Tracking Changes in Earth's Energy Flows

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Outline

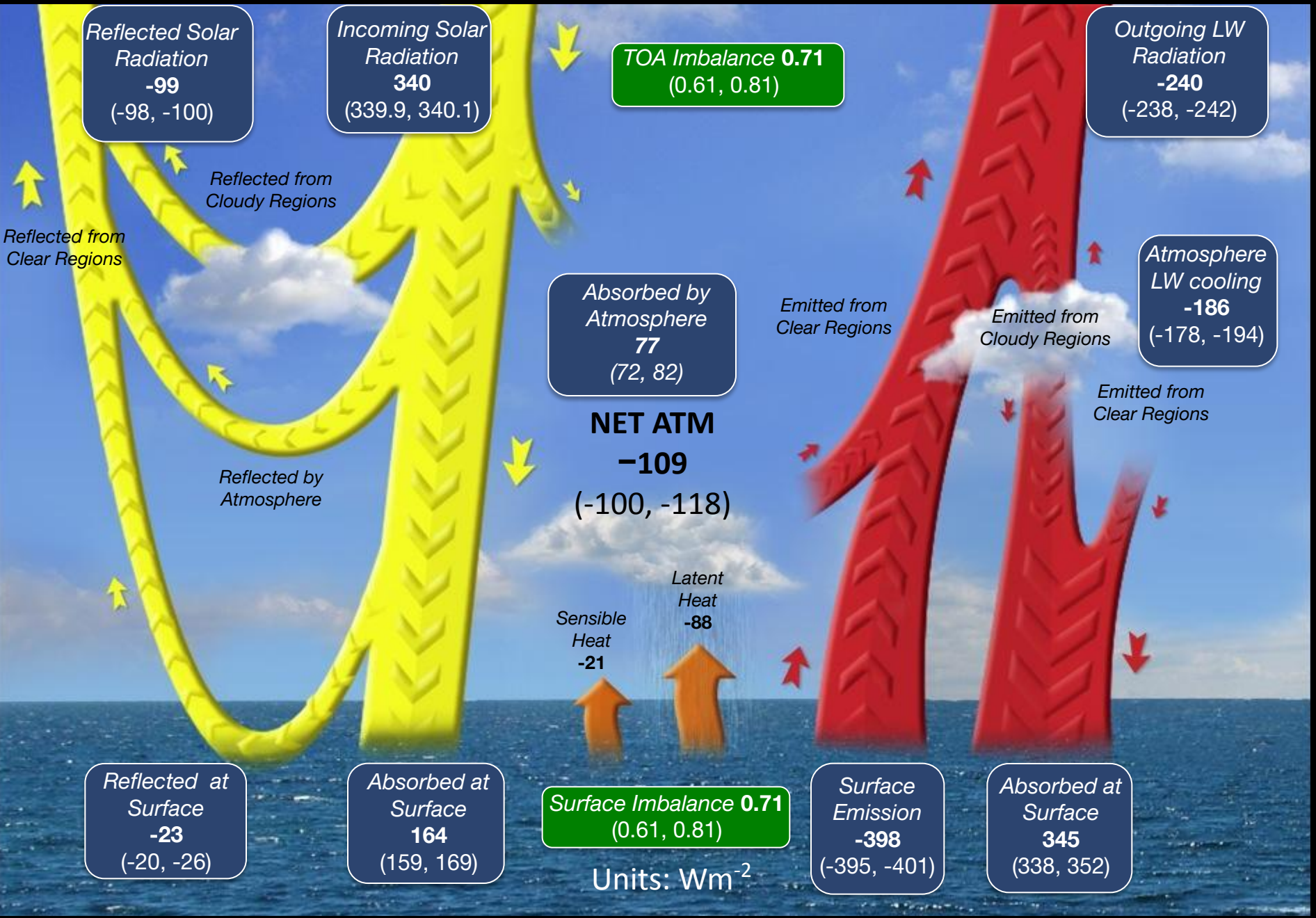
1) Earth's Energy Budget: Why it Matters

2) Clouds and the Earth's Radiant Energy System (CERES)

3) Tracking Recent Changes in Earth's Energy Imbalance

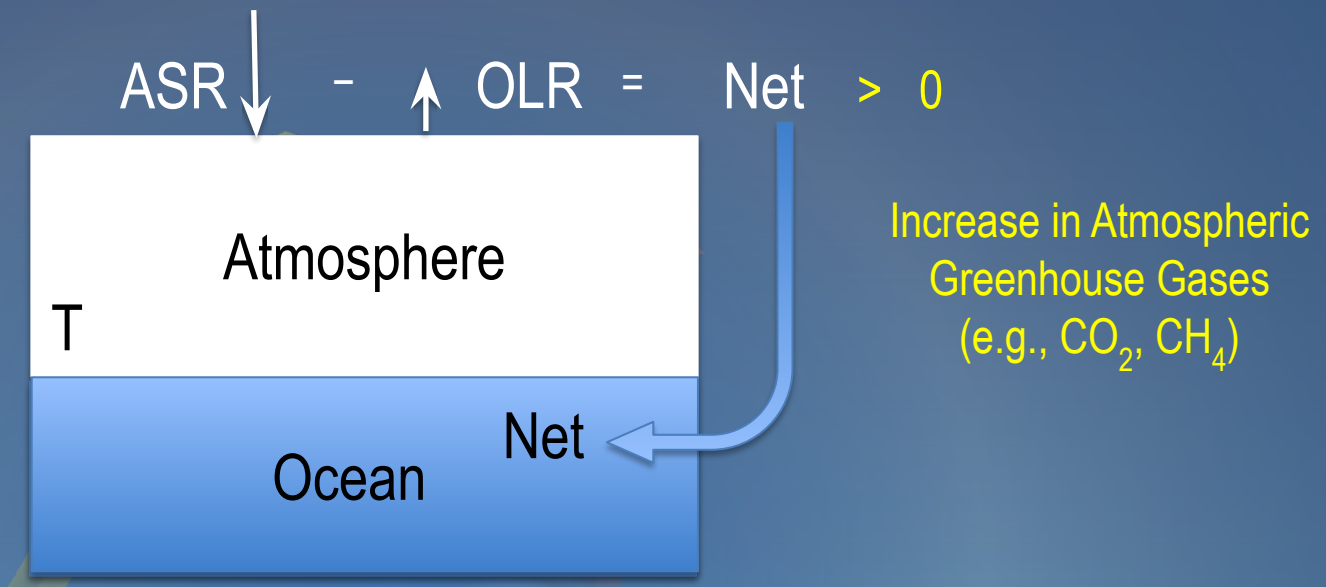
Earth’s Energy Budget: Why it Matters

Earth's Energy Budget (1σ Range): CERES



- Earth's energy imbalance: net forcing Earth has yet to respond to.
- Earth would be 33°C colder without the atmospheric greenhouse effect.
- Net radiation at surface sets the upper limit for global mean precipitation.

Planetary Energy Budget and Surface Temperature

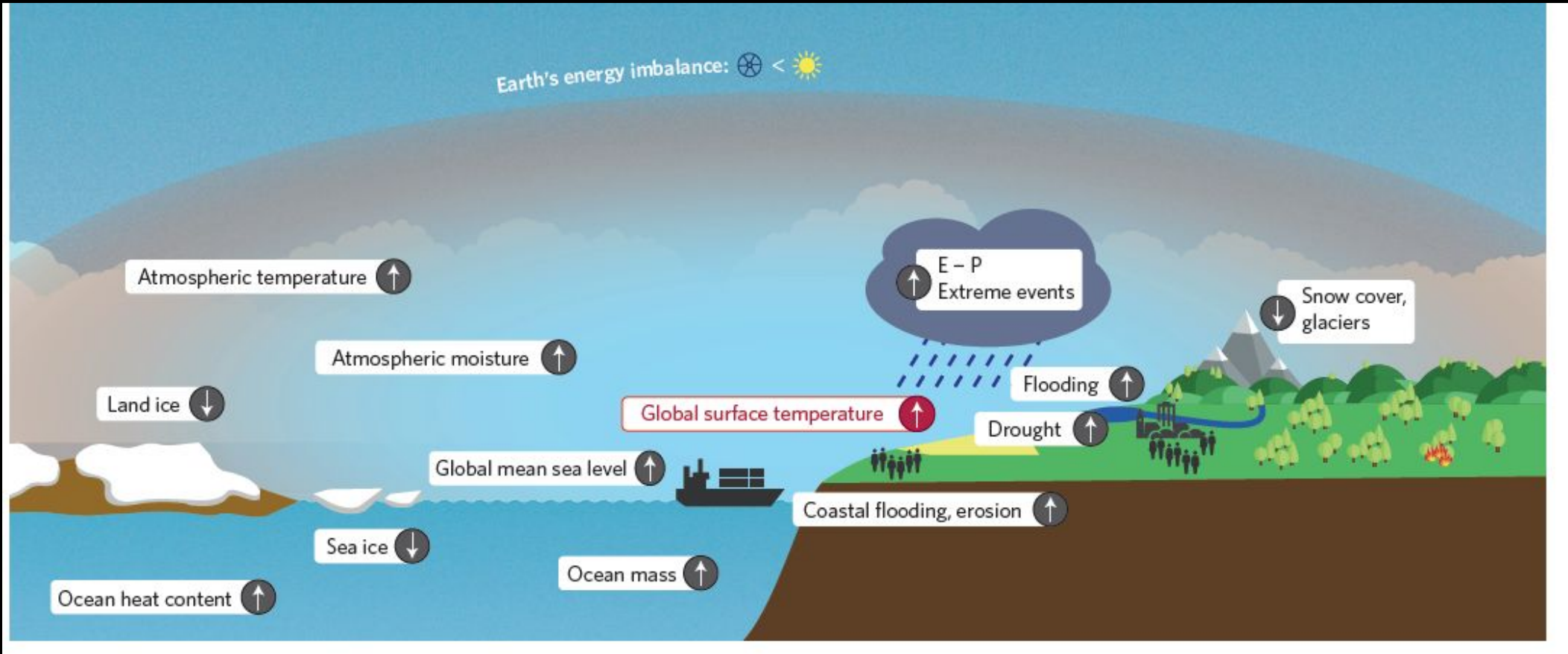


- Greenhouse gases trap emitted thermal radiation from surface, reducing ETR and heating Earth.
- 90% of the excess heat is stored in the ocean.
- Remainder warms atmosphere & land, melts snow and ice.

⇨ ***T_s increases when averaged over a long time period***

- **At timescales of up to a few decades, natural fluctuations in ocean currents and atmospheric wind patterns can cause T_s to vary, temporarily offsetting or augmenting the increase in T_s associated with global warming.**

“Symptoms” of a Positive Earth Energy Imbalance



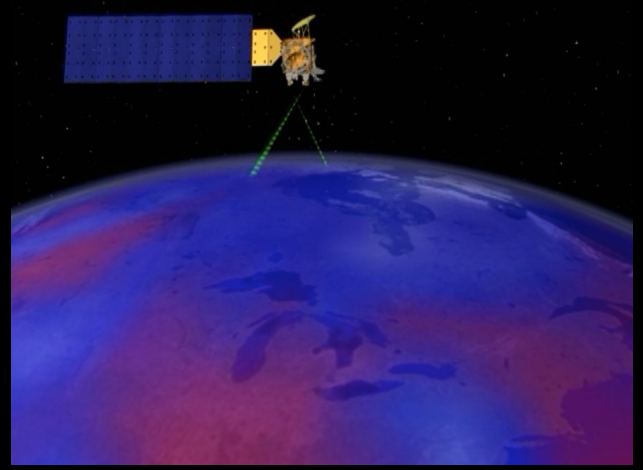
From von Schuckmann et a. (2016)

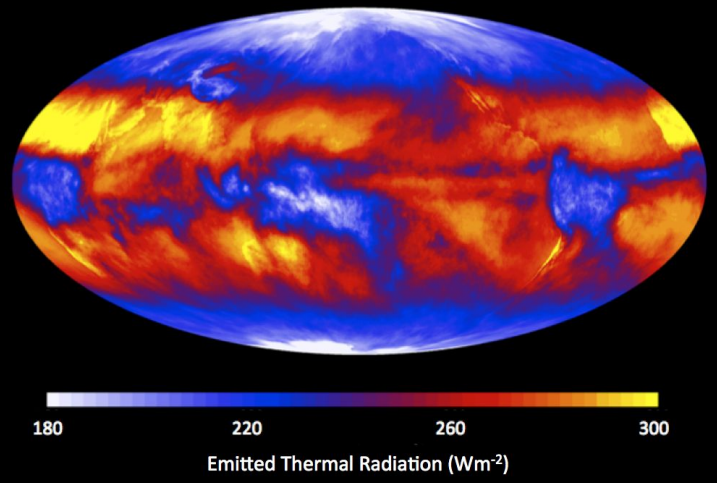
A positive EEI leads to:

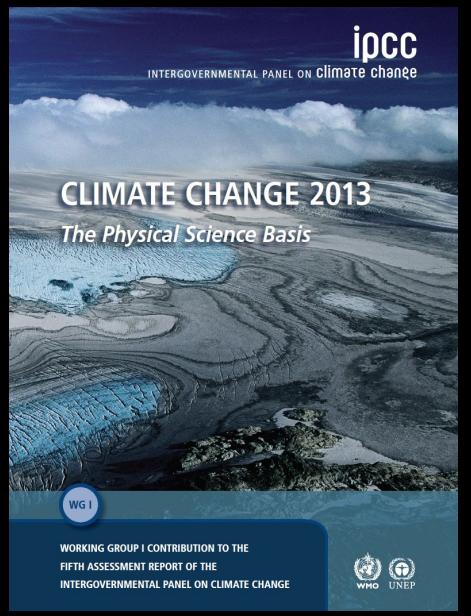
- A rise in Earth’s surface temperature, atmospheric moisture and global mean sea level
- Shifts in atmospheric circulation patterns, leading to more extreme weather (⇒ flooding, drought)
- Increase in ocean heat content, leading to ocean acidification, impacting fish and other marine biodiversity
-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

Clouds and the Earth’s Radiant Energy System (CERES)

Clouds and the Earth's Radiant Energy System







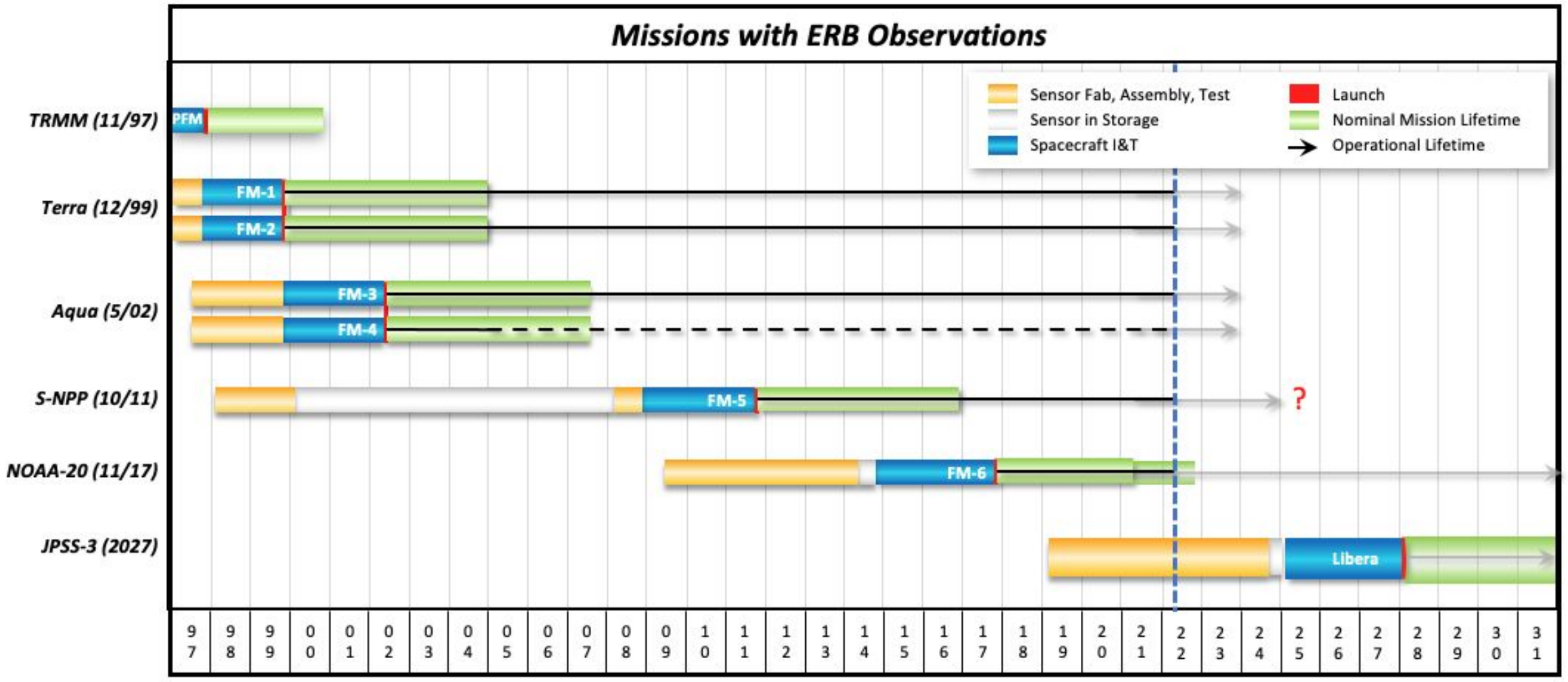
- Goal is to produce a long-term, integrated global climate data record (CDR) of Earth's radiation budget (ERB) from the surface to the top-of-atmosphere (TOA) together with the associated cloud, aerosol & surface properties.
- To enable improved understanding of the variability in Earth's radiation budget.
- To provide data products for climate model evaluation and improvement.

CERES Instruments

- 7 instruments on 5 satellites (TRMM, Terra, Aqua, SNPP, NOAA-20) for diurnal and angular sampling.
- Narrow field-of-view scanning radiometer with nadir footprint size of 10 km (TRMM); 20 km (Terra, Aqua), 24 km (SNPP, NOAA-20).
- Measures radiances in 0.3-5 μm, 0.3-200 μm and 8-12 μm (FM6 replaces WN with LW channel)

- Capable of scanning in several azimuth plane scan modes: fixed (FAP or crosstrack, rotating azimuth plane (RAP), programmable (PAP).
- Coincident Cloud and Aerosol Properties from VIRS/MODIS/VIIRS. Required for scene identification and addressing CERES science questions.
- Factor of 2-3 improvement over ERBE.

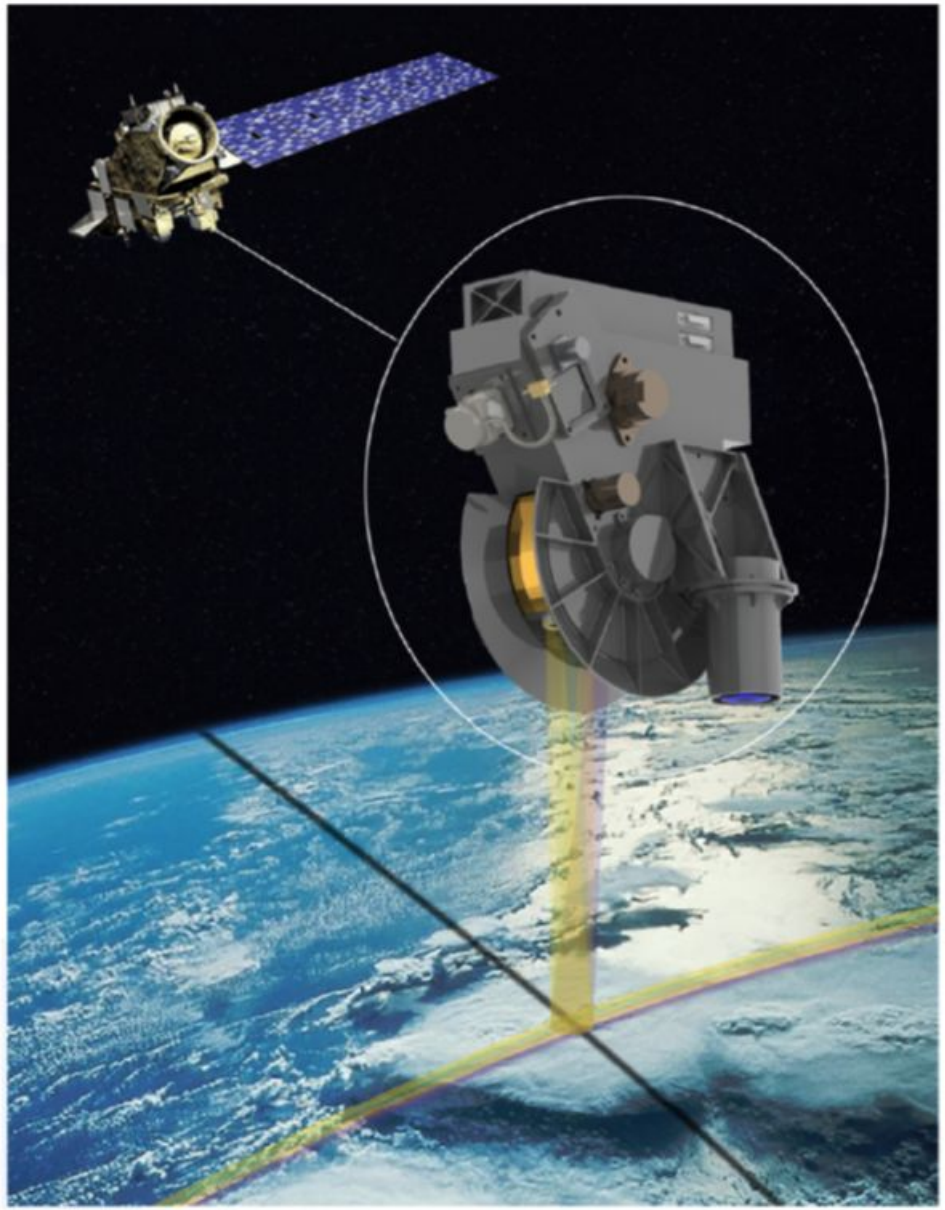
Flight Schedules



- Currently, 6 CERES instruments fly on 4 satellites: Terra (L1999), Aqua (L2002), SNPP(L2011), NOAA-20 (L2017)
- Libera scheduled for launch in 2028 on JPSS-3

Libera, First NASA EVC-1 Mission

'Li-be-ra, named for the daughter of Ceres in ancient Roman mythology



Provides continuity of the Clouds and the Earth's Radiant Energy System (CERES) Earth radiation budget (ERB)

- Measures integrated shortwave (0.3–5 µm), longwave (5–50 µm), total (0.3–>100 µm) and ***(new) split-shortwave (0.7–5 µm)*** radiance over 24 km nadir footprint at ***~ 0.2% uncertainty***.
- Includes a ***wide FOV camera*** for scene ID and simple ADM generation to pave way for future free-flyer ERB observing system

Innovative technology improves accuracy:

- ***Electrical Substitution Radiometers (ESRs) using Vertically Aligned Carbon Nanotube (VACNT) detectors***

Primary operational modes:

- Cross-track, azimuthal, along-track scanning; on-board calibrators; solar and lunar viewing.

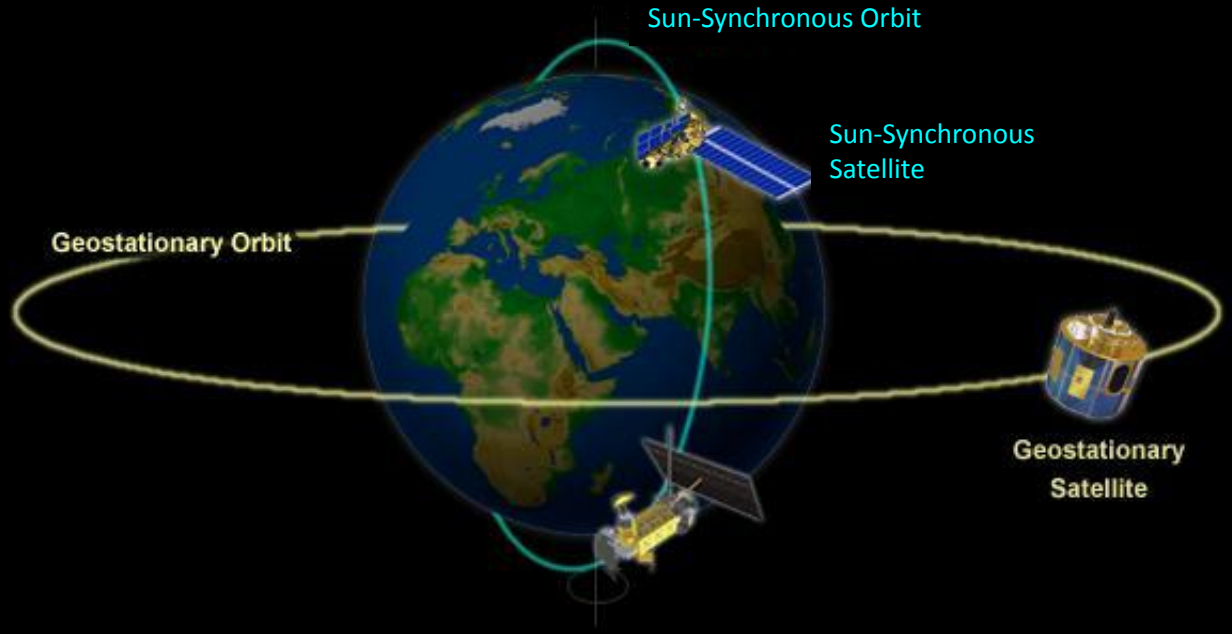
Flight:

- JPSS-3, 2028 launch; 5-year mission

Partners:

- Technical: LASP, Ball Aerospace, NIST Boulder, Space Dynamics Lab; CU, JPL, CSU, UA, UM, LBL
- Science: CU, JPL, CSU, UA, UM, LBL, ETH, U. Reading, UK. Met Office, Imperial College London

Earth Radiation Budget Data Fusion

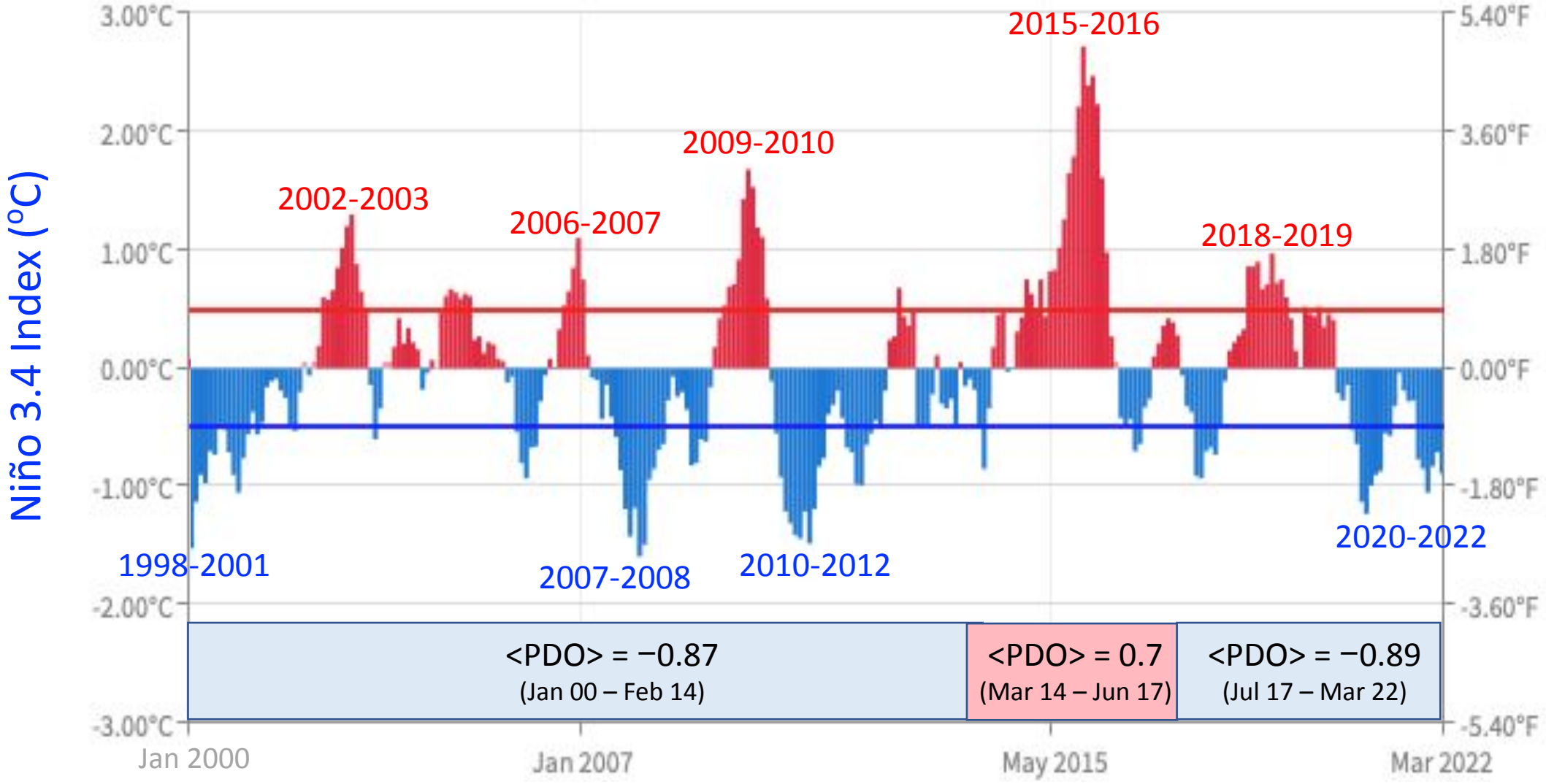


- In order to provide complete spatial coverage of Earth and resolve its diurnal cycle, a high level of data fusion is required.
- During the CERES period, the team has processed data from:
  - 7 CERES instruments
  - 1 VIRS imager (TRMM)
  - 2 MODIS imagers (Terra, Aqua)
  - 2 VIIRS imagers (S-NPP, NOAA-20)
  - 20 geostationary imagers
  - Solar irradiance measurements
  - Meteorological, ozone and aerosol assimilation data
  - Snow/ice maps

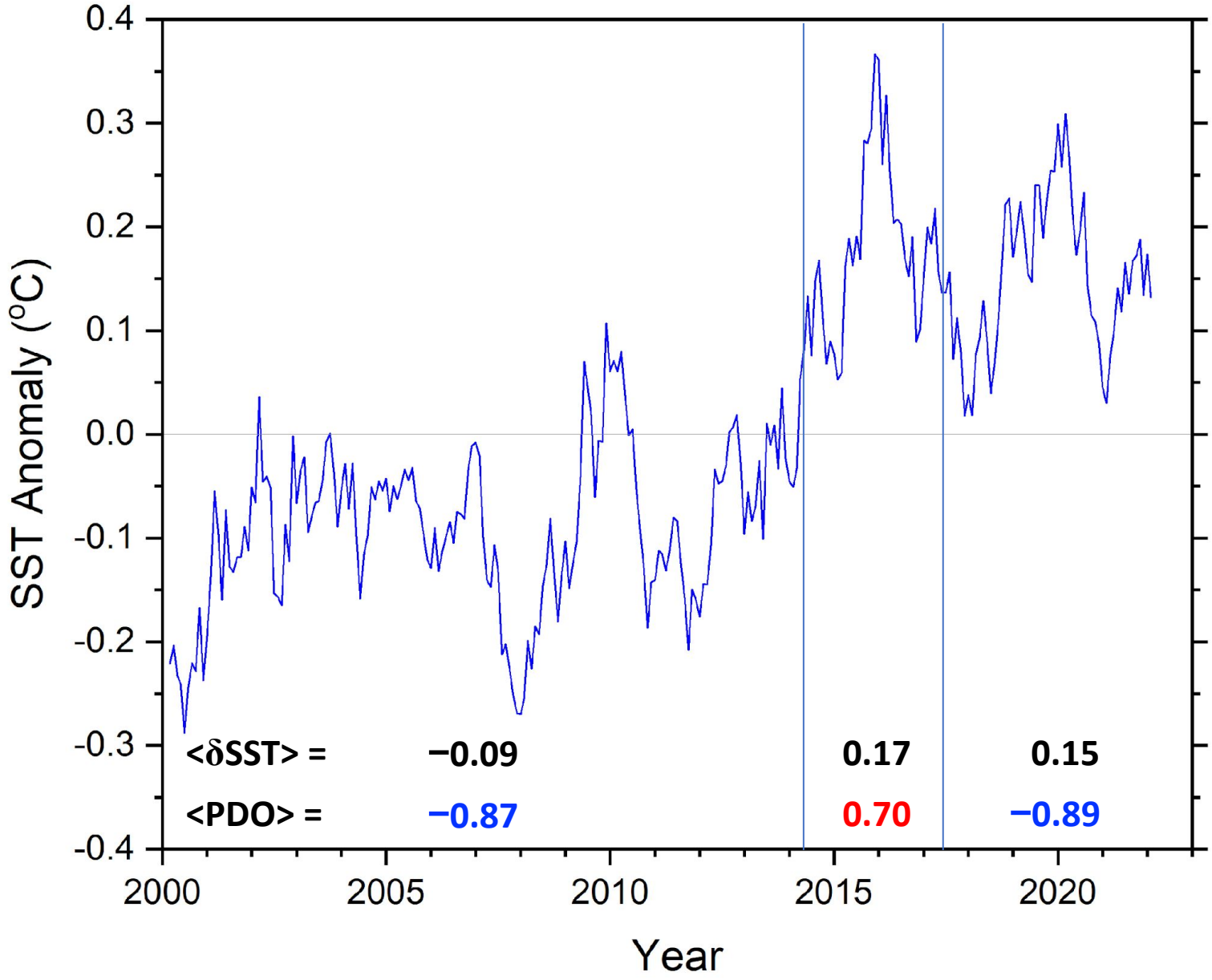
All data are integrated to obtain climate accuracy in radiative fluxes from the top to the bottom of the atmosphere.

Tracking Changes in Earth’s Energy Imbalance

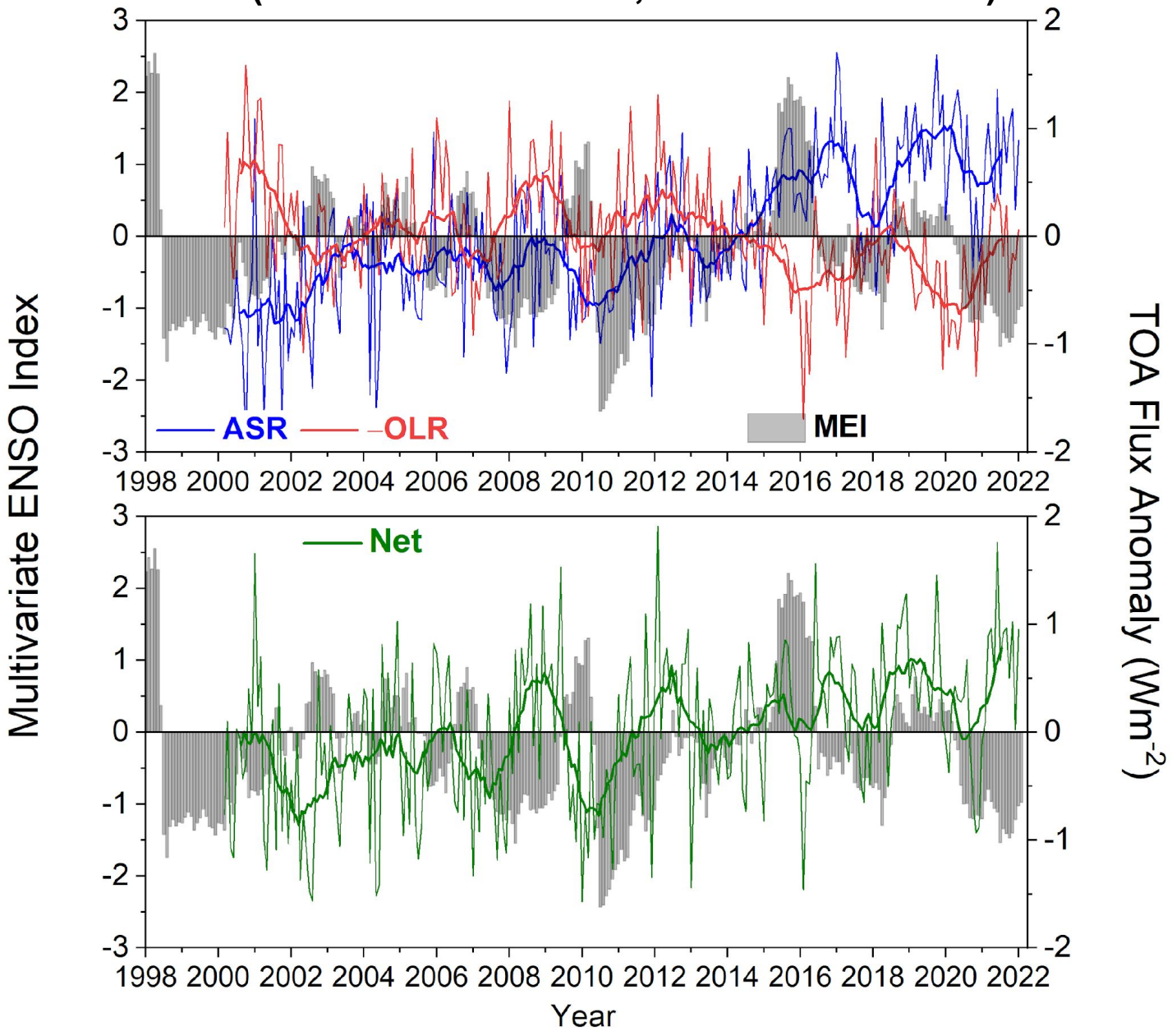
Niño 3.4 Index (ONI) Anomaly, PDO Index & δSST (01/2000 – 03/2022)



Global Mean SST Anomaly (03/2000-02/2022; HadSST.4.0.1.0)



Global Mean All-Sky TOA Flux Anomalies & Multivariate ENSO Index
(CERES EBAF Ed4.1; 03/2000 – 01/2022)



EBAF Trends (03/2000-01/2022)

ASR: 0.69 ± 0.20 Wm^{-2} per decade

LW: -0.27 ± 0.21 Wm^{-2} per decade

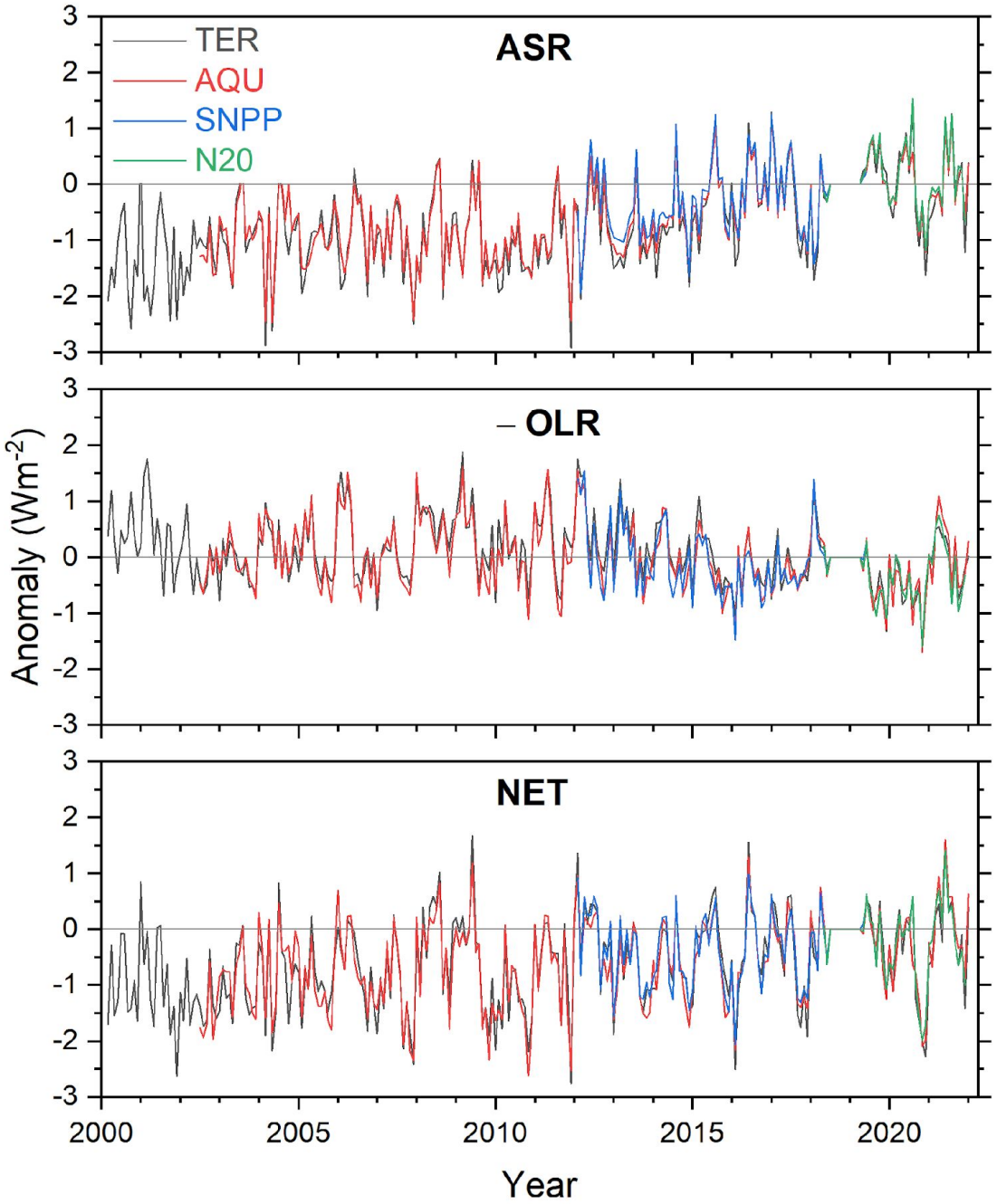
NET: 0.42 ± 0.20 Wm^{-2} per decade

EEI Changes: First and Last 5 years

- EEI (03/2000—02/2005): 0.44 Wm^{-2}
- EEI (02/2017—01/2022): 1.14 Wm^{-2}
- ΔEEI: 0.7 Wm^{-2}

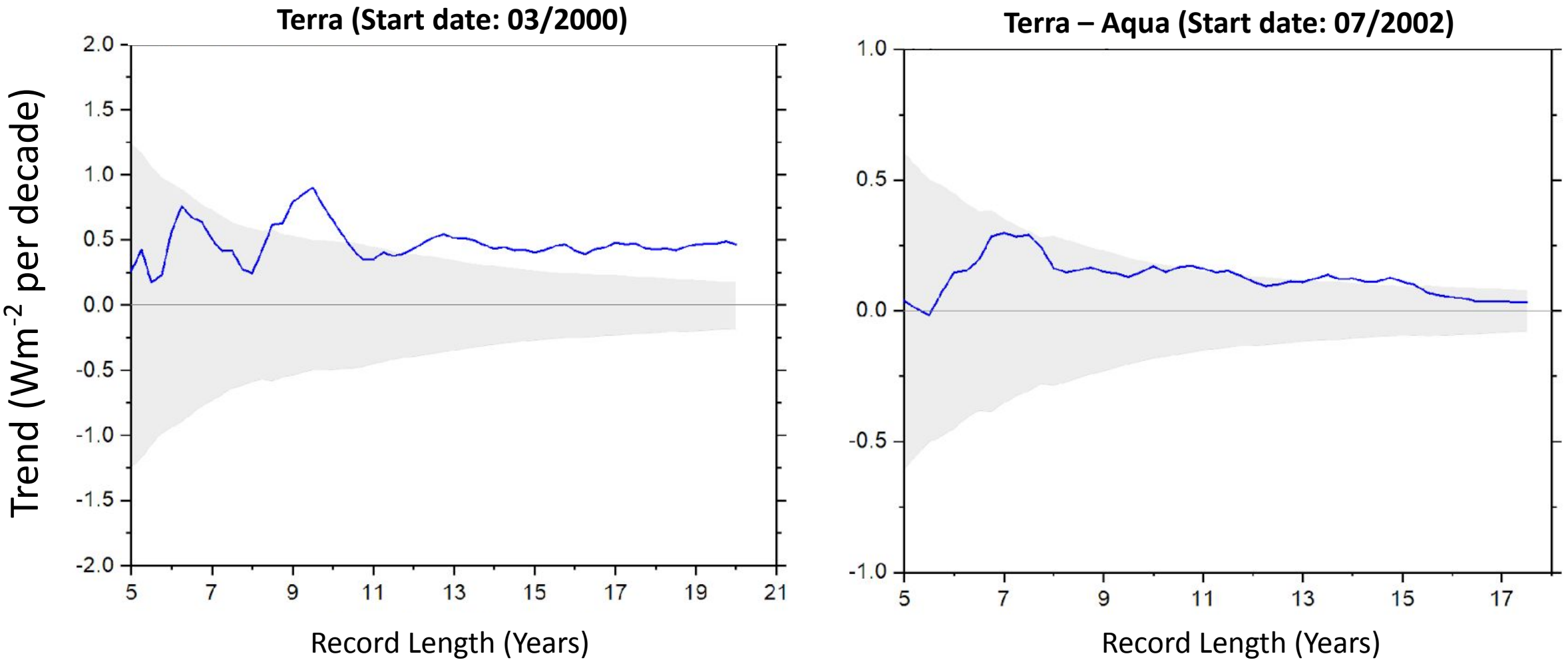
=> Approximate doubling of EEI

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

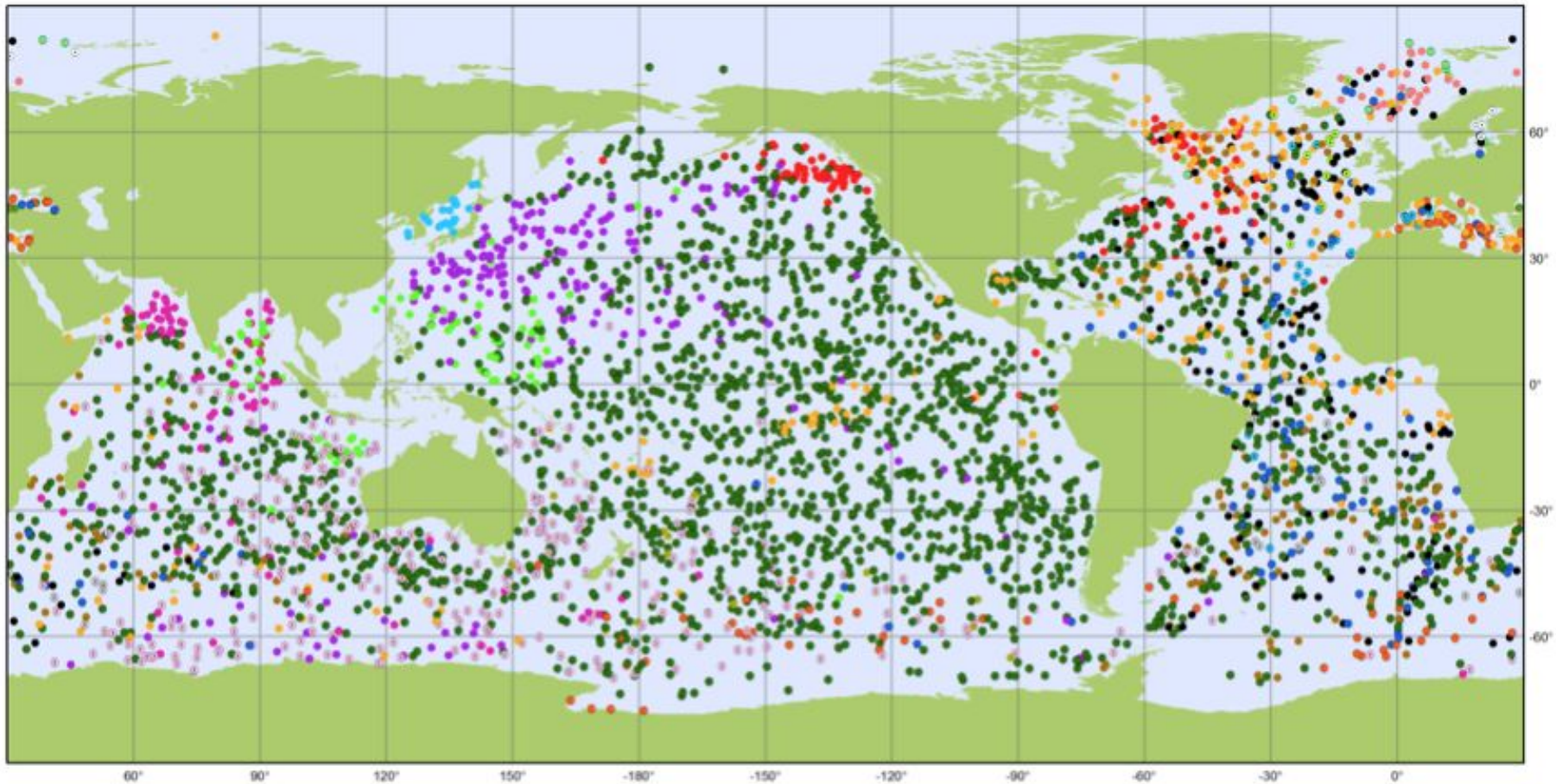
CERES Global Mean Net TOA Flux Trends vs Record Length



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

Loeb et al. JGR, 2022 (in press)

Argo Ocean Profiling Network



Argo

National contributions - 3918 Operational Floats

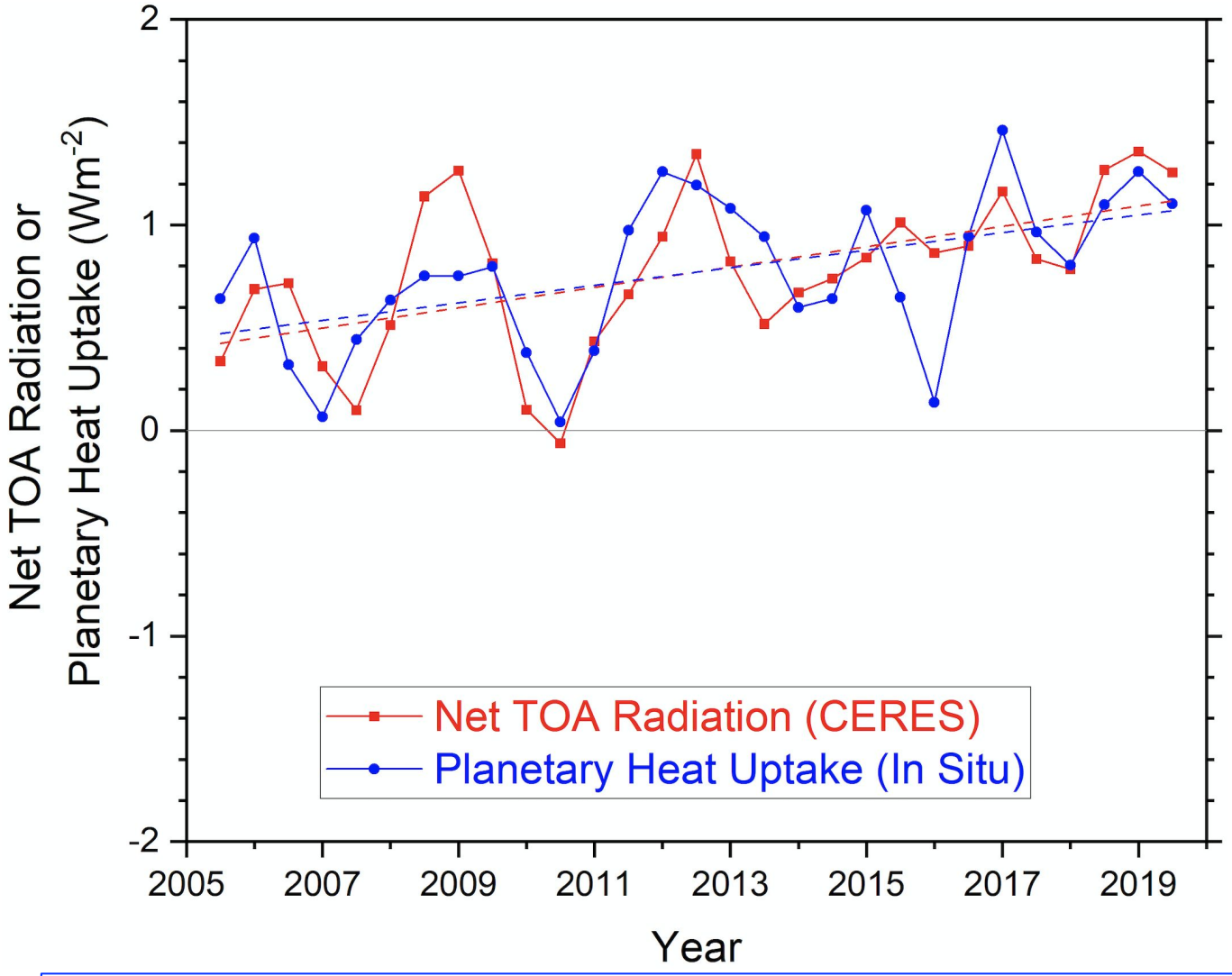
Latest location of operational floats (data distributed within the last 30 days)

February 2021

AUSTRALIA (327)	EUROPE (117)	GREECE (1)	JAPAN (219)	NEW ZEALAND (14)	KOREA, REPUBLIC OF (22)
BULGARIA (4)	FINLAND (7)	INDIA (87)	MEXICO (1)	NORWAY (31)	SPAIN (22)
CANADA (111)	FRANCE (242)	IRELAND (17)	MOROCCO (1)	PERU (3)	UK (170)
CHINA (85)	GERMANY (177)	ITALY (85)	NETHERLANDS (23)	POLAND (11)	USA (2142)

Generated by www.jcommops.org, 19/03/2021

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

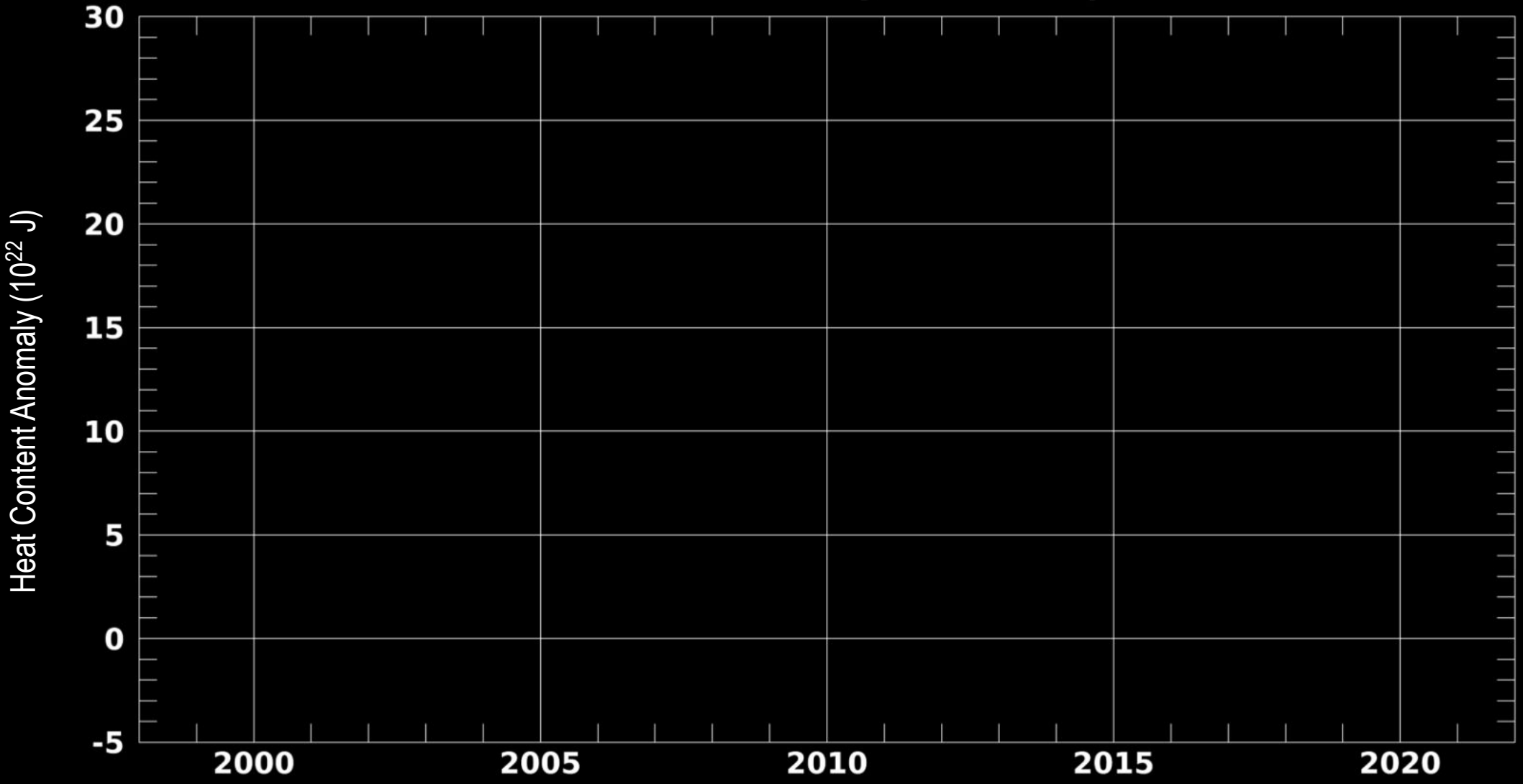
R^2 = 0.49

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.

Satellite and in situ observations independently show an approximate doubling of Earth's Energy Imbalance (EEI) from mid-2005 to mid-2019

Loeb et al. (2021)

CERES Planetary Heat Uptake

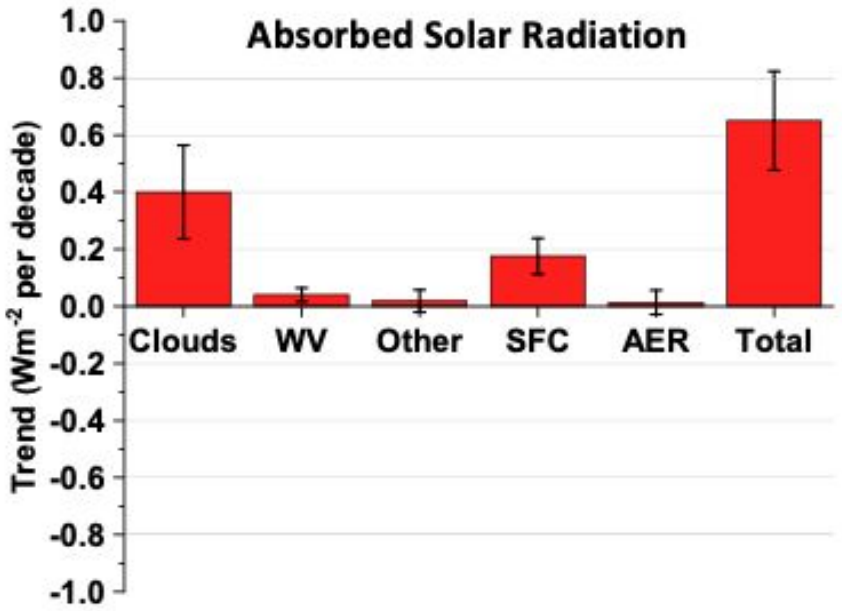


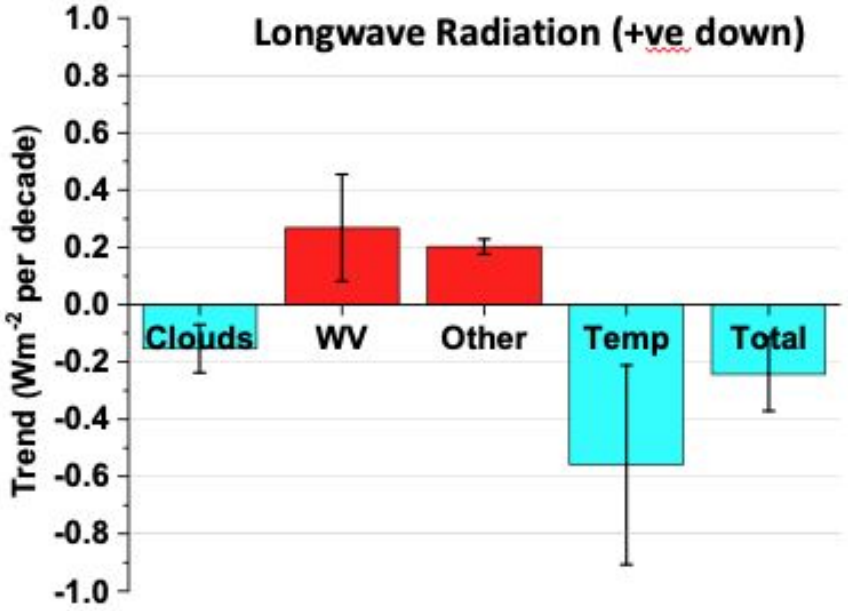
Cumulative Planetary Heating (2000-2020): 226 ZJ

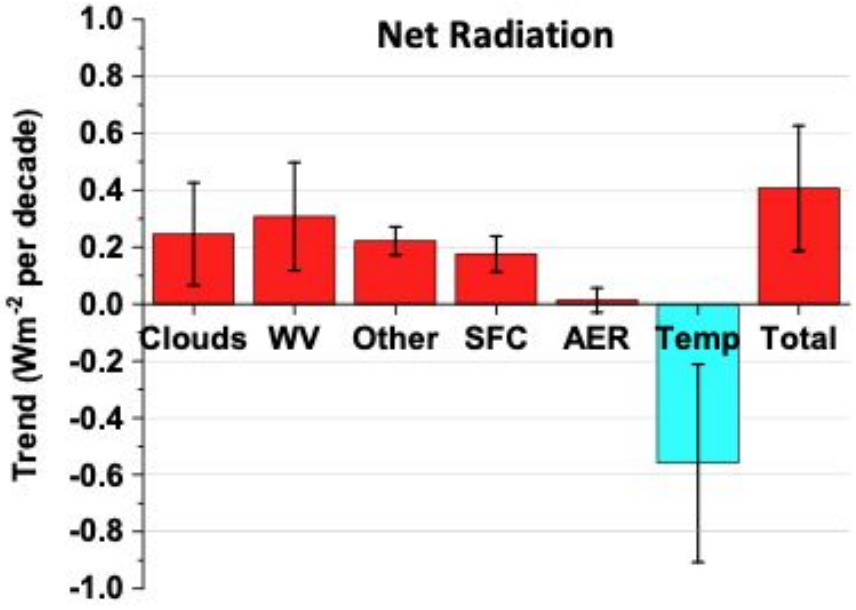
Global Primary Energy Consumption (2000-2020): 10.4 ZJ

⇒ Planetary heating is a factor of 22 greater

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

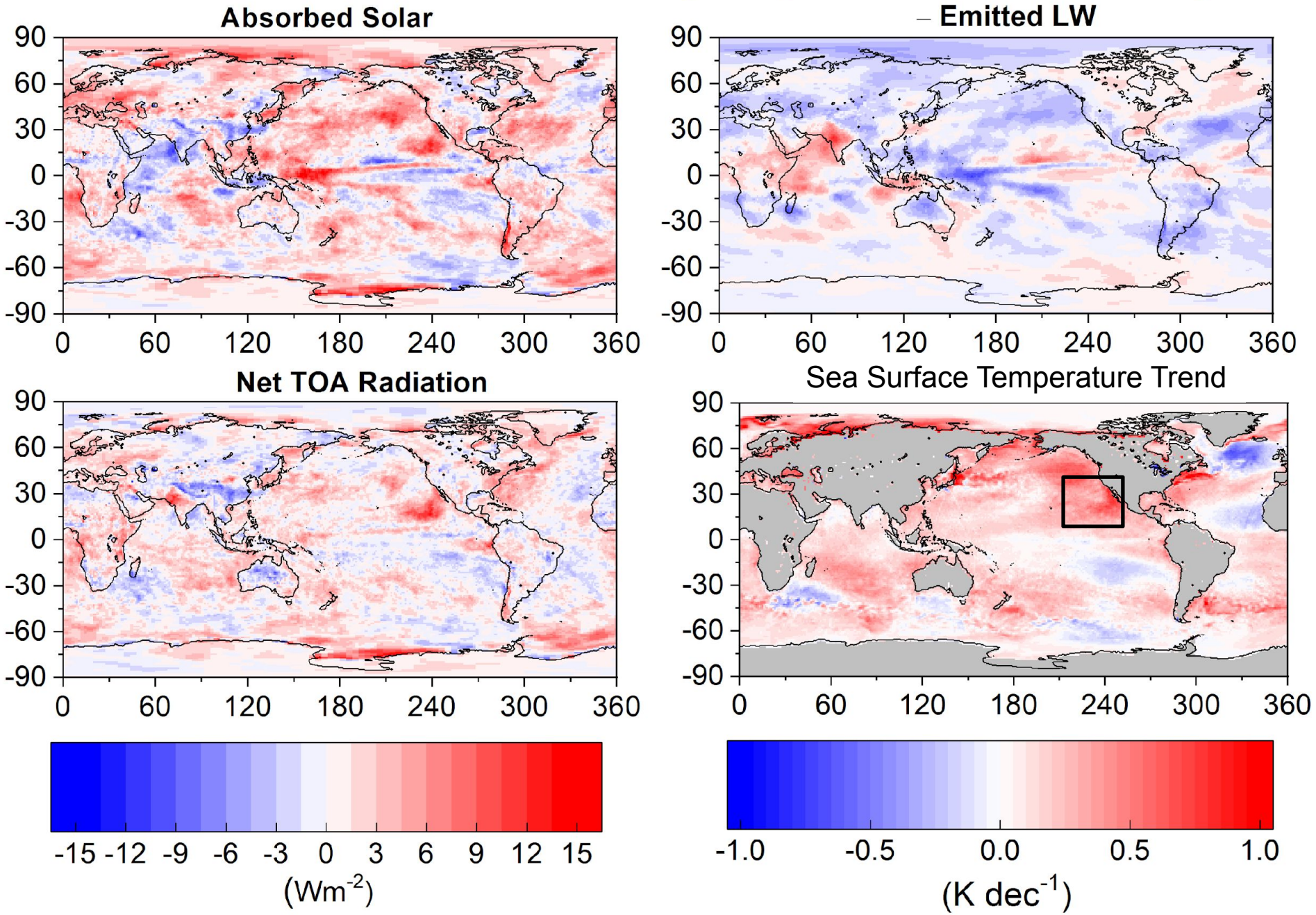




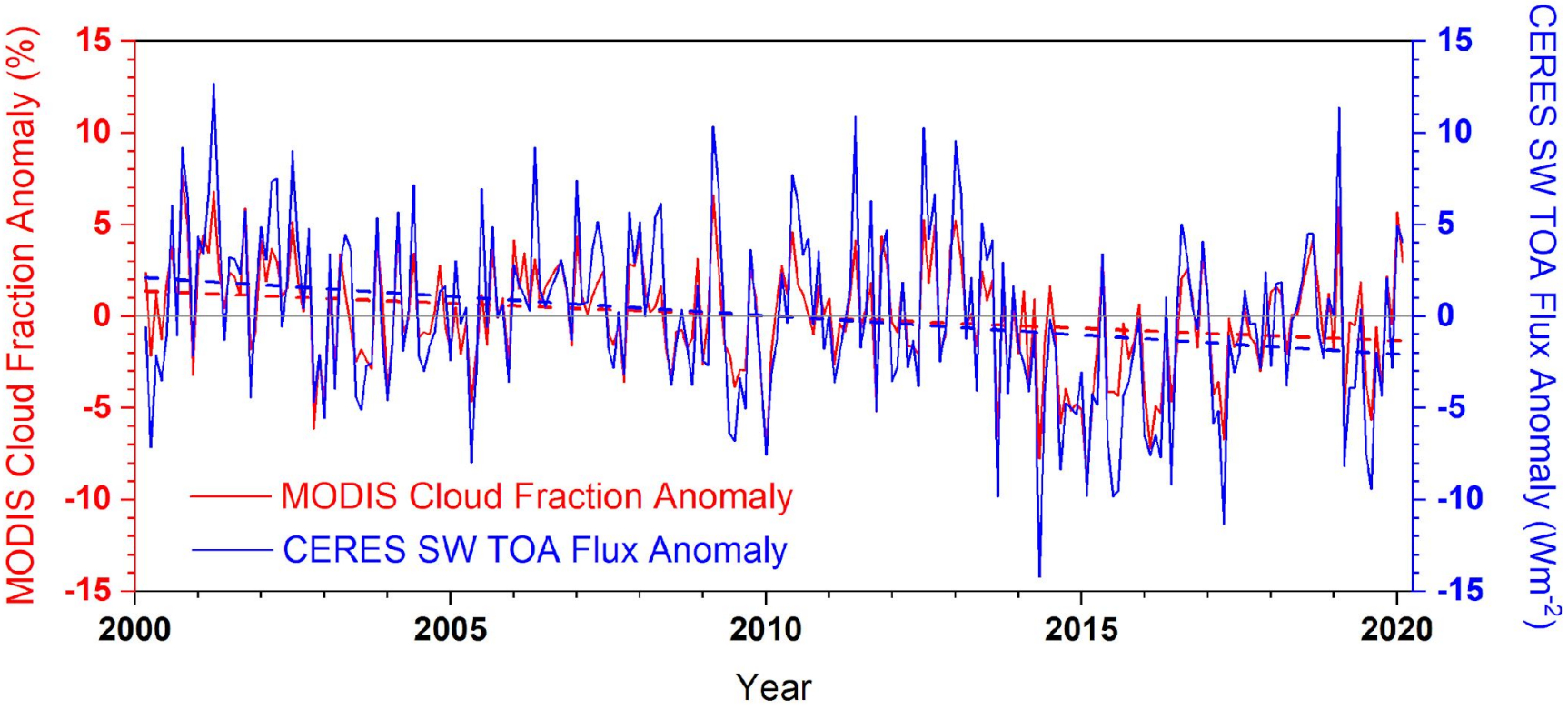


Combined changes in clouds, sea-ice, WV and trace gases exceed influence from temperature changes, resulting in a positive overall trend in net TOA flux.

CERES TOA Radiation Changes & ERA5 SST Trend (03/2000 – 01/2022)



MODIS Cloud Fraction and CERES SW TOA Flux Monthly Anomalies Over Eastern Pacific (10°-40°N, 150°-110°W) (March 2000 – February 2020)



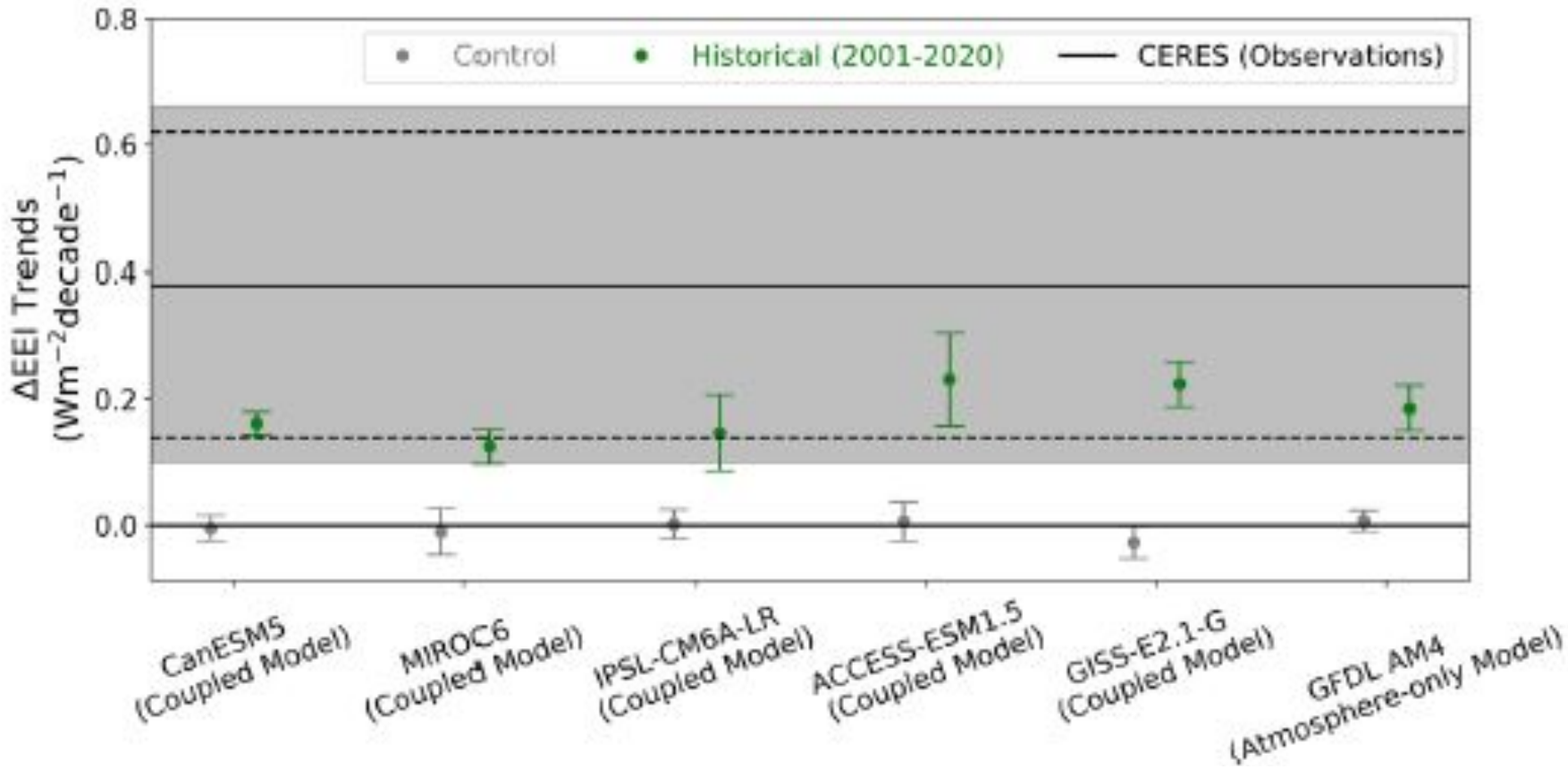
Trends

MODIS Cld frac: -1.4 ± 1.1 %/decade

CERES SW TOA: -2.1 ± 1.6 Wm^{-2}/decade

Loeb et al. JGR, 2022 (in press)

Global Mean Trend in Earth's Energy Imbalance (2001-2020): GCMs vs CERES



- The CERES EEI trend is exceptionally unlikely (<1% probability) to be explained by internal variability alone.
- Model simulations only fall within observational uncertainty when anthropogenic radiative forcing and the associated climate response are accounted for.
- Model EEI trends are in the lower range of the observed 95% confidence interval (dashed lines).

(Raghuraman et al., Nat. Comm., 2021)

Conclusions

- CERES provides the longest continuous dedicated global ERB record (2000-present) for tracking changes in EEI, constraining cloud feedback, climate model evaluation and quantifying aerosol direct radiative effect.
- Satellite and in situ observations independently show an approximate doubling of Earth's Energy Imbalance (EEI) from mid-2005 to mid-2019.
- Marked decreases in clouds and sea-ice and increases in trace gases and water vapor combine to increase the rate of planetary heat uptake.
- Anthropogenic forcing, internal variability, and climate feedbacks all contribute to the positive trend in EEI.