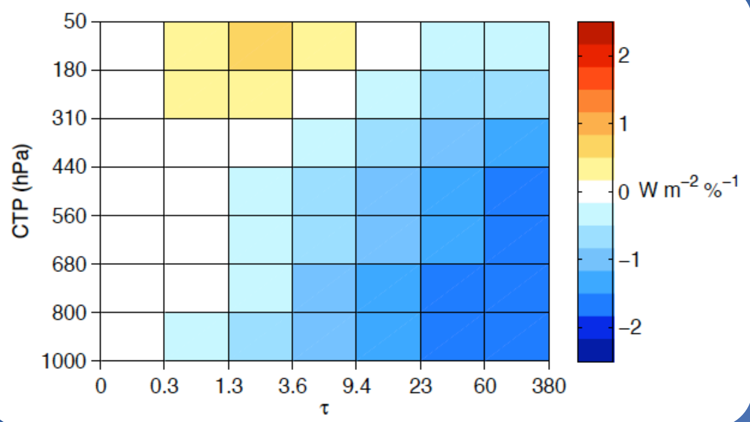
Computing and Partitioning Cloud Feedbacks Using Cloud Property Histograms



Mark D. Zelinka[1,2], Stephen A. Klein[1], & Dennis L. Hartmann[2]

1. Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Lab

2. Department of Atmospheric Sciences, University of Washington

Goals

- To provide a clean and simple method of computing cloud feedbacks that is highly informative
- Clean:
  - compute cloud feedback from ISCCP simulator-interpreted cloud changes directly (not inferred)
  - standard definition of "cloud" and radiation code across models
- Simple:
  - no need to correct for non-cloud effects
  - no partial radiative perturbation calculations are needed
  - can use monthly mean model output
- Informative:
  - can **quantify** the contribution to cloud feedback from **changing amounts of individual cloud types** (high, middle, low) and from **individual processes** (Δaltitude, Δoptical depth, Δtotal amount)

Data & Methodology

- Doubled CO_2 equilibrium slab ocean model simulations from 11 GCMs as part of CFMIP1
- ISCCP simulator (Klein & Jakob 1999) run inline during integration
  - Produce distribution of cloud fraction (as function of CTP and τ) that is consistent with how a satellite-borne passive sensor would "view" the model atmosphere
  - Simulated cloud fractions are defined consistently across models

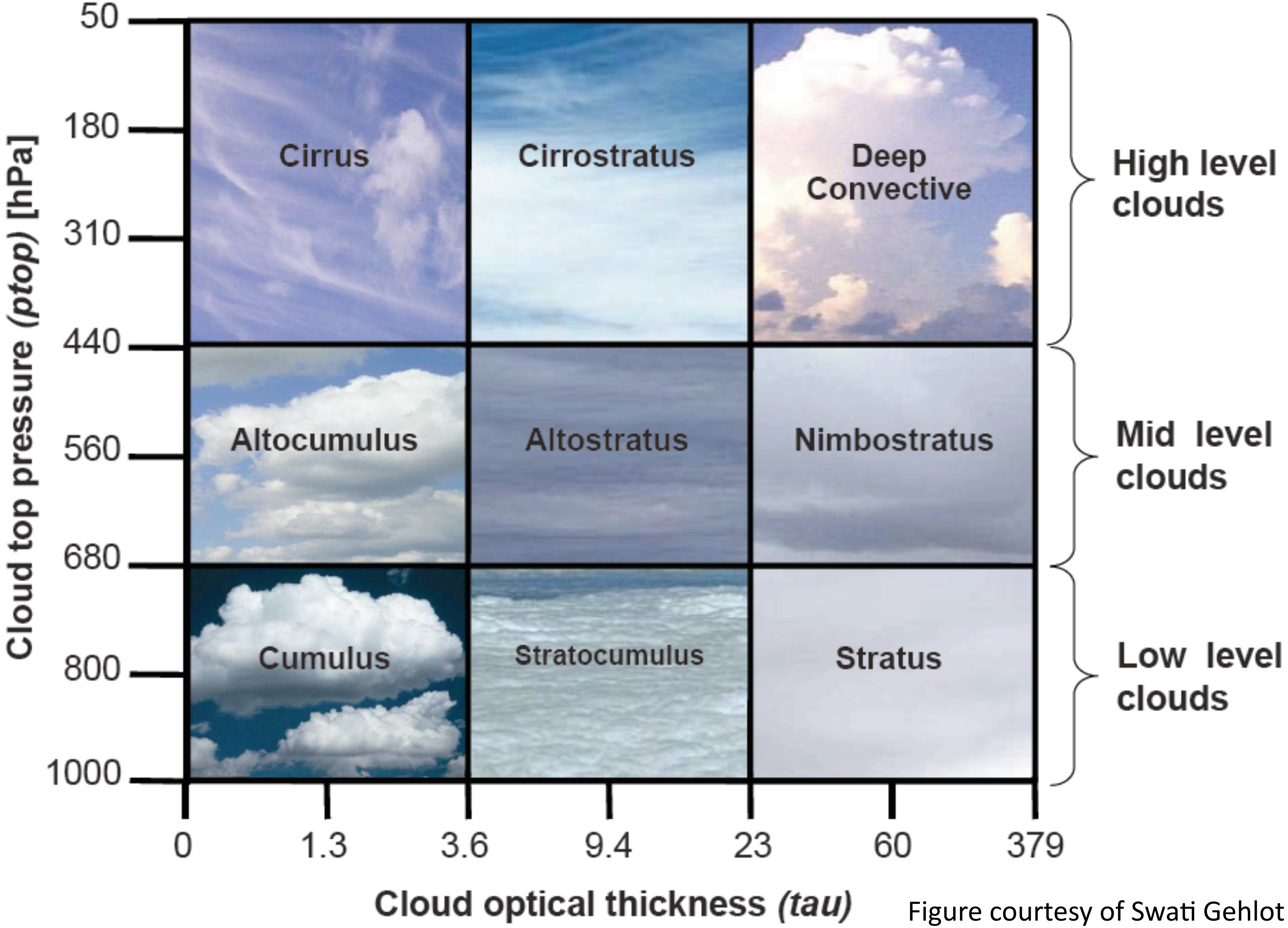


Figure courtesy of Swati Gehlot

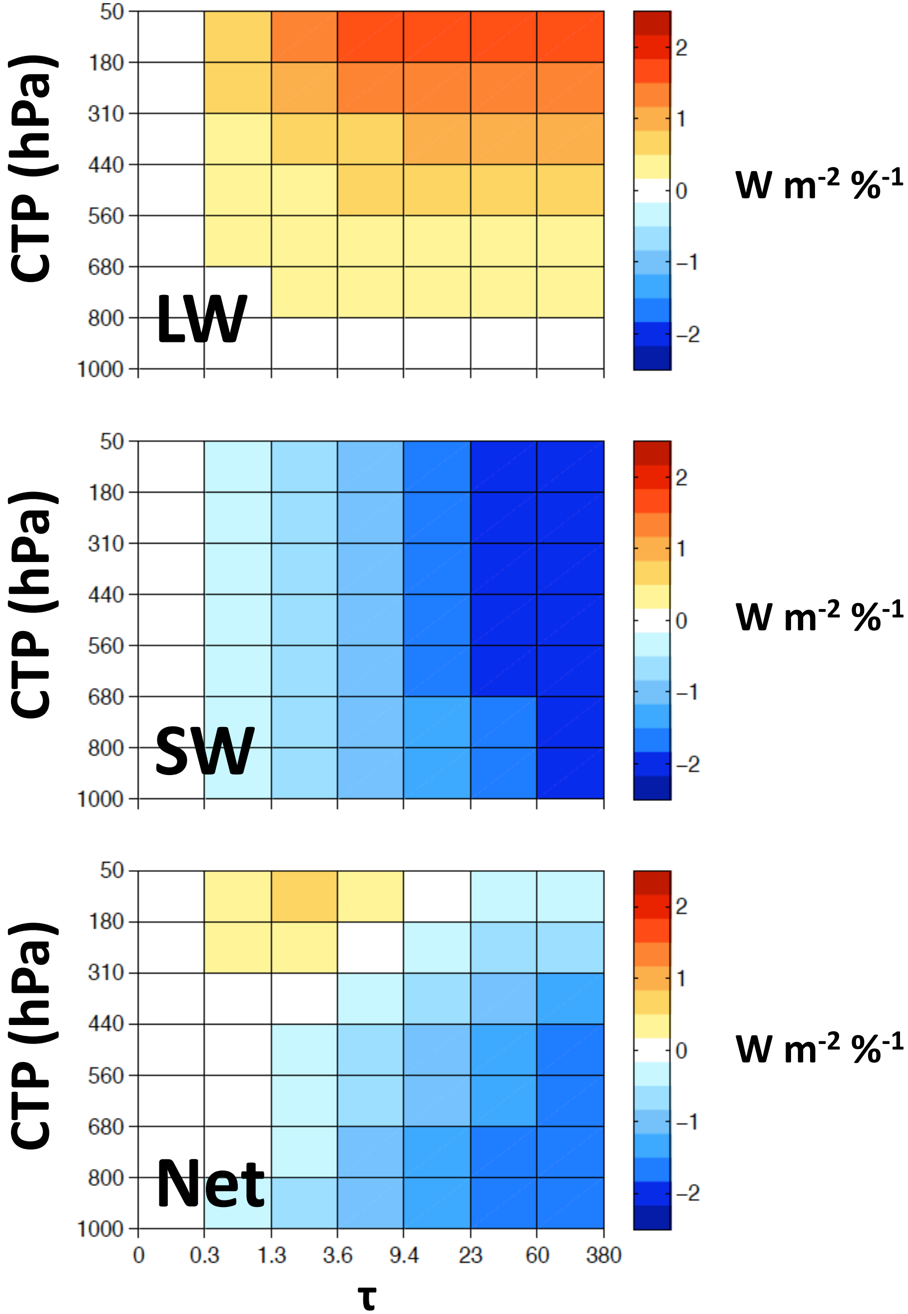
Data & Methodology

- Doubled CO_2 equilibrium slab ocean model simulations from 12 GCMs as part of CFMIP1
- ISCCP simulator run inline during integration
  - Produce distribution of cloud fraction (as function of CTP and τ) that is consistent with how a satellite-borne passive sensor would "view" the model atmosphere
  - Simulated cloud fractions are defined consistently across models
- We compute cloud radiative kernels → sensitivity of TOA radiation to cloud fraction changes in each CTP-τ bin
- Cloud feedback = Δcloud fraction times cloud kernel normalized by ΔT_{sfc}

Recipe for Constructing Cloud Radiative Kernels

- ❑ Input model mean zonal mean T and q profiles to Fu-Liou code
- ❑ Compute clear-sky TOA fluxes
- ❑ Compute overcast-sky fluxes for each CTP and τ bin by setting the LWC / IWC profiles to values appropriate for each cloud type
- ❑ Subtract overcast TOA fluxes in each bin from the clear-sky flux to compute a matrix of overcast sky cloud forcing
- ❑ Divide by 100 to get W m^{-2} $\%^{-1}$
- ❑ Repeat every calculation for 24 solar zenith angles, all latitudes, 12 months, and 3 surface albedos (0.0, 0.5, 1.0)

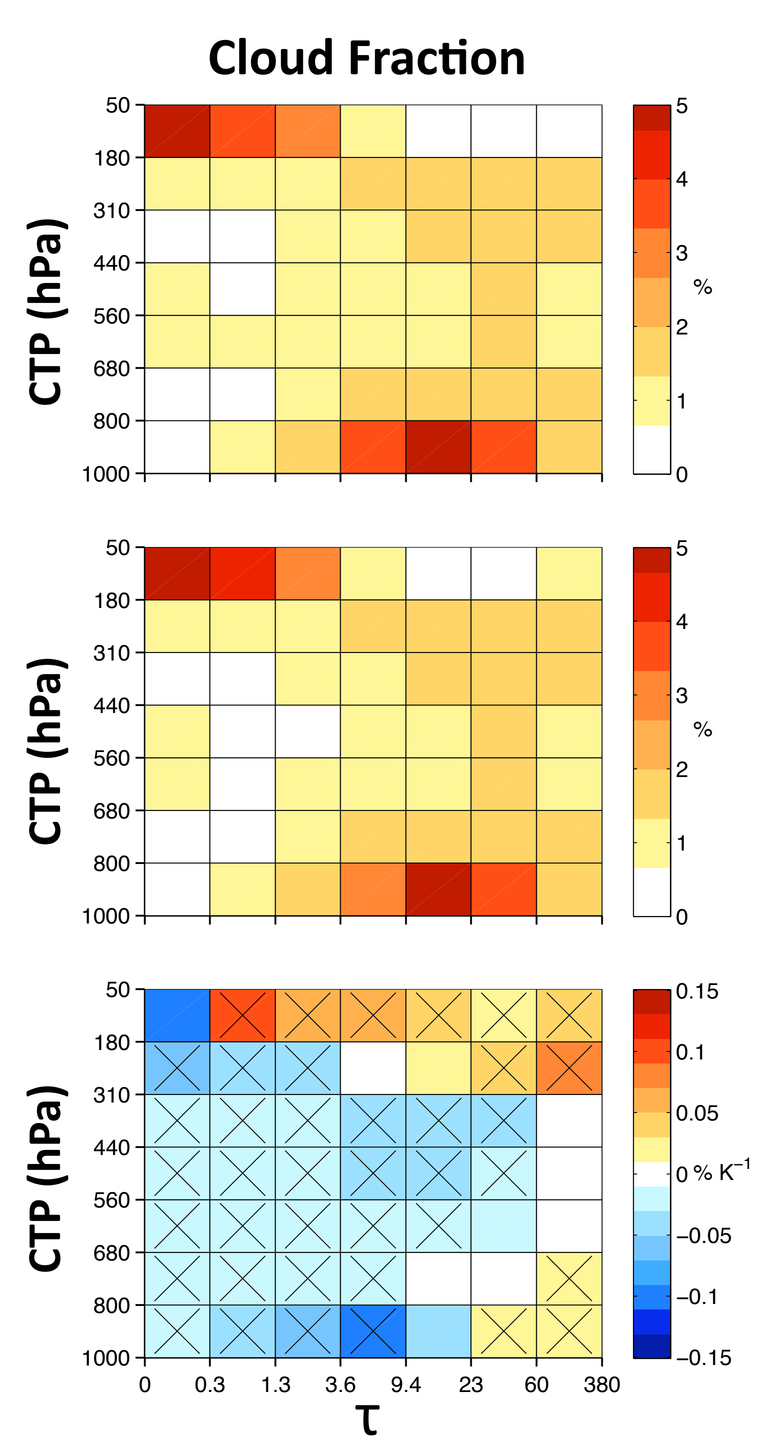
Global Annual Mean Cloud Kernels



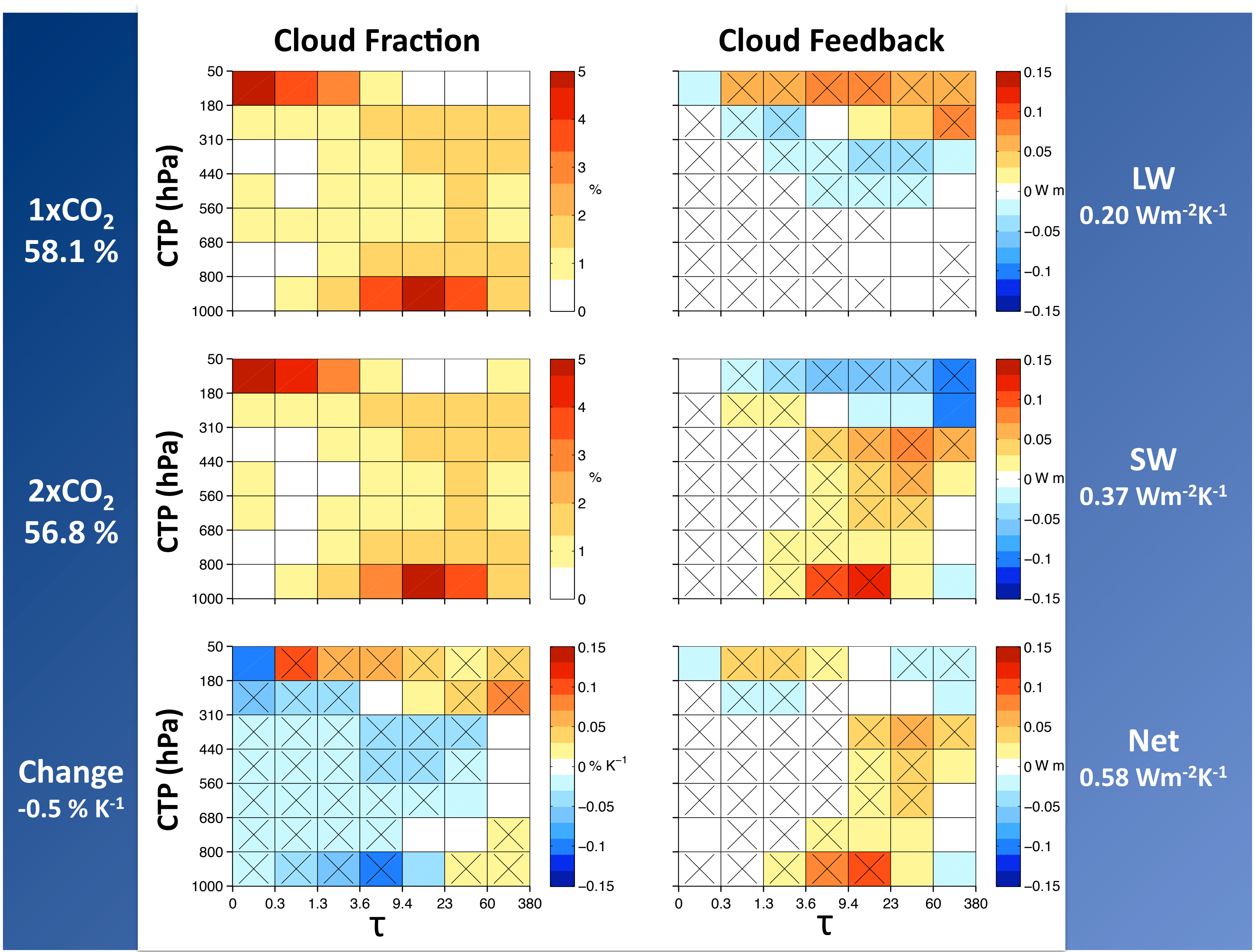
$1xCO_2$
58.1 %

$2xCO_2$
56.8 %

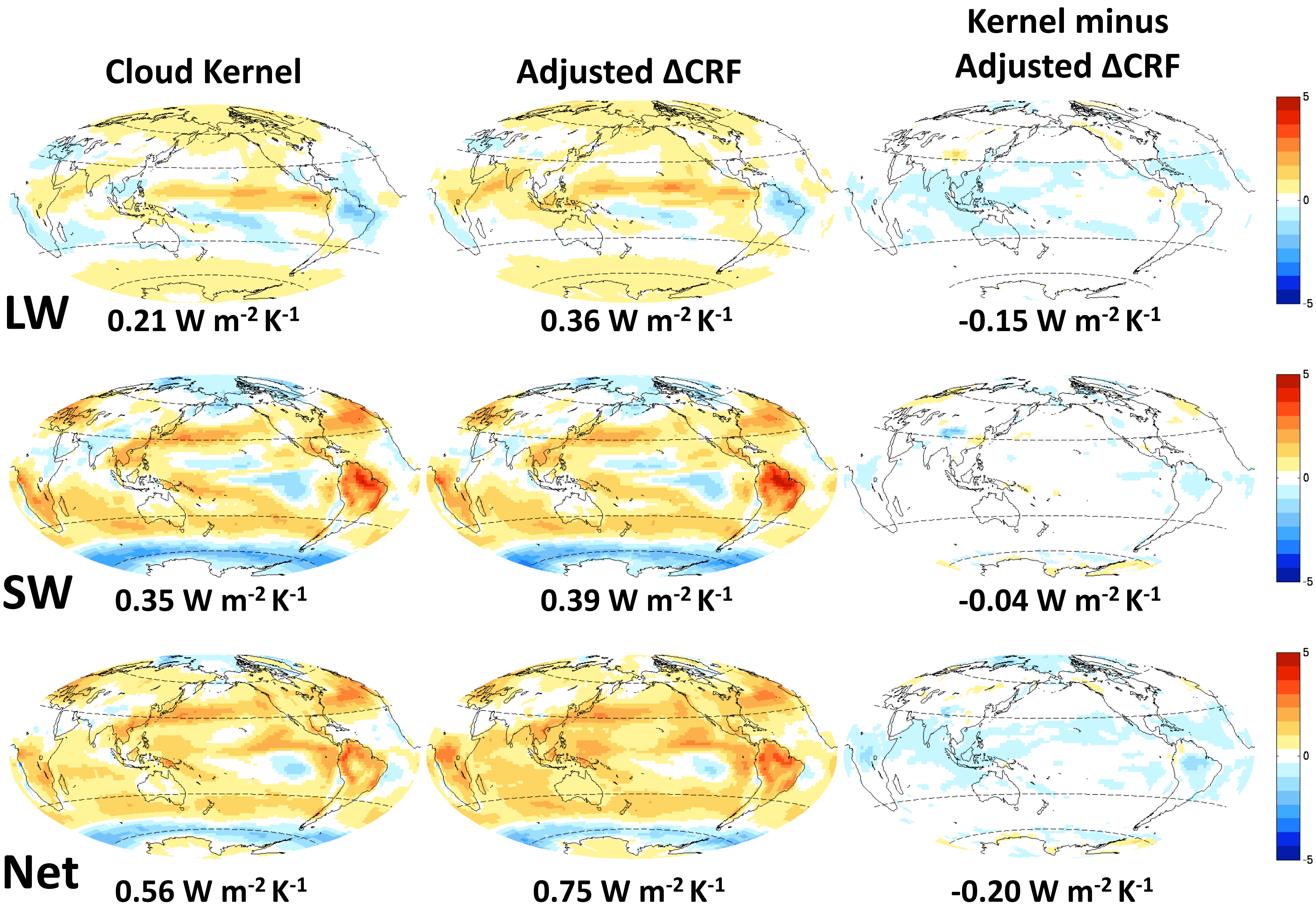
Change
-0.5 % K^{-1}



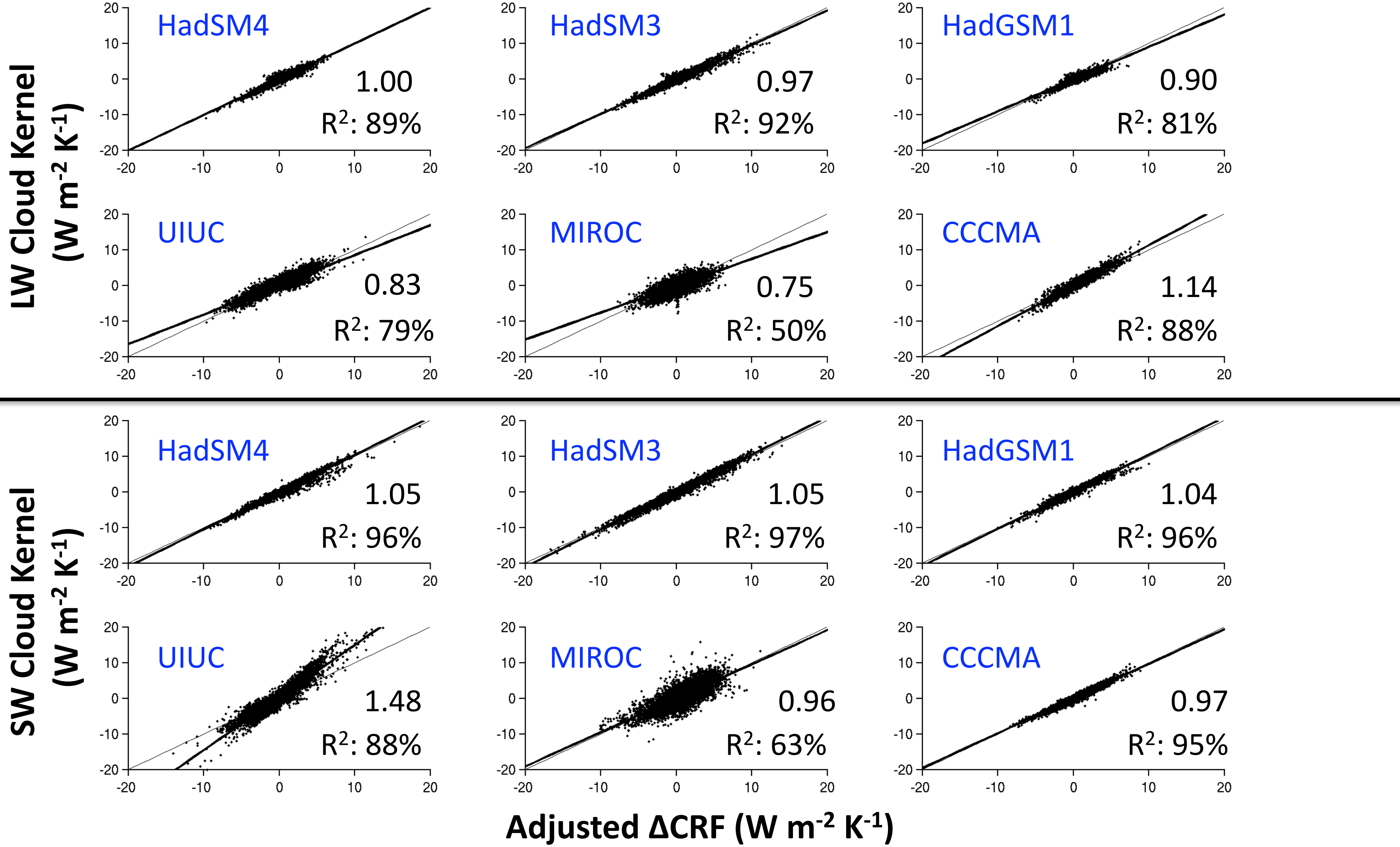
x Cloud Radiative Kernels
at each location and month,
then averaged annually,
globally, and across models…

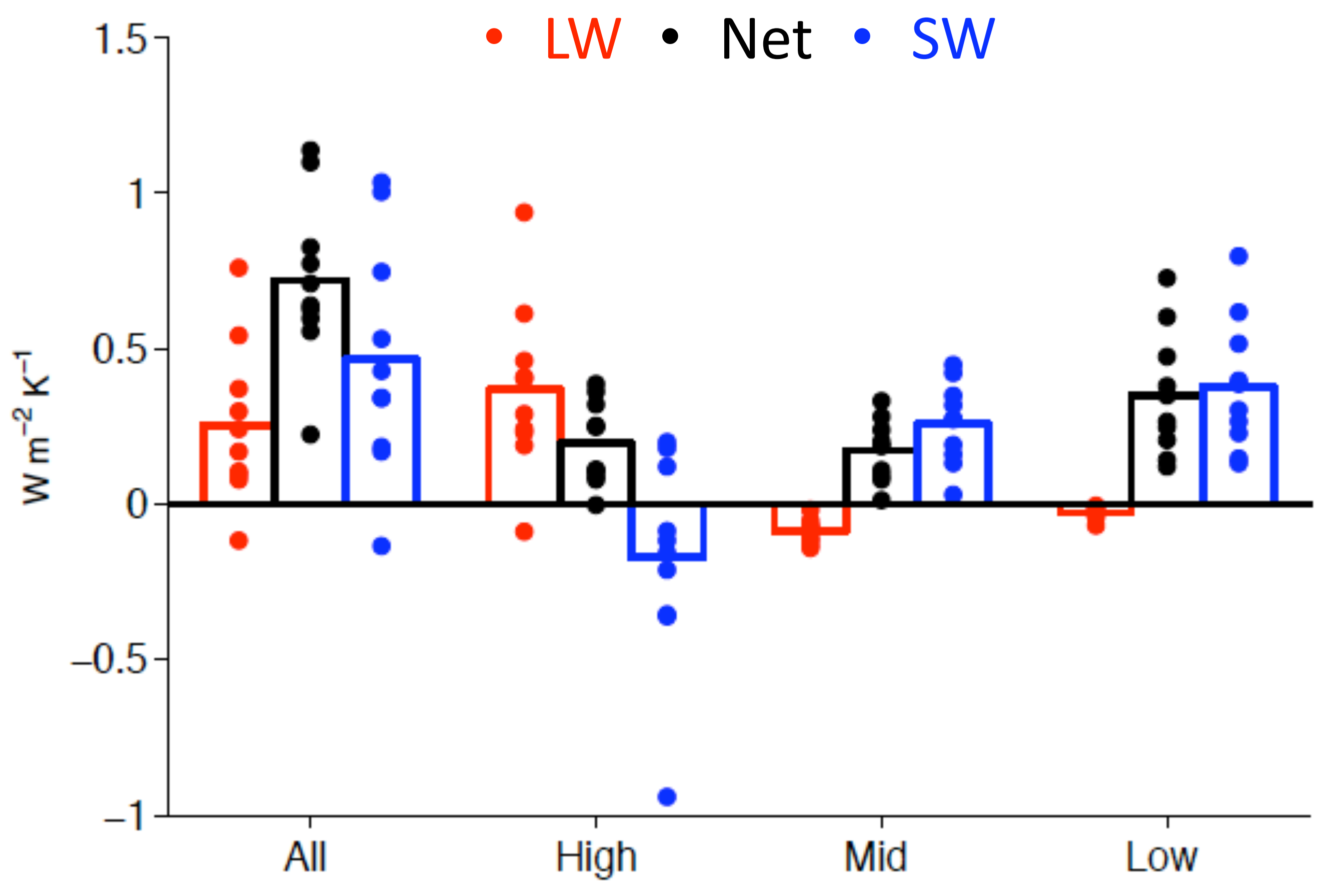


1xCO2
58.1 %
2xCO2
56.8 %
Change
-0.5 % K-1
Cloud Fraction
Cloud Feedback
CTP (hPa)
50
180
310
440
560
680
800
1000
%
0 % K−1
0 W m
0.15
0.1
0.05
−0.05
−0.1
−0.15
0
0.3
1.3
3.6
9.4
23
60
380
τ
LW
0.20 Wm-2K-1
SW
0.37 Wm-2K-1
Net
0.58 Wm-2K-1

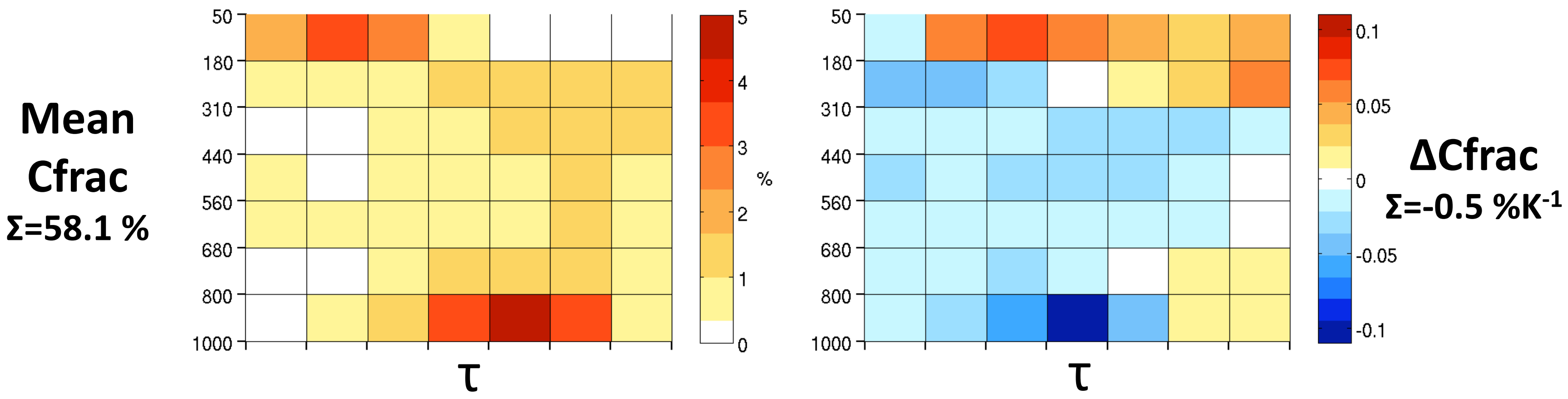


Cloud Kernel
Adjusted ΔCRF
Kernel minus
Adjusted ΔCRF
LW
0.21 W m-2 K-1
0.36 W m-2 K-1
-0.15 W m-2 K-1
SW
0.35 W m-2 K-1
0.39 W m-2 K-1
-0.04 W m-2 K-1
Net
0.56 W m-2 K-1
0.75 W m-2 K-1
-0.20 W m-2 K-1
5
0
-5


LW Cloud Kernel (W m-2 K-1)
SW Cloud Kernel (W m-2 K-1)
Adjusted ΔCRF (W m-2 K-1)
HadSM4
1.00
R2: 89%
HadSM3
0.97
R2: 92%
HadGSM1
0.90
R2: 81%
UIUC
0.83
R2: 79%
MIROC
0.75
R2: 50%
CCCMA
1.14
R2: 88%
HadSM4
1.05
R2: 96%
HadSM3
1.05
R2: 97%
HadGSM1
1.04
R2: 96%
UIUC
1.48
R2: 88%
MIROC
0.96
R2: 63%
CCCMA
0.97
R2: 95%



• LW • Net • SW
1.5
1
0.5
0
−0.5
−1
W m^{-2} K^{-1}
All
High
Mid
Low



- Decompose the cloud changes into

ΔAMOUNT

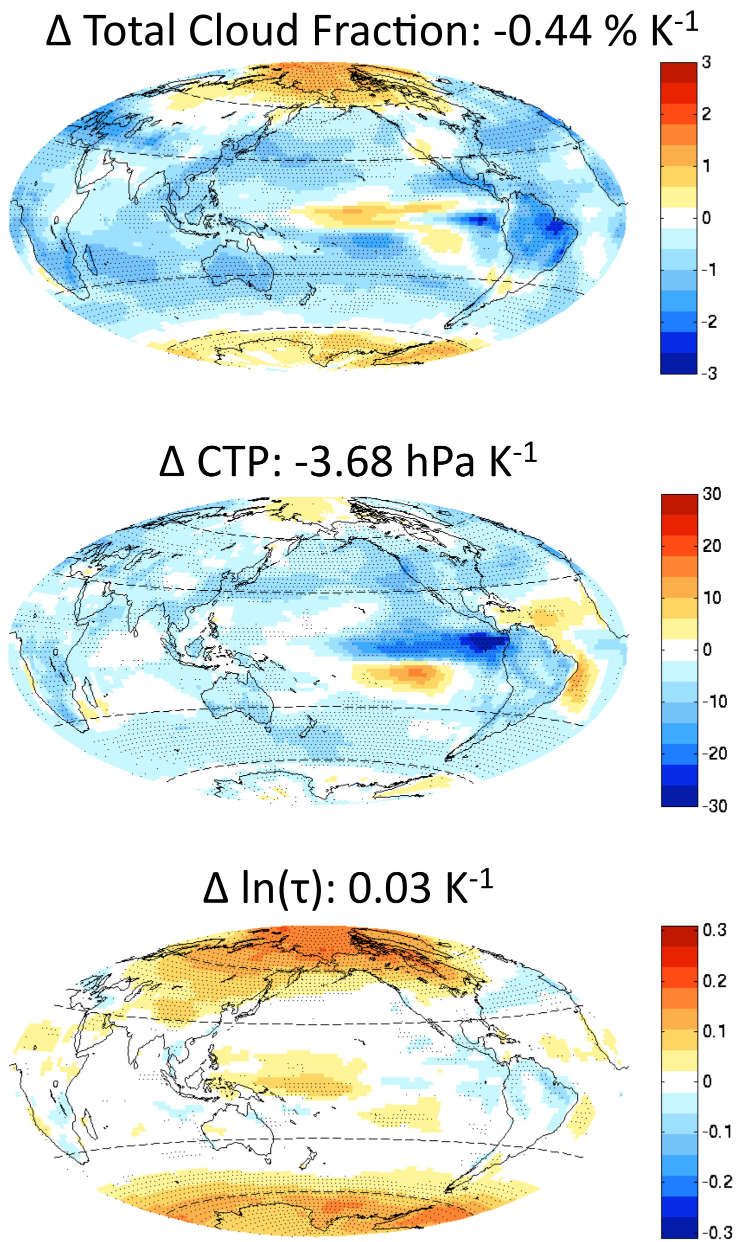
ΔALTITUDE

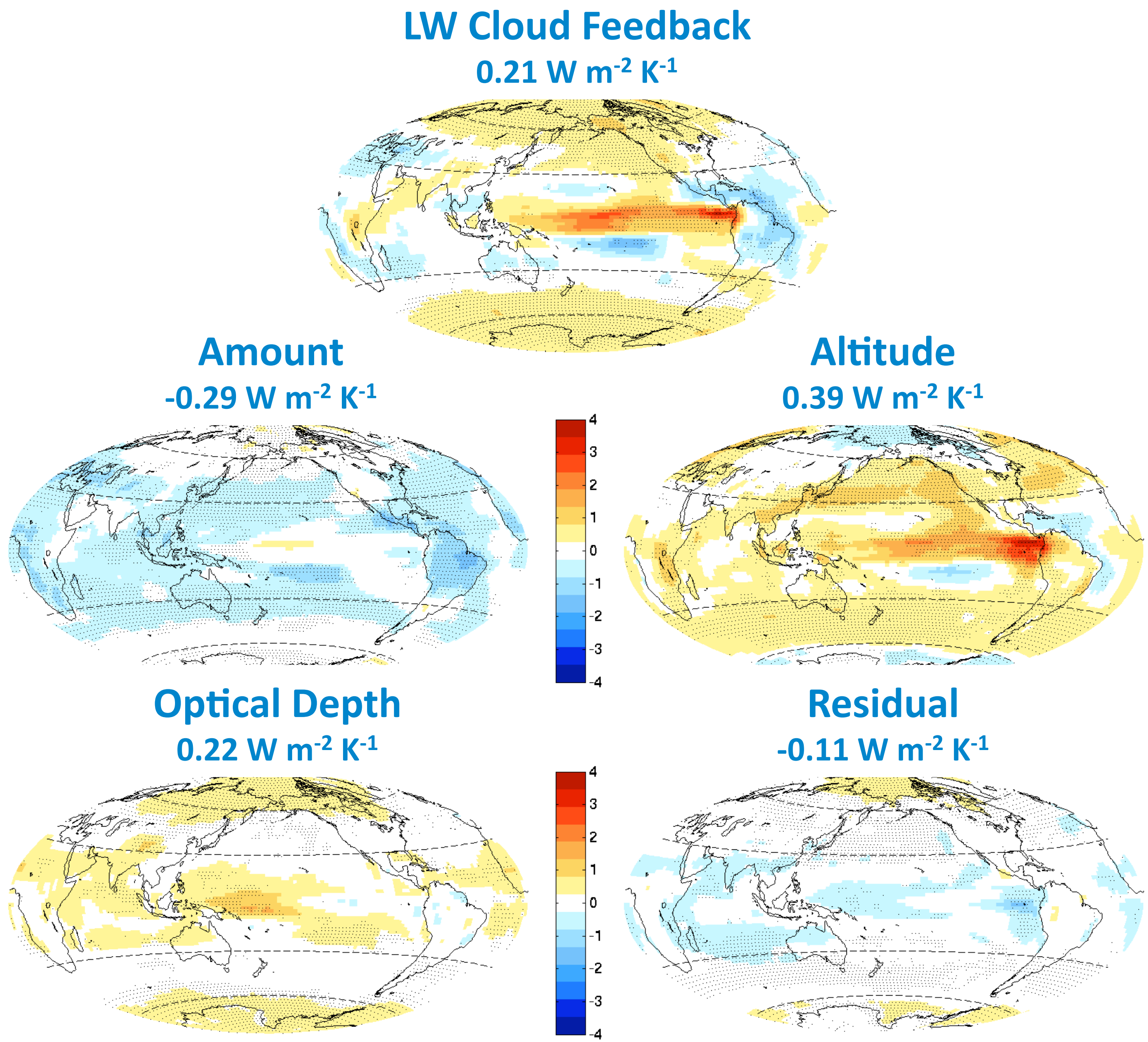
ΔOPTICAL DEPTH

Clouds go away

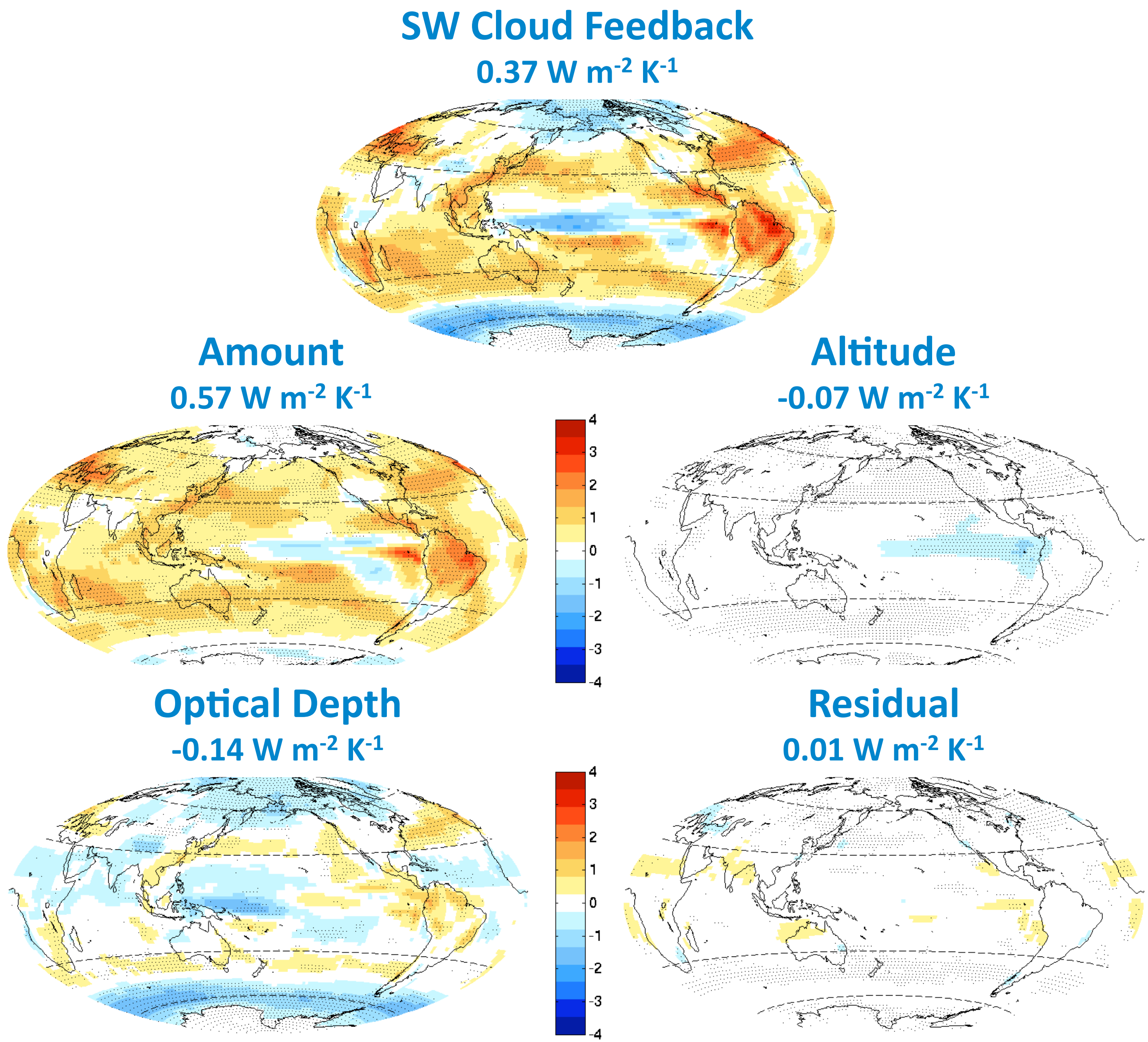
Clouds rise

Cold clouds get thicker

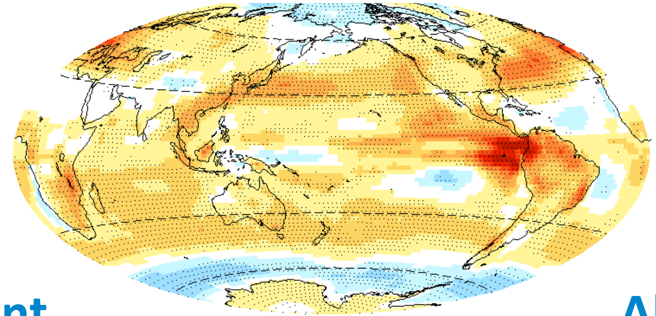




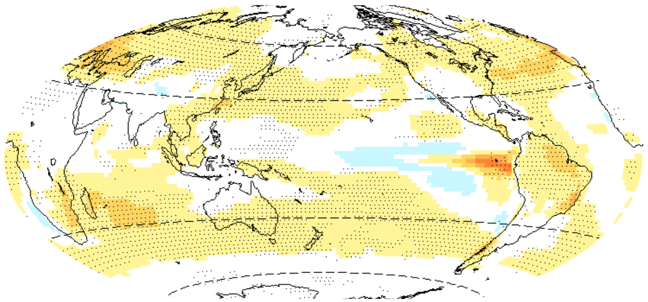
LW Cloud Feedback
0.21 W m^{-2} K^{-1}
Amount
-0.29 W m^{-2} K^{-1}
Altitude
0.39 W m^{-2} K^{-1}
Optical Depth
0.22 W m^{-2} K^{-1}
Residual
-0.11 W m^{-2} K^{-1}
4
3
2
1
0
-1
-2
-3
-4

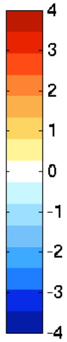

SW Cloud Feedback
0.37 W m^{-2} K^{-1}
Amount
0.57 W m^{-2} K^{-1}
Altitude
-0.07 W m^{-2} K^{-1}
Optical Depth
-0.14 W m^{-2} K^{-1}
Residual
0.01 W m^{-2} K^{-1}
4
3
2
1
0
-1
-2
-3
-4

Net Cloud Feedback
0.57 W m^{-2} K^{-1}

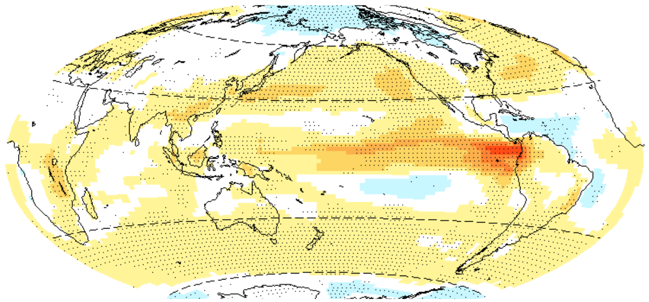


Amount
0.27 W m^{-2} K^{-1}

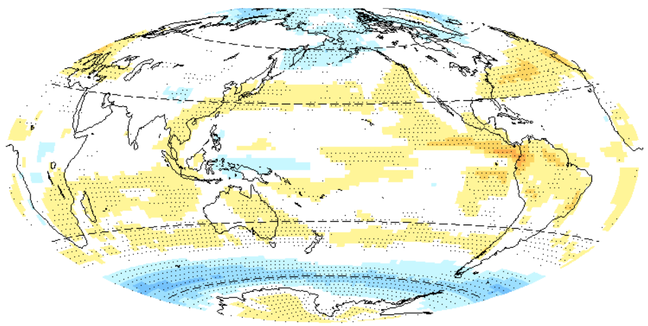


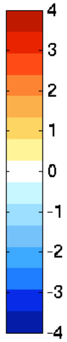


Altitude
0.33 W m^{-2} K^{-1}

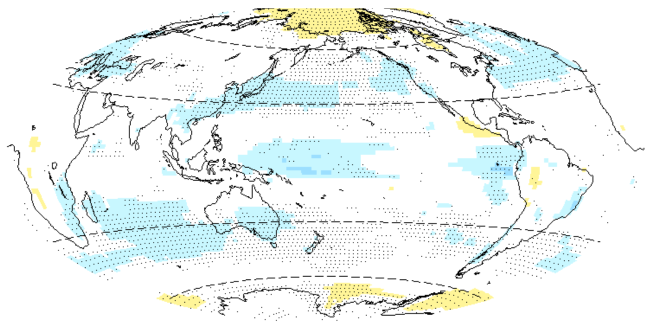


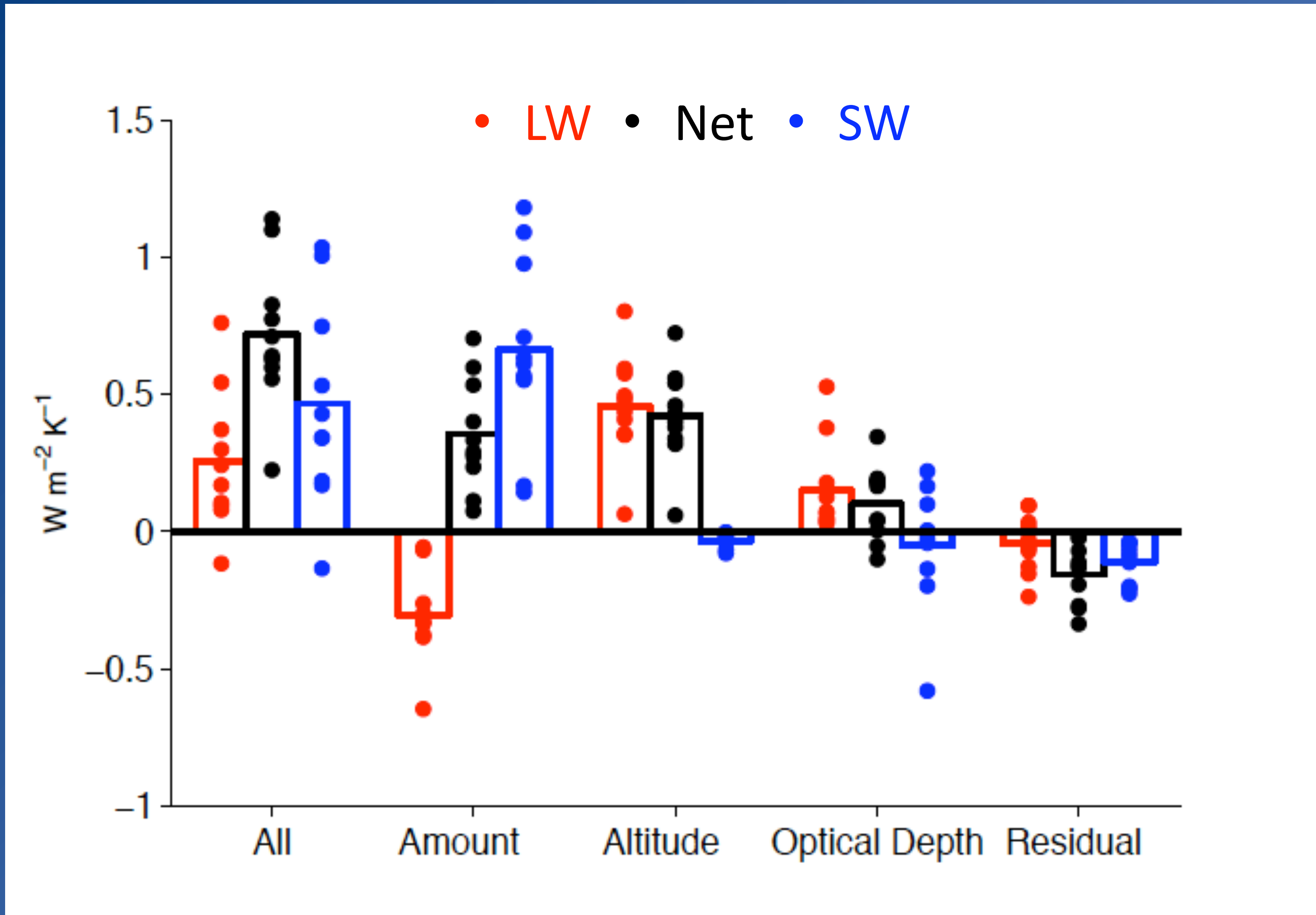
Optical Depth
0.07 W m^{-2} K^{-1}





Residual
-0.10 W m^{-2} K^{-1}





• LW • Net • SW
1.5
1
0.5
0
−0.5
−1
W m−2 K−1
All
Amount
Altitude
Optical Depth
Residual

Conclusions

- Cloud radiative kernels allow computation of cloud feedback directly from cloud fraction histograms produced by ISCCP simulator
- Feedbacks computed with cloud kernels compare very well with those computed by adjusting the change in cloud forcing
- More than half of the global mean net cloud feedback can be attributed to the combined response of middle- and high-level clouds
- High cloud changes induce a wider range of LW and SW cloud feedbacks across models than do low clouds
- Increasing cloud top altitude is dominant contributor to the positive global mean LW and net cloud feedbacks (positive in every model)
- Decreasing total cloud fraction is dominant contributor to global mean positive SW cloud feedback (positive in every model)
- Large negative net cloud feedback at high latitudes is caused by increased optical depth, not increased cloud amount

Thank you!

Drafts of papers: Google "Mark Zelinka"

- This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and was supported by the Regional and Global Climate Program of the Office of Science at the U. S. Department of Energy and by NASA Grant NNX09AH73G at the University of Washington.

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Conclusions (1 of 2)

- Cloud radiative kernels allow computation of cloud feedback directly from cloud property histograms generated by ISCCP simulator
  - Standard radiative transfer and definition of "cloud" across models
  - No cloud masking adjustments necessary
  - Simple calculation (multiply two matrices) on monthly mean output
  - Can quantify contribution to feedback from individual cloud types / processes
- Feedbacks computed with cloud kernels compare very well with those computed by adjusting the change in cloud forcing
- Ensemble (10 model) mean results:
  - Low cloud changes are dominant contributor to SW cloud feedback
  - High cloud changes are dominant contributor to LW cloud feedback
  - More than half of the global mean net cloud feedback can be attributed to the combined response of middle- and high-level clouds
  - High cloud changes induce wider range of LW and SW cloud feedbacks across models than do low clouds

Conclusions (2 of 2)

- **Increasing cloud top altitude** is dominant contributor to the **positive global mean LW and net cloud feedbacks (positive in every model)**

- **Decreasing total cloud fraction** is dominant contributor to global mean **positive SW cloud feedback (positive in every model)**
  - Inter-model **spread is greater** than for any other feedback component
  - Overall cloud amount reductions have **2x as large** an impact on SW as on LW fluxes

- **Large negative net cloud feedback at high latitudes** is caused by **increased optical depth**, not increased cloud amount
  - Results from **increased cloud water content and phase changes from ice to liquid**

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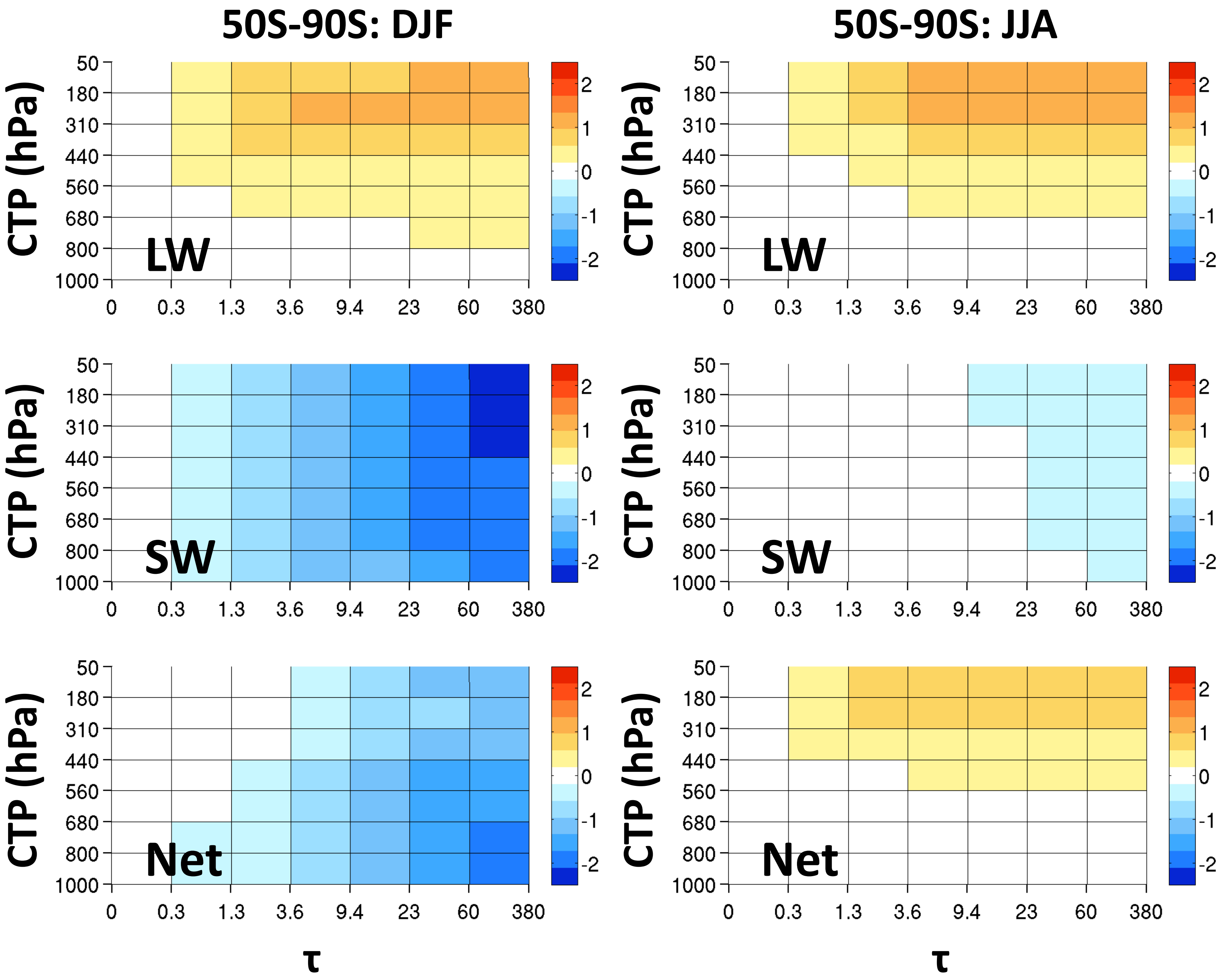
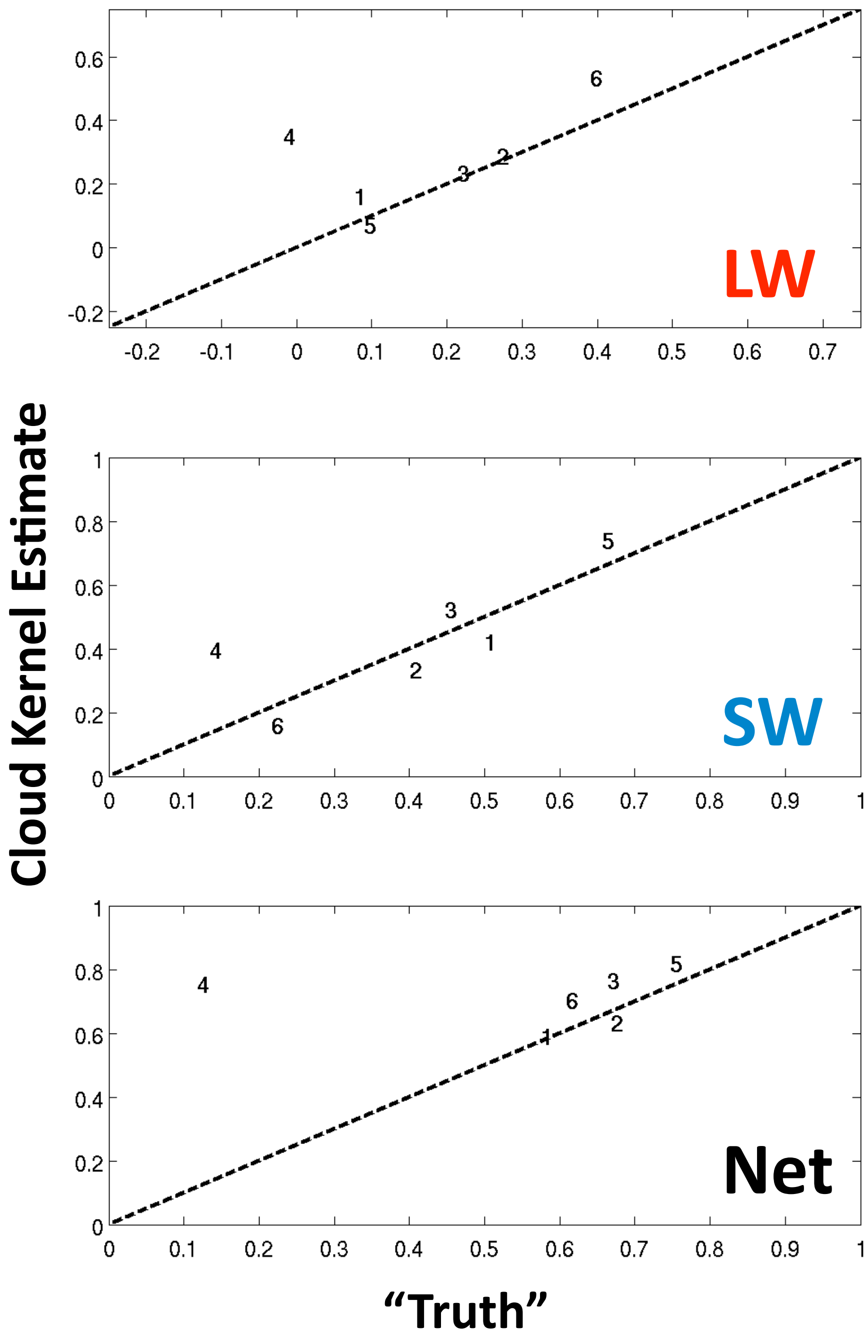
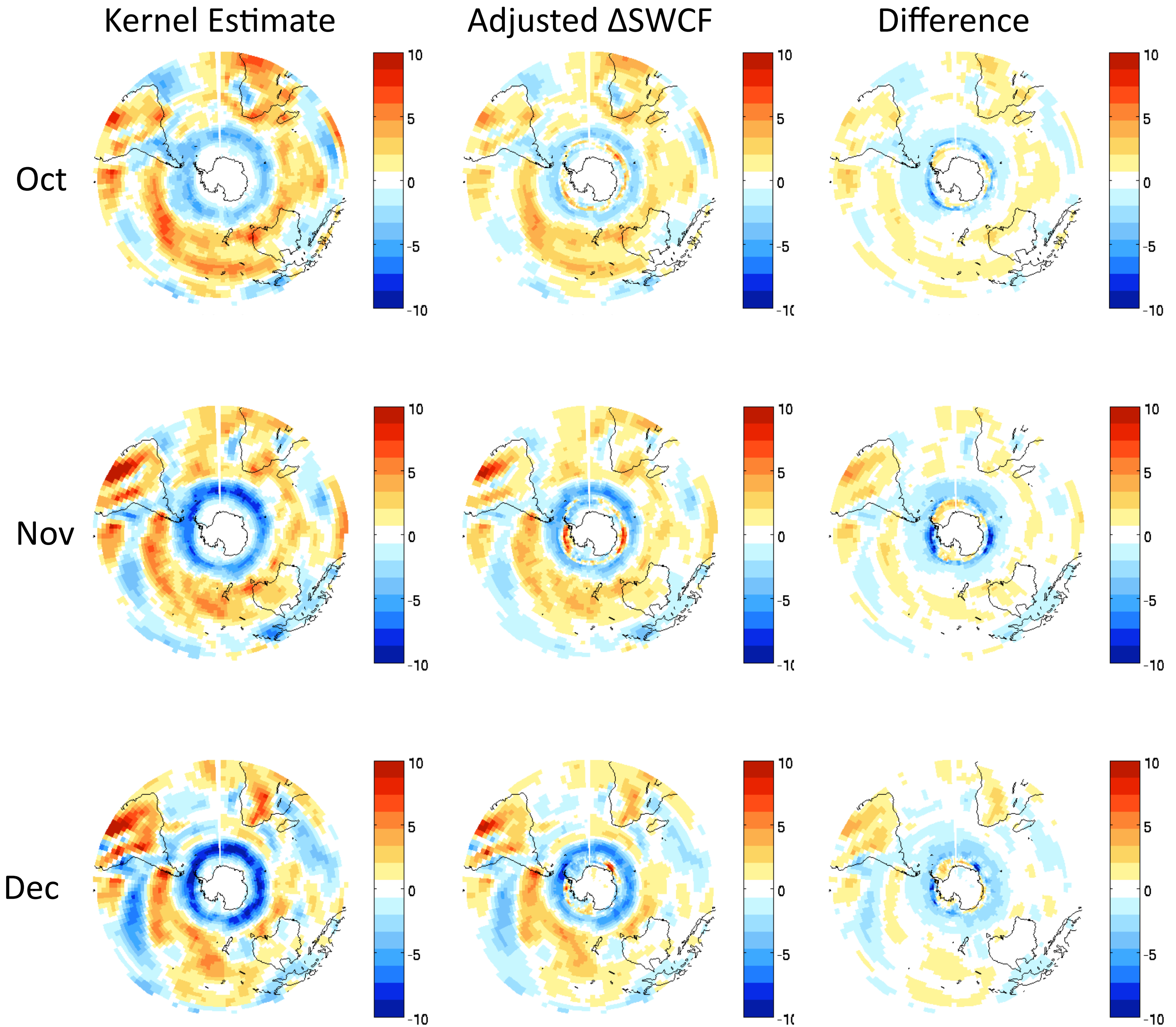
Extra Slides

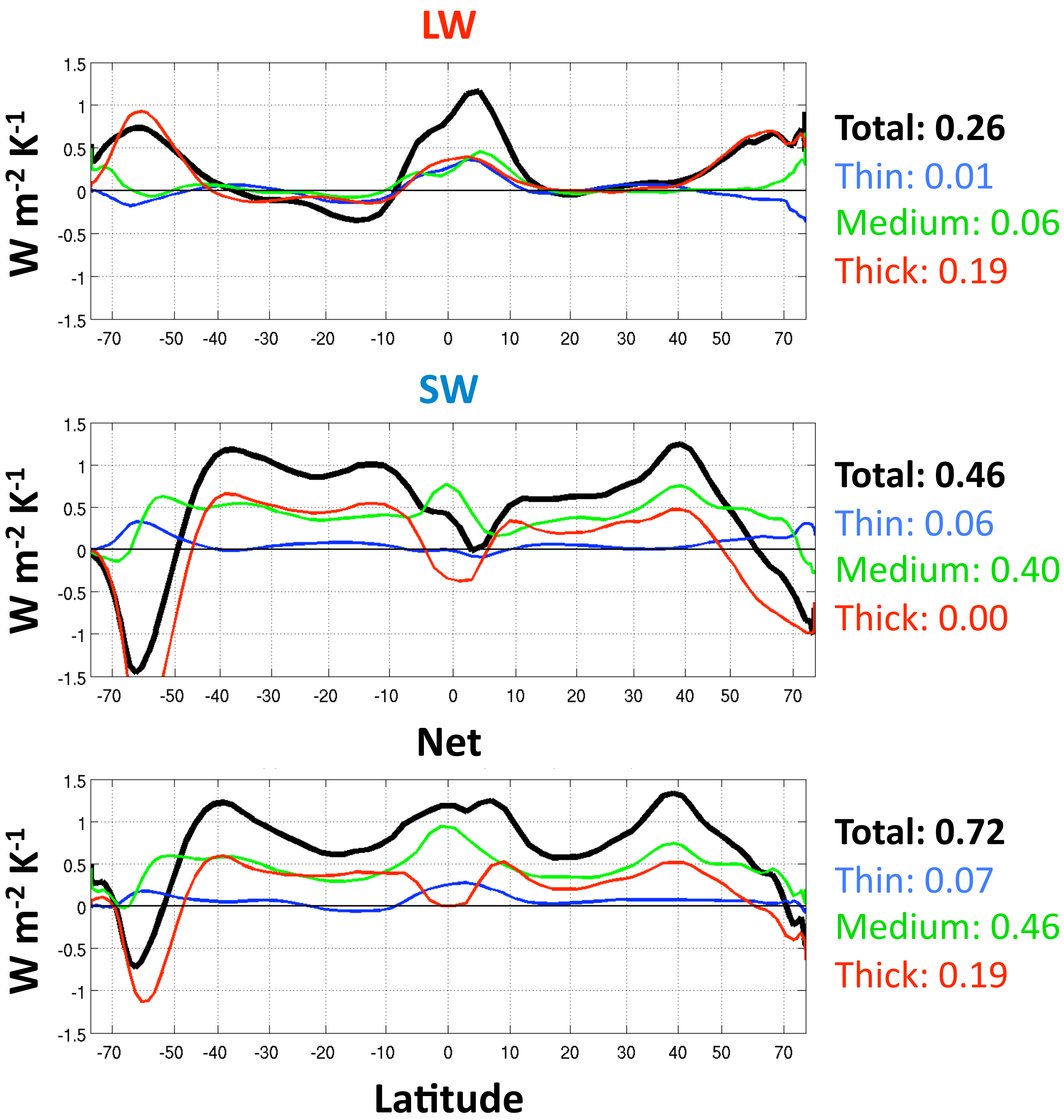


50S-90S: DJF
50S-90S: JJA
CTP (hPa)
LW
SW
Net
50
180
310
440
560
680
800
1000
0
0.3
1.3
3.6
9.4
23
60
380
2
1
0
-1
-2
τ

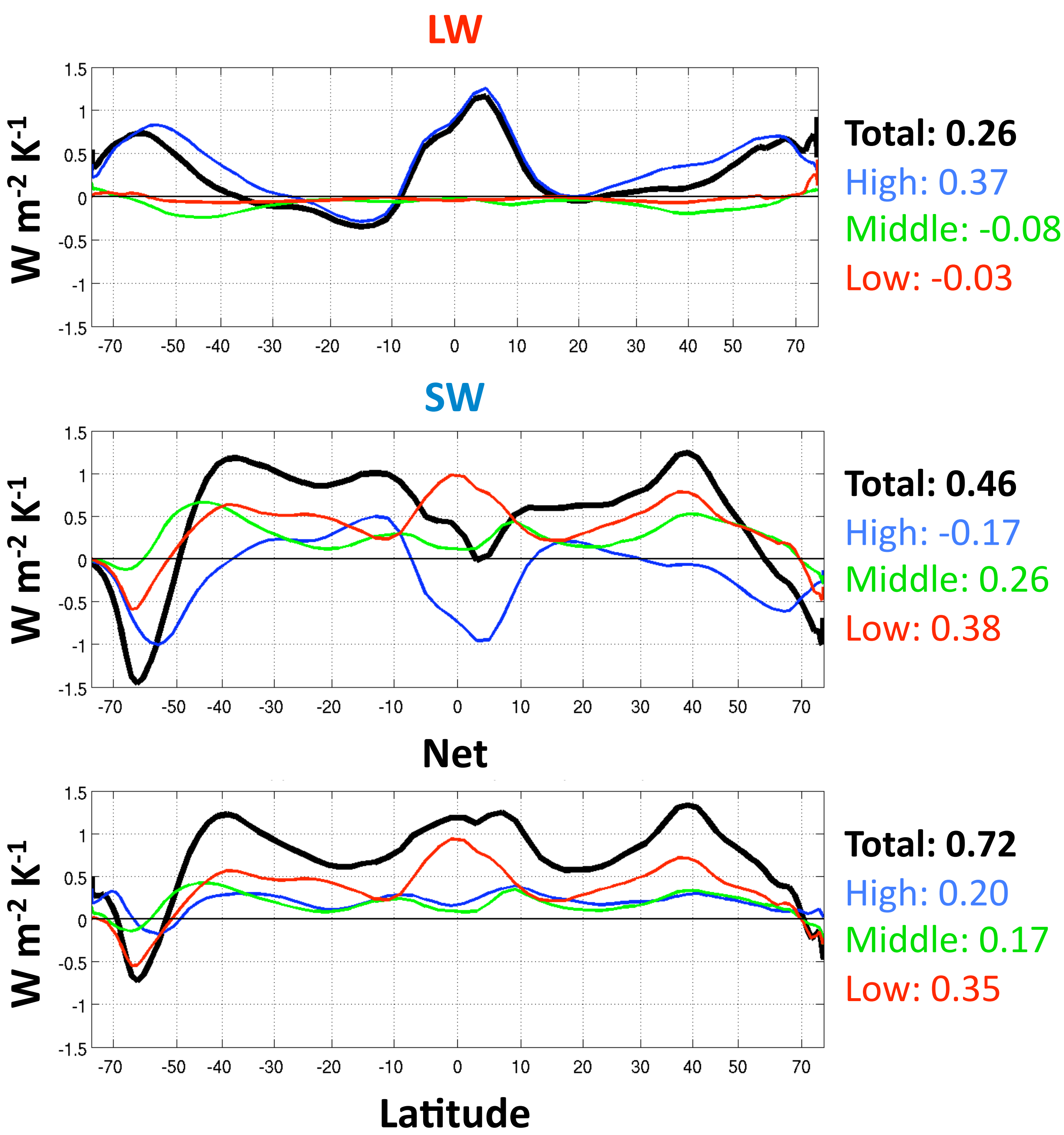
1. ukmo_hadsm4
2. ukmo_hadsm3
3. ukmo_hadgsm1
4. uiuc
5. miroc_losens
6. cccma_agcm4.0

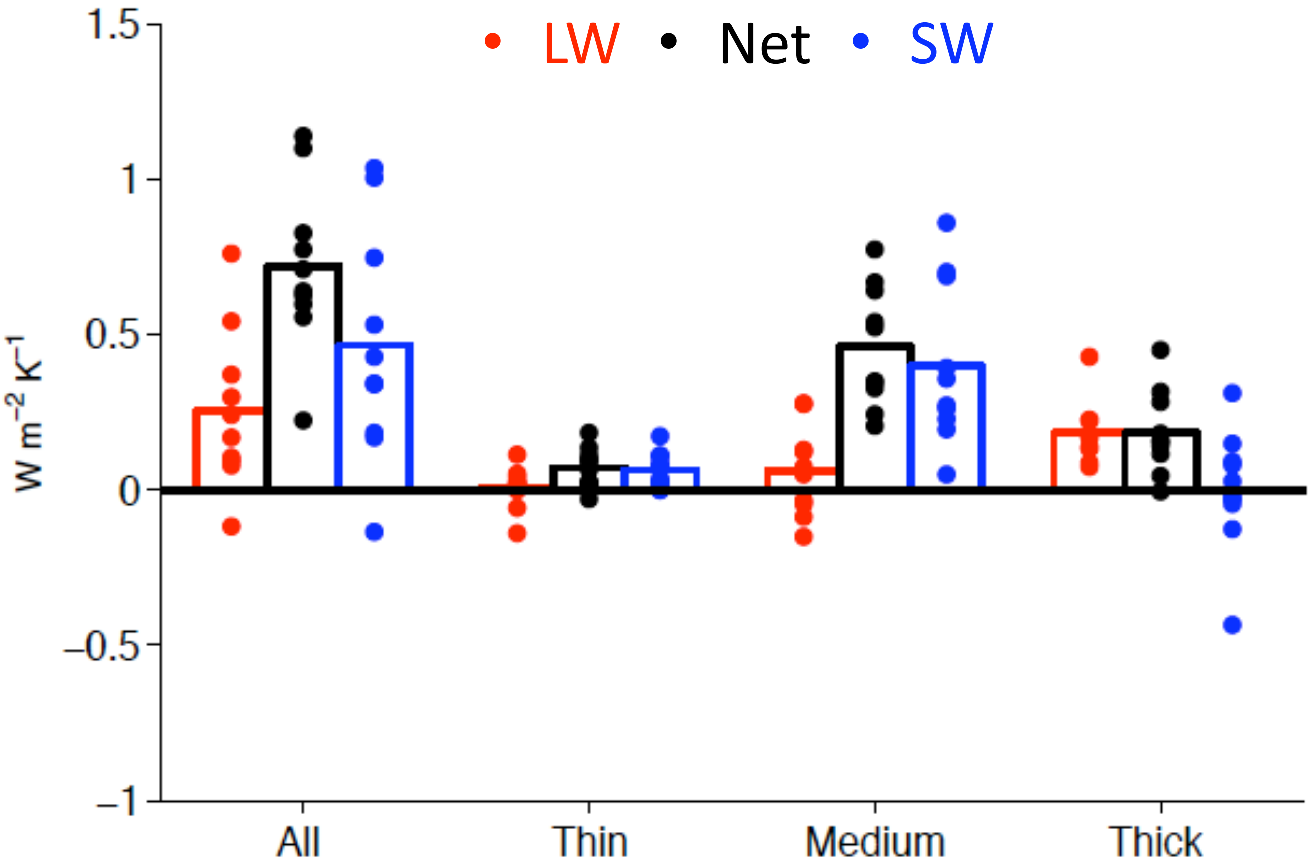



Kernel Estimate
Adjusted ΔSWCF
Difference
Oct
Nov
Dec
10
5
0
-5
-10

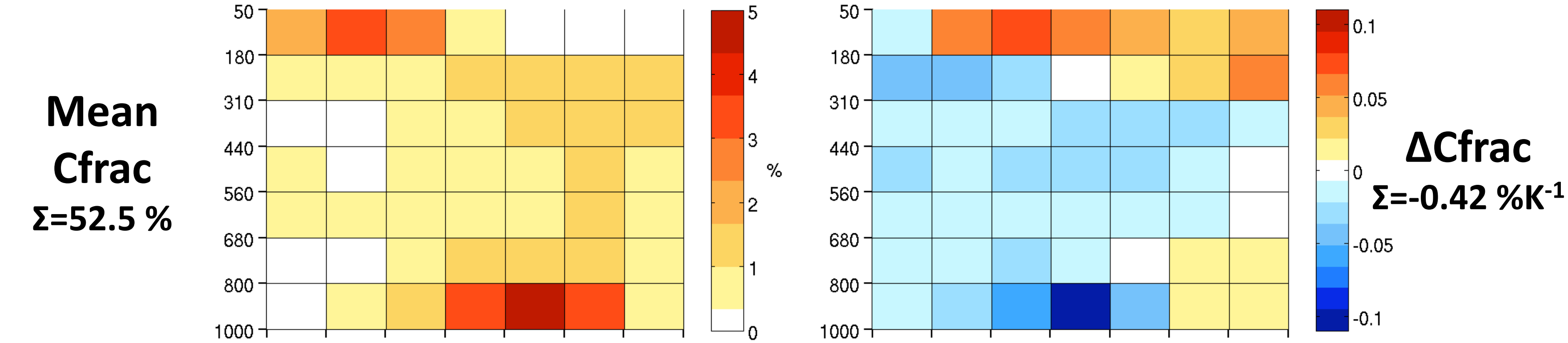


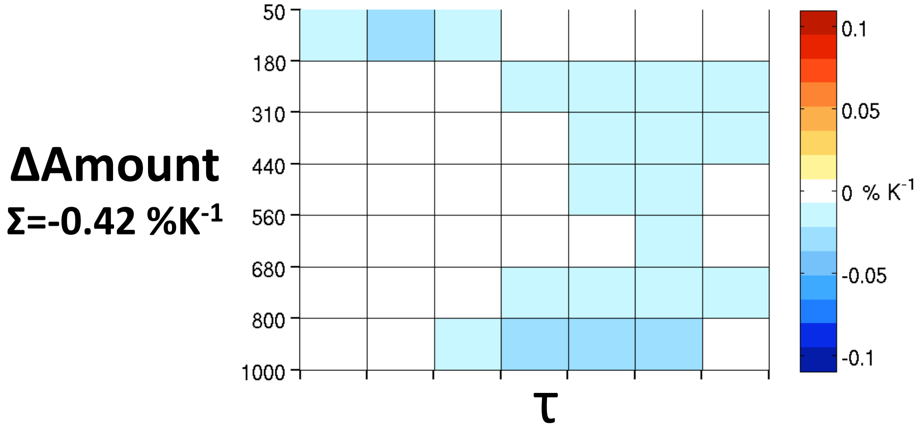
LW
Total: 0.26
Thin: 0.01
Medium: 0.06
Thick: 0.19
SW
Total: 0.46
Thin: 0.06
Medium: 0.40
Thick: 0.00
Net
Total: 0.72
Thin: 0.07
Medium: 0.46
Thick: 0.19
W m-2 K-1
1.5
1
0.5
0
-0.5
-1
-1.5
-70
-50
-40
-30
-20
-10
0
10
20
30
40
50
70
Latitude


LW
W m-2 K-1
Total: 0.26
High: 0.37
Middle: -0.08
Low: -0.03
SW
Total: 0.46
High: -0.17
Middle: 0.26
Low: 0.38
Net
Total: 0.72
High: 0.20
Middle: 0.17
Low: 0.35
Latitude

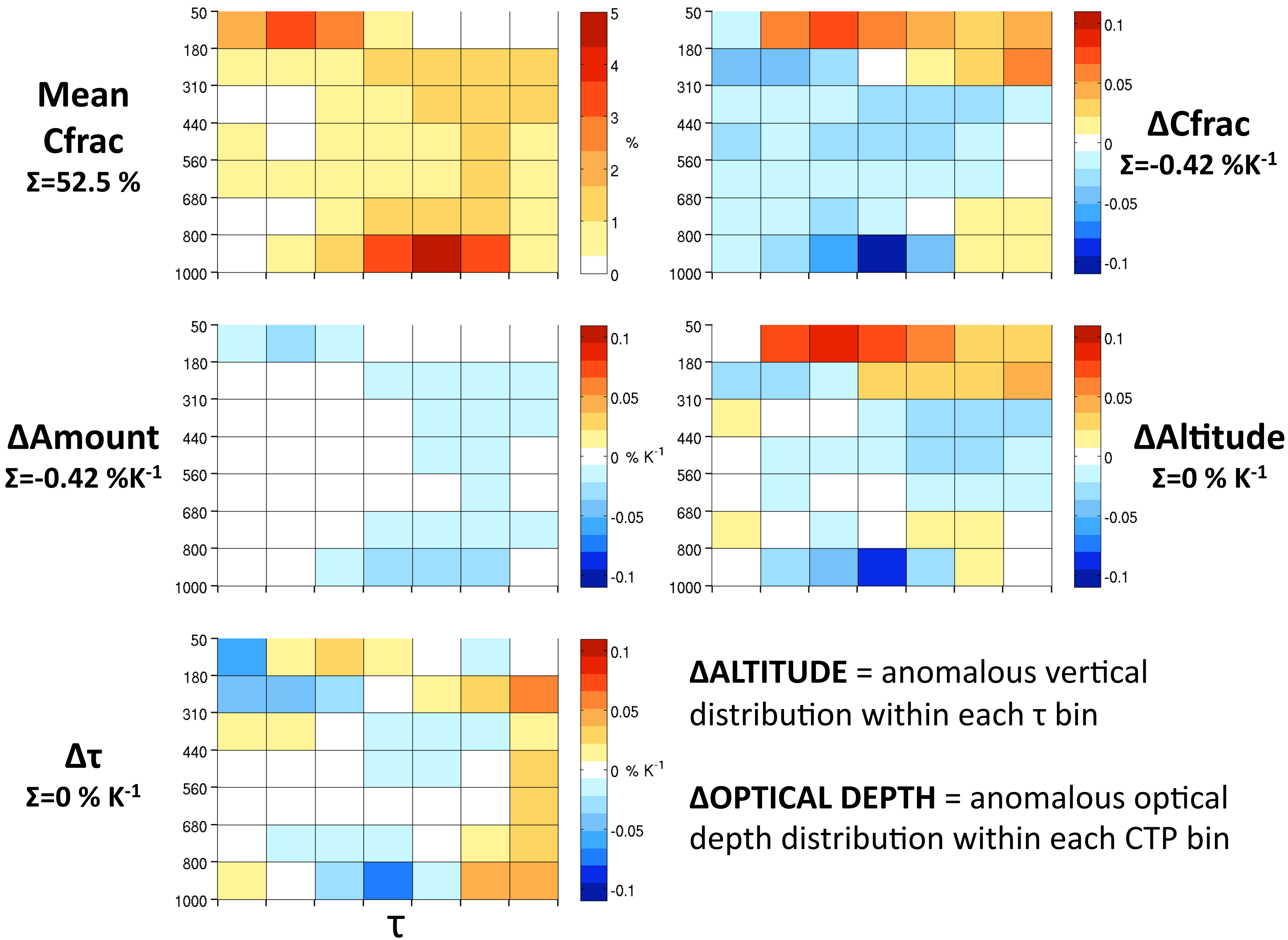


• LW • Net • SW
1.5
1
0.5
0
–0.5
–1
W m^{-2} K^{-1}
All
Thin
Medium
Thick



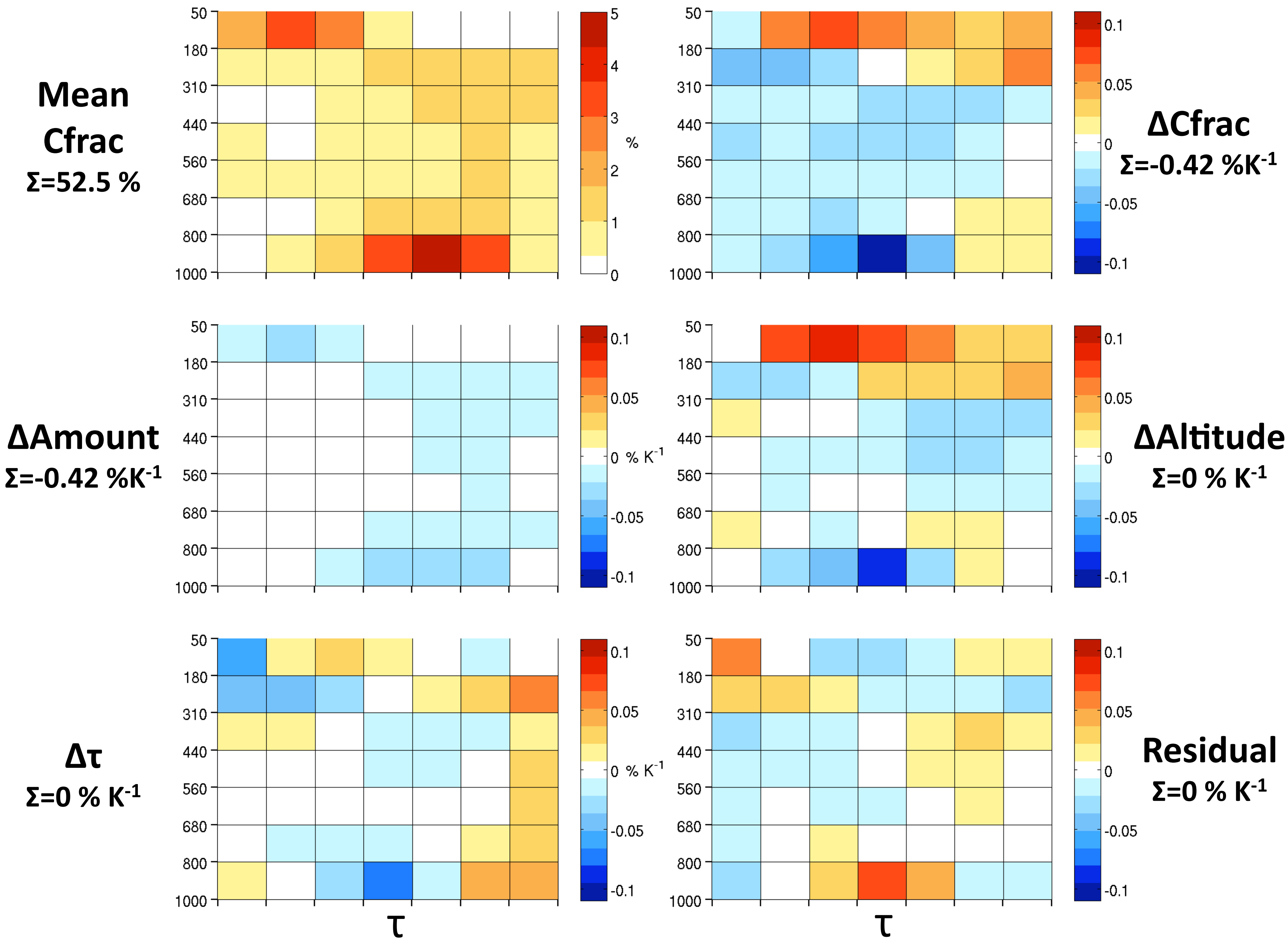


ΔAMOUNT = cloud fraction altered in proportion to amount in $1xCO_2$ histogram; no change in vertical or optical depth distribution

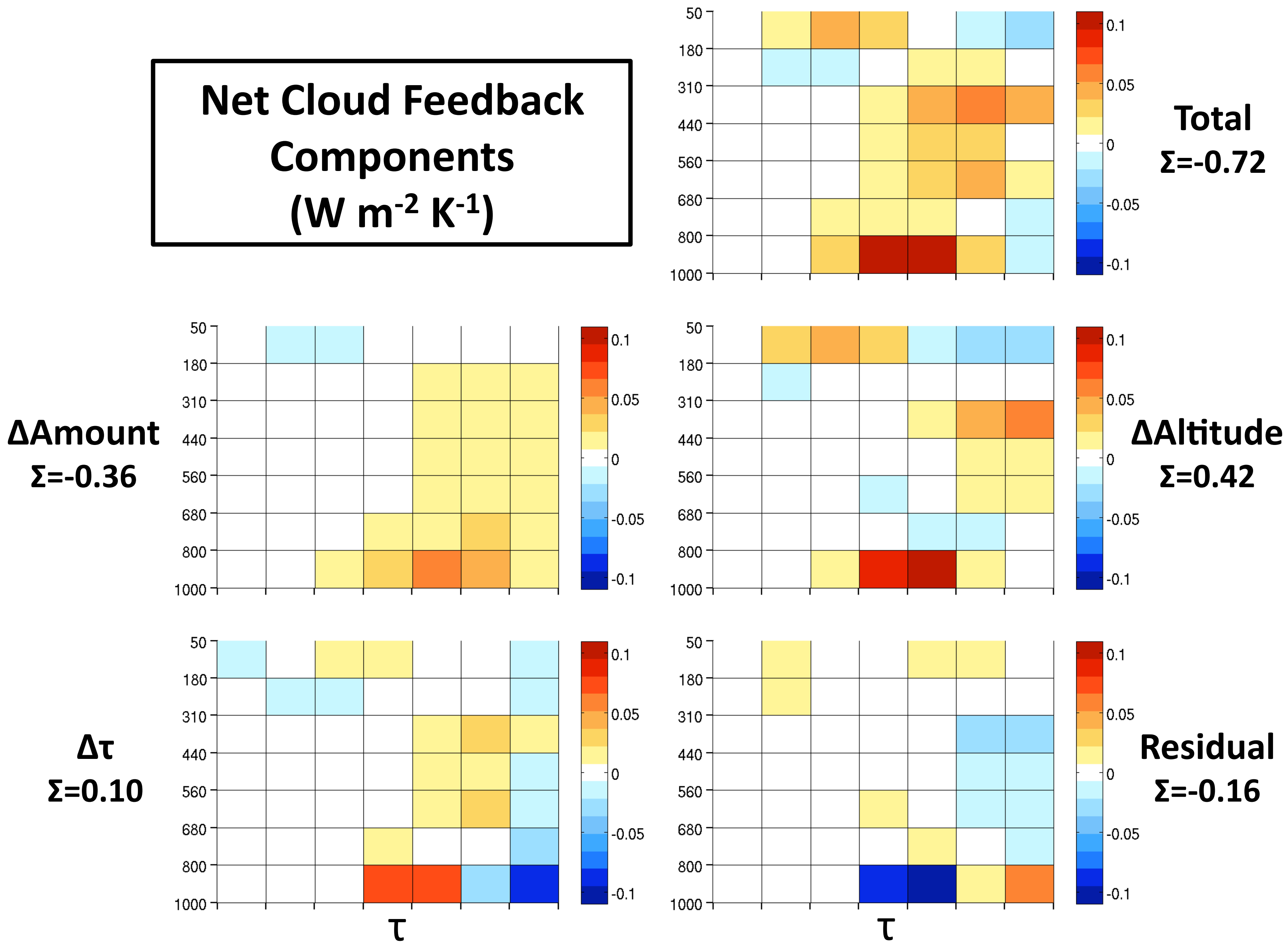


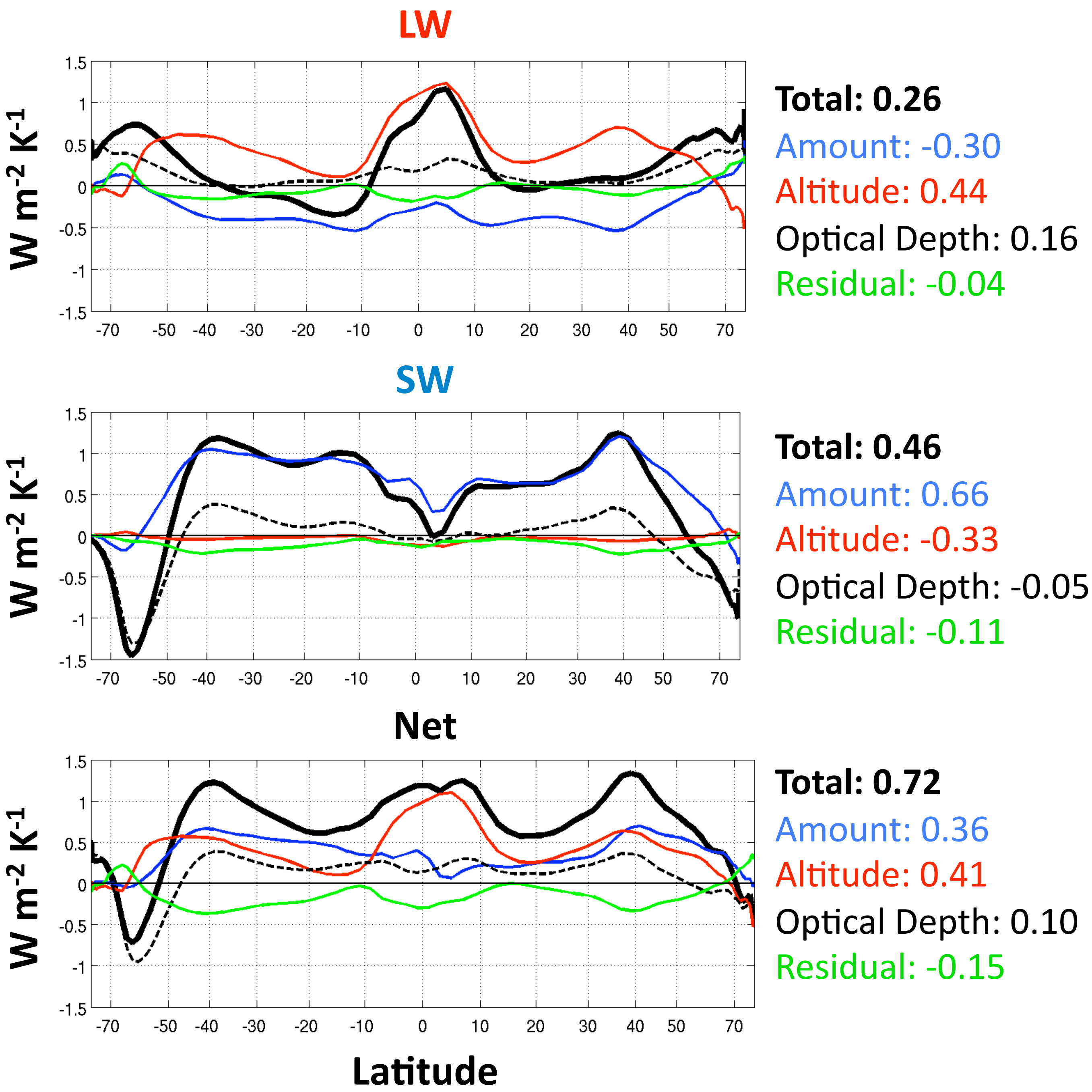
ΔALTITUDE = anomalous vertical distribution within each τ bin

ΔOPTICAL DEPTH = anomalous optical depth distribution within each CTP bin



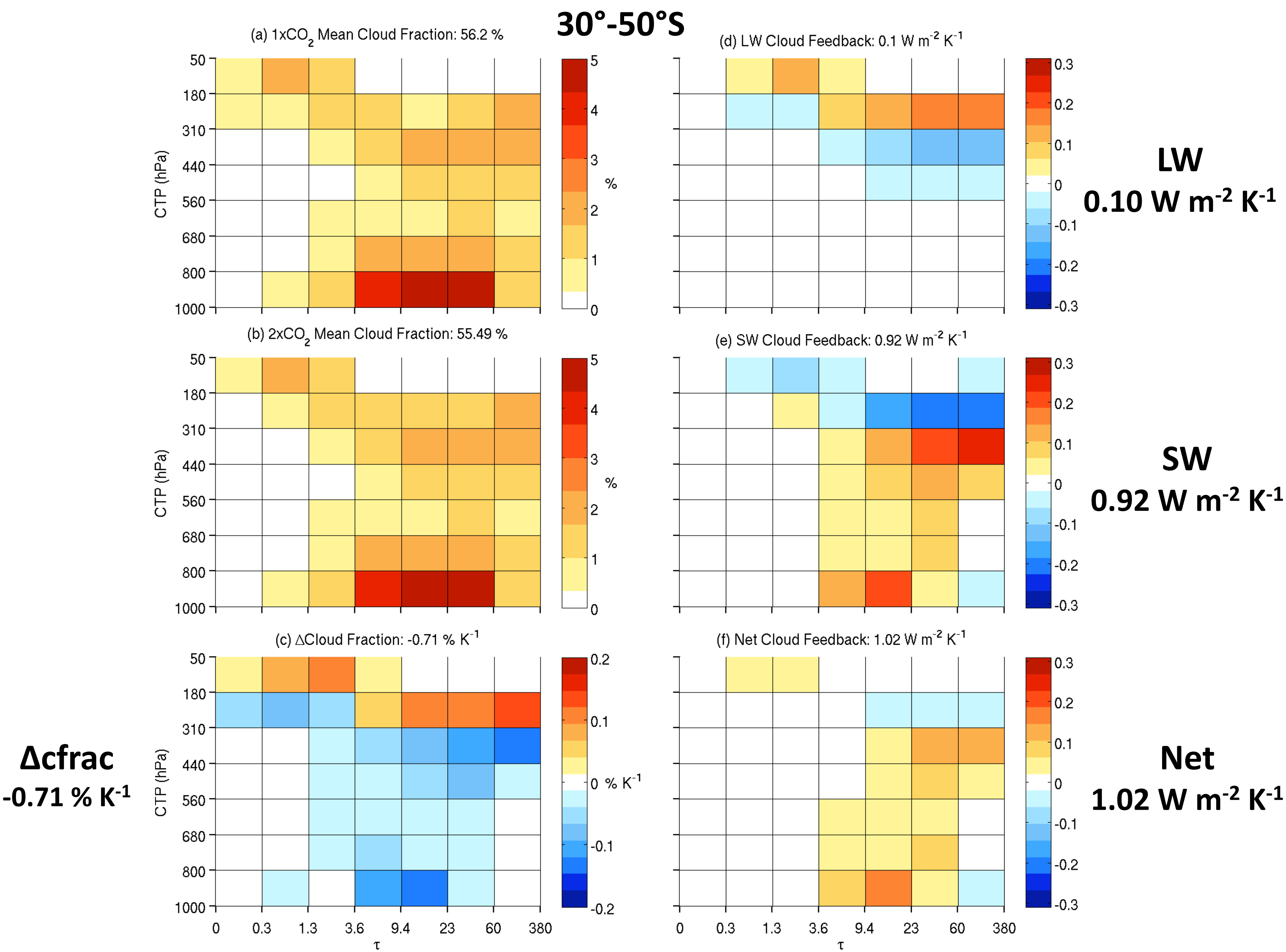
Mean Cfrac
Σ=52.5 %
ΔCfrac
Σ=-0.42 %K-1
ΔAmount
Σ=-0.42 %K-1
ΔAltitude
Σ=0 % K-1
Δτ
Σ=0 % K-1
Residual
Σ=0 % K-1
τ
τ
%
% K-1
50
180
310
440
560
680
800
1000


Net Cloud Feedback Components
(W m-2 K-1)
Total
Σ=-0.72
ΔAmount
Σ=-0.36
ΔAltitude
Σ=0.42
Δτ
Σ=0.10
Residual
Σ=-0.16
50
180
310
440
560
680
800
1000
0.1
0.05
0
-0.05
-0.1
τ
τ

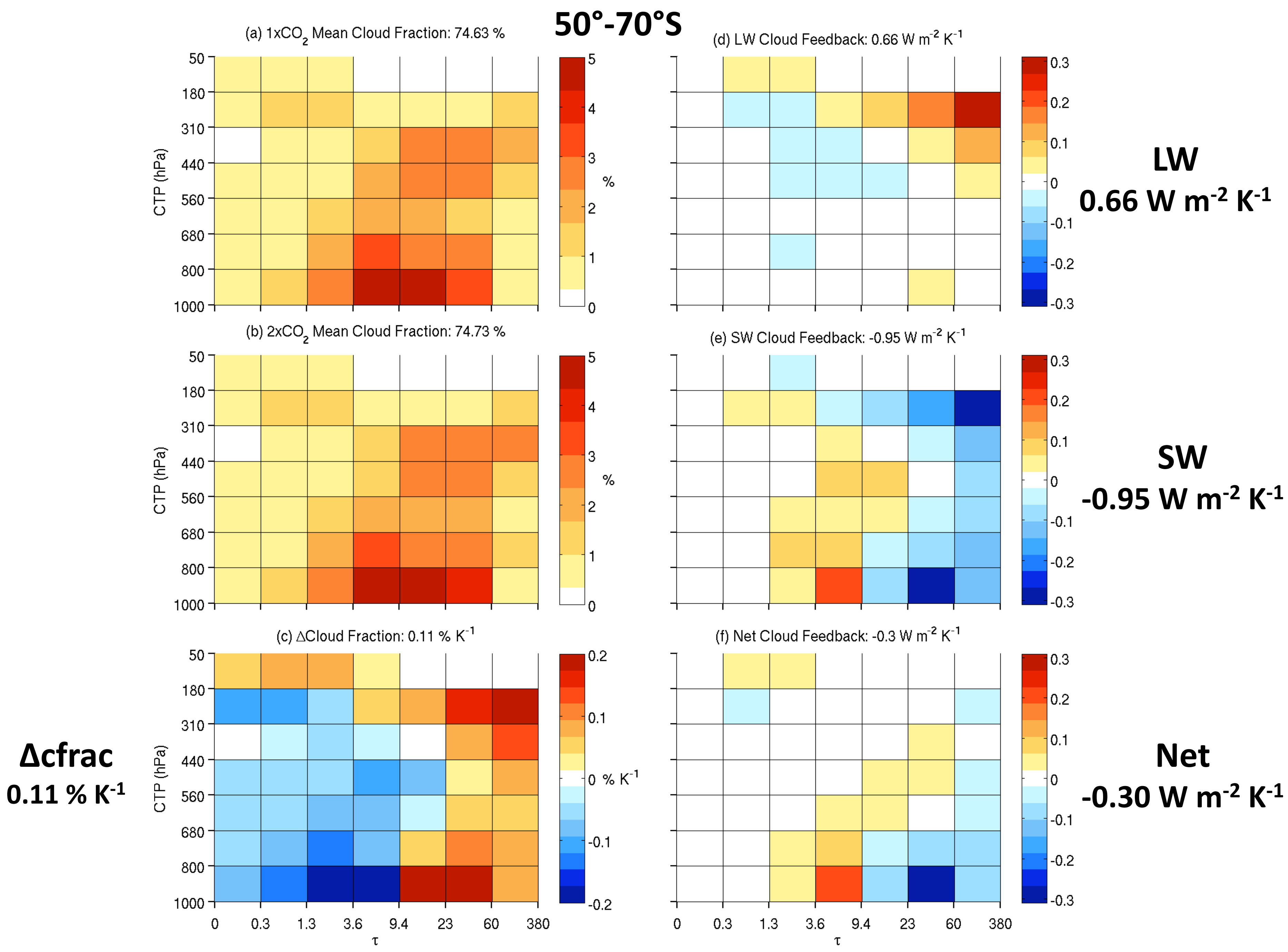

LW
Total: 0.26
Amount: -0.30
Altitude: 0.44
Optical Depth: 0.16
Residual: -0.04
SW
Total: 0.46
Amount: 0.66
Altitude: -0.33
Optical Depth: -0.05
Residual: -0.11
Net
Total: 0.72
Amount: 0.36
Altitude: 0.41
Optical Depth: 0.10
Residual: -0.15
W m-2 K-1
Latitude

SW optical depth feedback: Negative at high latitudes, Positive at low latitudes

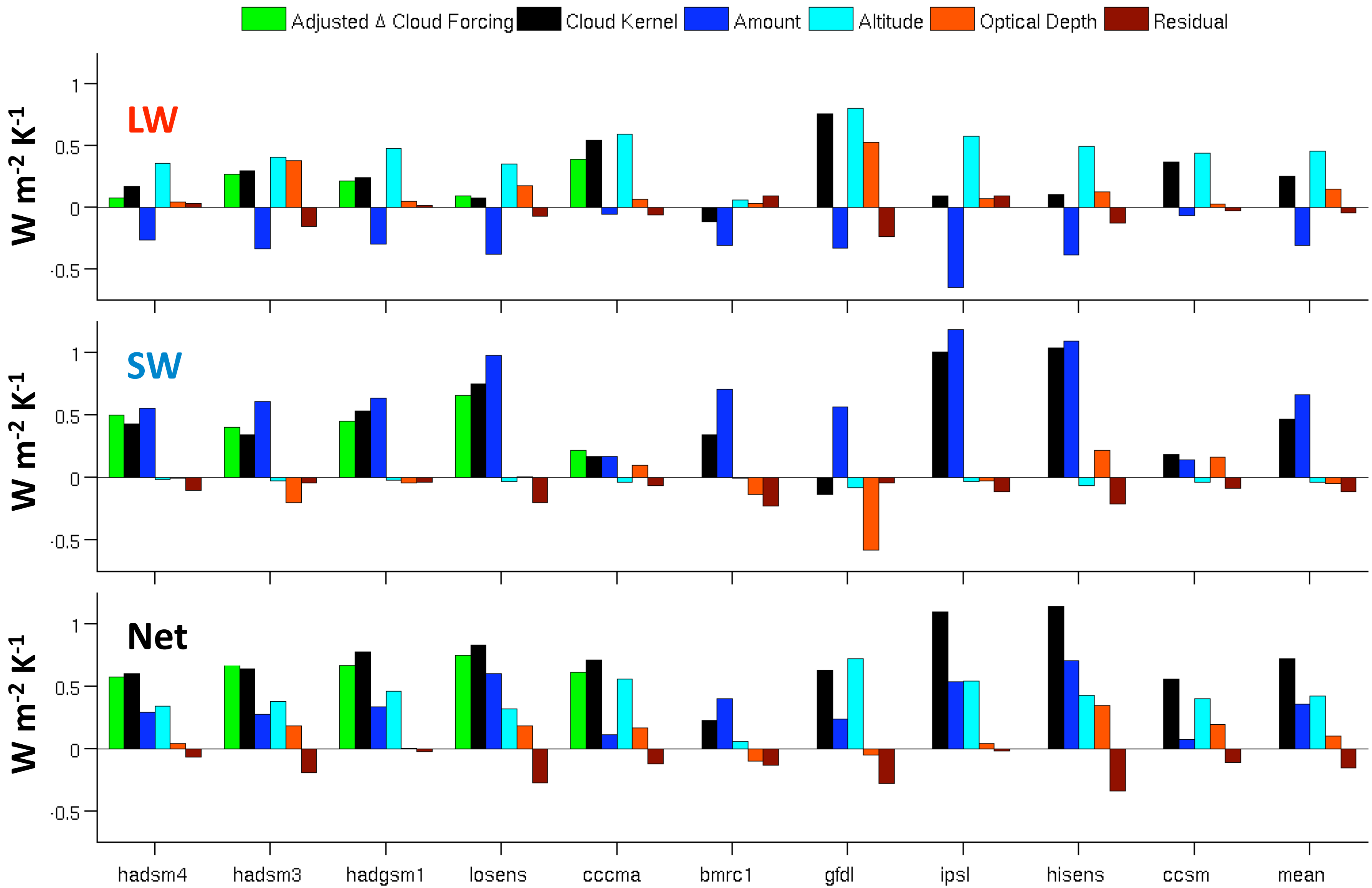
- Somerville & Remer (1984), Betts & Harshvardan (1987): warmer → more liquid water in clouds → brighter clouds (temperature sensitivity is twice as large at high latitudes)
- Tselioudis et al. (1992), Tselioudis & Rossow (1994), Chang and Coakley (2007): satellite observations indicate low cloud τ increases with T for cold clouds; opposite sensitivity for warm (low- and mid-latitude) clouds
- Senior & Mitchell (1993), Tsushima et al. (2006): replacing ice with liquid → less efficient to precipitate (B-F effect) → more cloud water
- Timescale invariance of optical depth feedback?
  → Neil Gordon's talk yesterday



30°-50°S
(a) 1xCO2 Mean Cloud Fraction: 56.2 %
(b) 2xCO2 Mean Cloud Fraction: 55.49 %
(c) ΔCloud Fraction: -0.71 % K-1
(d) LW Cloud Feedback: 0.1 W m-2 K-1
(e) SW Cloud Feedback: 0.92 W m-2 K-1
(f) Net Cloud Feedback: 1.02 W m-2 K-1
CTP (hPa)
τ
%
% K-1
LW
0.10 W m-2 K-1
SW
0.92 W m-2 K-1
Net
1.02 W m-2 K-1
Δcfrac
-0.71 % K-1



50°-70°S
(a) 1xCO2 Mean Cloud Fraction: 74.63 %
(b) 2xCO2 Mean Cloud Fraction: 74.73 %
(c) ΔCloud Fraction: 0.11 % K-1
(d) LW Cloud Feedback: 0.66 W m-2 K-1
(e) SW Cloud Feedback: -0.95 W m-2 K-1
(f) Net Cloud Feedback: -0.3 W m-2 K-1
CTP (hPa)
50
180
310
440
560
680
800
1000
τ
0
0.3
1.3
3.6
9.4
23
60
380
%
% K-1
LW
0.66 W m-2 K-1
SW
-0.95 W m-2 K-1
Net
-0.30 W m-2 K-1
Δcfrac
0.11 % K-1



Adjusted Δ Cloud Forcing
Cloud Kernel
Amount
Altitude
Optical Depth
Residual
LW
SW
Net
W m-2 K-1
1
0.5
0
-0.5
hadsm4
hadsm3
hadgsm1
losens
cccma
bmrc1
gfdl
ipsl
hisens
ccsm
mean