Trend in EEI During the CERES Period

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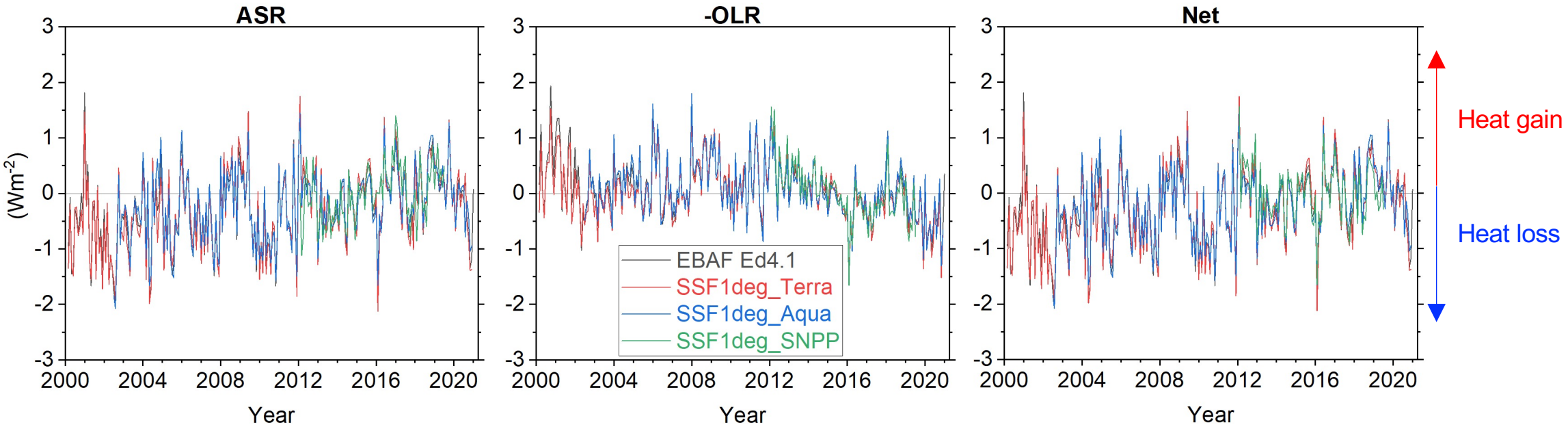
CERES-Libera Science Team Meeting, May 13, 2021 (Virtual Meeting)

Global Mean All-Sky TOA Flux Anomalies

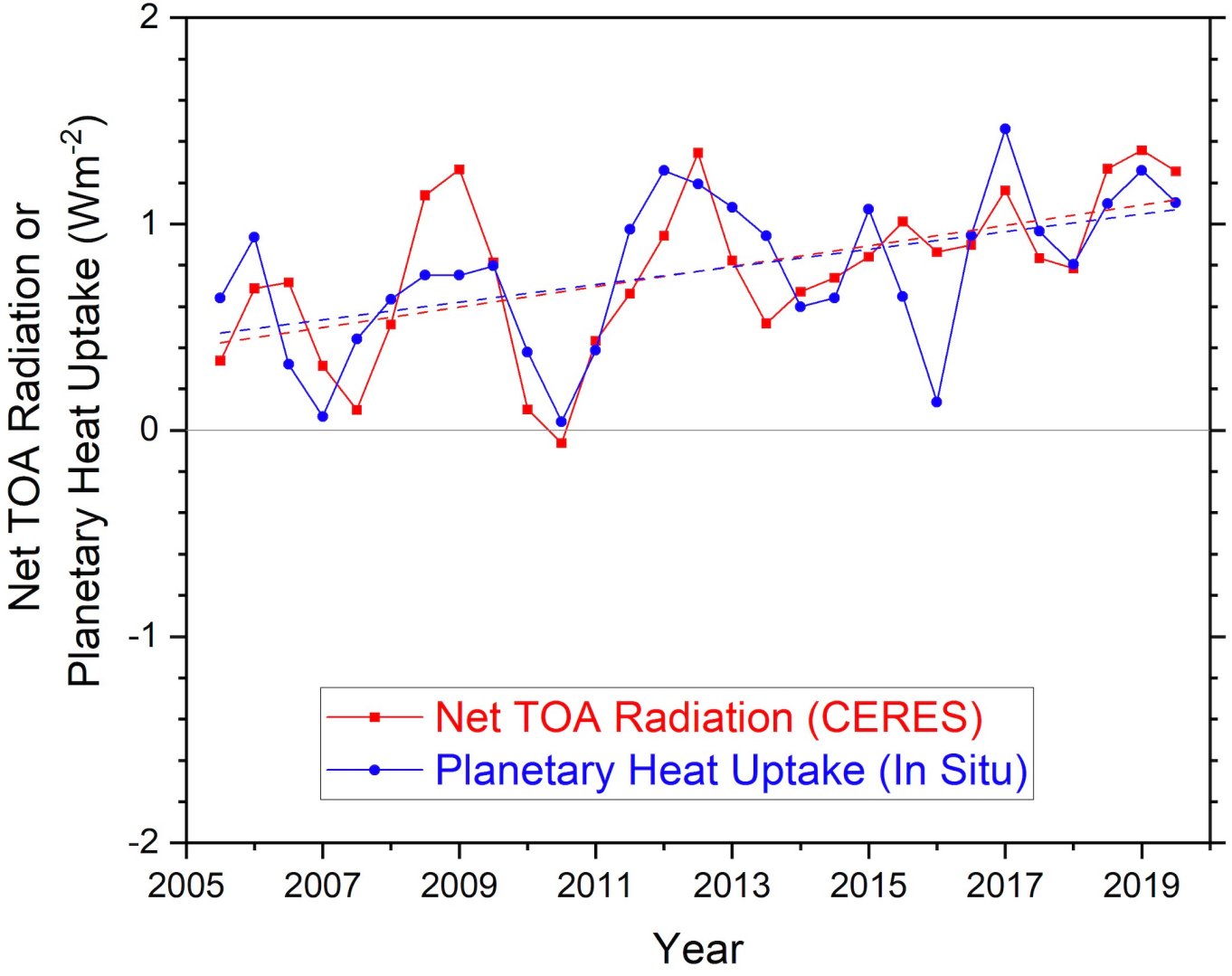
(Relative to Climatology for 02/2012-09/2019)



EBAF Trends (03/2000-02/2021)		
0.68 ± 0.12 Wm^{-2} per decade	-0.31 ± 0.12 Wm^{-2} per decade	0.37 ± 0.15 Wm^{-2} per decade

- Earth's energy imbalance (EEI) averaged over 2005-2015 is 0.71 ± 0.1 Wm^{-2} (Johnson et al. 2016)
- A trend in global mean net TOA flux of 0.37 Wm^{-2} per decade implies an increase of ≈0.74 Wm^{-2} in EEI during the 20-year CERES record.
  - ➢ **Earth's heating rate has shown a marked increase since 2000**

Annual Mean Net TOA Radiation & In-Situ Planetary Heat Uptake (07/2005-06/2019)



- CERES Net radiation & In-Situ PHU show consistent increasing trends with good agreement in year-to-year variability.

Trend and Uncertainty (Wm^{-2} per decade; 5%-95% CI)

Trend : 0.50 ± 0.47

Trend Diff : 0.07 ± 0.29

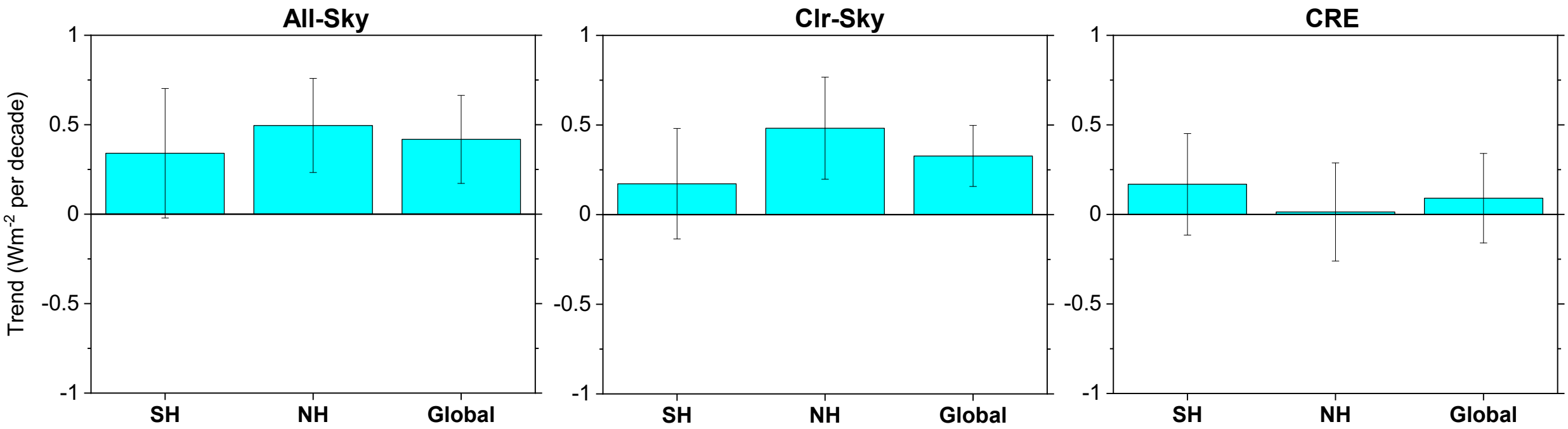
R^2 = 0.49

Note: CERES and Argo+Altimeter are anchored to an EEI of 0.76±0.1 Wm^{-2} for 2005-2020 based upon in-situ data.

Loeb et al. (GRL; 2021)

Trend in Net TOA Flux

(03/2000-07/2020)



- Greater hemispheric contrast for clear-sky than all-sky.
- Compensation between clear-sky changes in polar regions and all-sky changes in non-polar regions (mainly clouds) leads to near-zero CRE trends.
  - ➢ Need to subtract non-cloud changes in CRE in order to isolate influence of clouds

Attribution of CERES TOA Flux Trends Using Partial Radiative Perturbation Method

(What are the contributions from individual variables to observed CERES TOA flux trends?)

(a) Non-Cloud Contributions:

The effect on the flux (δF) due to some perturbation Δx of variable *x* is:

$$\delta F_{\Delta x} = F(x + \Delta x, y_1, \ldots, y_N) - F(x, y_1, \ldots, y_N) \quad (1)$$

$x, y_1, \ldots, y_N$ = Gridded monthly mean input variables to radiative transfer model calculations

$\Delta x, \Delta y_1, \ldots, \Delta y_N$ = Gridded deseasonalized monthly mean anomalies of input variables

F = Fu-Liou radiative transfer model computed TOA flux

Input variables (non-cloud): Skin temperature, profiles of temperature and water vapor, surface albedo, aerosols, gases (ozone, carbon dioxide, methane, nitrous oxide, CFC-11, CFC-12, and HCFC-22) and incoming solar irradiance.

Source: Adjusted SSF1deg inputs.

- Inputs are "tuned" to force match between computed and observed EBAF clear-sky TOA fluxes

(b) Cloud Contributions:

$$\boxed{\delta F_{\Delta c} = \Delta CRE - \sum_i \left[\delta F_{\Delta x_i} - \delta F^{o}_{\Delta x_i}\right]} \qquad (2)$$

ΔCRE = Anomaly in cloud radiative effect (CRE) from EBAF Ed4.1 observations

$\delta F_{\Delta x_i}$ = All-sky flux perturbation due to anomaly in variable $\boldsymbol{x}_i$

$\delta F^{o}_{\Delta x_i}$ = Clear-sky flux perturbation due to anomaly in variable $\boldsymbol{x}_i$

Perturbations (Δx_i) Considered

1) Skin Temperature and atmospheric temperature profile
2) Water vapor profile
3) Surface albedo
4) Aerosols
5) Other (gases and incoming solar irradiance)
6) Clouds (Eq. 2)

Time Period: 03/2000– 02/2020

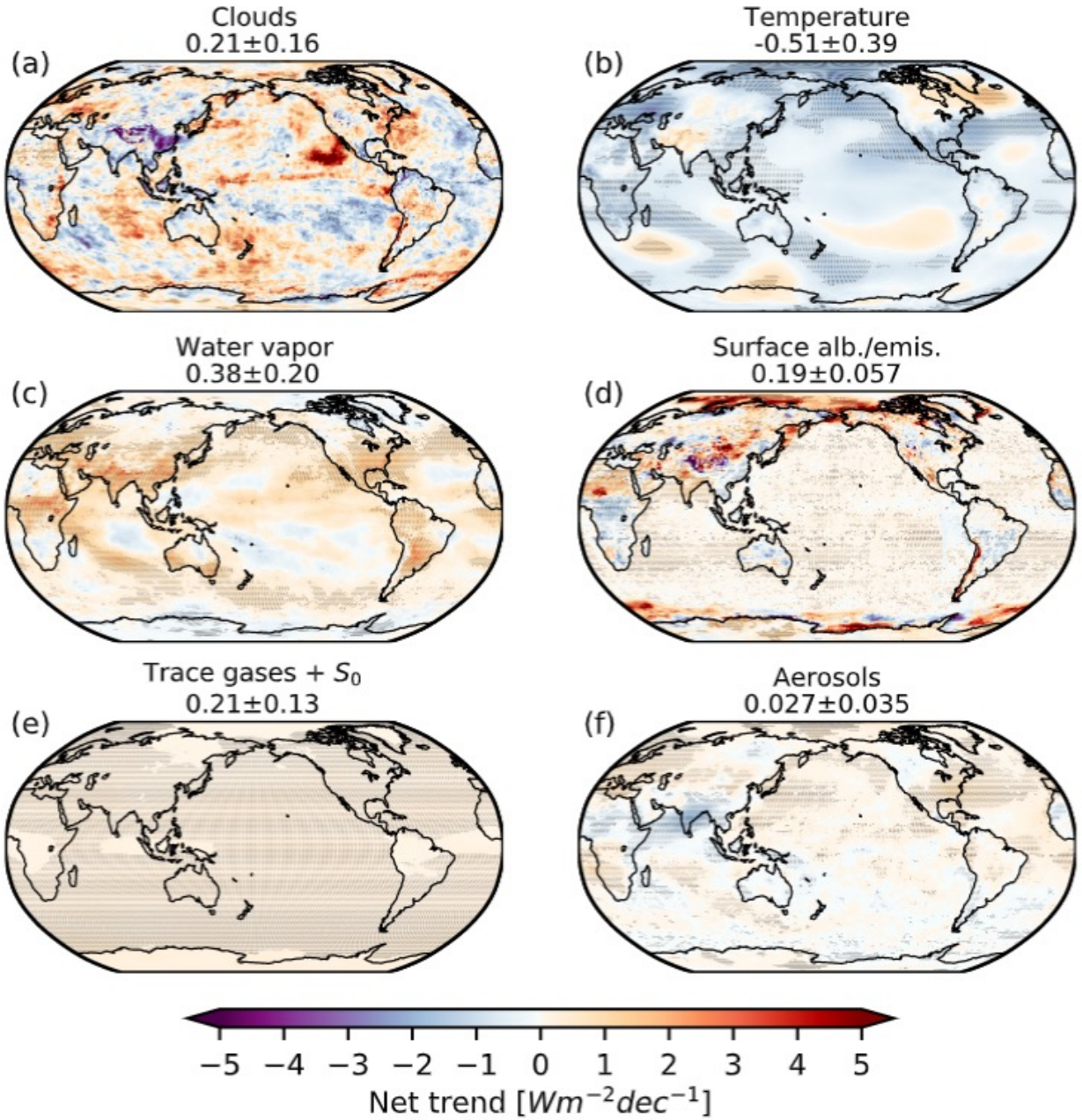
Input Data Sources for PRP Calculations

TABLE 1. Radiative transfer inputs used in CERES-PRP. Note that the spectral surface emissivity is also inputted into the radiative transfer model but is omitted from this table since it remains fixed over time and is therefore not perturbable.

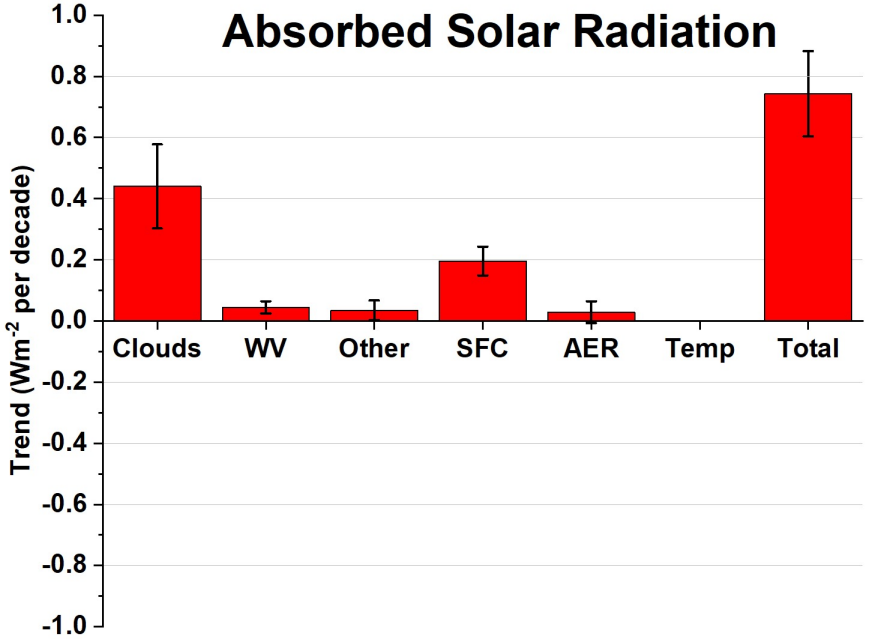
Variables	Dimensions	Sources
Temperature, water vapor, ozone	Pressure level, hour, latitude, longitude	GEOS or AIRS
Skin temperature, surface pressure	Hour, latitude, longitude	GEOS or AIRS
Carbon dioxide, methane	Latitude, longitude	AIRS/NOAA ESRL
Nitrous oxide, CFC-11, CFC-12, HCFC-22	Global means	NOAA-ESRL
Cloud fraction	Cloud condition, hour, latitude, longitude	SYN or C3M or SSF or SSFC3M
Cloud base pressure, top pressure, phase, optical depth (log mean), optical depth (linear mean), ice generalized effective diameter, liquid effective radius	Cloud layer, cloud condition, hour, latitude, longitude	SYN or C3M or SSF or SSFC3M
Surface albedo	SW band, cloudy or clear, zenith angle, latitude, longitude	CERES-SAH
Aerosol optical depth	Aerosol type, latitude, longitude	MATCH
Aerosol vertical distribution	Aerosol type, pressure layer, latitude, longitude	MATCH
TOA solar irradiance	Global mean	SORCE TSI

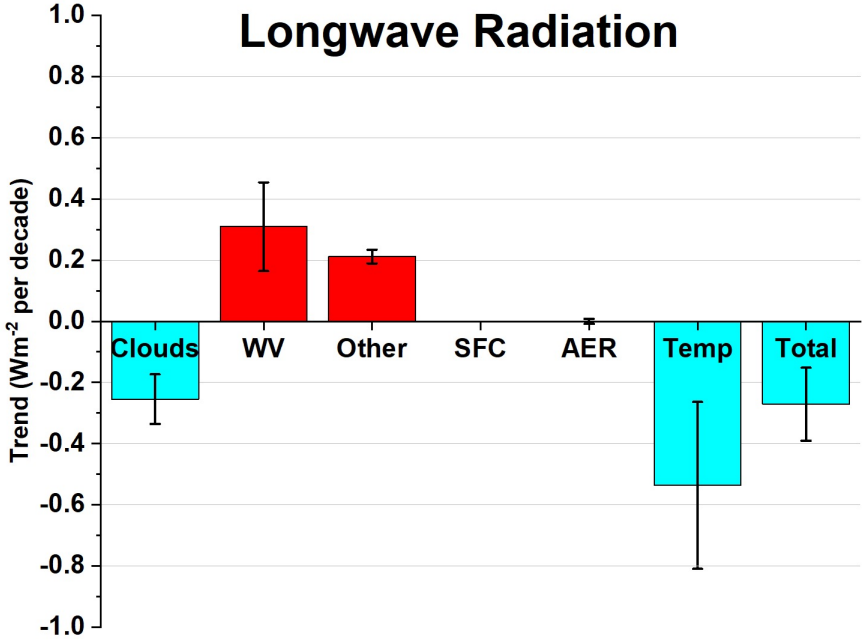
Thorsen et al. (2018)

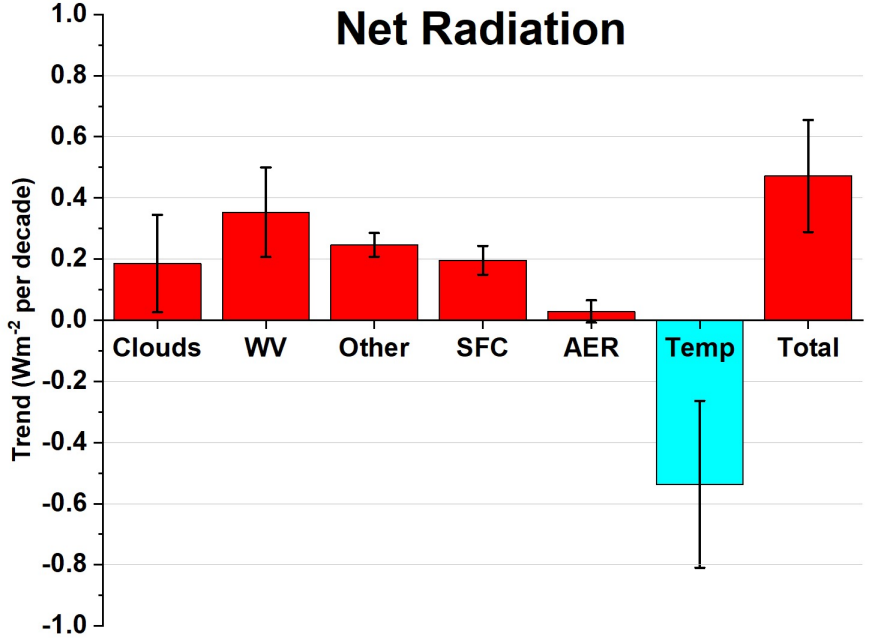
Attribution of CERES TOA Net Flux Trends (03/2000-02/2020)



Global Mean Trends (03/2000-02/2020)

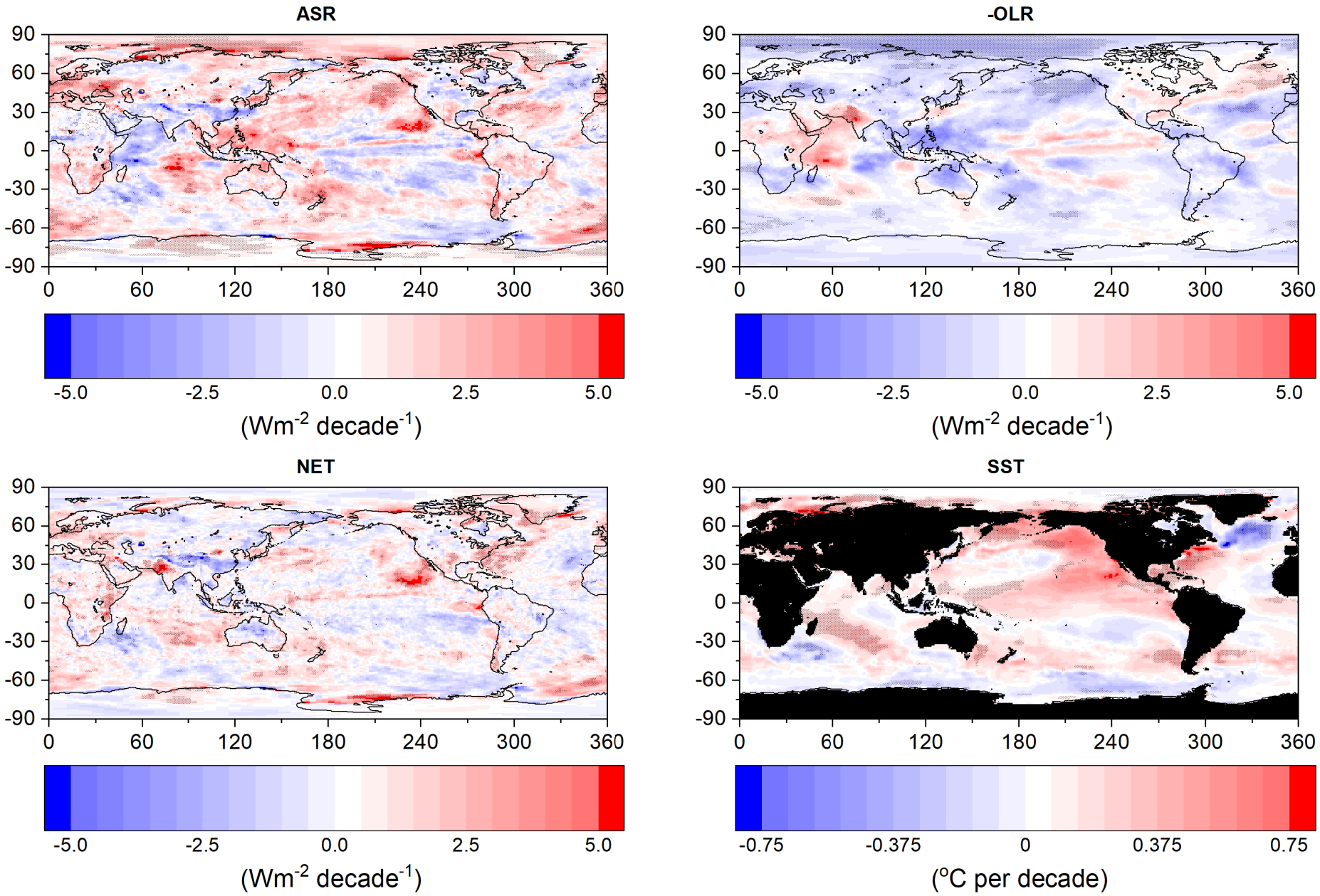




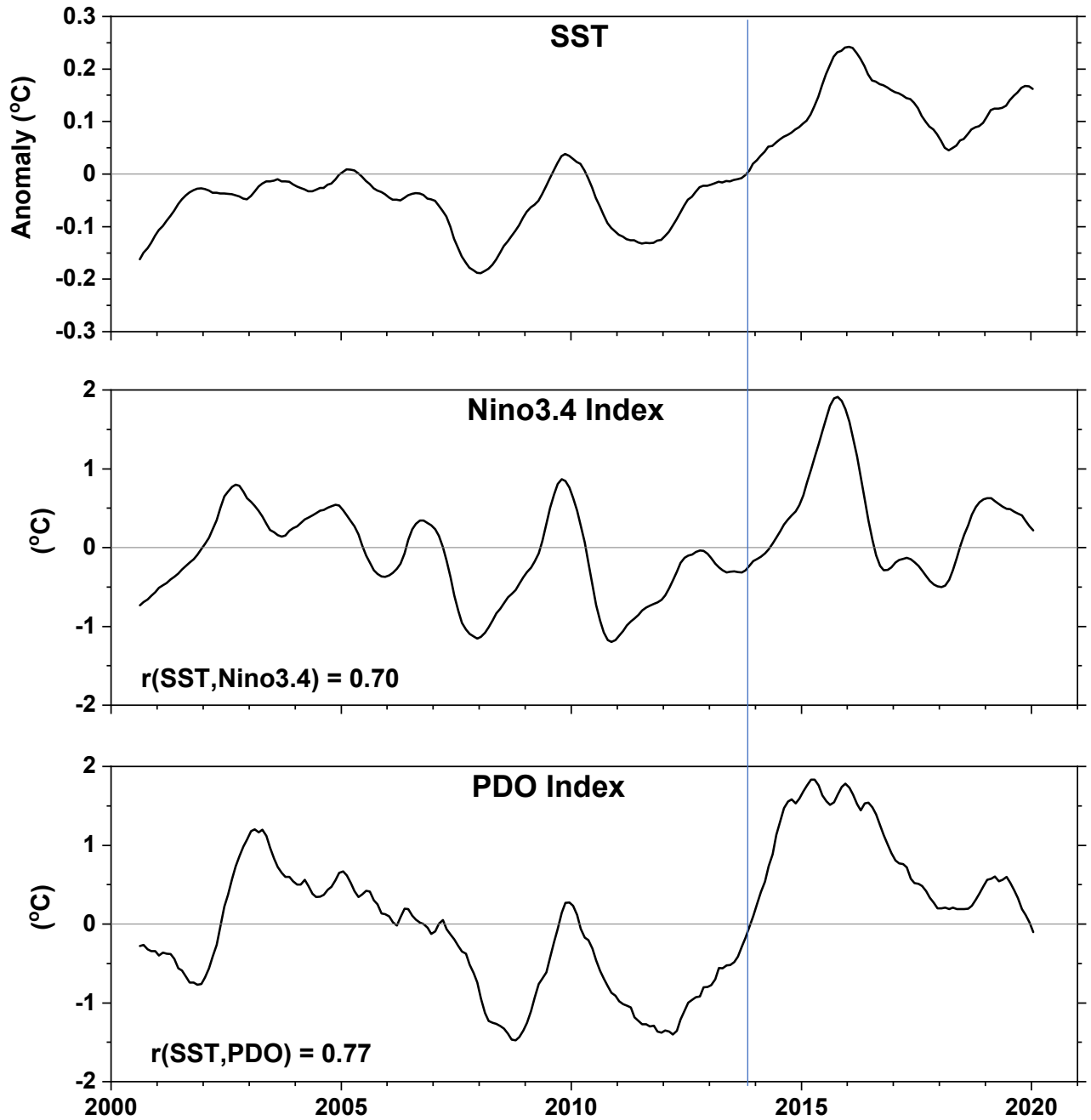


- Decreases in cloud amount and sea-ice contribute most to positive ASR trend (62% and 27%, respectively).
- Increase in global mean temperature is the main reason for the overall increase in LW emission to space. Some compensation from WV and greenhouse gases.
- Combined changes in clouds, sea-ice, WV and greenhouse gases exceed influence from temperature, resulting in a positive overall trend in net TOA flux.

All-Sky Trends (03/2000 - 07/2020; Positive Down)

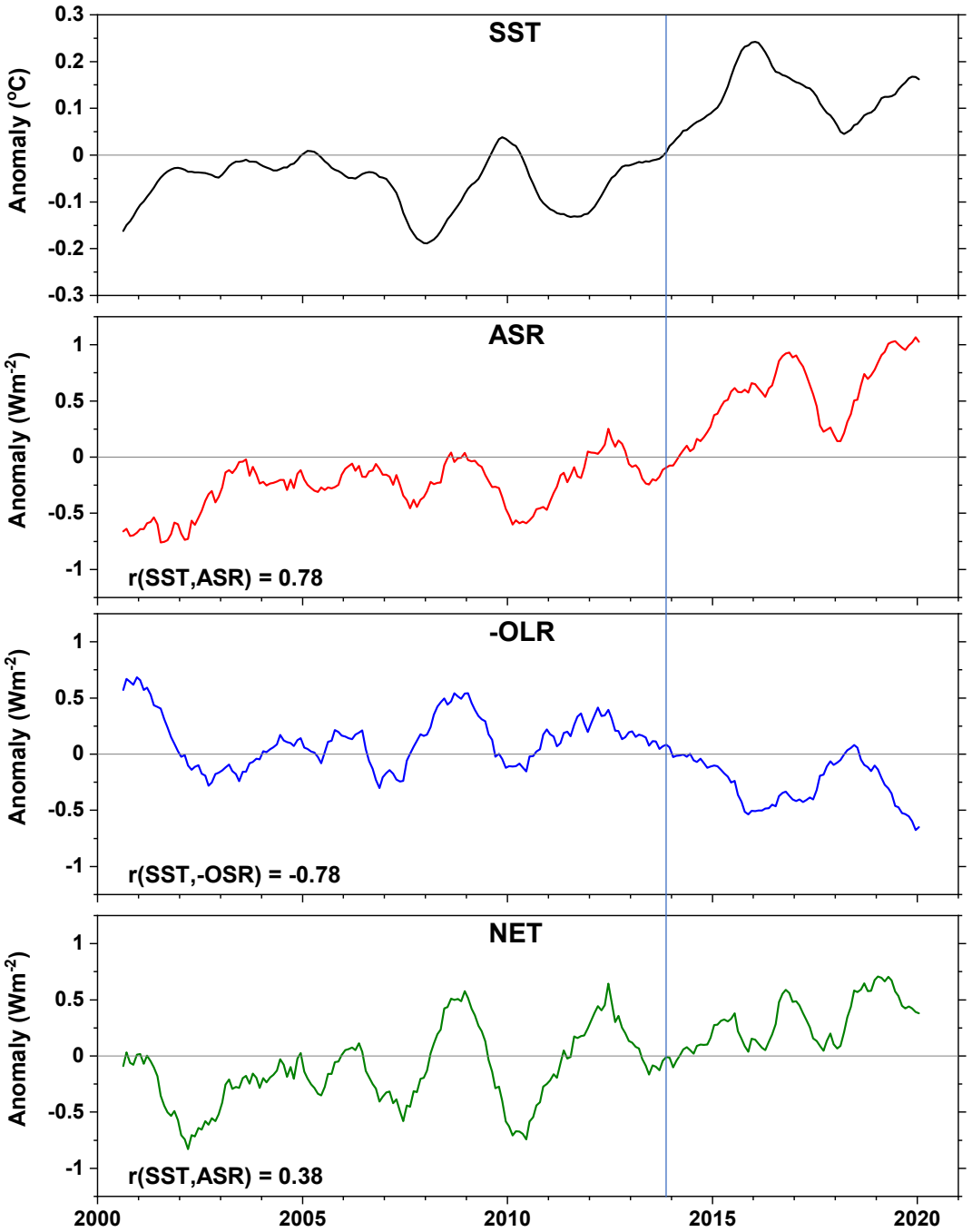


Global Mean SST Anomalies and Nino3.4 & PDO Indices



- End of “hiatus” corresponds to shift in sign of PDO index to positive.
- Precedes major 2015/2016 El Nino event.
- Sharp increase in SST after sign of PDO shifts from negative to positive.

Anomalies in Global Mean SST & TOA Radiation (12-month running averages)



Following the shift in sign of the PDO index from negative to positive in 2014:

Warmer SSTs (end of "hiatus")

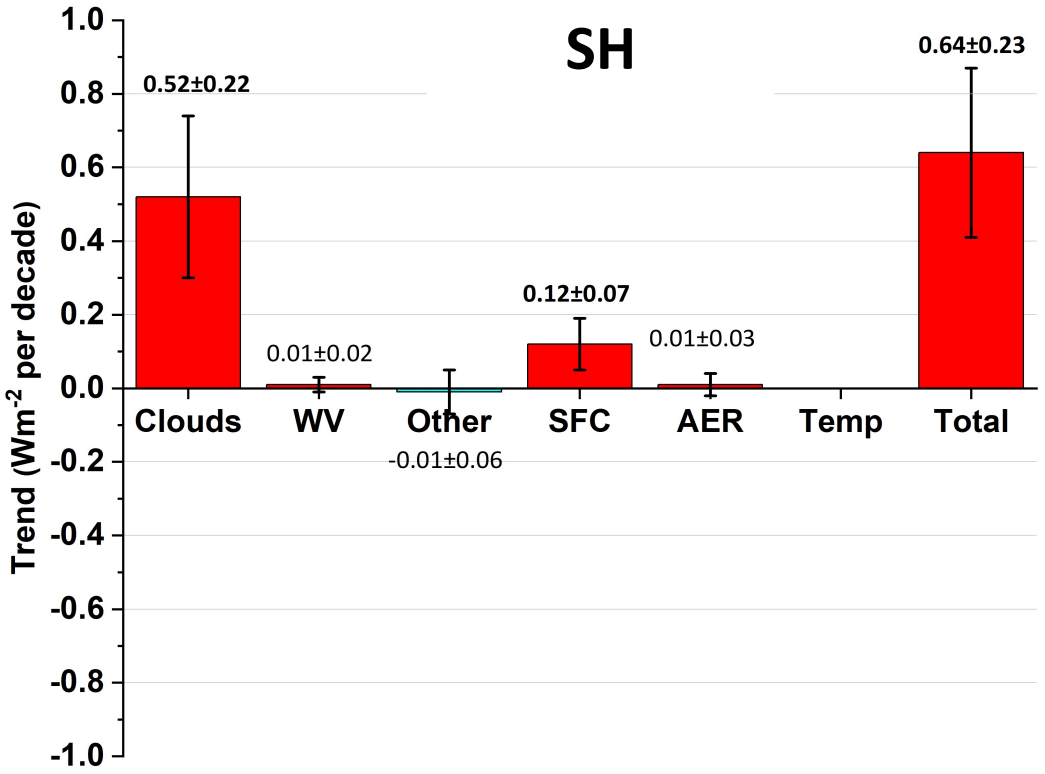
Factor of 4 increase in trend of ASR

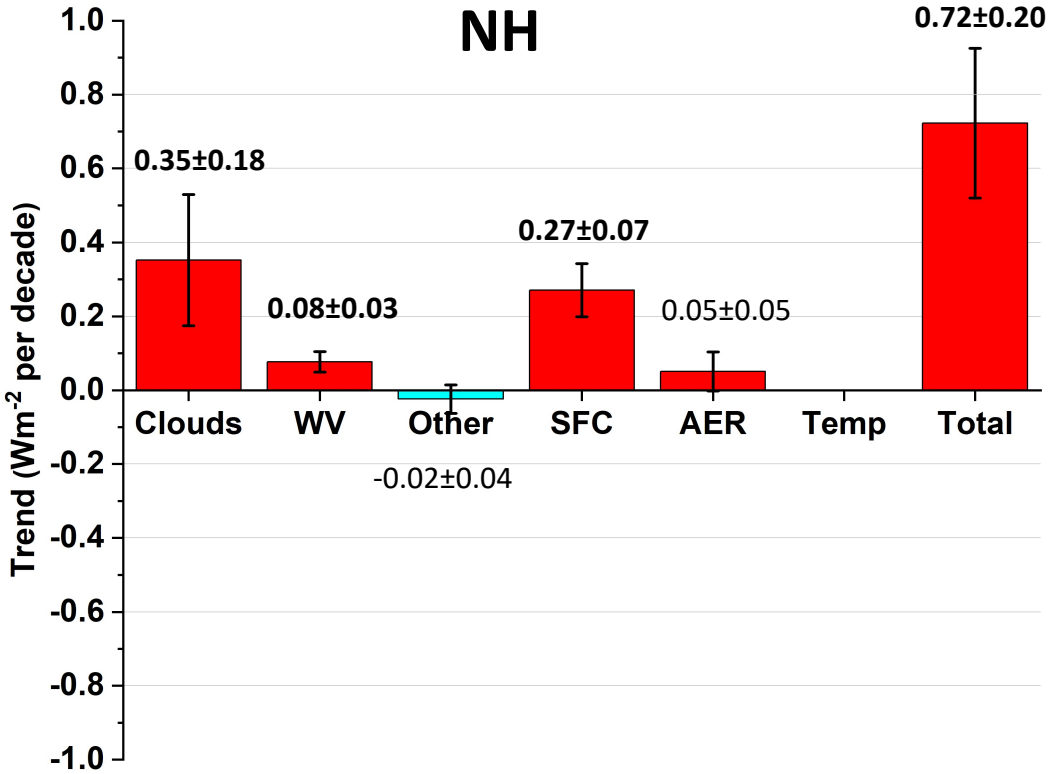
Slight increase in LW emission to space

Factor of 2.5 increase in net TOA flux trend

How does the attribution of trends compare for the Southern and Northern Hemispheres?

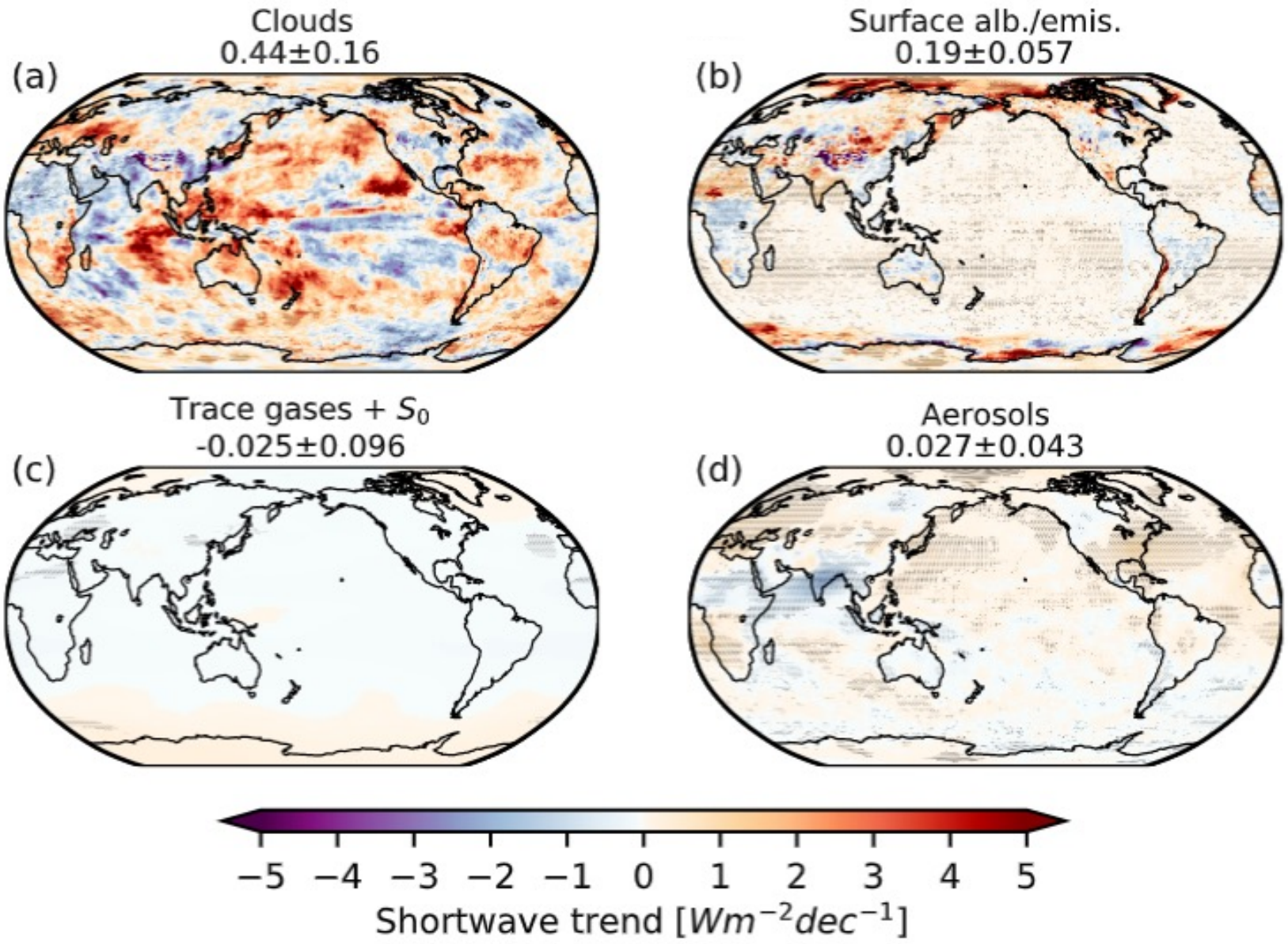
Trends in Absorbed Solar Radiation (positive down; 03/2000-02/2020)



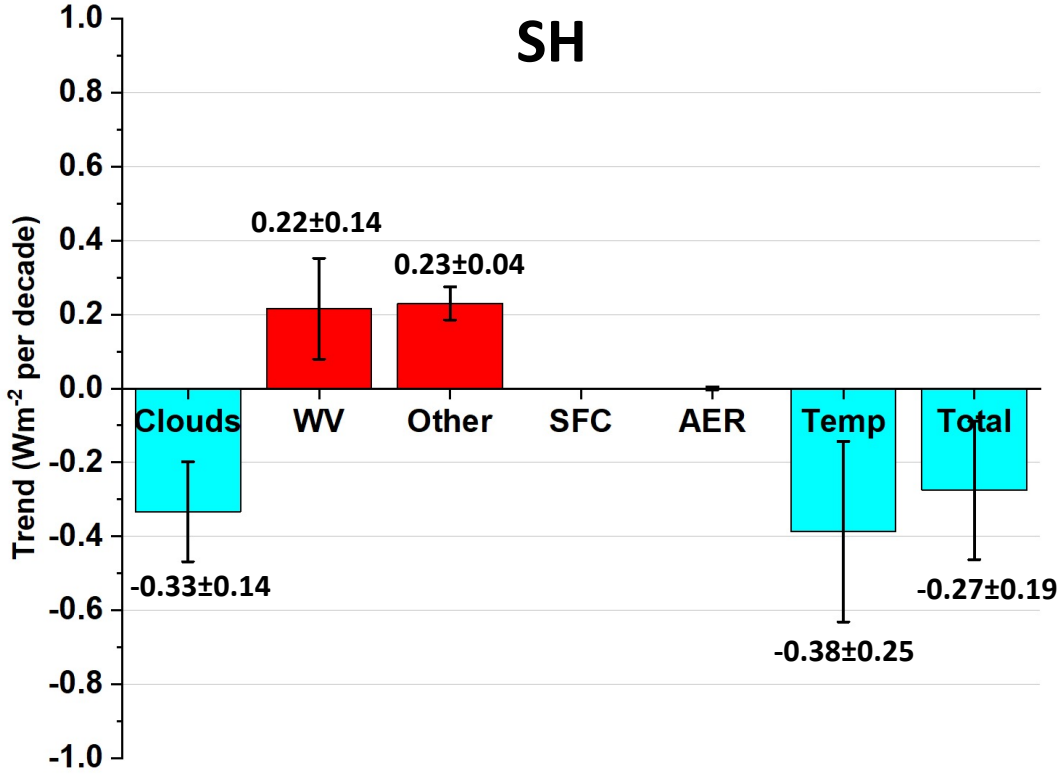


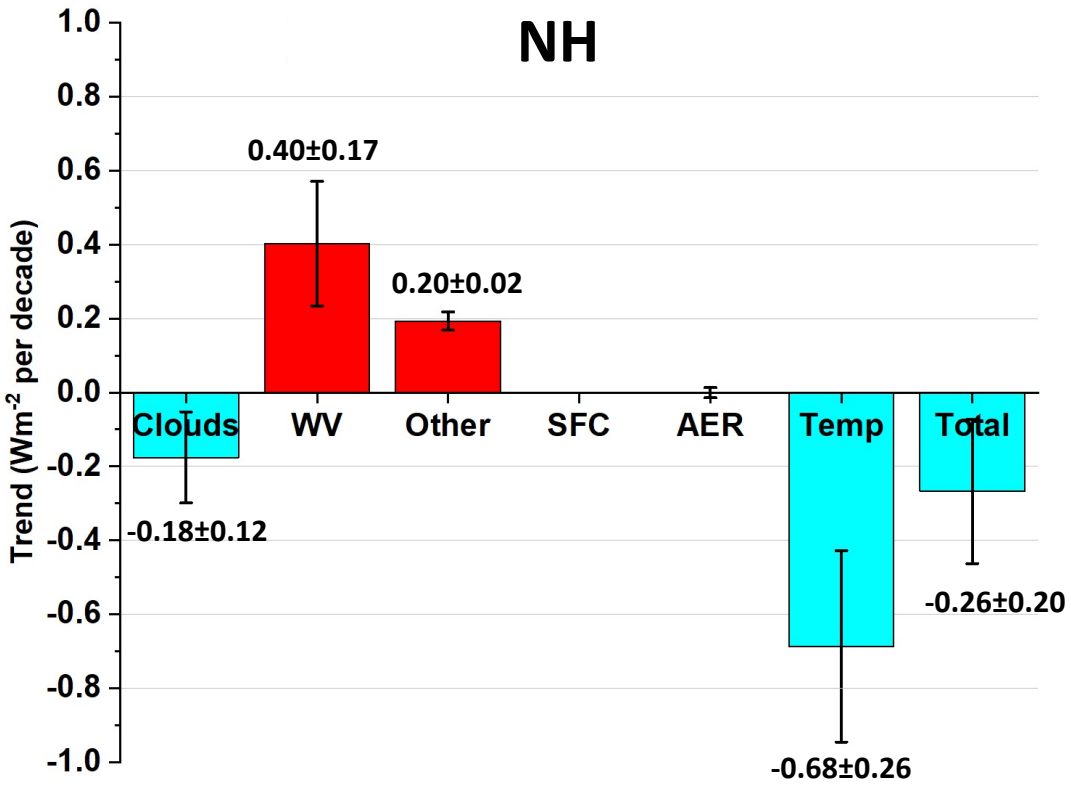
- Hemispheric mean albedos are the same for SH and NH (=0.291)
- ASR trends are also nearly identical.
  - ➢ In SH, clouds dominate
  - ➢ In NH, clouds contribution is weaker but SFC contribution makes up difference

Trends in Absorbed Solar Radiation (03/2000-02/2020)



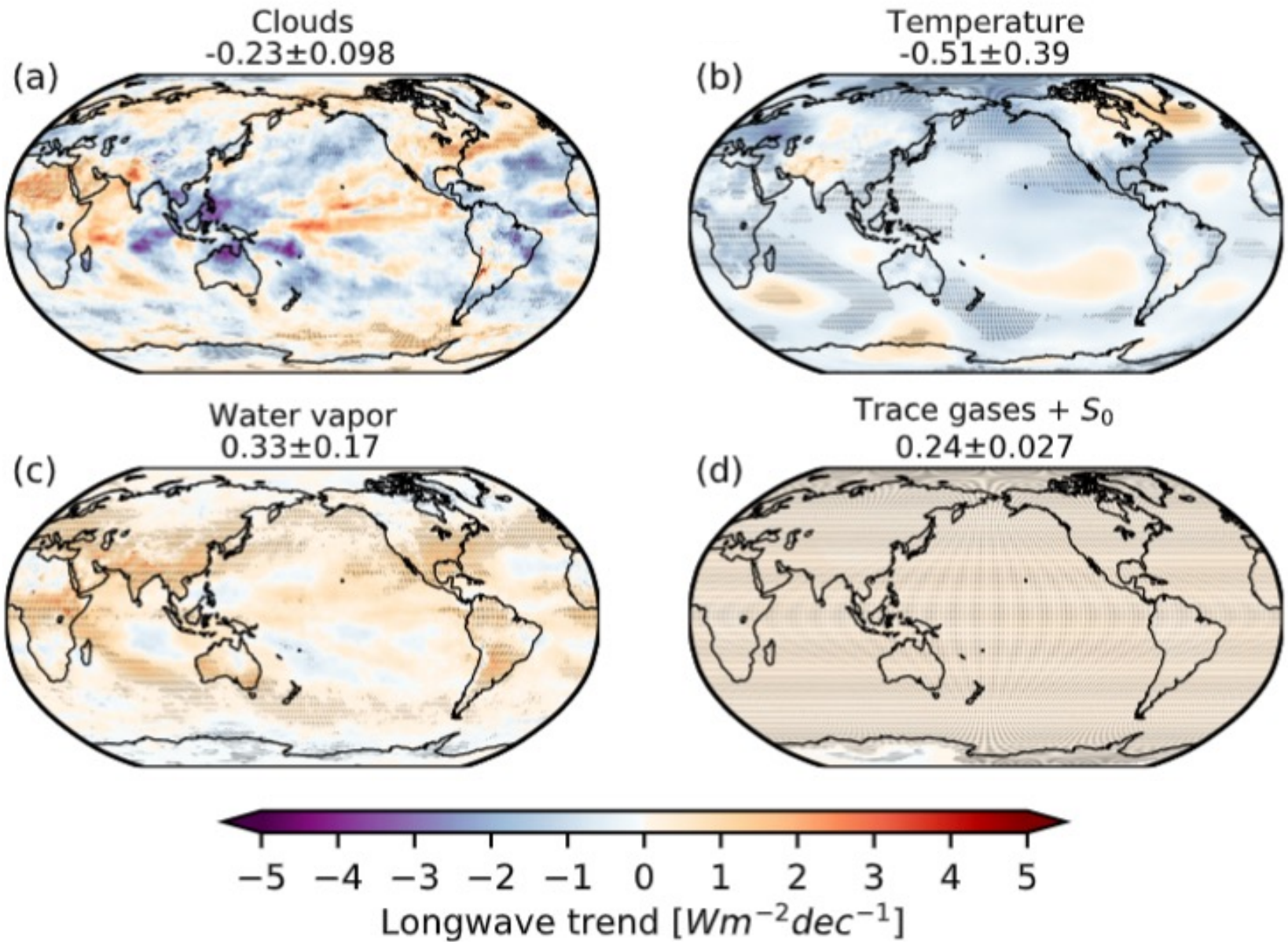
Trends in Longwave Radiation (positive down; 03/2000-02/2020)



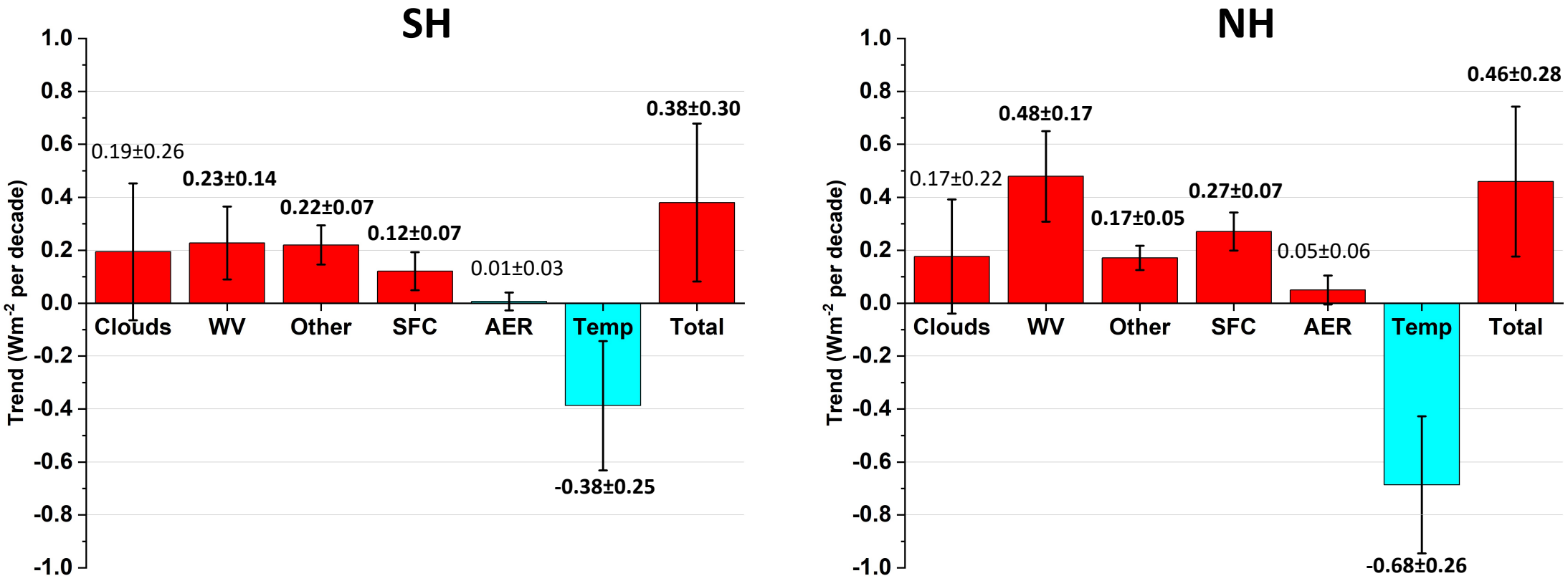


- Hemispheric mean OLR: SH: -239.6 Wm^{-2}; NH -240.9 Wm^{-2}
- OLR trends are consistent to 0.01 Wm^{-2} per decade.
- Stronger Temp and WV contributions in NH.

Trends in Longwave Radiation (positive down; 03/2000-02/2020)

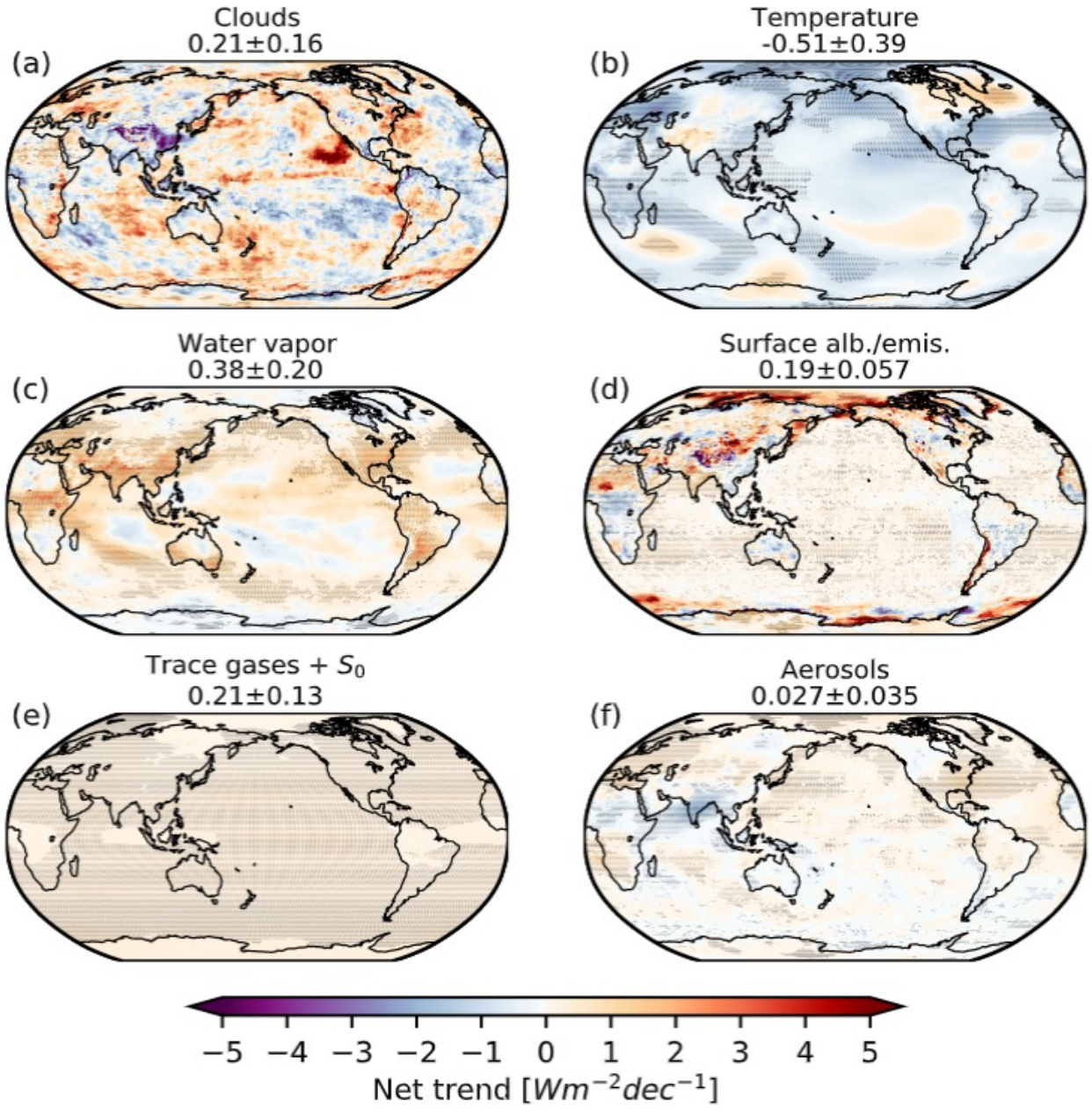


Trends in Net Radiation (positive down; 03/2000-02/2020)



- Hemispheric 20-year mean NET: SH: 1.39 Wm^{-2}; NH 0.076 Wm^{-2}
  => **0.17 PW** SH—>NH heat transport by atmosphere and ocean
- Hemispheric net TOA flux trend difference = –0.08 Wm^{-2} per decade
  ⇒ **–0.02±0.08 PW** SH—>NH change in cross-equatorial heat transport over 20 years
  ⇒ No significant change in rate of total cross-equatorial heat transport during the CERES period.

Trends in Net Radiation (positive down; 03/2000-02/2020)



Conclusions

- A robust positive trend in global mean net TOA flux is observed (0.37 ± 0.15 Wm^{-2} per decade for 03/2000-02/2021). Doubling of EEI during CERES period.
- Positive trend in net TOA flux is due to a large increase in ASR associated with decreases in cloud amount and sea-ice and a decrease in OLR due to increases in water vapor and other greenhouse gases.
- ASR, OLR and Net trends are remarkably similar for the southern and northern hemispheres, implying there is no significant change in the rate of total cross-equatorial heat transport during the CERES period.
- Internal variability (PDO), anthropogenic forcing and climate feedbacks likely all contributed to the positive trend in net TOA flux.