Tracking Changes in Earth's Energy Budget

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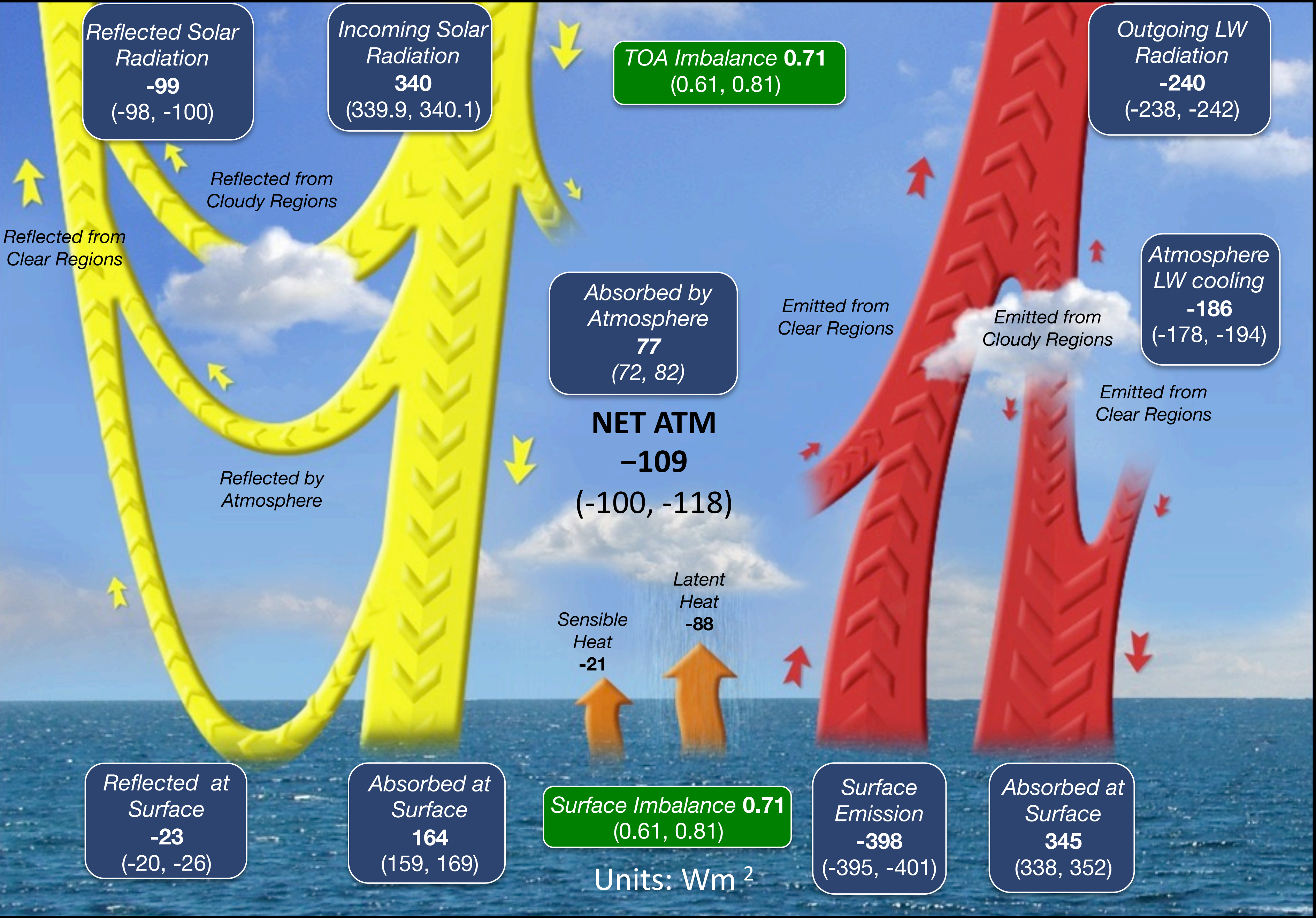
Outline

1) Earth's Energy Budget: Why it Matters
2) Stewardship Required to Produce and Sustain an Earth Radiation Budget CDR
3) Future challenges

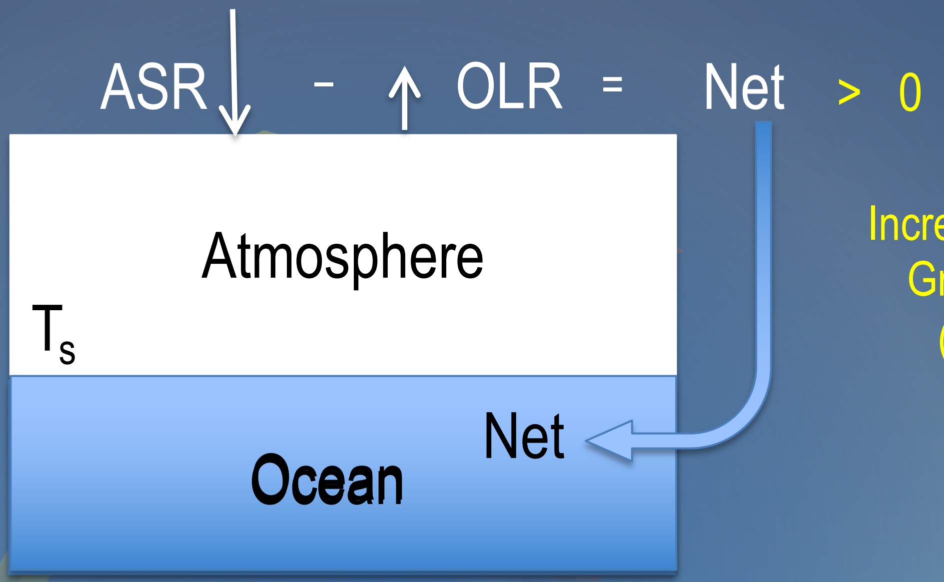
Earth’s Energy Budget: Why it Matters

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



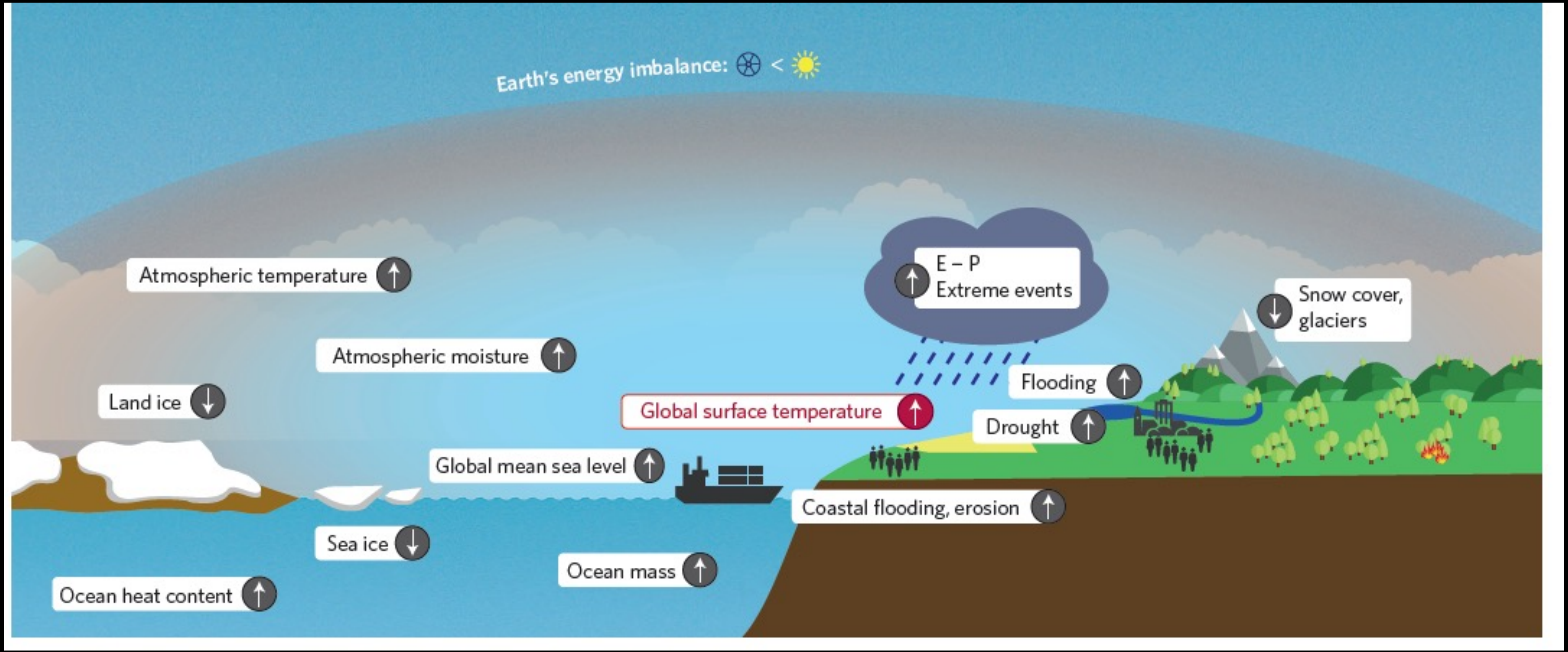
Increase in Atmospheric Greenhouse Gases (e.g., CO_2, CH_4)

- 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

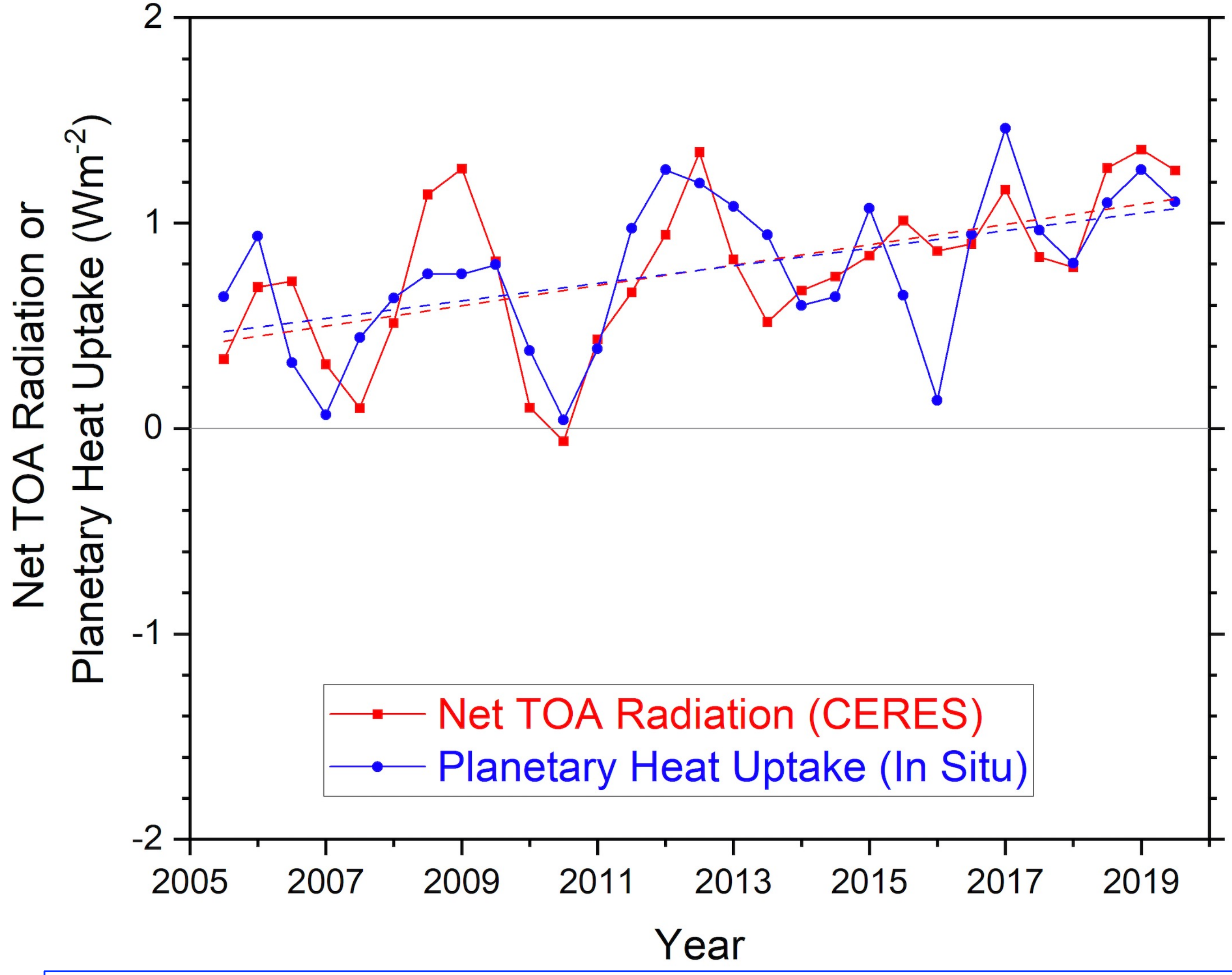


From von Schuckmann et a. (2016)

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

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)

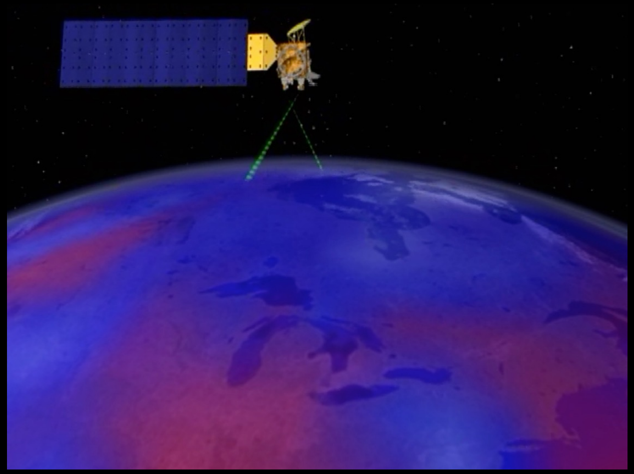
Stewardship Required to Produce and Sustain an Earth Radiation Budget CDR

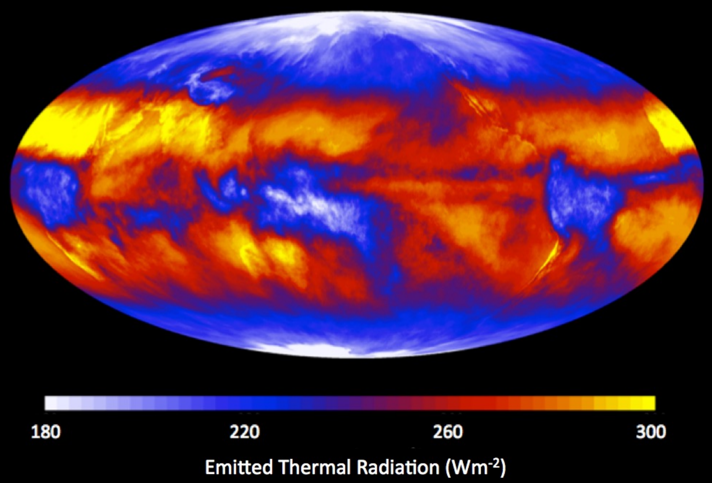
Climate Data Record (CDR)

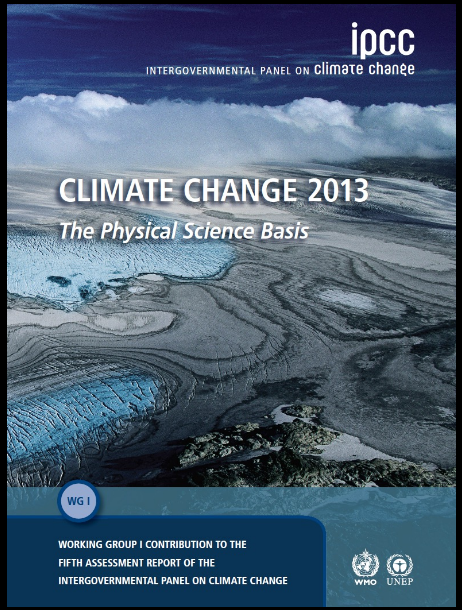
"A time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change" (US National Research Council, 2004)

- **"Continuity"** of an Earth measurement exists when the **quality** of the measurement for a specific quantified Earth science objective is maintained over the required temporal and spatial domain set by the objective.
- **"Quality"** is characterized by the combined standard uncertainty, which includes instrument calibration uncertainty, repeatability, time and space sampling, and data systems and delivery for climate variables (algorithms, reprocessing, and availability).
- **"Consistency"** requires that instruments introduced to continue an existing CDR produce "backward compatible" measurements that allow continuation of the CDR without introducing discontinuities in the record.
- Since there is no "truth" available, ensuring that a data record satisfies the CDR criteria is challenging: multiple independent intercomparisons involving both satellite and surface/in-situ measurements are needed.

Clouds and the Earth's Radiant Energy System



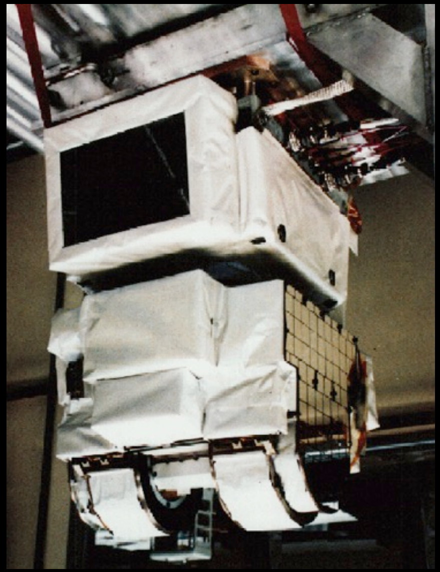




- Goal is to produce a long-term, integrated global climate data record (CDR) of Earth's radiation budget (ERB) from the surface to the top-of-atmosphere (TOA) together with the associated cloud, aerosol & surface properties.
- To enable improved understanding of the variability in Earth's radiation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

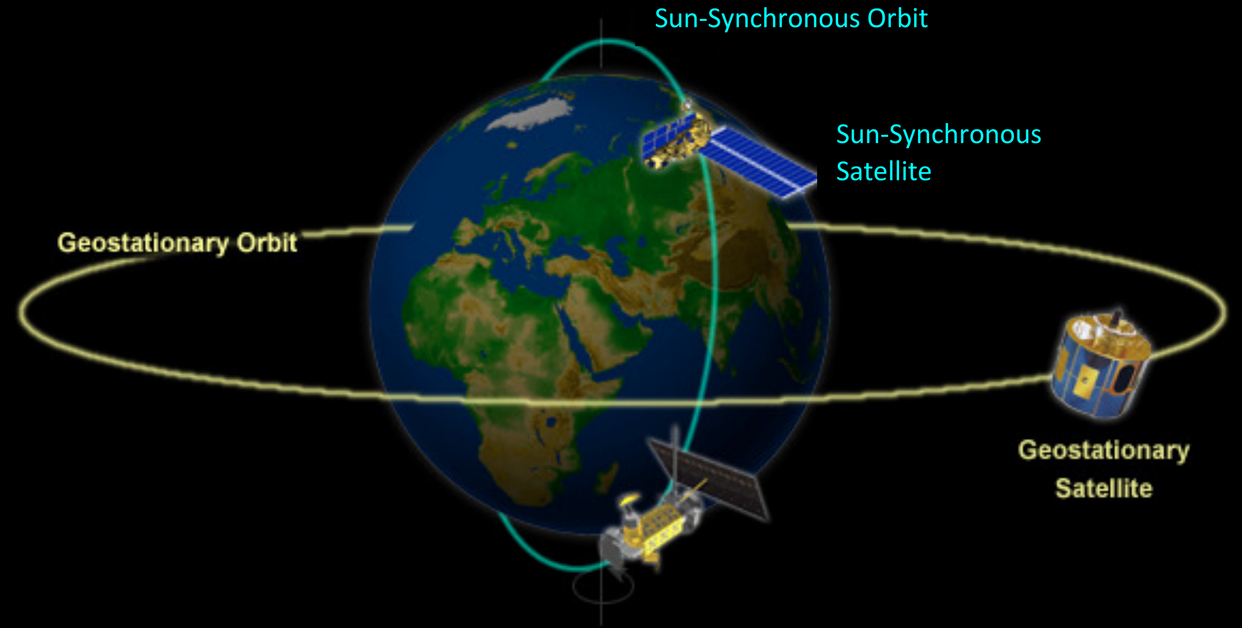
CERES Instruments

- 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.

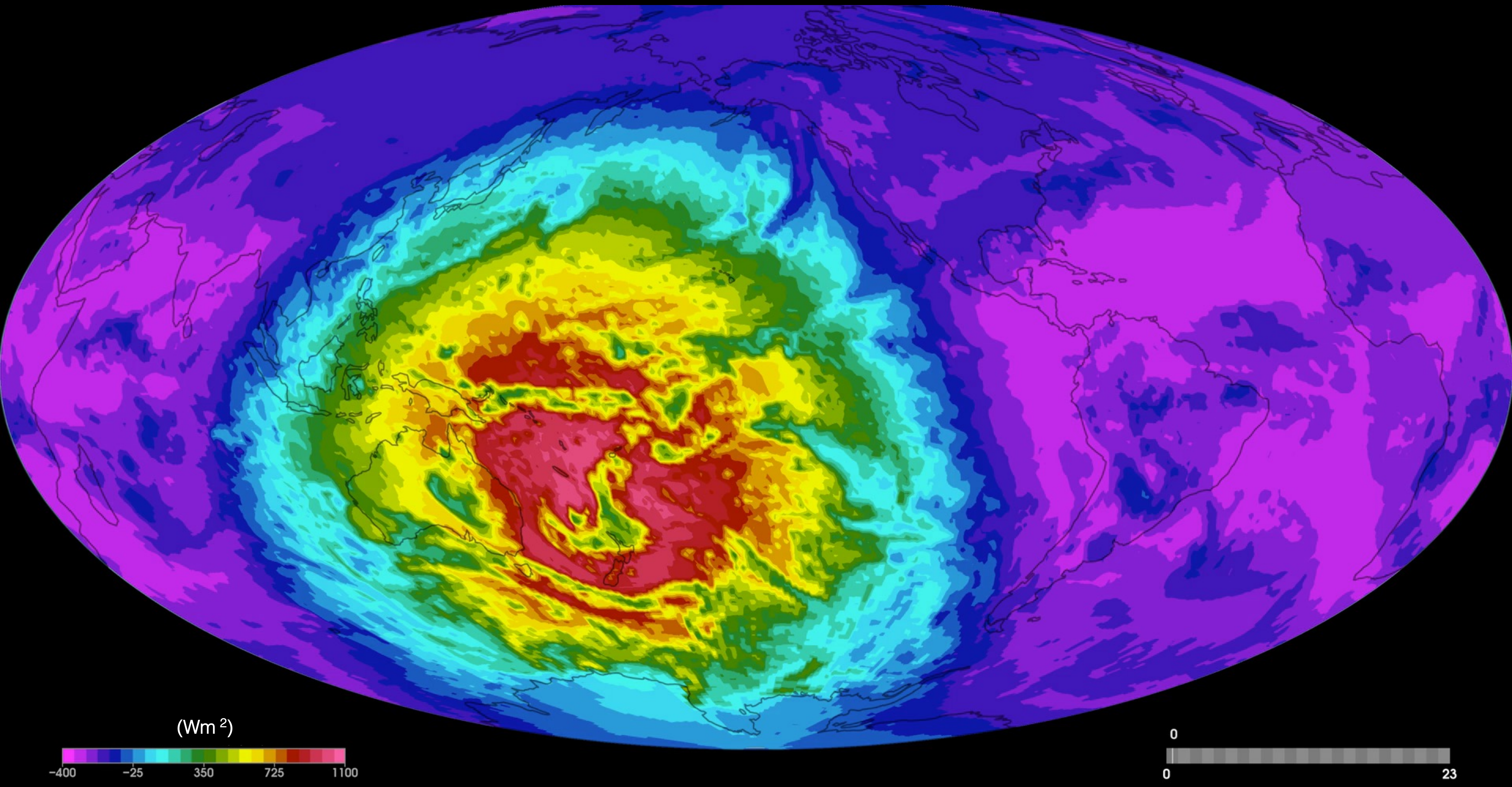
Earth Radiation Budget Data Fusion



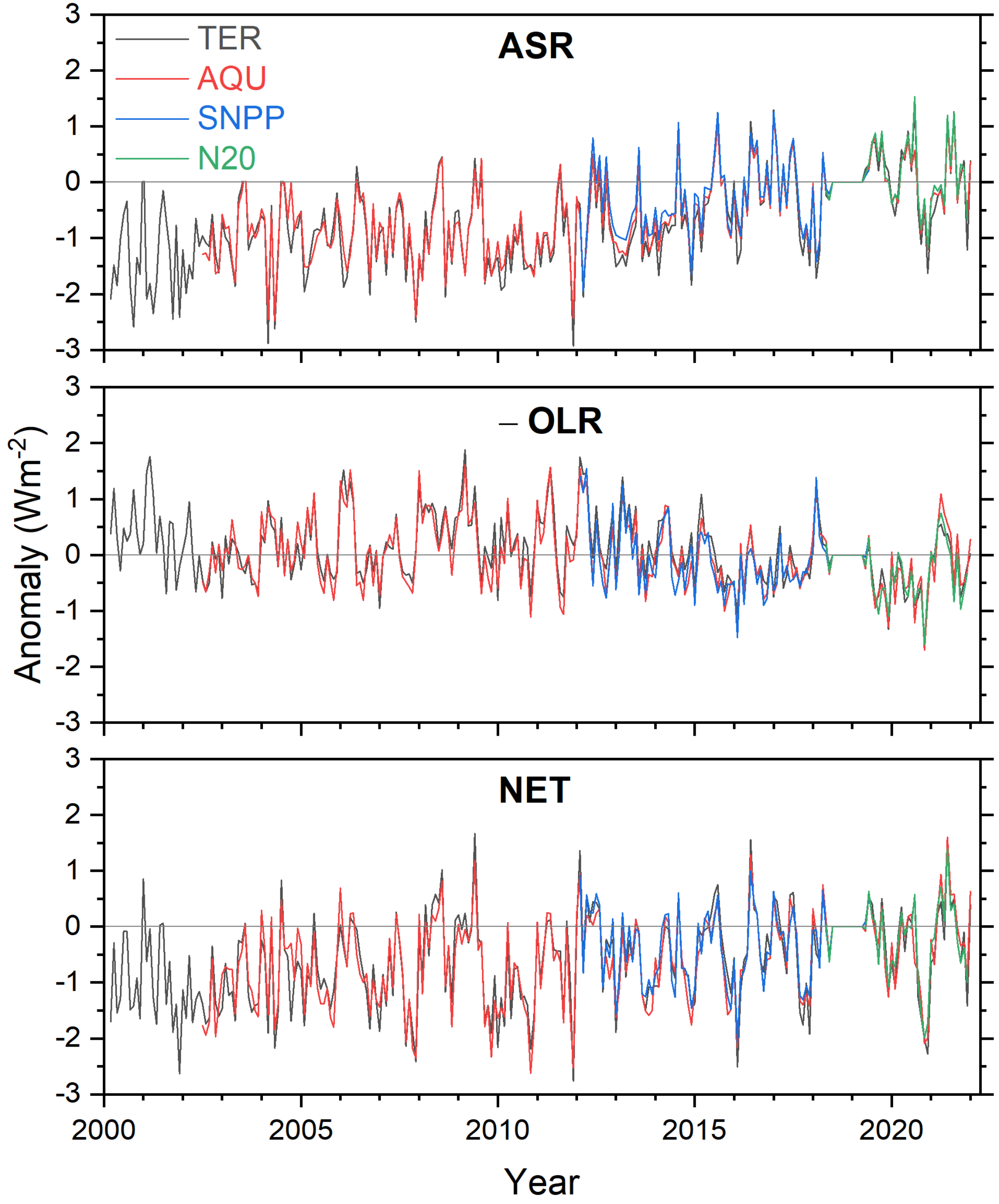
- In order to provide complete spatial coverage of Earth and resolve its diurnal cycle, a high level of data fusion is required.
- During the CERES period, the team has processed data from:
  - 7 CERES instruments
  - 1 VIRS imager (TRMM)
  - 2 MODIS imagers (Terra, Aqua)
  - 2 VIIRS imagers (S-NPP, 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.**

All-Sky Net Flux (All-Sky; Hourly)

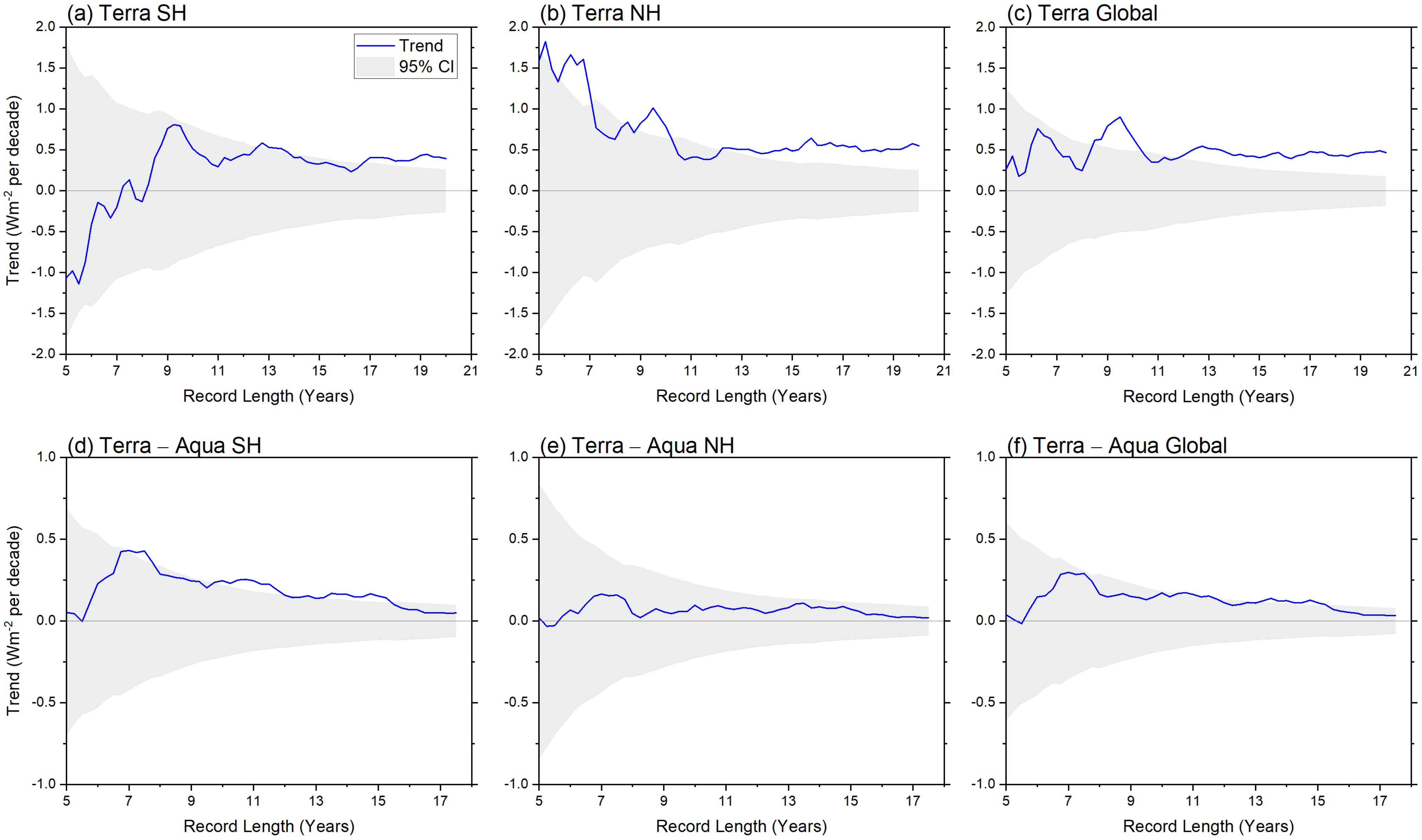


Global Mean All-Sky TOA Flux Monthly Anomalies (03/2000-01/2022; Climatology: 05/2018—06/2019)



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

CERES Net TOA flux Trends against Record Length for CERES SSF1deg Terra (top) and Terra – Aqua (bottom)
(Start date is 03/2000 for Terra and 07/2002 for Terra – Aqua. Gray shading corresponds to 95% confidence interval.)



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

CERES EBAF

Serves as the CERES monthly CDR product for multiple scientific purposes (climate model evaluation, climate variability, trend analysis, etc.).

Requirements:

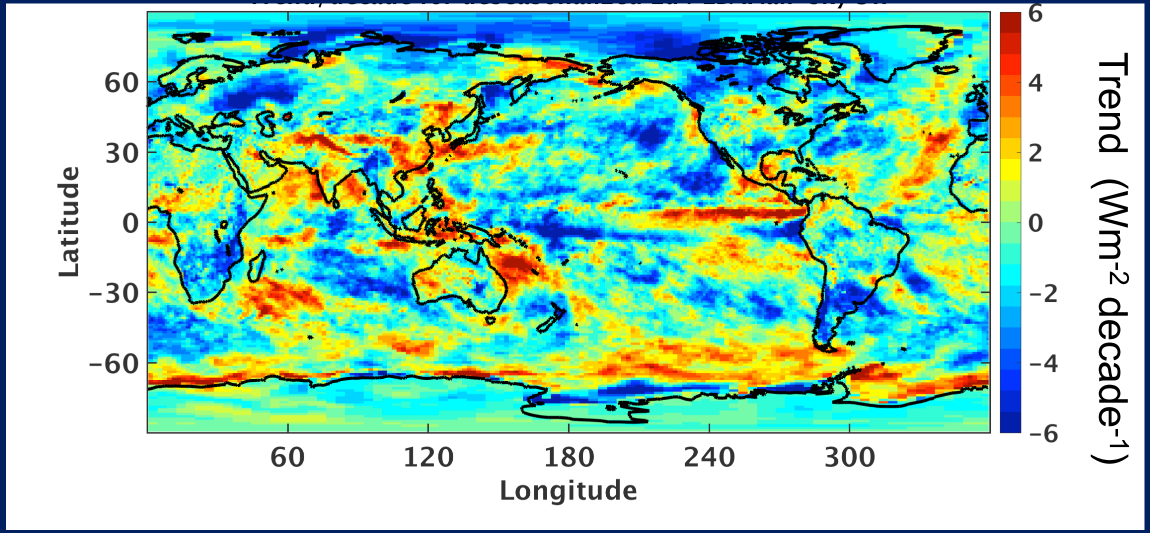
- Same level of stability as SSF1deg.
- Accurate regional averages, which requires diurnal sampling. Involves “careful” use of GEOs.
- Accurate global mean SW, LW and NET. We use in situ EEI as constraint.
- Clear-sky fluxes to be defined in the same manner as GCMs (”cloud removed”).
- Computed surface fluxes that are consistent with observed TOA fluxes.

  - Use a constrainment algorithm to adjust inputs to Fu-Liou RTM within uncertainty so that computed and observed TOA fluxes agree.

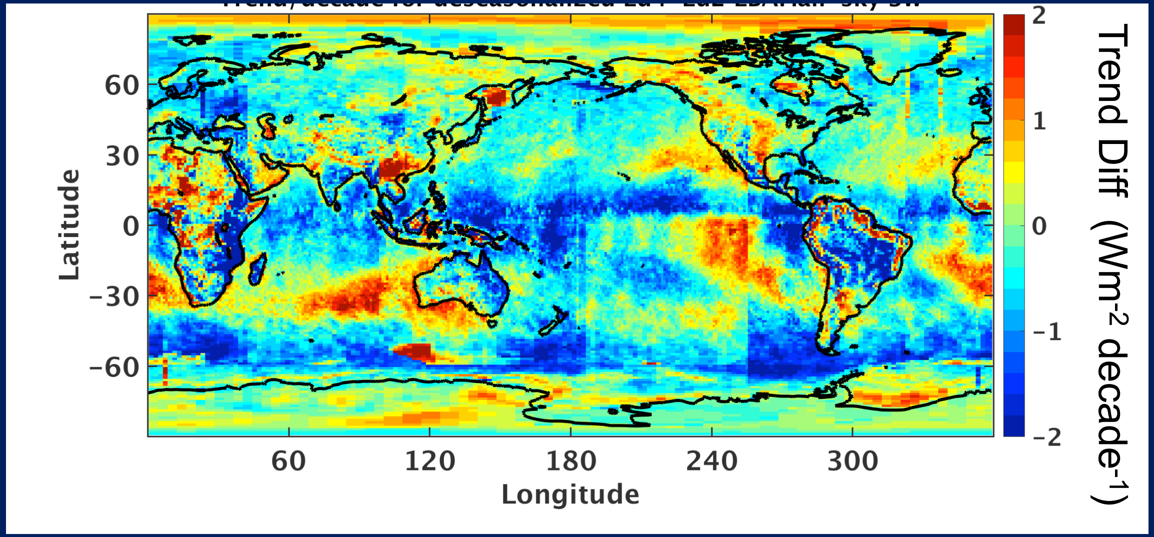
EBAF has been an evolutionary process. We continue to refine the product in order to accommodate observing system changes to ensure a seamless record.

All-Sky SW TOA Flux Trend (03/2000-06/2015)

EBAF Ed4.0

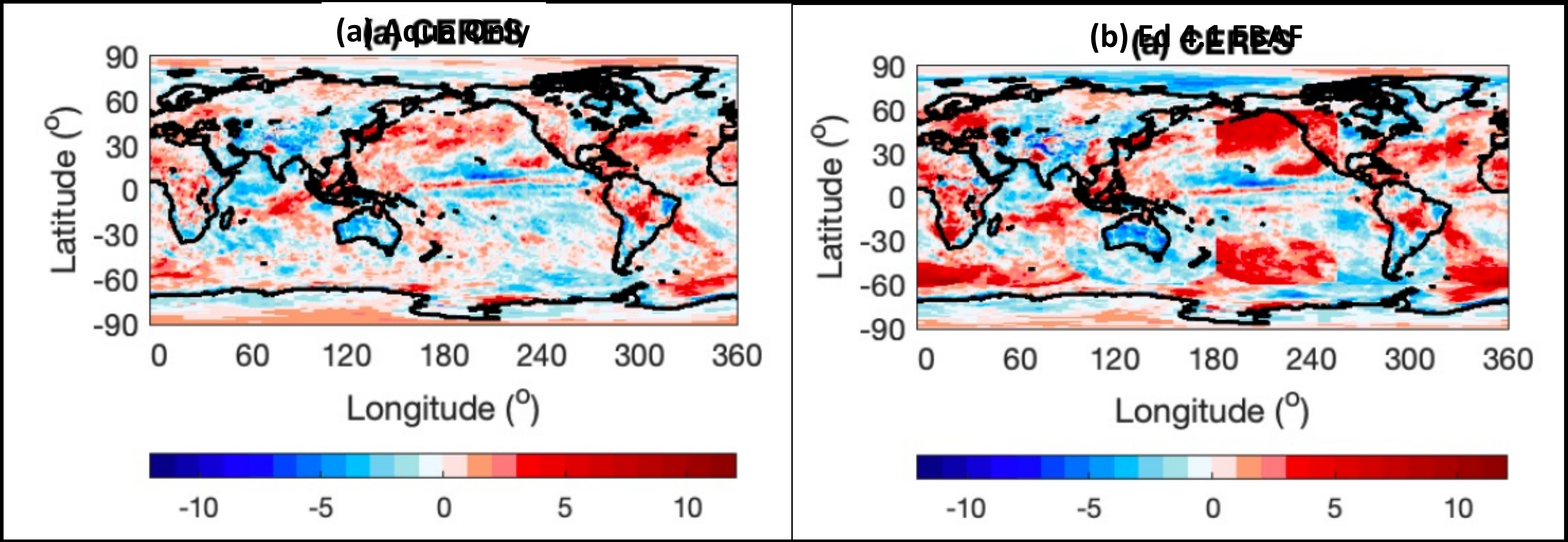


EBAF Ed4.0 minus Ed2.8



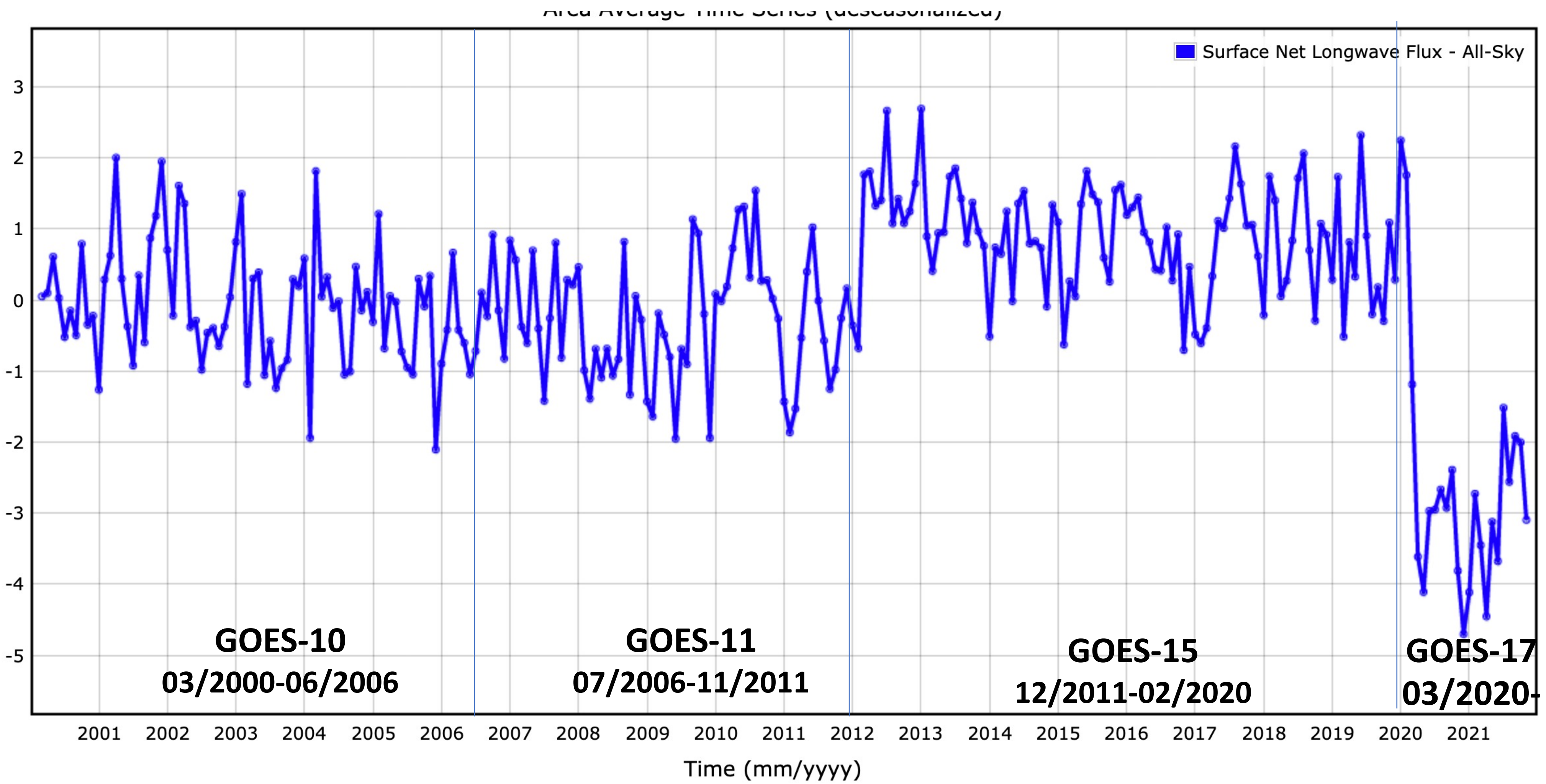
- Geostationary satellite boundaries appear in Ed2.8 trends, not Ed4.0.
- Improved Ed4.0 diurnal corrections avoid discontinuities due to geostationary satellite artifacts.

Surface net radiative flux trend (08/2002-02/2020)



- Ed4.1 EBAF relies on GEO imager-derived cloud properties, which can vary across GEO platforms.

Surface Net Longwave Flux Anomaly (60ºN to 60ºS, Lon: 180º to 255º)

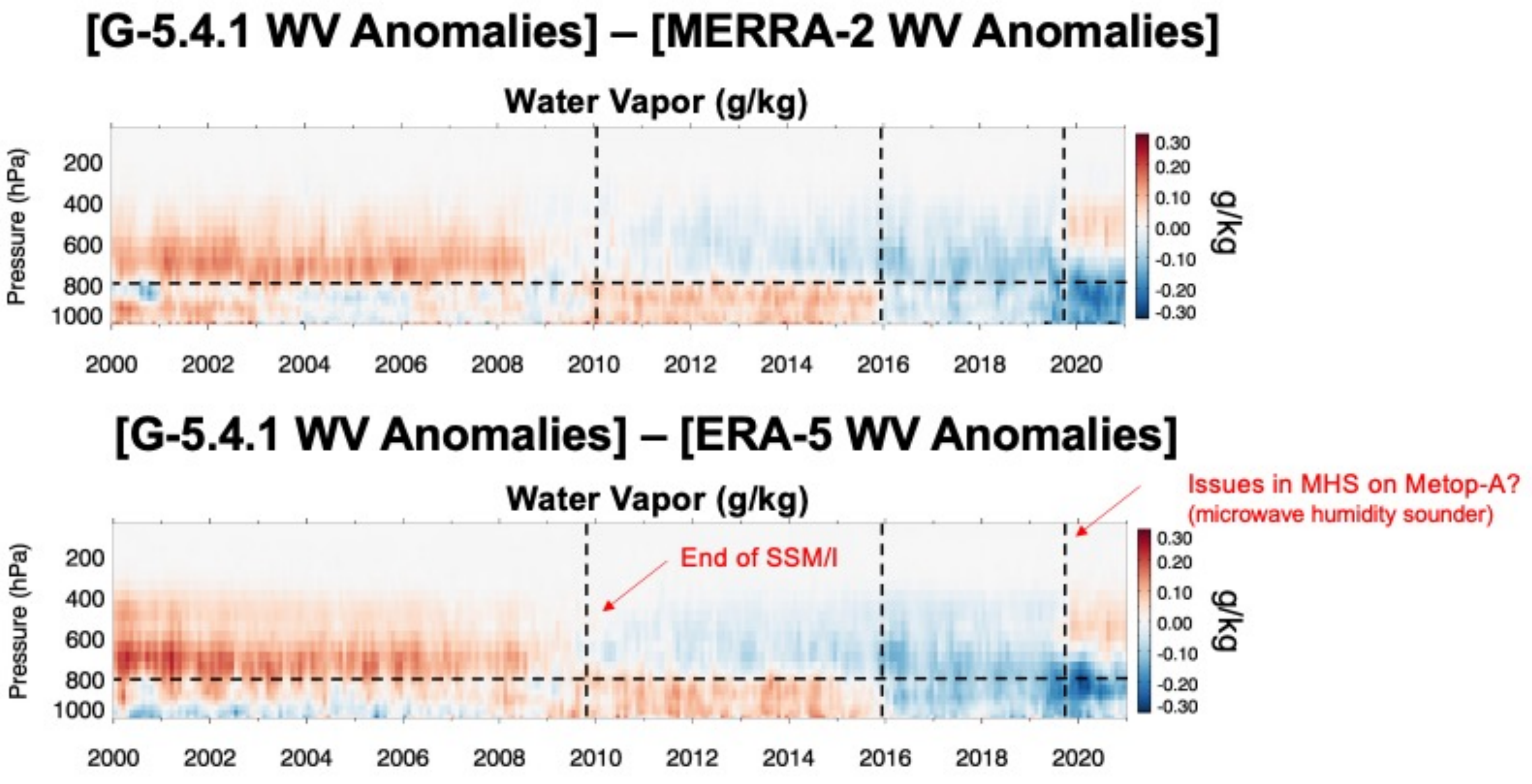


- Discontinuities in cloud IR emissivity (optical depth) and cloud height cause discontinuities in net downward LW flux at the surface.

Discontinuities in GEOS 5.4.1 Water Vapor Profiles

60S-60N Land+Ocean

Area weighted; climatology is obtained using 2003-2020

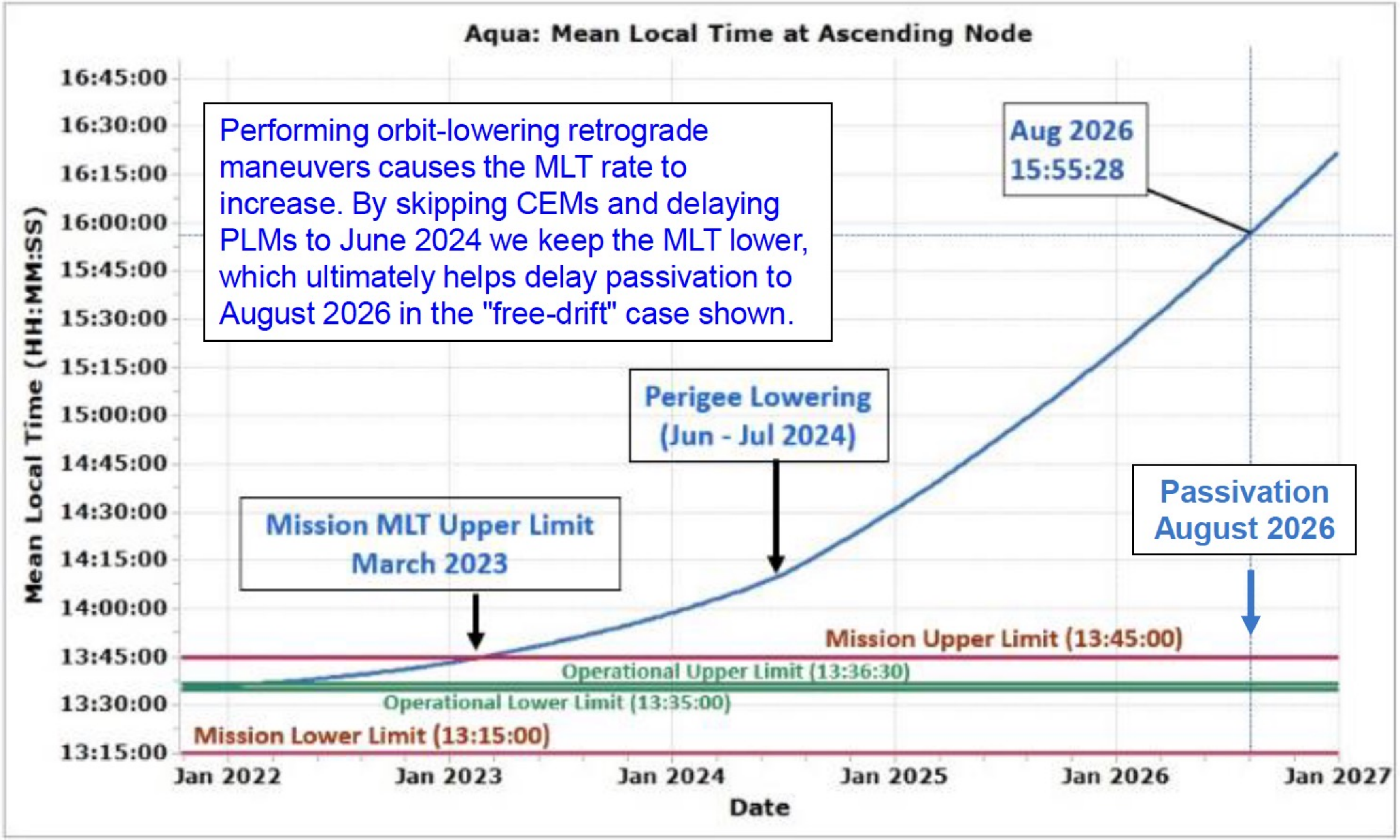


- The differences between G541 and ERA5 are similar to those between G541 and MERRA-2.
- This implies that the differences are mainly driven by G541 problems.
- The discontinuities in G541 might be related to input observing data changes.

Seung-Hee Ham (Spring 2021 CERES meeting)

Mean Local Time (MLT)

Free-Drift, Drag-Down Exit with Cd = 2.1
June-July 2024 PLMs



Planned Changes in EBAF Processing

1) Transition to NOAA-20:

Terra-Only (03/2000-06/2002)	→	Terra+Aqua (07/2002-06/2022)	→	NOAA20 (07/2022-onwards)

Note: Climatology of Terra-Only and NOAA20-Only will be anchored to Terra+Aqua climatology using overlapping periods.

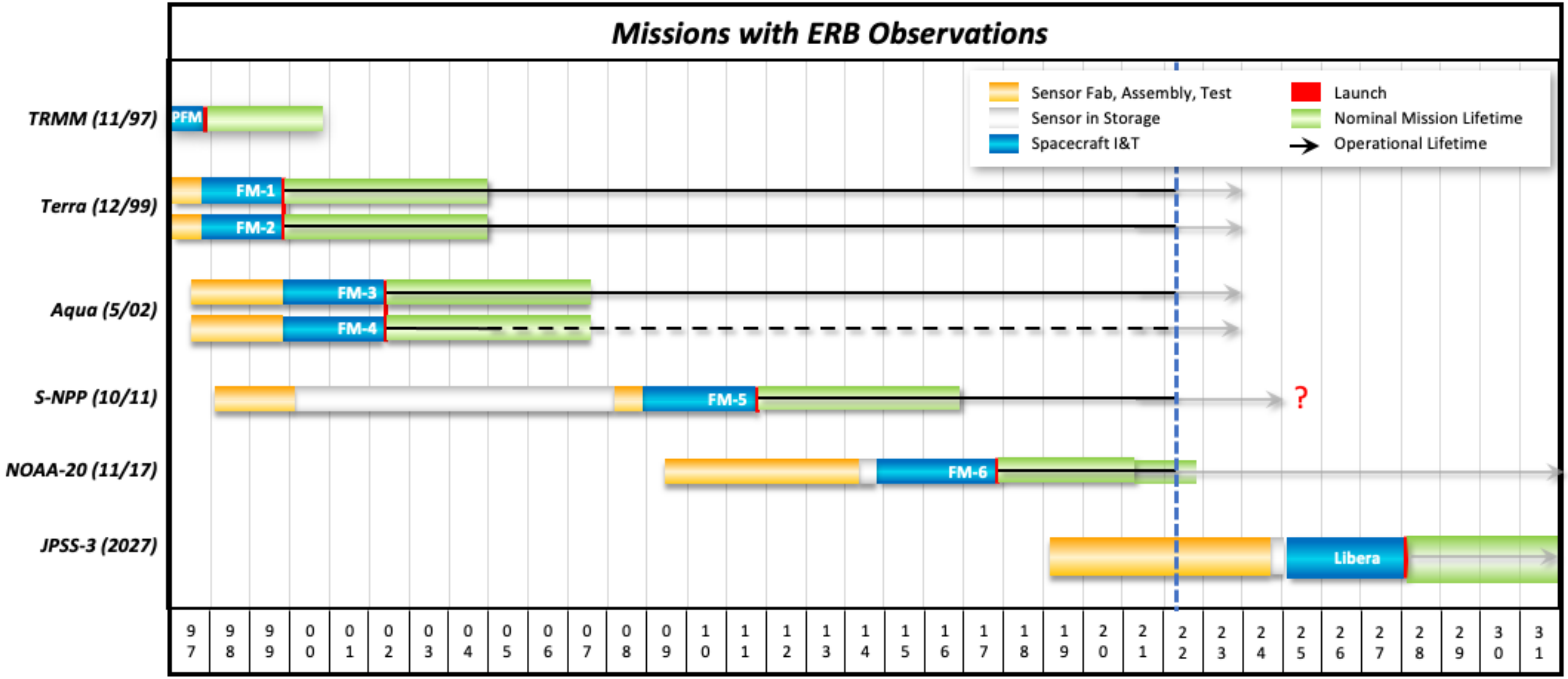
2) EBAF-Surface fluxes will be processed with MODIS/VIIRS imager cloud retrievals (no GEO).

3) EBAF-Surface fluxes will be re-calculated using MERRA-2 meteorological inputs.

- MODIS/VIIRS imager cloud properties will not be reprocessed (based upon GEOS 5.4.1)

The Future

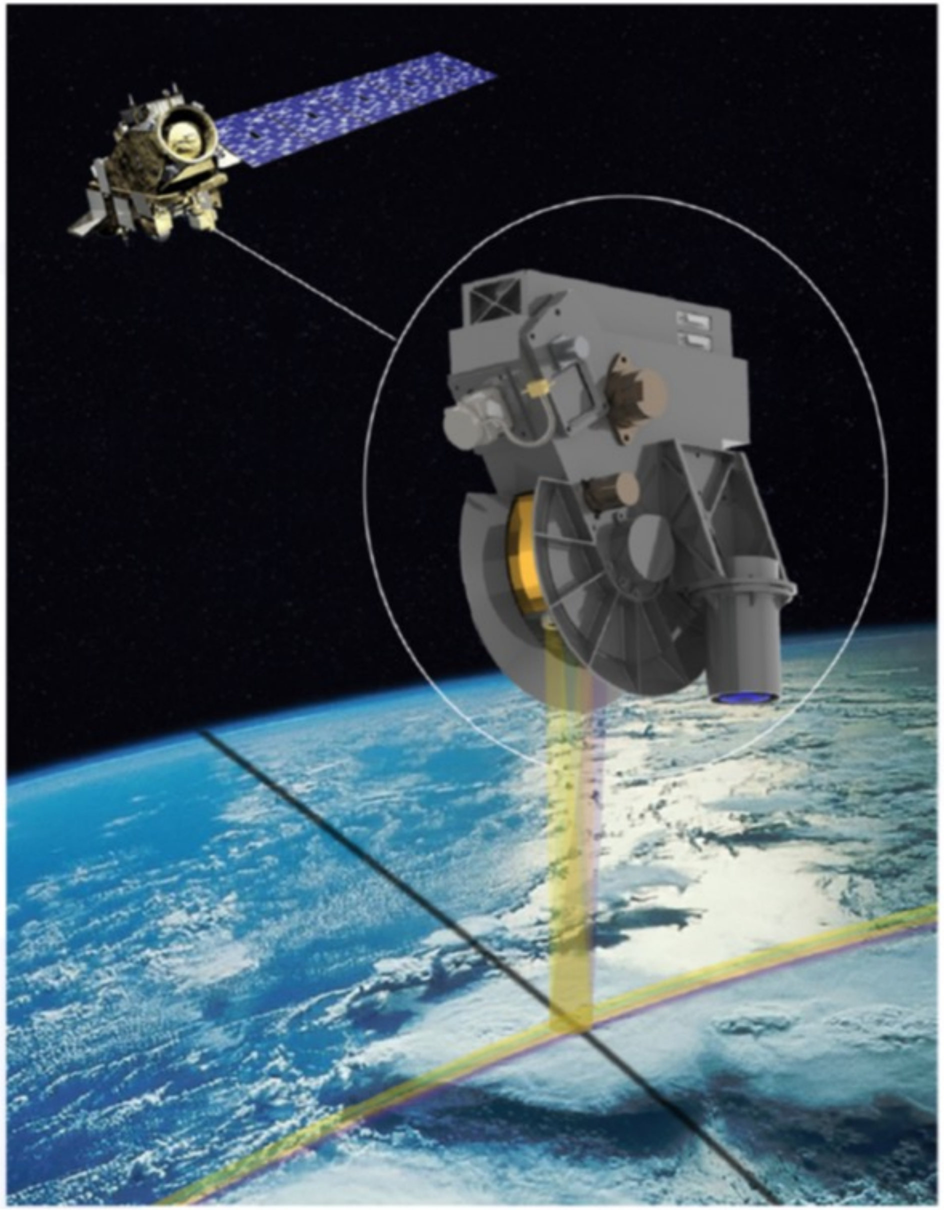
Flight Schedules



- 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

ˈLi-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:

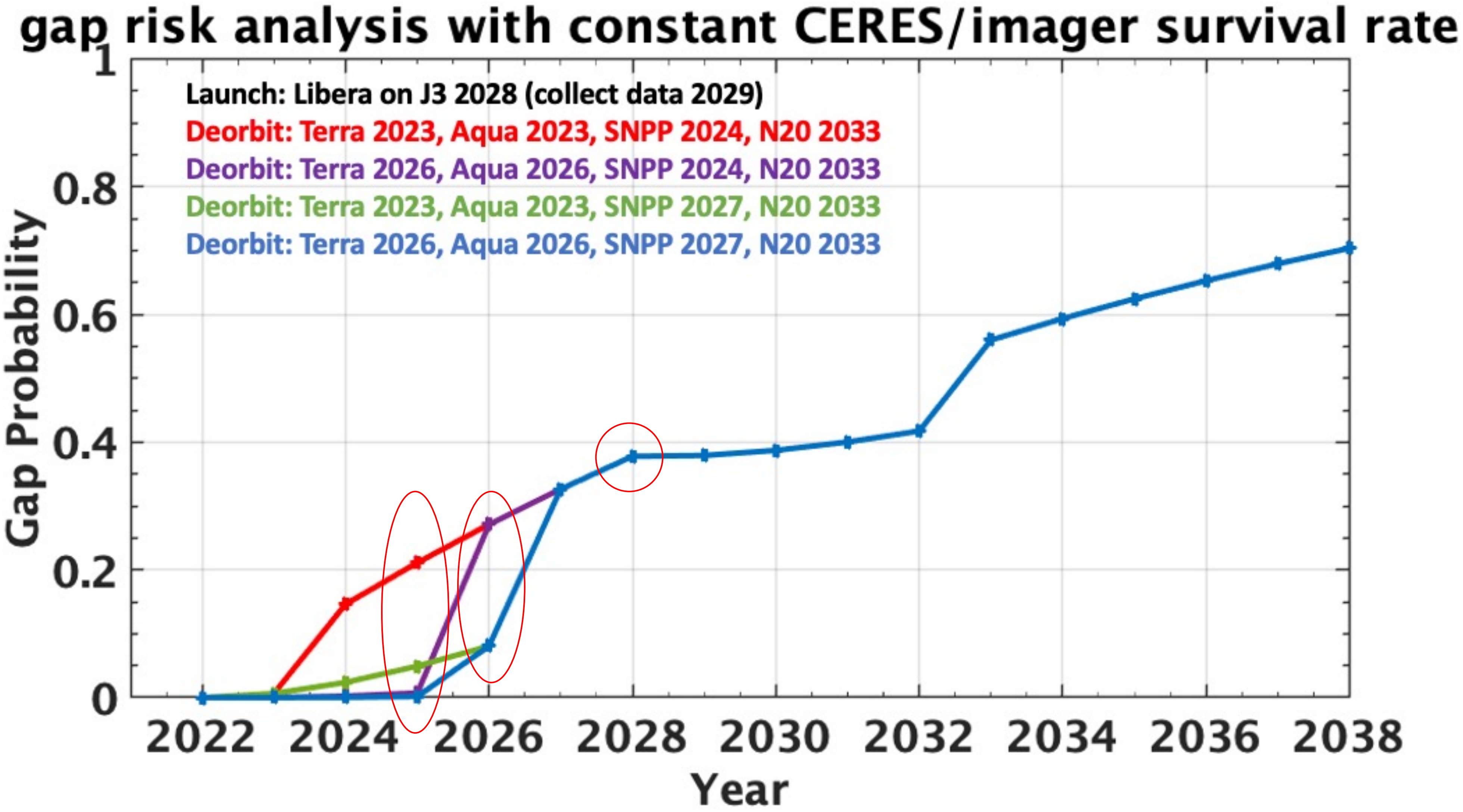
- JPSS-3, 2028 launch; 5-year mission

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

Gap Risk Analysis

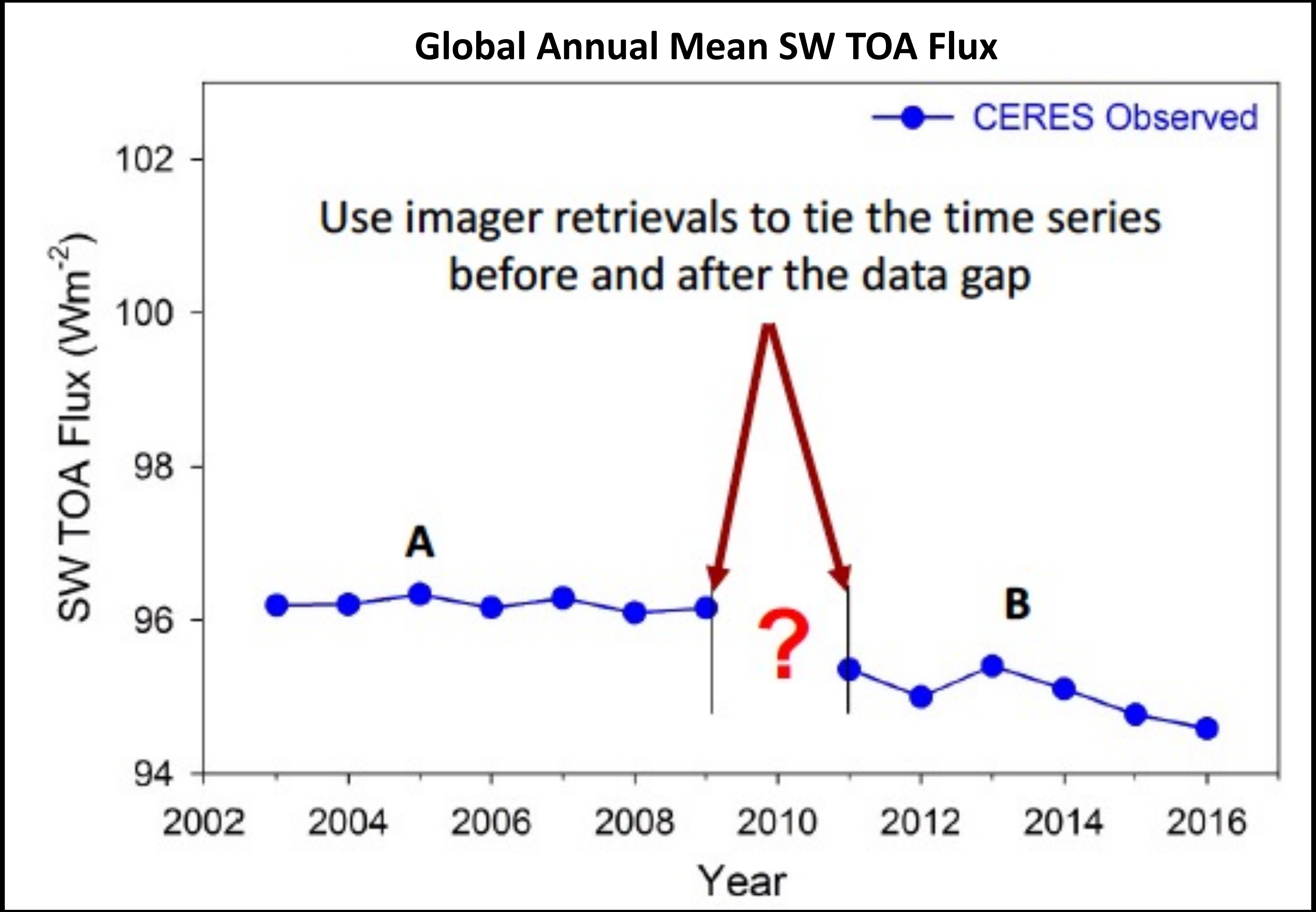
- Goal is to estimate of the probability that a data gap will occur in the Earth Radiation Budget climate data record given the ERB instrument flight schedule and historical spacecraft and instrument survival rates
- Period considered: present to 2032
- We assume that a mission terminates if either the ERB instrument, imager it flies with, or spacecraft fails.
- A further assumption is that an ERB instrument can bridge a data gap and maintain radiometric continuity of the ERB CDR even if its orbit drifts in mean local time (MLT) past its nominal mission requirement.



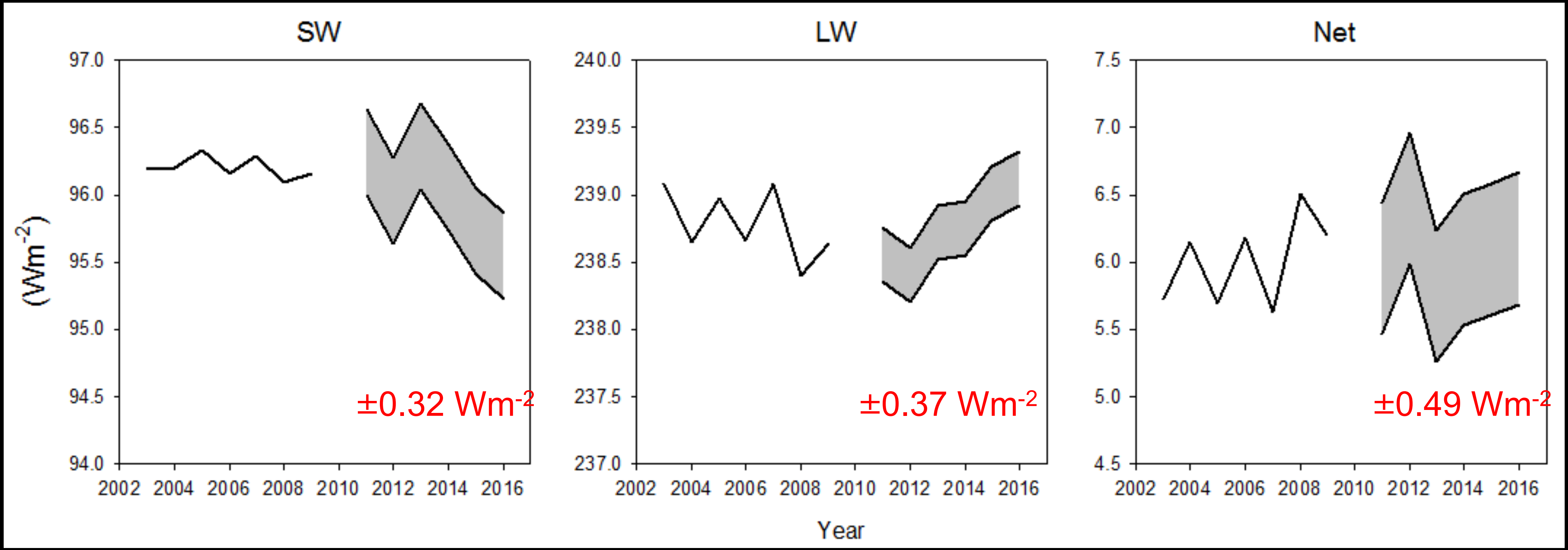
- Gap risk in 2025 exceeds 20% if SNPP ends in 2024 and TER & AQU end in 2023. Remains <5% if either SNPP ends in 2027 or TER & AQU end in 2026.
- Gap risk in 2026 reaches 27% if SNPP ends in 2024 but remains <10% if SNPP ends in 2027.
- Gap risk reaches 38% when Libera launches in 2028 for all scenarios.

Bridging a Data Gap in the ERB CDR

<u>Goal</u>: Examine the feasibility of using less-accurate imager retrievals to compute radiative fluxes and tie the time series before and after a data gap together.



Bridging a Data Gap in the ERB CDR



- Assumes imager remains healthy and perfectly stable across the data gap. The longer the gap, the greater the risk.
- The resulting uncertainty is too large to enable decade-to-decade changes in EEI to be resolved.
- Time to detect a real trend above uncertainty would increase substantially.
- A gap would require considerable extra post-processing effort, thereby delaying release of the ERB data products.

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.
- A tremendous amount of effort is needed to ensure a seamless long-term CDR across multiple satellite missions.
- A data gap significantly increases uncertainty for tracking decade-to-decade changes and long-term trends in ERB.
- Continuing existing missions (especially S-NPP) reduces the probability of a data gap.
- The gap risk when Libera launches in 2028 is 38%.
- An ERB follow-on mission after Libera has not been identified.