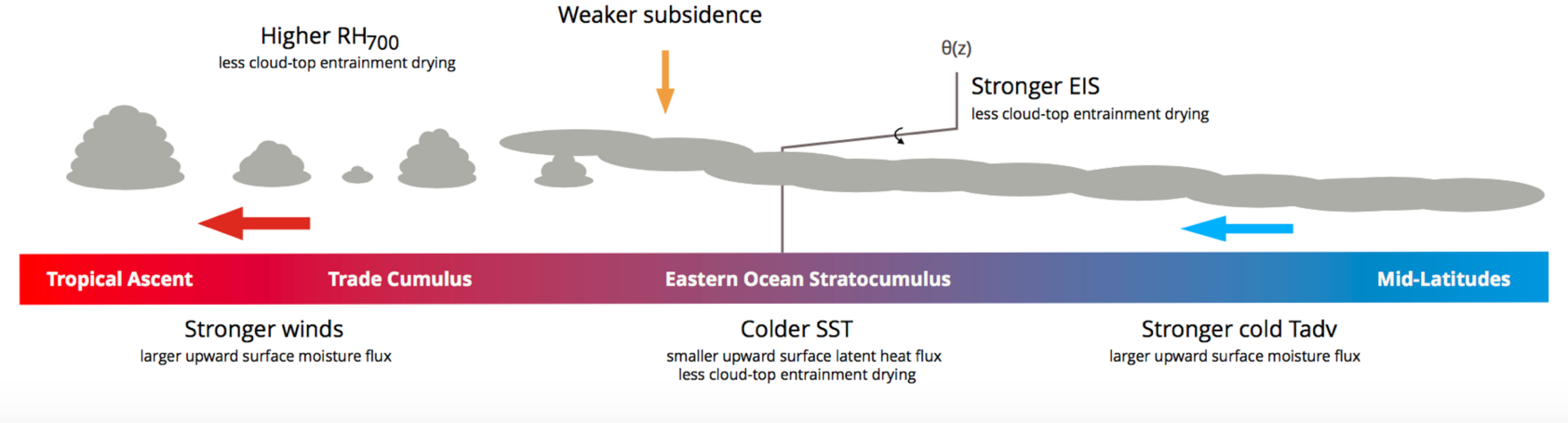

Reconstructed
Observed
Reconstructed
Observed
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
W/m²
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
W/m²


2023 R_{cld} anomaly due to CCFs
SST
(a)
EIS
(b)
Tadv
(c)
RH_{700}
(d)
ω_{700}
(e)
WS
(f)
ln(SAOD)
(g)
Reconstructed
(h)
Observed
(i)
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
W/m^2


R_{cld} trend due to CCFs
SST
(a)
EIS
(b)
Tadv
(c)
RH_{700}
(d)
ω_{700}
(e)
WS
(f)
ln(SAOD)
(g)
Reconstructed
(h)
Observed
(i)
−4
−2
0
2
4
W/m^2/decade

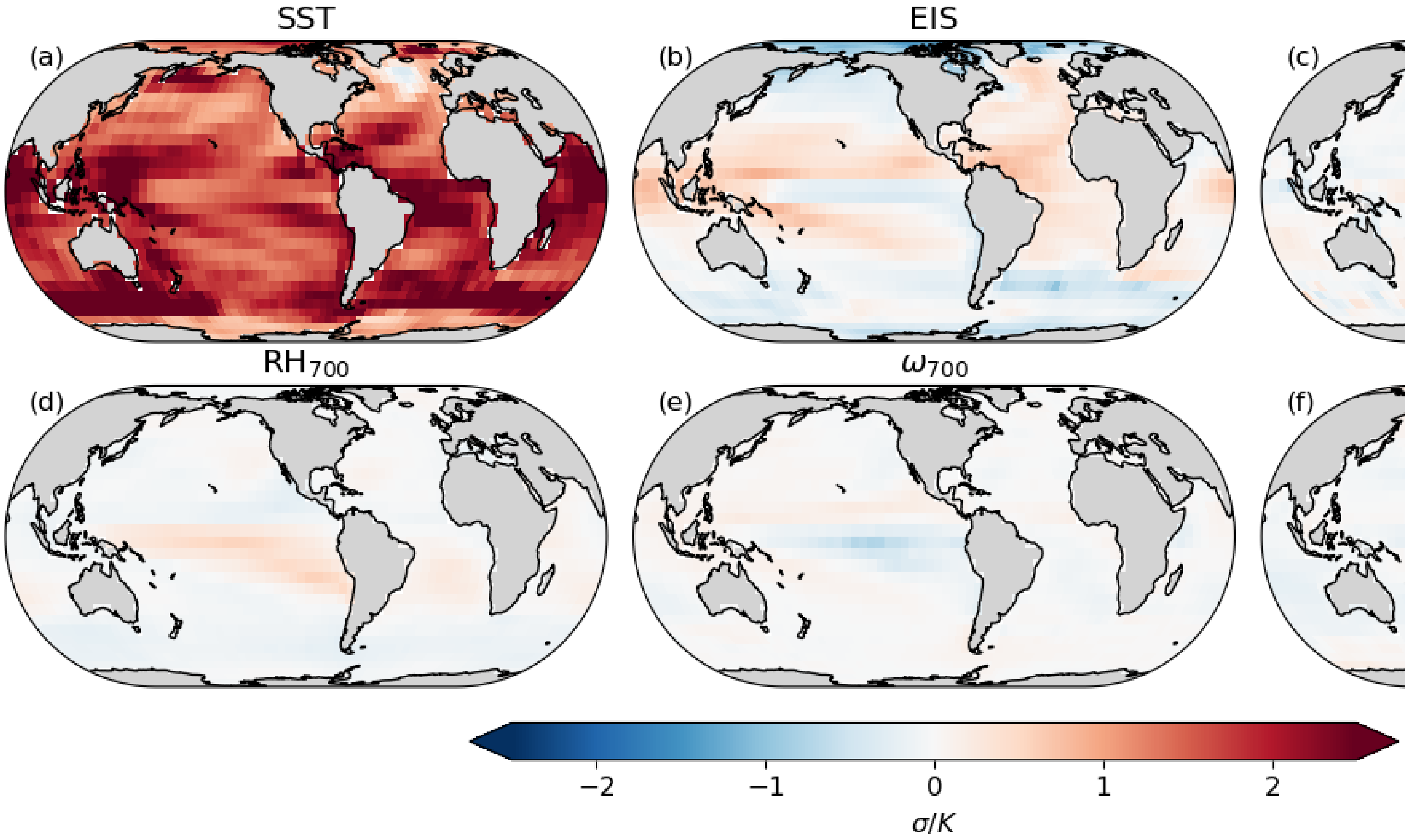
Cloud Controlling Factors

Meteorological conditions that favor **more** low cloud:

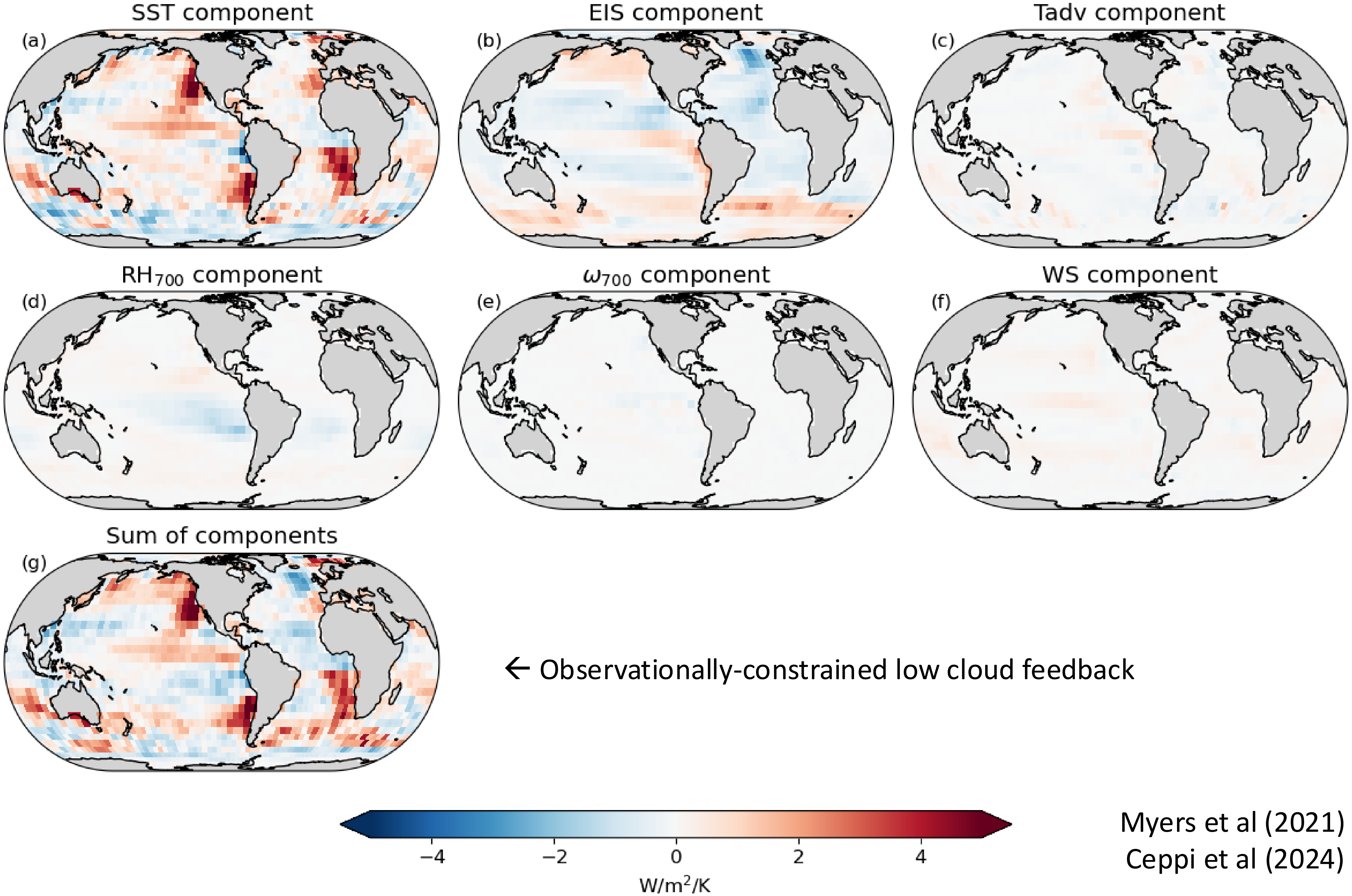


Scott et al., *J. Clim.* (2020)

Abrupt-4xCO2 ΔCCFs – averaged across 85 CMIP5/6 models



abrupt-4xCO2
ΔCCFs
x
observed
coefficients



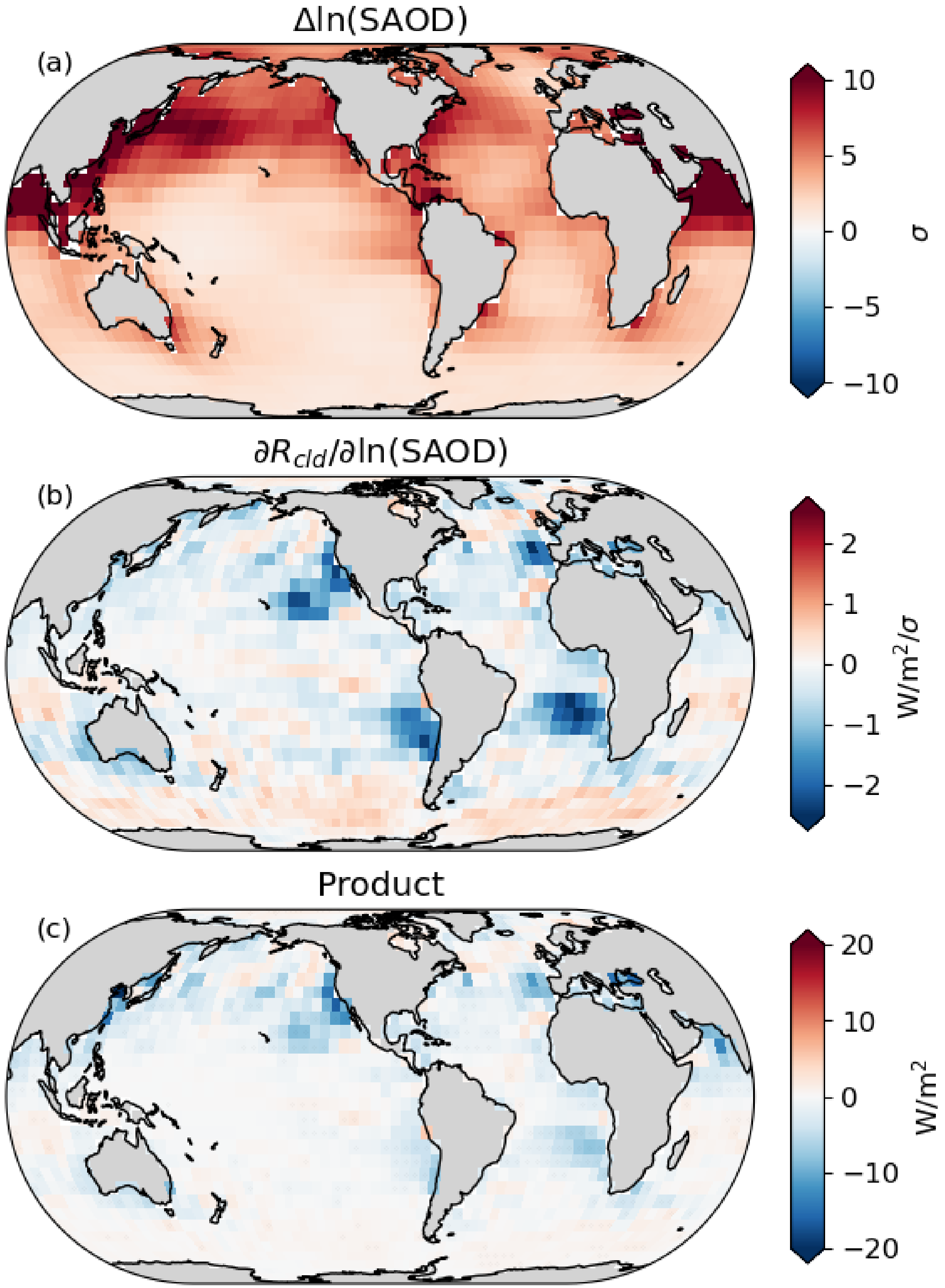
← Observationally-constrained low cloud feedback

Myers et al (2021)
Ceppi et al (2024)

Obs-constrained ERF_{aci}

- Multiply observed $dR_{cld}/d\ln(\text{SAOD})$ coefficients by $\Delta\ln(\text{SAOD})$ from climate models
- $\Delta\ln(\text{SAOD})$ is (2005-2014) minus (1850-1859) in historical simulations from 24 CMIP6 models
- Relate 55˚S - 55˚N oceanic obs-constrained ACI to global land+ocean ACI via $\text{ERF}_{aci,g} = \chi\ \text{ERF}_{aci,d}$, where χ is estimated via aerosol-only RFMIP experiments (19 models).

Wall et al. (2022)



Observationally constrained ERF$_{aci}$

$$\Delta R_{cld} \approx \sum_i \frac{\partial R_{cld}}{\partial x_i} \frac{dx_i}{dT_g}$$

$$x_i \in \cancel{\{\mathrm{SST}, \text{inversion strength}, \text{advection}, \ldots\}}$$

ln(SAOD)

Predictor Choices

T_{700}→ EIS

- ERA5
- MERRA2
- JRA
- AIRS
- CLIMCAPS

Aerosol predictor

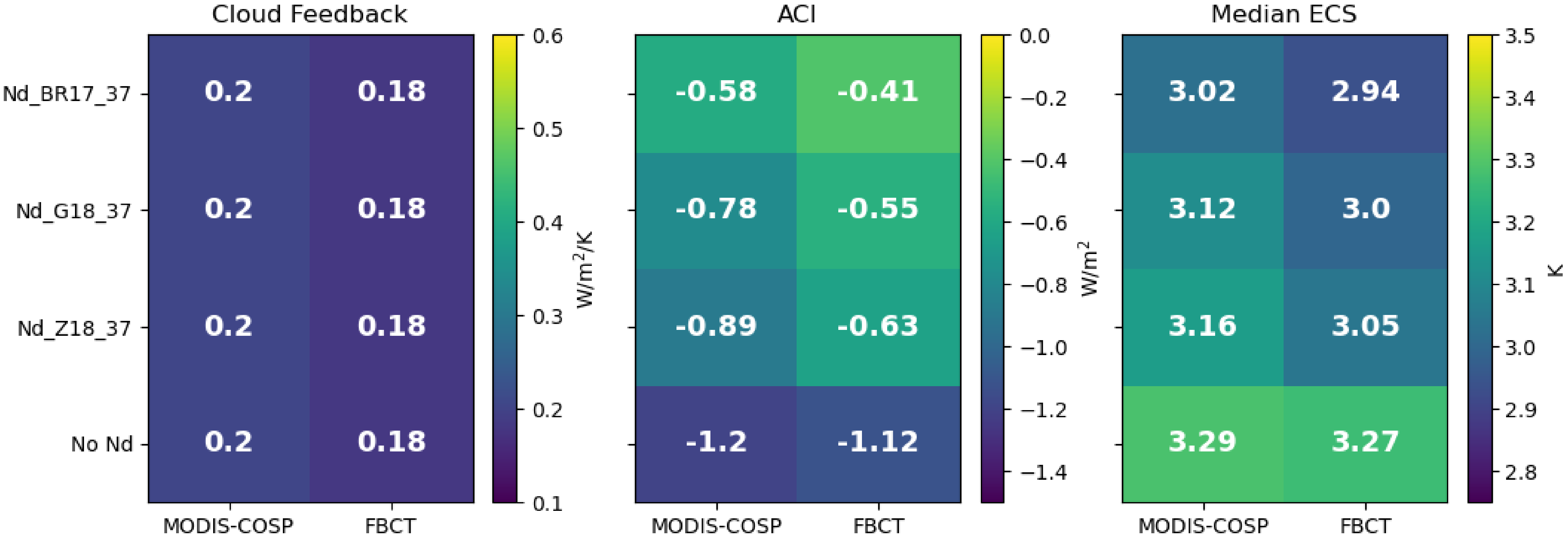
- SAOD (CAMS)
- AOD (CAMS)
- AI (MODIS)
- 910 hPa log10s (MERRA2)

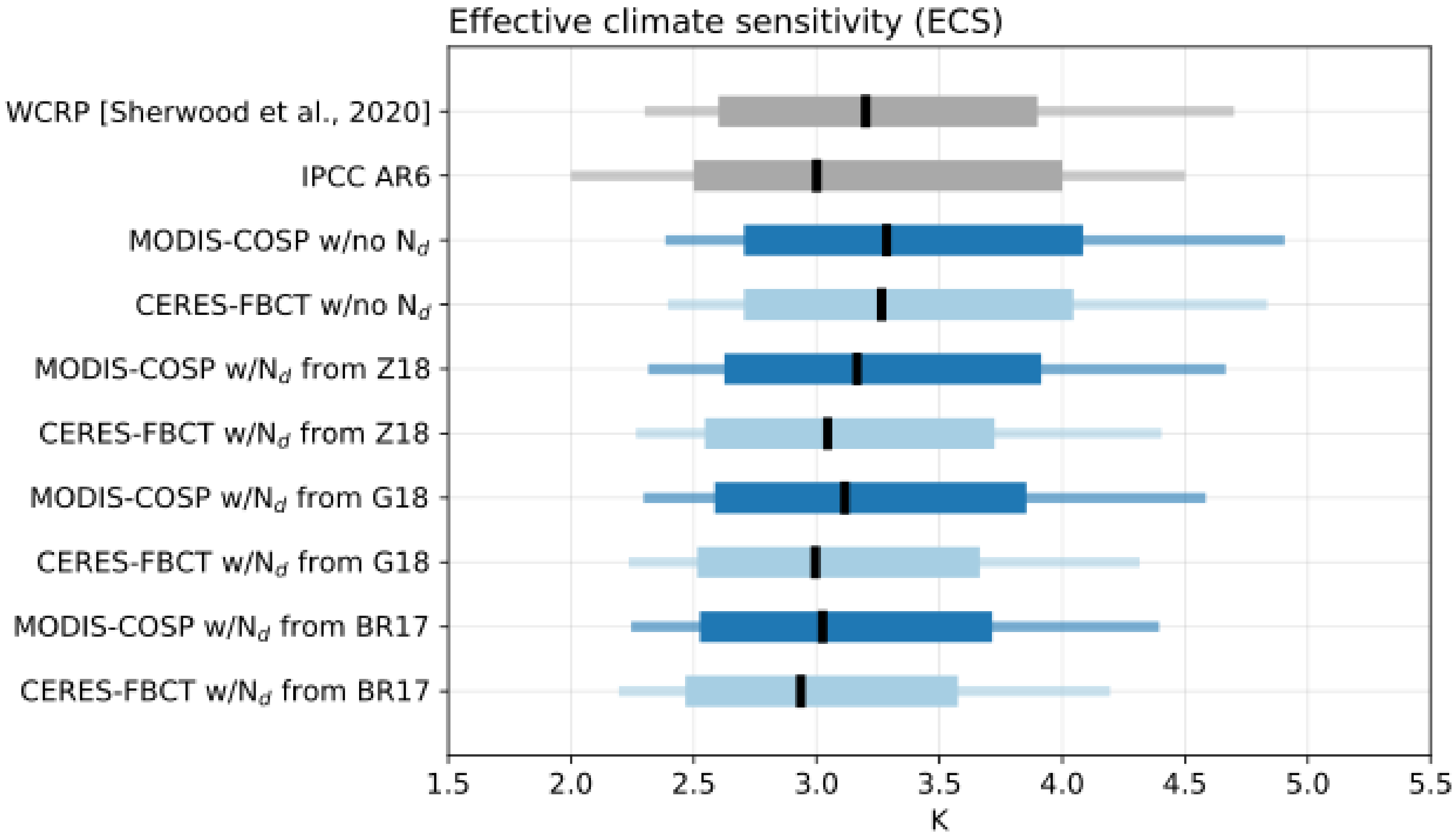
Mediation by N_d? If so, which flavor of N_d?

- No
- BR17_37
- G18_37
- Z18_37

Predictand Choices

- MODIS-COSP
- CERES-FBCT


Cloud Feedback
ACI
Median ECS
Nd_BR17_37
Nd_G18_37
Nd_Z18_37
No Nd
MODIS-COSP
FBCT
0.2
0.18
0.2
0.18
0.2
0.18
0.2
0.18
W/m^2/K
0.6
0.5
0.4
0.3
0.2
0.1
-0.58
-0.41
-0.78
-0.55
-0.89
-0.63
-1.2
-1.12
W/m^2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
3.02
2.94
3.12
3.0
3.16
3.05
3.29
3.27
K
3.5
3.4
3.3
3.2
3.1
3.0
2.9
2.8


Effective climate sensitivity (ECS)
WCRP [Sherwood et al., 2020]
IPCC AR6
MODIS-COSP w/no N_d
CERES-FBCT w/no N_d
MODIS-COSP w/N_d from Z18
CERES-FBCT w/N_d from Z18
MODIS-COSP w/N_d from G18
CERES-FBCT w/N_d from G18
MODIS-COSP w/N_d from BR17
CERES-FBCT w/N_d from BR17
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
K