Trends in Earth's Energy Flows Since 2000

Norman G. Loeb[1], Michael Mayer[2], Seiji Kato[1], John Fasullo[3], Magdalena Balmaseda[2], and Hao Zuo[2]

[1]NASA Langley Research Center, Hampton, VA 23681, USA
[2]European Centre for Medium-Range Weather Forecasts, Reading, UK
[3]Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, CO

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Motivation

- Use of ERB satellite observations combined with atmospheric reanalysis has seen increased use recently for determining mean energy budgets, mean meridional transports as well as their annual cycle and interannual variability.

- With the CERES record spanning more than 20 years and continued improvements in reanalysis systems, we address the following question:

"To what extent can we trust 20-year trends in different components of Earth's energy budget and energy flows within the climate system?"

- We focus our study on: TOA radiation, atmospheric transport, and surface fluxes.

Datasets Used

1) **TOA Radiation**
   - CERES EBAF Ed4.1 (03/2000-02/2020)
   - CERES SSF1deg-Terra (03/2000-02/2020); CERES SSF1deg-Aqua (07/2002-02/2020)

2) **Surface Radiation**
   - CERES EBAF Ed4.1 (03/2000-02/2020)
   - CERES Aqua-only SYN1deg-Month (07/2002-02/2020)

3) **Atmospheric Reanalysis – ERA5**
   - **"Analysis"**: Observed atmospheric wind, temperature and humidity profiles for calculating vertically integrated divergence of total atmospheric energy transport (TEDIV).
   - **"Forecast"**: Shortrange forecasts of TOA & surface radiation and surface turbulent heat fluxes using analyzed fields at 0600 and 1800 UTC.
   - **"IFS AMIP"**: Similar to "Forecast" but only assimilates SST and sea-ice boundary conditions.

Note: ERA5 uses forcing files from CMIP historical forcing through 2005 and RCP2.6 from 2006-2020.

Methodology

1) Vertically Integrated Divergence of Total Atmospheric Energy Transport (TEDIV) and Surface Energy flux (F_S)

a) Inferred:

F_S (positive downwards) is determined as a residual term in the atmospheric energy budget:

$$F_S = R_T - \nabla \cdot F_A - AET$$

R_T = net downward radiation at the TOA (CERES EBAF)
$\nabla \cdot F_A$ = divergence of lateral atmospheric energy transports (ERA5 analyzed T, q, w)
AET = vertically integrated atmospheric energy tendency (ERA5 analyzed T, q, w)

b) ERA5 Short-Term Forecasts & IFS AMIP:

$$\nabla \cdot F_A = R_T - F_S$$
$$F_S = R_S + H_L + H_S$$

R_S = net downward radiation at the surface
H_L = surface latent heat flux
H_S = surface sensible heat flux

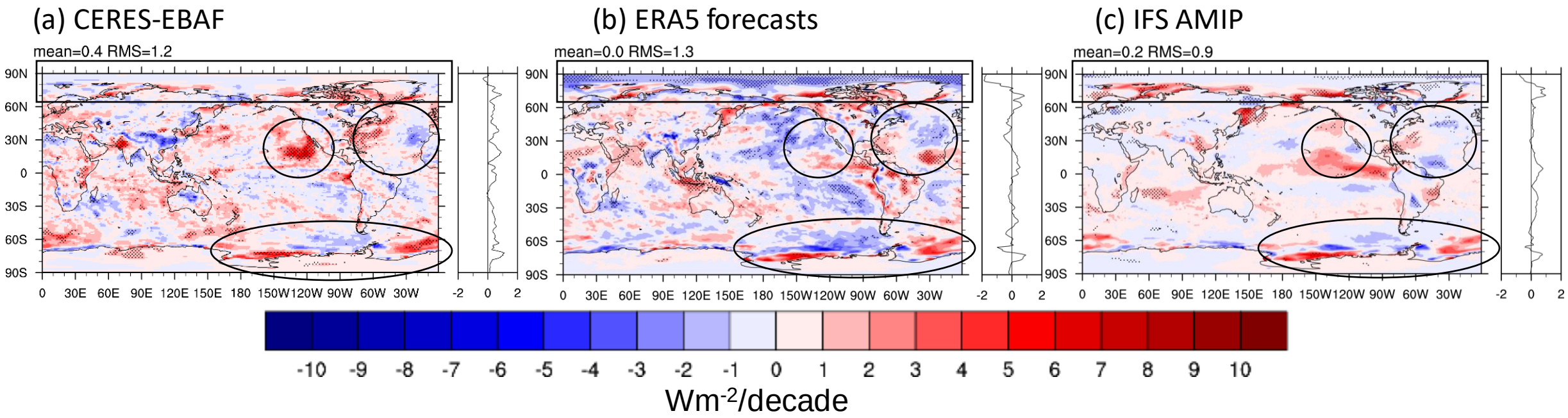
Methodology

2) Inferred Surface Turbulent Heat Fluxes

$$Q_S = H_L + H_S = F_S - R_S$$

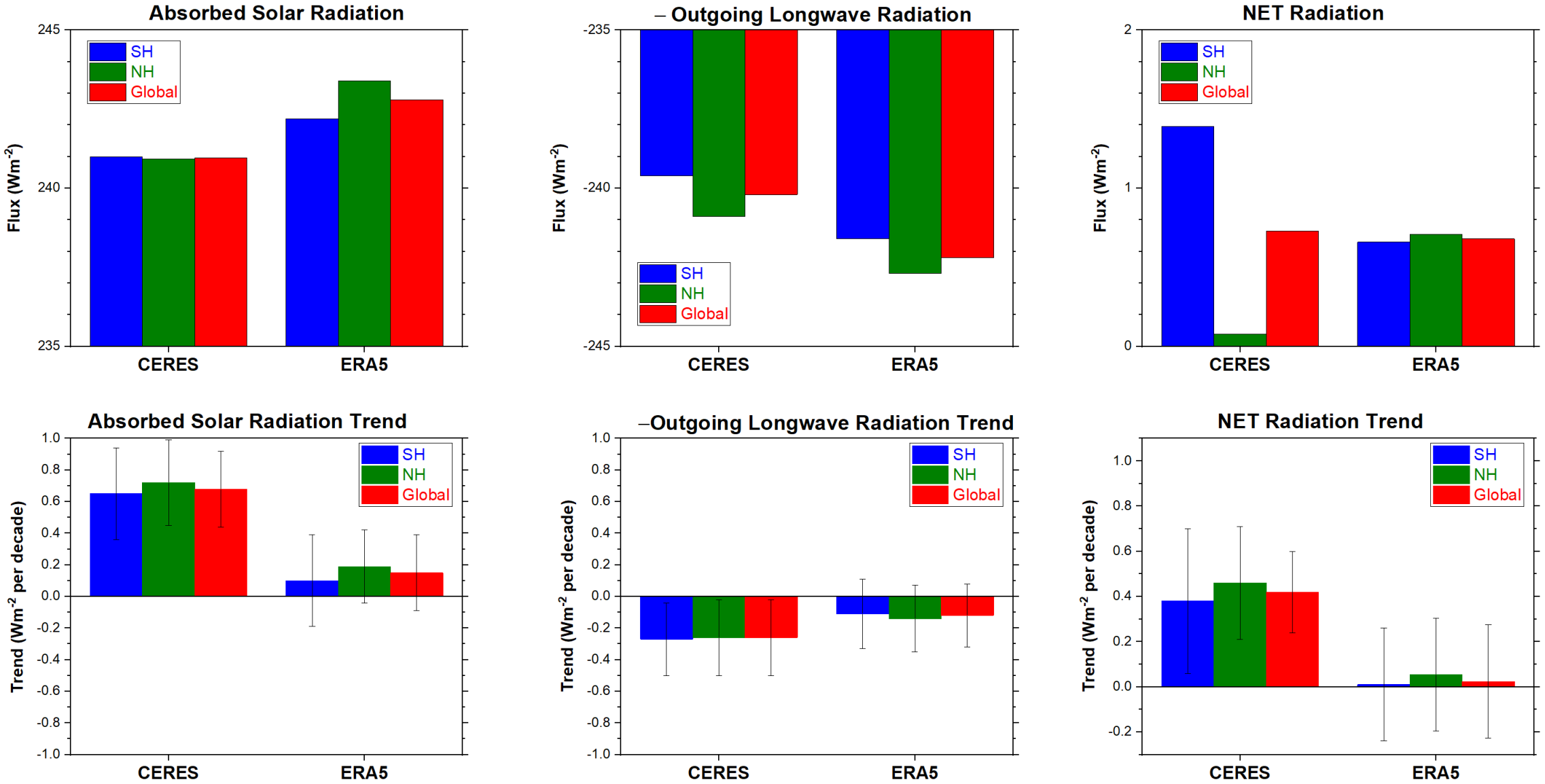
Q_S = sum of surface latent (H_L) and sensible (H_S) heat flux
F_S = surface flux from "Inferred" approach (previous slide)
R_S = net downward radiation at the surface (CERES EBAF)

Trends in TOA Net Radiation for 2000/03-2020/02



- Pronounced positive trends over the Eastern Pacific Ocean off North America in CERES is not seen in ERA5, which instead shows negative trends throughout most of the Eastern Pacific Ocean region.
- IFS AMIP shows weak positive trends in this region and larger positive trends along the equator.
- Over the Arctic, CERES shows weak trends in net TOA flux while ERA5 shows strong negative trends there. IFS AMIP is in reasonable agreement with CERES.
- ERA5 and IFS AMIP show better agreement with CERES over the Atlantic off the coast of North America, to the southwest of Spain and over the sea ice regions off the coast of Antarctica.

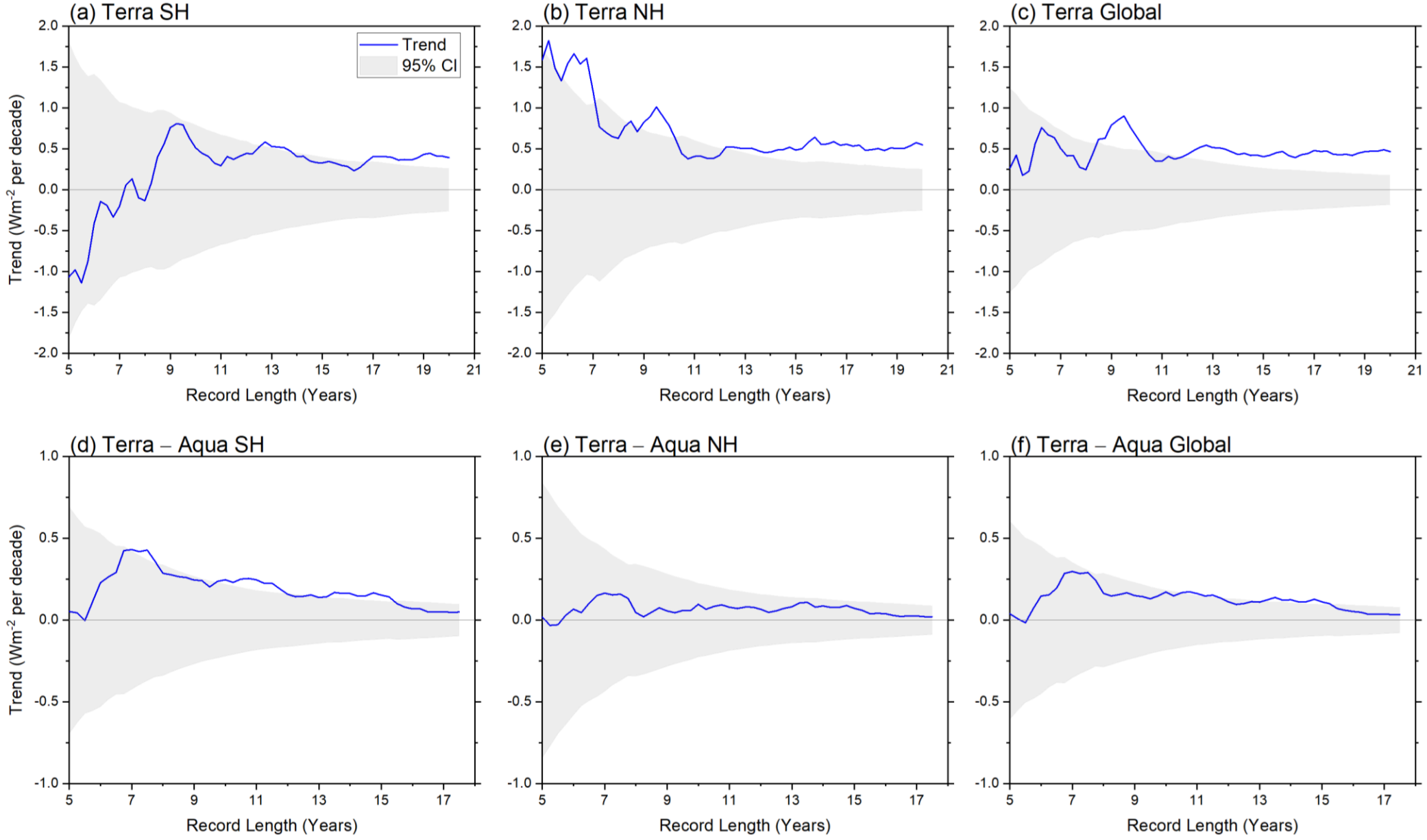
TOA Flux Hemispheric and Global Averages and Trends



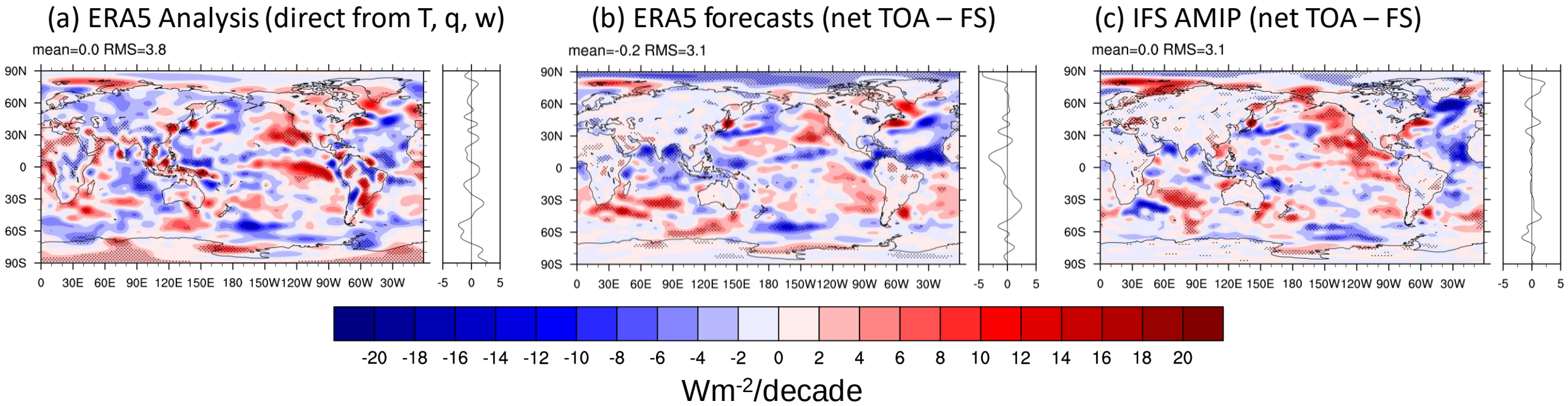
- CERES shows hemispheric symmetry in ASR means and near symmetry in their trends.
- ERA5 hemispheric mean net radiation implies near-zero cross-equatorial heat transport in contrast to CERES.
- Neither CERES nor ERA5 show evidence of a trend in cross-equatorial total heat transport.

CERES net TOA flux trends against record length for CERES SSF1deg Terra and Terra – Aqua

(Start date is 03/2000 for Terra and 07/2002 for Terra – Aqua. Gray shading corresponds to 95% confidence interval)

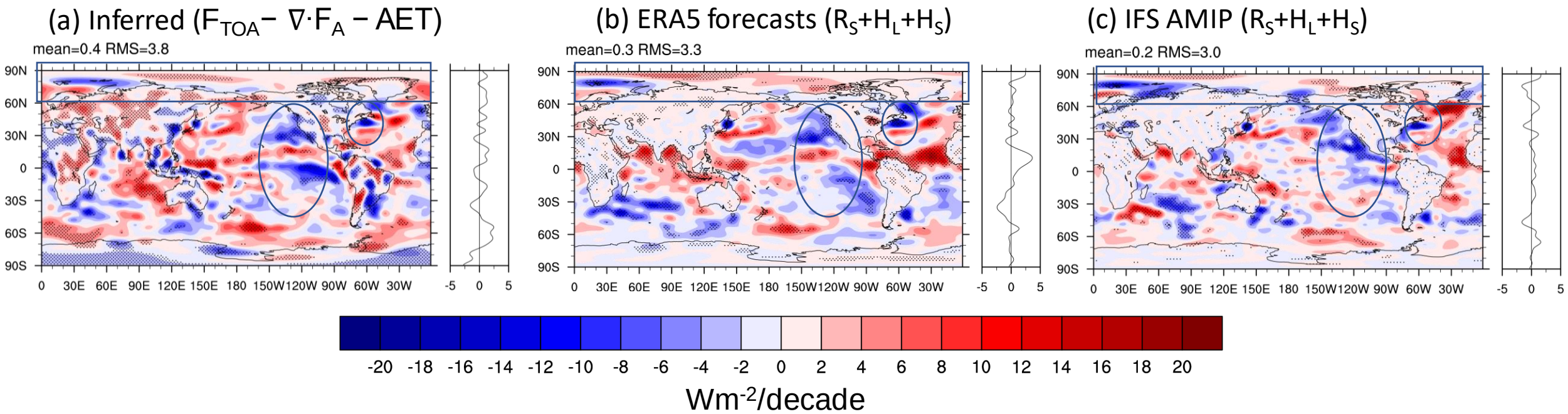


Trends in Vertically Integrated Divergence of Total Atmospheric Energy Transport (TEDIV) (2000/03-2020/02)



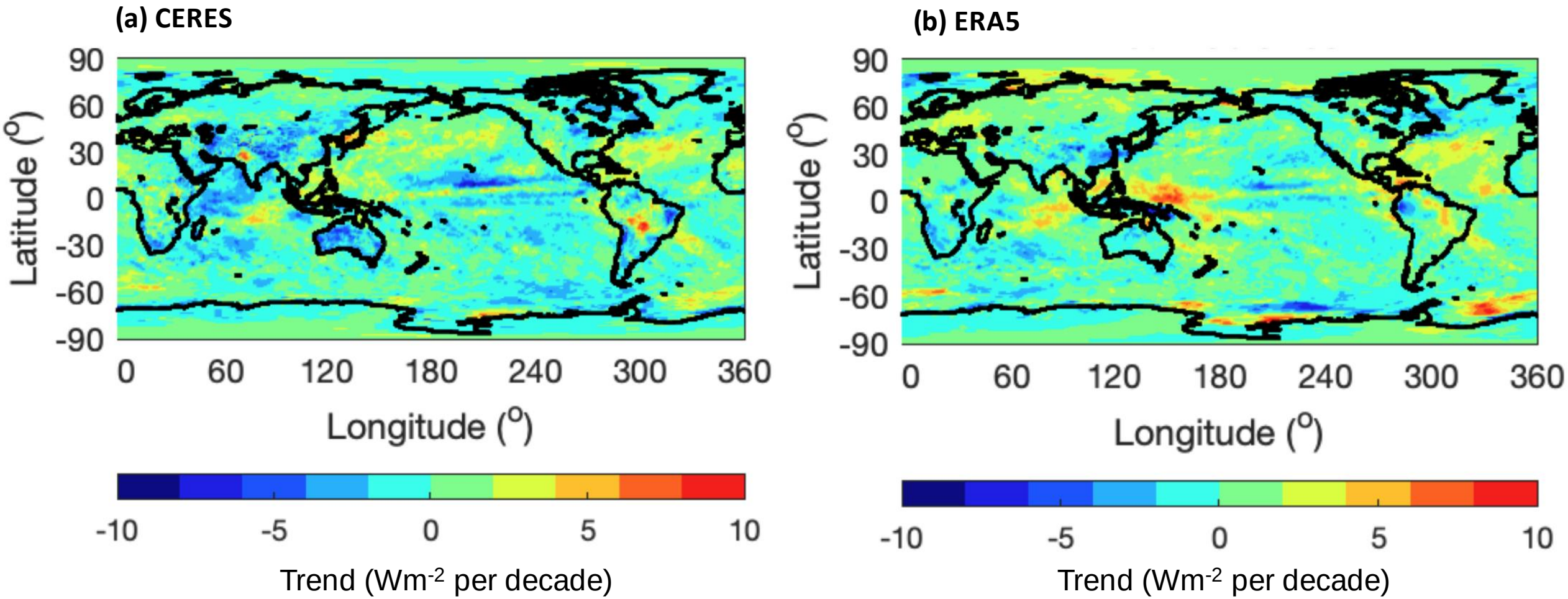
- Magnitudes of the trends in TEDIV are much greater than those in net TOA flux.
- Over land, trends for ERA5 analysis are highly uncertain. This is related to numerical noise over topography and spurious jumps in the observing system.
- Large positive trends in TEDIV over the eastern Pacific Ocean to the north and south of the ITCZ.
- Strong positive trend over the Gulf Stream, where the climatological mean TEDIV is strongly positive since the atmosphere is supplied with energy from warm water masses transporting energy poleward.
- Trends are generally similar in all 3 cases over ocean, suggesting that the ERA5 patterns are not a spurious signal from changes in the observing system.

Trends in Surface Flux (F_S; positive downward) (2000/03-2020/02)



- Trend patterns and magnitudes in F_S are mainly determined by trends in TEDIV.
- Trends over land for "Inferred" are spurious due to uncertainties in TEDIV.
- Large negative trends for all three methods over eastern Pacific Ocean and Gulf Stream.
- Similar trend patterns over Arctic Ocean

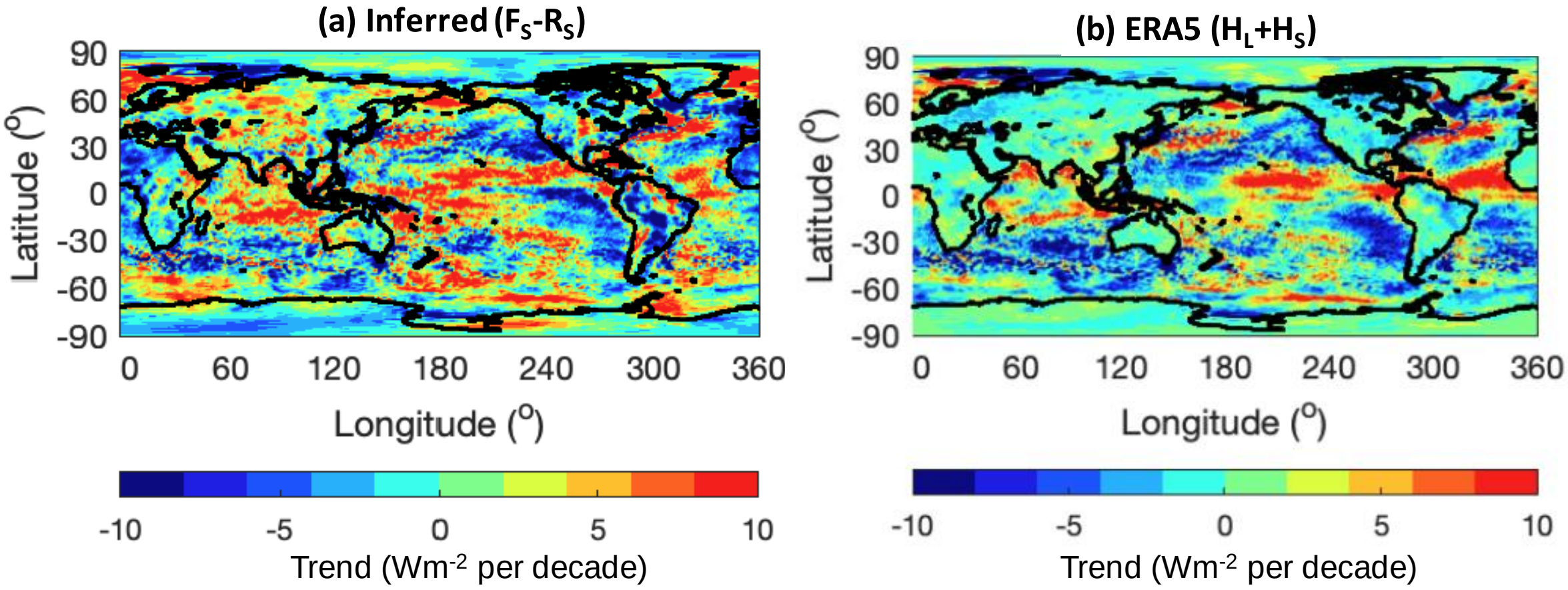
Trend in Net Total Radiative Flux at the Surface (positive down; 200208-202002)



- CERES trends are based upon computed fluxes using Aqua MODIS cloud properties (no GEO).
- While the trend patterns in R_S are quite similar between CERES and ERA5, their magnitudes are quite different.
- Large differences are evident over the west tropical Pacific Ocean, where ERA5 shows large positive trends that are absent in CERES.

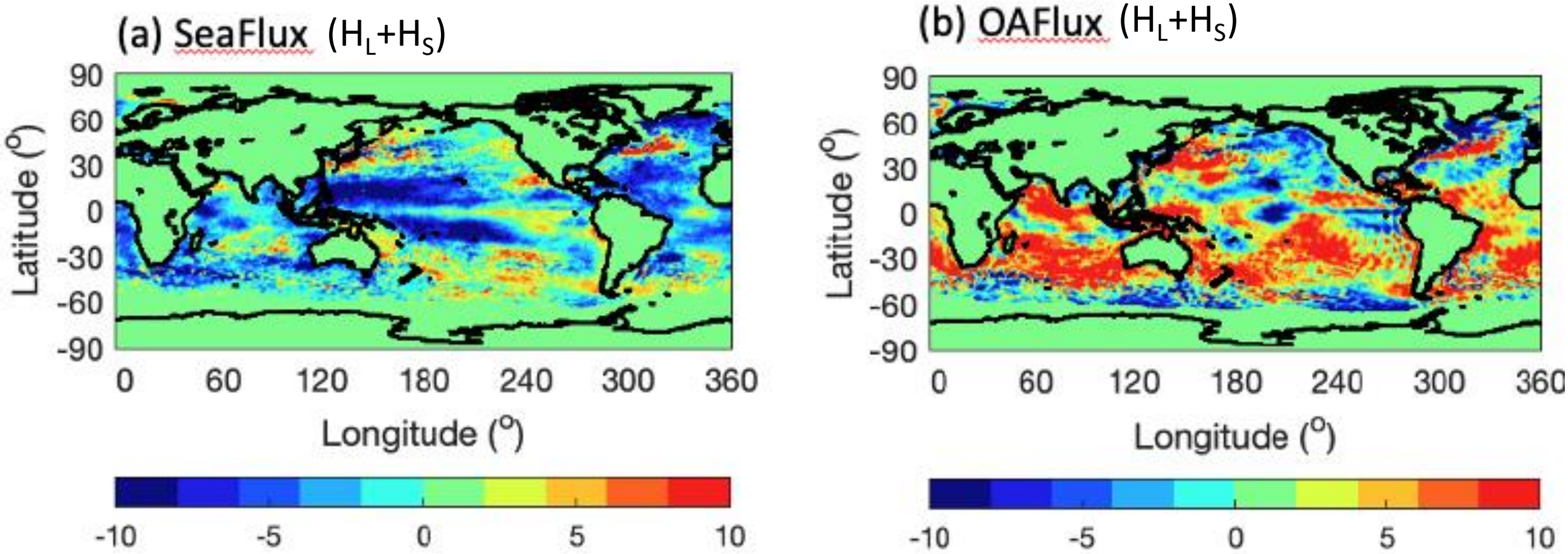
Trends in Surface Turbulent Heat Flux (positive downward)

(2002/08-2018/07)



- Good agreement over the eastern Pacific off the west coast of the Americas, where trends are predominantly negative (increased surface-to-atmosphere heat transport).
- Magnitude of turbulent flux trends is much greater than net surface radiation.

Trends in Surface Turbulent Heat Flux (positive downward)
(2002/08-2018/07)



- Generally poor agreement everywhere except over Gulf Stream where both show positive trends (consistent with previous slide).

Summary

- Large regional and global mean differences between CERES and ERA5 NET TOA flux trends.
  - ERA5 shows a negative trends in NET TOA flux over Eastern Pacific Ocean while CERES shows a pronounced positive trends.
- Neither CERES nor ERA5 show evidence of a trend in cross-equatorial total heat transport.
- CERES Terra and CERES Aqua 20-year trends in net TOA flux are consistent to < 0.1 Wm^{-2} per decade.
- Many similarities in large-scale patterns in TEDIV and F_S between "Inferred", Forecast and ERA5 IFS.
  - Negative F_S trends over east Pacific Ocean and Gulf Stream (implying increase in surface-to-atmosphere heat transport).
- Inconsistent trend patterns in surface turbulent heat fluxes.

Table 1 CERES and ERA5 Southern Hemisphere (SH), Northern Hemisphere (NH) and Global ASR, −OLR and NET TOA flux averages, monthly anomaly standard deviations (Stdev) and trends for 03/2000-02/2020.

	CERES								
	ASR			−OLR			Net		
	SH	NH	Global	SH	NH	Global	SH	NH	Global
Mean (Wm^{-2})	240.99	240.92	240.96	–239.6	–240.9	–240.2	1.39	0.076	0.73
Stdev (Wm^{-2})	0.98	0.94	0.67	0.74	0.83	0.51	0.89	0.88	0.69
Trend (Wm^{-2} dec^{-1})	0.65 (0.29)	0.72 (0.27)	0.68 (0.24)	−0.27 (0.23)	−0.26 (0.24)	−0.26 (0.24)	0.38 (0.32)	0.46 (0.25)	0.42 (0.18)
	ERA5								
	ASR			-OLR			Net		
	SH	NH	Global	SH	NH	Global	SH	NH	Global
Mean (Wm^{-2})	242.2	243.4	242.8	−241.6	−242.7	−242.1	0.66	0.71	0.68
Stdev (Wm^{-2})	0.89	0.76	0.52	0.69	0.73	0.41	0.82	0.79	0.62
Trend (Wm^{-2} dec^{-1})	0.10 (0.29)	0.19 (0.23)	0.15 (0.24)	−0.11 (0.22)	−0.14 (0.21)	−0.12 (0.20)	0.010 (0.25)	0.055 (0.25)	0.024 (0.25)