This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. IM Release: LLNL-PRES-822359

Constraints on Low Cloud Feedbacks from Observed Climate Variability

Tim Myers[1], Ryan Scott[2,3], Mark Zelinka[1], Steve Klein[1], Joel Norris[2], Peter Caldwell[1]

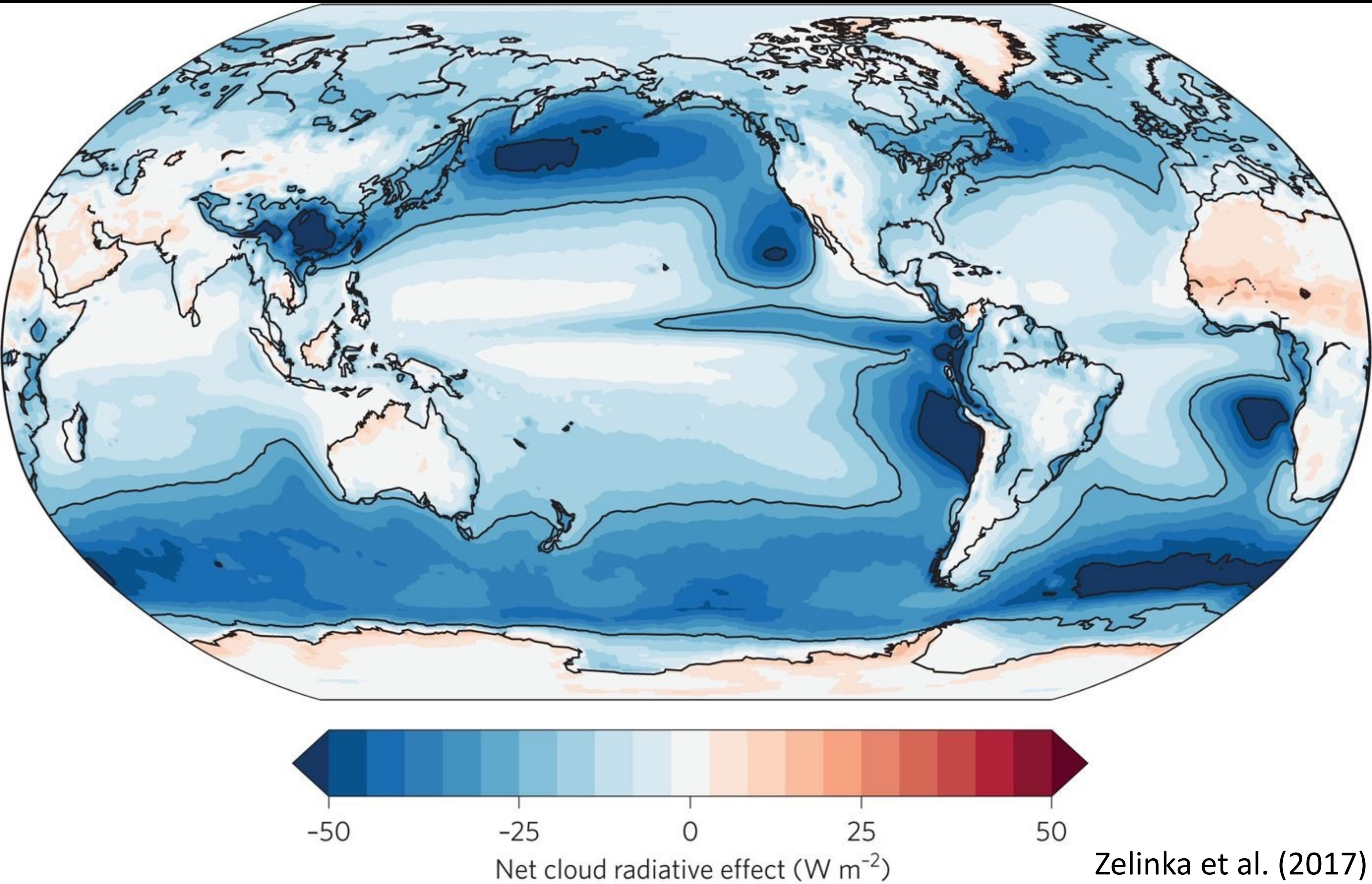
[1]Lawrence Livermore National Laboratory

[2]Scripps Institution of Oceanography

[3]Science Systems and Applications, Inc.

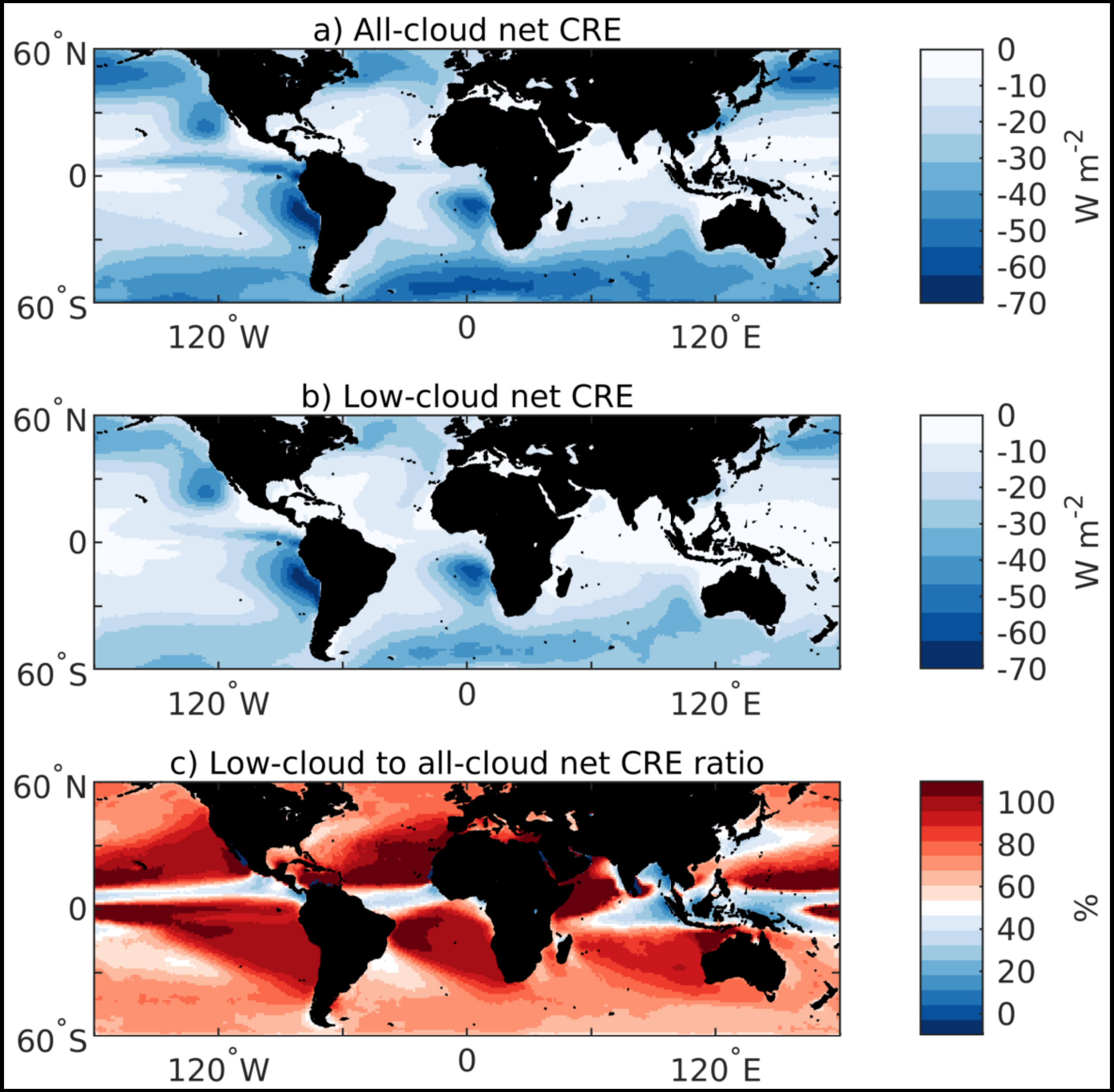
A view from the International Space Station (NASA)

Climatology of Net Cloud Radiative Effect from CERES-EBAF



Zelinka et al. (2017)

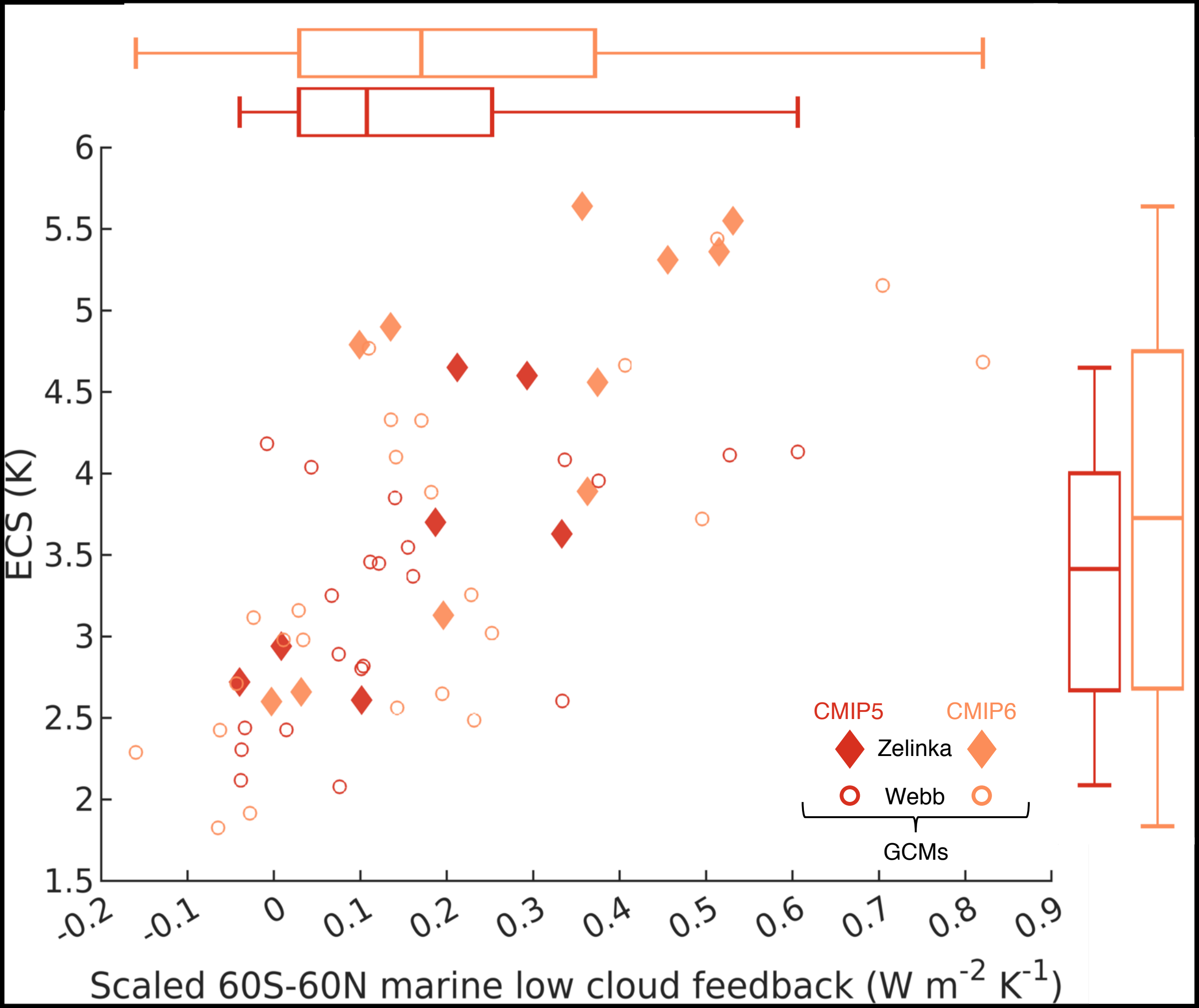
Low Clouds: Primary Contributor to net CRE over Global Oceans



CERES
Flux-by-Cloud-Type
Dataset

Myers et al.,
upcoming AGU Monograph

In CMIP6, spread of low cloud feedback and ECS has increased relative to CMIP5



Myers et al. (2021)

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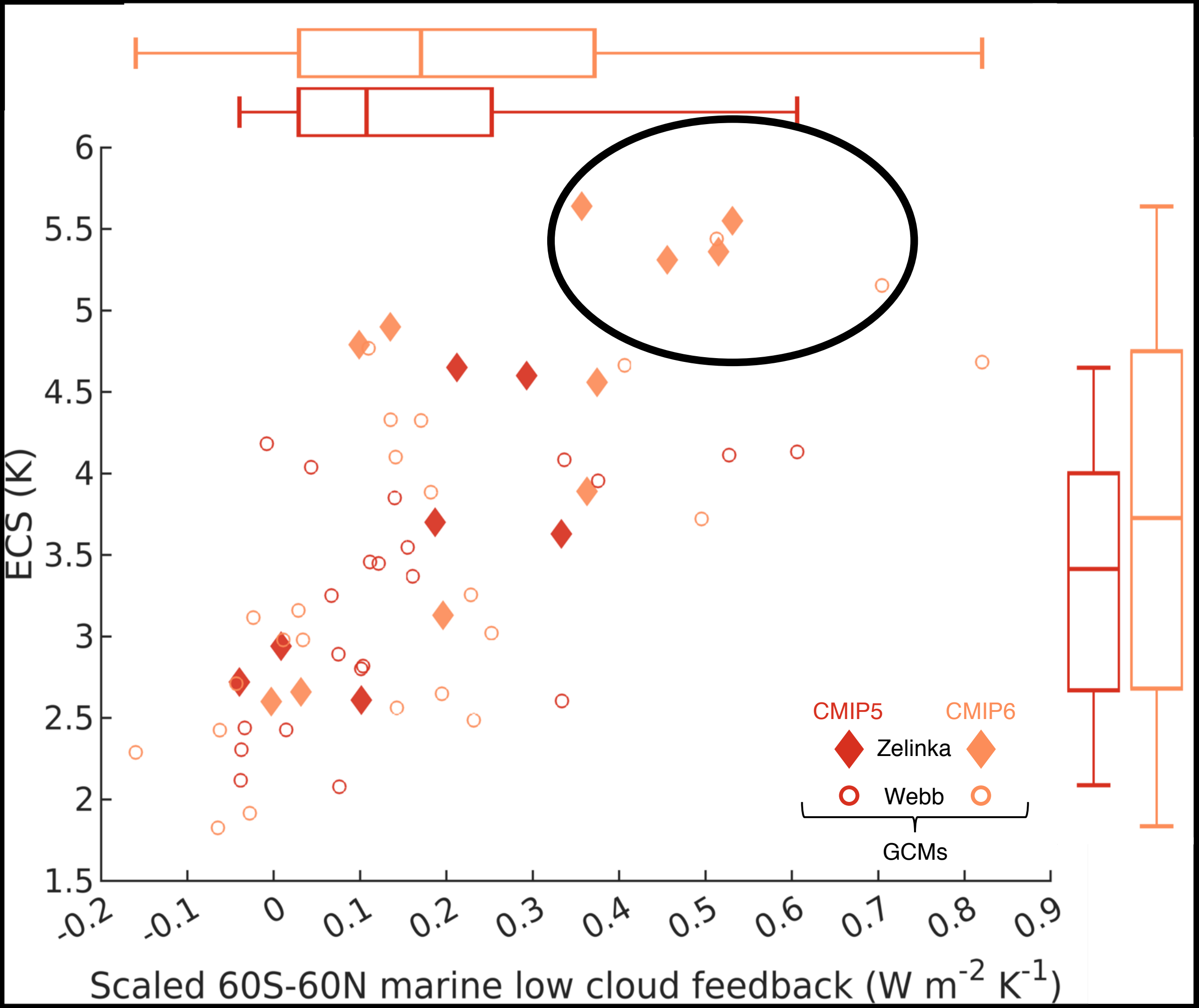
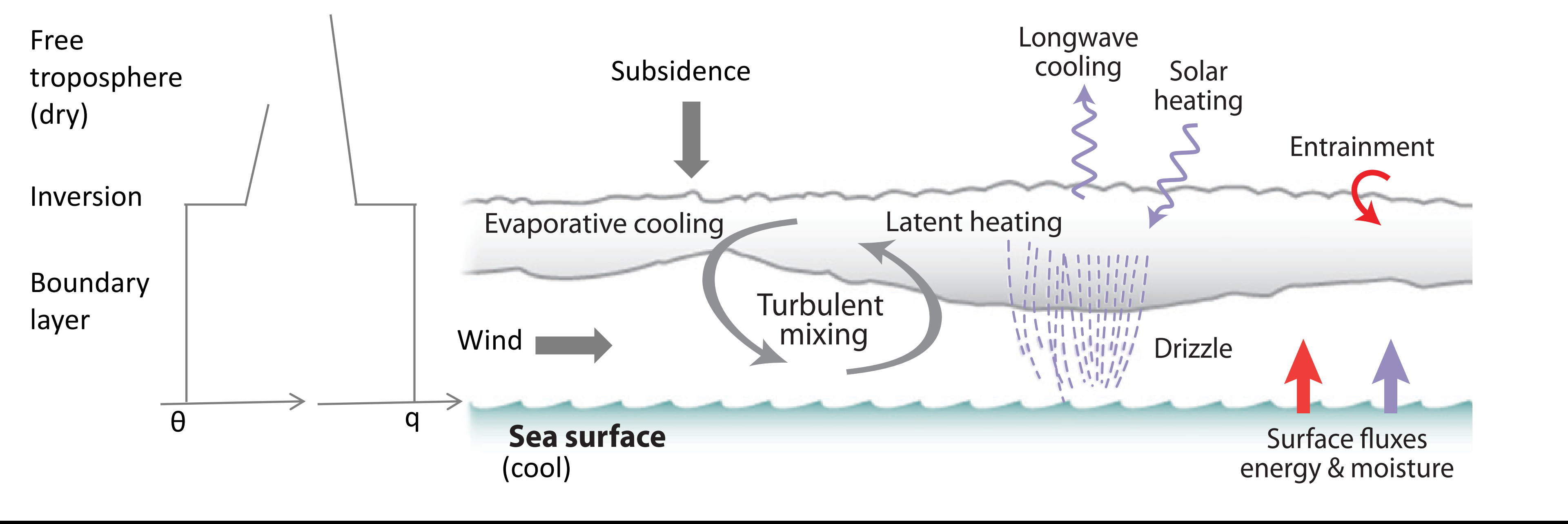


Myers et al. (2021)

Parameterization of unresolved boundary layer process likely explains model uncertainty



adapted from Wood 2012

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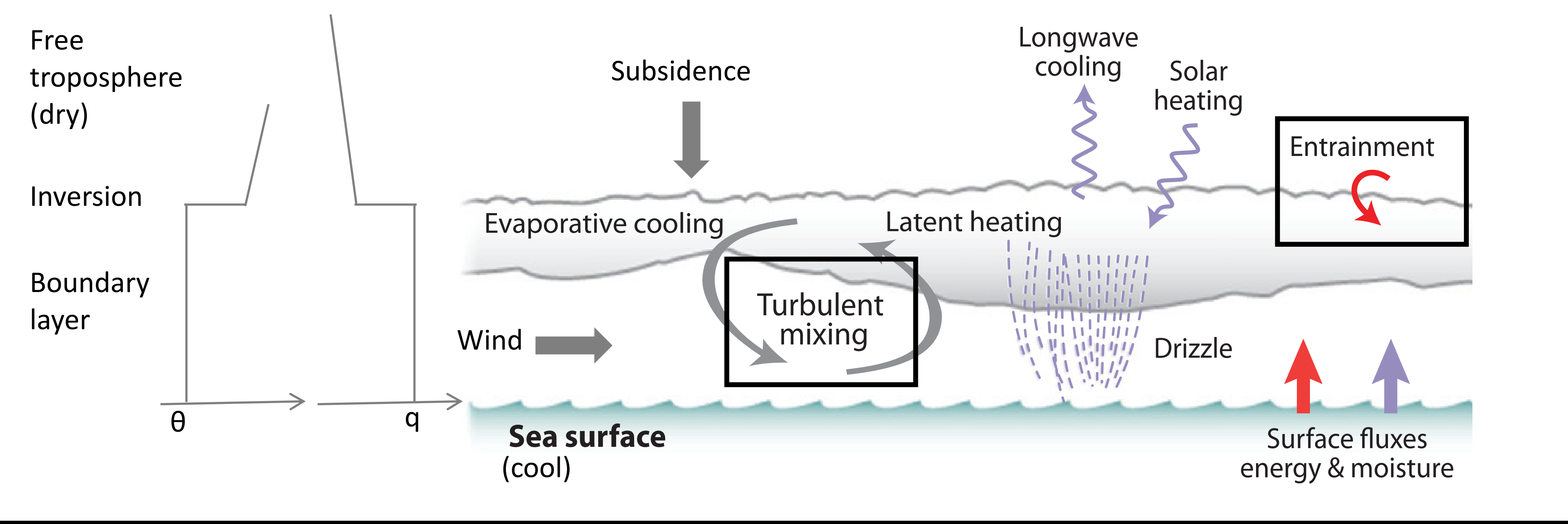
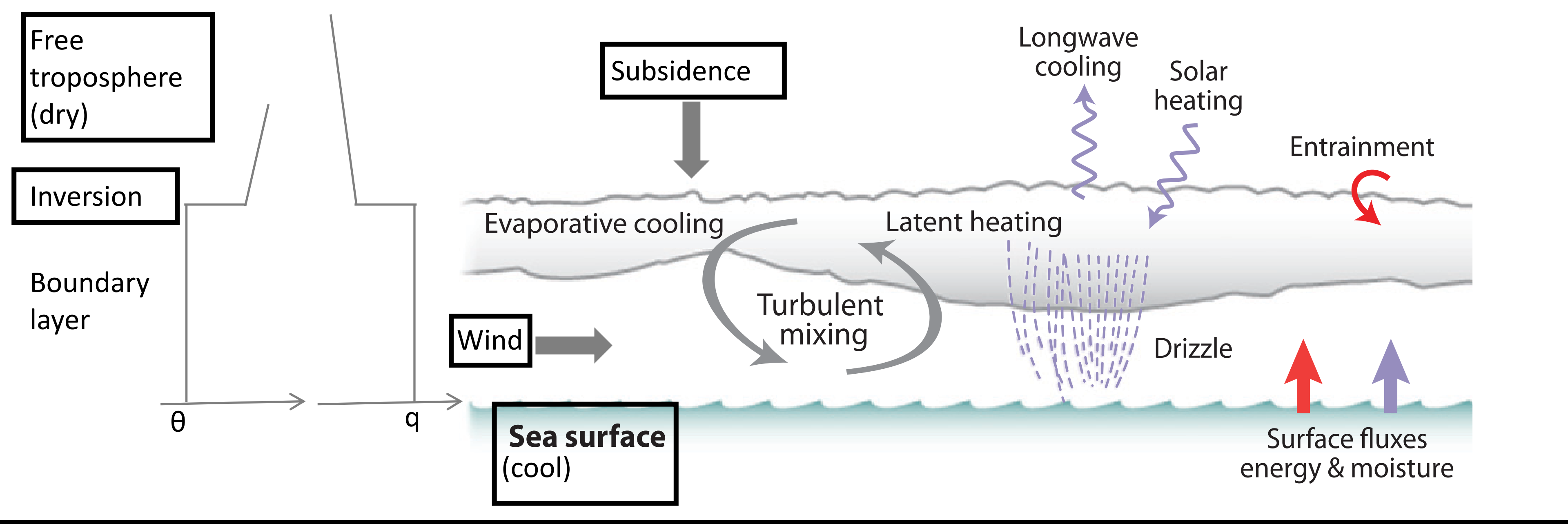


adapted from Wood 2012

External Cloud-Controlling Factors



adapted from Wood 2012

Framework to Observationally Constrain Low Cloud Feedbacks

Given

i. spatially-resolved sensitivity of low cloud radiative fluxes to meteorological cloud-controlling factors from observed climate variability

(meteorological cloud radiative kernels developed by Scott et al. (2020))

ii. how these factors will change in response to climate warming

(resolved by GCMs)

we can predict the marine low cloud feedback.

Not first to apply this framework*.

Our study is unique in its near-global scale and its constraints on the pattern of the low feedback.

*Qu et al. 2015; Zhai et al. 2015; Myers and Norris 2016; Brient and Schneider 2016; McCoy et al. 2017; Cesana and Del Genio 2021

Framework to Observationally Constrain Low Cloud Feedbacks

We decompose the low cloud feedback at each 5° x 5° ocean grid box between 60°S and 60°N as

$$\boxed{\lambda_{cloud} = \frac{dR}{dT} = \sum \frac{\partial R}{\partial x_i}\frac{dx_i}{dT}}$$

R low cloud radiative flux

x_i one of six cloud-controlling factors

T global mean surface temperature

Framework to Observationally Constrain Low Cloud Feedbacks

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T global mean surface temperature

$\frac{\partial R}{\partial x_i}$ **observation-based** sensitivity of low cloud radiative flux to a perturbation in some cloud-controlling factor *(meteorological cloud radiative kernels from Scott et al. (2020))*

$\frac{dx_i}{dT}$ change in cloud-controlling factor per degree global mean warming, **predicted by 18 CMIP5 and CMIP6 models in abrupt4xCO2 simulations**

Framework to Observationally Constrain Low Cloud Feedbacks

Complete set of cloud-controlling factors x_i includes (from reanalysis)

- sea-surface temperature (SST)
- estimated inversion strength (EIS)
- horizontal surface temp. advection
- free-tropospheric relative humidity
- free-tropospheric subsidence
- near-surface wind speed

Using Satellite Cloud Observations to Constrain the Feedback

How do we estimate low cloud radiative anomalies R' globally?

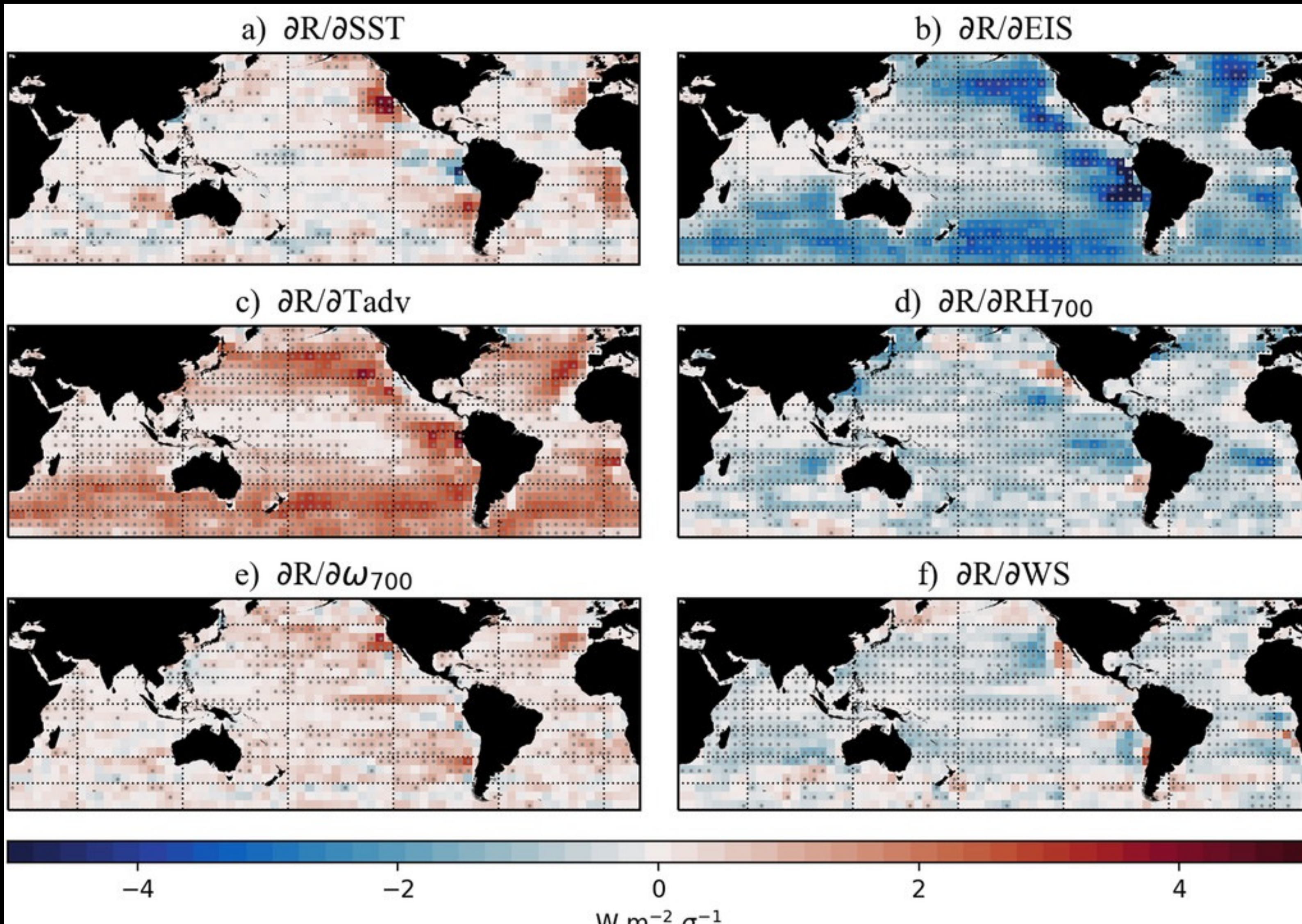
We apply Zelinka cloud radiative kernels $k = k(\tau, p)$ to satellite-retrieved low-level (>680 hPa) cloud fraction $L = L(\tau, p)$ normalized by the fraction F of the grid box unobscured by higher-level clouds:

$$R' = \bar{F} \sum_{p=1}^{2} \sum_{\tau=1}^{T} k(L/F)'$$

Cloud fraction histograms from **MODIS (TERRA+AQUA), ISCCP, PATMOS-x**

- These fluxes are exclusively due to changes in unobscured low-level clouds
- We apply a similar equation to the **CERES Flux-by-Cloud-Type dataset**

Observational Meteorological Cloud Radiative Kernels



derived from July 2002 – December 2018 CERES-FBCT data

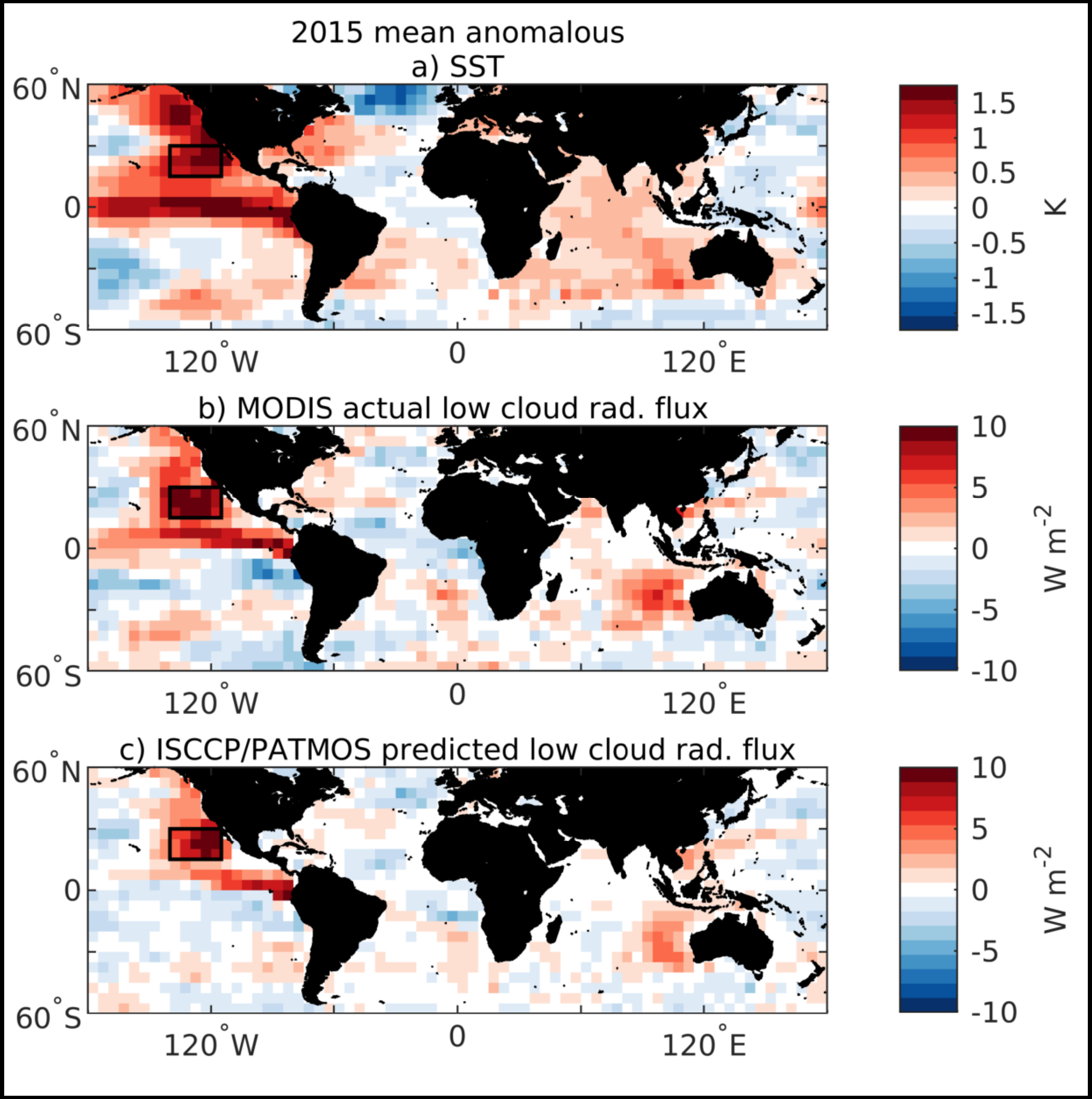
Scott et al. (2020)

Validation of the multi-linear approach

How well does the method predict out-of-sample extremes in the observational record?

Test Case: Northeast Pacific Marine Heatwave

Marine Heatwave Test Case

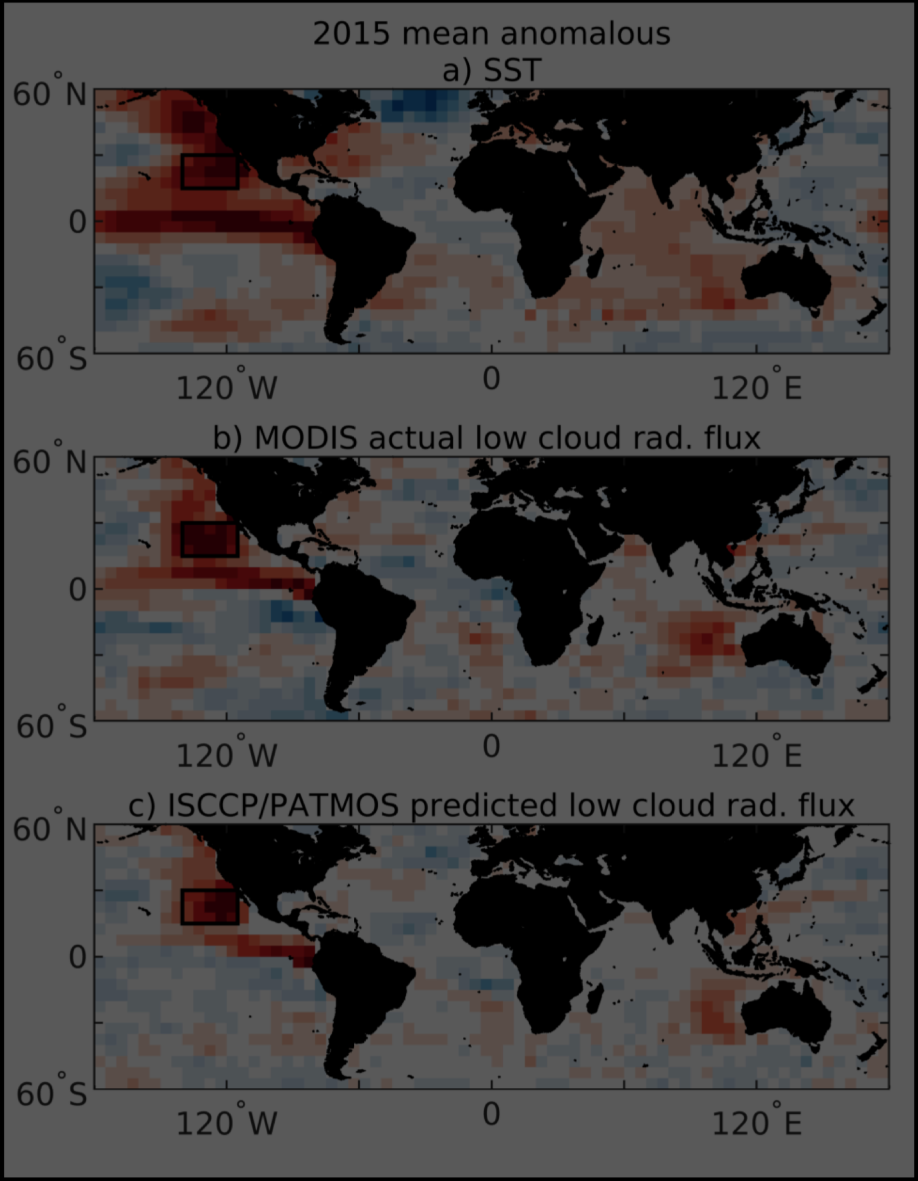


2015 observations

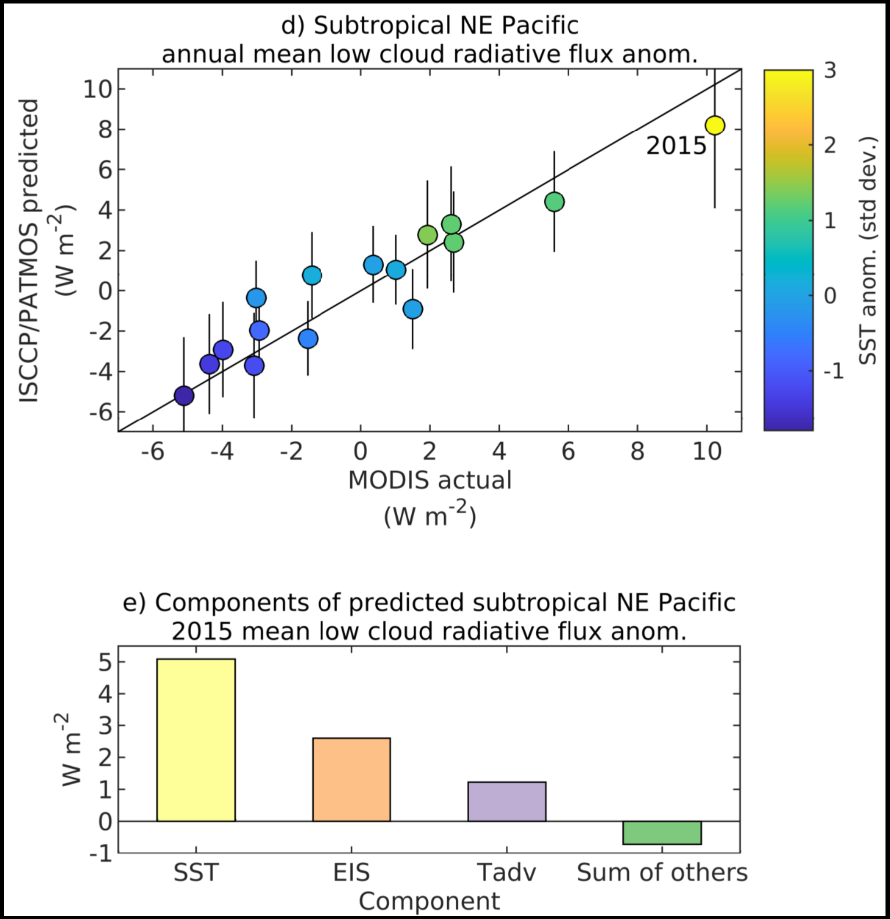
Out-of-sample prediction

based on 1983-2002-derived *meteorological kernels*

Marine Heatwave Test Case



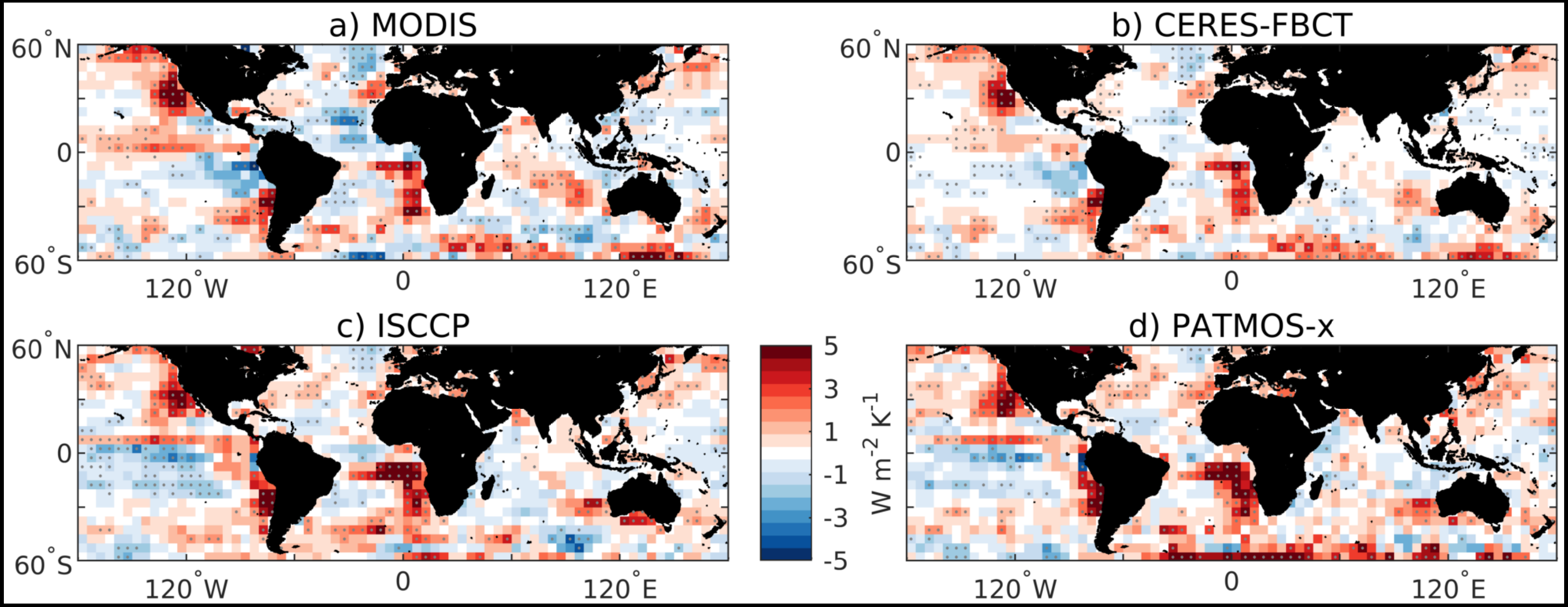
The linear method is valid for SST perturbations spanning ~2.4 K



Increasing SST was the primary driver of the low cloud reduction

Results: Feedback Constrained by Satellite Cloud Observations

$$\lambda_{cloud} = \frac{dR}{dT} = \sum \frac{\partial R}{\partial x_i}\frac{dx_i}{dT}$$

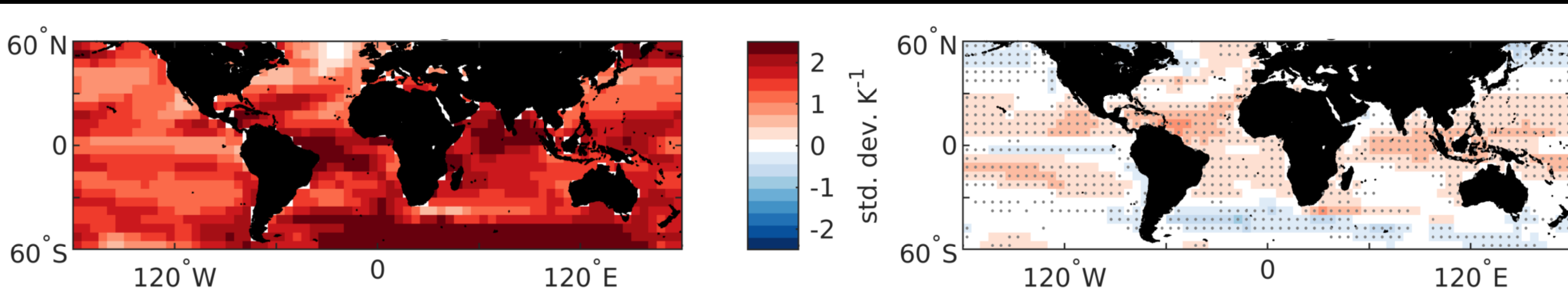


- Positive feedback in eastern ocean basins and middle latitude North Pacific
- Weaker feedback in trade cumulus regions

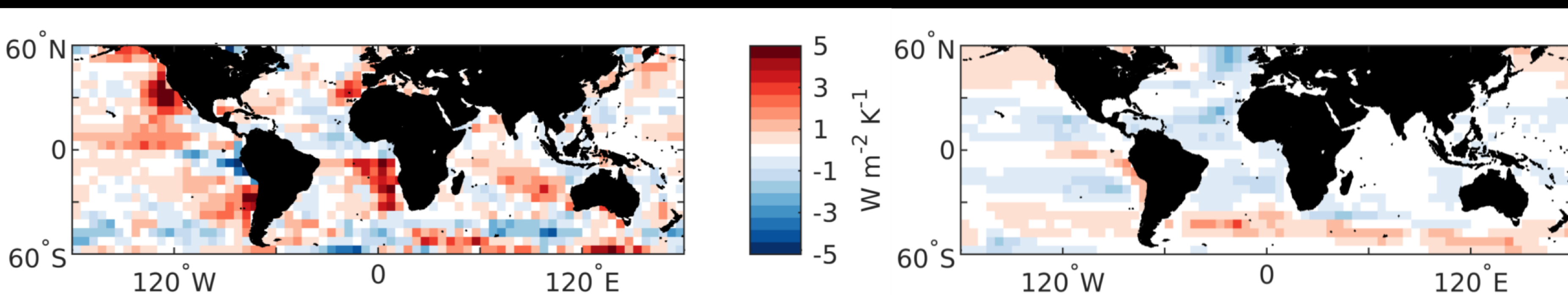
Which cloud-controlling factors drive this feedback?

Dominant Feedback Components: SST and Est. Inv. Strength

$\frac{dSST}{dT}$ Due to 4xCO2 $\frac{d\text{EIS}}{dT}$



$\frac{\partial R}{\partial \text{SST}} \frac{d\text{SST}}{dT}$ Feedback component $\frac{\partial R}{\partial \text{EIS}} \frac{d\text{EIS}}{dT}$



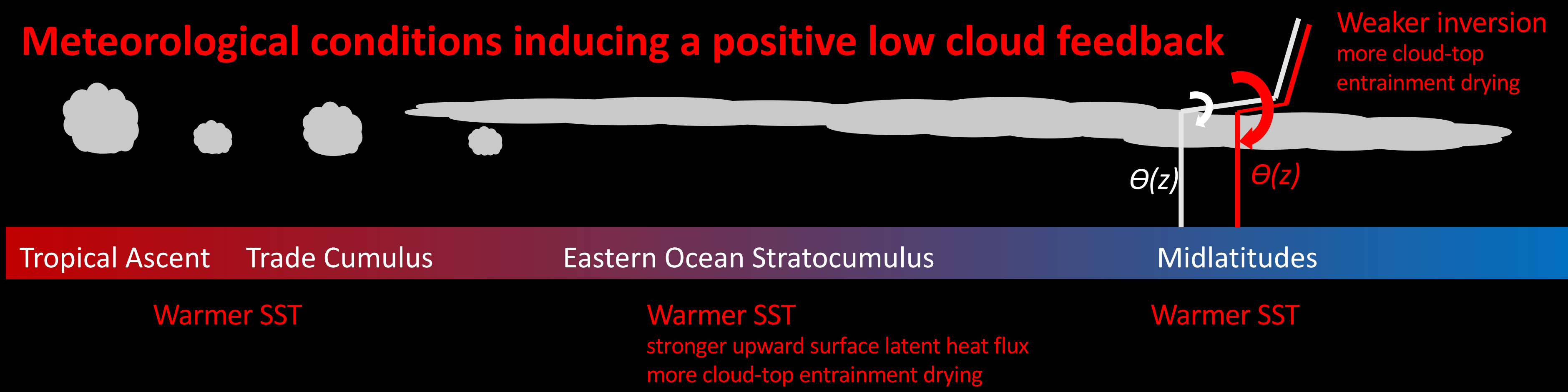
Strong positive SST-driven feedback in eastern ocean basins

Positive EIS-driven feedback in midlatitudes

Negative EIS-driven feedback in tropics

What physical mechanisms produce these feedback components?

Meteorological conditions inducing a positive low cloud feedback



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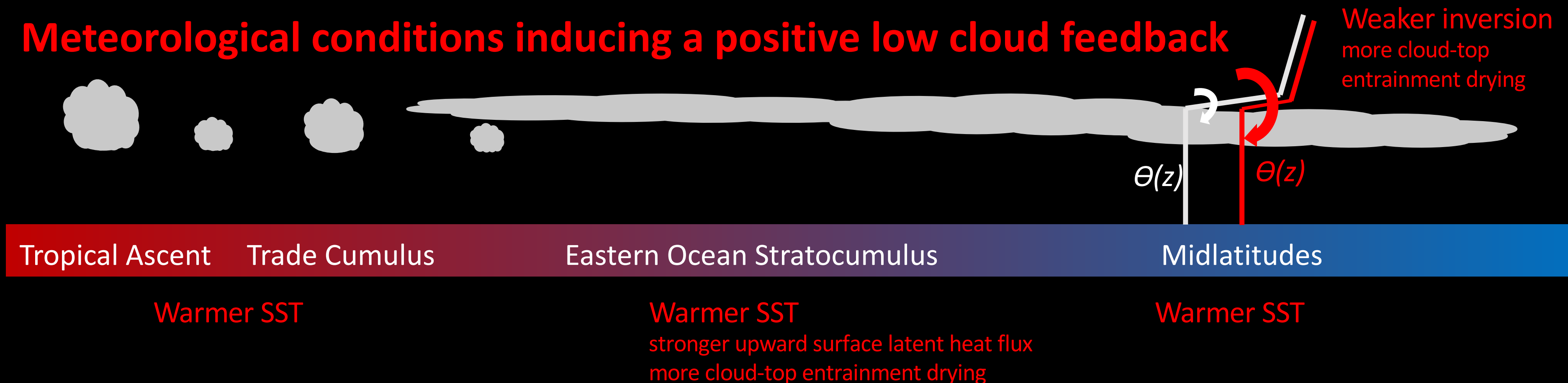
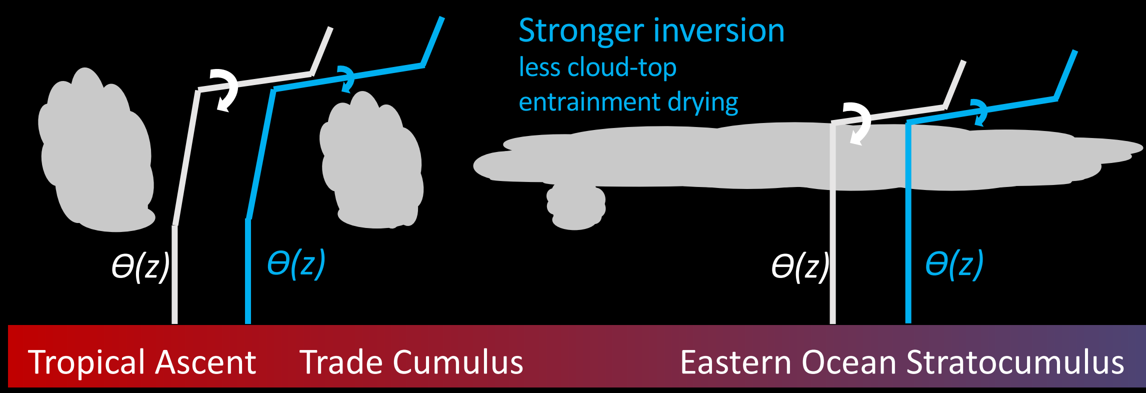
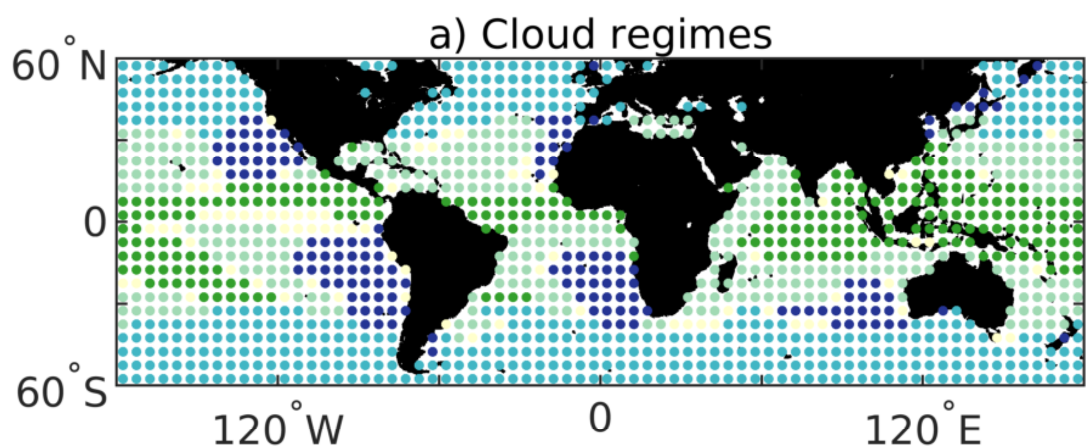


Meteorological conditions inducing a *small* negative low cloud feedback

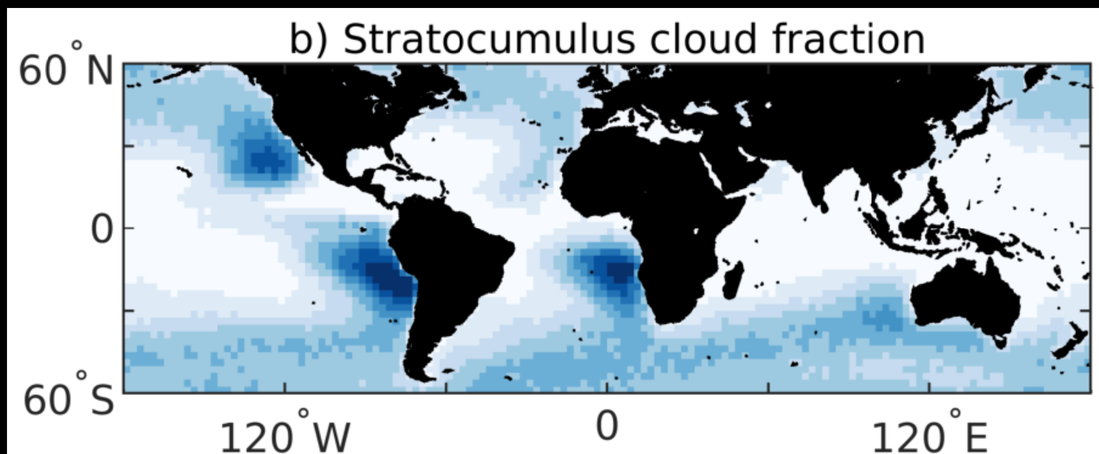


Regime-partitioned cloud feedbacks

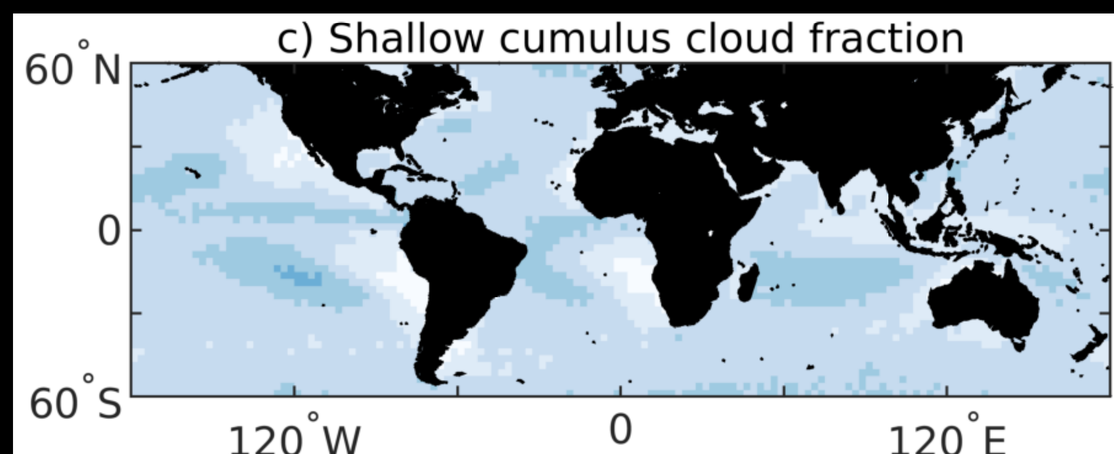
(defined using climatological EIS, ω_{700})



Stratocumulus
(strong subsidence, sharp inversion)
Trade cumulus
(weak subsidence, weak inversion)
Tropical ascent
Midlatitudes
(variable ω_{700}, sharp inversion)

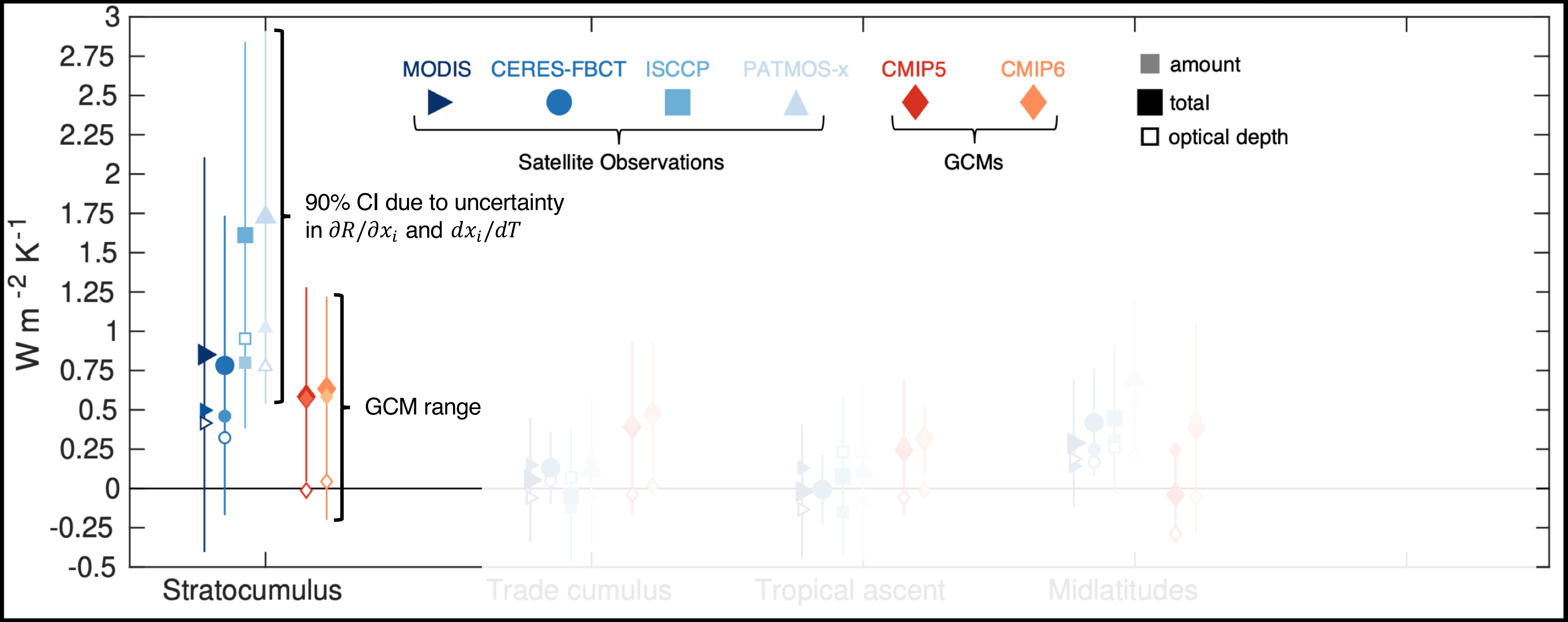


Cumulus And Stratocumulus CloudSat-CAlipso Dataset (CASCCAD; Cesana et al. 2019)

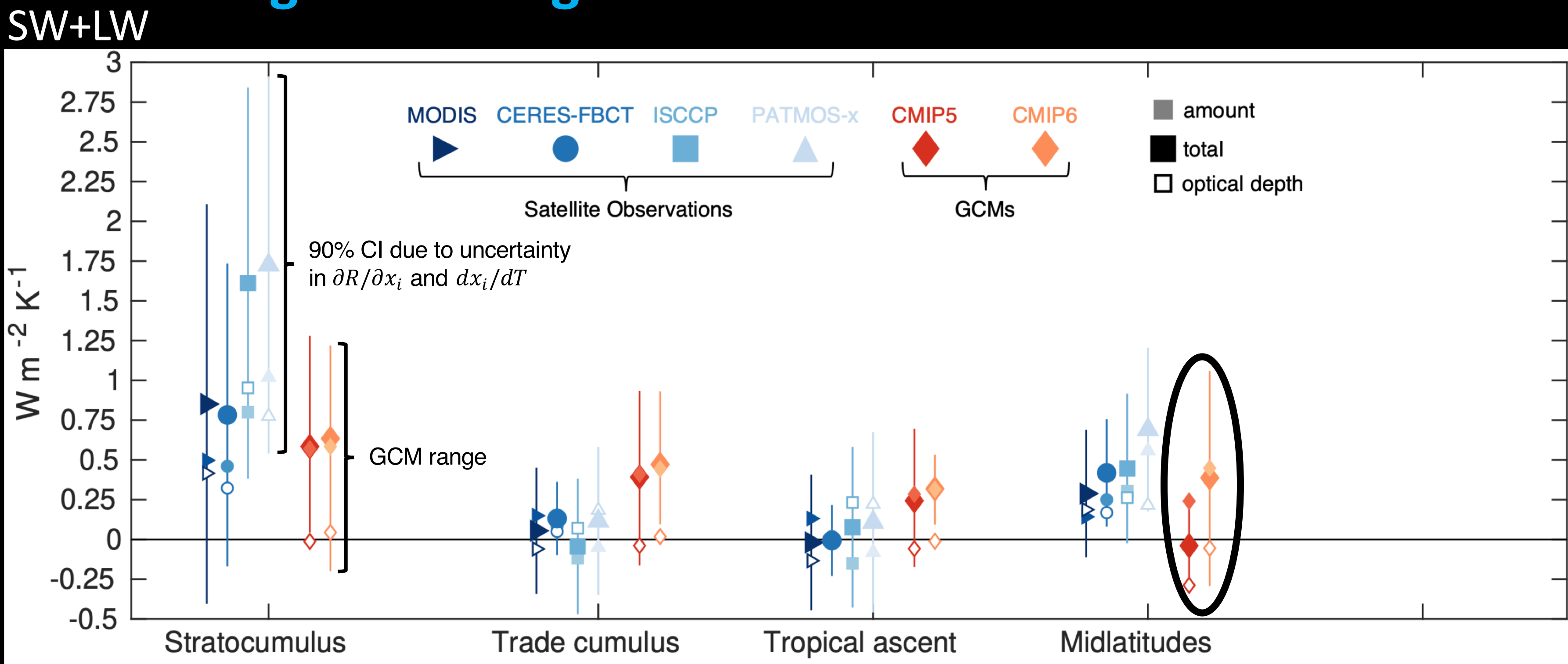


Regime-averaged Marine Low Cloud Feedbacks

SW+LW



Regime-averaged Marine Low Cloud Feedbacks



Obs: Positive stratocumulus & midlatitude cloud feedbacks (from amount *and* optical depth)

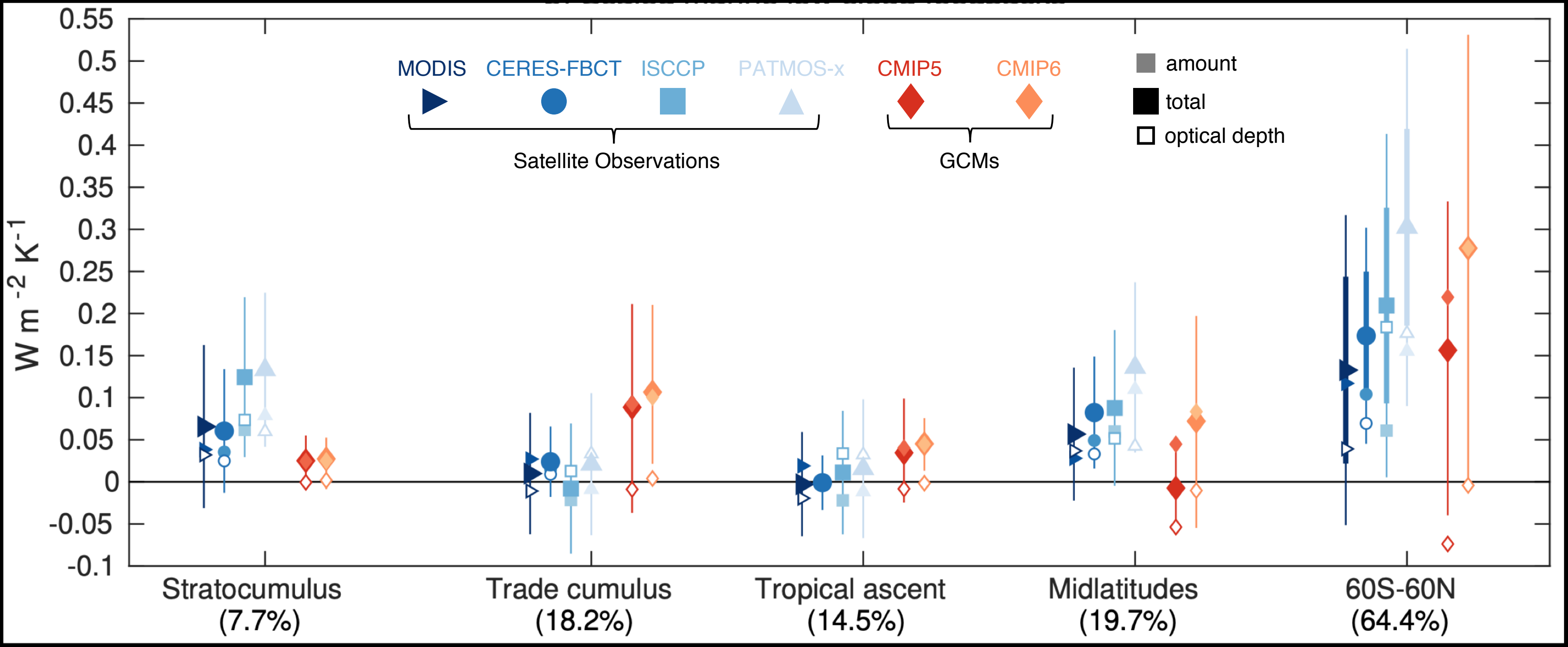
Obs: Near-zero trade cumulus feedback, consistent with large-eddy simulations*

CMIP6: more realistic midlatitude feedback

*e.g. Radtke et al. (2021)

Feedbacks Scaled by Fractional Planetary Area

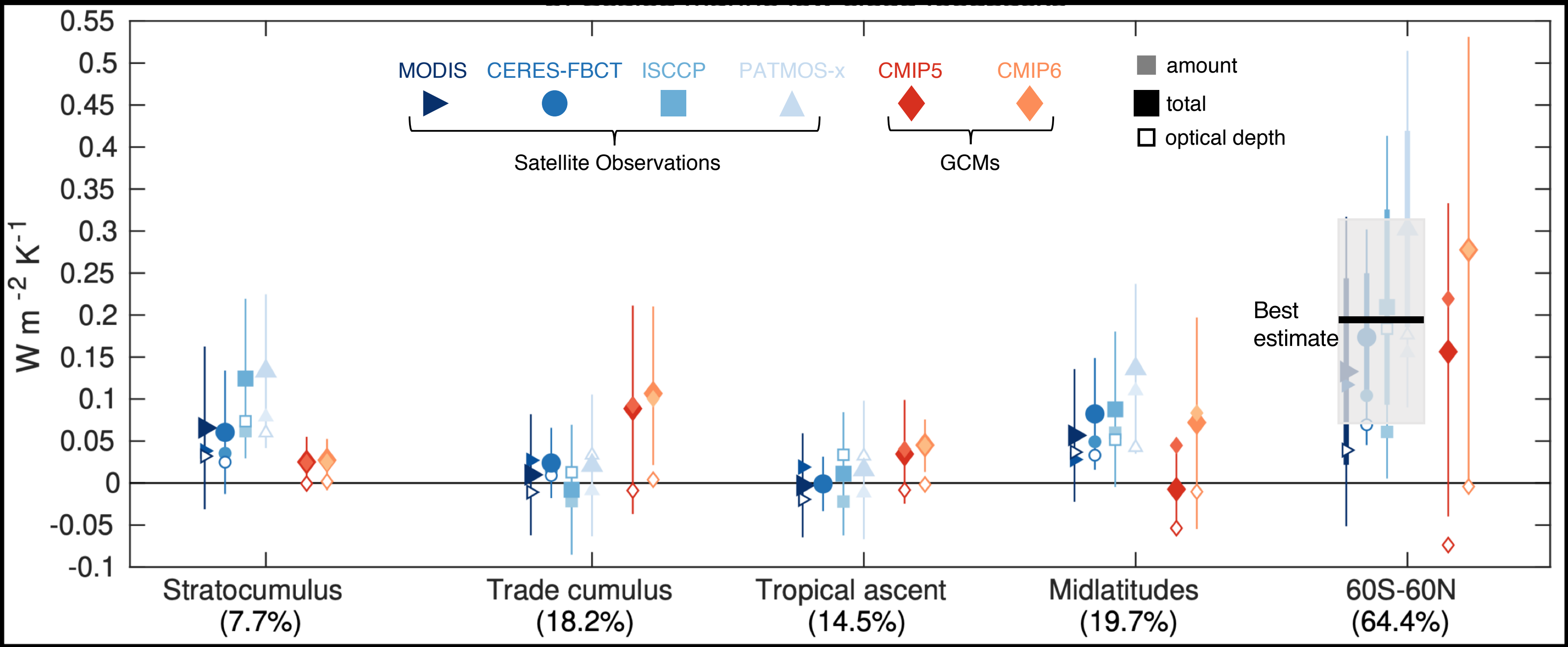
SW+LW



Obs: Positive 60S-60N feedback

Feedbacks Scaled by Fractional Planetary Area

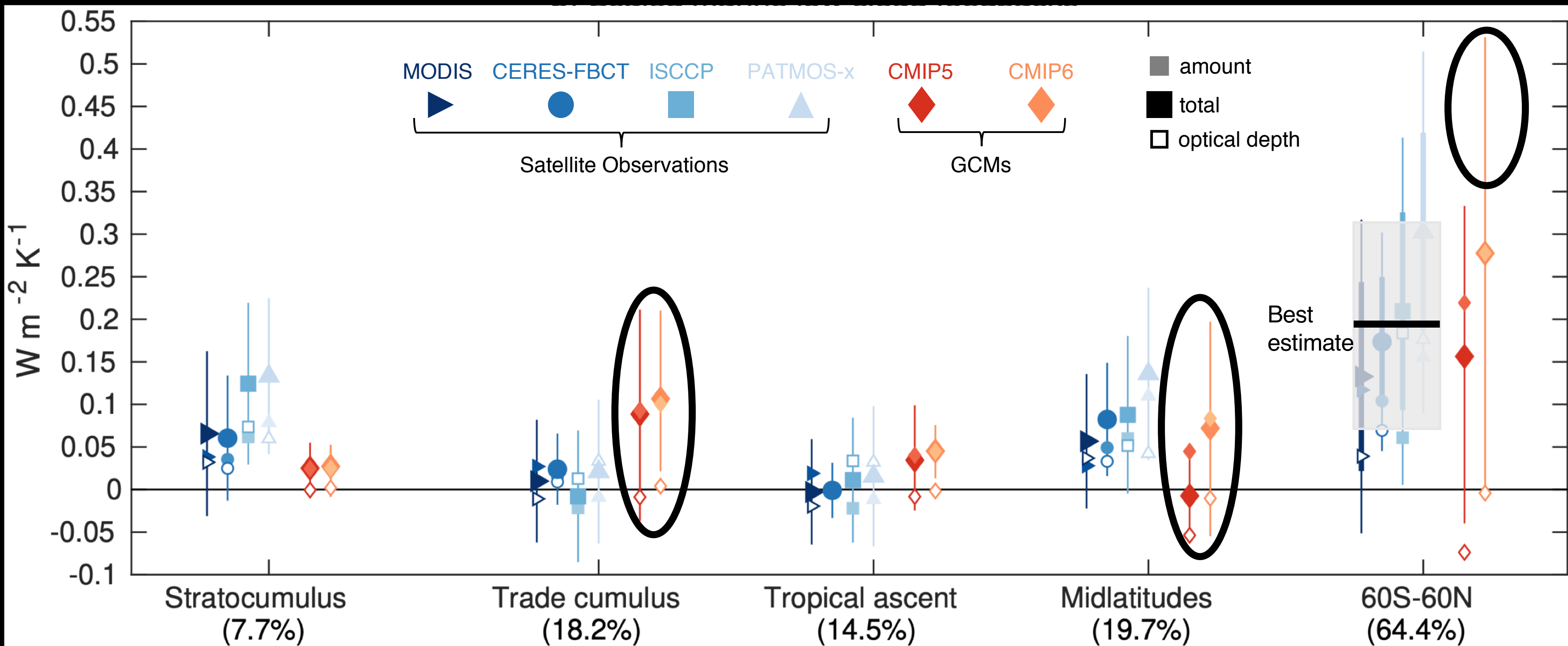
SW+LW



Obs: Positive 60S-60N feedback
0.19 ± 0.12 W m^{-2} K^{-1}

Feedbacks Scaled by Fractional Planetary Area

SW+LW

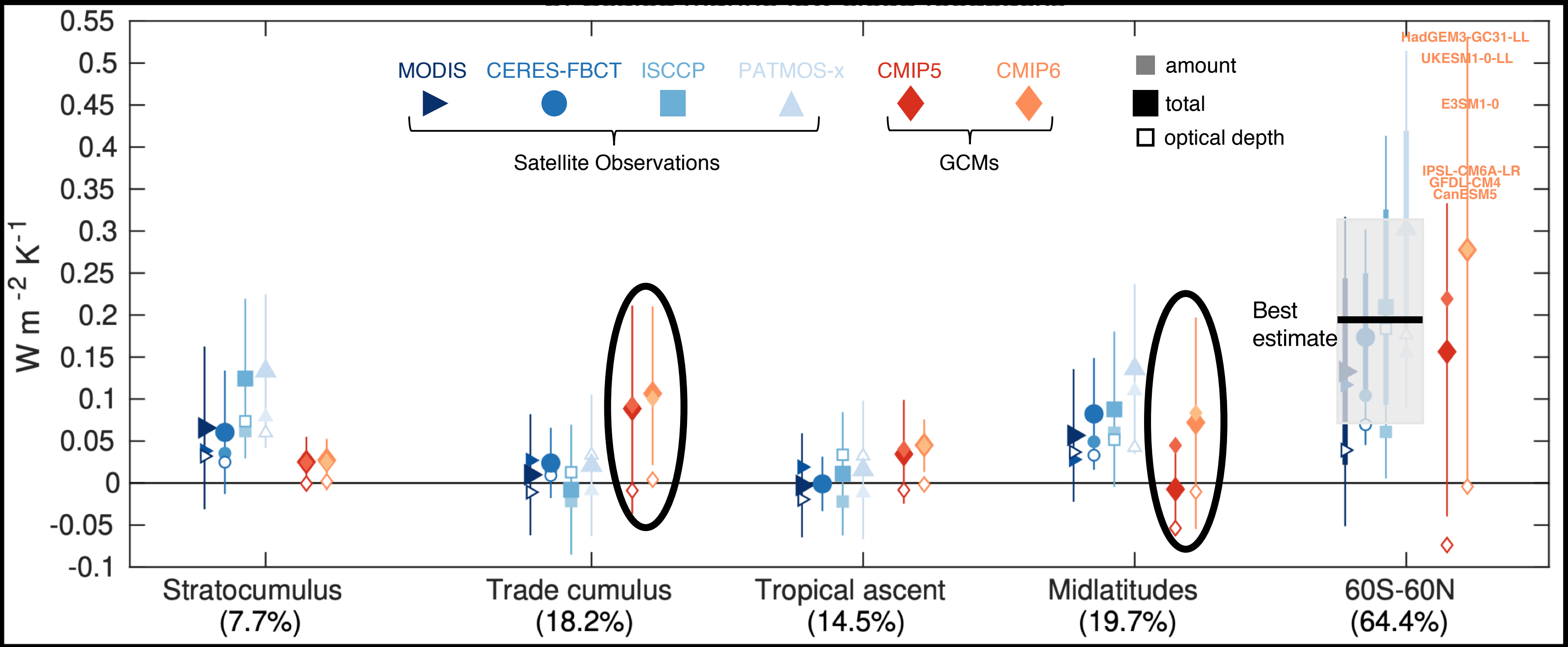


Obs: Positive 60S-60N feedback
0.19 ± 0.12 W m^{-2} K^{-1}

Several CMIP6 models:
beyond upper limit of best estimate due to:
i) more realistic midlatitude feedback yet
ii) persistently positive trade cumulus feedback

Feedbacks Scaled by Fractional Planetary Area

SW+LW



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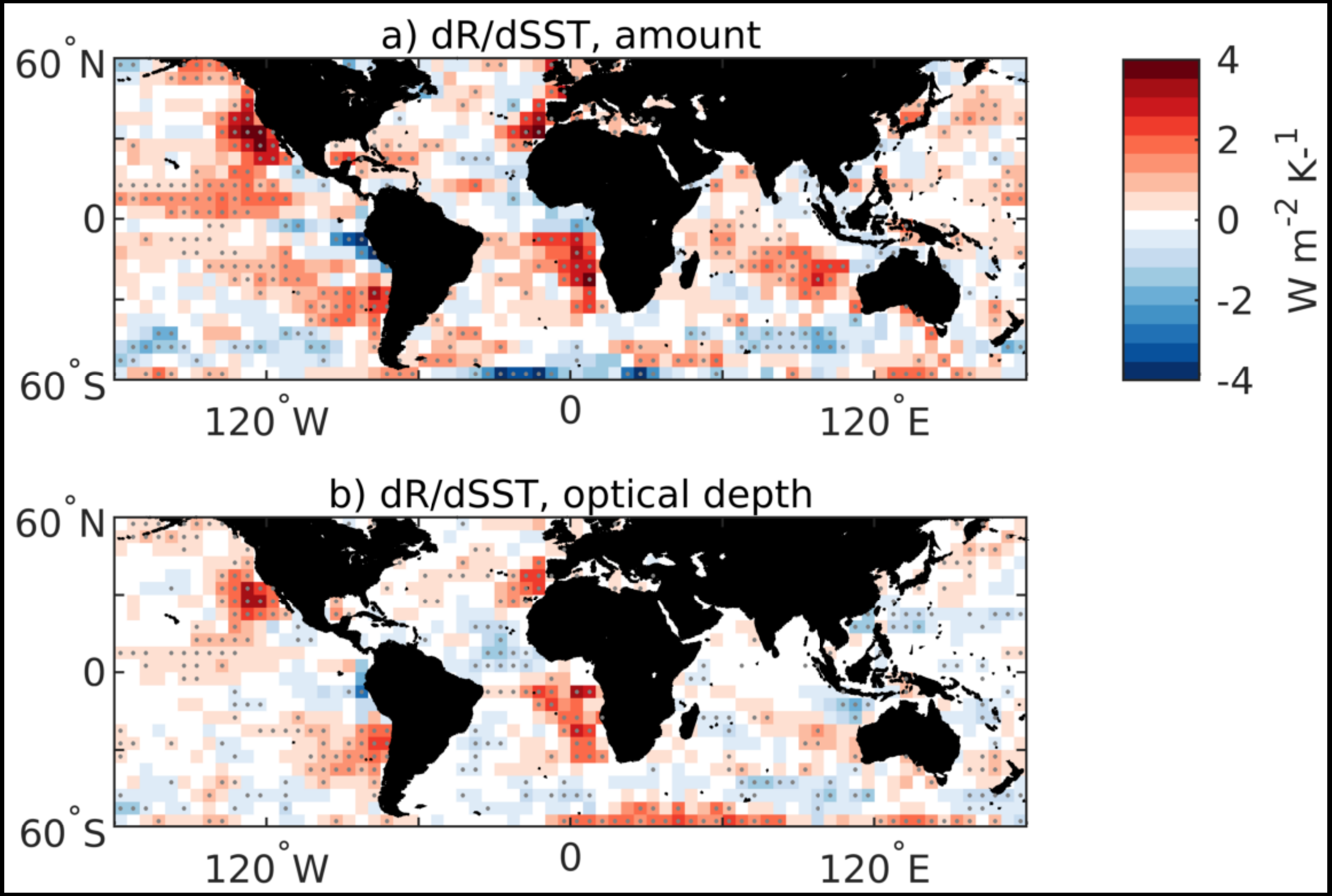
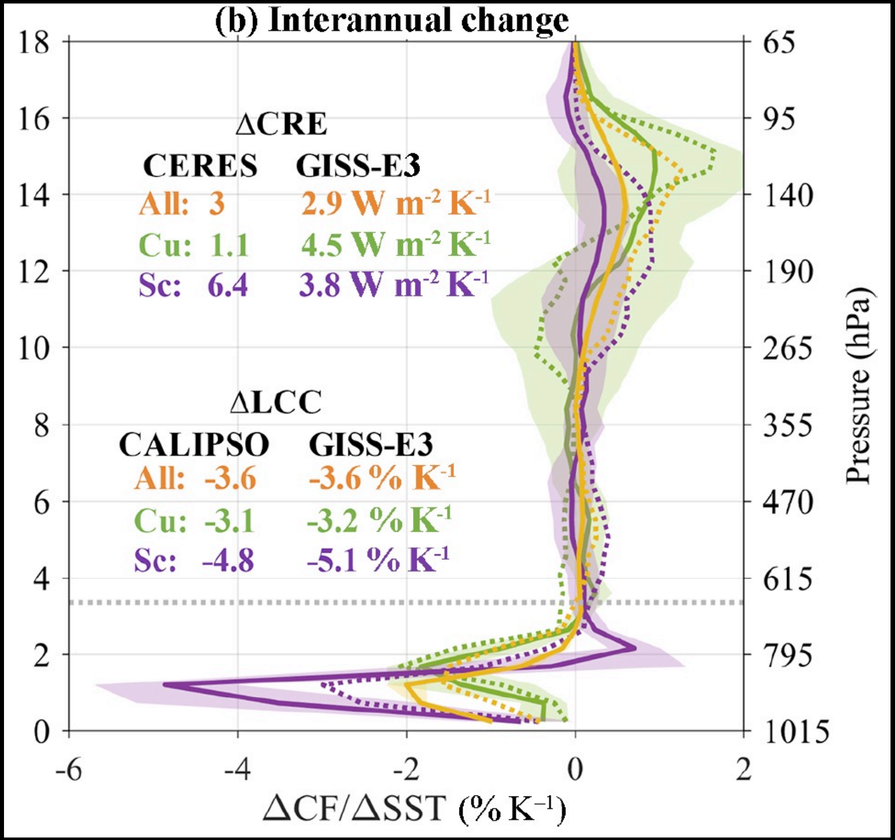
Several CMIP6 models:
beyond upper limit of best estimate due to:
i) more realistic midlatitude feedback yet
ii) persistently positive trade cumulus feedback

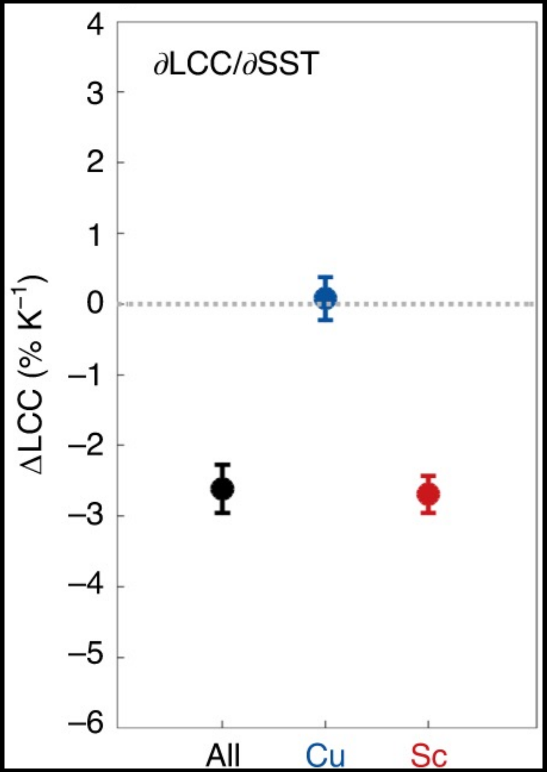
Weak sensitivity of trade cumulus to SST perturbations relative to stratocumulus explains different feedbacks



Independent observational evidence from active satellites



Cesana et al. (2019)

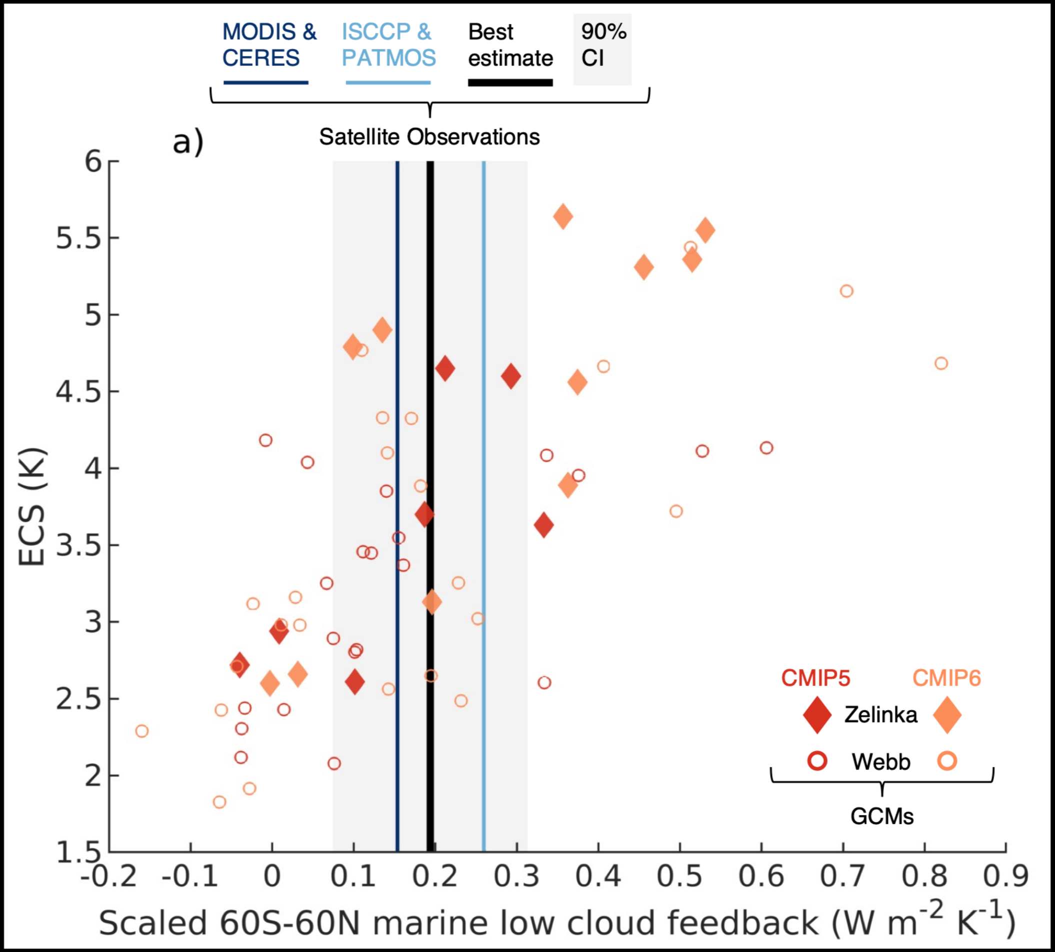


Cesana and Del Genio (2021)

Cesana and Del Genio (2021) also conclude that the trade cumulus feedback is near-zero.

Implications for ECS
Two methods

Implications for ECS Method 1: Emergent-Constraint Approach



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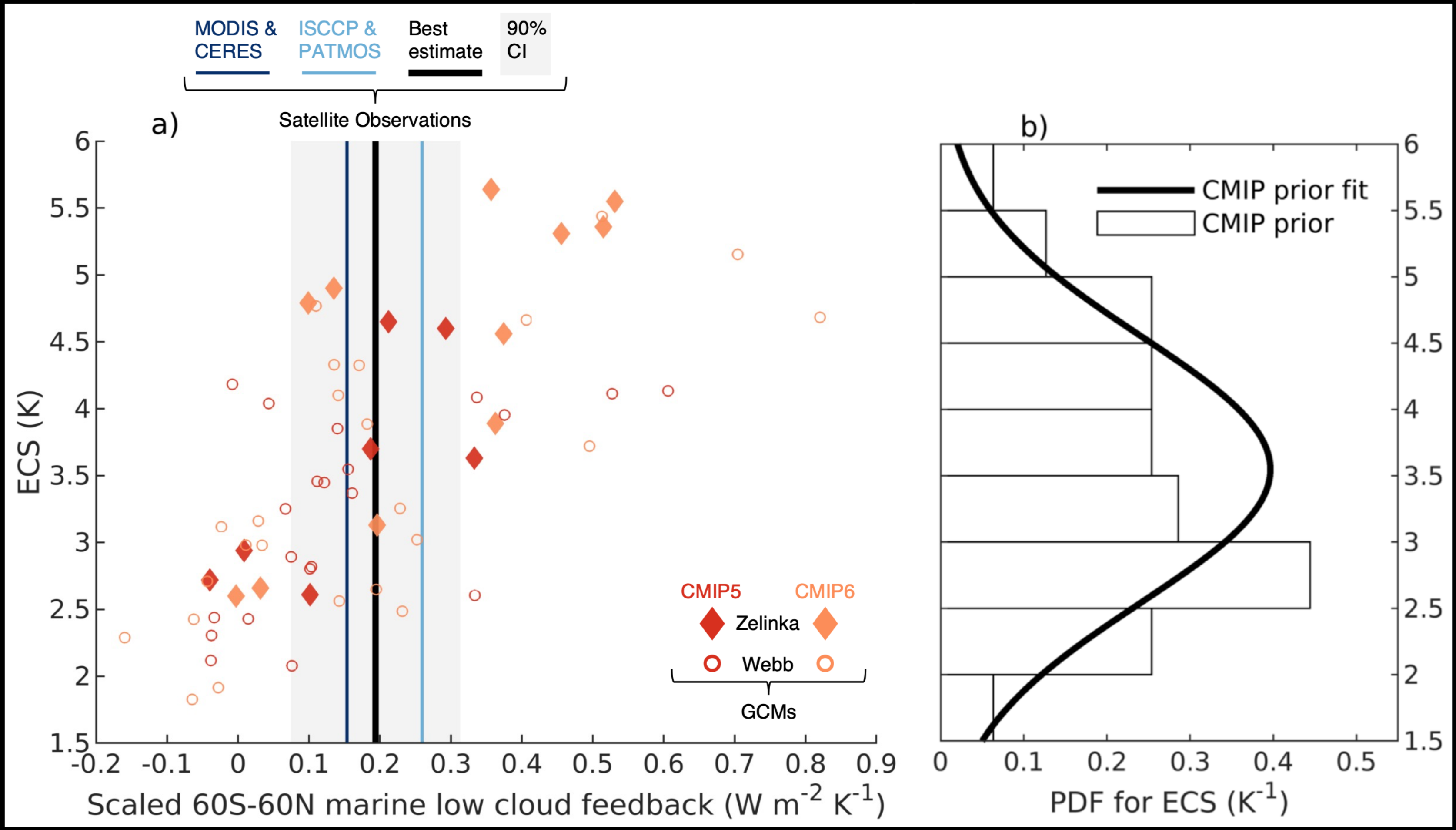
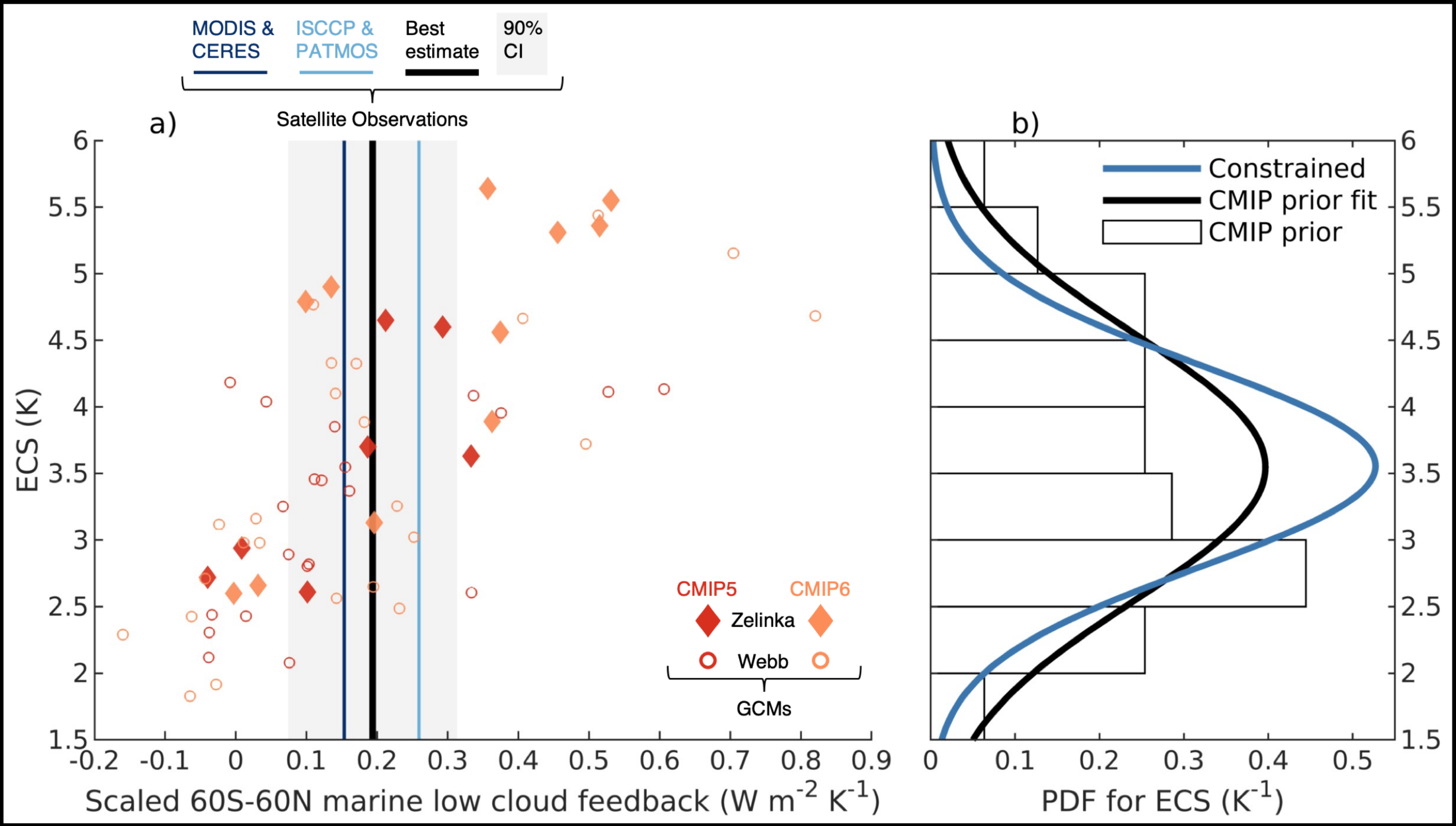


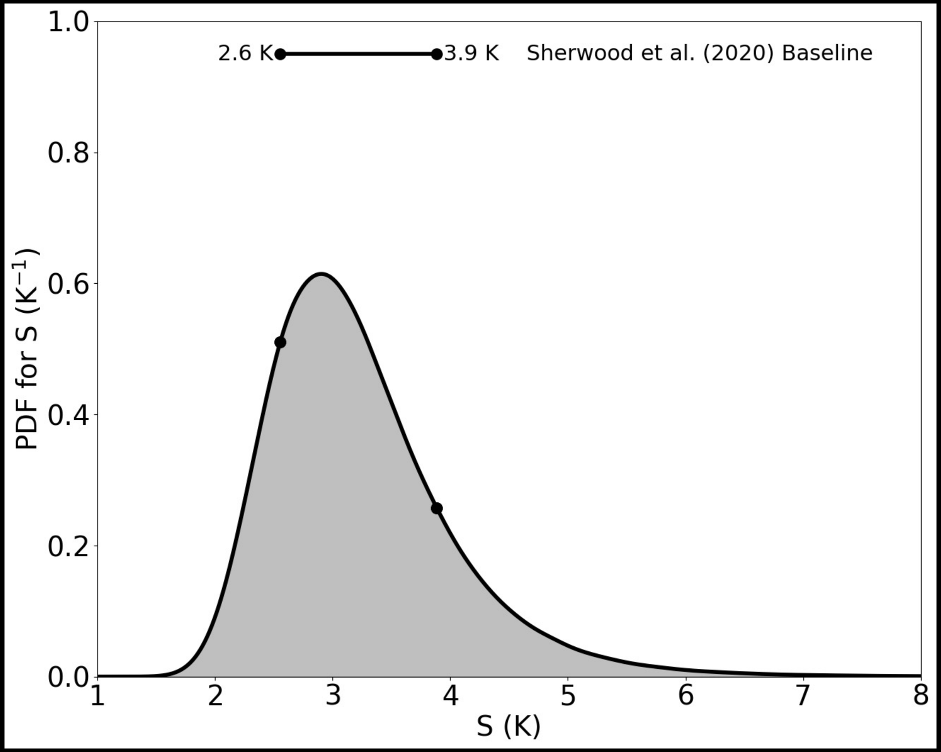
Implications for ECS Method 1: Emergent-Constraint Approach



3% chance that ECS > 5 K
8% chance that ECS < 2.5 K

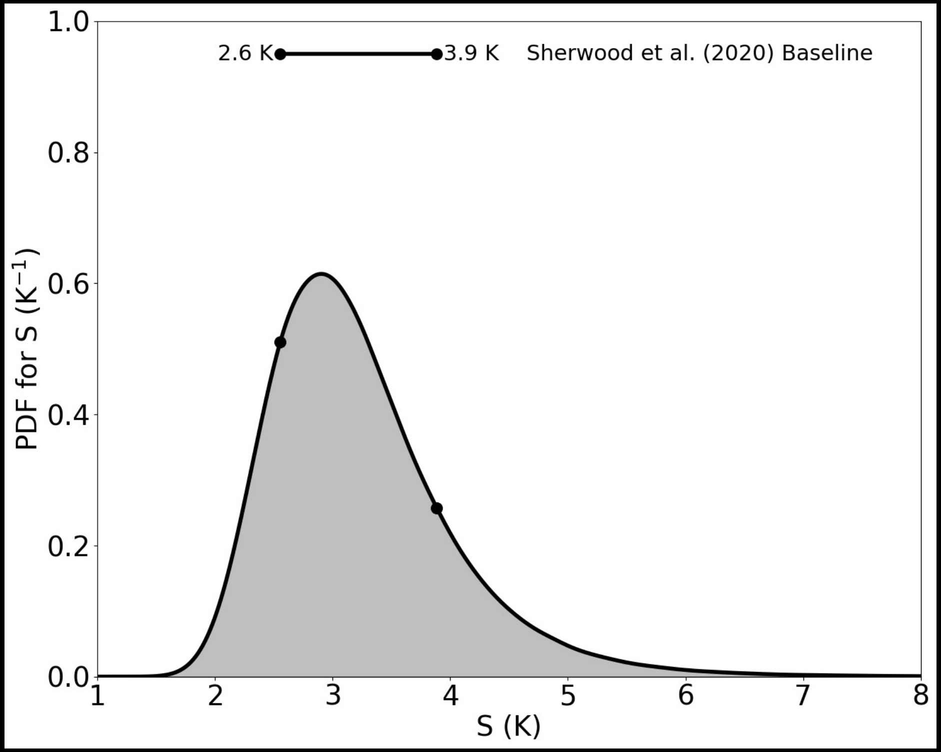
Models with very low or very high climate sensitivities are likely unrealistic.

Implications for ECS Method 2: Update to Climate Sensitivity (S) Inferred from Multiple Lines of Evidence



Sherwood et al. (2020) derive near-global marine low cloud feedback of **0.37±0.37 W m^{-2} K^{-1}** (sum of tropical and midlatitude marine low cloud amount and high-latitude low cloud optical depth feedbacks)

Implications for ECS Method 2: Update to Climate Sensitivity (S) Inferred from Multiple Lines of Evidence



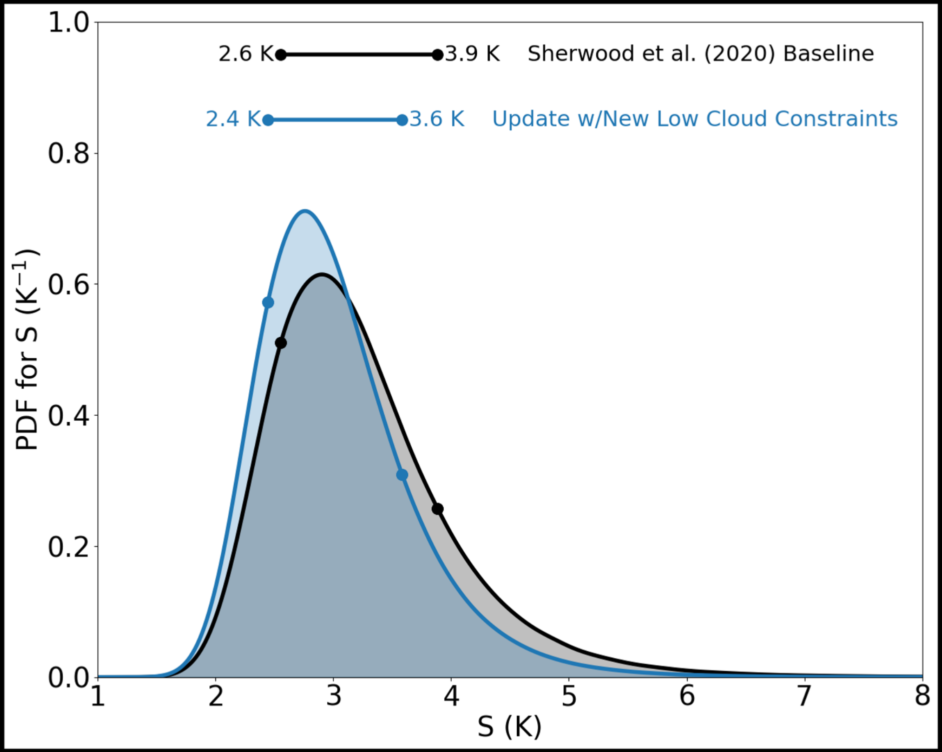
Sherwood et al. (2020) derive near-global marine low cloud feedback of **0.37±0.37 W m^{-2} K^{-1}** (sum of tropical and midlatitude marine low cloud amount and high-latitude low cloud optical depth feedbacks)

Our estimate: **0.19±0.12 W m^{-2} K^{-1}**. More realistic because:

i) Explicit evidence that trade cumulus feedback weaker than stratocumulus feedback, in agreement with LES and independent observational evidence
ii) Most comprehensive set of cloud-controlling factors of all studies

→ Replace Sherwood et al. (2020) low cloud feedback value with ours, leaving all other terms unchanged.

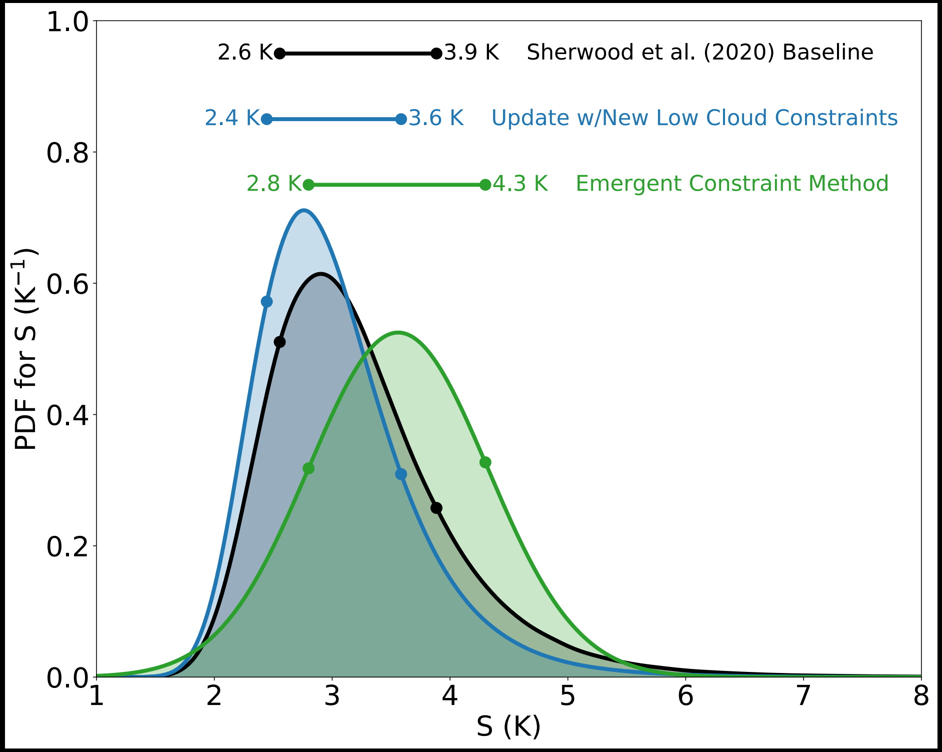
Implications for ECS Method 2: Update to Climate Sensitivity (S) Inferred from Multiple Lines of Evidence



Our estimate points to a more moderate climate sensitivity (~3 K)

The chance that S > 5 K has been reduced by more than half, from 3.1 % to 1.2 %

Implications for ECS Method 2: Update to Climate Sensitivity (S) Inferred from Multiple Lines of Evidence



Our estimate points to a more moderate climate sensitivity (~3 K)

The chance that S > 5 K has been reduced by more than half, from 3.1 % to 1.2 %

Emergent-Constraint Approach: major limitations for inferring real-world climate sensitivity

Summary

Observational *meteorological cloud radiative kernels* × GCM simulations of *meteorological changes with warming* = low cloud feedbacks

- ✓ Valid for observed out-of-sample extreme event
- ✓ Predicts positive stratocumulus and midlatitude low cloud feedbacks
- ✓ Predicts near-zero trade cumulus feedback
- ✓ Predicts 60S-60N feedback of 0.19±0.12 W m^{-2} K^{-1}
- ✓ Implies ECS near 3 K, reduces likelihood of very low or very high ECS

References

Myers, T. A., R .C. Scott, M. D. Zelinka, S. A. Klein, J. R. Norris, and P. M. Caldwell, 2021: Observational Constraints on Low Cloud Feedback Reduce Uncertainty of Climate Sensitivity. *Nature Climate Change*

Scott, R. C., T. A. Myers, J. R. Norris, M. D. Zelinka, S. A. Klein, M. Sun, and D. R. Doelling, 2020: Observed sensitivity of low cloud radiative effects to meteorological perturbations over the global oceans. *J. Climate,* doi: https://doi.org/10.1175/JCLI-D-19-1028.1.

Meteorological Cloud Radiative Kernels Available at:

https://github.com/tamyers87/meteorological_cloud_radiative_kernels

tamyers87 / meteorological_cloud_radiative_kernels

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main | 1 branch | 0 tags | Go to file | Code

tamyers87 Update README.md cb56e6e on Jan 5 4 commits

README.md	Update README.md	4 months ago
Scott_Myers_meteorological_kernel...	Add files via upload	4 months ago
Scott_Myers_meteorological_kernel...	Add files via upload	4 months ago
Scott_Myers_meteorological_kernel...	Add files via upload	4 months ago
Scott_Myers_meteorological_kernel...	Add files via upload	4 months ago

README.md

Meteorological Cloud Radiative Kernels

Meteorological cloud radiative kernels quantify the response of top-of-atmosphere marine low cloud radiative effect to local large-scale meteorological perturbations. They were developed by Scott et al. (2020) and applied in Myers et al. (2021). These kernels are derived using cloud-controlling factor (CCF) analysis, which is based upon theoretical and high-resolution model evidence that marine boundary layer properties, including cloudiness, are predominantly determined by large-scale meteorological environmental factors. In our analysis, these CCFs include sea-surface temperature (SST), estimated inversion strength (EIS), horizontal surface temperature advection (Tadv), relative humidity at 700 hPa (RH_{700}), vertical velocity at 700 hPa (ω_{700}), and near-surface wind speed (WS).

The *meteorological cloud radiative kernels* are calculated by applying multi-linear regression of detrended interannual monthly anomalies of satellite-derived low cloud radiative flux onto anomalies in CCFs from a reanalysis

About

Netcdf files of meteorological cloud radiative kernels developed by Scott et al. (2020) and applied in Myers et al. (2021).

Readme

Releases

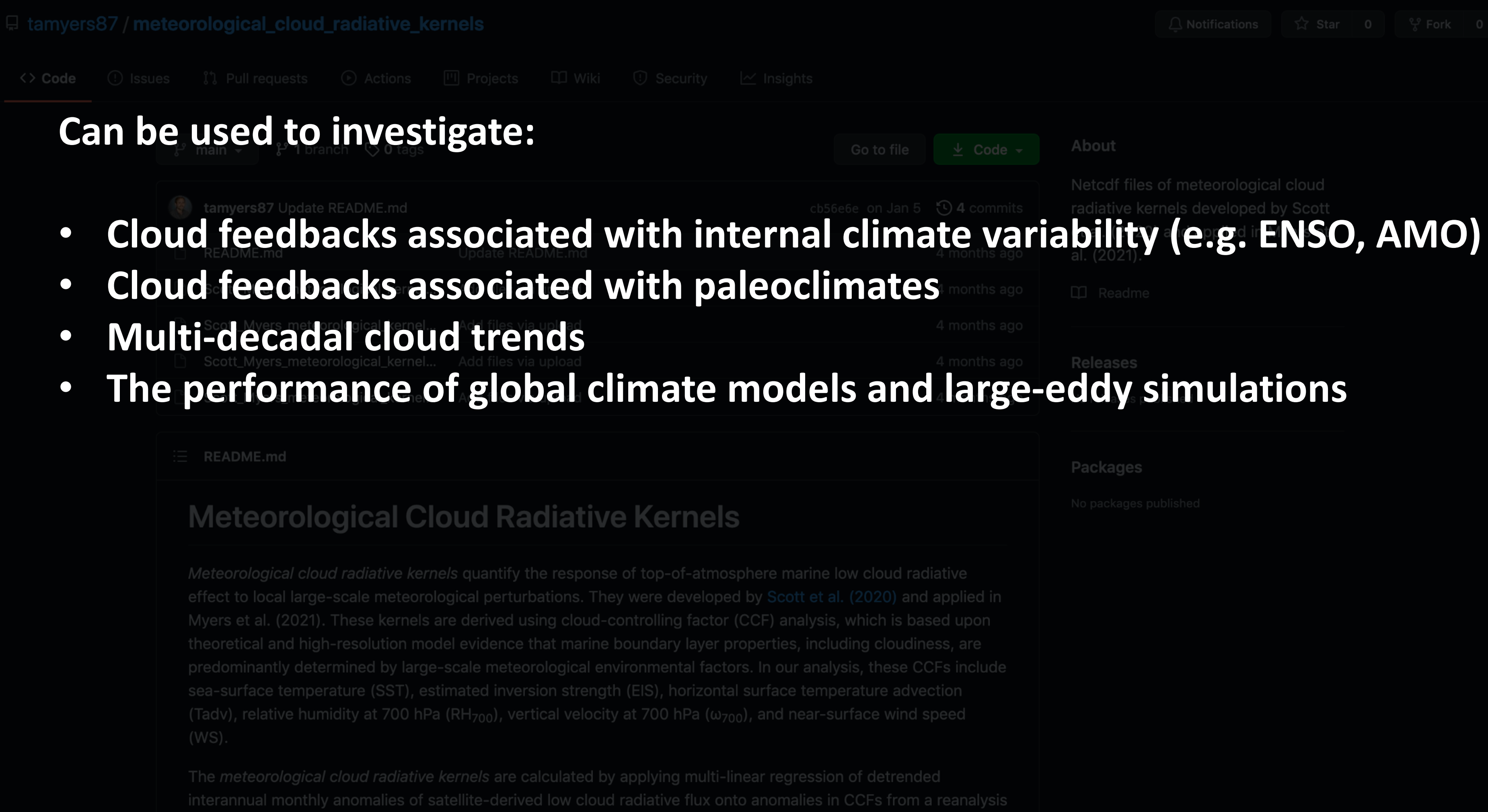
No releases published

Packages

No packages published

Meteorological Cloud Radiative Kernels Available at:

https://github.com/tamyers87/meteorological_cloud_radiative_kernels

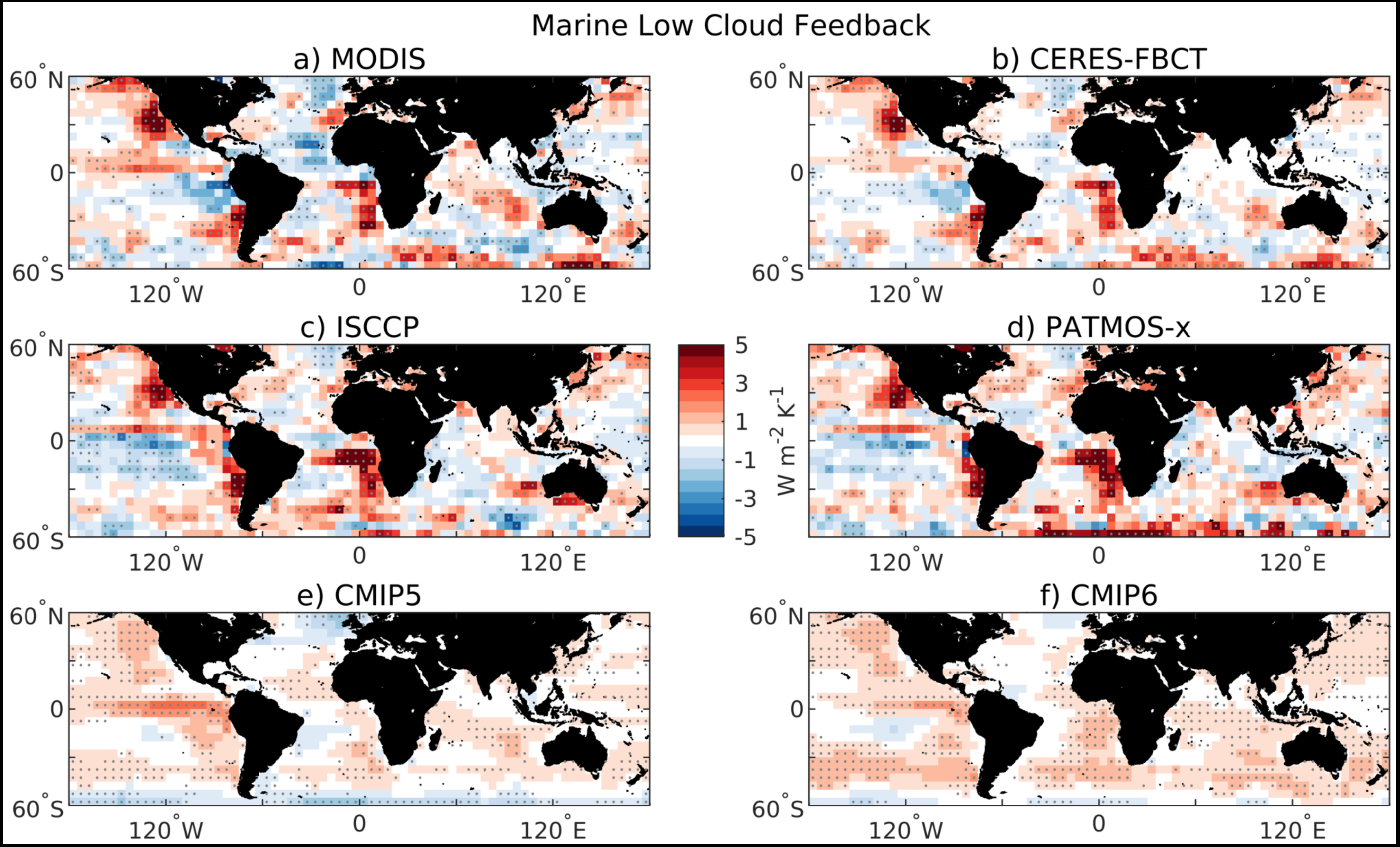


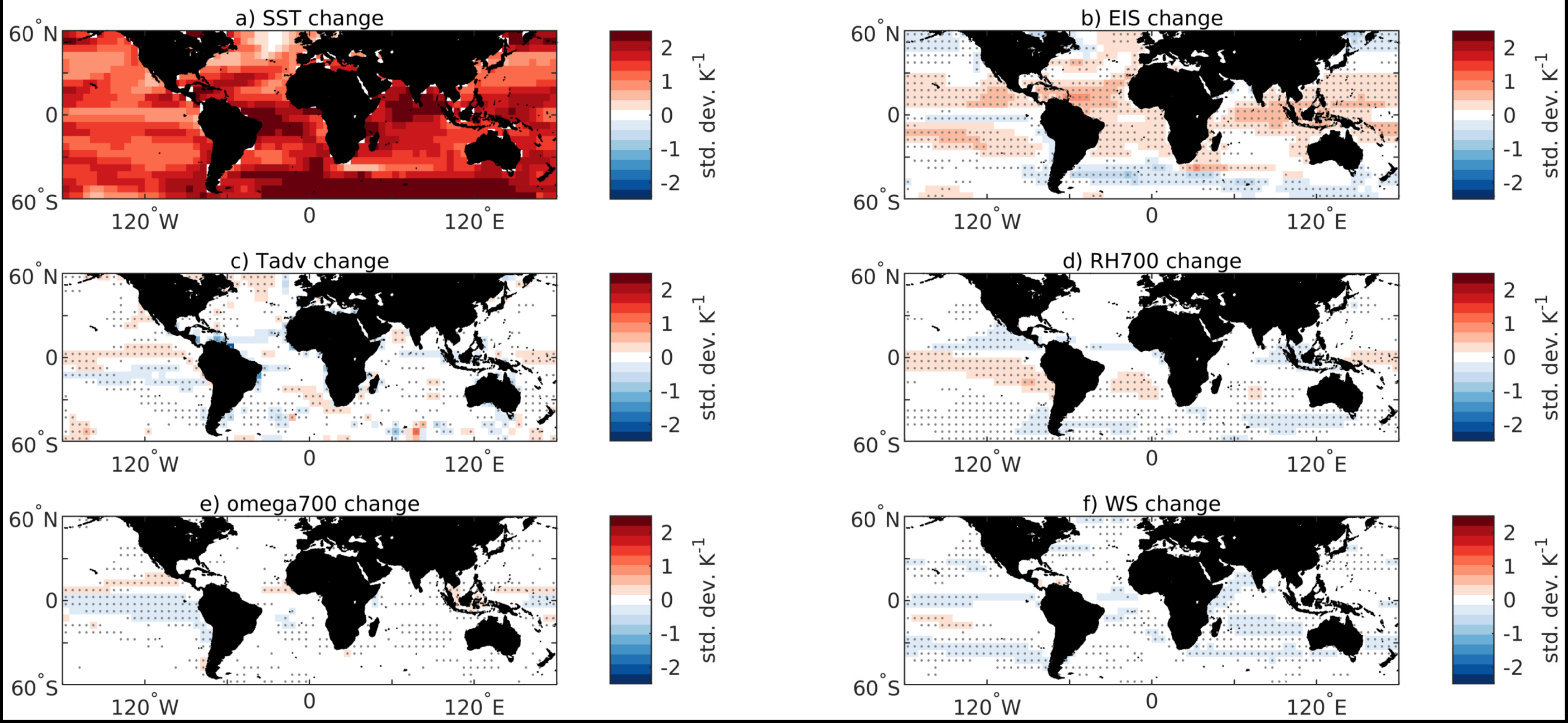
Can be used to investigate:

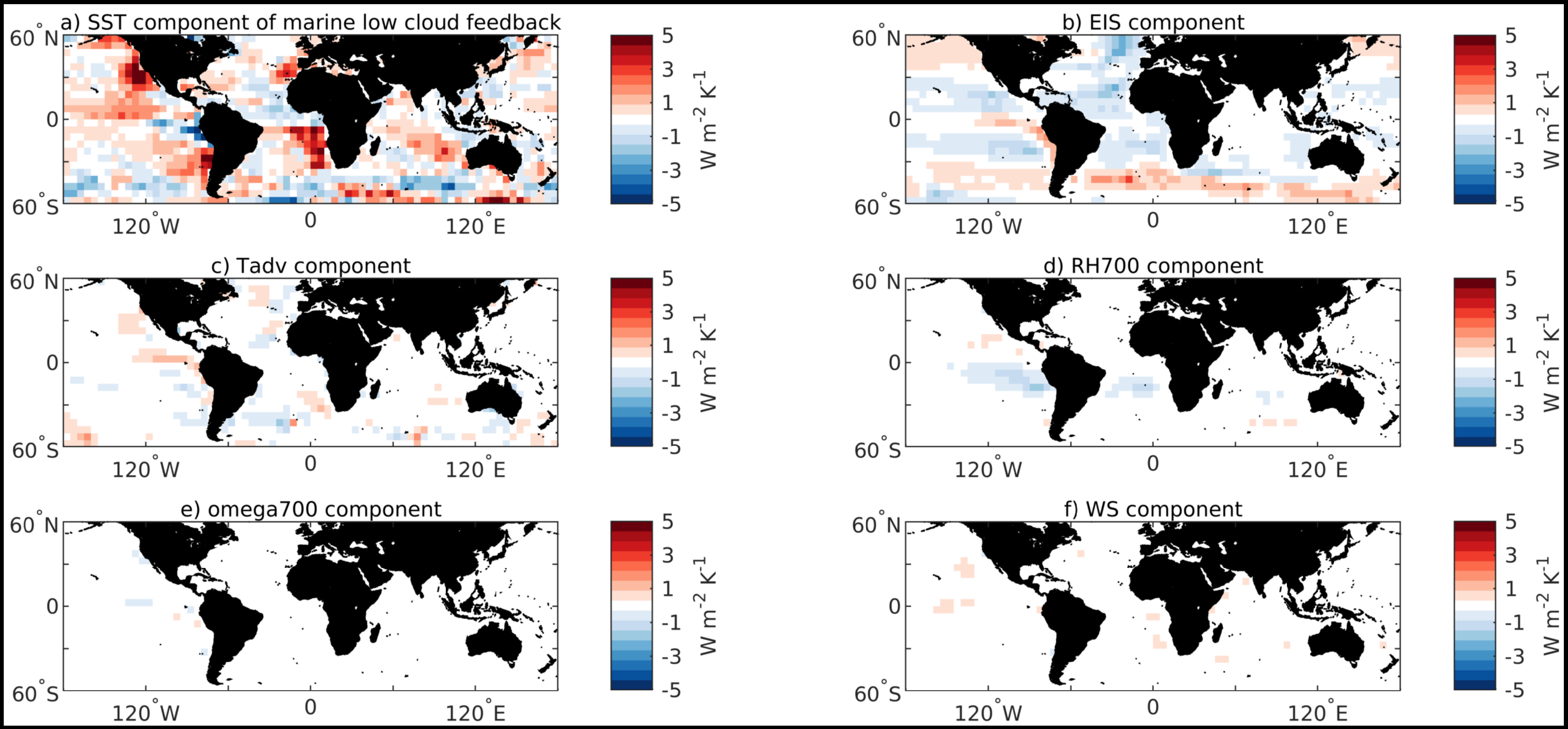
- **Cloud feedbacks associated with internal climate variability (e.g. ENSO, AMO)**
- **Cloud feedbacks associated with paleoclimates**
- **Multi-decadal cloud trends**
- **The performance of global climate models and large-eddy simulations**

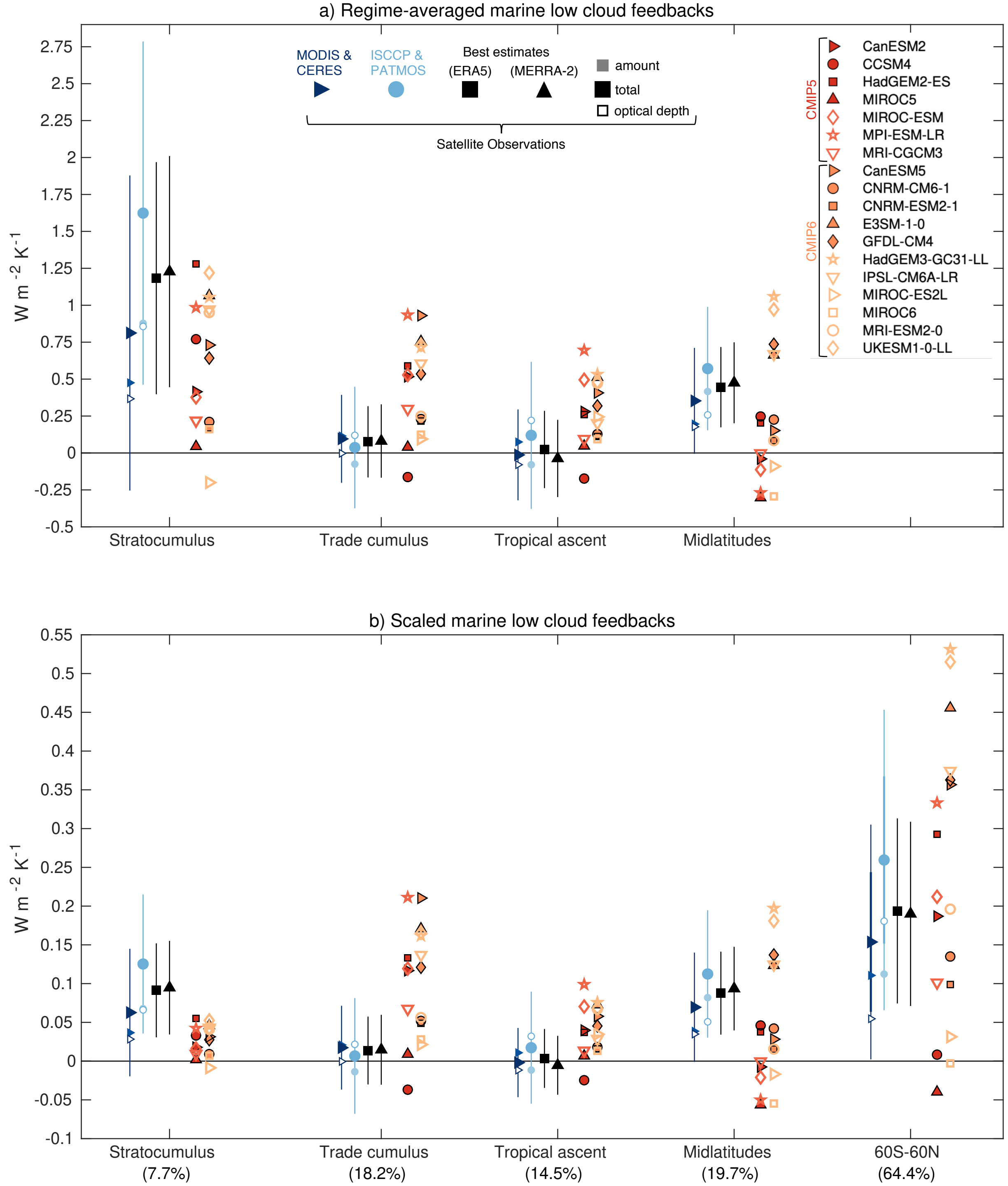

Thank you!
MODIS

Extras slides

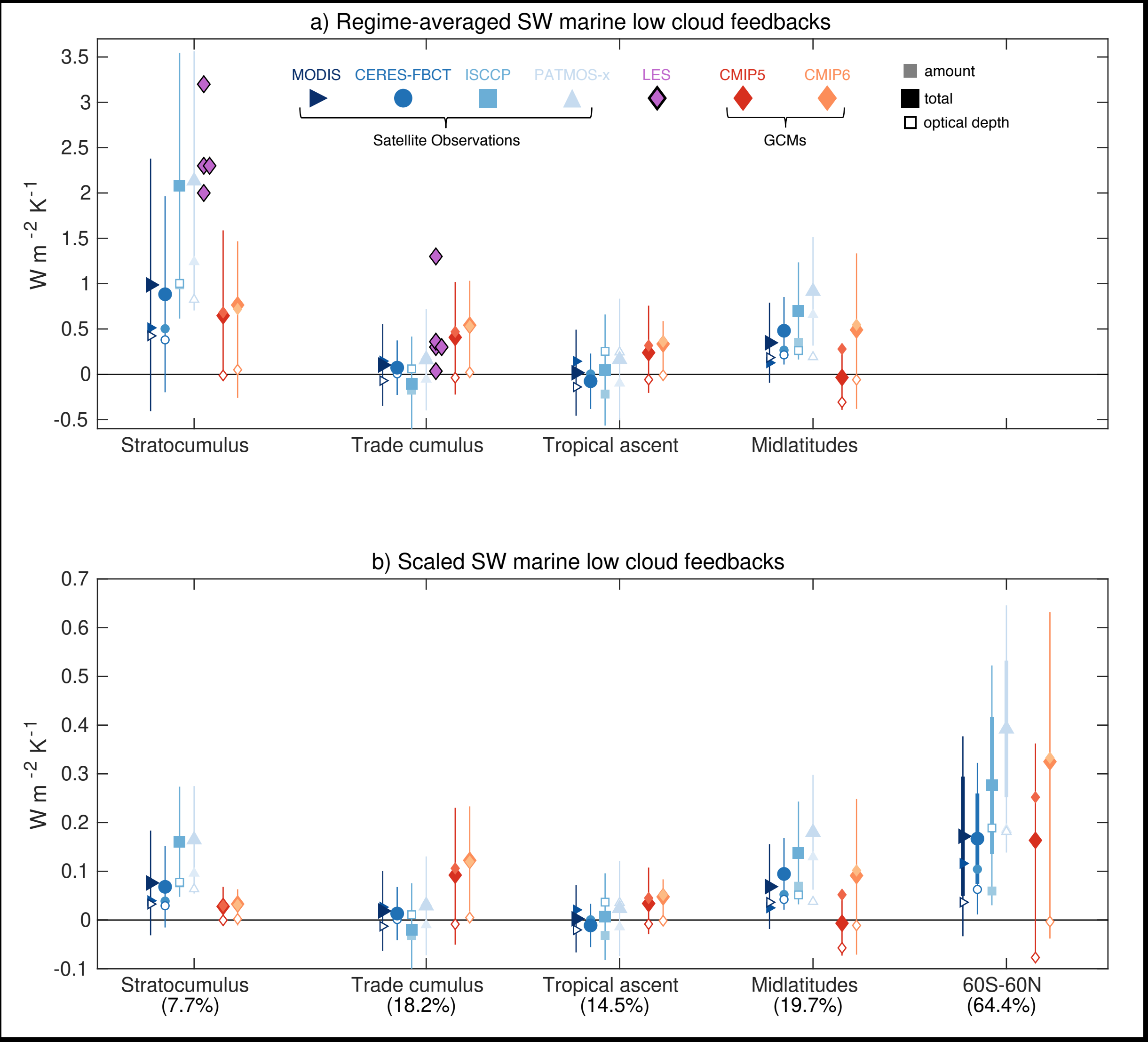

Marine Low Cloud Feedback
a) MODIS
b) CERES-FBCT
c) ISCCP
d) PATMOS-x
e) CMIP5
f) CMIP6
60°N
0
60°S
120°W
0
120°E
5
3
1
-1
-3
-5
W m^{-2} K^{-1}

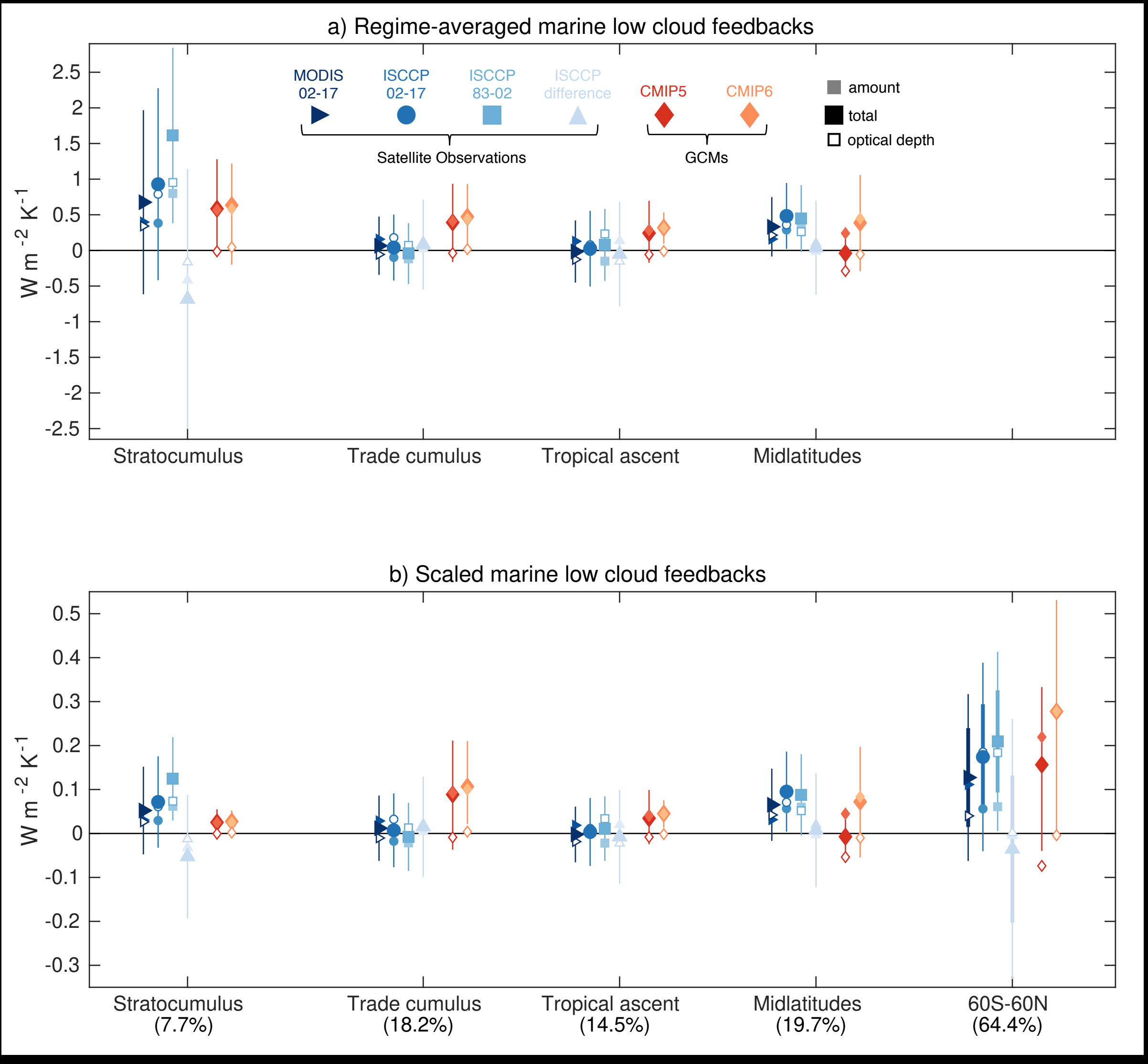

a) SST change
b) EIS change
c) Tadv change
d) RH700 change
e) omega700 change
f) WS change
60°N
0
60°S
120°W
0
120°E
2
1
0
-1
-2
std. dev. K^{-1}

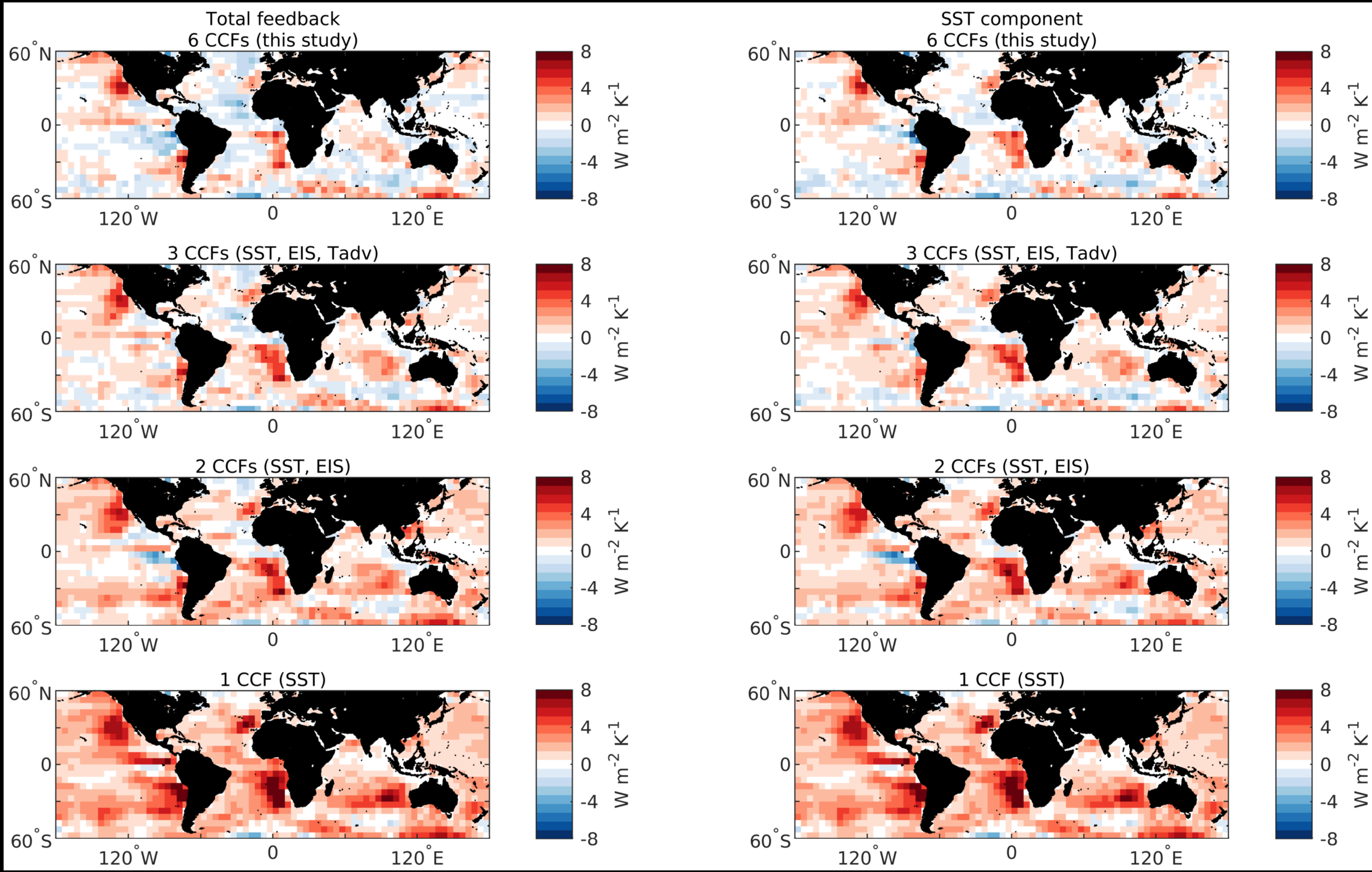

a) SST component of marine low cloud feedback
b) EIS component
c) Tadv component
d) RH700 component
e) omega700 component
f) WS component
60°N
0
60°S
120°W
0
120°E
5
3
1
-1
-3
-5
W m-2 K-1



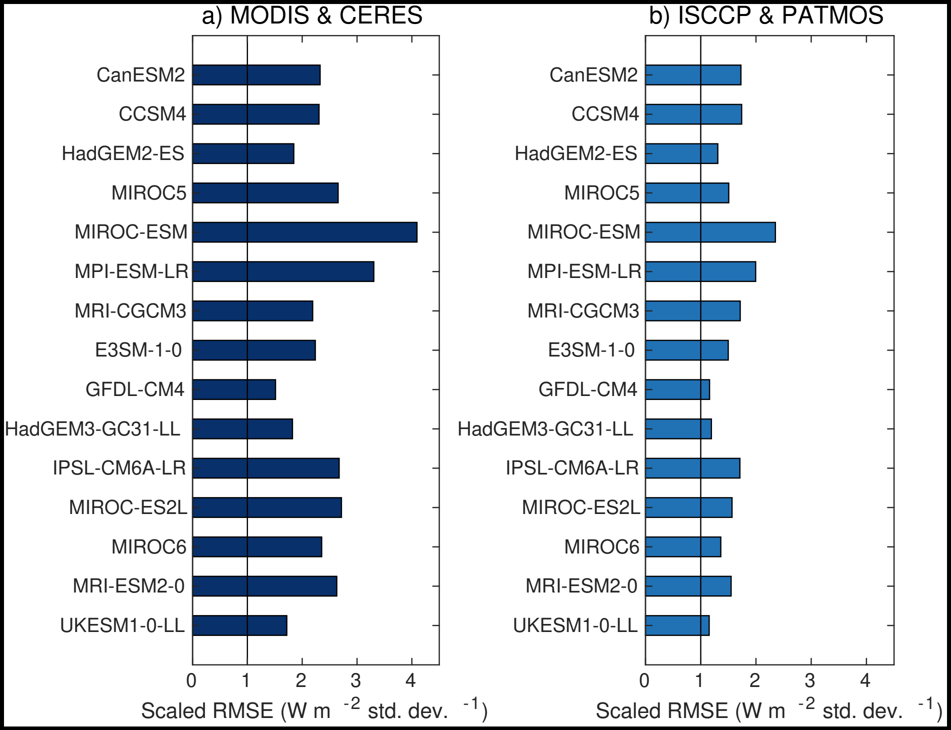
a) Regime-averaged marine low cloud feedbacks
W m -2 K -1
MODIS & CERES
ISCCP & PATMOS
Best estimates
(ERA5)
(MERRA-2)
amount
total
optical depth
Satellite Observations
CMIP5
CanESM2
CCSM4
HadGEM2-ES
MIROC5
MIROC-ESM
MPI-ESM-LR
MRI-CGCM3
CMIP6
CanESM5
CNRM-CM6-1
CNRM-ESM2-1
E3SM-1-0
GFDL-CM4
HadGEM3-GC31-LL
IPSL-CM6A-LR
MIROC-ES2L
MIROC6
MRI-ESM2-0
UKESM1-0-LL
Stratocumulus
Trade cumulus
Tropical ascent
Midlatitudes
b) Scaled marine low cloud feedbacks
W m -2 K -1
Stratocumulus (7.7%)
Trade cumulus (18.2%)
Tropical ascent (14.5%)
Midlatitudes (19.7%)
60S-60N (64.4%)

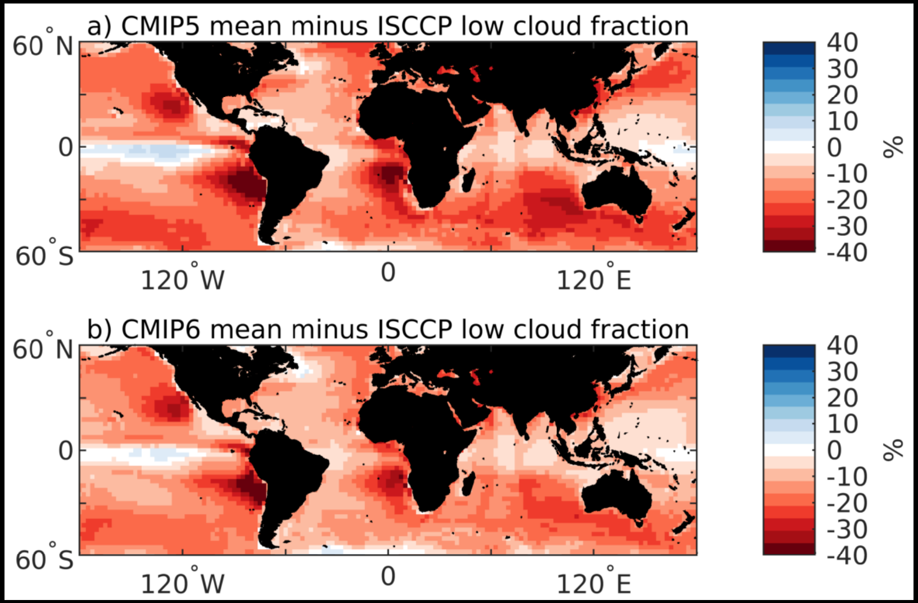

a) Regime-averaged SW marine low cloud feedbacks
MODIS
CERES-FBCT
ISCCP
PATMOS-x
LES
CMIP5
CMIP6
Satellite Observations
GCMs
amount
total
optical depth
W m -2 K -1
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
Stratocumulus
Trade cumulus
Tropical ascent
Midlatitudes
b) Scaled SW marine low cloud feedbacks
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
Stratocumulus (7.7%)
Trade cumulus (18.2%)
Tropical ascent (14.5%)
Midlatitudes (19.7%)
60S-60N (64.4%)


a) Regime-averaged marine low cloud feedbacks
MODIS 02-17
ISCCP 02-17
ISCCP 83-02
ISCCP difference
CMIP5
CMIP6
Satellite Observations
GCMs
amount
total
optical depth
W m -2 K -1
Stratocumulus
Trade cumulus
Tropical ascent
Midlatitudes
b) Scaled marine low cloud feedbacks
Stratocumulus (7.7%)
Trade cumulus (18.2%)
Tropical ascent (14.5%)
Midlatitudes (19.7%)
60S-60N (64.4%)



Total feedback
6 CCFs (this study)
SST component
6 CCFs (this study)
3 CCFs (SST, EIS, Tadv)
2 CCFs (SST, EIS)
1 CCF (SST)
60°N
0
60°S
120°W
0
120°E
8
4
0
-4
-8
W m^{-2} K^{-1}


a) MODIS & CERES
b) ISCCP & PATMOS
CanESM2
CCSM4
HadGEM2-ES
MIROC5
MIROC-ESM
MPI-ESM-LR
MRI-CGCM3
E3SM-1-0
GFDL-CM4
HadGEM3-GC31-LL
IPSL-CM6A-LR
MIROC-ES2L
MIROC6
MRI-ESM2-0
UKESM1-0-LL
0 1 2 3 4
Scaled RMSE (W m -2 std. dev. -1)


a) CMIP5 mean minus ISCCP low cloud fraction
b) CMIP6 mean minus ISCCP low cloud fraction
60°N
0
60°S
120°W
0
120°E
40
30
20
10
0
-10
-20
-30
-40
%