Observational Assessment of Changes in Earth's Energy Imbalance Since 2000

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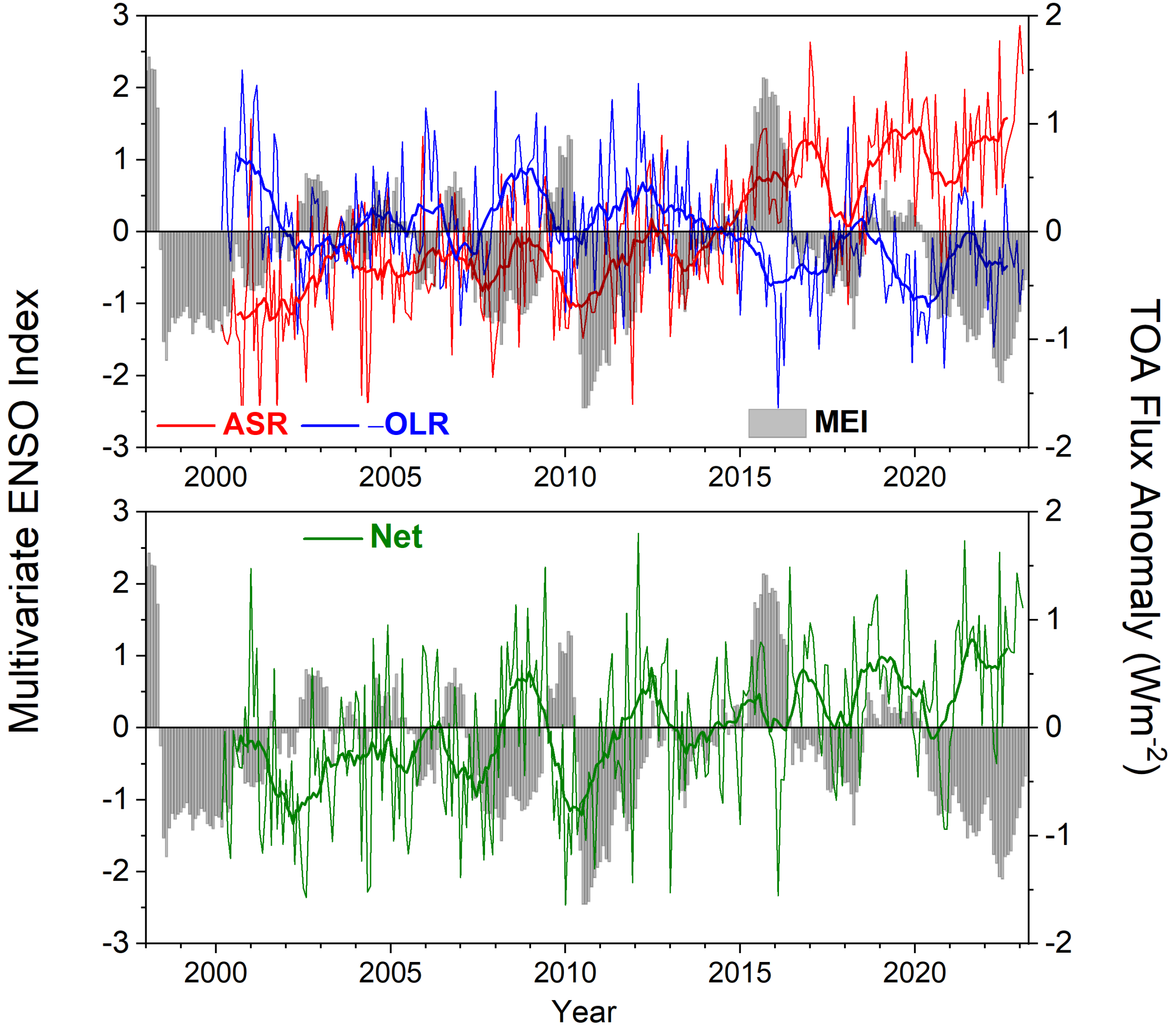
Global Mean All-Sky TOA Flux Anomalies (CERES EBAF Ed4.2; 03/2000–02/2023)



Trends (Wm^{-2} per decade; 2.5-97.5% CI)

ASR: 0.73 ± 0.19

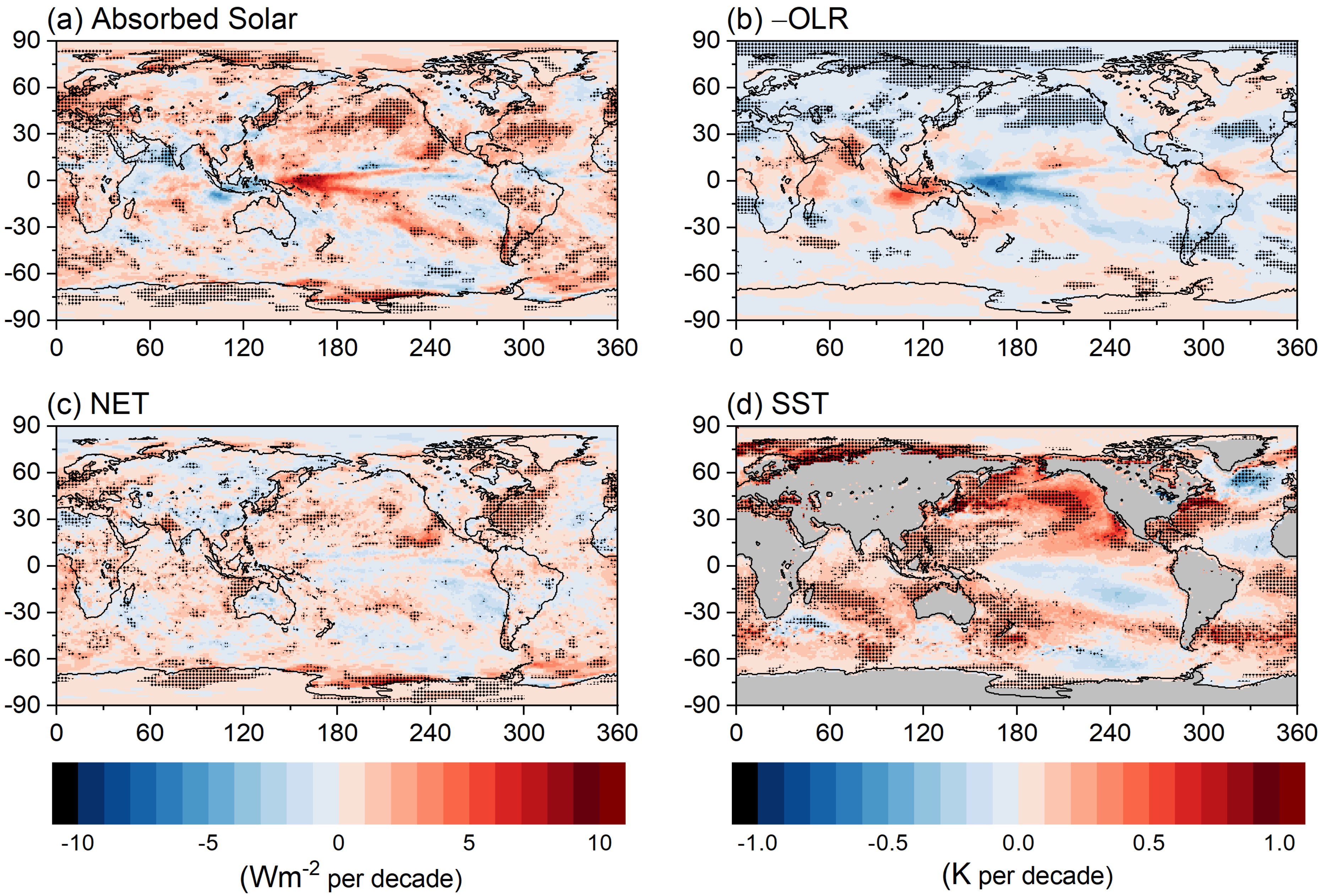
–OLR: –0.27 ± 0.19

NET: 0.47 ± 0.18

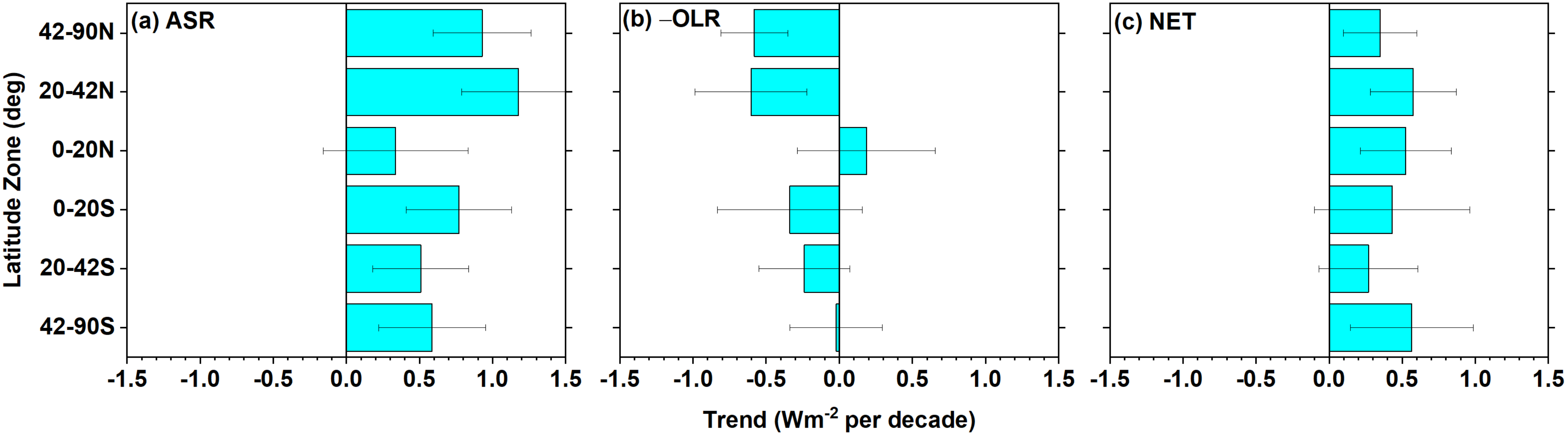
Units: Wm^{-2}	Solar Irradiance	ASR	–OLR	NET
03/2000-02/2010	340.14	240.7	–240.2	0.53
03/2013-02/2023	340.17	241.7	–240.6	1.08
Difference	0.03	1.0	–0.4	0.55

Doubling in EEI!

Regional Trends in TOA Radiation and SST (03/2000–02/2023)

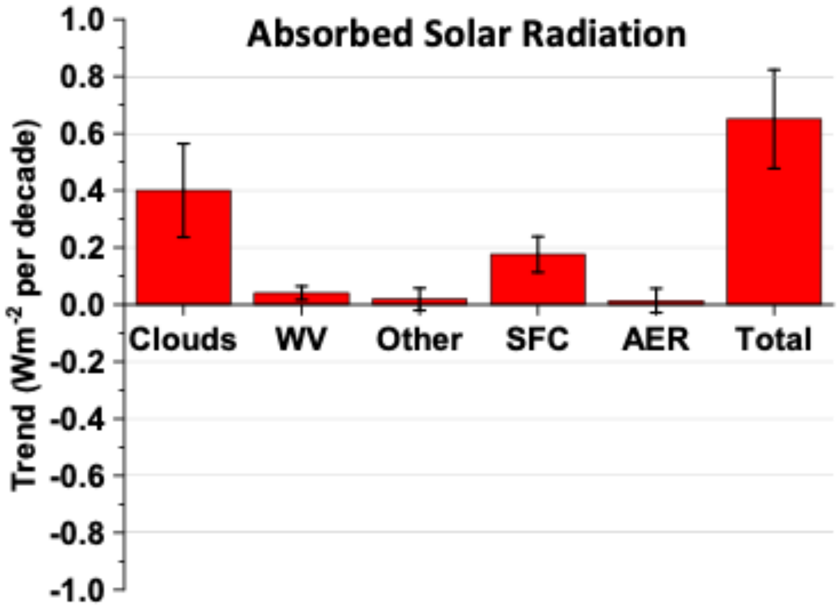


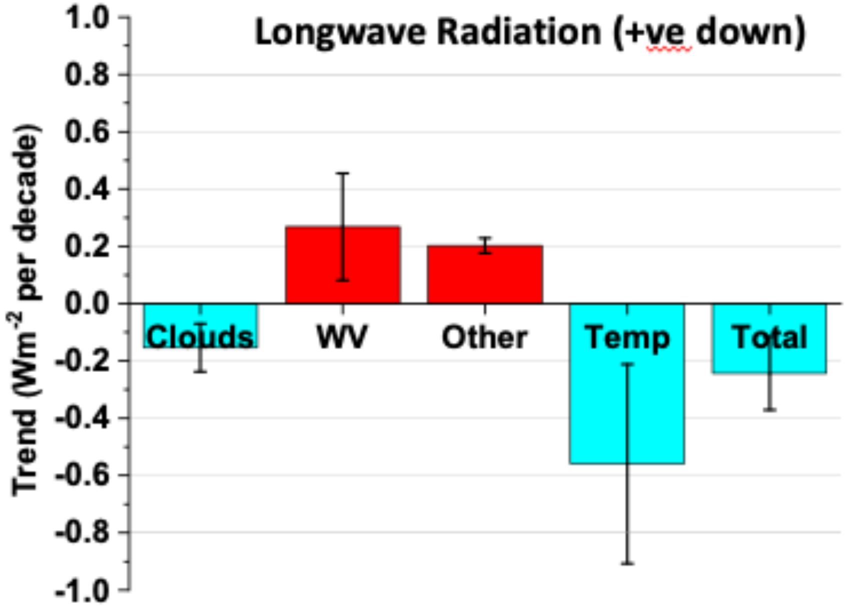
Zonal Mean All-Sky TOA Flux Trends (03/2000–12/2022)

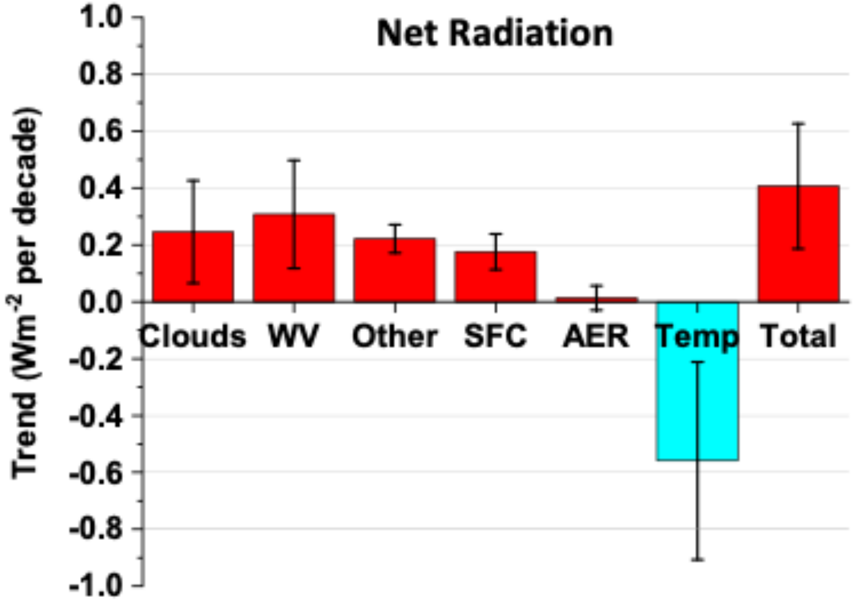


Global:	**0.71 ± 0.19**	**–0.26 ± 0.19**	**0.45 ± 0.18**

Global Mean Trends (09/2002-03/2020)

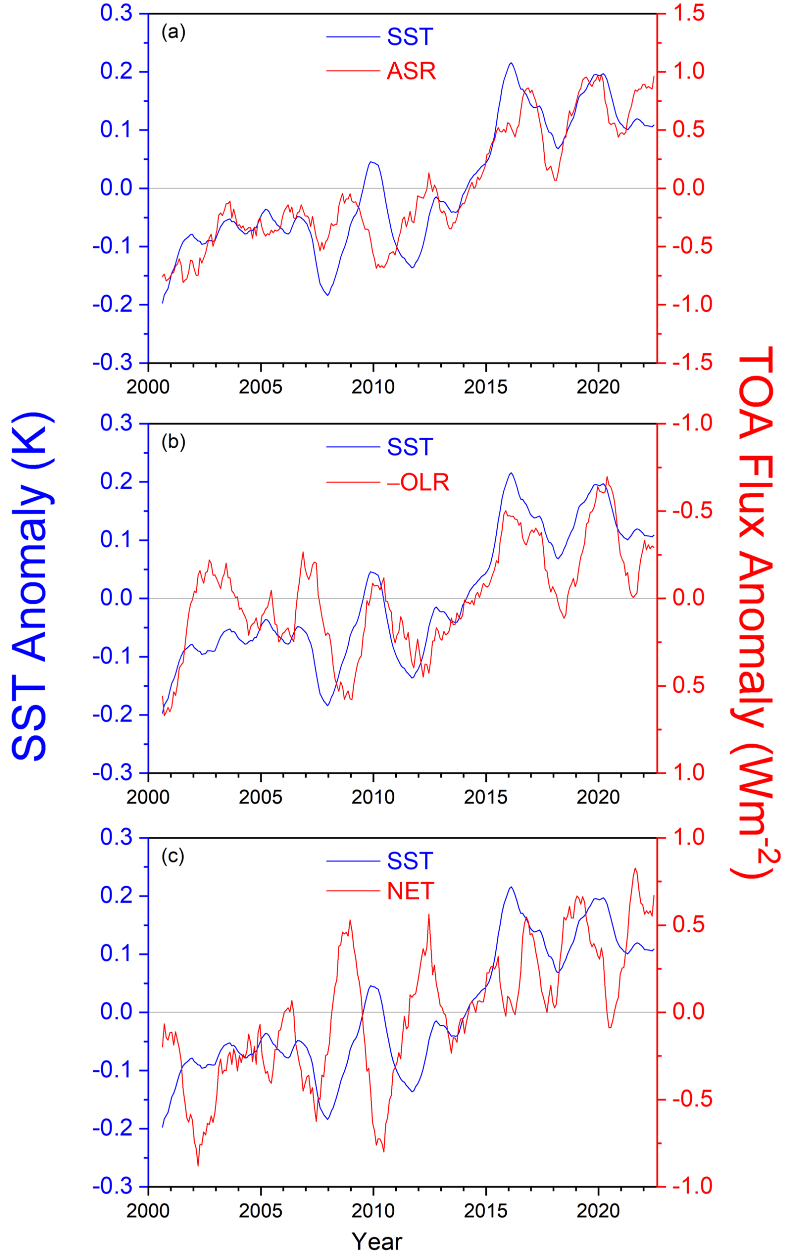




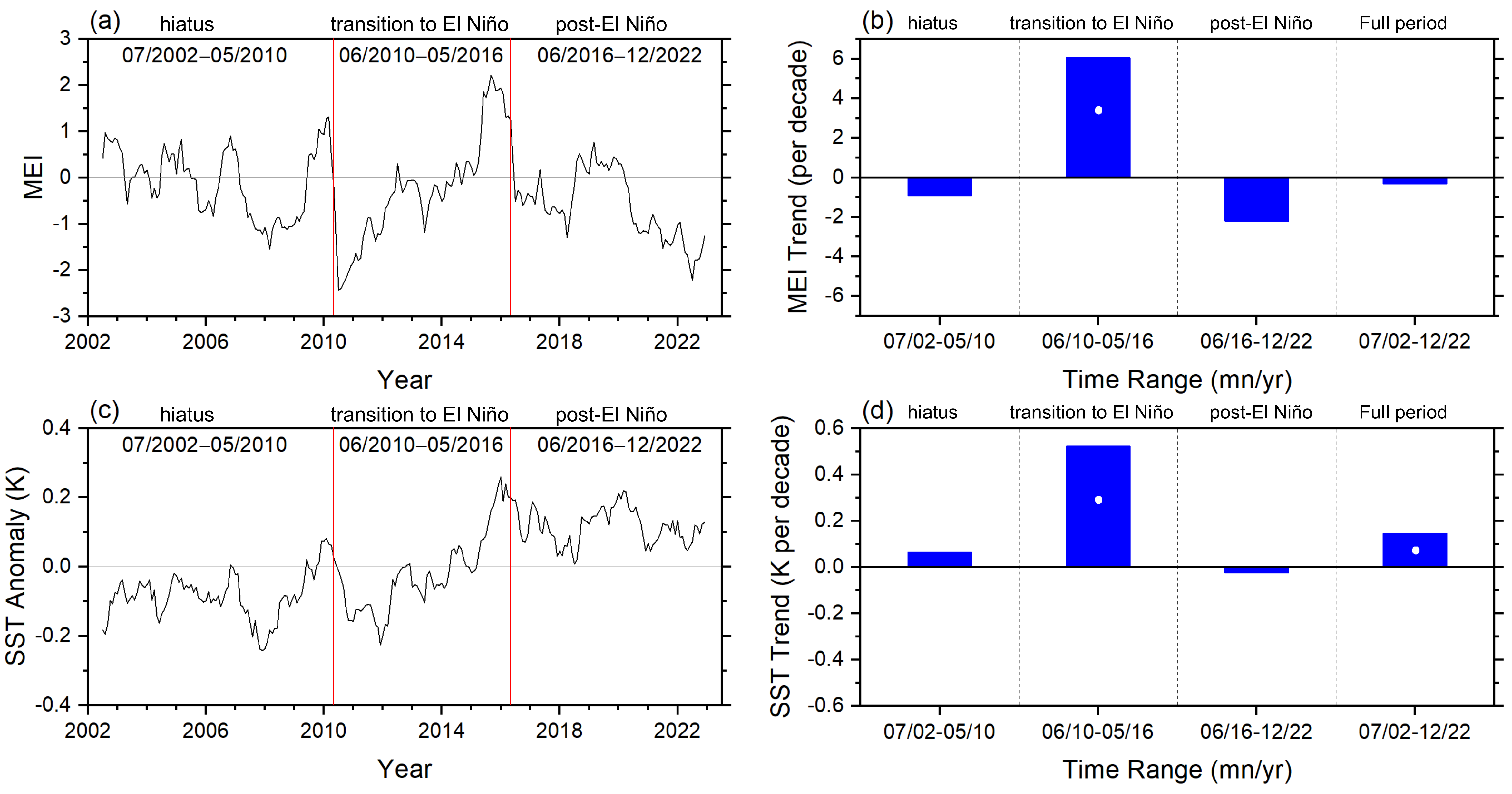


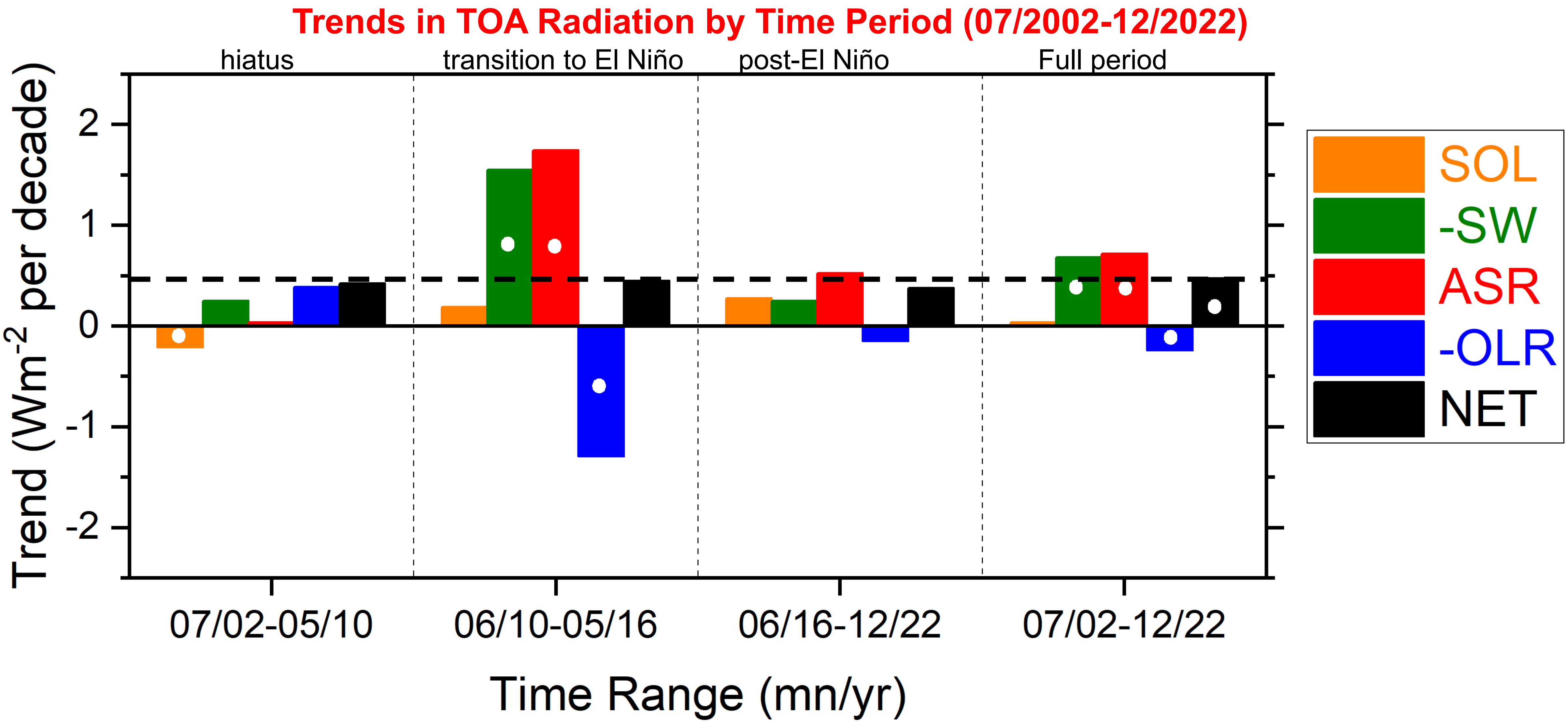
Combined changes in clouds, sea-ice, WV and trace gases exceed influence from temperature changes, resulting in a positive overall trend in net TOA flux.

Twelve-Month Running Average Global Anomalies in SST and TOA radiation (03/2000–12/2022)



Monthly Time Series and Trends in MEI and SST (07/2002-12/2022)





- Despite large variations in ASR and –OLR trends (>1 Wm^{-2} dec^{-1}), NET trends are nearly constant (< 0.1 Wm^{-2} dec^{-1} variation).

⇒ Rate of increase in planetary heat uptake (i.e., d(NET)/dt) is relatively insensitive to internal climate variability during CERES.

⇒ Is this by chance? Or does it say something more fundamental about climate system?

Methodology

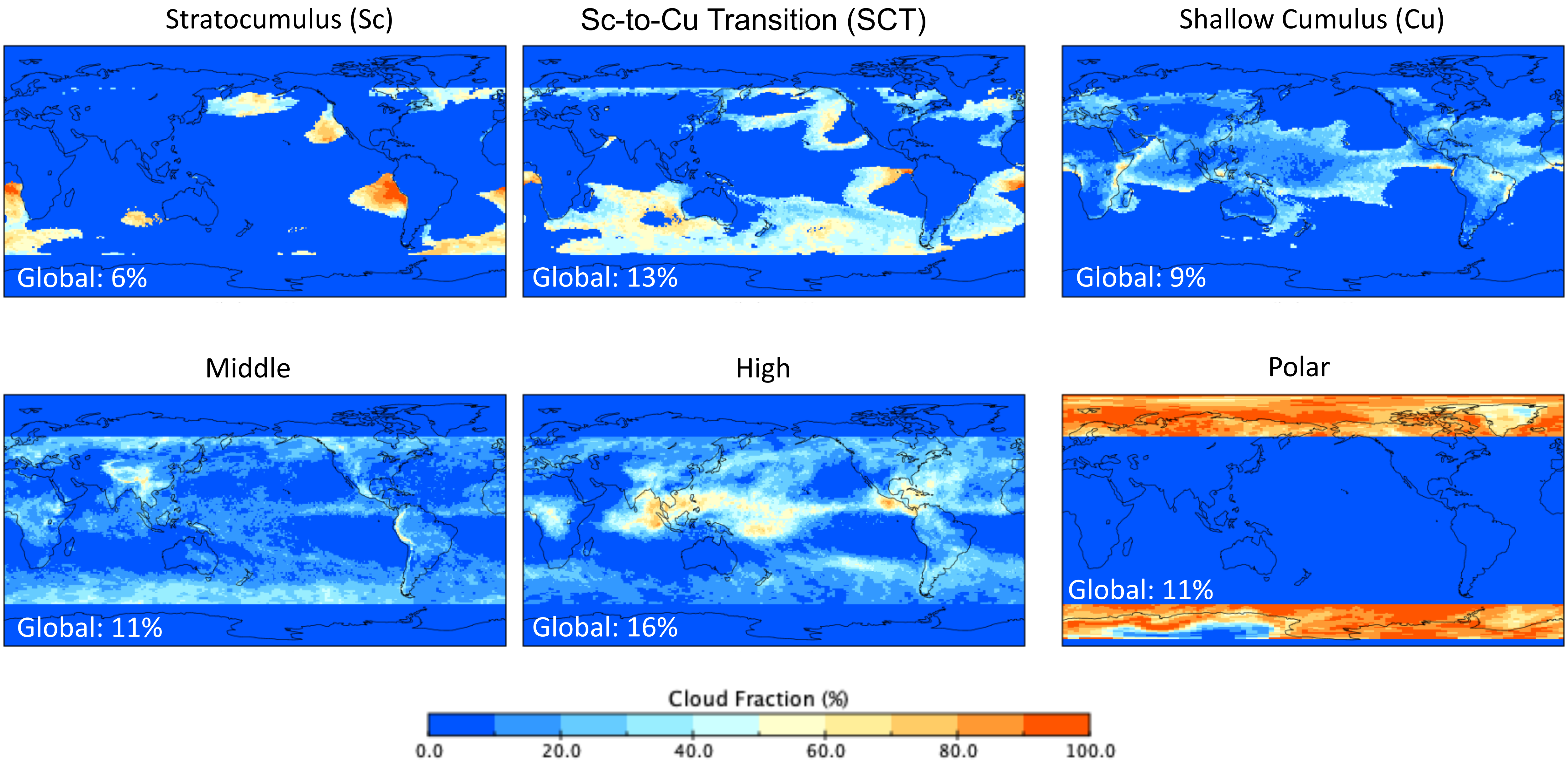
1) **Determine meteorology by cloud type**:
   - Read in meteorological variables (EIS, T_{skin}) in SSF1deg-daily for one month.
   - Sort and average meteorology by cloud type categories in FluxbyCldTyp-daily files to produce monthly meteorology by cloud type (6 cloud optical depth, 7 cloud-top pressure).

2) **Determine flux by cloud class**:
   - Read in monthly meteorology by cloud type from step 1.
   - For each gridbox, determine overall cloud fraction and mean SW TOA flux contribution for the following cloud classes:

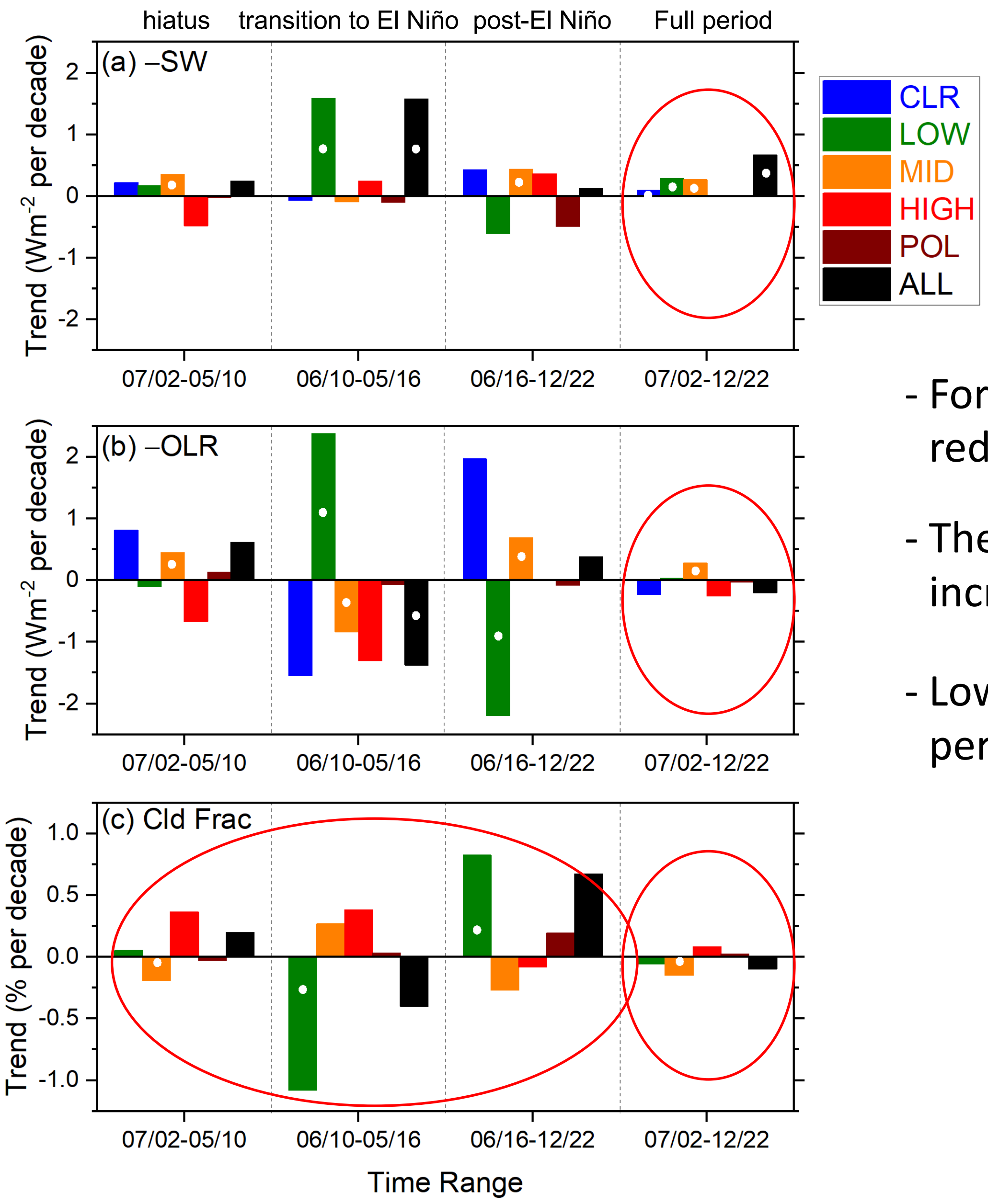
Cloud Class	Cloud Top Press (hPa)	EIS (K)	Latitude Range
Stratocumulus (Sc)	> 680	> 5	$\lvert\lambda\rvert < 60^\circ$
Stratocumulus-to-Cumulus Transition (SCT)	> 680	0 – 5	$\lvert\lambda\rvert < 60^\circ$
Shallow Cumulus (Cu)	> 680	< 5	$\lvert\lambda\rvert < 60^\circ$
Middle	440 – 680	–	$\lvert\lambda\rvert < 60^\circ$
High	< 440	–	$\lvert\lambda\rvert < 60^\circ$
Polar	–	–	$\lvert\lambda\rvert \geq 60^\circ$

   - Determine anomalies and trends for each cloud class (07/2002-12/2021)

Cloud Fraction by Cloud Class (September 2002)

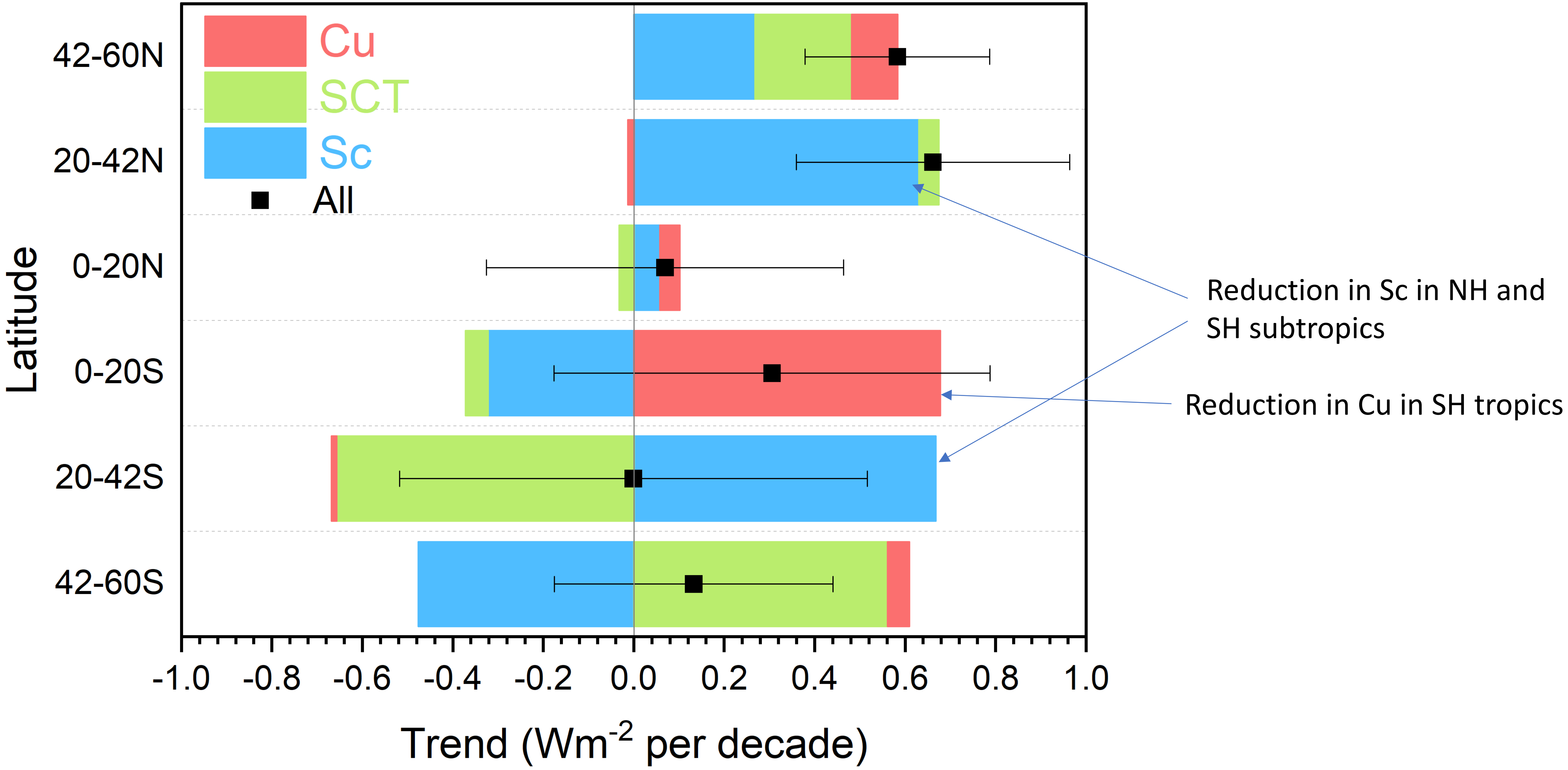


Trends in Daytime SW flux, –OLR Flux and Cloud Fraction by Cloud Type (07/2002-12/2022)

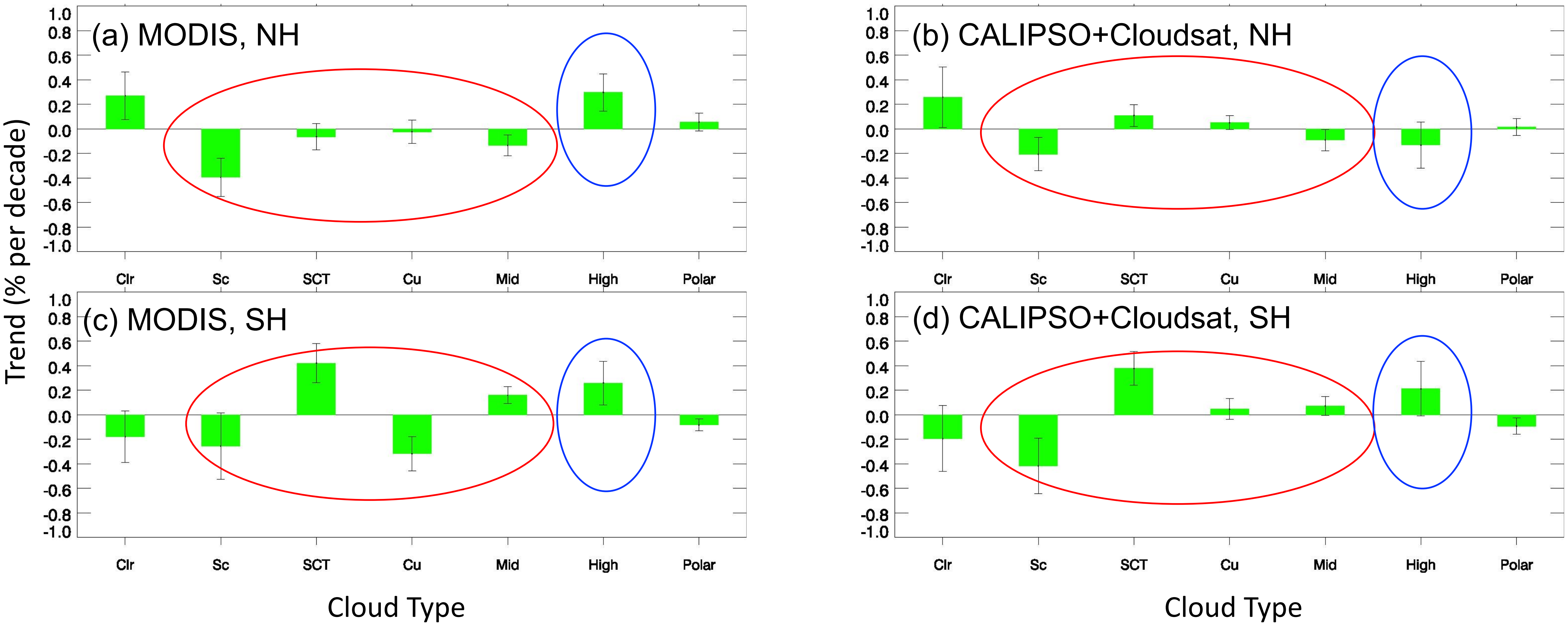


- For the entire period, the large positive ASR trend is primarily driven by reductions in low and middle clouds.
- The increase in OLR (decrease in -OLR) is primarily due to increased emission from cloud-free regions.
- Low clouds exhibit far more variability across the different periods than any other cloud type.

Zonal ASR Trends by Low Cloud Type (07/2002–12/2022)

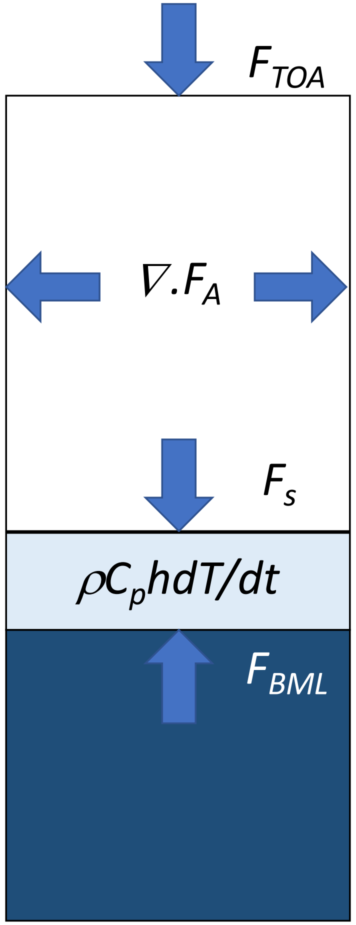


Hemispheric Clear and Cloud Fraction Trends by Cloud Type: MODIS vs CALIPSO+Cloudsat (01/2007-12/2017)



- Similar low and middle cloud trends in both hemispheres
- Consistent high cloud trends in SH but opposite in NH

Ocean Mixed Layer Heat Budget (01/2006–12/2021)
(Monthly in 1x1 deg latitude-longitude oceanic regions)



F_{TOA}: Net TOA Flux } CERES EBAF Ed4.1

F_S: Surface Energy Flux $= F_{\mathrm{TOA}} - \nabla \cdot F_A - AET$

$\nabla . F_A$: divergence of lateral atmospheric energy transports

AET: vertically integrated atmospheric energy tendency

} Mayer et al. (2017)

$\rho C_p hdT/dt$ = Ocean mixed layer heat content tendency

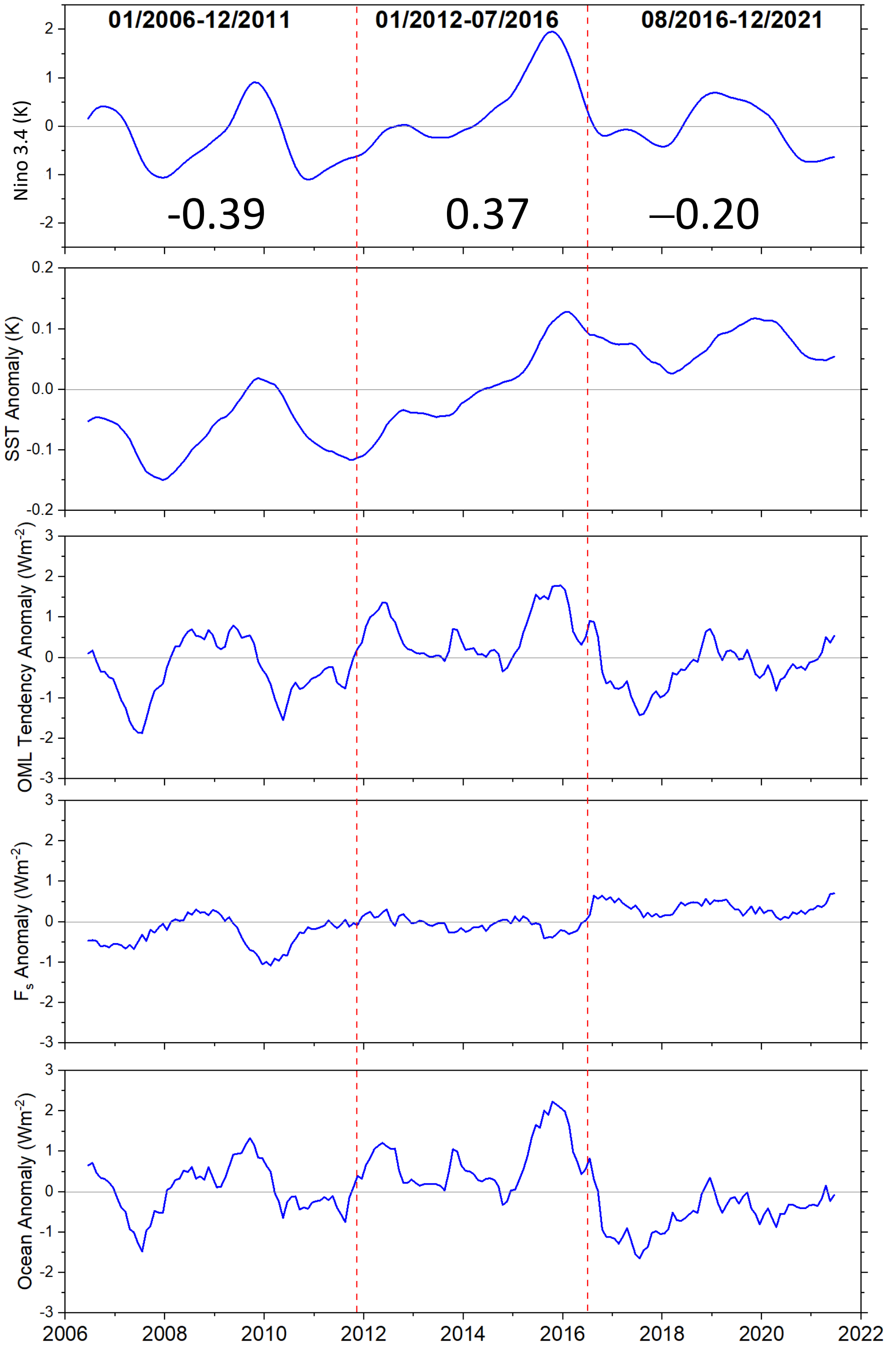
h = Ocean mixed layer depth (GODAS)

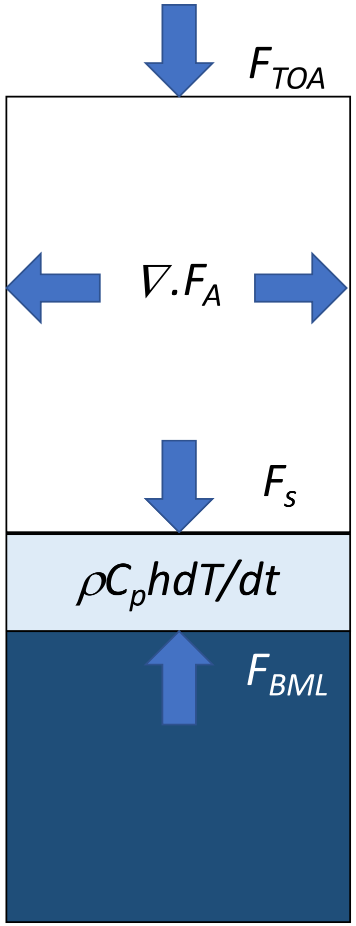
T = Sea-surface temperature (ERA5)

F_{BML} : $F_S - \rho C_p hdT/dt$

Global Ocean Mixed Layer (OML) Energy Budget (01/2006-12/2021)

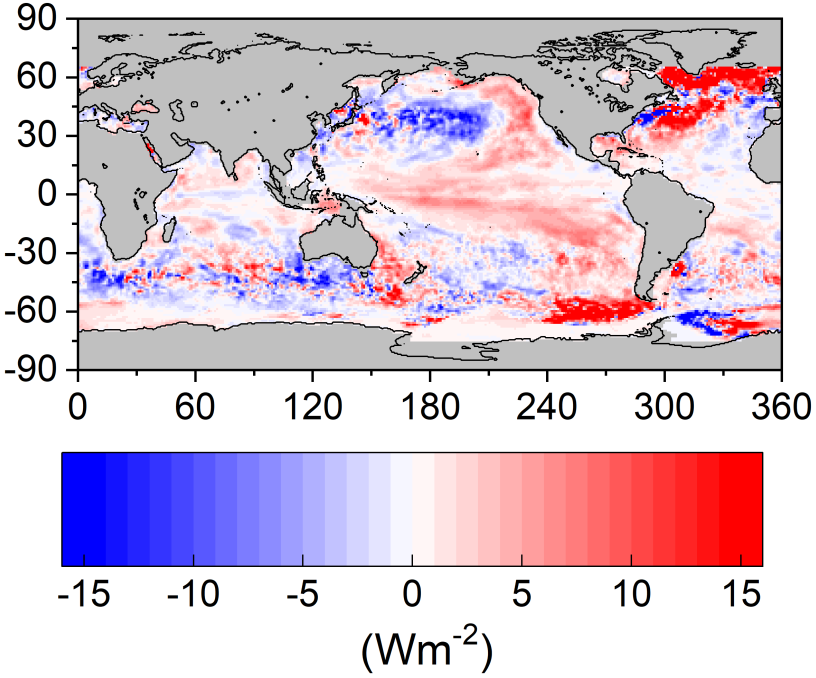
Anomalies
Niño 3.4 (K)
SST (K)
OML Heat Content Tendency ($\rho C_p h dT/dt$; (Wm^{-2}))
Surface Heat Flux (F_s) (Wm^{-2})
Ocean Heat Flux (F_{MBL}) (Wm^{-2})



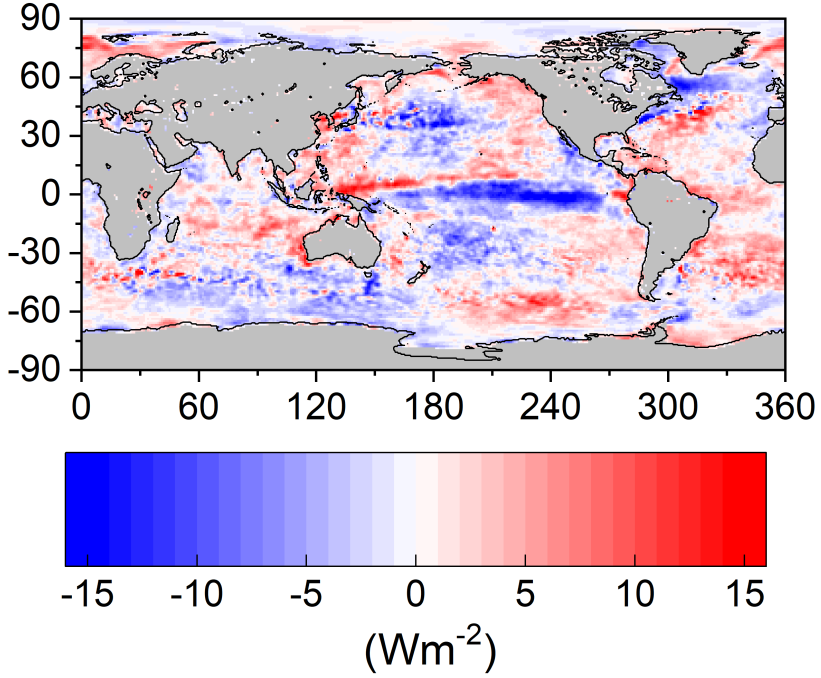


Regional Ocean Mixed Layer (OML) Energy Budget
(01/2012–07/2016)

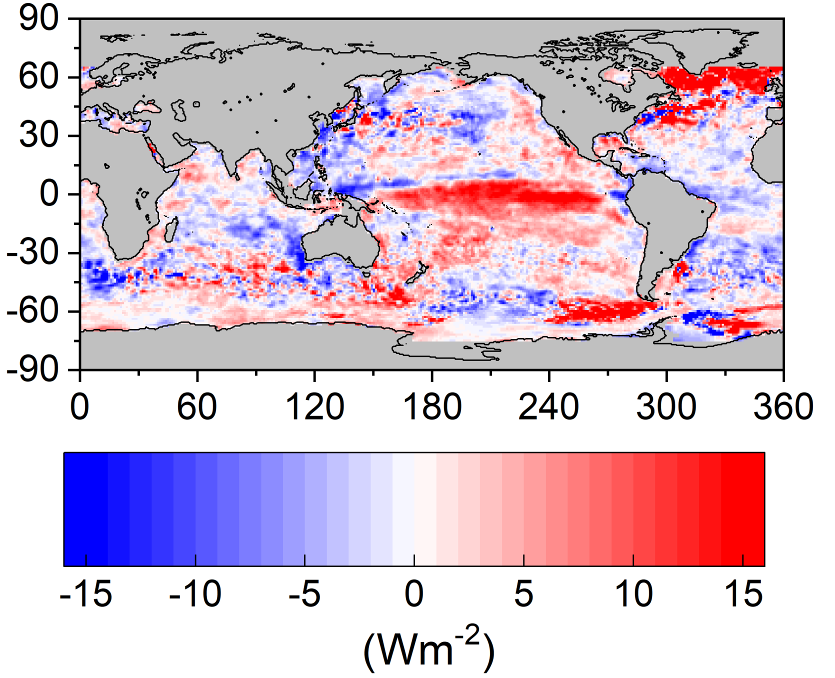
OML Tendency Anomaly



Fs Anomaly

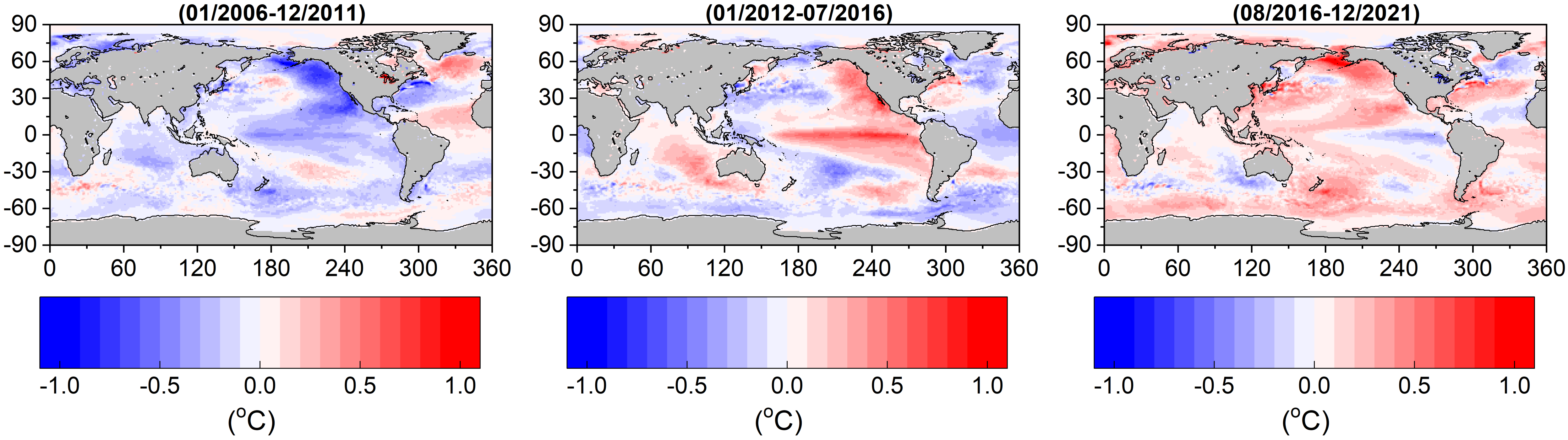


Ocean Mixing/Advection Anomaly



- OML heating over much of Pacific Ocean and N. Atlantic.

Mean Anomaly in SST



Mean Niño 3.4 Index		
-0.39	0.37	–0.20

Conclusions

- CERES observations show a doubling in Earth's Energy Imbalance (EEI) during the CERES period.

- The EEI trend is primarily associated with an increase in absorbed solar radiation (ASR) partially offset by an increase in OLR.

- ASR and SST global and regional trends track one another.

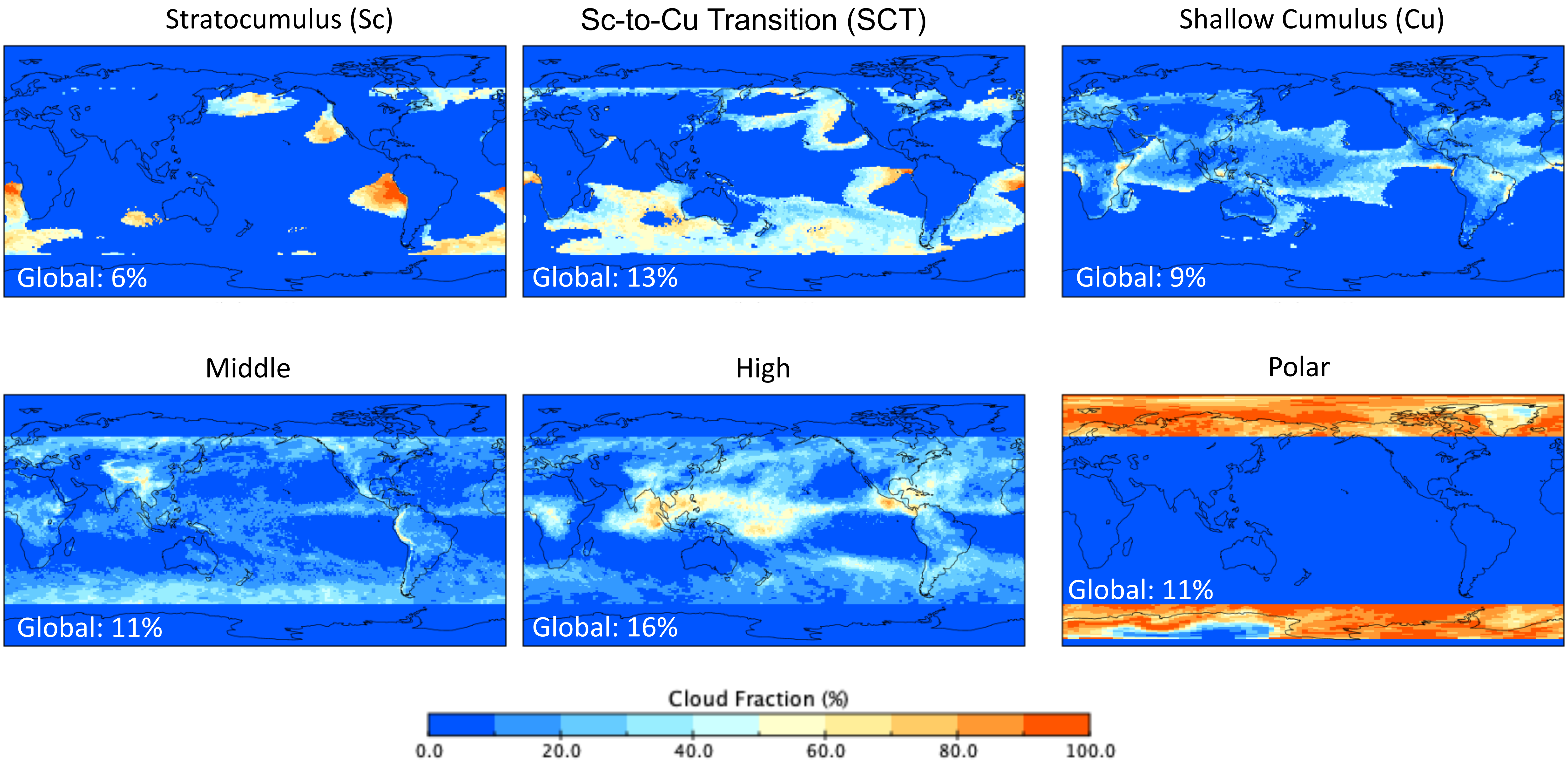
  ⇒ Large ASR trend primarily driven by reductions in low and middle clouds.

  ⇒ Ocean mixed layer heating (and SST) variations primarily associated with ocean heat fluxes as opposed to surface heat fluxes.

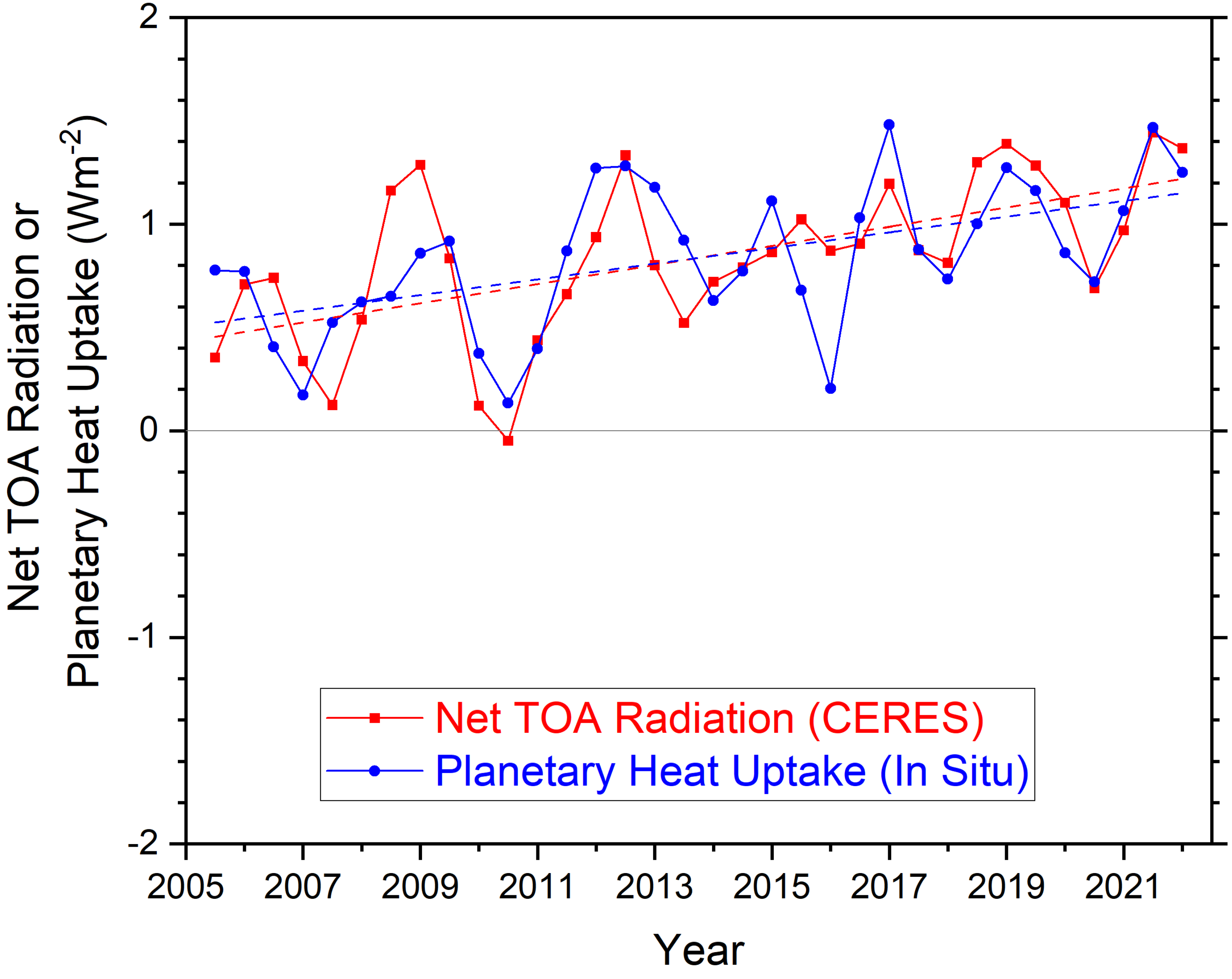
- Despite substantial variations in ASR and OLR trends for “hiatus”, “transition to El Niño”, and “post-El Niño” periods, NET trends are nearly identical in all 3 periods (within 0.1 Wm^{-2} dec^{-1}).

  ⇒ Implies rate of increase in planetary heat uptake is relatively insensitive to internal climate variability during CERES.

Cloud Fraction by Cloud Class (September 2002)



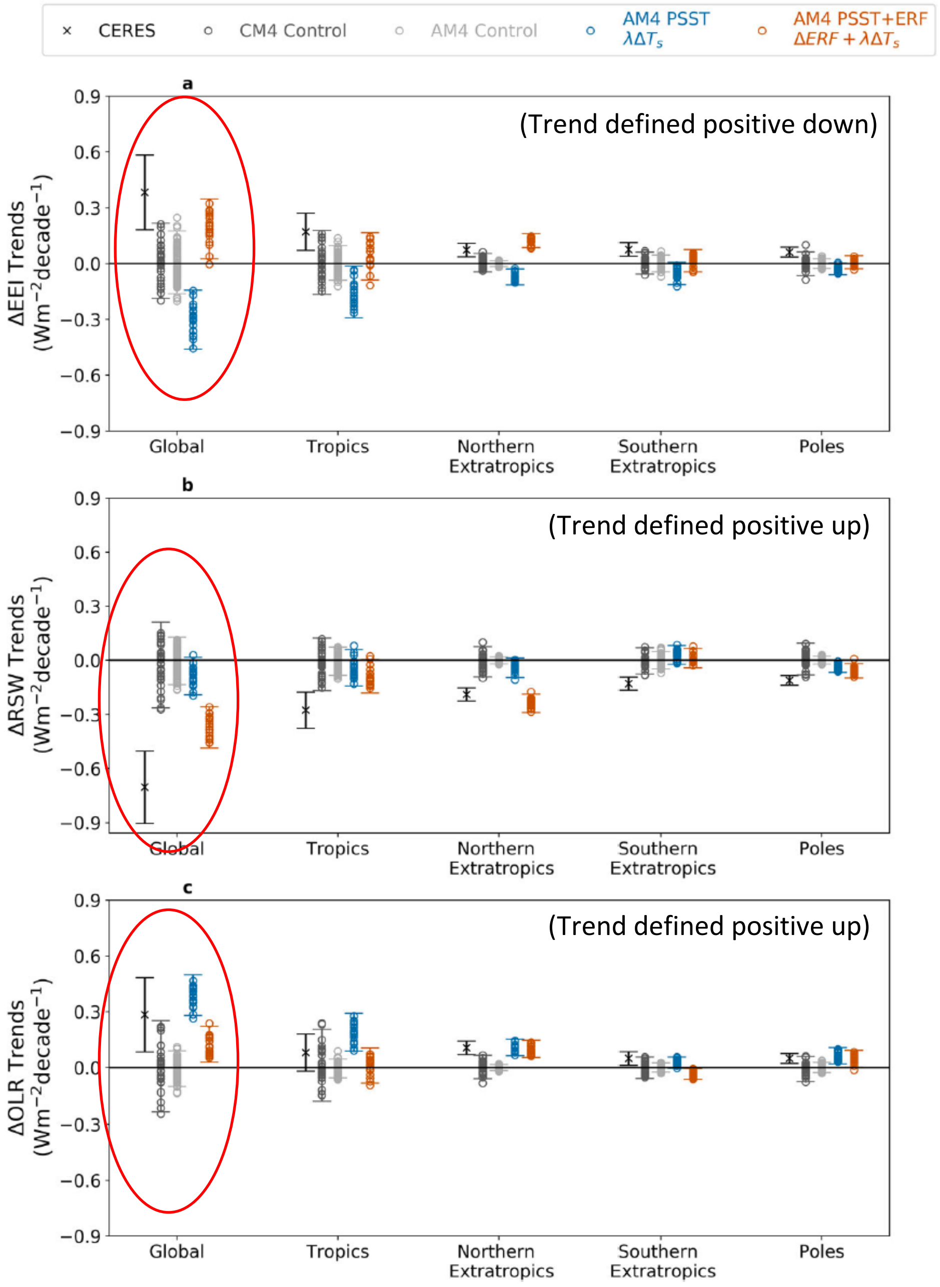
Annual Mean Net TOA Radiation & In-Situ Planetary Heat Uptake (07/2005-06/2022)



	Trend (Wm^{-2} dec^{-1})
CERES EBAF Ed4.2	0.46 ± 0.33
In-Situ	0.38 ± 0.31
Difference	0.084 ± 0.24
R^2	0.54

(update to Loeb et al., 2021)

Climate Model vs CERES Trend Comparison



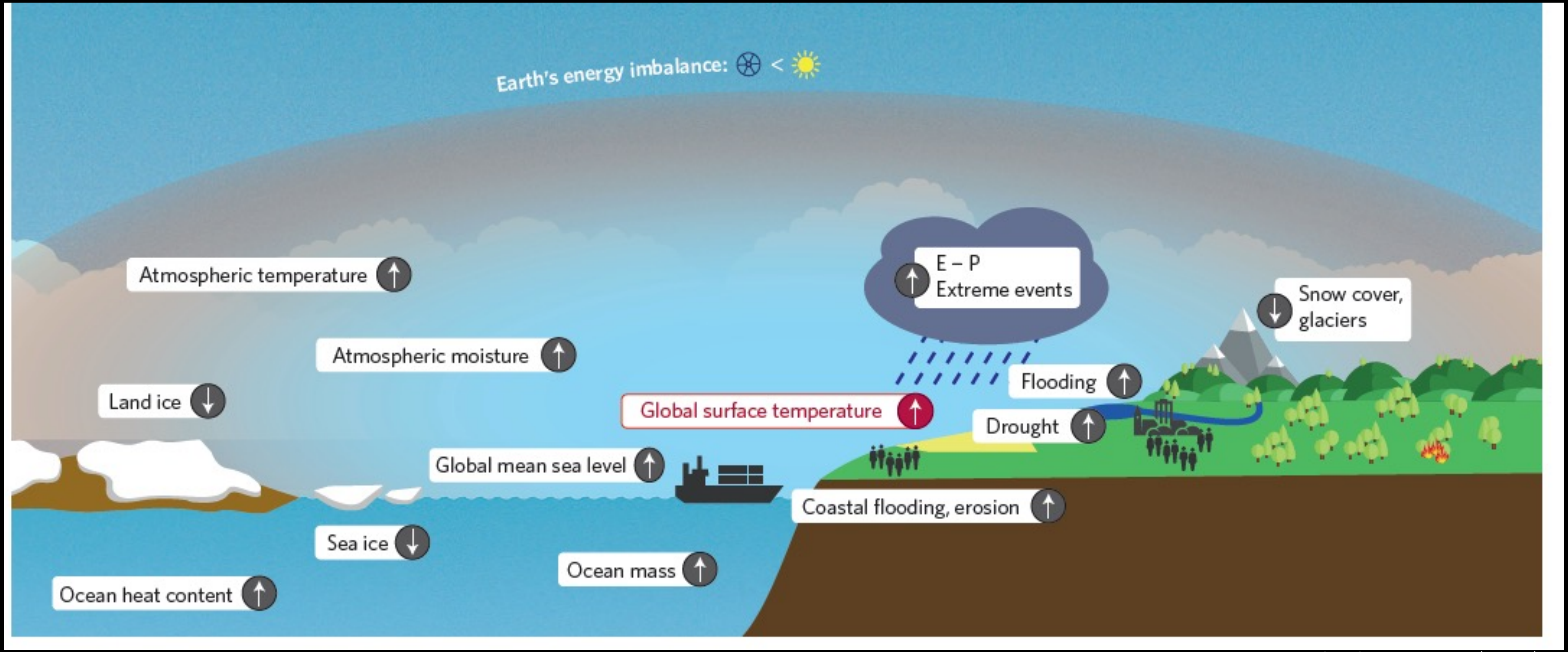
- Including climate forcing changes EEI trend from negative to positive, but still lower than CERES.

- Including climate forcing causes decrease in both reflected SW and OLR trends.

- Decrease in AM4 reflected SW is significantly weaker than CERES, even when climate forcing is included.

Raghuraman et al. (2021)

"Symptoms" of a Positive Earth Energy Imbalance

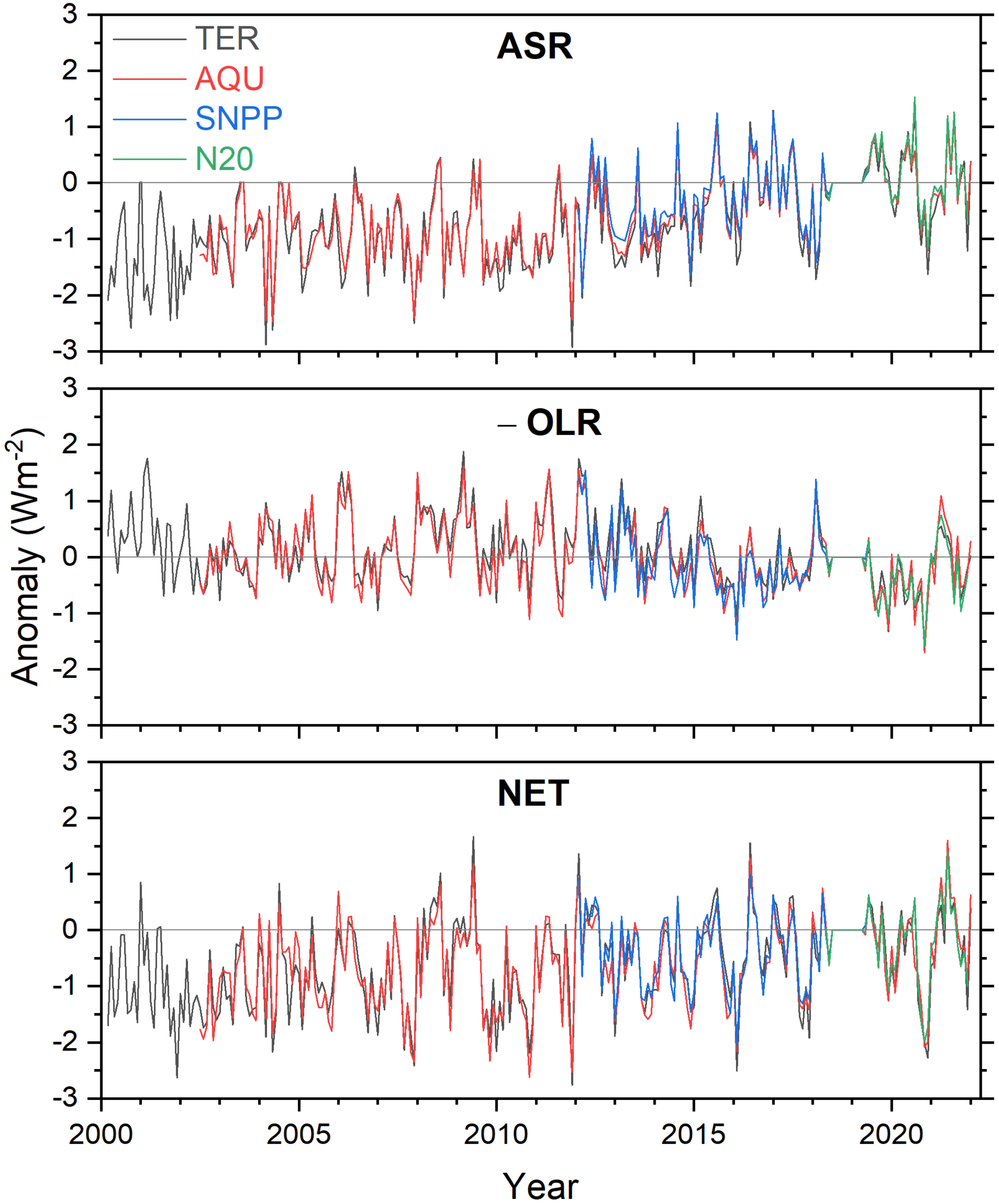


From von Schuckmann et a. (2016)

A positive EEI leads to:

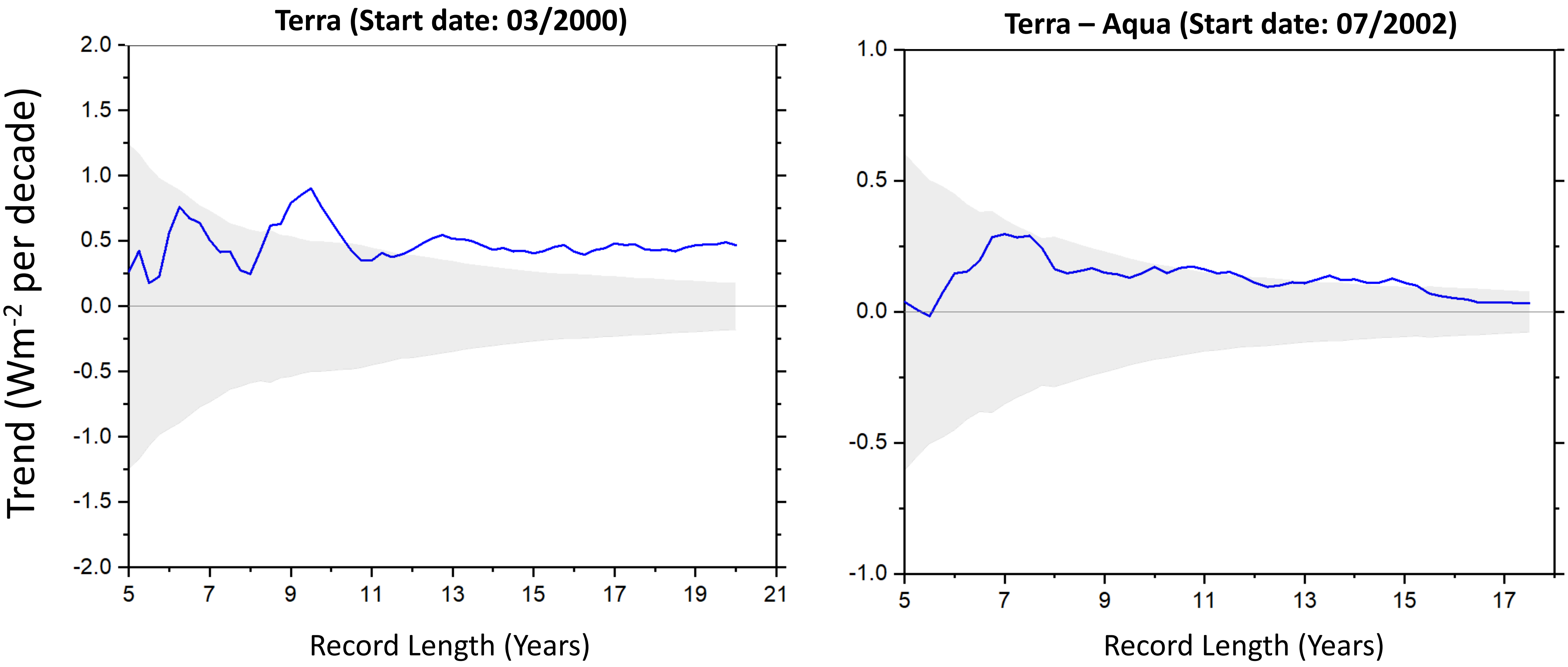
- A rise in Earth's surface temperature, atmospheric moisture and global mean sea level
- Shifts in atmospheric circulation patterns, leading to more extreme weather (⇒ flooding, drought)
- Increase in ocean heat content, leading to ocean acidification, impacting fish and other marine biodiversity
- Decrease in land and sea ice, snow cover and glaciers

Global Mean All-Sky TOA Flux Monthly Anomalies (03/2000-01/2022; Climatology: 05/2018—06/2019)



- Based upon CERES SSF1deg products (no GEO)
- NET monthly anomalies consistent to 0.3 Wm^{-2} (1σ)
- No evidence of CERES instrument drift

CERES Global Mean Net TOA Flux Trends vs Record Length



- Terra & Aqua net TOA flux trends are consistent to < 0.1 Wm^{-2} per decade for the full period

Loeb et al. JGR, 2022