Looking for answers in the clouds

Assessing clouds in CESM2 to understand its high climate sensitivity

Brian Medeiros

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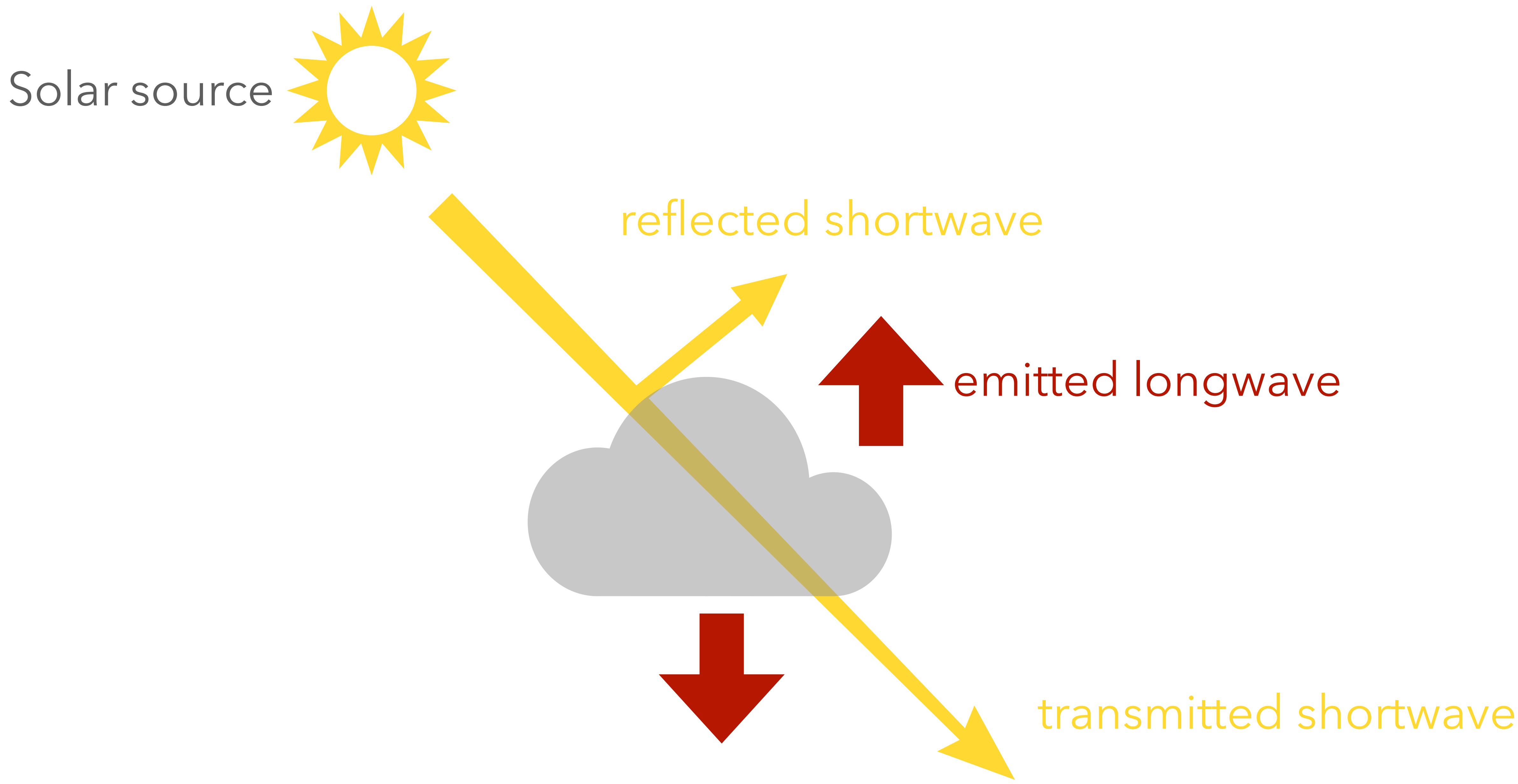
Earth energy budget & clouds



Global average energy balance: $N = S_{\odot}^{\downarrow} - S^{\uparrow} - L^{\uparrow}$

In equilibrium, $N \doteq 0$.

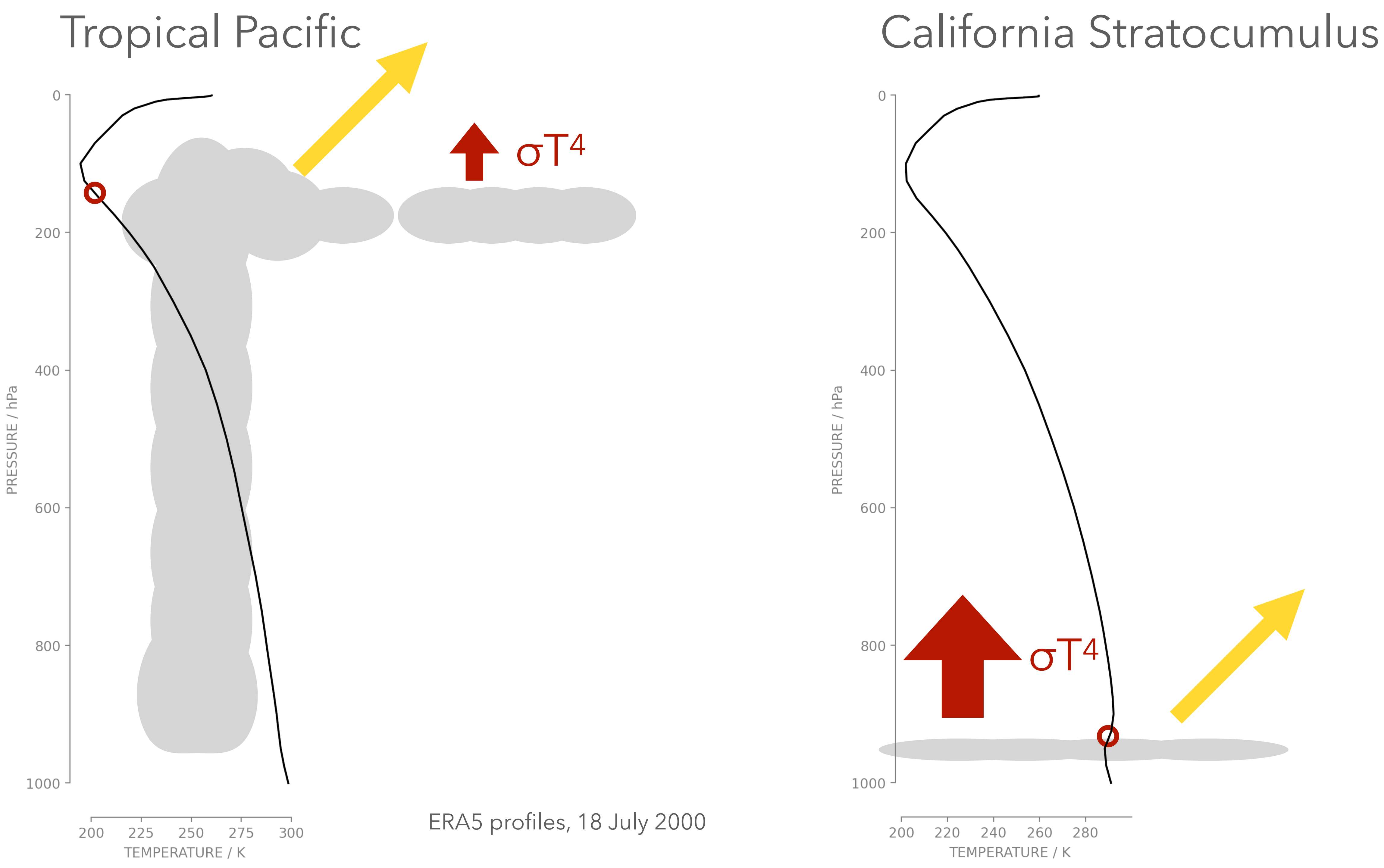
Cloud Radiative Effect:
the top-of-atmosphere flux difference between all-sky and clear-sky

In disequilibrium, write as a sum of forcing and feedback:
$N = F - \lambda \Delta T_s$

$N=0 \Rightarrow F/\lambda = \Delta T_s$

If F is $2\times CO_2$, ΔT_s is "equilibrium climate sensitivity"

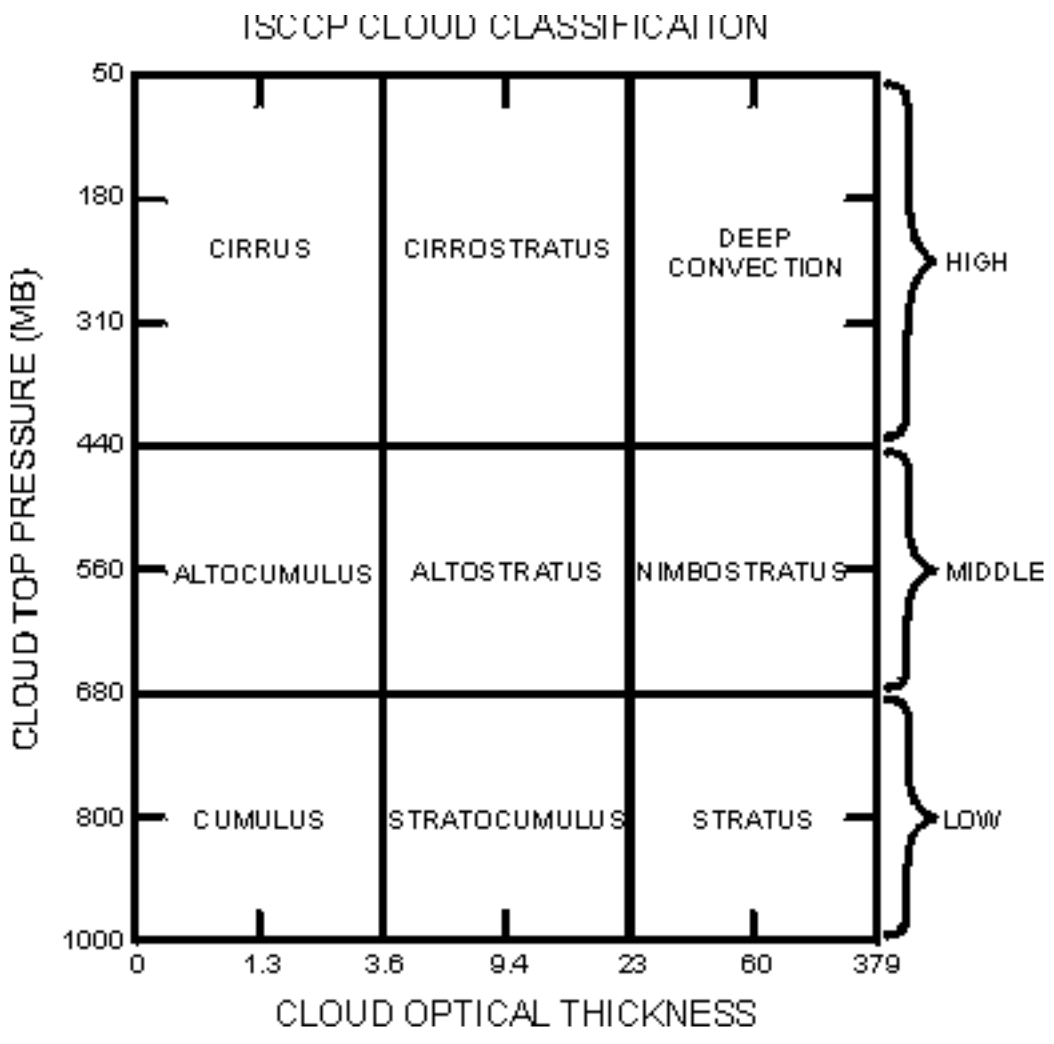
Different kinds of clouds



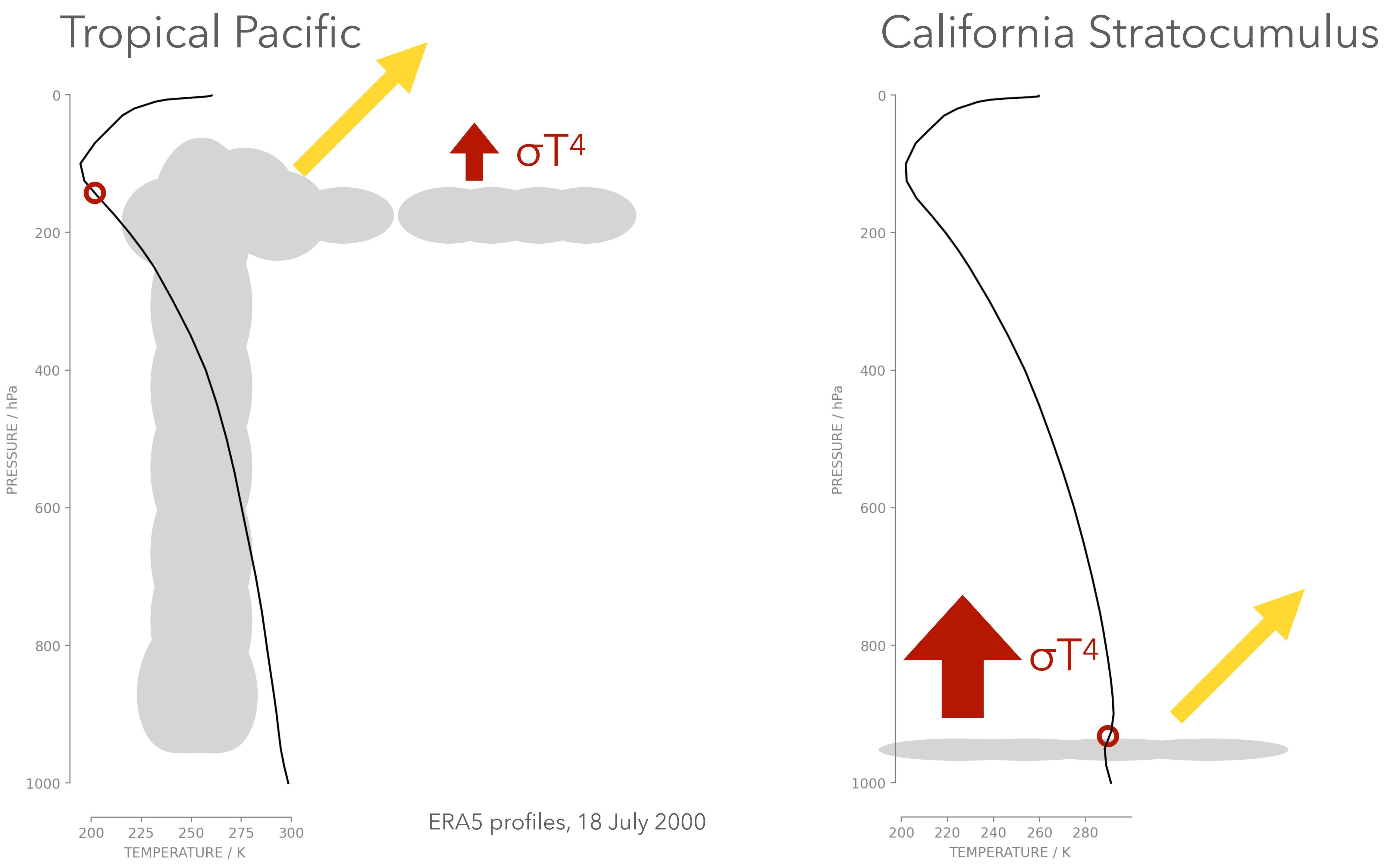
$$\tau = \frac{3}{4}\frac{Q_{\mathrm{ext}}\mathrm{LWP}}{r_e}$$

The cloud optical thickness is related to the liquid water path and the effective radius, and is strongly correlated with cloud albedo. (Han et al. 1998)

Different kinds of clouds



source: [old ISCCP website]()



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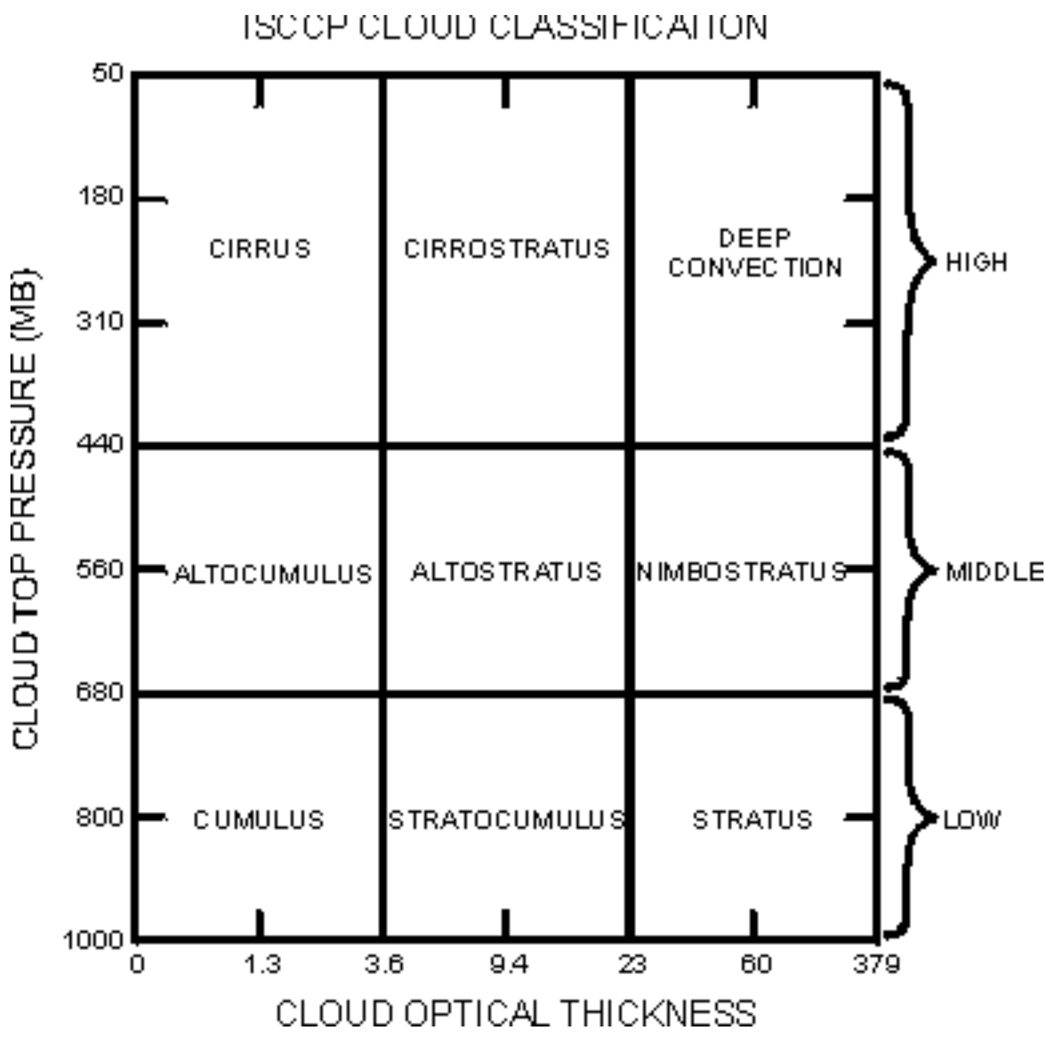
CTP-τ Histograms



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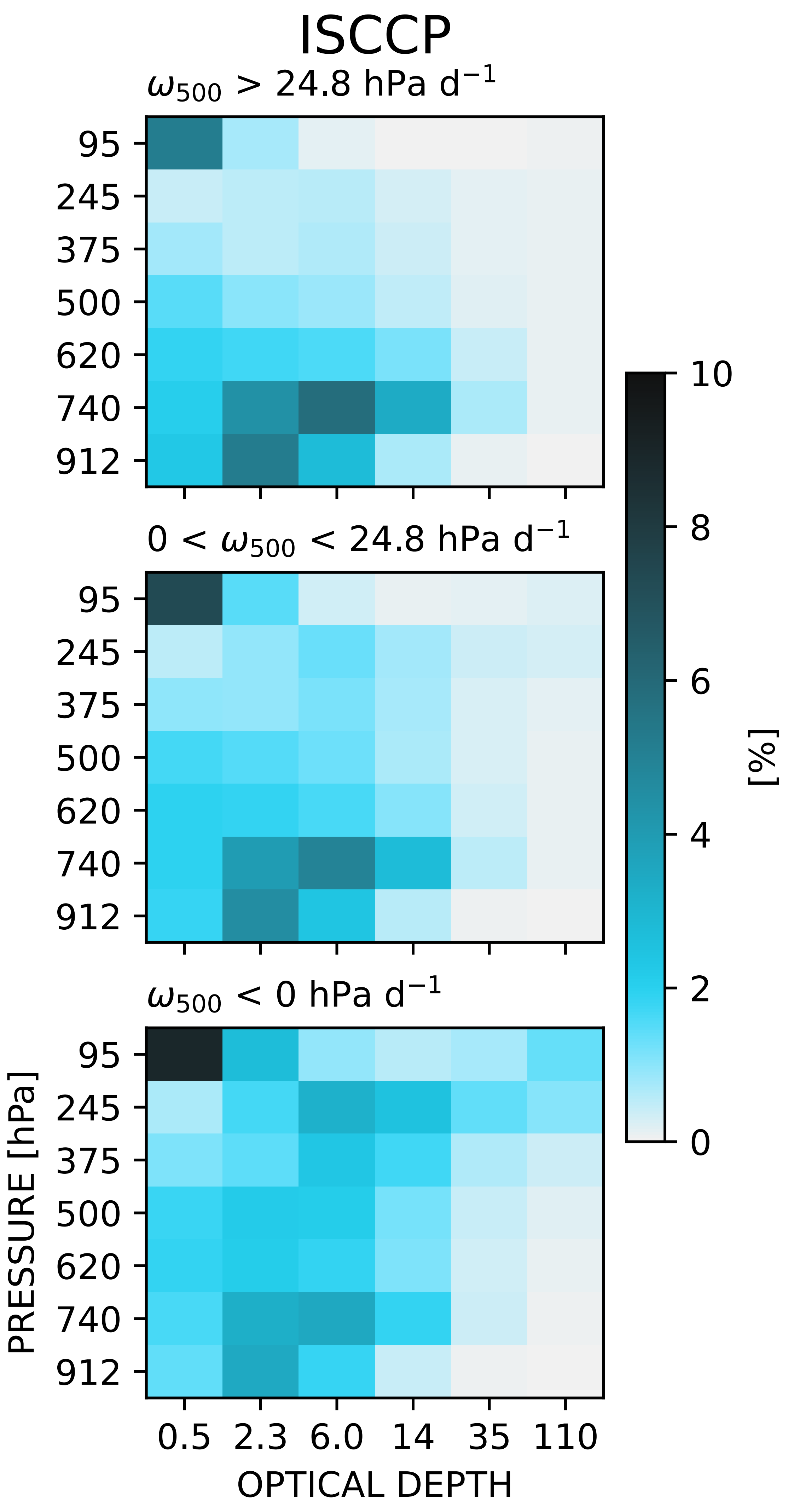
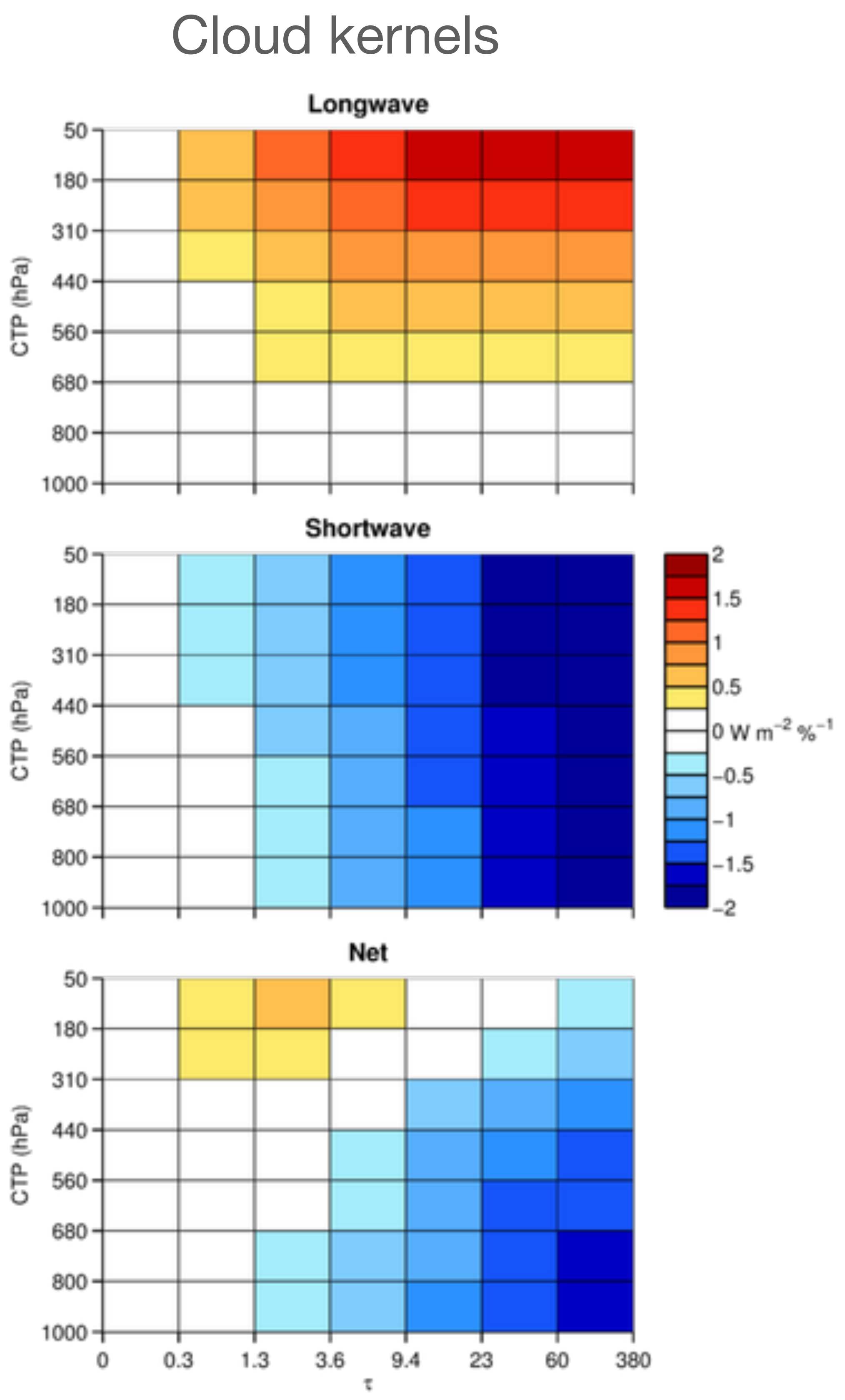


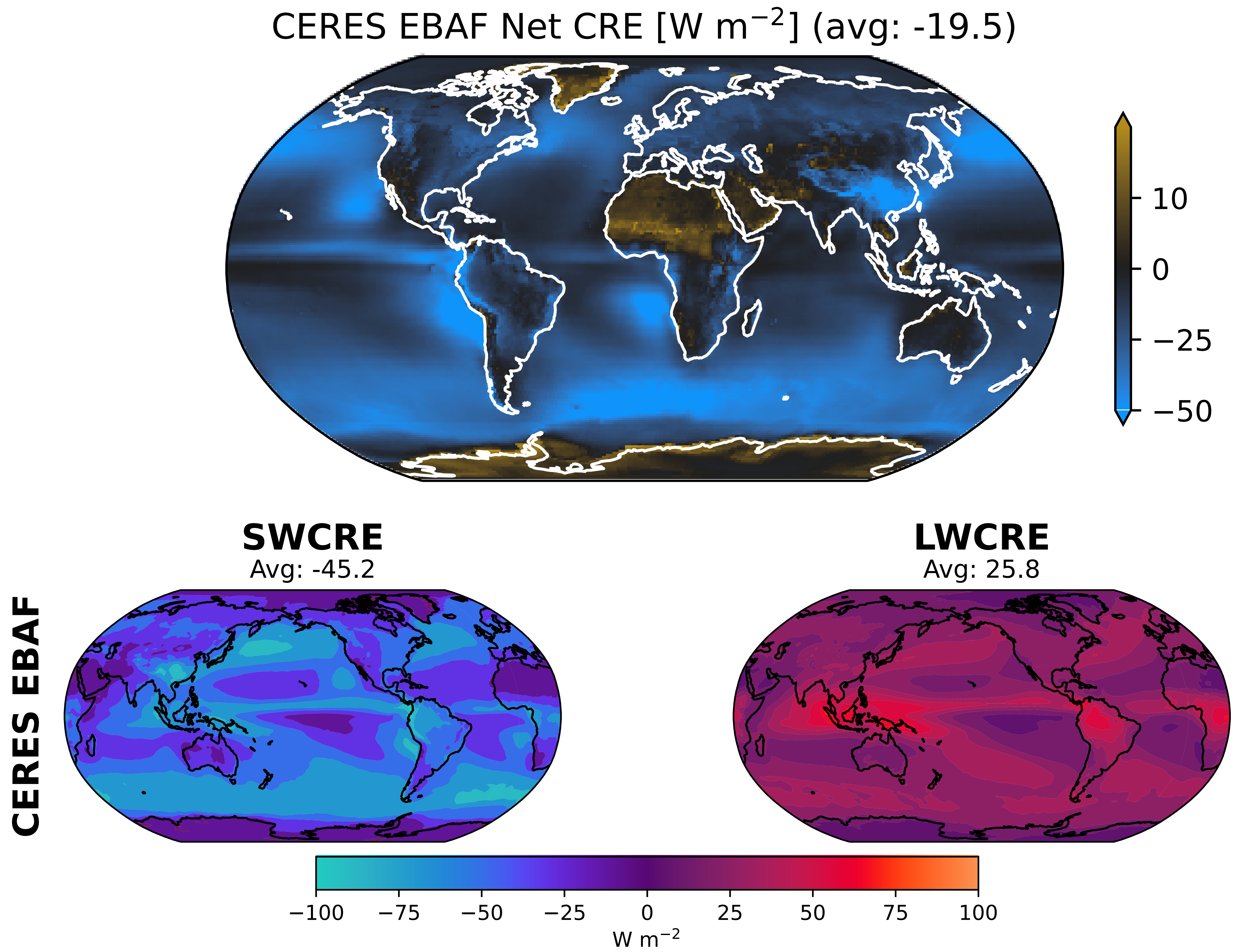
Medeiros et al. 2023



Zelinka et al. 2012

COSP: “satellite simulator” software that can be run in climate models to provide cloud data comparable to satellite products.

Observed Cloud Radiative Effect



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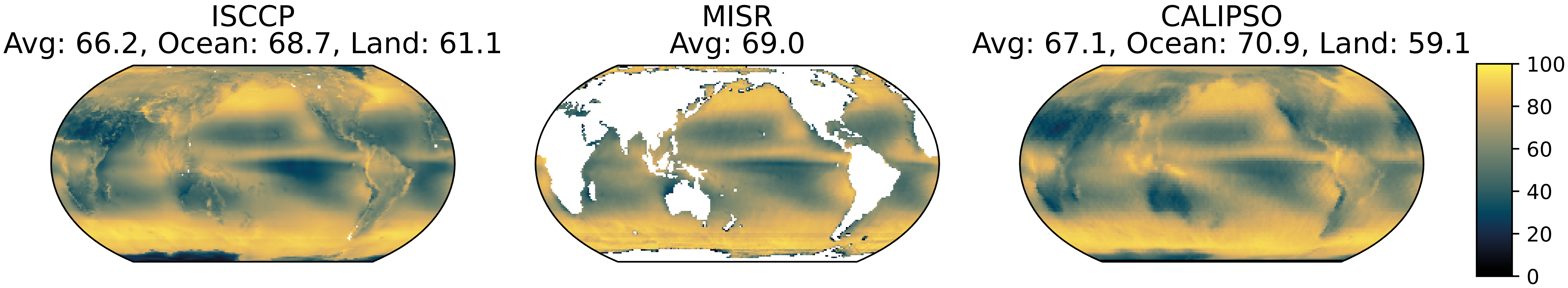
Observed Cloud Cover Climatology



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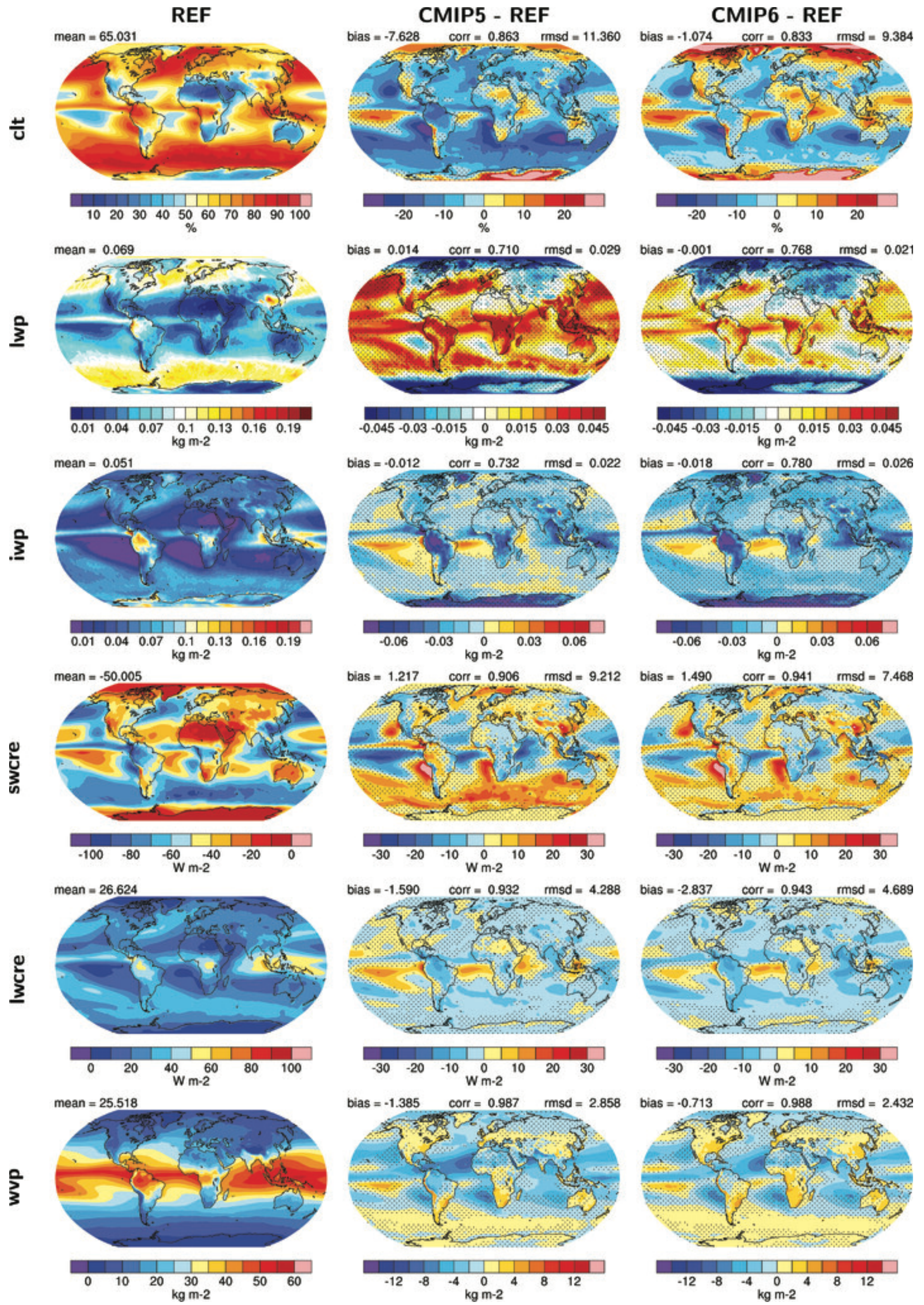
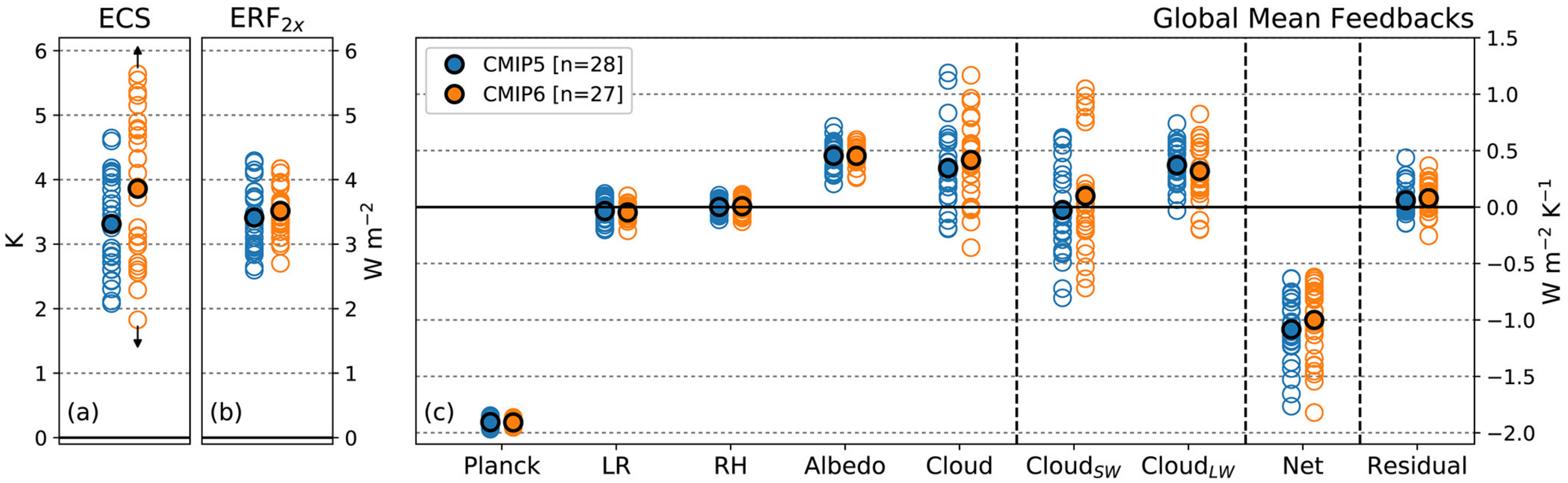
How do climate models do?

- “**intermodel spread** in CMIP6, however, is not reduced or is even slightly larger than in CMIP5”
- “CMIP5/6 models **overestimate cloud ice** particularly in the lower and middle troposphere”
- “many known biases such as an **underestimation in cloud cover in stratocumulus** regions or unrealistic cloud distributions in the tropics due to a double-ITCZ in some models remain a problem in CMIP6”
- “**Total cloud water path** in the extratropical regime is more sensitive to vertical velocity than to SST and is overestimated by the models.”
- “Among the most notable improvements is an improved agreement of cloud amount and reflectivity of clouds over the Southern Ocean.”



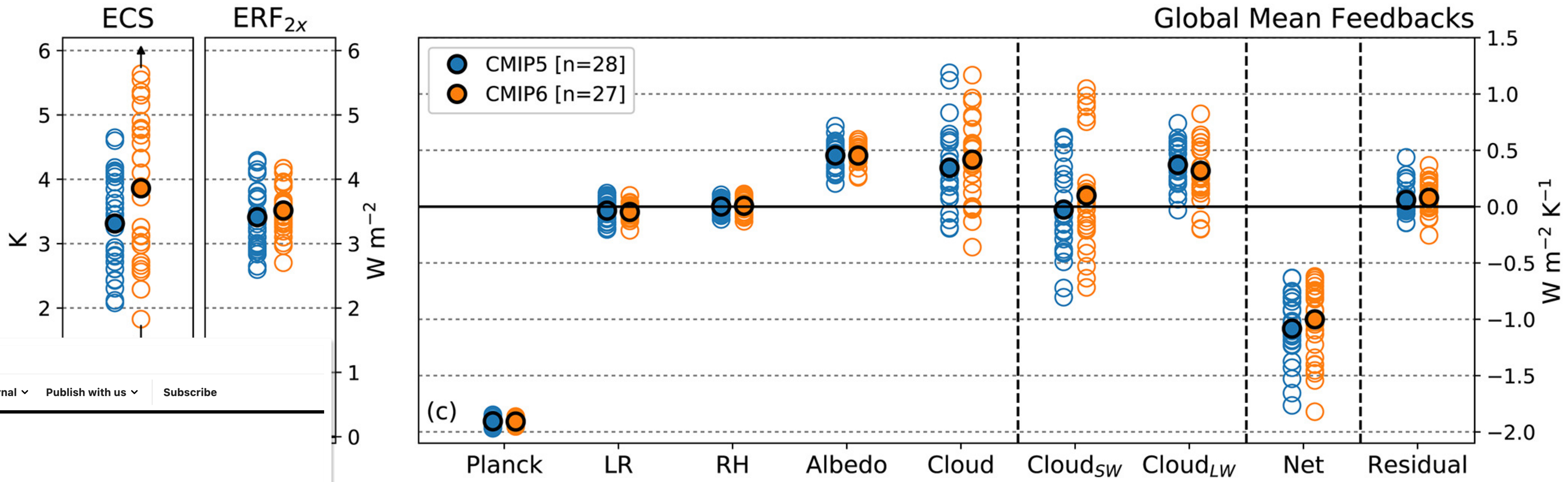
Lauer et al. 2023

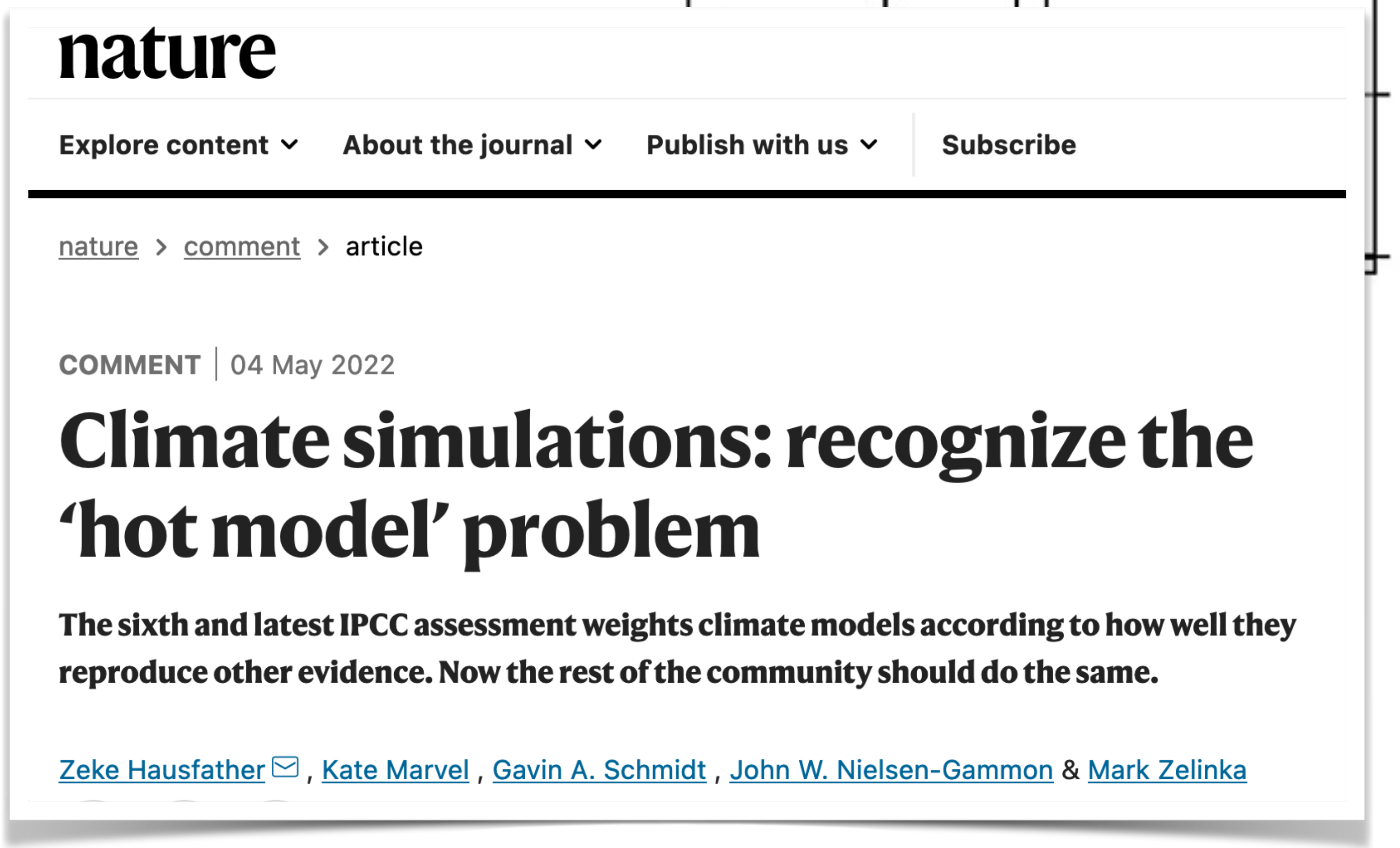
Climate sensitivity and feedbacks



Zelinka et al. 2020

Climate sensitivity and feedbacks

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Climate simulations: recognize the 'hot model' problem

The sixth and latest IPCC assessment weights climate models according to how well they reproduce other evidence. Now the rest of the community should do the same.

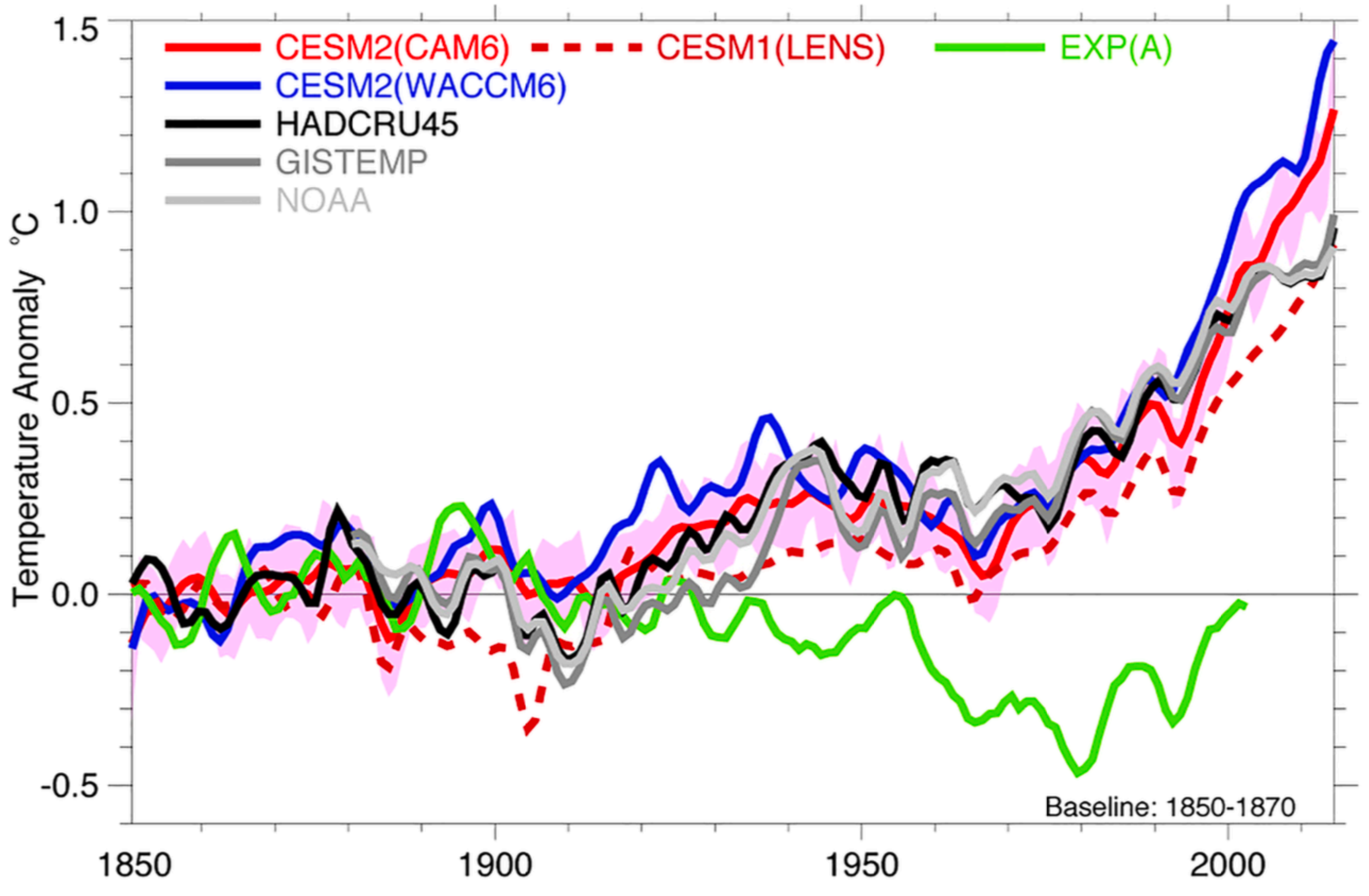
Zeke Hausfather, Kate Marvel, Gavin A. Schmidt, John W. Nielsen-Gammon & Mark Zelinka

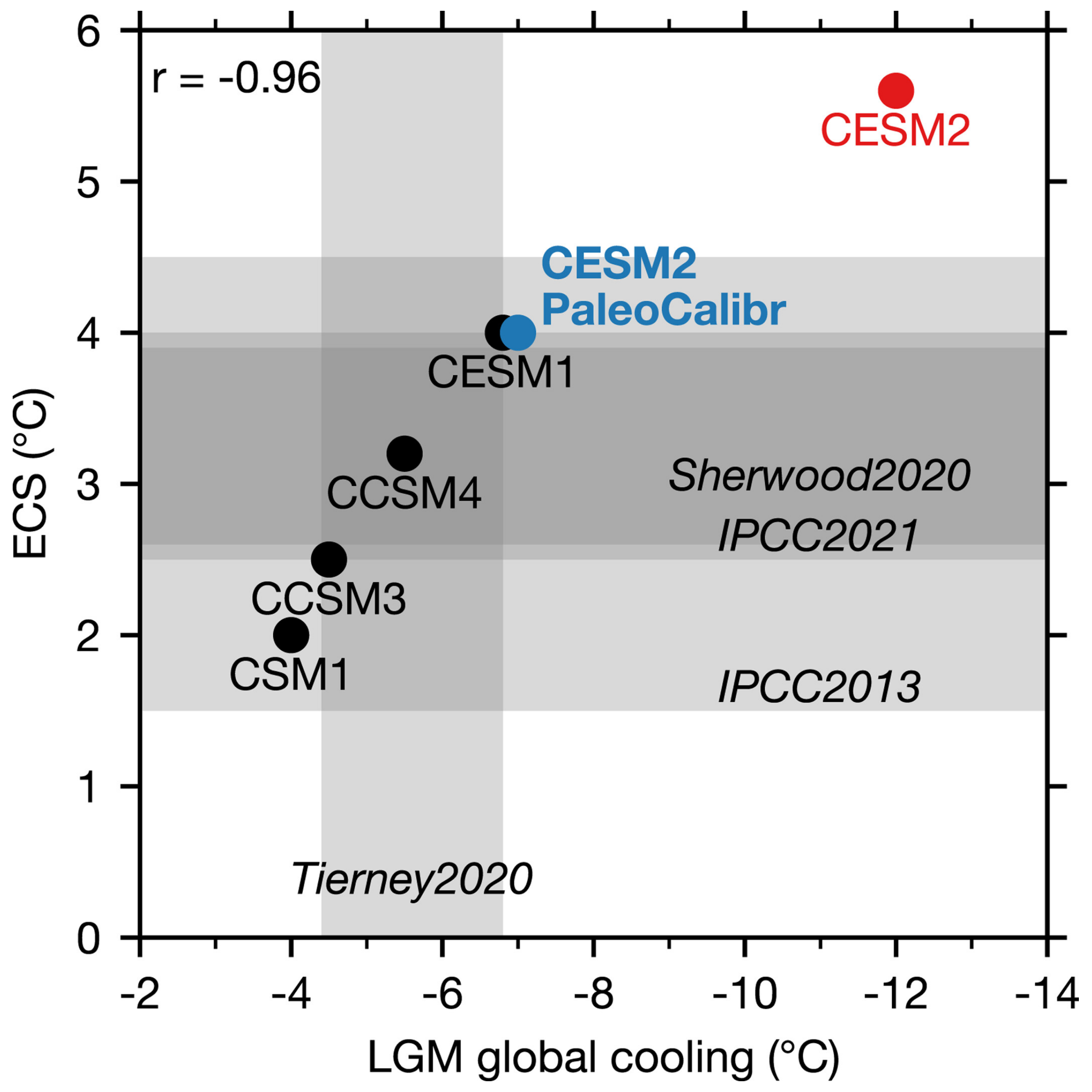
Zelinka et al. 2020

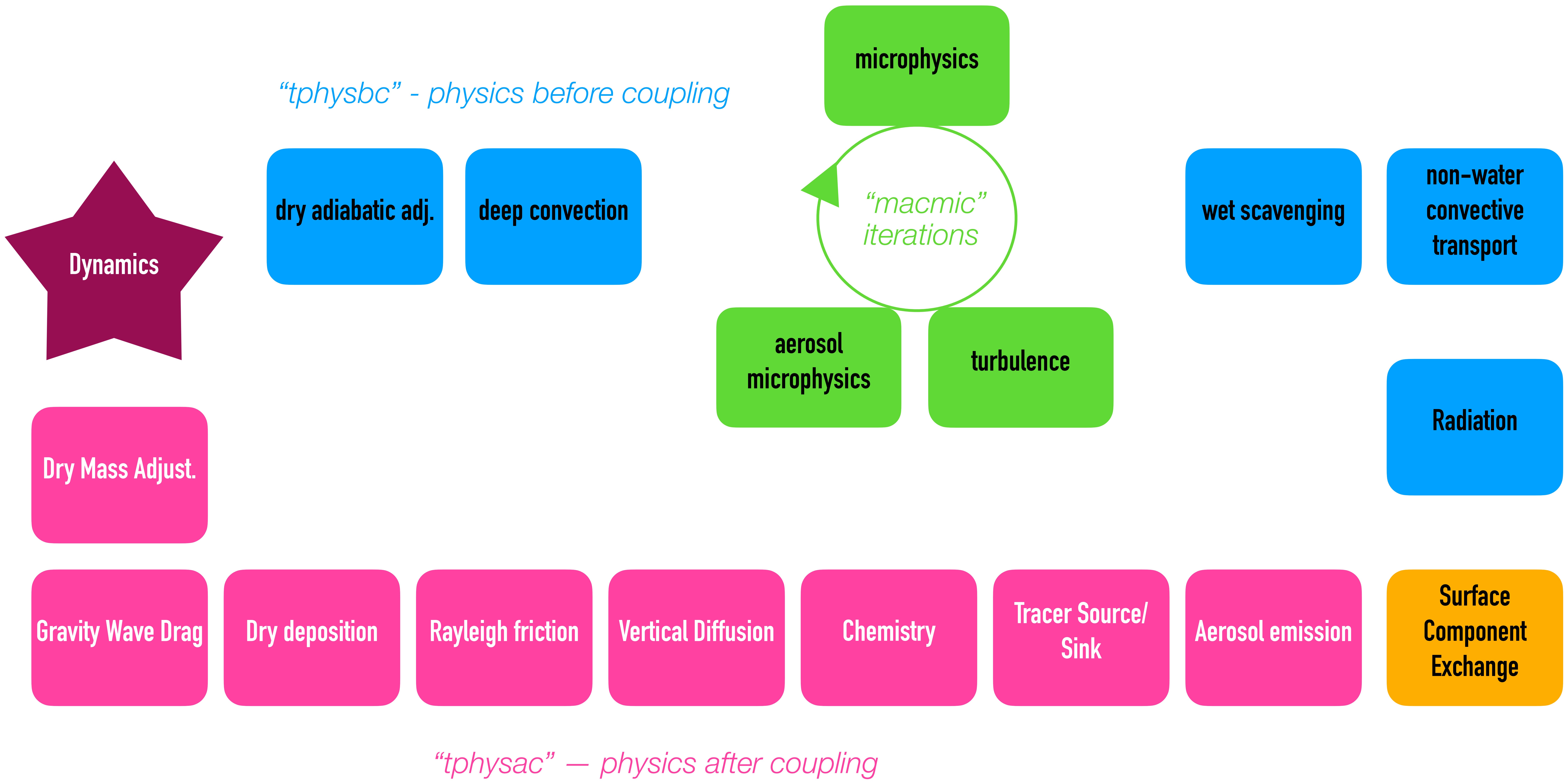
CESM2 as a "hot model"

- High ECS and it's because of clouds:
  - Gettelman et al. 2019 (ECS 5.3K, Cloud feedbacks in southern hemisphere subtropics and storm tracks)
  - Bacmeister et al. 2020 (ECS 5.3-6.5K, Cloud feedbacks in tropical oceans and southern ocean)
  - Bjordal et al. 2020 (transition from mixed phase to liquid clouds)
- E3SM is also a "hot model", very closely related to CESM2
  - Golaz et al. 2019 (ECS 5.3K, solely shortwave cloud feedbacks)
  - Qin et al. 2024 (mostly tropical low-cloud feedbacks)
- CESM2 does a good job in representing the 20th Century and variability
  - Fasullo 2020 (multivariate energy/water/circulation/variability)
  - Danabasoglu et al. 2020 (e.g., 20th century global Ts)
  - Simpson et al. 2020 (large-scale circulation)
- Doesn't do a good job with the Last Glacial Maximum
  - Zhu et al. 2022 (cloud microphysical processes including ice nucleation)

- Questions for the rest of the talk:
  - *How do the clouds look in the present climate?*
  - *Can we say anything about which clouds change with warming?*
  - *How robust are the cloud feedbacks in CAM6?*

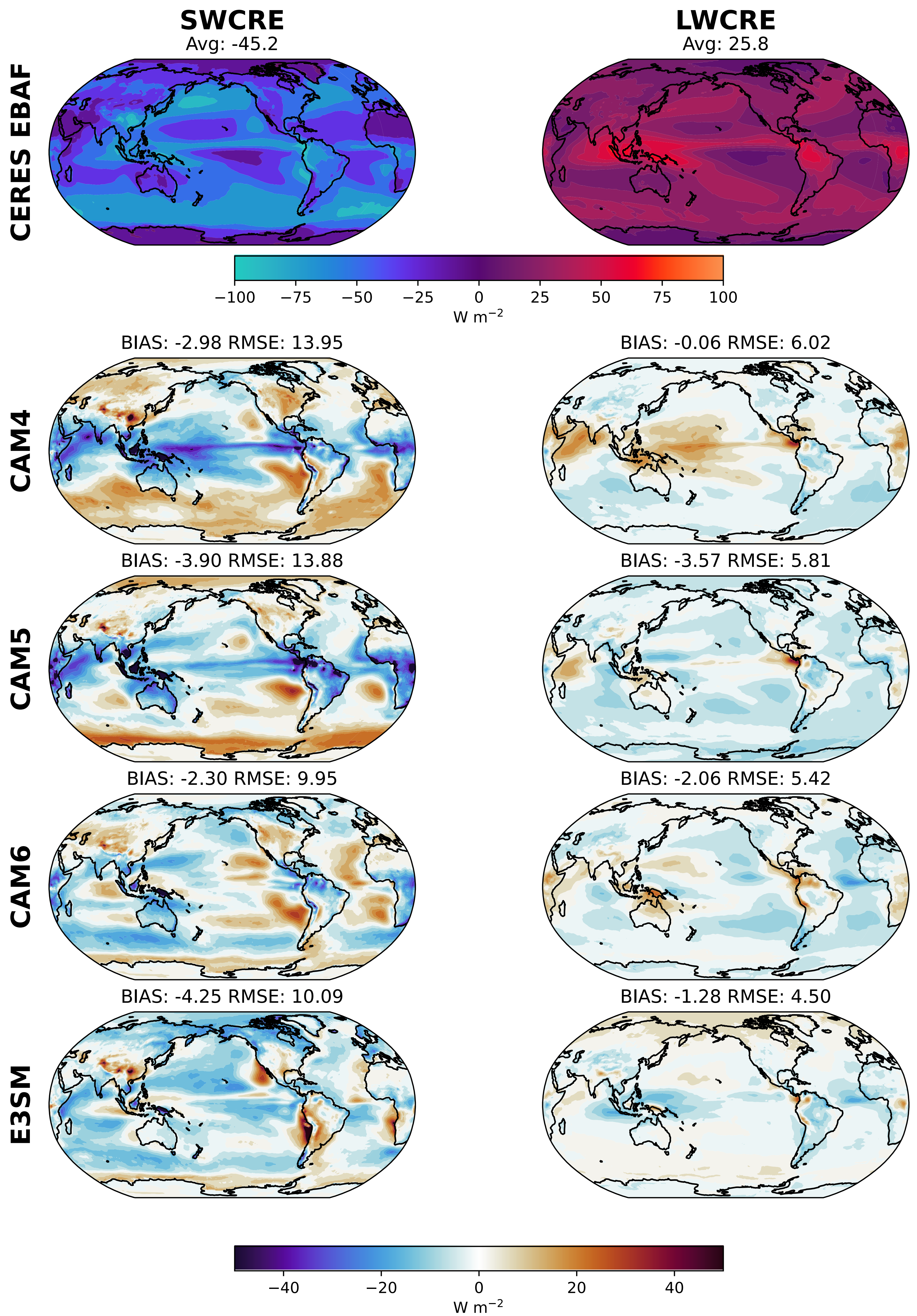




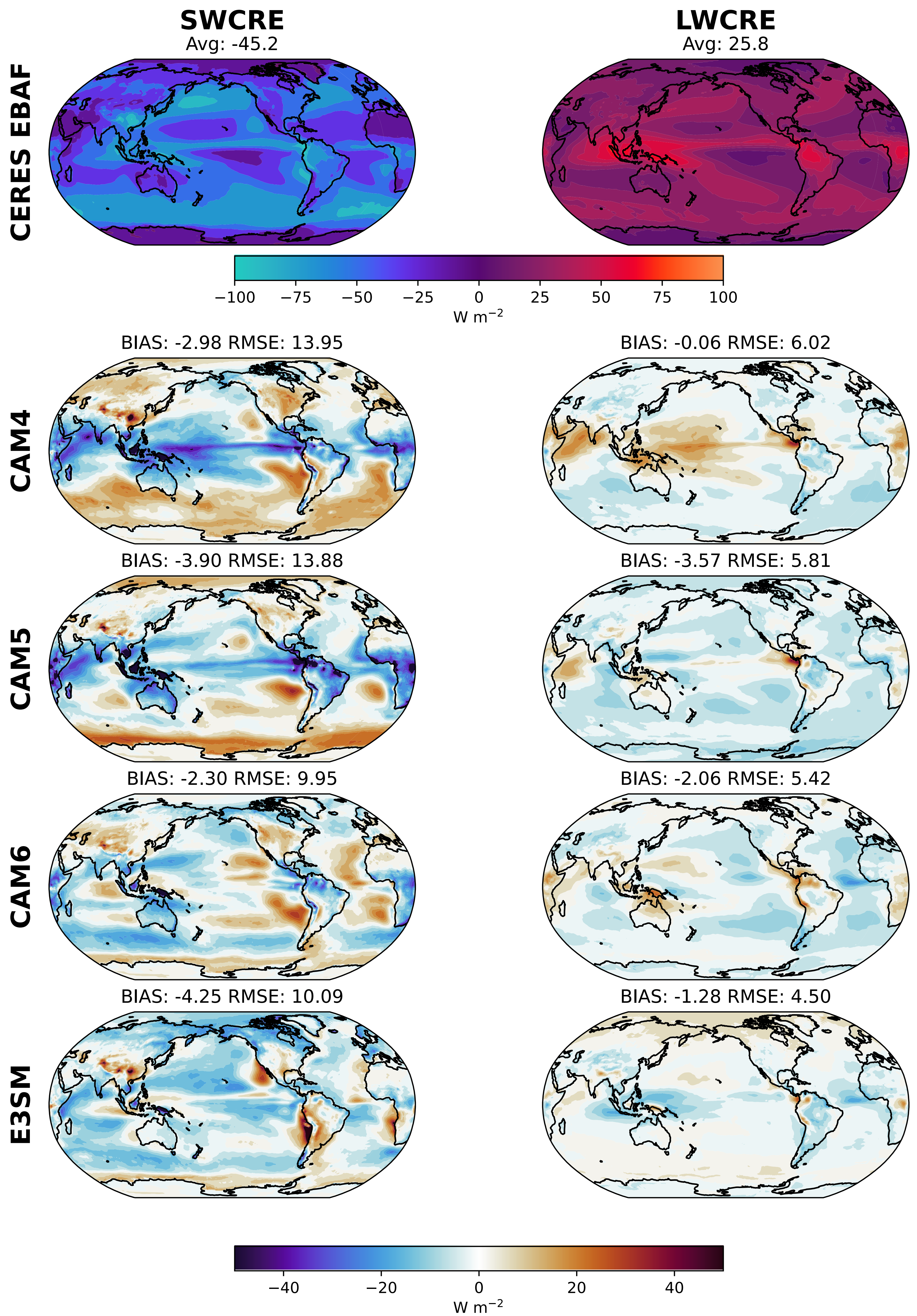


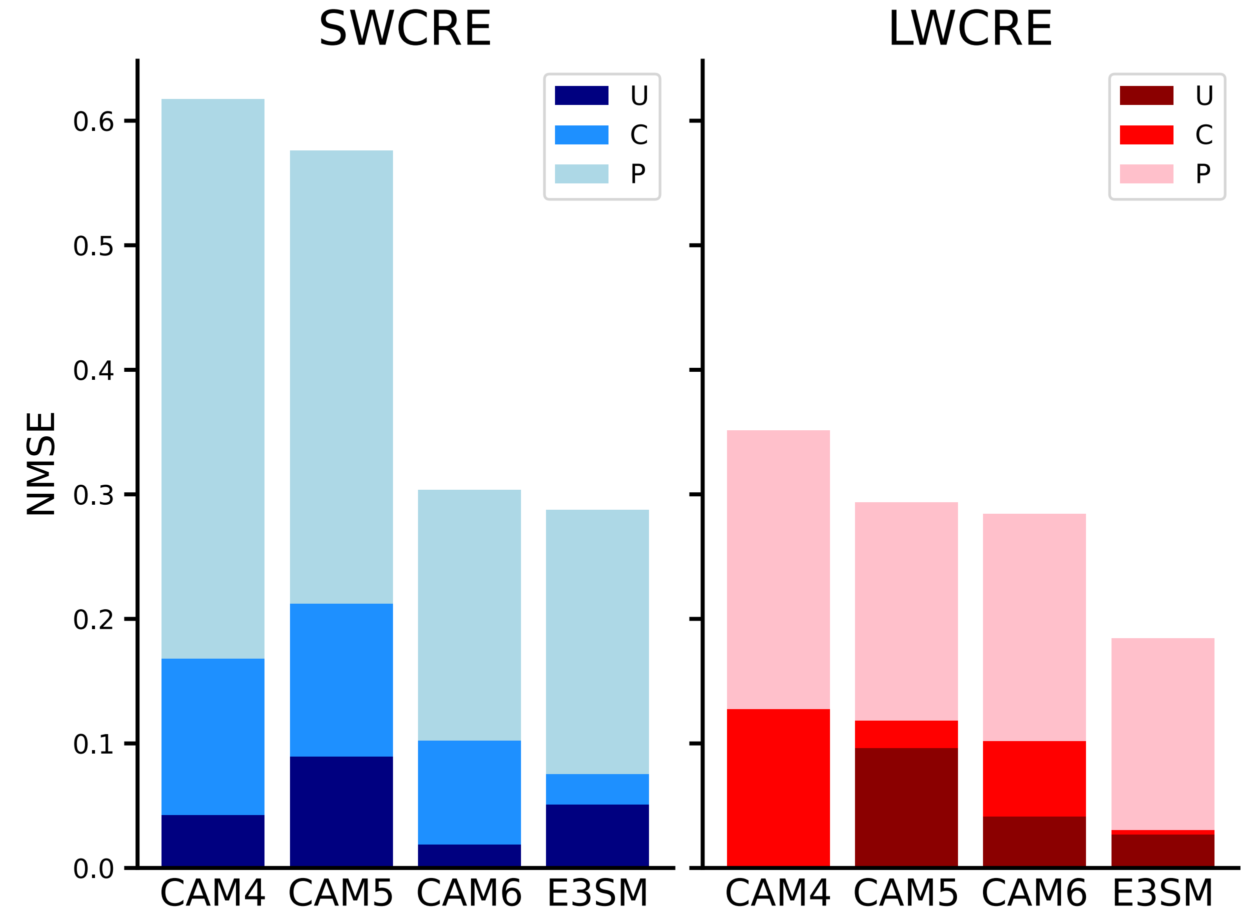
"tphysbc" - physics before coupling
Dynamics
dry adiabatic adj.
deep convection
microphysics
"macmic" iterations
aerosol microphysics
turbulence
wet scavenging
non-water convective transport
Radiation
Dry Mass Adjust.
Gravity Wave Drag
Dry deposition
Rayleigh friction
Vertical Diffusion
Chemistry
Tracer Source/ Sink
Aerosol emission
Surface Component Exchange
"tphysac" — physics after coupling

Cloud radiative effect biases through model generations



Cloud radiative effect biases through model generations





$$\text{NMSE} = \frac{[(\overline{X_m} - \overline{X_o})^2]}{[\overline{X_o'}]}$$

$$\text{NMSE}(X_m) = U + C + P$$

$$U = \left(\frac{[\overline{X_m}] - [\overline{X_o}]}{\sigma_o}\right)^2 \qquad C = \left(r - \frac{\sigma_m}{\sigma_o}\right)^2 \qquad P = \left(1 - r^2\right)$$

Temporal average

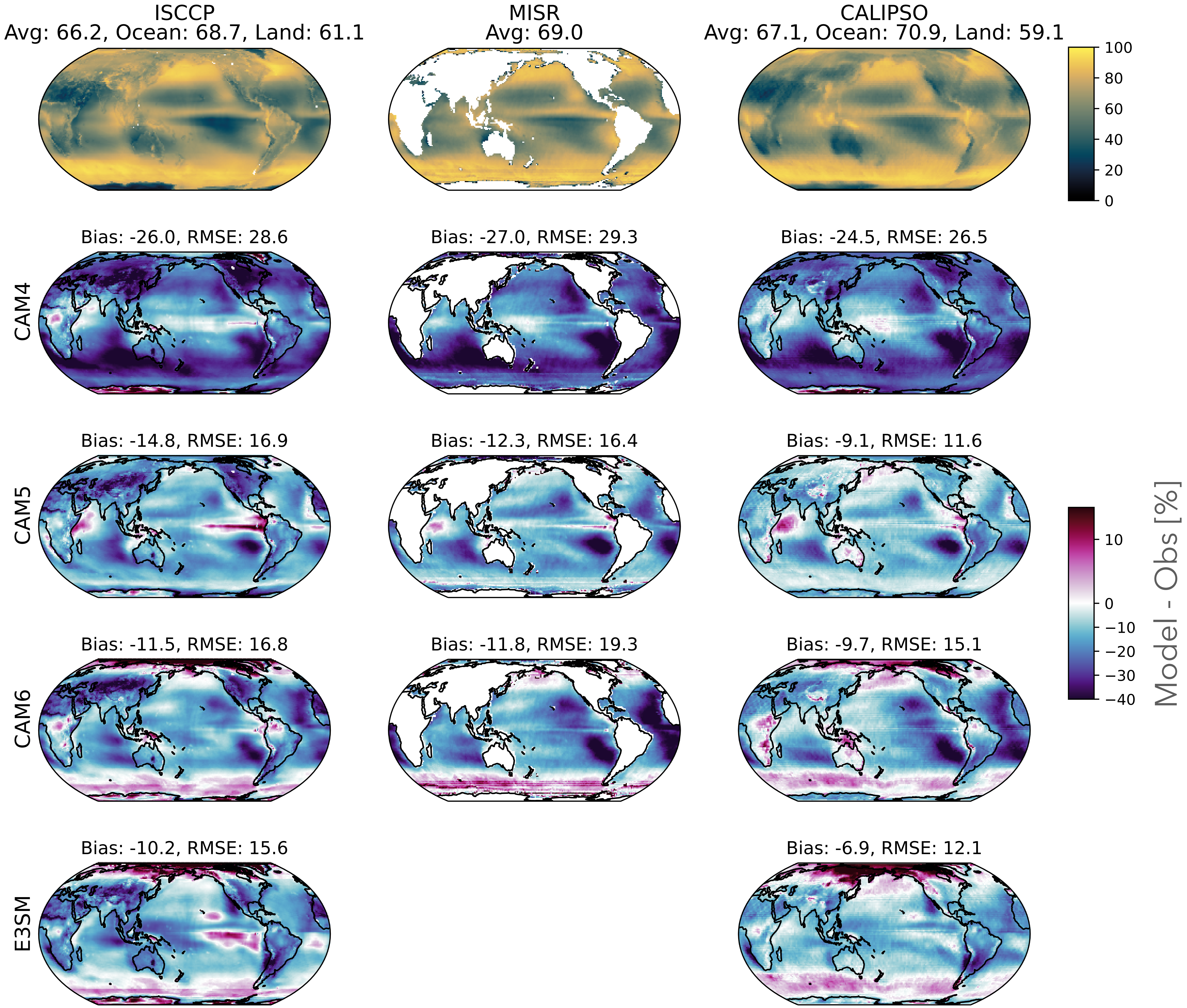
$$\overline{\chi} = \frac{1}{N_t}\sum_t \chi_t(\lambda, \phi)$$

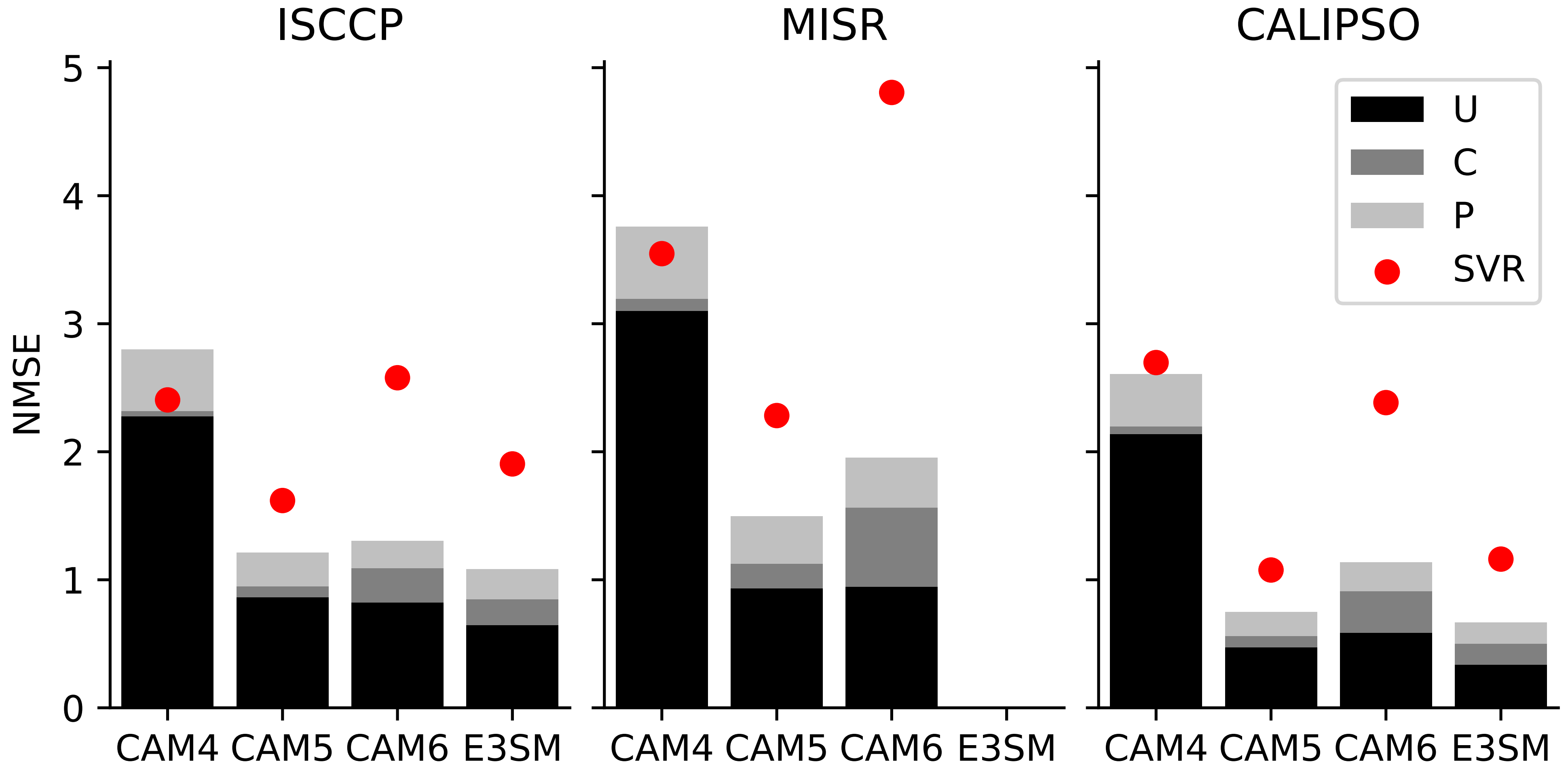
Spatial average

$$[\chi] = \frac{\sum_i \cos(\phi_i)\chi_i}{\sum_i \cos(\phi_i)}$$

See also Simpson et al. 2020; Murphy 1988

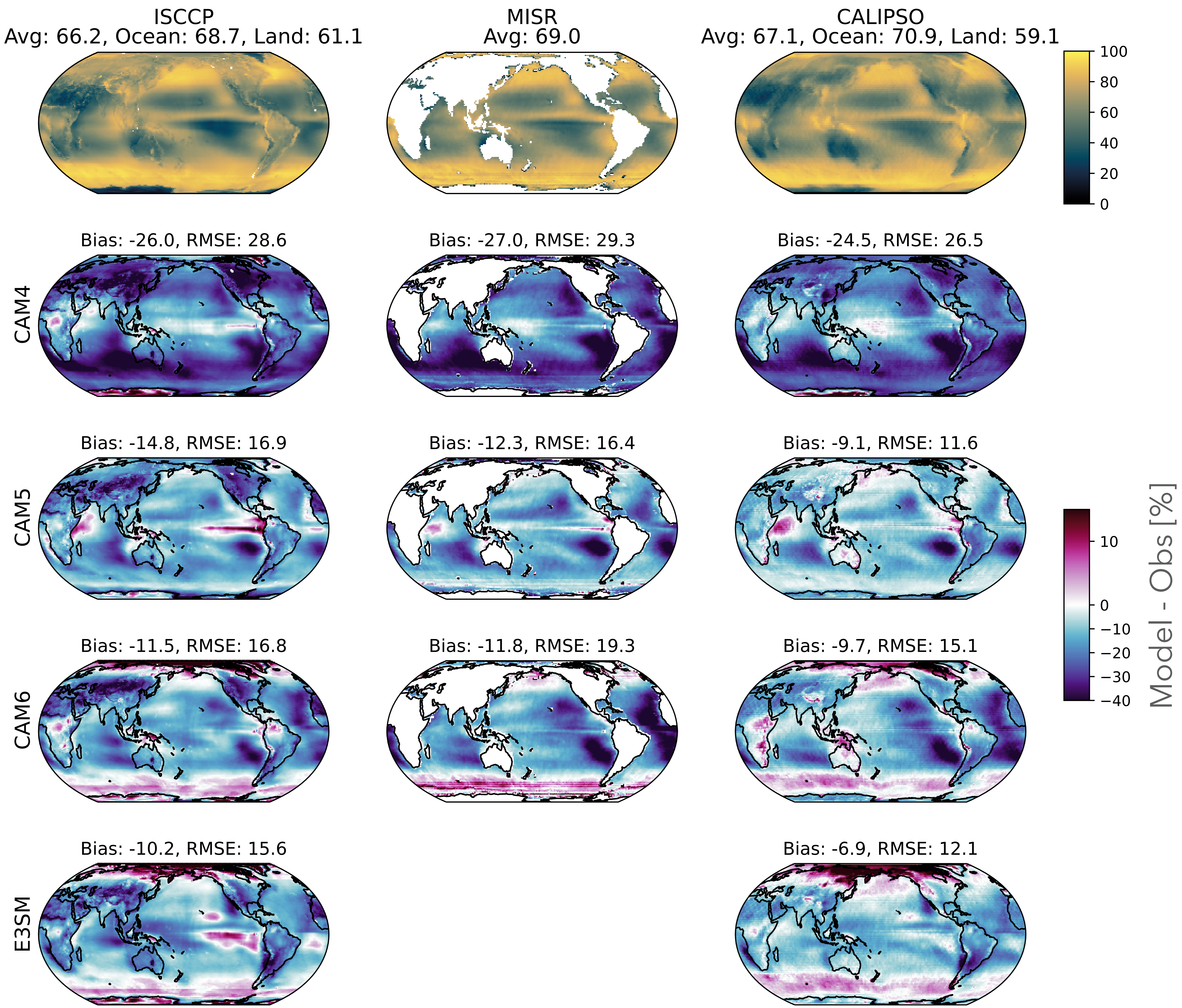
Cloud cover biases through model generations

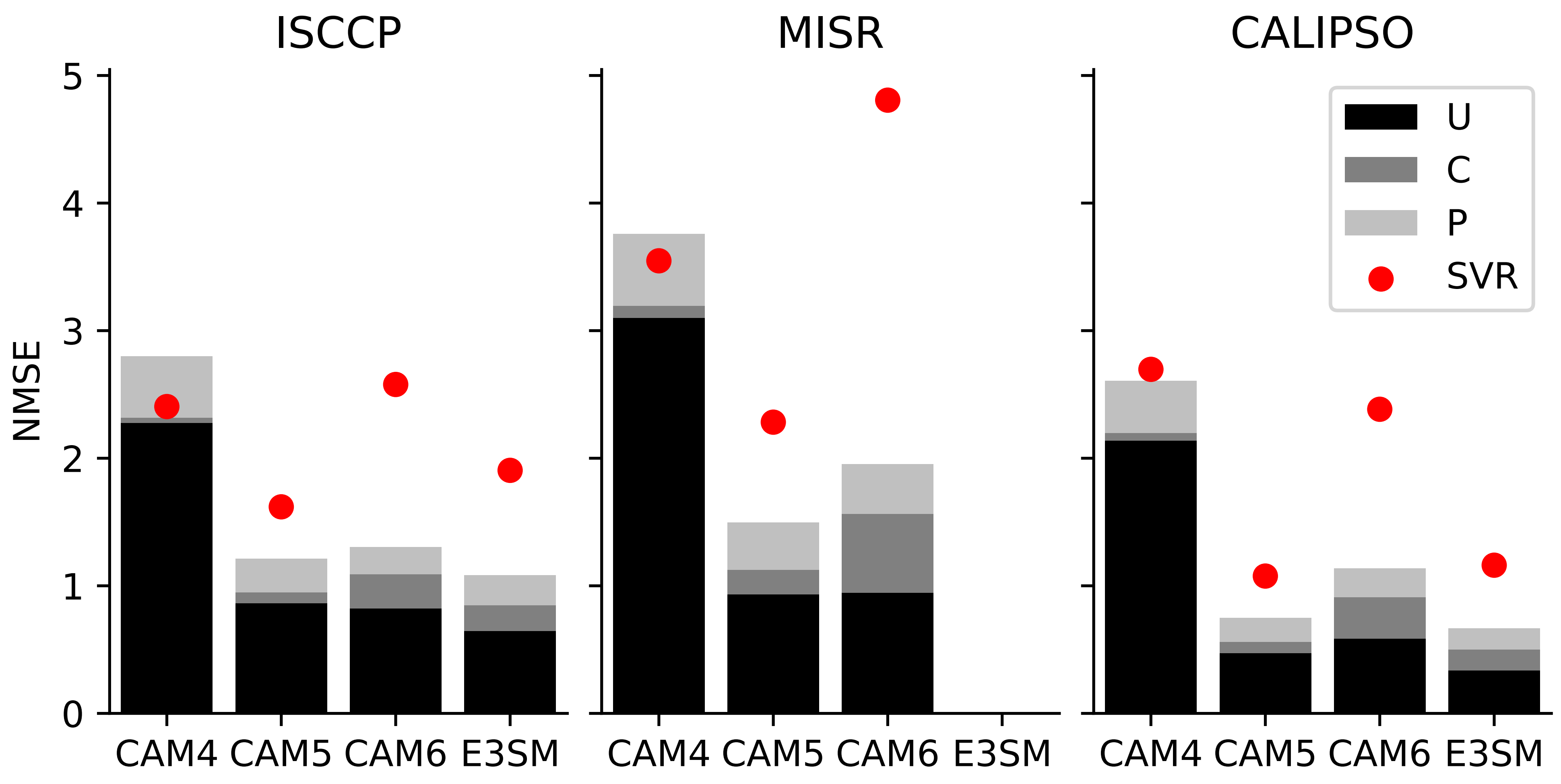


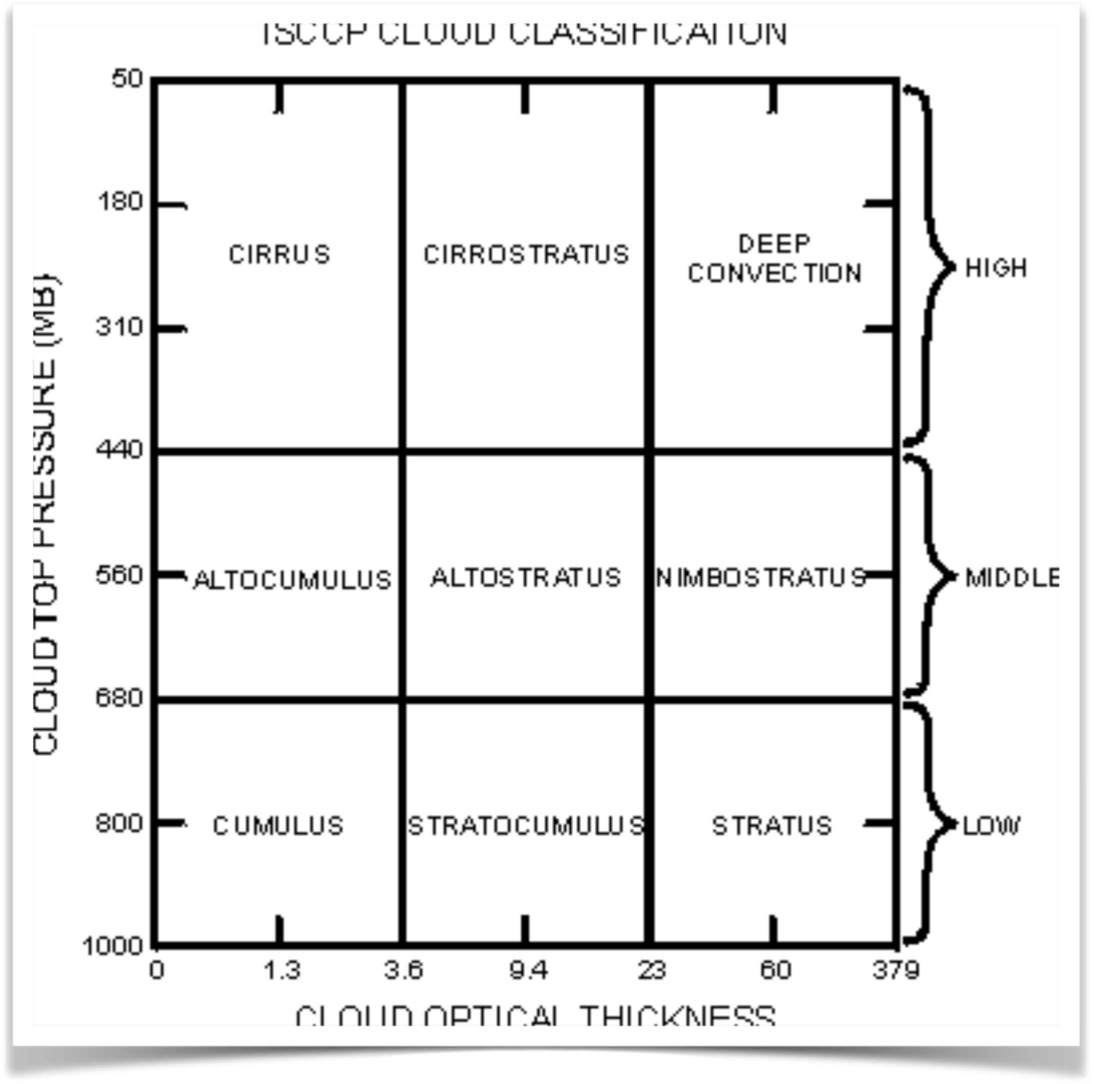


Medeiros et al. 2023

Cloud cover biases through model generations







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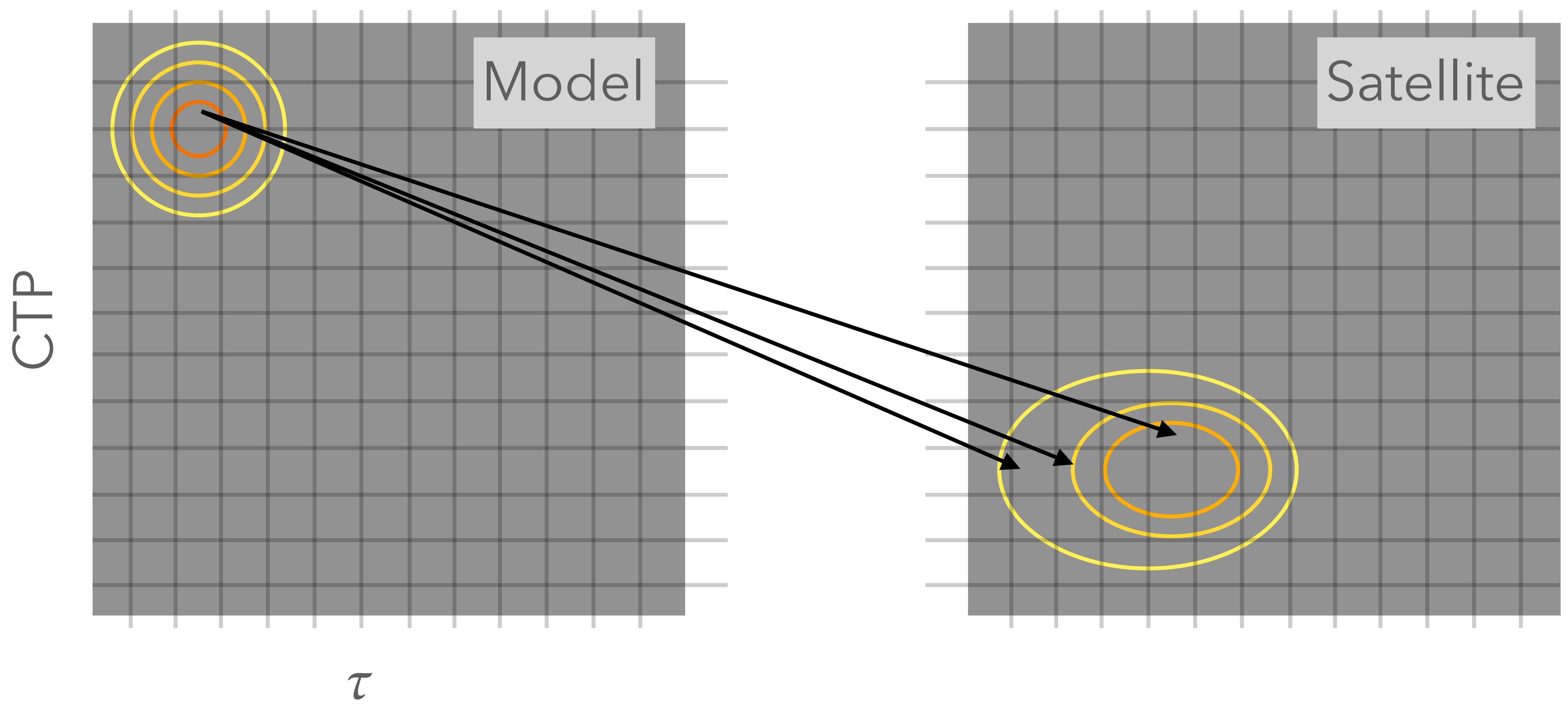
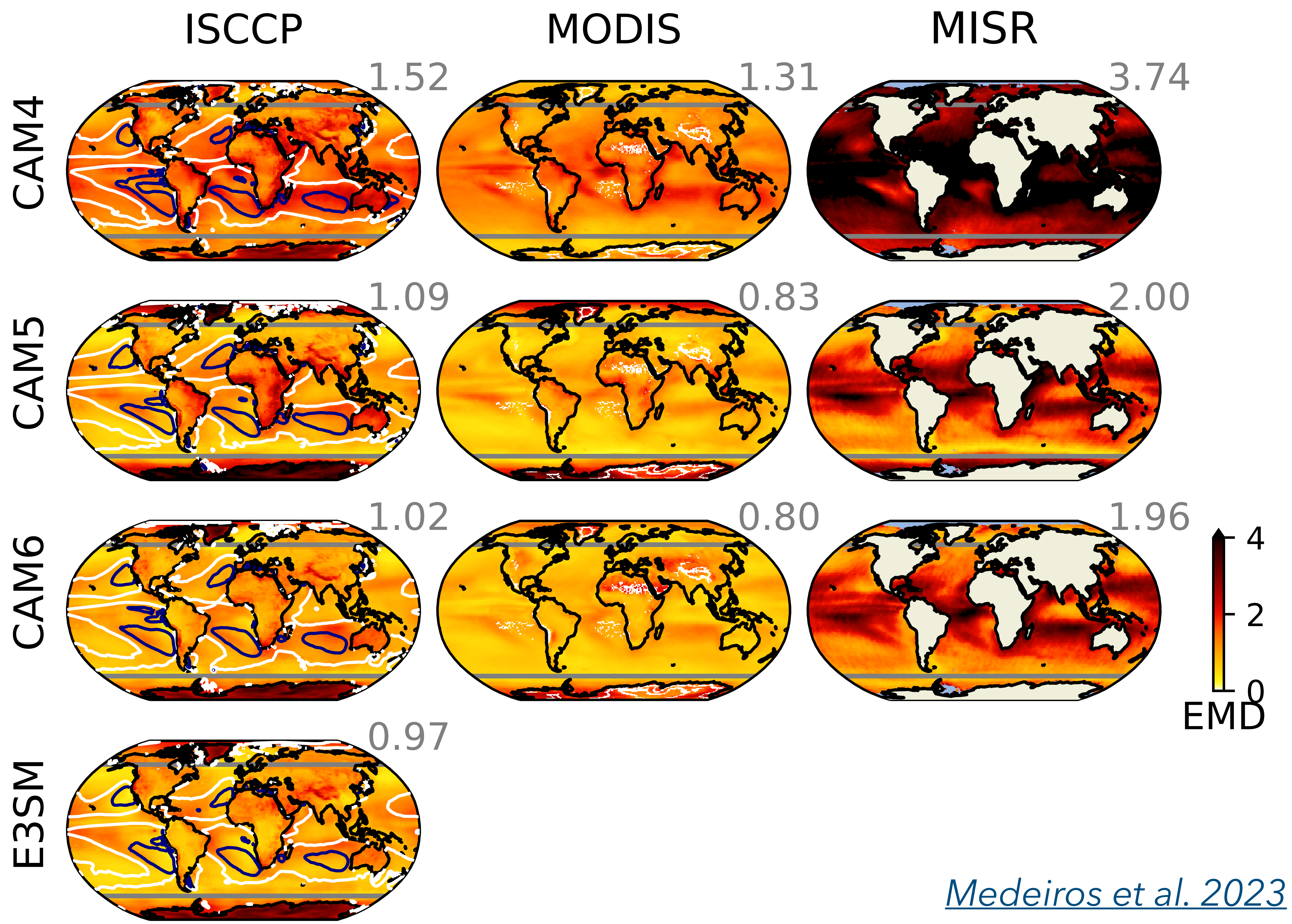
Earth Mover's Distance, aka Wasserstein Distance

$$EMD(P,Q) = \inf_{\gamma \in \Pi(P,Q)} \mathbb{E}_{(x,y)\sim\gamma}\left[\, \| x - y \| \,\right] \quad \longrightarrow \quad EMD = \sum \gamma_i C_i$$

Transport — Cost

Transform one distribution to another by "transporting" "mass" such that the amount of "work" is minimized.





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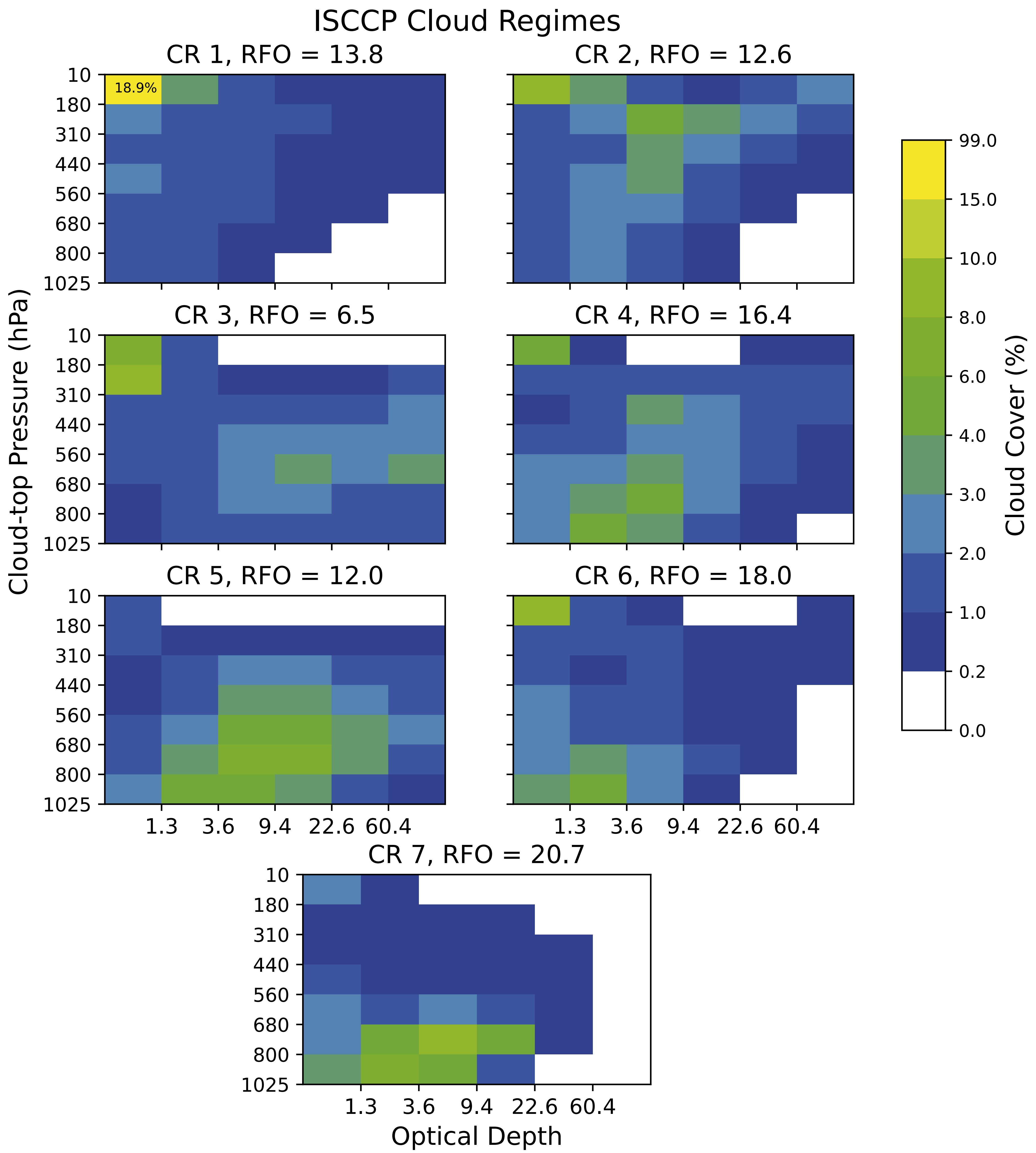
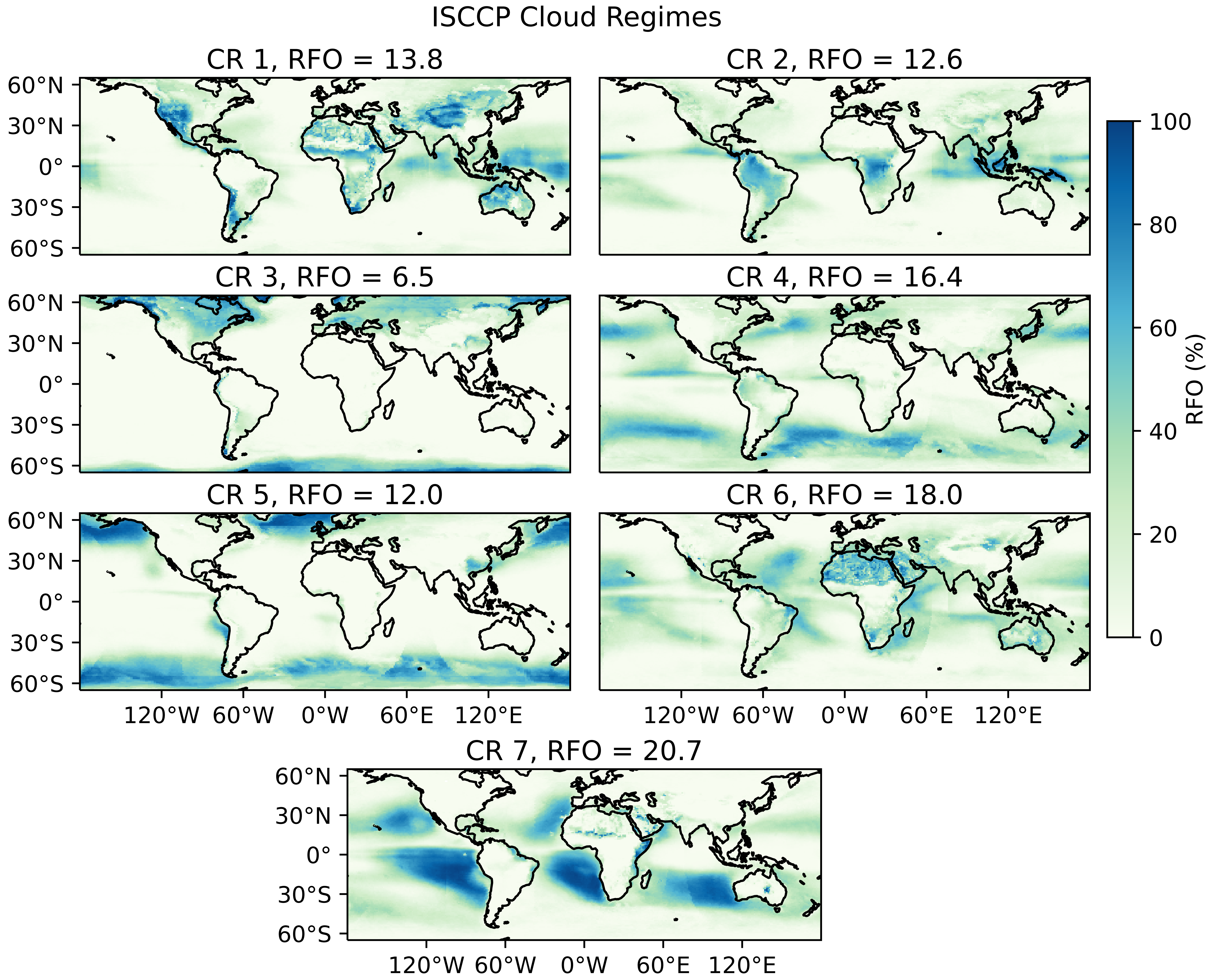
Can we say anything about which clouds change with warming?

What are the “typical” arrangements of clouds in CTP-τ space? That is, are there “cloud regimes”?

Does CESM capture those arrangements? And do they change with warming?

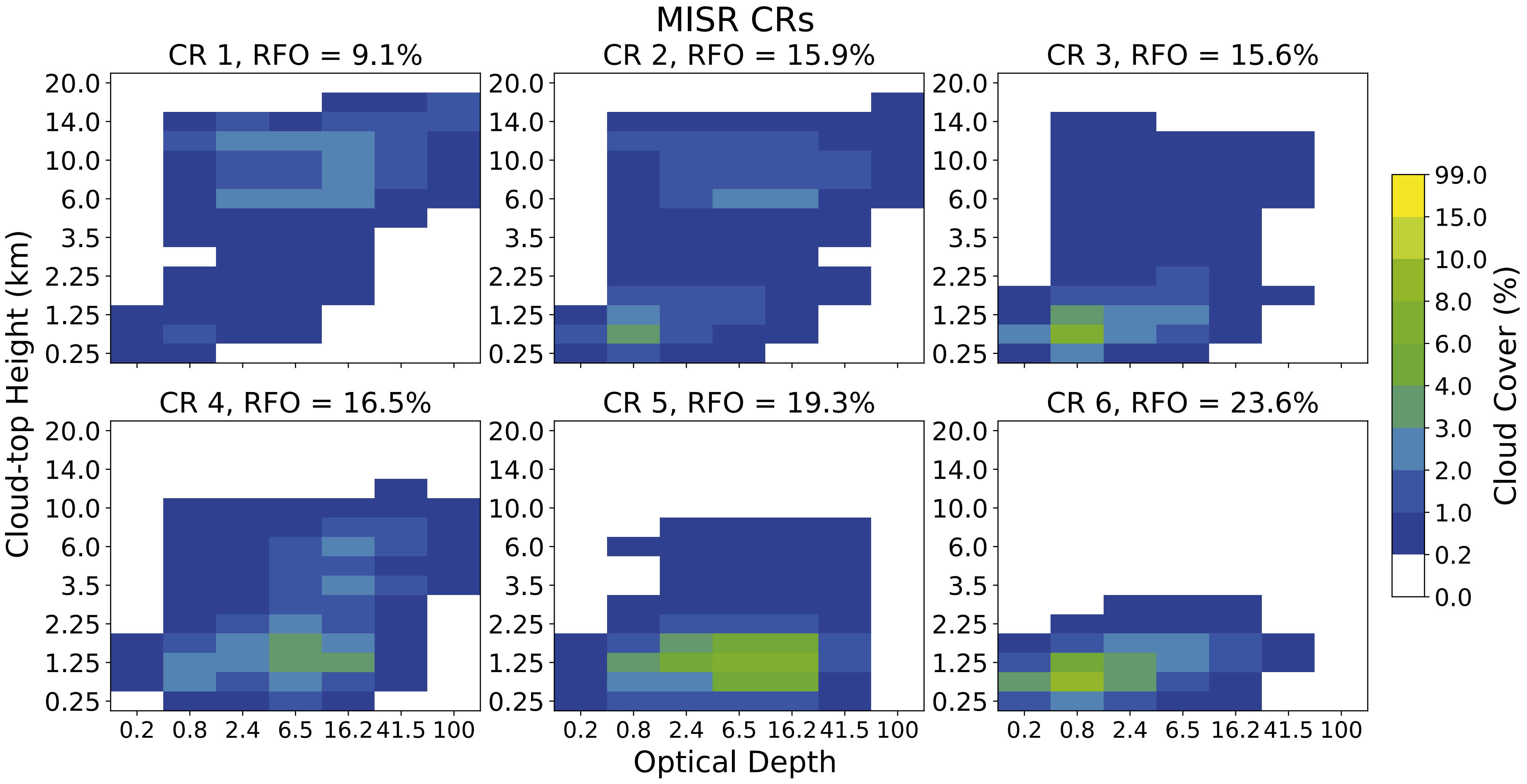
Cloud regimes using k-means clustering

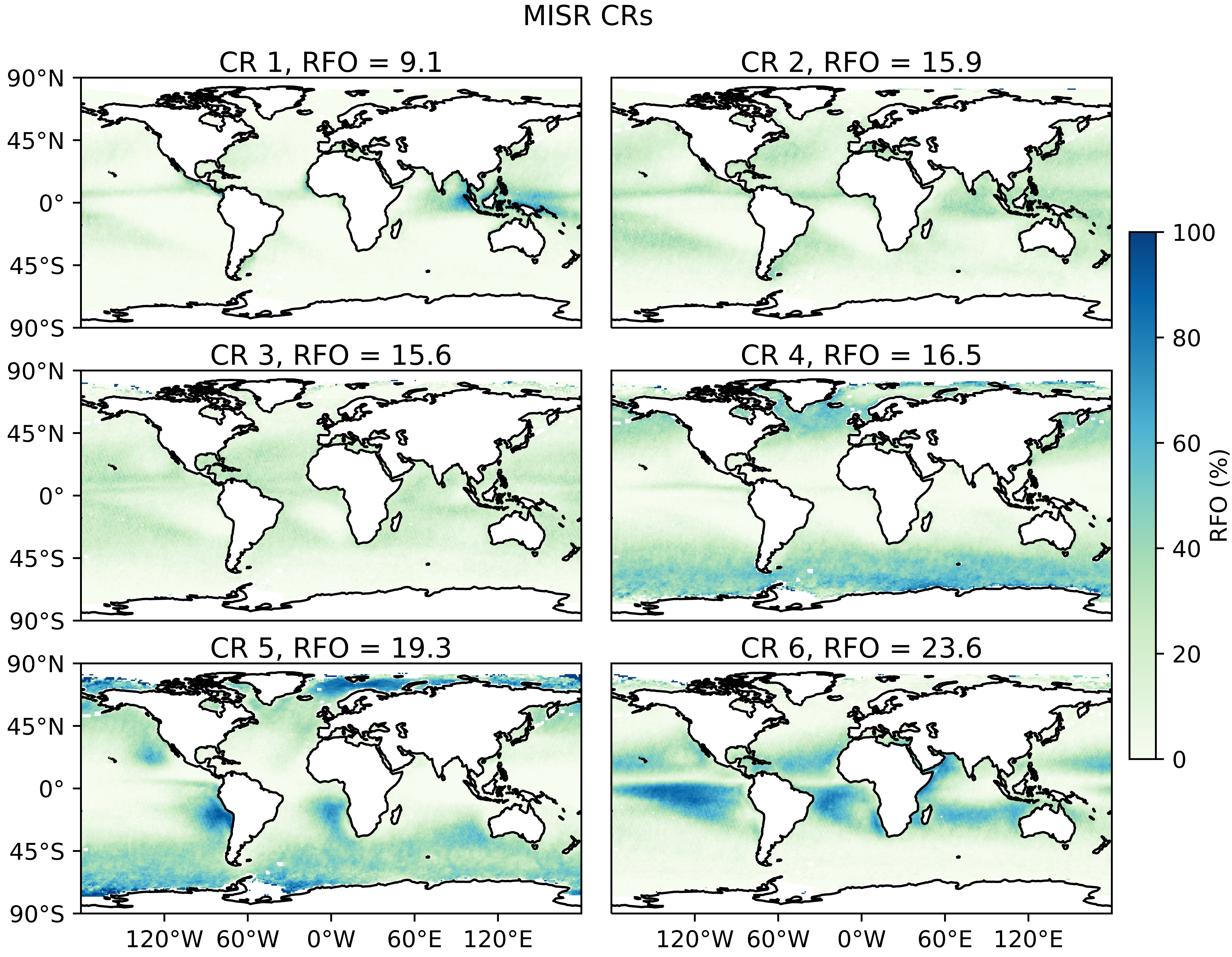




Davis & Medeiros 2024

Cloud regimes using k-means clustering



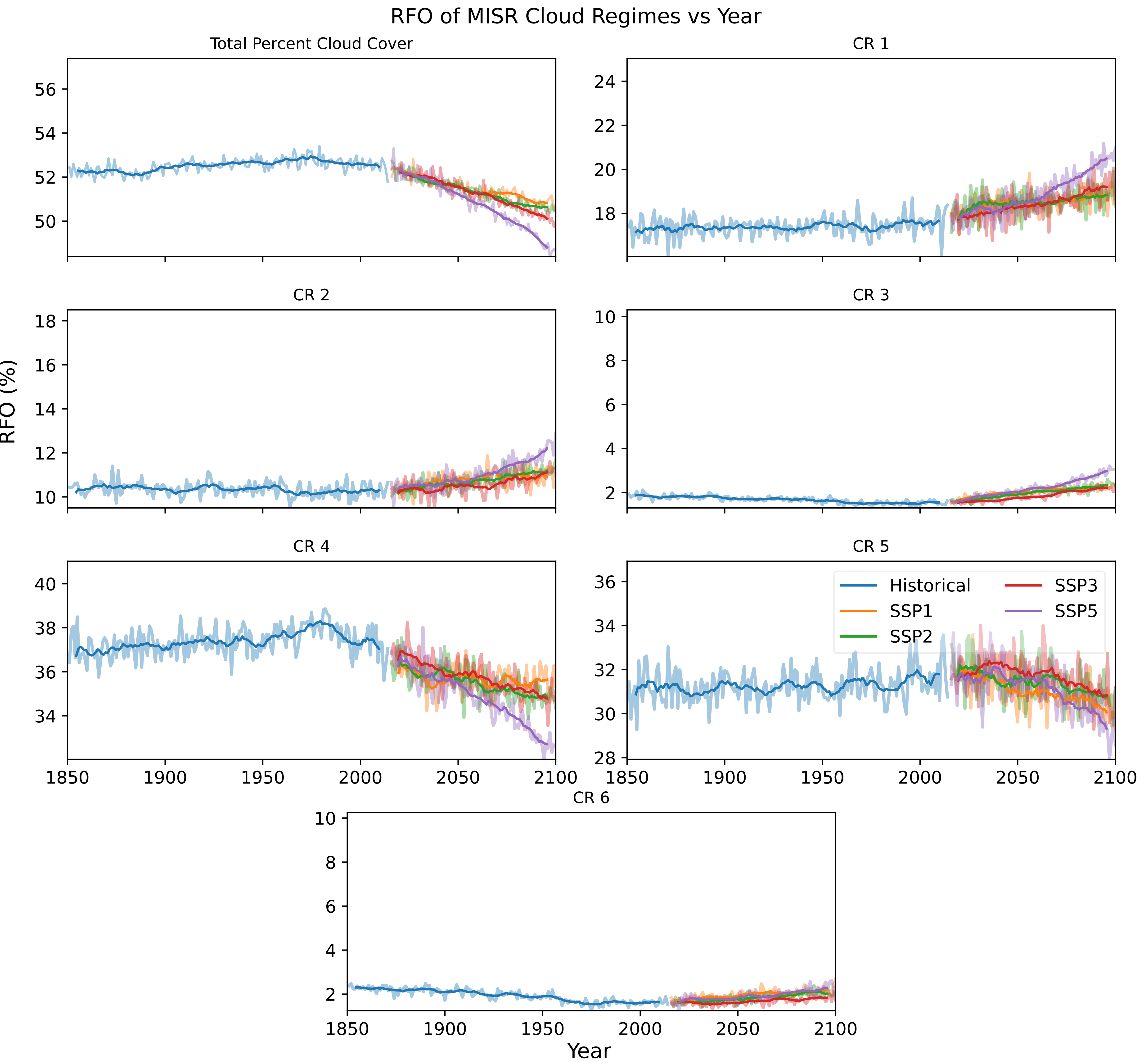


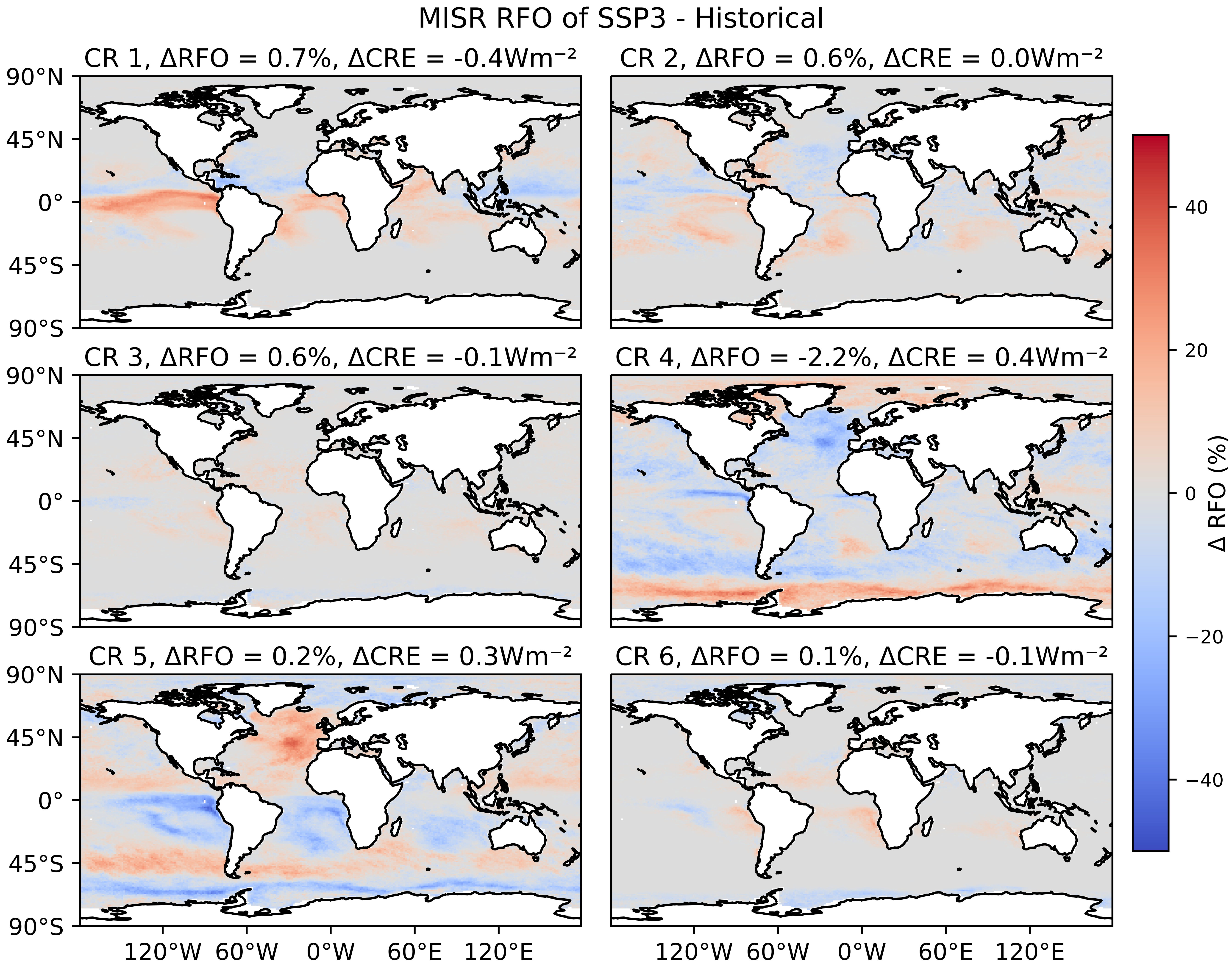
Davis & Medeiros 2024

CESM clouds classified into observed cloud regimes

Davis & Medeiros 2024

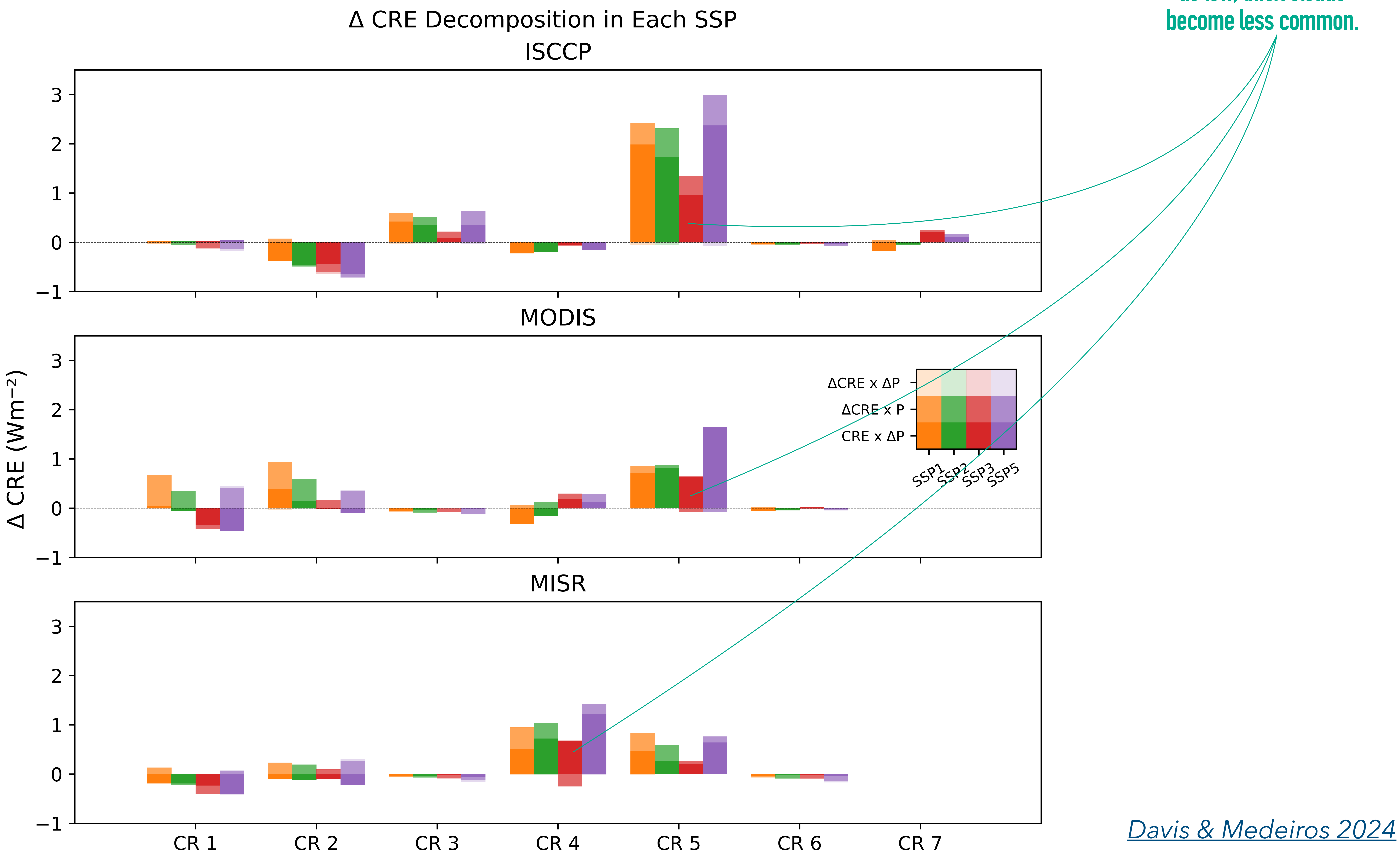
Cloud regime changes in climate projections





Davis & Medeiros 2024

Radiative consequences of cloud regime changes



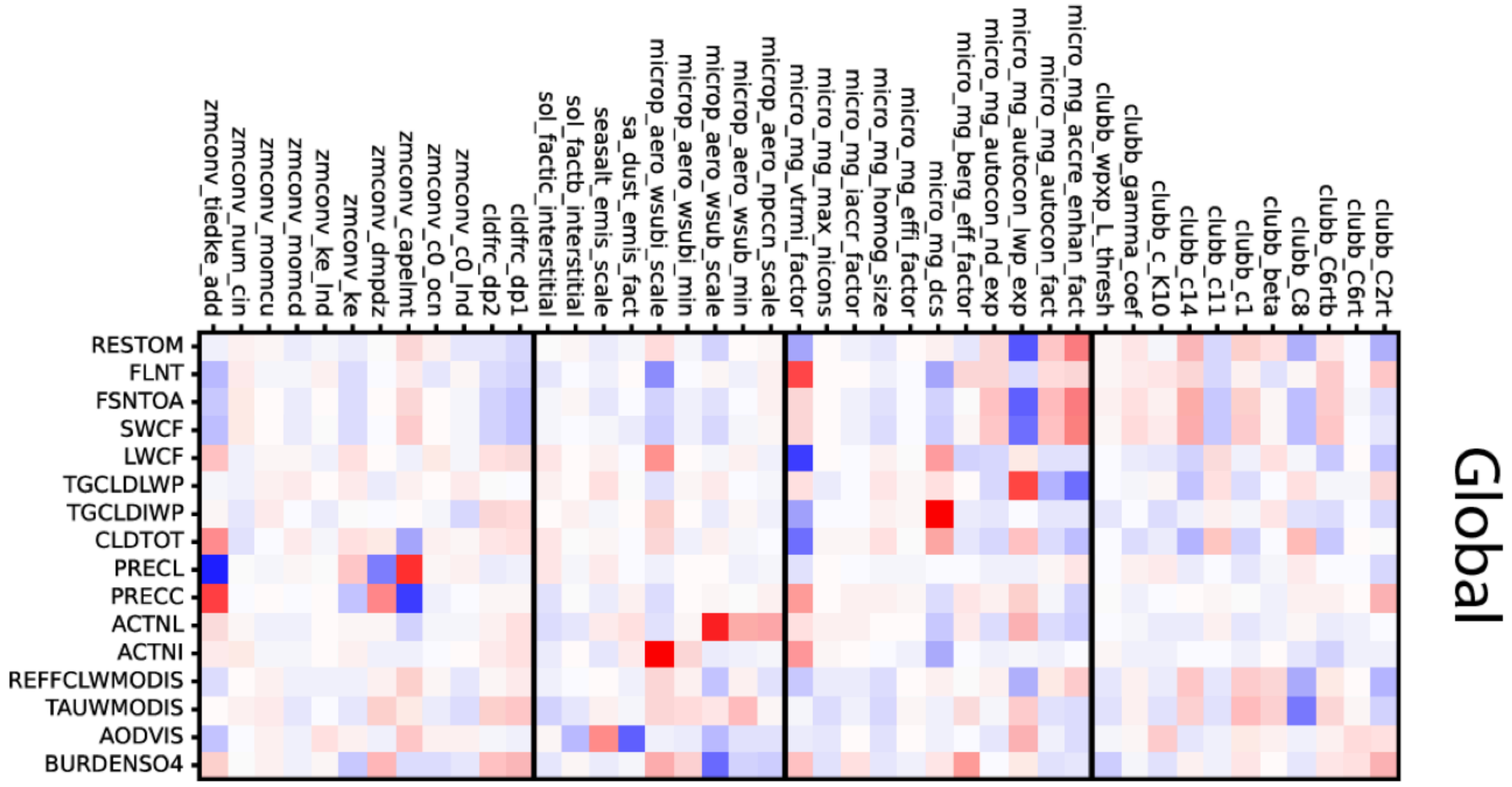
Davis & Medeiros 2024

How robust are the cloud feedbacks in CAM6?

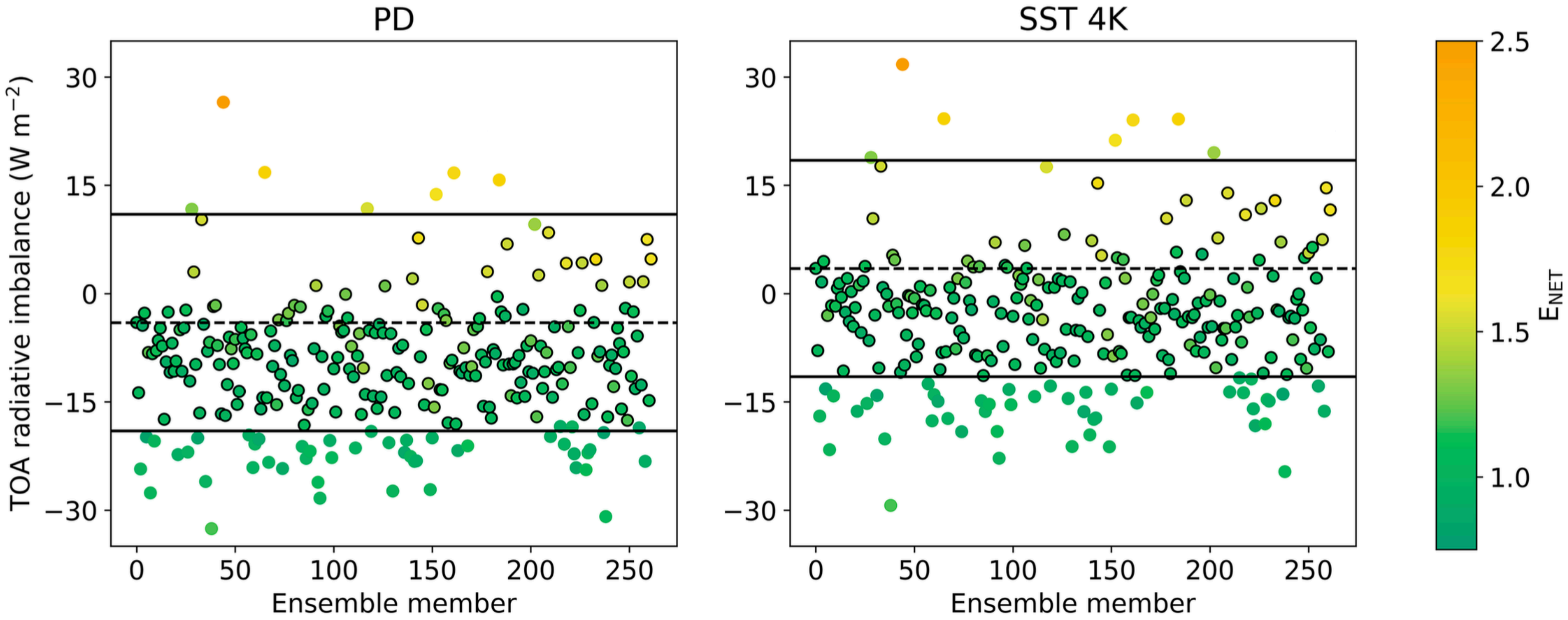
Is this strong cloud feedback intrinsic to the CAM6 physics?

CAM6 Perturbed Physics Ensemble (PPE)

45 parameters varied simultaneously within specified ranges



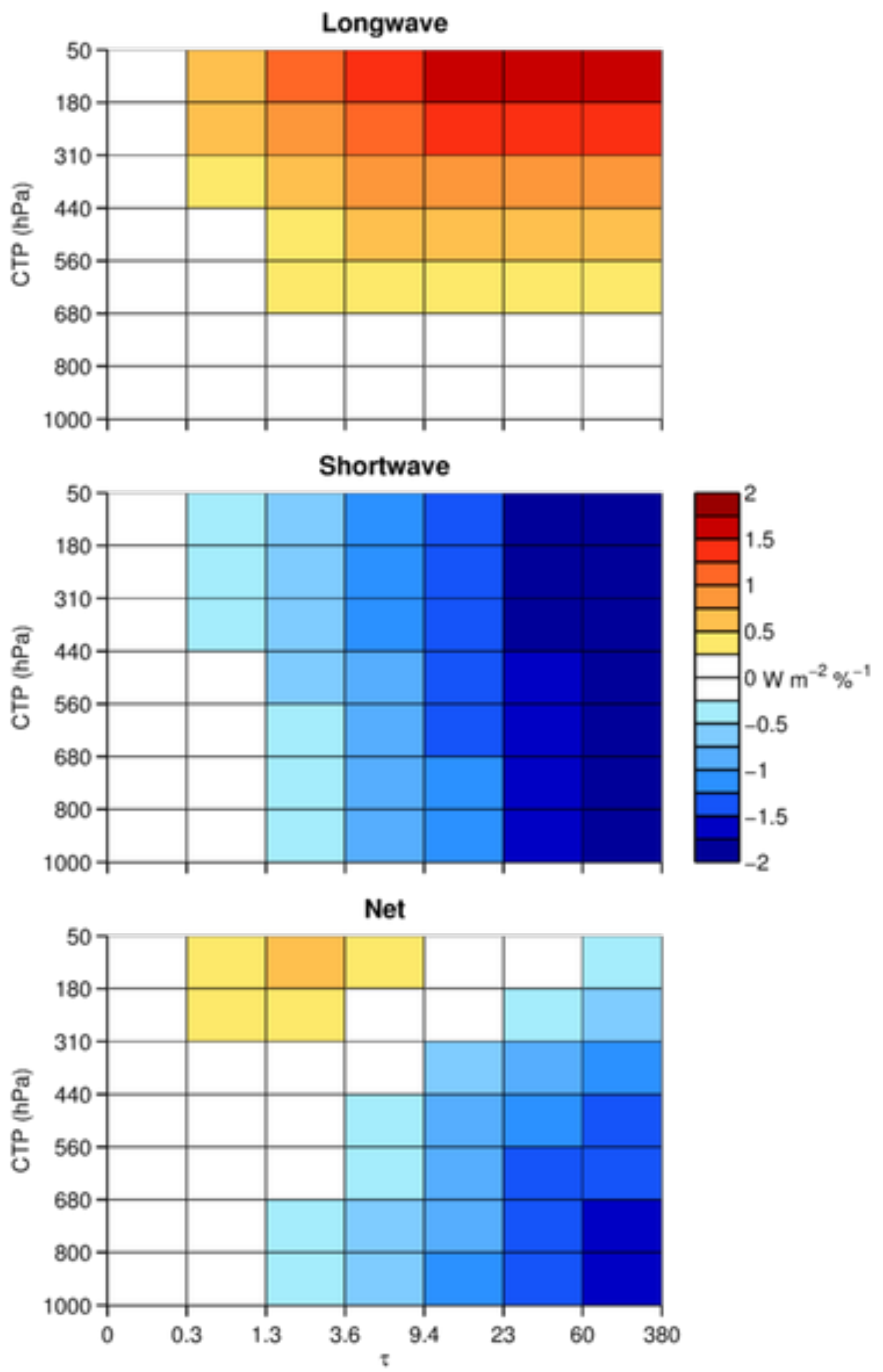
262 experiments: Present Day SST and uniform 4K SST warming



Documentation: [Eidhammer et al. 2024]
Data: [DASH page]

[Duffy et al. 2024]

Cloud feedbacks in the PPE



$$K = \frac{\partial R}{\partial C}$$

Cloud radiative kernel: sensitivity of radiative flux to cloud cover

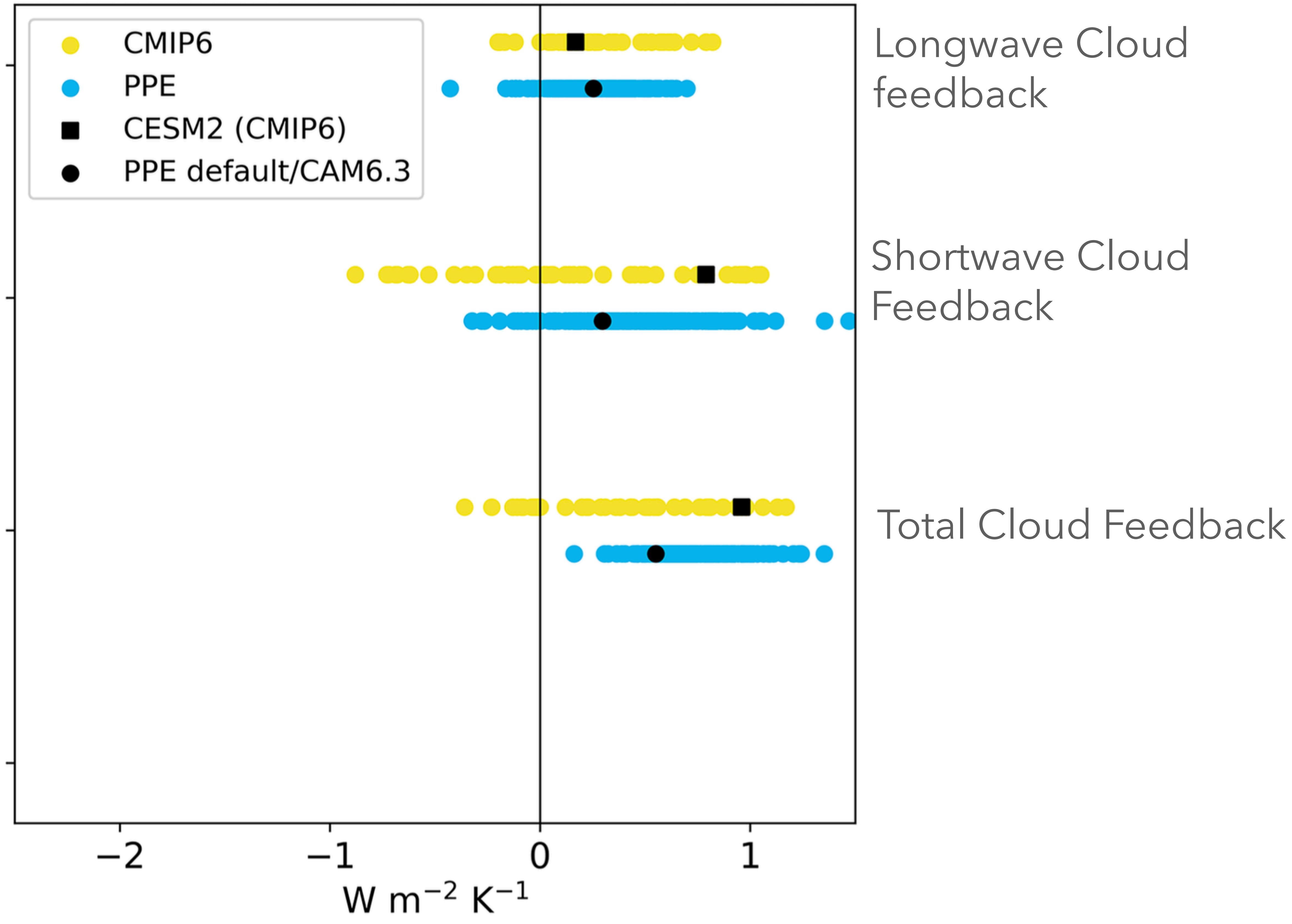
$$\Delta R = K \Delta C$$

Climate change in radiative flux is K multiplied by climate change in cloud cover

$$\lambda_{cld} = \frac{\Delta R}{\Delta T} = K\frac{\Delta C}{\Delta T} = \frac{\partial R}{\partial C}\frac{\Delta C}{\Delta T}$$

Cloud feedback is K times climate change in cloud cover per change in surface temperature

Zelinka et al. 2012

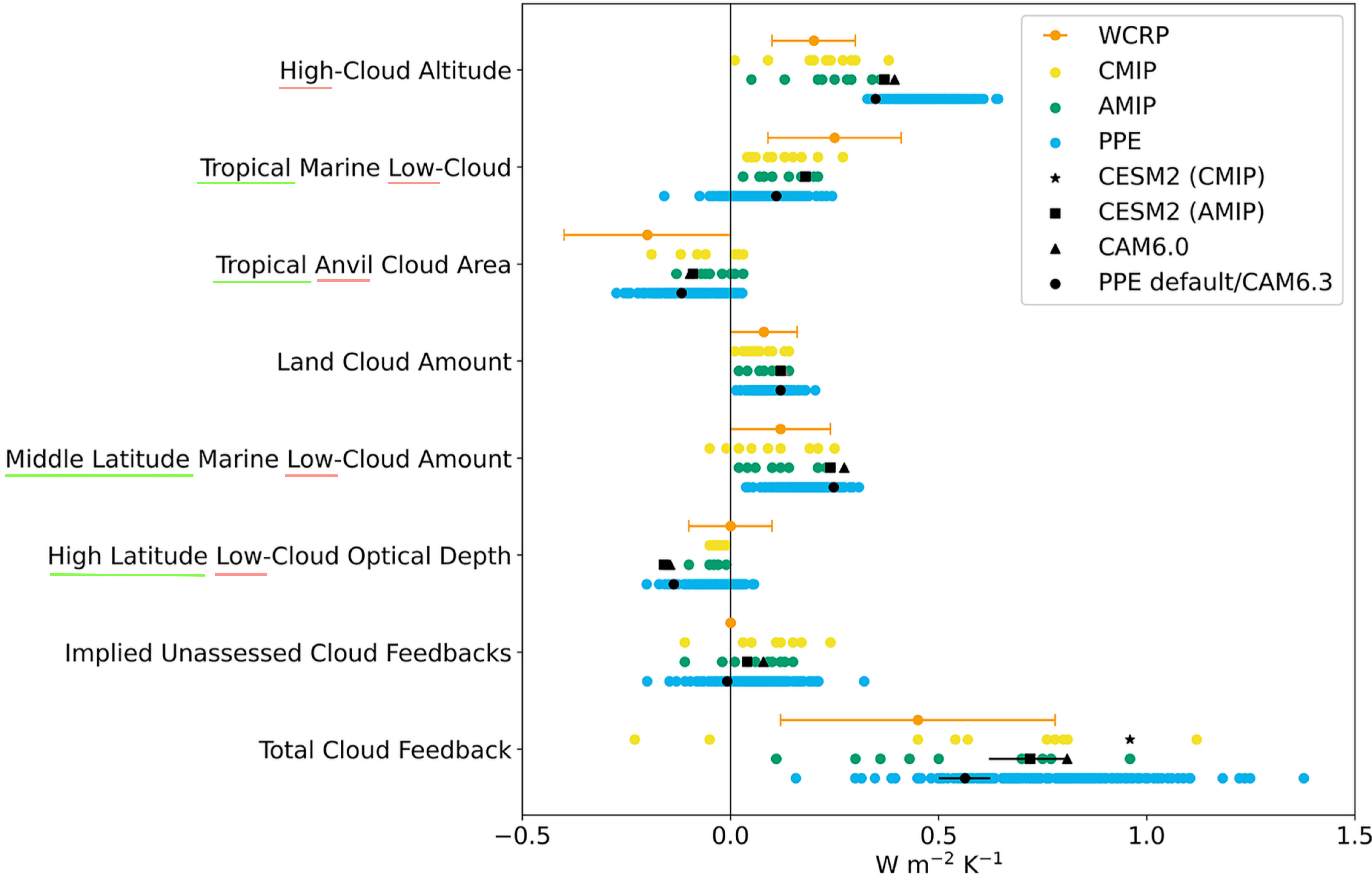


Duffy et al. 2024

Cloud feedbacks in the PPE

These feedbacks were defined in the WCRP climate sensitivity assessment (Sherwood et al. 2020).

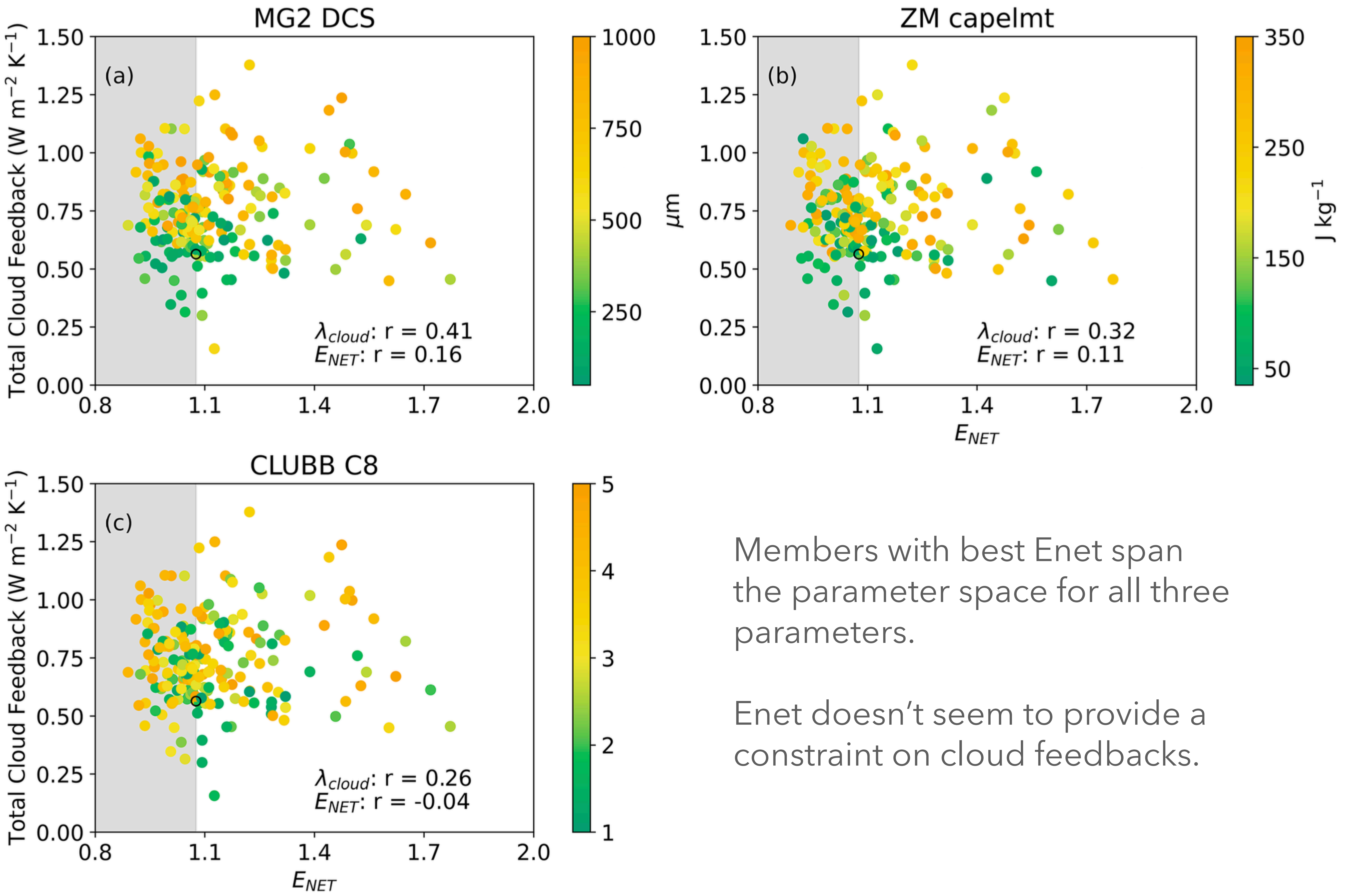
They are quantified by summing over specified parts of the ISCCP histogram and/or specified geographic regions.



Duffy et al. 2024

Most relevant parameters for cloud feedbacks

Apply LASSO regression to assess the contribution of each parameter to the cloud feedback components.
Three stand out, one each from microphysics (MG2), deep convection (ZM), and shallow convection / turbulence (CLUBB).



Members with best Enet span the parameter space for all three parameters.

Enet doesn't seem to provide a constraint on cloud feedbacks.

Duffy et al. 2024

Conclusions

- Part 1
  - CESM2 / CAM6 forced with observed SST: better than CAM5 and CAM4,
  - but still shows significant cloud biases in both CRE and cloud cover.
  - Too little cloud in subtropical eastern oceans, underestimates SW CRE in those regions
  - Too much cloud in southern ocean, but modest CRE bias
  - EMD as diagnostic shows shallow cumulus regions are particularly difficult
- Part 2
  - Cloud regimes methodology improved using EMD
  - Cloud Regimes stresses errors in CTP-τ and indicates CAM6 does not distinguish low-cloud regimes well
  - Climate change experiments show transition to optically thinner cloud regimes, which carry much of the CRE response
- Part 3
  - Parametric uncertainty in CAM6 physics can almost match CMIP6 structural uncertainty
  - CAM6 cloud feedbacks generally fall within “expected” range
  - Mean state cloud error (Enet) does not provide a constraint on cloud feedback
- Matching present-day cloud properties is necessary, but insufficient for confident climate projections
- Constraining both CRE and cloud cover (and structure) could an avenue for progress.
  - Can they both be consistent with observations with current CAM parameterizations?