On the variability of tropical radiative effects in CERES EBAF and historical CMIP6 simulations

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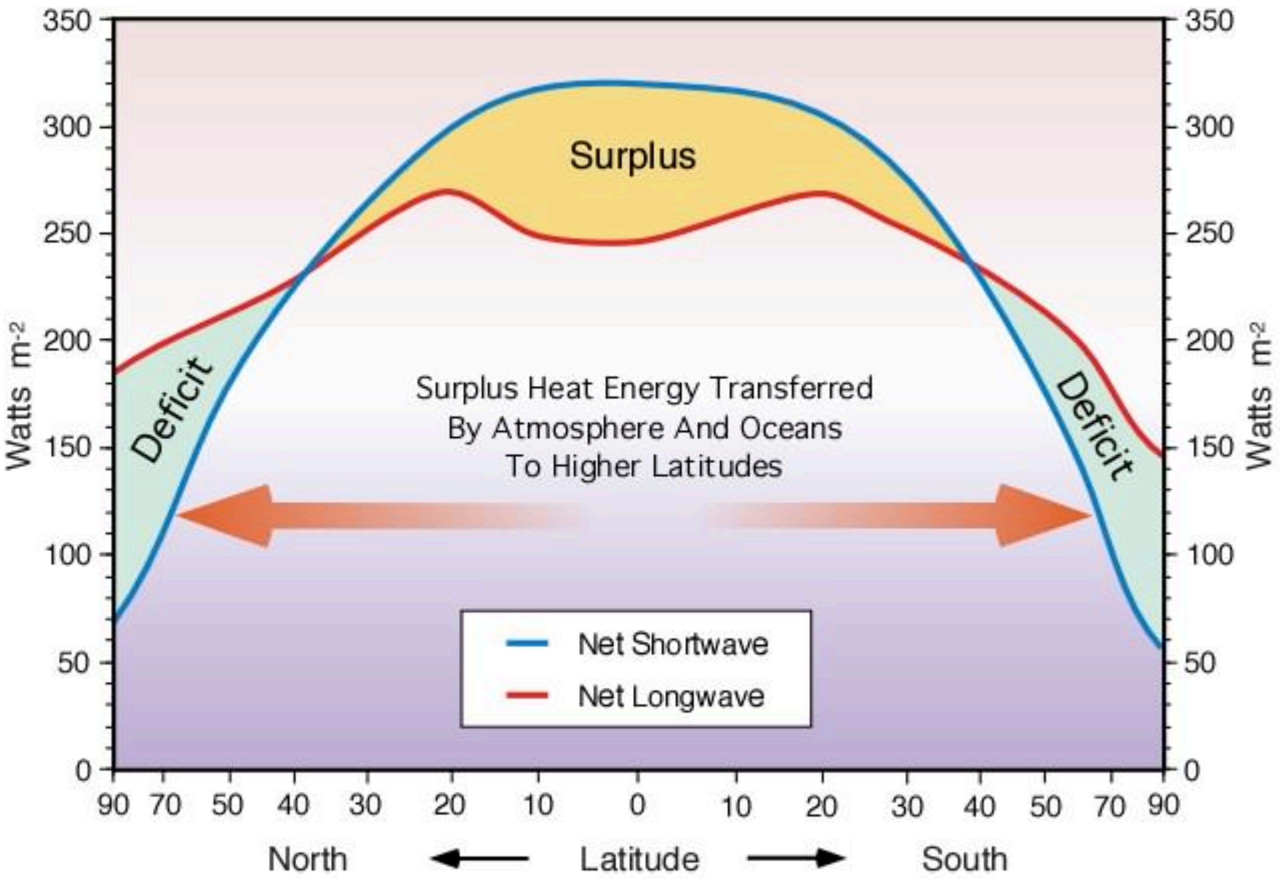
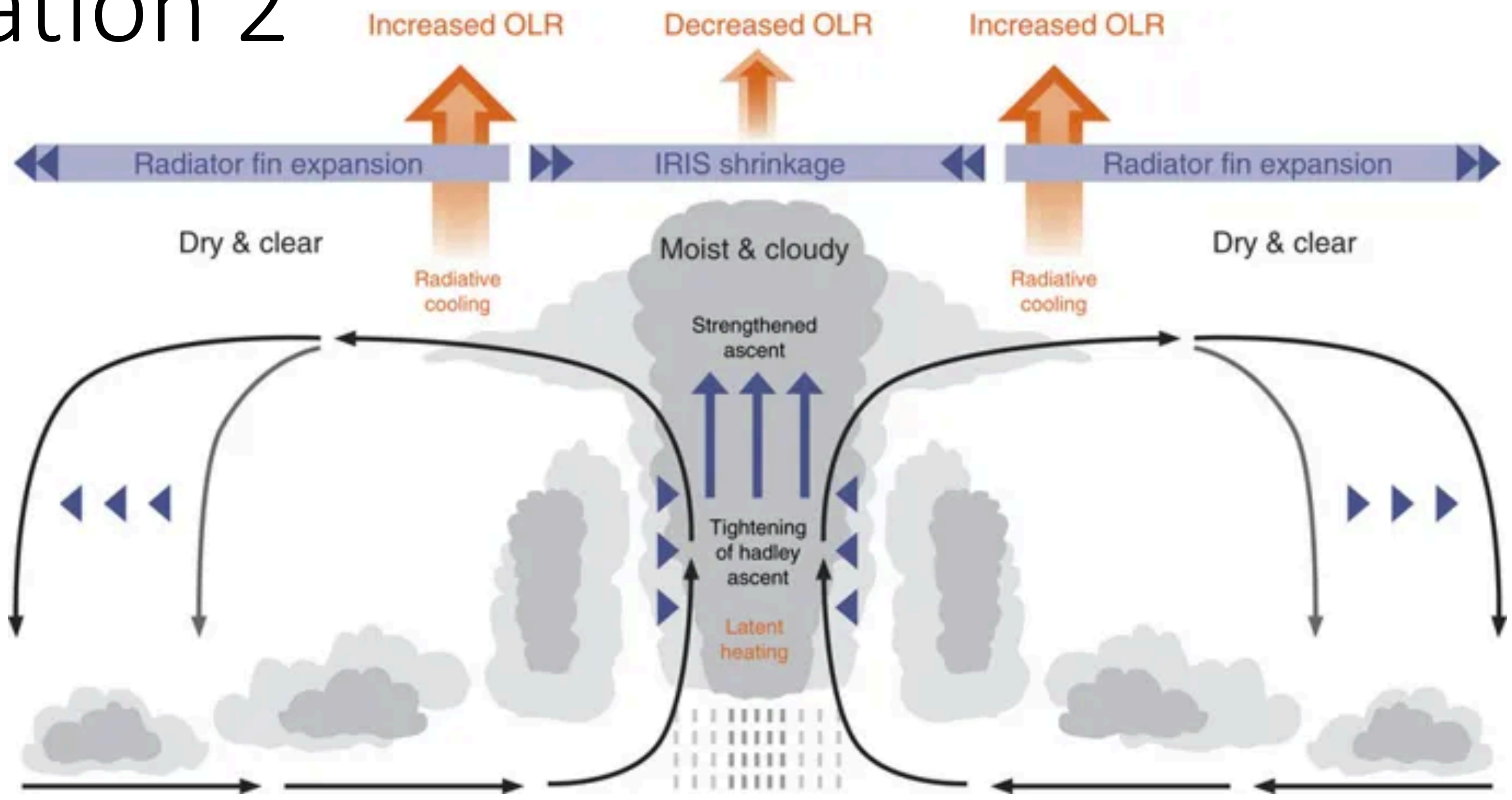
Why the tropics?

Motivation 1



Tropics co-determine efficiency of climate heat engine.
(Regional changes are linked to processes, while global mean changes cannot predict such linkages.)

Motivation 2

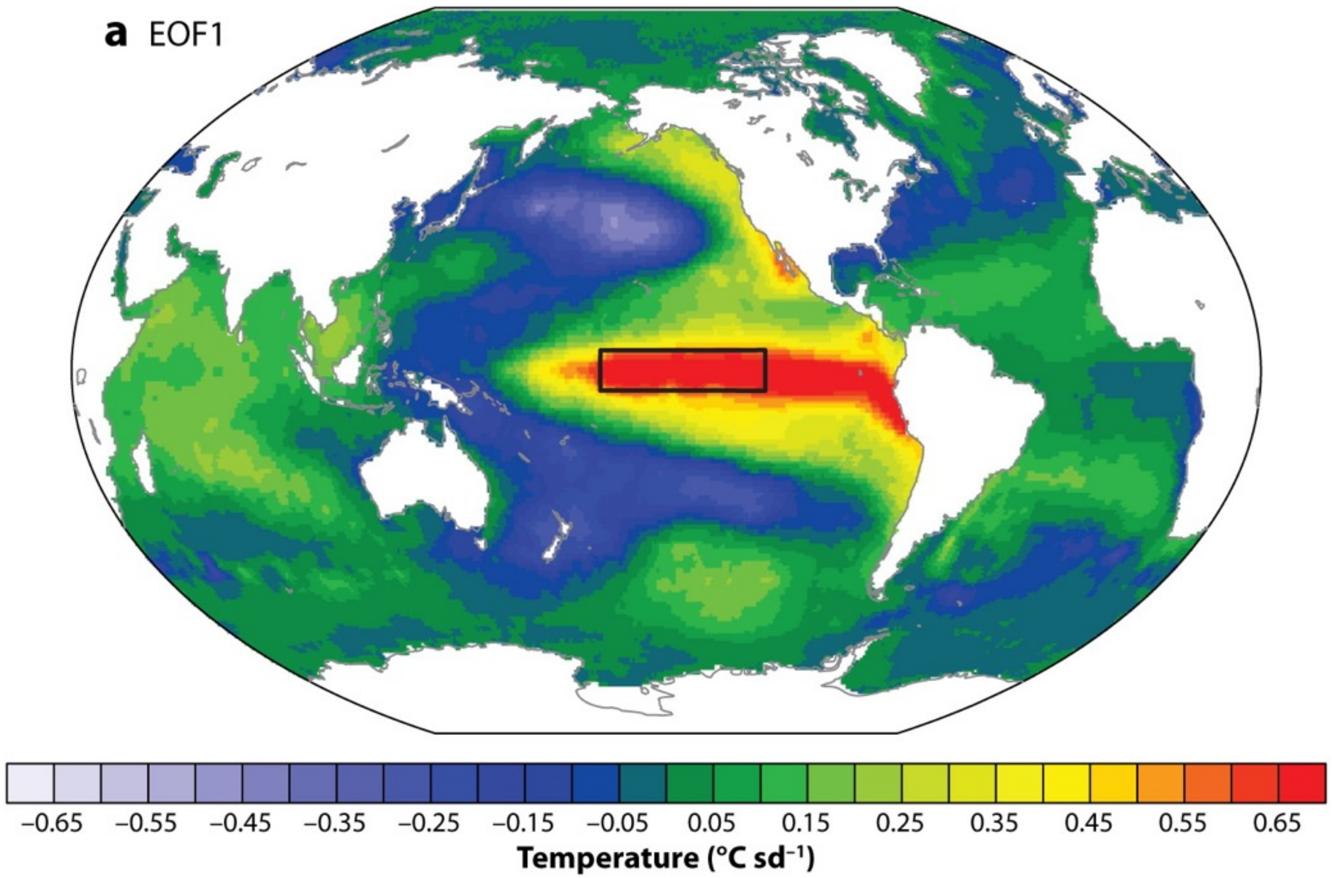


Su et al., 2017

Tropics are prone to climate forcings and feedbacks that shape regional and global climate

Example: Tightening of the ascending branch of the Hadley Circulation coupled with a decrease in tropical high cloud fraction and more intense precipitation

Motivation 3

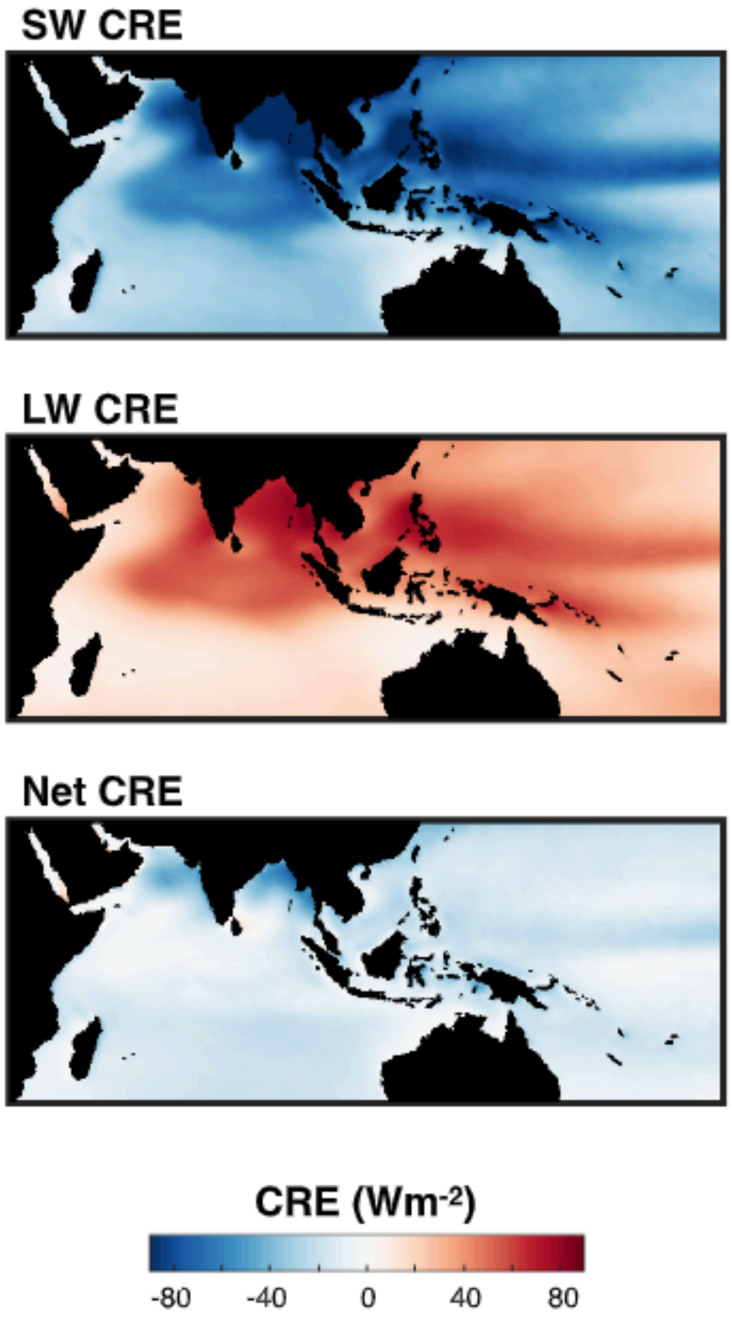


Deser et al., 2010

ENSO is leading source of interannual variability in tropics (and world wide).
We expect variability to be a response to equatorial surface heating.

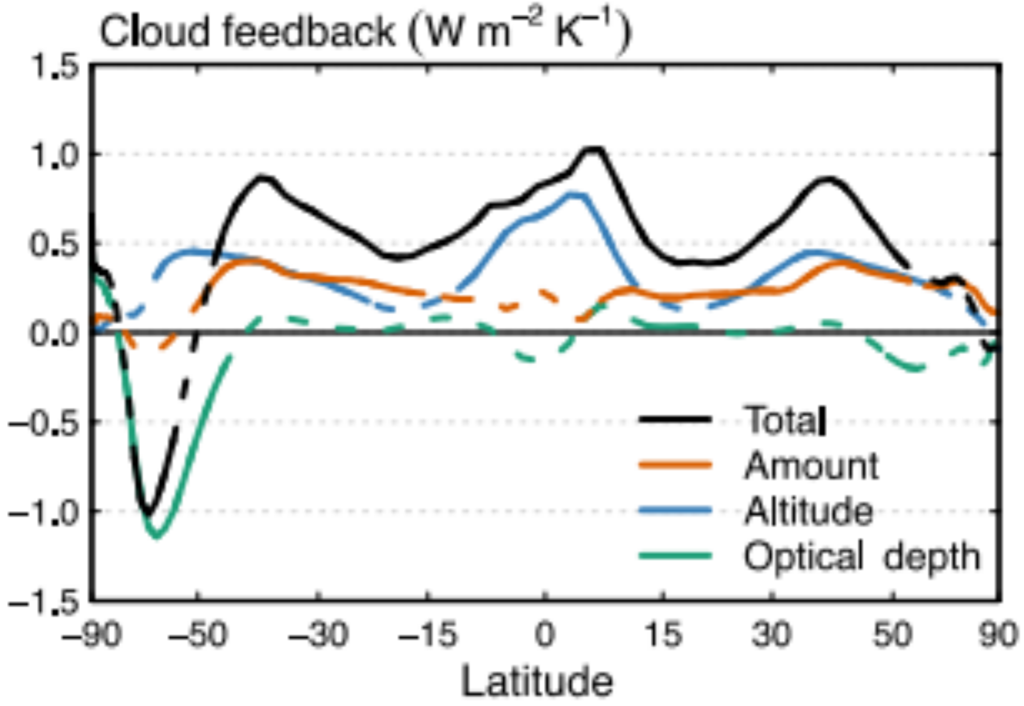
Motivation 4

Wall et al., 2019



Presently, radiative effects of convective clouds largely cancel out in the tropics, but future cloud changes may disrupt this balance

Motivation 4



Ceppi et al., 2017

- Different hypothesis for feedbacks leading to disruption or stabilization of balance: changes in **cloud height** (FAT, PHAT; e.g. Hartmann & Larson, 2002), changes in **aggregation** (IRIS; Mauritsen & Stevens, 2015), changes in **cloud thickness** (Hartmann & Berry, 2017).
- In climate models, the tropical cloud feedback is dominated by cloud height changes
- Changes in CRE ≠ cloud feedback, but expected to correlate (Soden et al., 2008).

Objectives

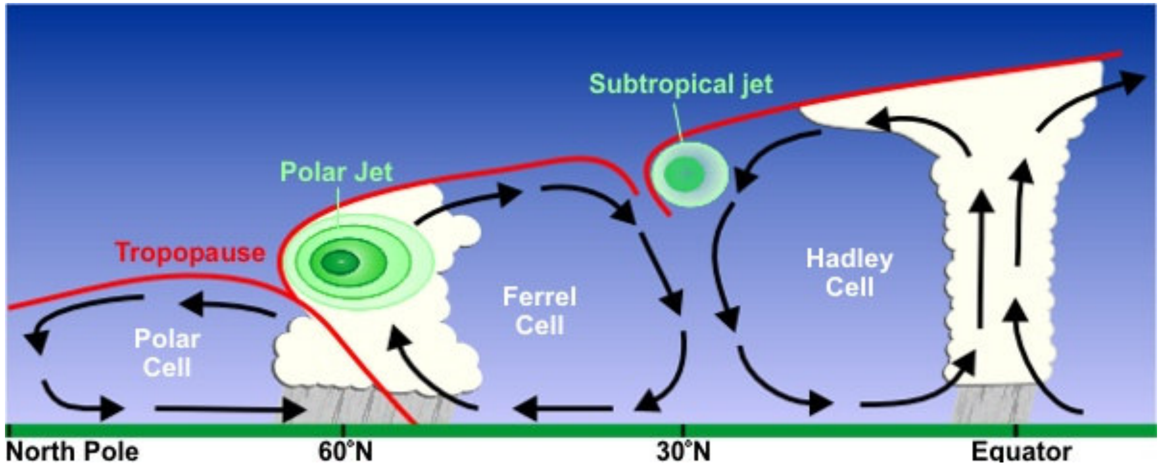
1. Better understanding of interannual variability in tropical radiation budget and cloud radiative effects (CRE) at the TOA

2. Drivers of variability and short-term response to SST (very briefly)

3. How do CMIP6 models reproduce variability, climatological means, and short-term responses

Methods

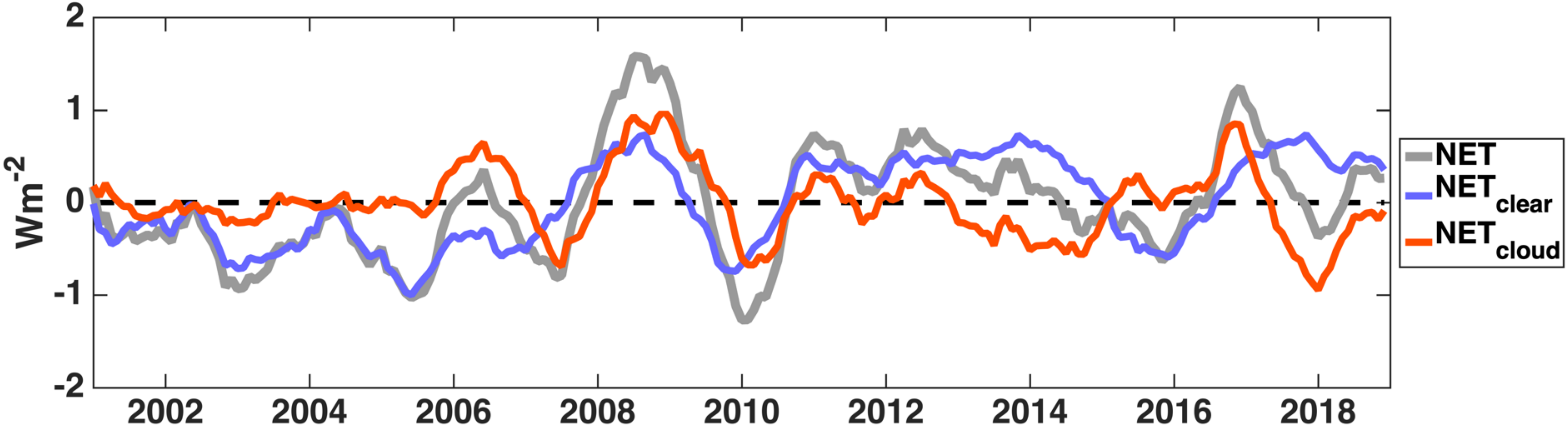
- 2001-2018 CERES EBAF 4.0 and 4.1 give me the same results
- Shortwave (SW) and longwave (LW) are adjusted to be negative upwards and positive downward
- CRE = all-sky minus clear-sky such that positive CRE means clouds enhance energy input
- Deep tropics 10° S to 10° N: frequent deep convection as opposed to 20° S to 20° N and 30° S to 30° N, bounded by zones of subsidence and sub-tropical jets, respectively.



Results

- Interannual variability in CERES EBAF net, shortwave and longwave radiative fluxes, all-sky, clear-sky, cloudy-sky, and cloud properties
- Monthly anomalies are smoothed with 12 months running average filter in figures, but not for regression and correlation analysis.

Interannual variability NET (LW+SW) radiative flux



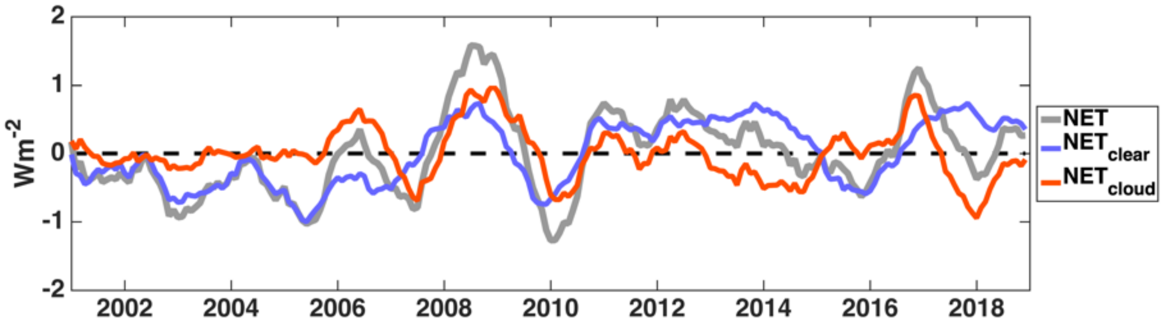
NET vs NET_{clear} R: 0.71
57% of NET amplitude

NET_{clear} and NET_{cloud} contribute equally to NET interannual variability in deep tropics

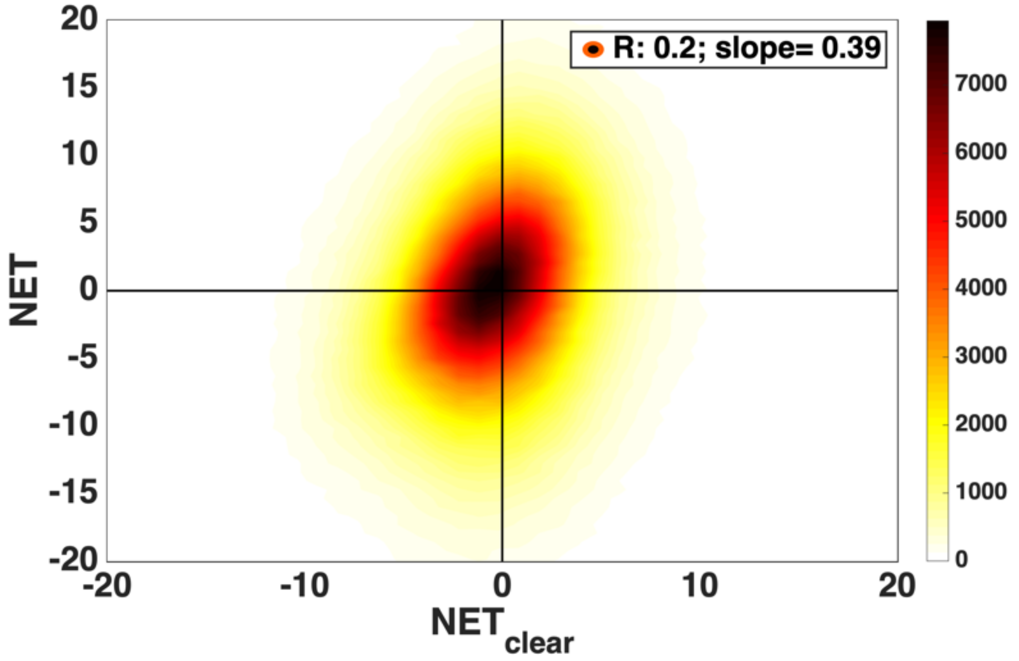
NET vs NET_{cloud} R: 0.80
78% of NET amplitude

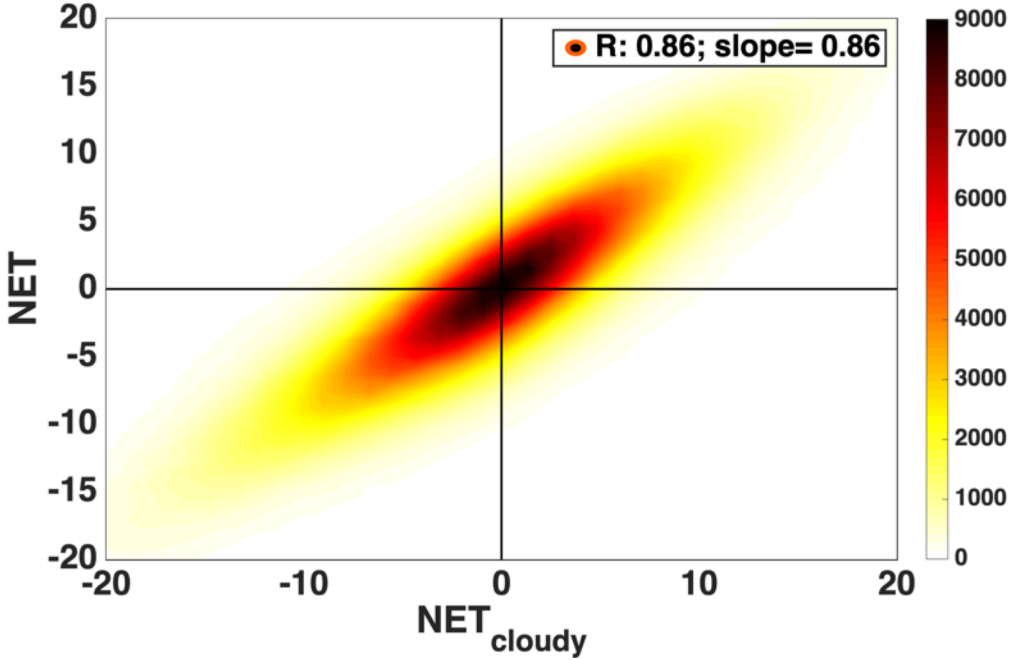
Note: shown are 12-months running means, but statistics are based on raw monthly anomalies

Spatio-temporal variability NET radiative flux



Spatio-temporal scatter suggest spatial variability is dominated by NET_{cloud}



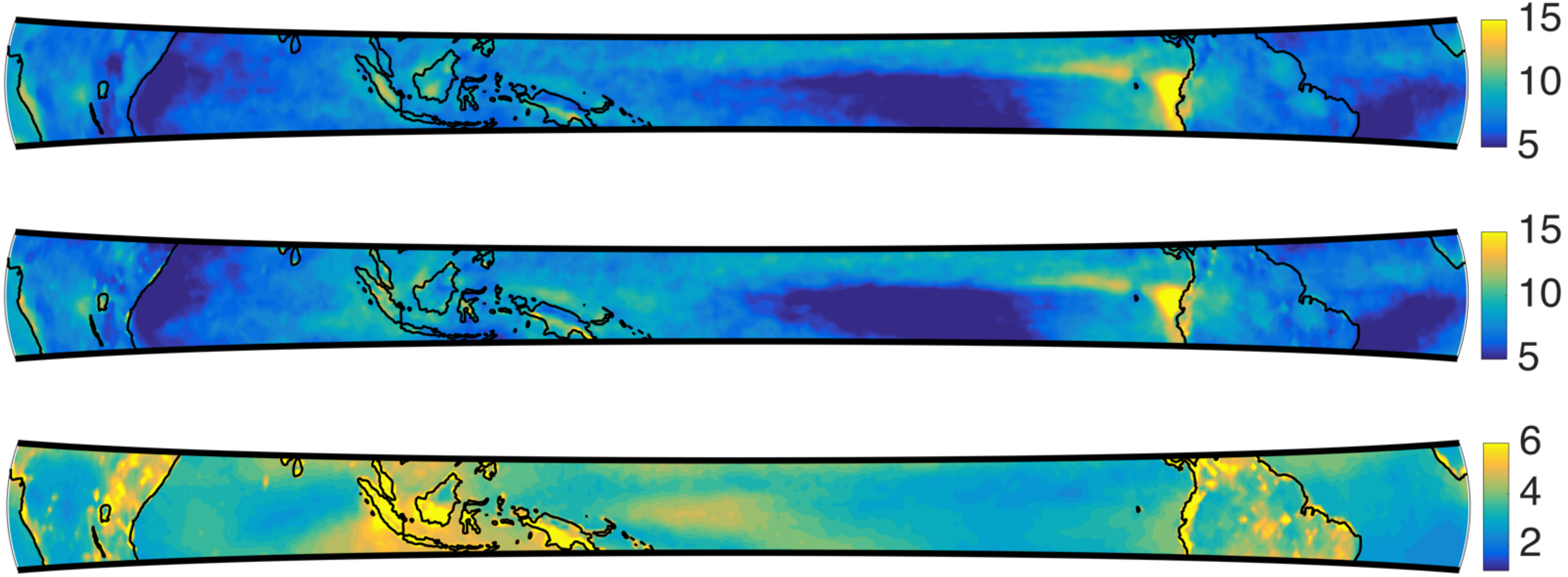


Spatial variability NET radiative flux

NET

NET_{cloud}

NET_{clear}



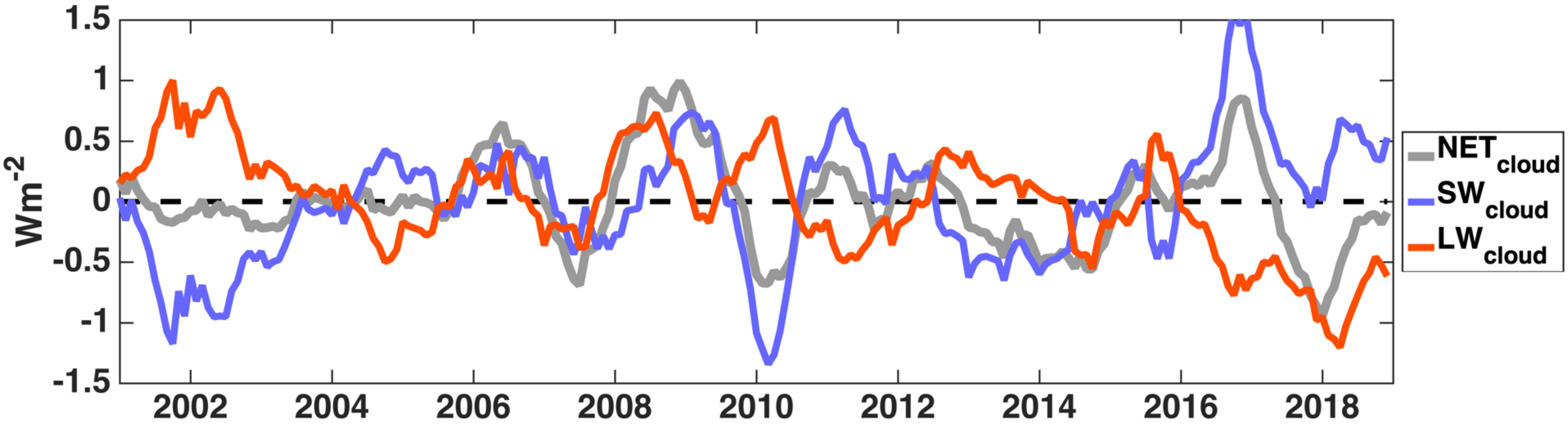
Maps of temporal variability in terms of standard deviation

NET vs. NET_{clear} R: 0.2

NET_{cloud} governs variability in NET

NET vs. NET_{cloud} R: 0.86

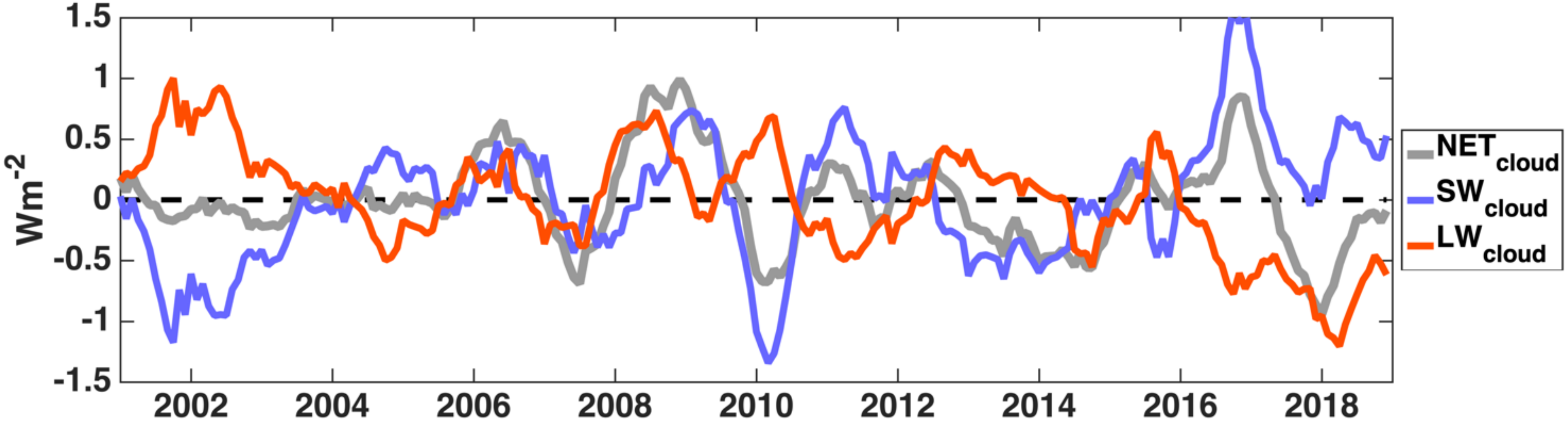
Interannual variability cloudy NET radiative flux



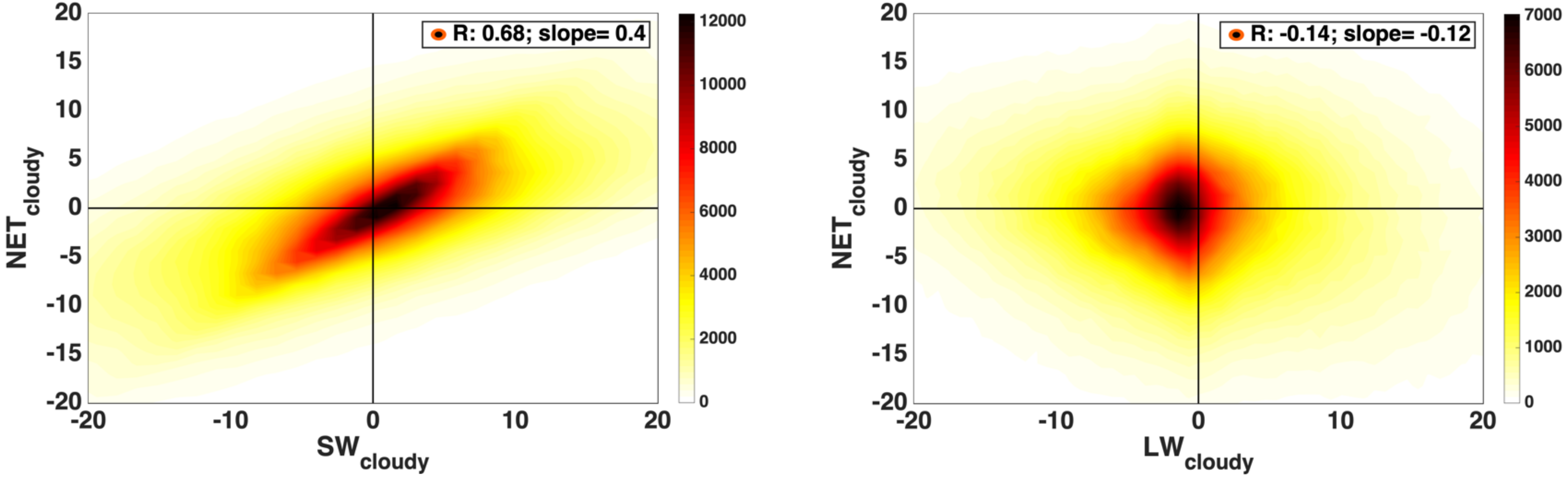
Although compensations are evident,
SW_{cloud} dominates NET_{cloud} interannual variability

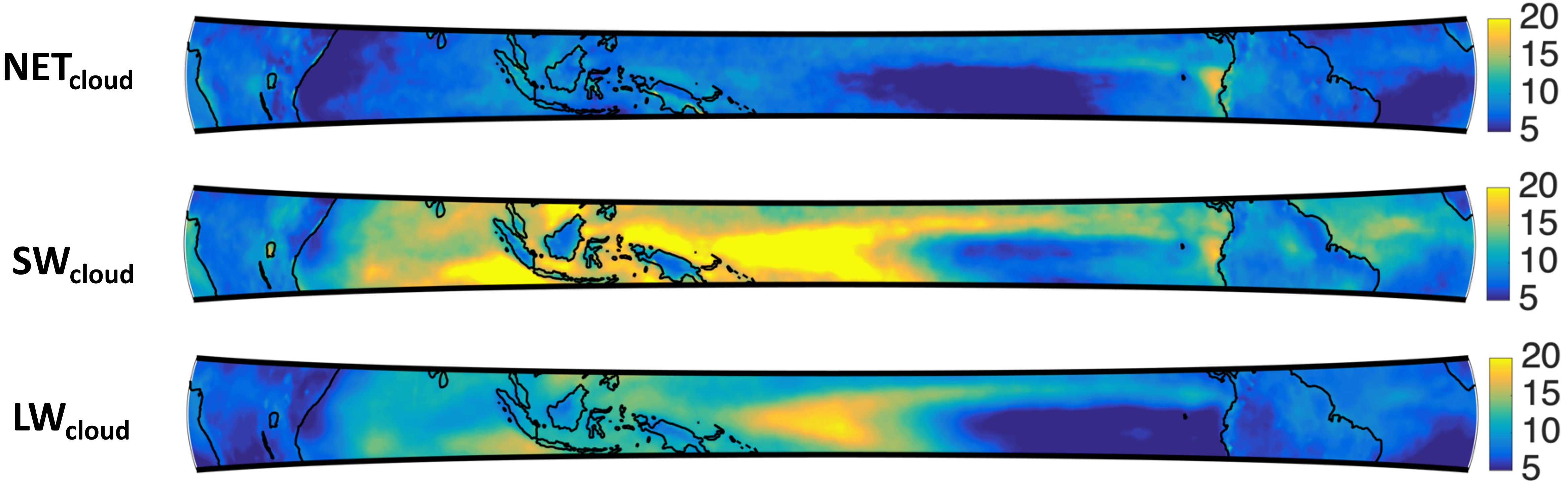
NET_{cloud} vs. LW_{cloud} R: 0.11
138% of NET_{cloud} amplitude

NET_{cloud} vs. SW_{cloud} R: 0.59
152% of NET_{cloud} amplitude



Spatio-temporal scatter suggests NET_{cloud} variability is dominated by SW_{cloud}





Maps of standard deviation; of temporal variability

NET$_{cloud}$ vs LW$_{cloud}$ R: -0.14

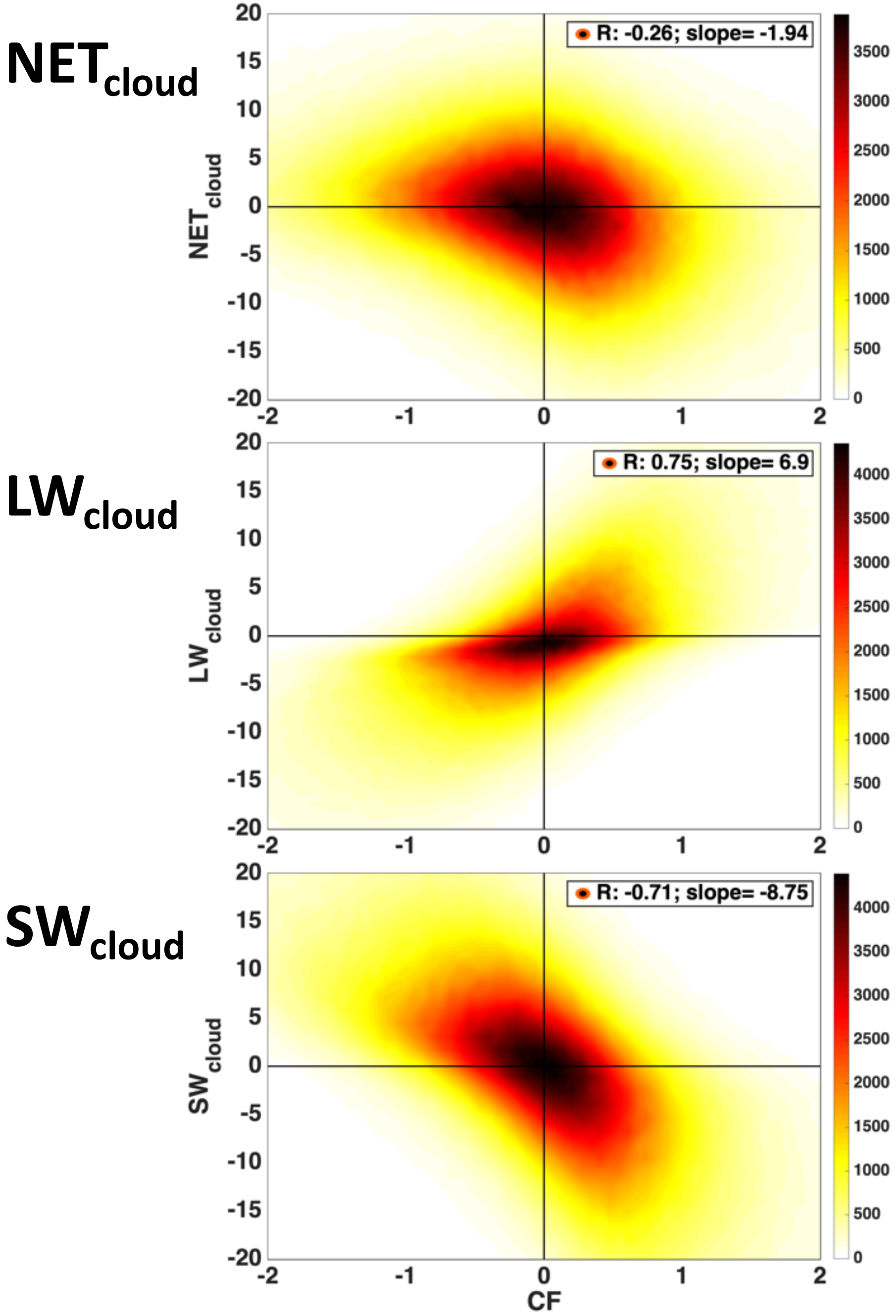
SW$_{cloud}$ governs variability in NET; specifically in NINO 1+2 region

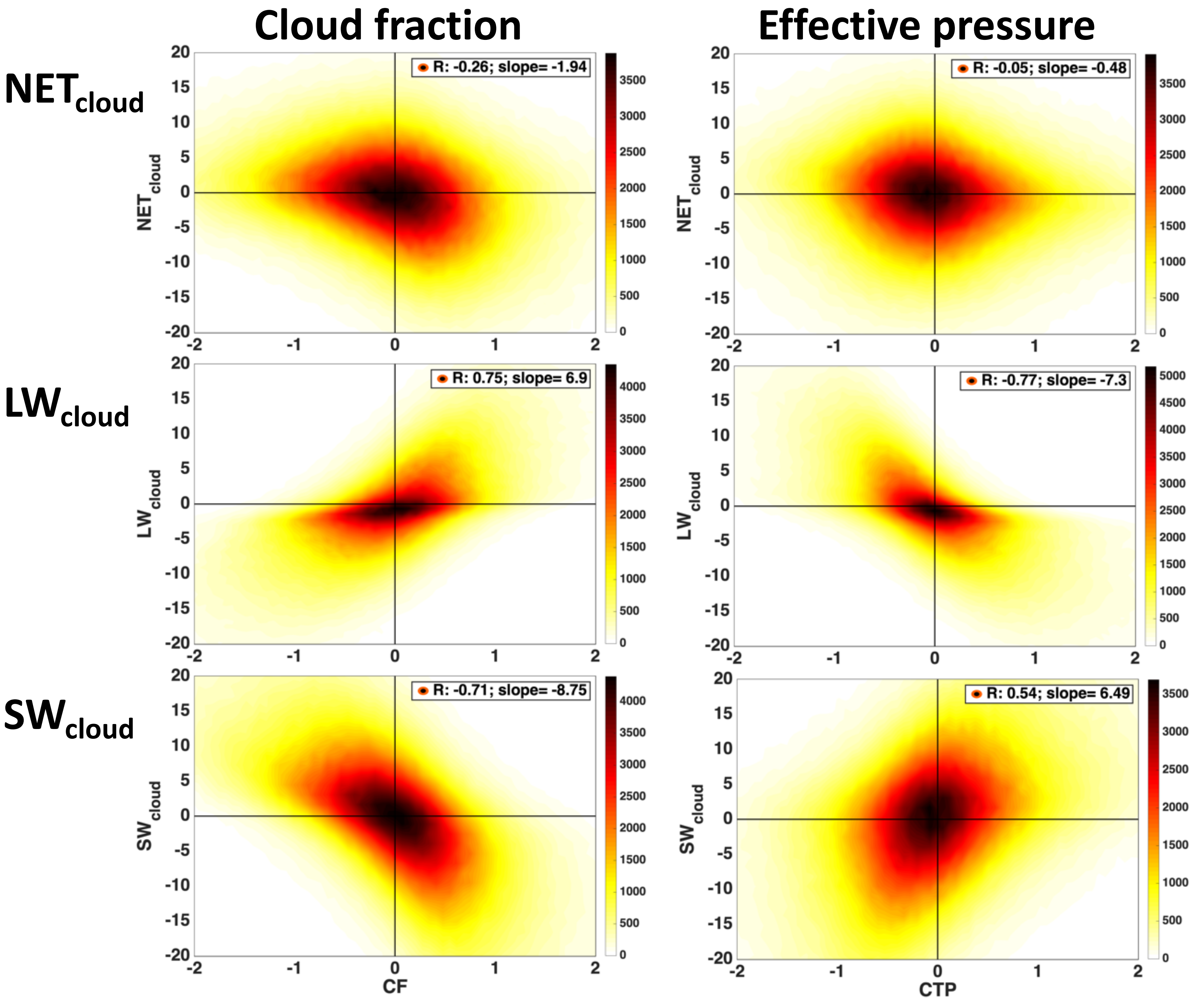
NET$_{cloud}$ vs SW$_{cloud}$ R: 0.68

Results

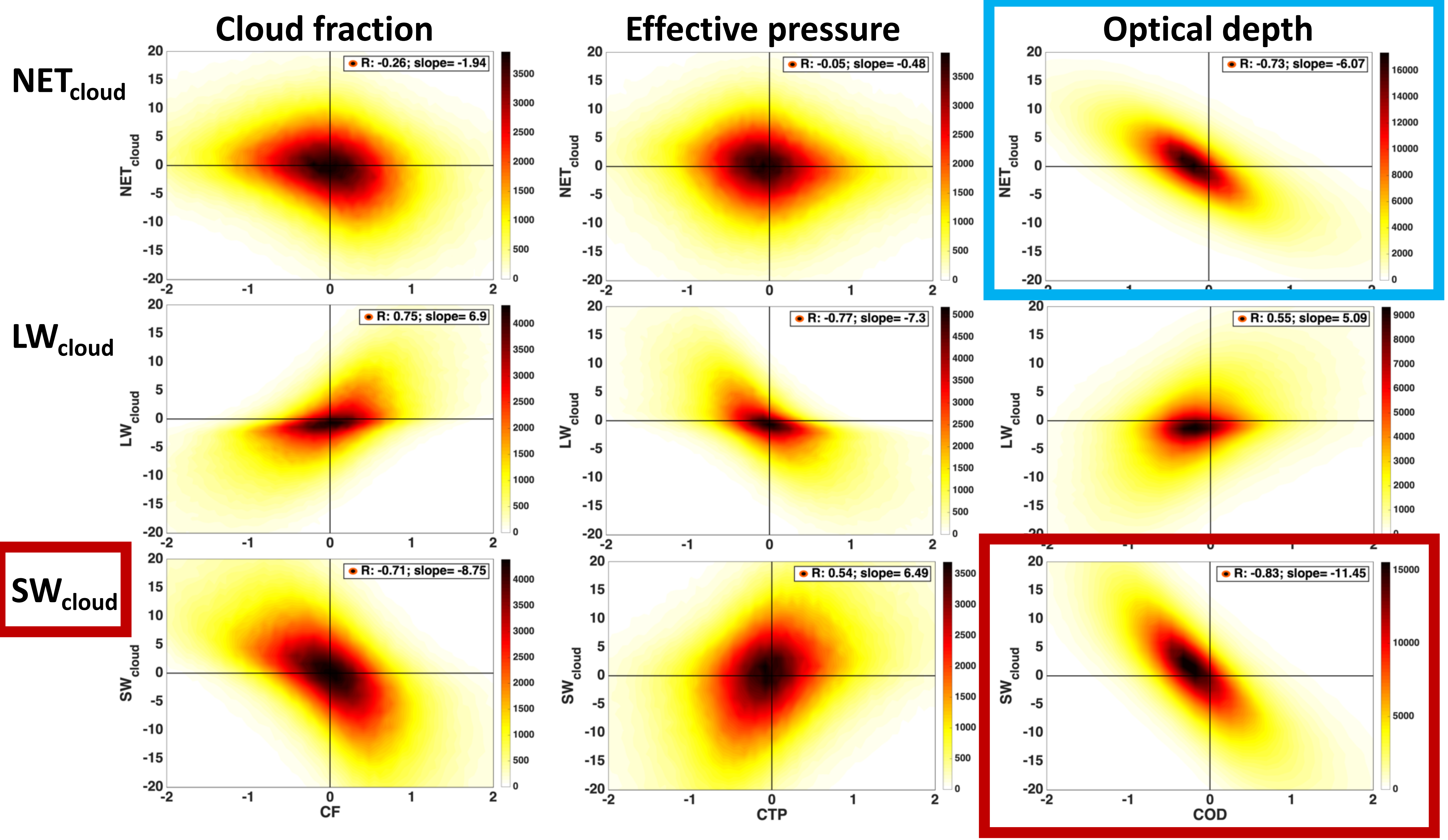
- Spatio-temporal scatters of CREs against cloud properties: cloud fraction, cloud effective pressure, Cloud optical depth

Cloud fraction





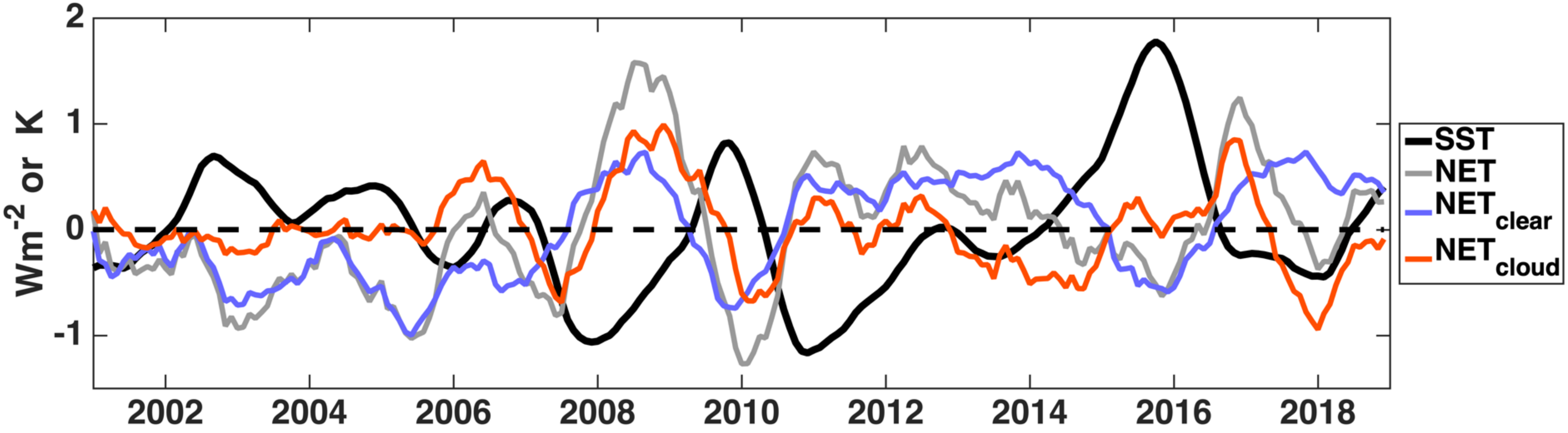
Cloud fraction
Effective pressure
NETcloud
LWcloud
SWcloud
R: -0.26; slope= -1.94
R: -0.05; slope= -0.48
R: 0.75; slope= 6.9
R: -0.77; slope= -7.3
R: -0.71; slope= -8.75
R: 0.54; slope= 6.49
CF
CTP



Cloud fraction
Effective pressure
Optical depth
NET_{cloud}
LW_{cloud}
SW_{cloud}
R: -0.26; slope= -1.94
R: -0.05; slope= -0.48
R: -0.73; slope= -6.07
R: 0.75; slope= 6.9
R: -0.77; slope= -7.3
R: 0.55; slope= 5.09
R: -0.71; slope= -8.75
R: 0.54; slope= 6.49
R: -0.83; slope= -11.45
CF
CTP
COD

Driver of interannual variability: ENSO

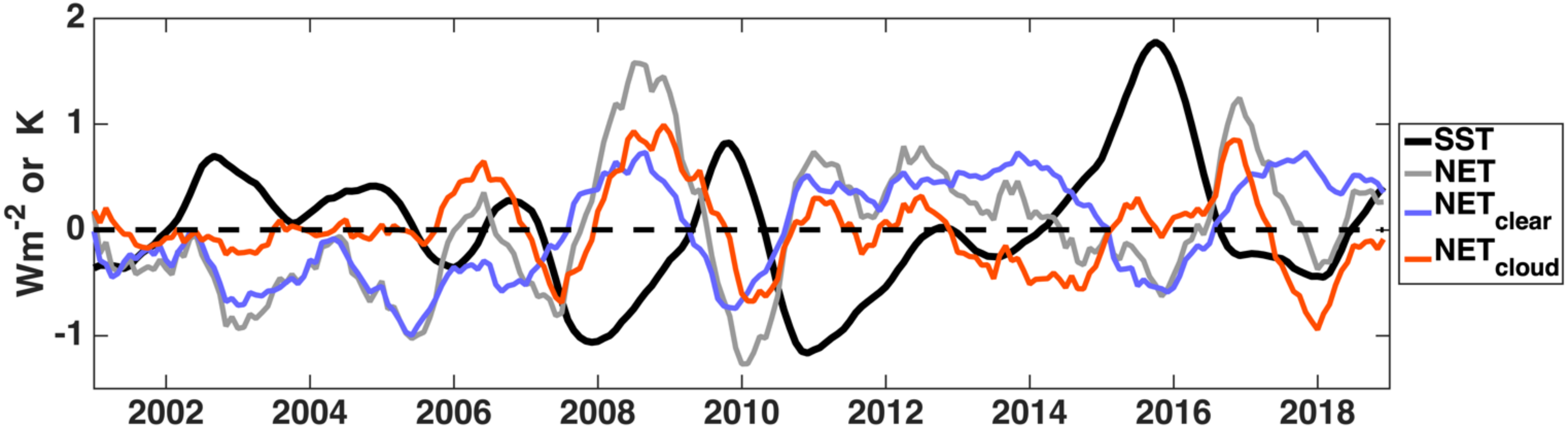
- NET, NET_{clear} and NET_{cloud} are anticorrelated with NINO3.4 SST
- Correlations maximize at 4 months delay
- Radiative cooling is a delayed response to equatorial surface heating?
- Not a new finding: delayed responses of tropospheric temperature and humidity;
  e.g. Chen et el. (2017), Scherllin-Pirscher et al. (2012), Su et al. (2004), Yualeva & Wallace (1994)



Radiative responses to SST in NINO3.4 (Wm^{-2}/K)

	$\frac{NET}{SST}$	$\frac{NET_{clear}}{SST}$	$\frac{NET_{cloud}}{SST}$
No lag	**-0.38** [-0.61, -0.16]	**-0.35** [-0.48, -0.21]	**-0.03** [-0.2, 0.12] **Not significant at 95%**
with 4-mon lag	**-0.72** [-0.92, -0.51]	**-0.38** [-0.52, -0.25]	**-0.34** [-0.5, -0.18] **Significant at 95%**

Note: Based on unsmoothed anomalies



CMIP6 models

- **HadGEM3** (Hadley Centre Global Environment Model 3) GC3.1 (coupled GCM)
- **UKESM1**-0-LL = HadGEM3_GC3.1 + land carbon cycle + ocean biogeochemistry+ atm chemistry and aerosols + ice sheets
- **GISS-E2**-1-G-CC= ModelE atmospheric code + GISS ocean model+interactive Carbon Cycle
- **CESM2**: NCAR's fully coupled GCM
- All these models provide COD and pressure at cloud top for at least one historical simulation (1995-2014)

Comparison of spatio-temporal correlations

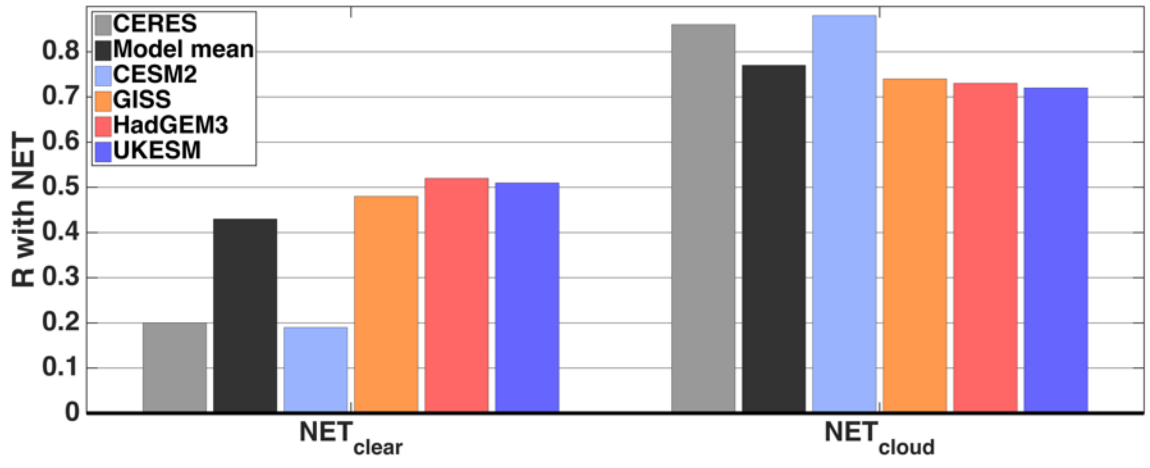
CMIP6 models show overall similar co-variabilities

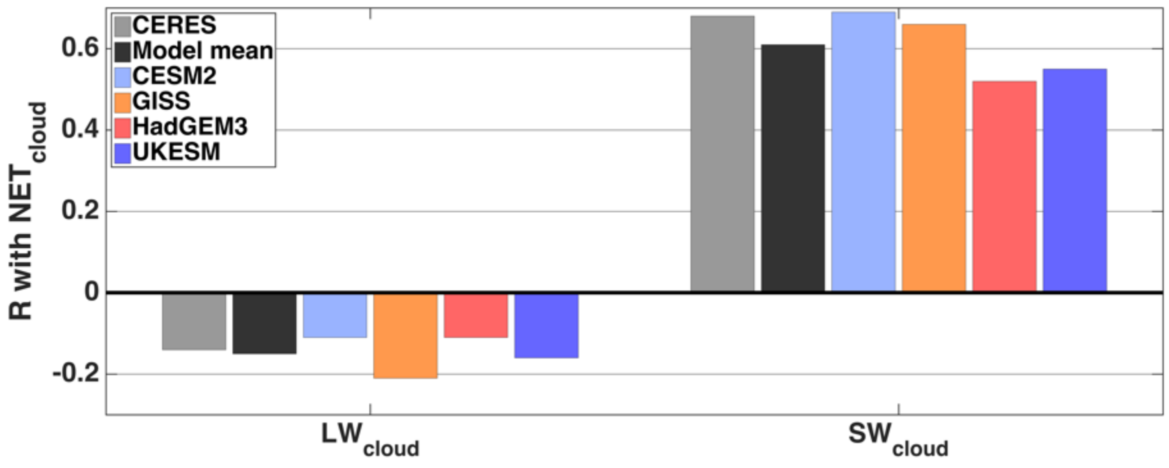
NET_{cloud} dominates variability in NET

SW_{cloud} dominates NET_{cloud}

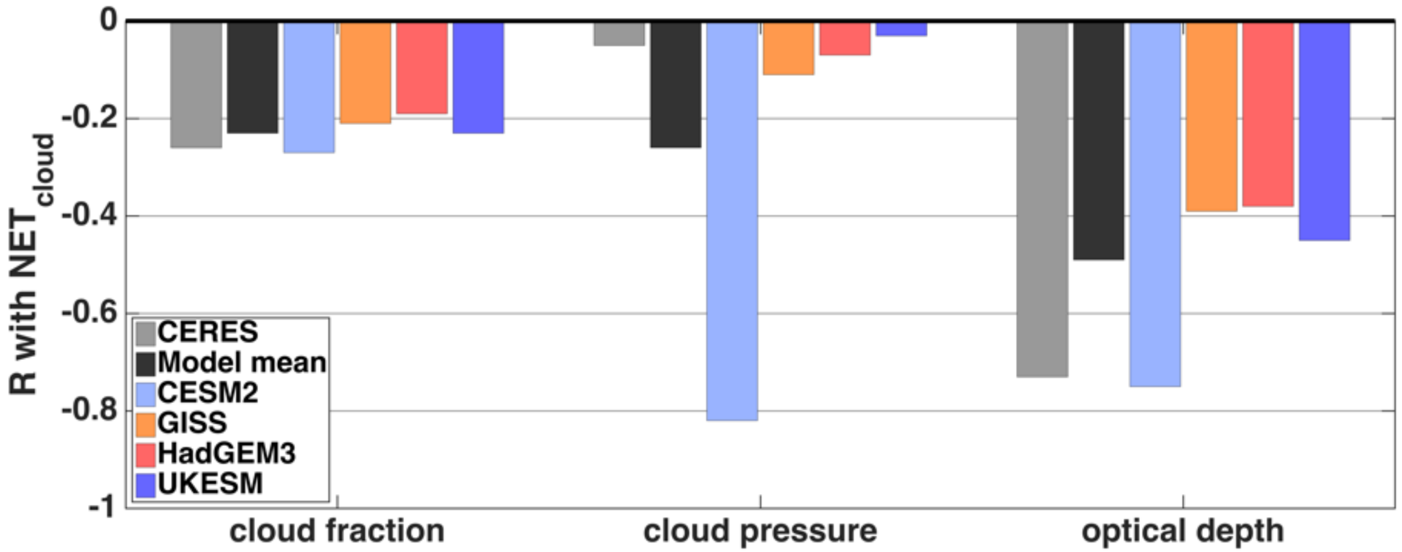
CESM2 is most similar to CERES EBAF

other models show larger correlations between NET and NET_{clear}



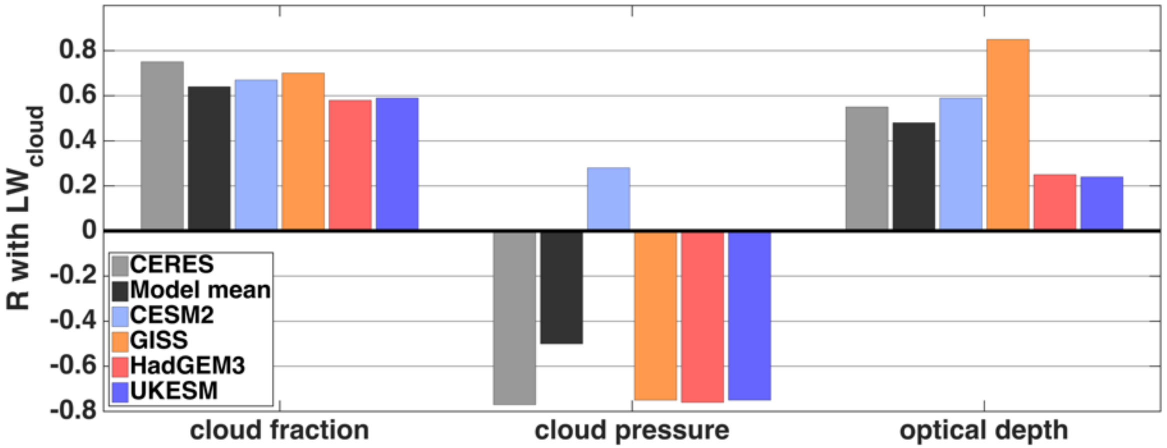


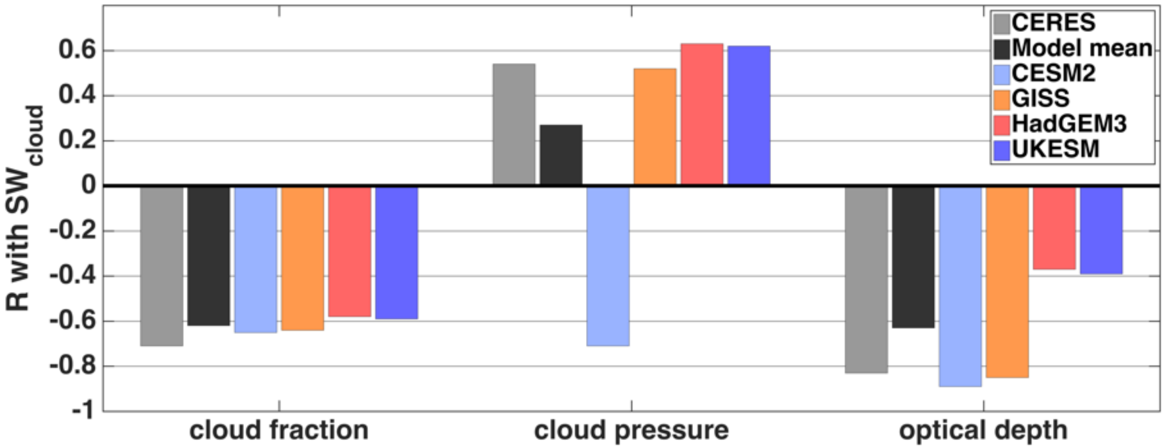
Comparison of spatio-temporal correlations



Model mean: COD is main driver of NET_{cloud}, but relationships not as distinct

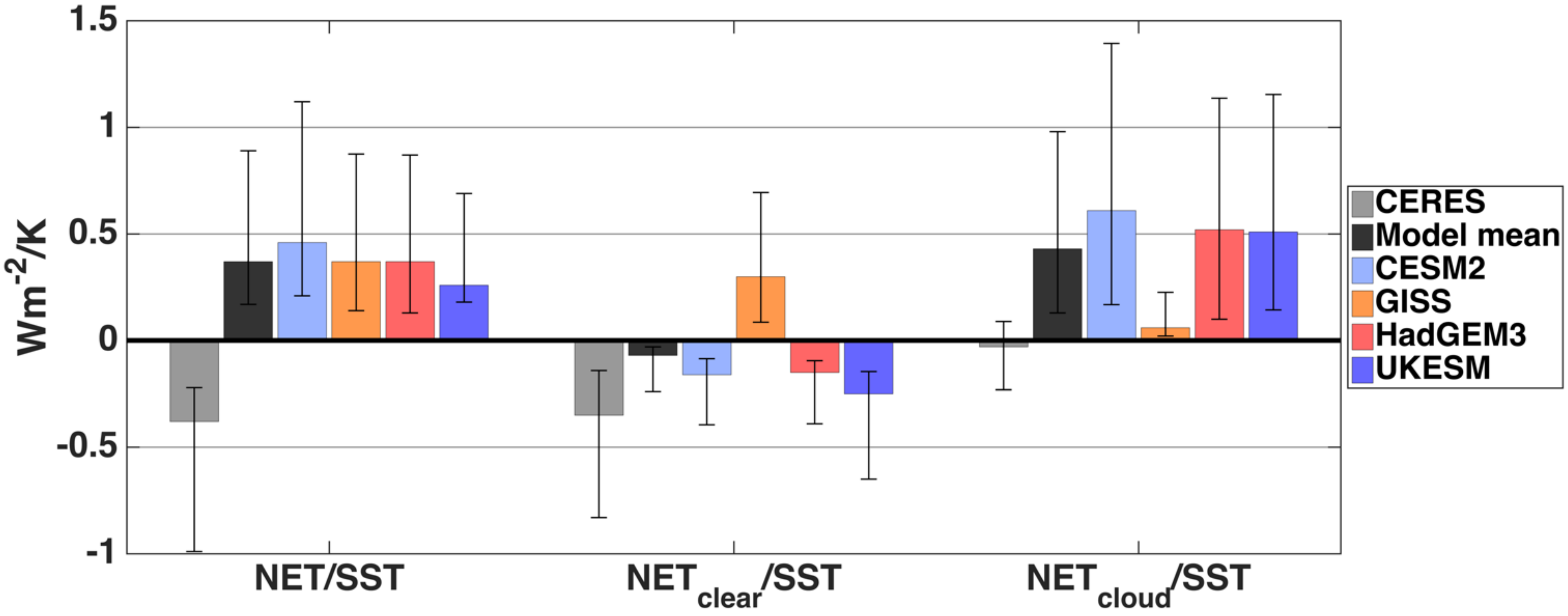
CESM2: large correlation for both cloud top pressure and COD; some unphysical relationships?



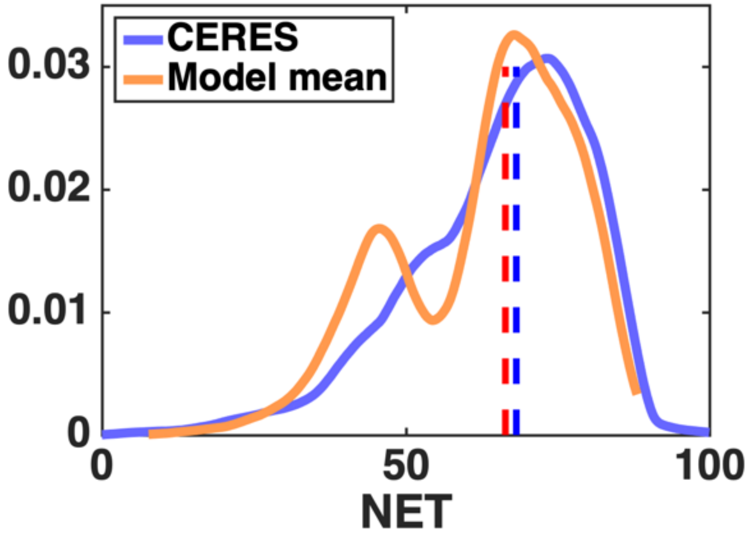


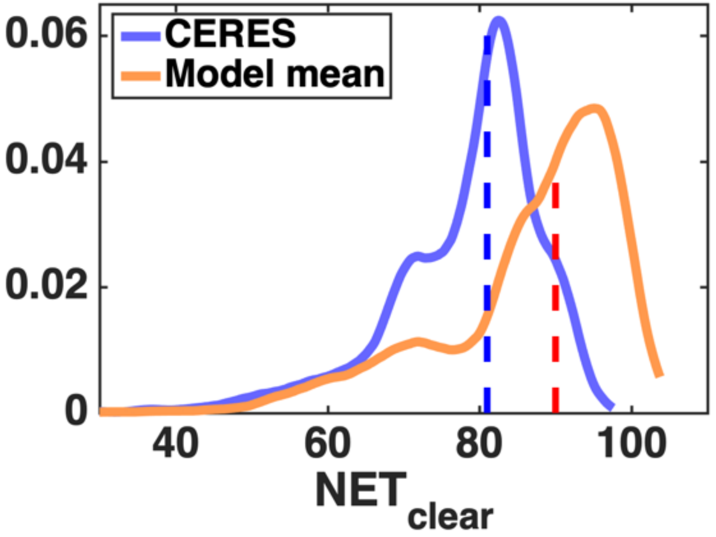
Response to NINO3.4 SST variability

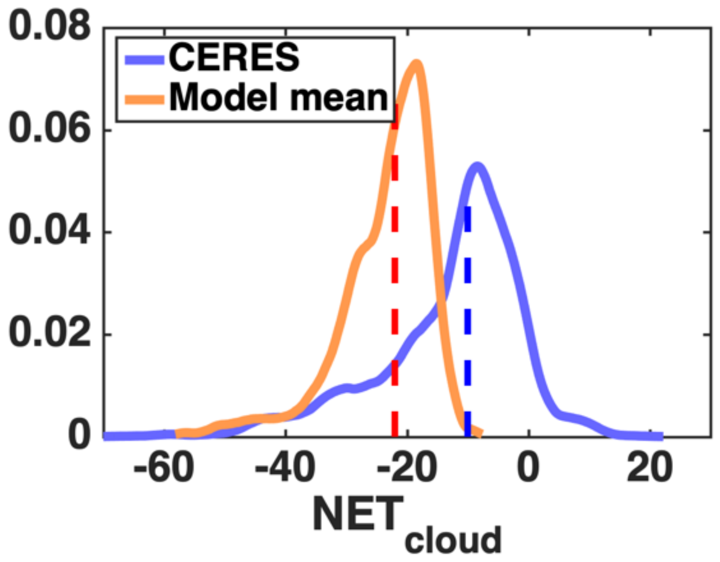
All models exhibit positive net "feedback", while CERES suggests negative

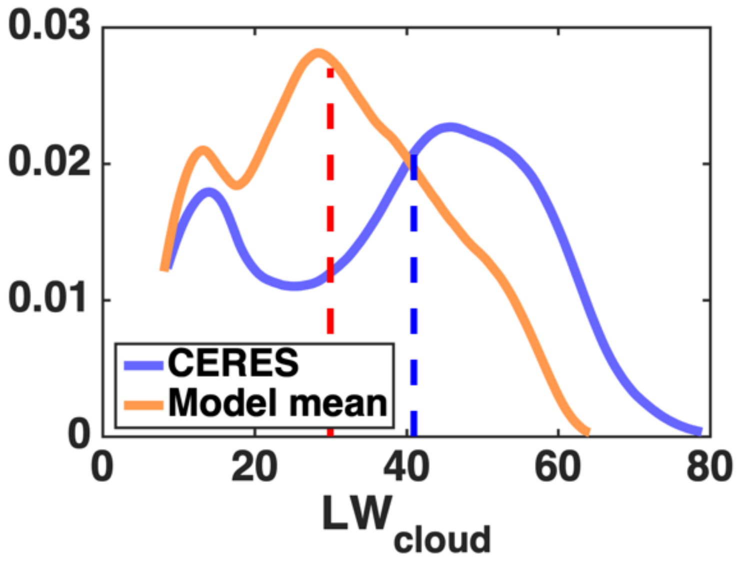


Climatological distribution functions



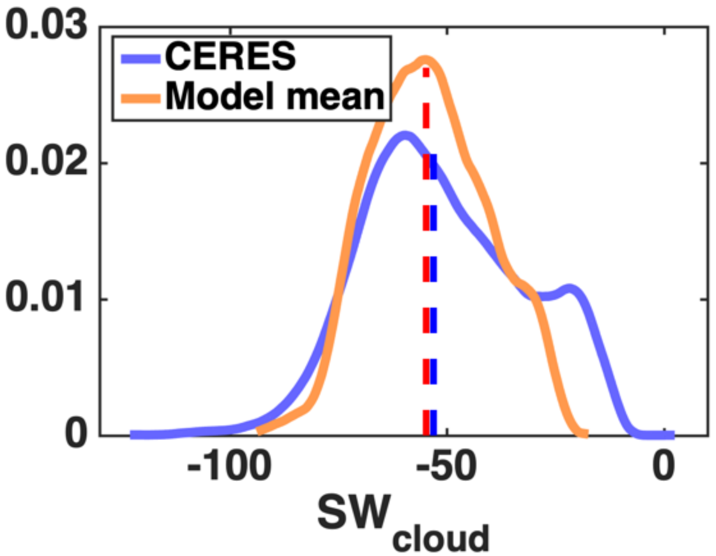




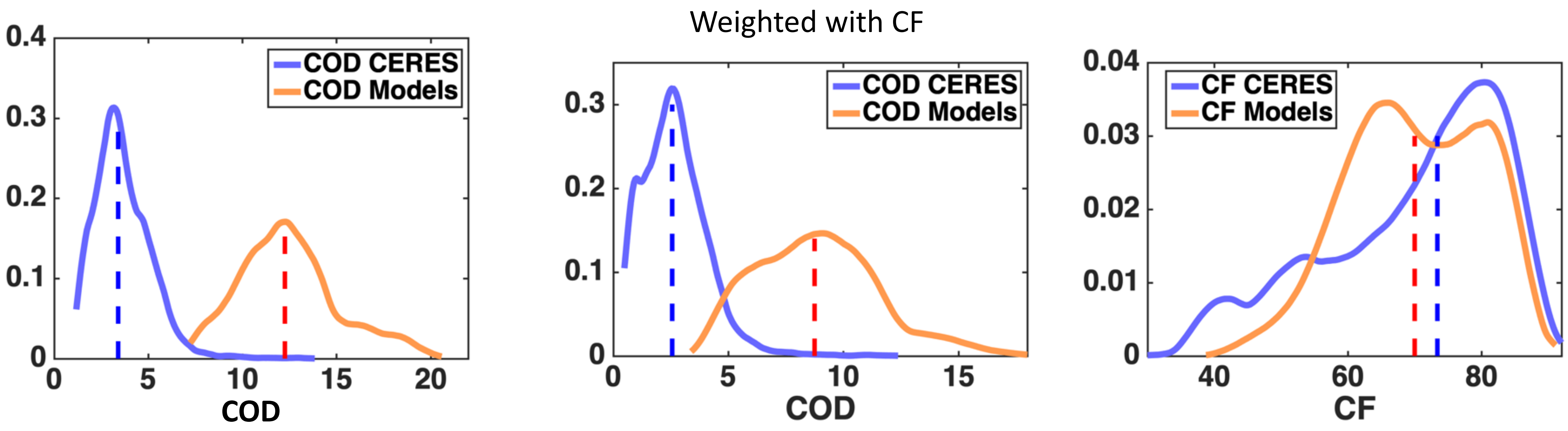


NET is the same due to compensating biases in clear & cloudy

LW_{cloud} is biased low



Climatological distribution functions



Clouds in models are brighter – but not necessarily fewer. Still, SW_{cloud} is nearly the same, while LW_{cloud} is biased low.

Outlook

- Other regions and global mean (spoiler: global mean exhibits similar relationships)
- High, mid, low clouds
- What is up in equatorial eastern pacific?
- Individual models: what are cloud properties, properties of clear sky, and resulting fluxes
- Investigate drivers, lagged response and its physicality
- Compare individual ENSO events and their different impacts
- Long-term relationships in historical and scenario runs

Thank you!

backup

Both temporal & spatial correlations agree:
COD variability dominates variability in SW_{cloud} and NET_{cloud};
Cloud height variability affects LW_{cloud}, but lesser impact on NET_{cloud}

$R_{temporal}$	NET_{cloud}	LW_{cloud}	SW_{cloud}
CF	-0.22	0.64	-0.67
CP	-0.37	-0.71	0.32
COD	-0.74	-0.24	-0.7

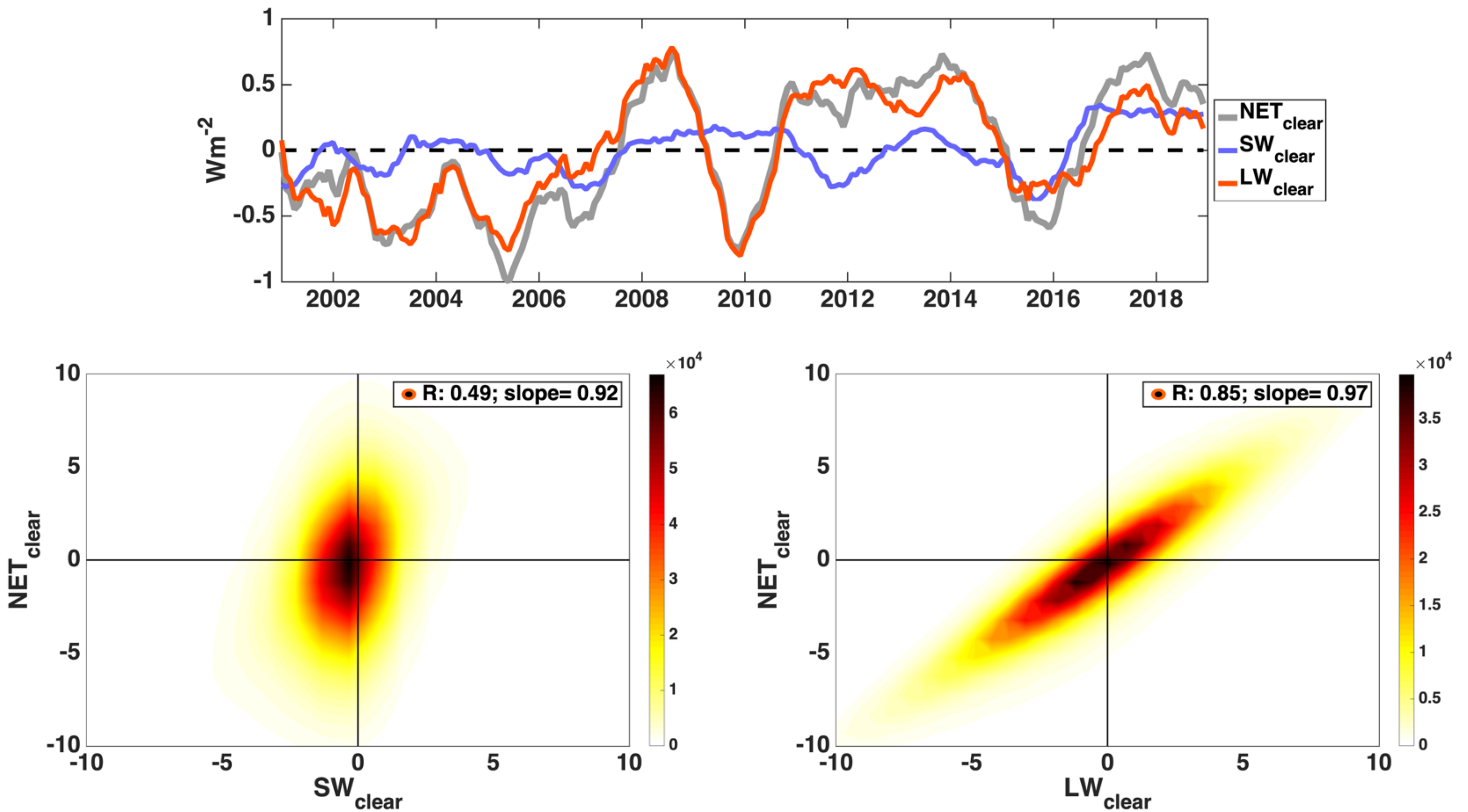
$R_{spatial}$	NET_{cloud}	LW_{cloud}	SW_{cloud}
CF	-0.26	0.75	-0.71
CP	-0.05	-0.77	0.56
COD	-0.73	0.55	-0.83

R $_{temporal}$	CERES EBAF	Model mean	CESM2	GISS-E2-1-G-CC	HadGEM3-GC31-LL	UKESM1-0-LL
NET vs. NET_{clear}	**0.71**	**0.59**	0.48	0.7	0.53	0.56
NET vs. NET_{cloud}	**0.8**	**0.85**	0.92	0.73	0.74	0.6
NET_{cloud} vs. LW_{cloud}	**0.11**	**0.29**	0.35	0.06	0.11	-0.06
NET_{cloud} vs. SW_{cloud}	**0.59**	**0.53**	0.7	0.49	0.58	0.65

R $_{spatio\text{-}temporal}$	CERES EBAF	Model mean	CESM2	GISS-E2-1-G-CC	HadGEM3-GC31-LL	UKESM1-0-LL
NET vs. NET_{clear}	**0.2**	0.43	**0.19**	0.48	0.52	0.51
NET vs. NET_{cloud}	**0.86**	0.77	**0.88**	0.74	0.73	0.72
NET_{cloud} vs. LW_{cloud}	**-0.14**	-0.15	**-0.11**	-0.21	-0.11	-0.16
NET_{cloud} vs. SW_{cloud}	**0.68**	0.61	**0.69**	0.66	0.52	0.55

$R_{temporal}$	CERES EBAF			Model mean			CESM2			GISS-E2-1-G-CC			HadGEM3-GC31-LL			UKESM1-0-LL		
	CF	CP	COD	CF	CP	COD	CF	CP	COD	CF	CP	COD	CF	CP	COD	CF	CP	COD
NET_{cloud}	-0.22	-0. 37	-0.74	-0.07	-0.44	-0.22	0.06	-0.9	-0.76	0.04	-0.25	-0.29	-0.12	-0.4	-0.17	-0.24	-0.22	0.34
SW_{cloud}	-0.67	0.32	-0.7	-0.31	0.21	-0.66	-0.5	-0.62	-0.91	-0.65	0.65	-0.87	-0.47	0.35	-0.42	0.38	0.46	-0.43
LW_{cloud}	0.64	-0.71	0.24	0.38	-0.31	0.42	0.73	-0.31	0.23	0.77	-0.89	0.82	0.47	-0.75	0.38	-0.44	-0.77	0.28

Spatio-temporal scatter suggests NET_{clear} variability is dominated by LW_{clear}



Response to NINO3.4 SST variability

Same situation when considering the 4-months delay in response