

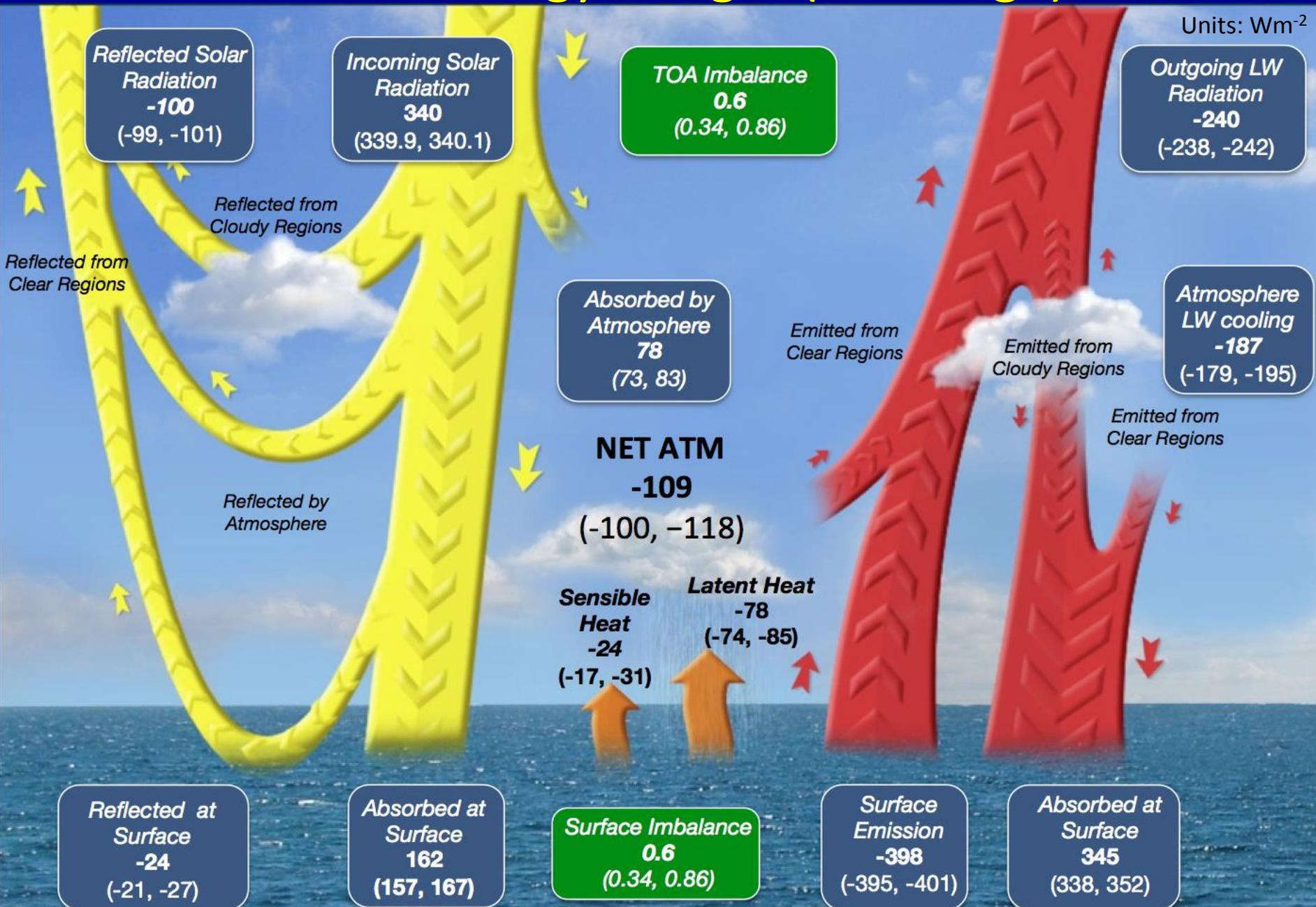
Earth's Radiation Imbalance Observed from Space

Norman G. Loeb

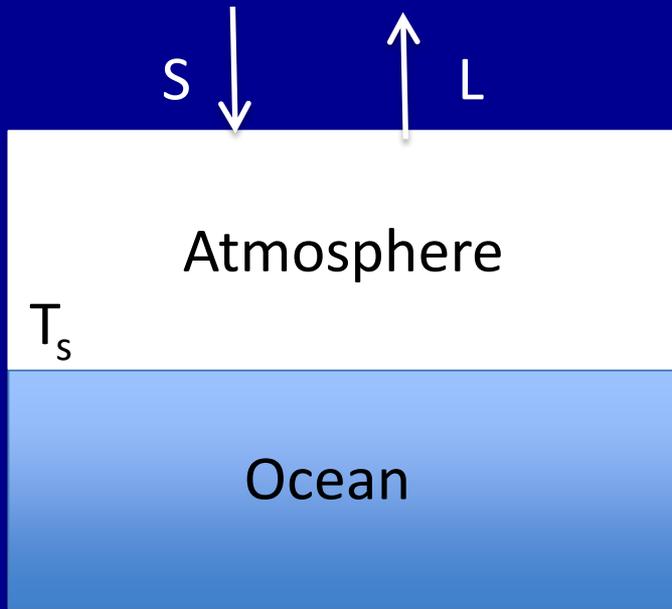
NASA Langley Research Center, Hampton, VA

Earth's Energy Budget (1 σ Range)

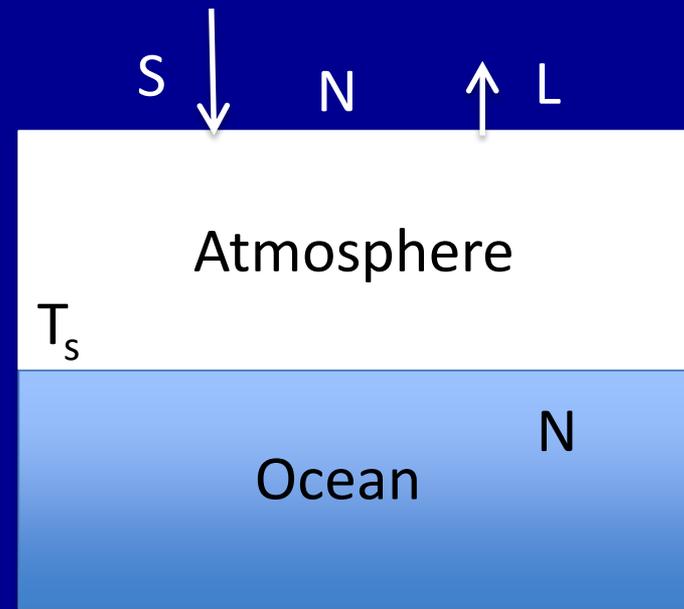
Units: Wm^{-2}



Temperature and Earth's Energy Imbalance



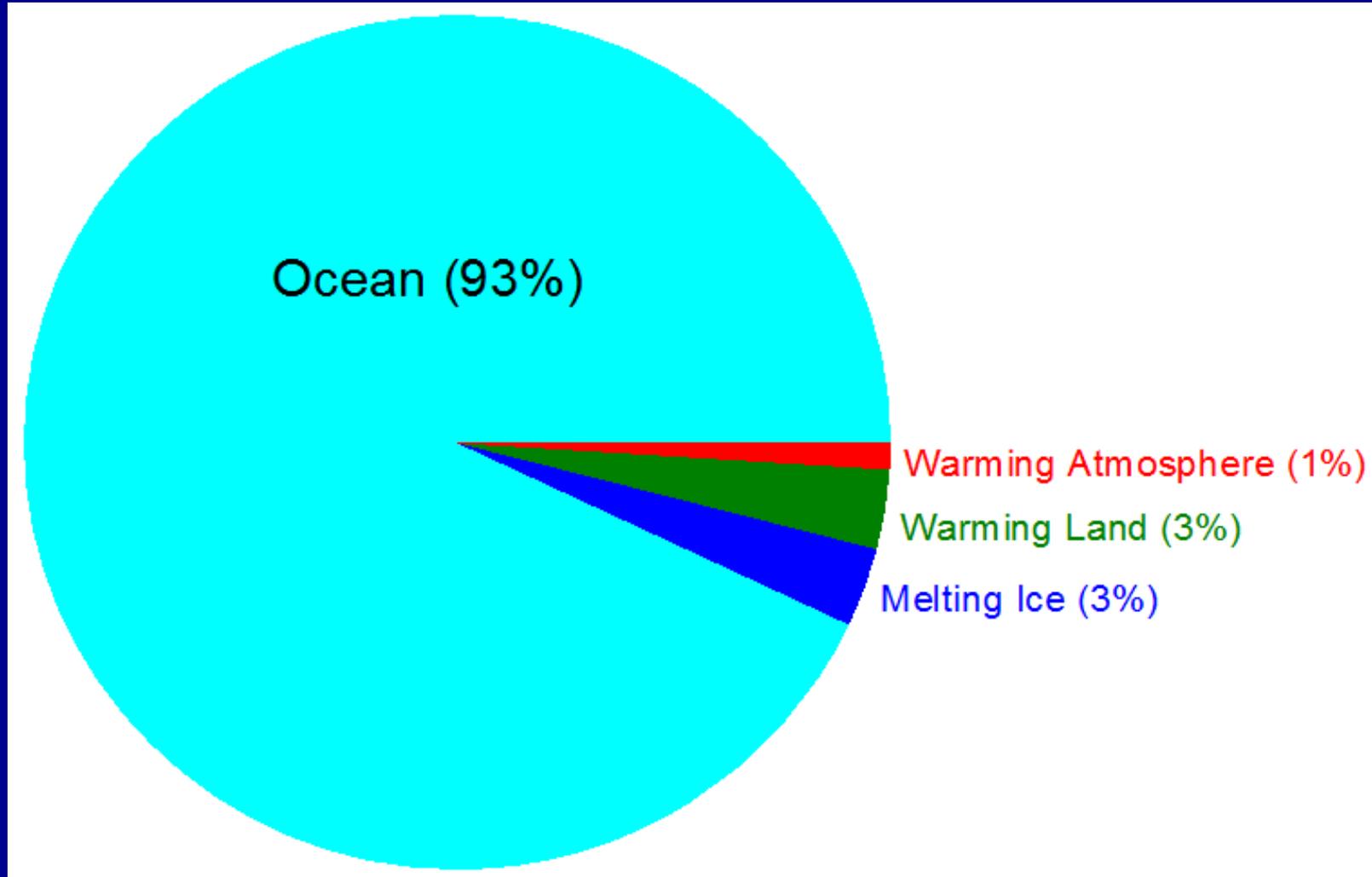
- No external forcing ($S=L$)
- T_s remains constant when averaged over a long time period.



- Imposed external forcing causes energy imbalance ($S \neq L$) at the top-of-atmosphere (TOA).
- 90% of the excess energy is stored in the ocean.
- Over long time period, T_s increases to offset energy imbalance.

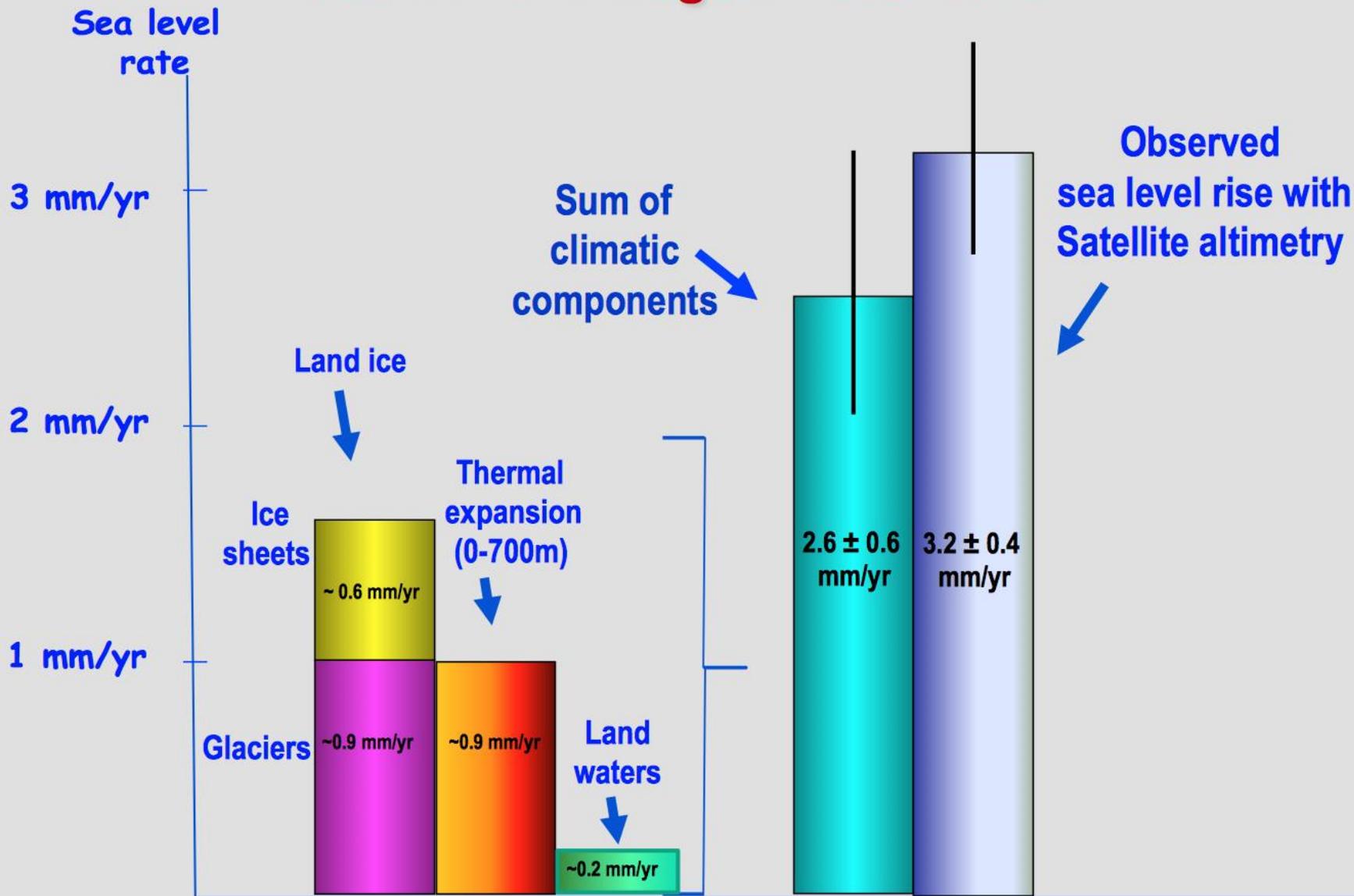
At timescales of up to a few decades, T_s can fluctuate naturally due to internal variability in the system, whether or not external forcings are applied.

Earth's Heat Budget



- Most of the excess heat in the climate system ends being stored in the ocean.
- Only 1% of the energy is used to change global mean surface temperature.

Sea Level Budget: 1993-2010

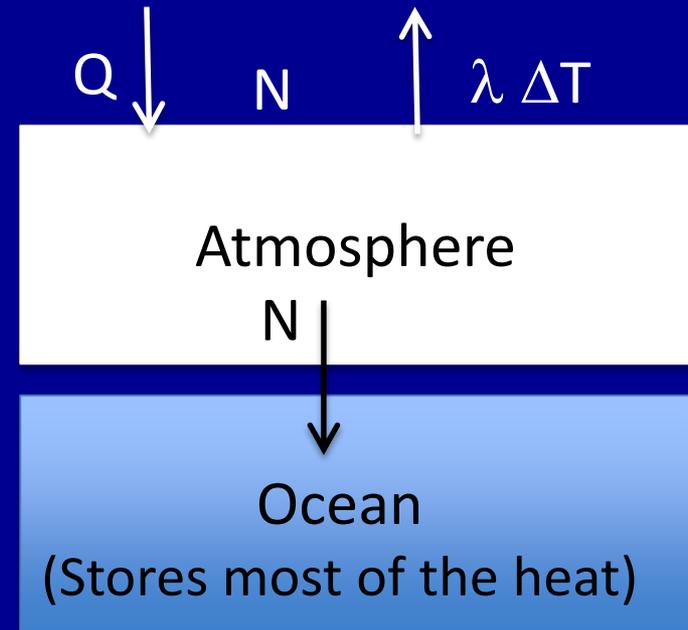


- 0.6 mm/yr discrepancy with SLR from satellite altimetry: Uncertainties + marginal seas and deep ocean warming.

Earth's Energy Imbalance, Climate Forcing, Climate Feedback

$$N = S_0/4 - (F^{SW} + F^{LW}) \approx Q - \lambda \Delta T + \varepsilon$$

- Earth's energy imbalance (N) provides a measure of the net climate forcing acting on Earth.
- If λ (climate feedback parameter) were known, the ratio N/λ would provide an estimate of the warming “in the pipeline”, even if climate forcings remain fixed at present-day levels.
- Uncertainty in λ responsible for spread in climate sensitivity amongst climate models: Global average surface warming following a doubling of CO_2 : 2°C to 4.5°C .
- Largest uncertainty in Q from aerosols (direct & indirect effects)



N = Earth Energy Imbalance (net heat flux into climate system)

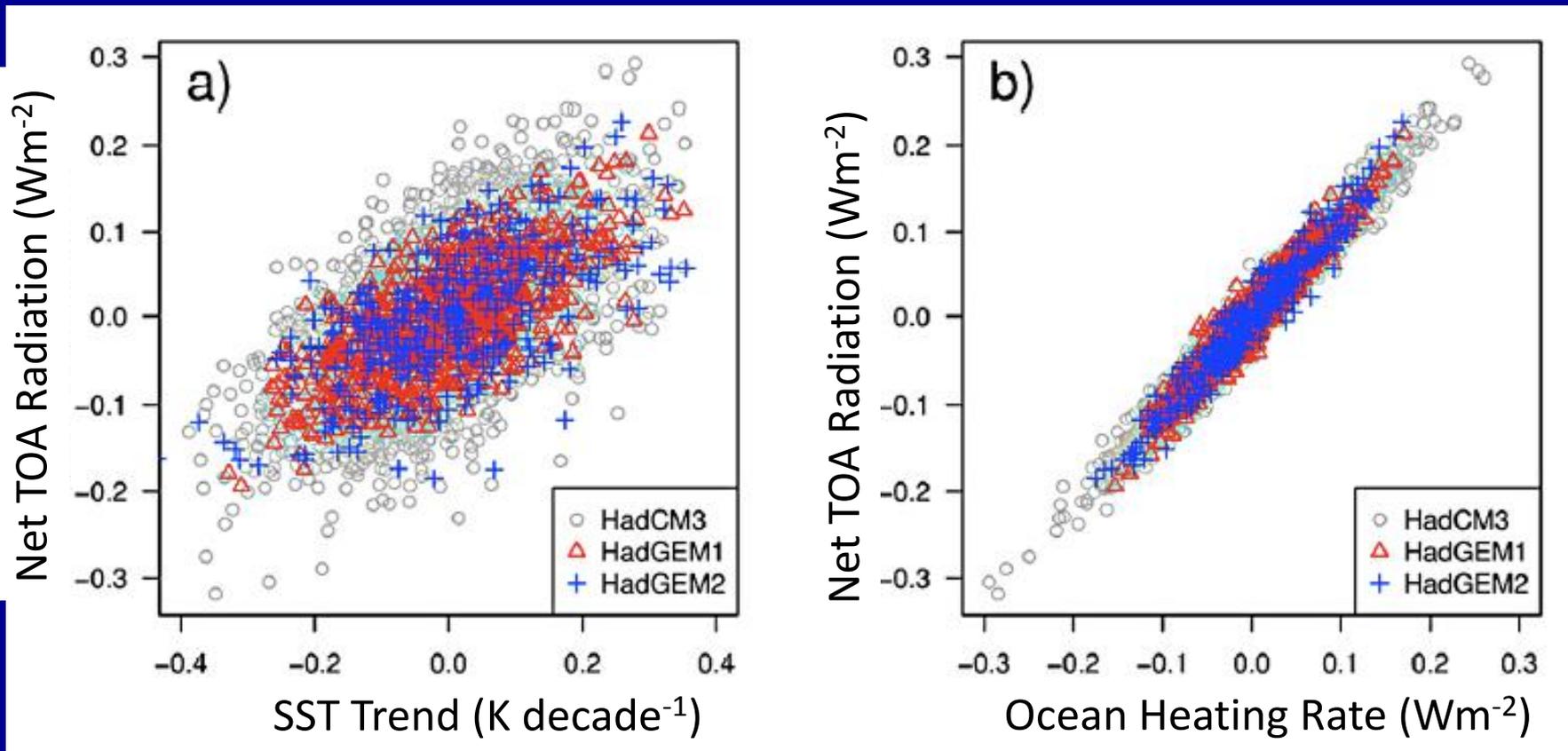
Q = Forcing (LLGHG, aerosols, sun)

ΔT = Temperature change

λ = Climate Feedback Parameter

ε = Internal variability of system not related to surface temperature.

Decadal Variations in Net TOA Radiation, SST Trend and Ocean Heating Rate



- Control run data from multi-century Met Office Hadley Centre coupled climate model simulations.
- Approximately 30% of decades show a trend in net TOA radiation and SST that are of opposite sign.
- Ocean re-distribution of heat is the primary reason for the larger scatter between SST and total energy.

Earth's Energy Imbalance

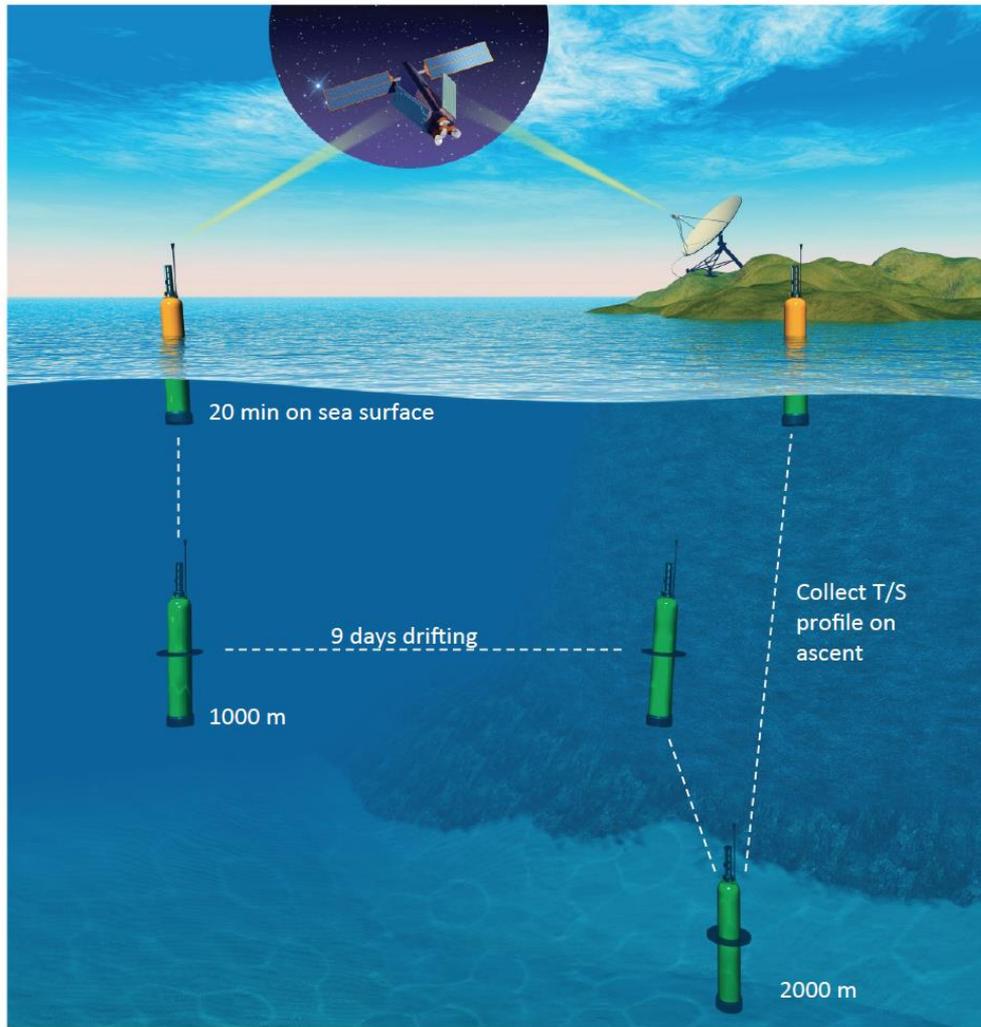
- Short-term variability:
 - ENSO-related changes in atmospheric and oceanic circulations
 - Clouds
 - Aerosols (including volcanic eruptions)
 - Surface properties.
- Longer-term variability:
 - Anthropogenic forcing due to greenhouse gases and aerosols
 - Natural forcing by aerosols and solar radiation
 - Feedbacks involving water vapor, temperature, clouds, and the surface.

Tracking Earth's Energy

Observing Ocean Heat Uptake

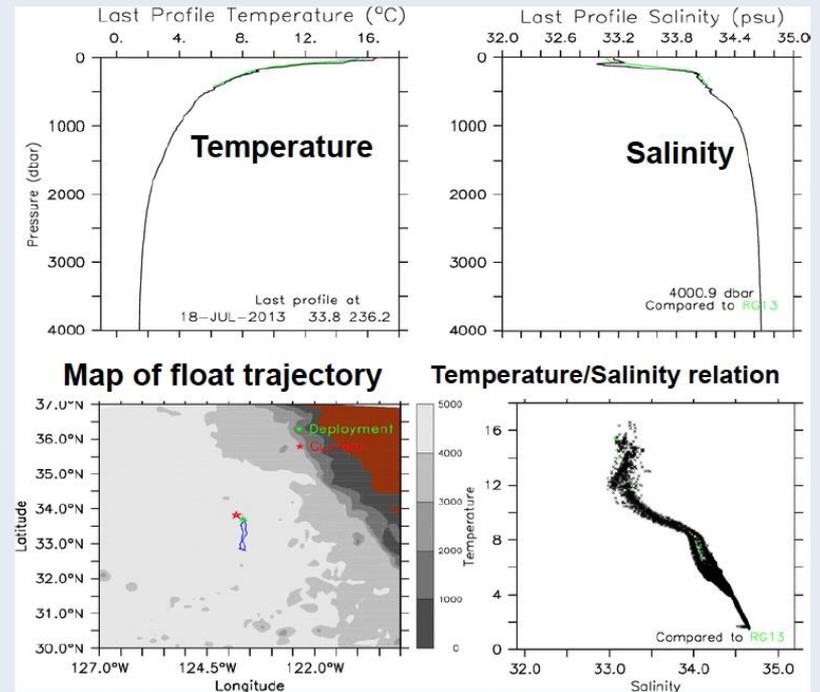
How do Argo floats work?

Argo floats collect a temperature and salinity profile and a trajectory every 10 days, with data returned by satellite and made available within 24 hours via the GTS and internet (<http://www.argo.net>).

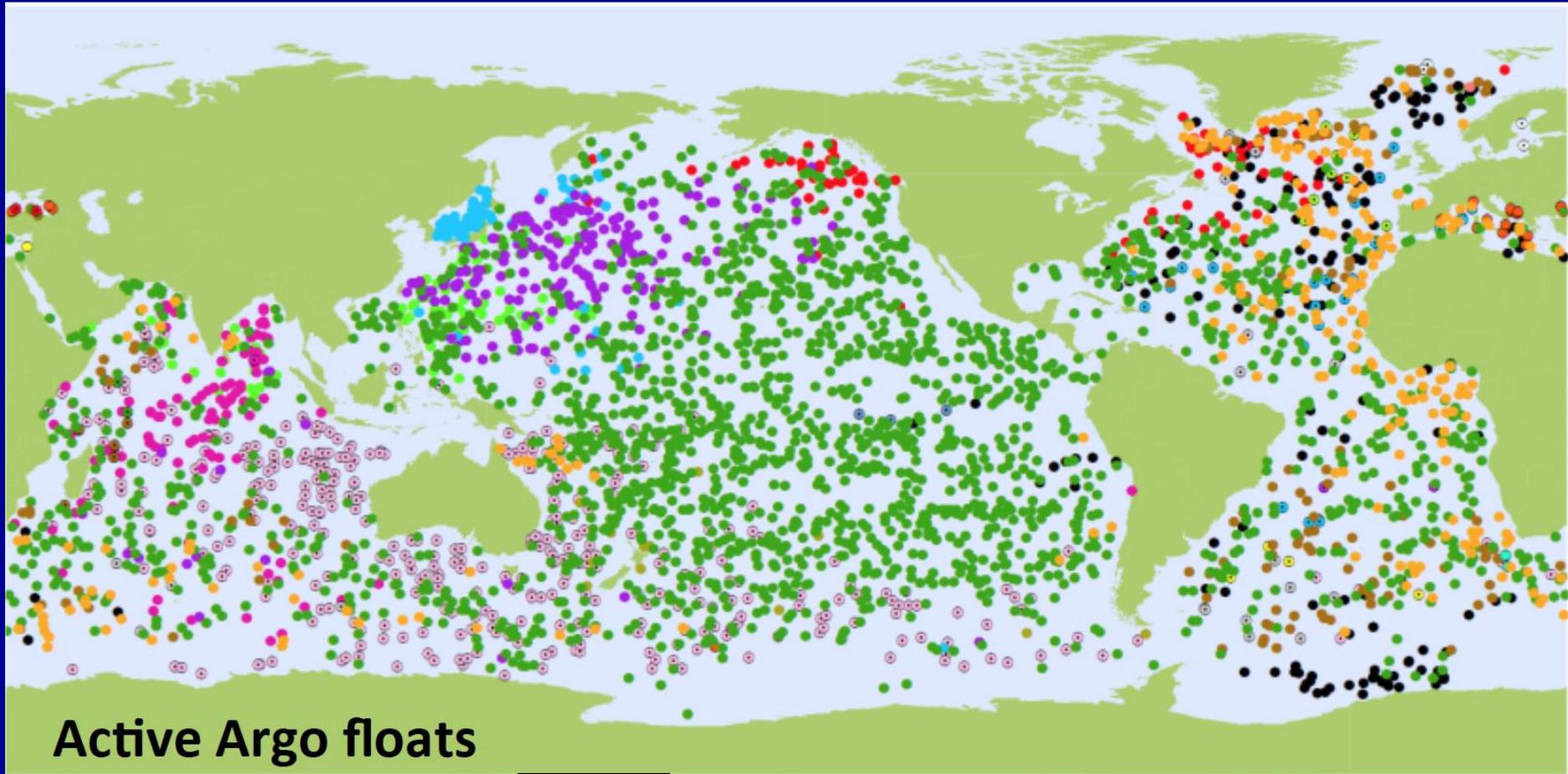


Cost of an Argo T,S profile is ~ \$170.

Typical cost of a shipboard CTD profile ~\$10,000.



Argo Float Regional Distribution



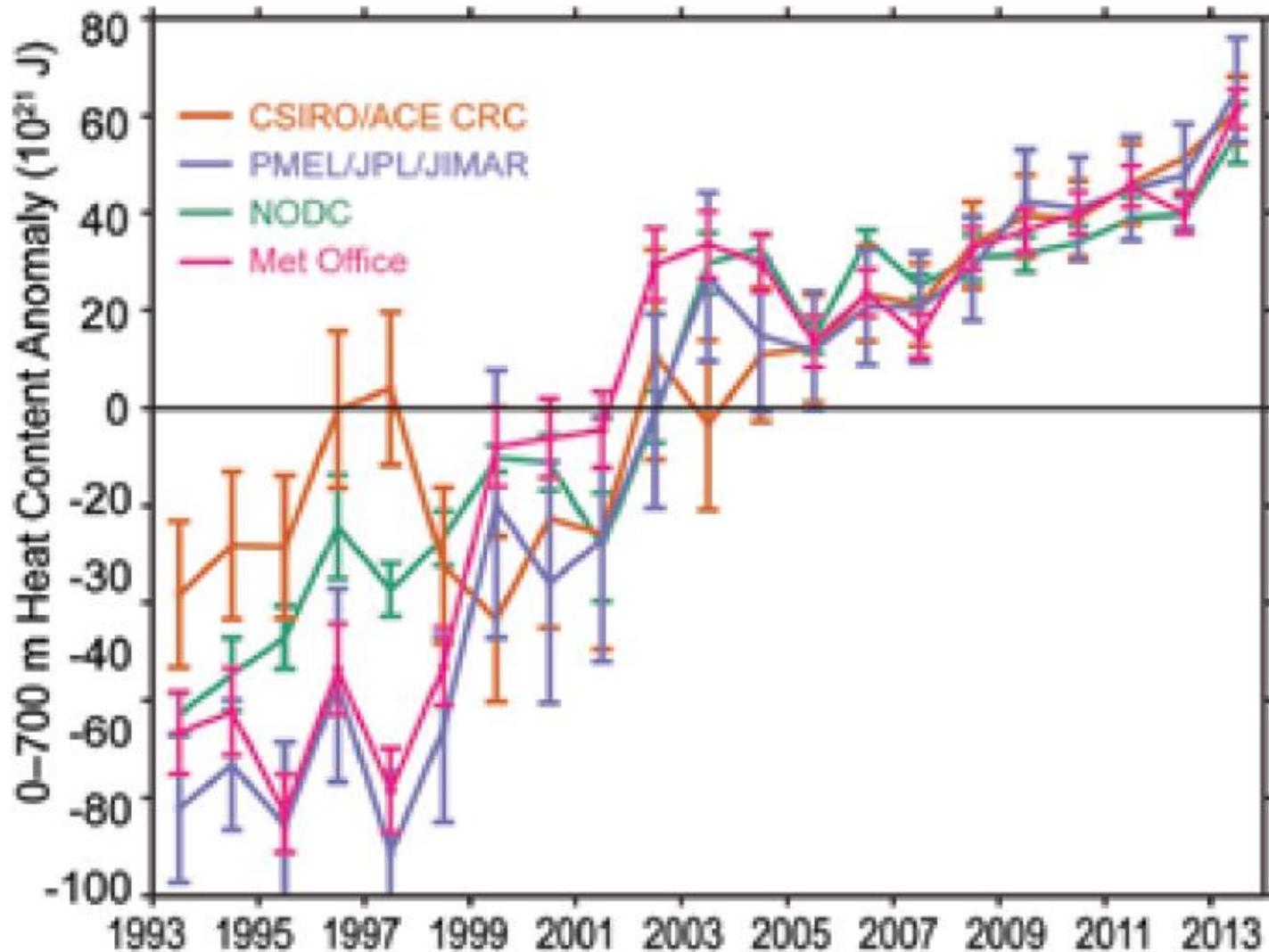
Active Argo floats

3606 Floats

ARGENTINA (4)	CANADA (83)	FRANCE (256)	IRELAND (10)	SOUTH KOREA (86)	NEW ZEALAND (12)	SRI LANKA (1)
AUSTRALIA (389)	CHINA (85)	GABON (1)	ITALY (19)	LEBANON (1)	NORWAY (2)	TURKEY (2)
BRAZIL (2)	ECUADOR (3)	GERMANY (166)	JAPAN (208)	MAURITIUS (6)	SOUTH AFRICA (2)	UNITED KINGDOM (132)
BULGARIA (3)	FINLAND (5)	INDIA (103)	KENYA (3)	NETHERLANDS (20)	SPAIN (29)	UNITED STATES (1 973)

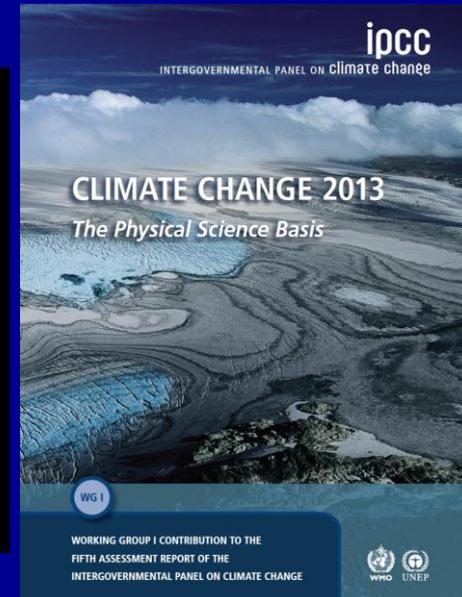
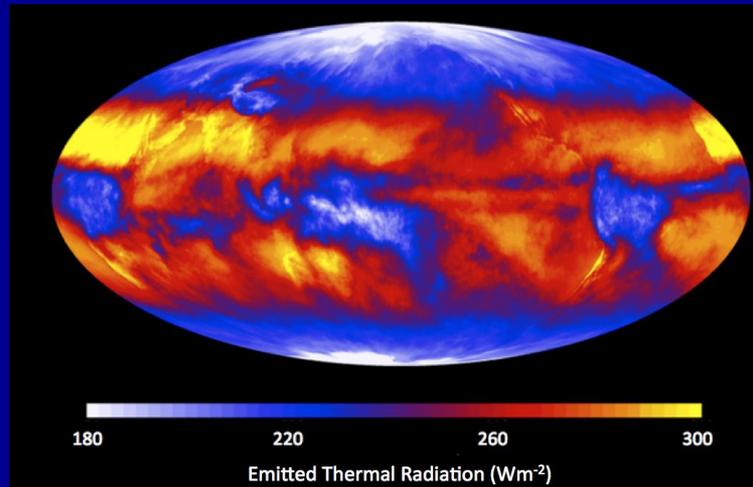
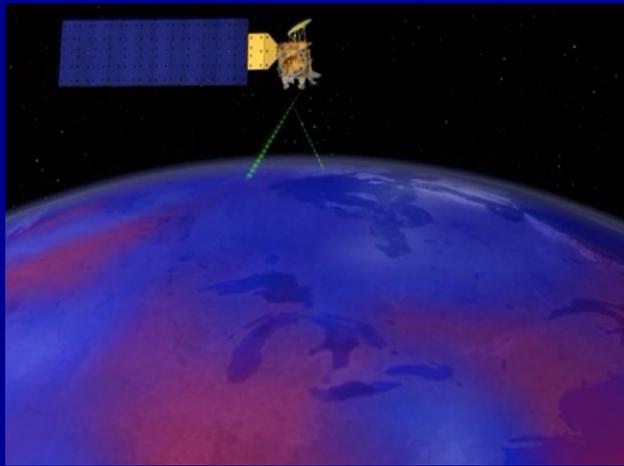
September 2013

Change in global average upper ocean heat content (0-700 m)



The globally averaged rate of upper ocean (0-700 m) heat gain for 1993-2013 is (Wm^{-2}): **0.29** (± 0.12) CSIRO/ACE CRC, **0.48** (± 0.13) PMEL/JPL/JIMAR, **0.34** (± 0.09) NODC, and **0.42** (± 0.25) UK Met Office.

CERES Objectives



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

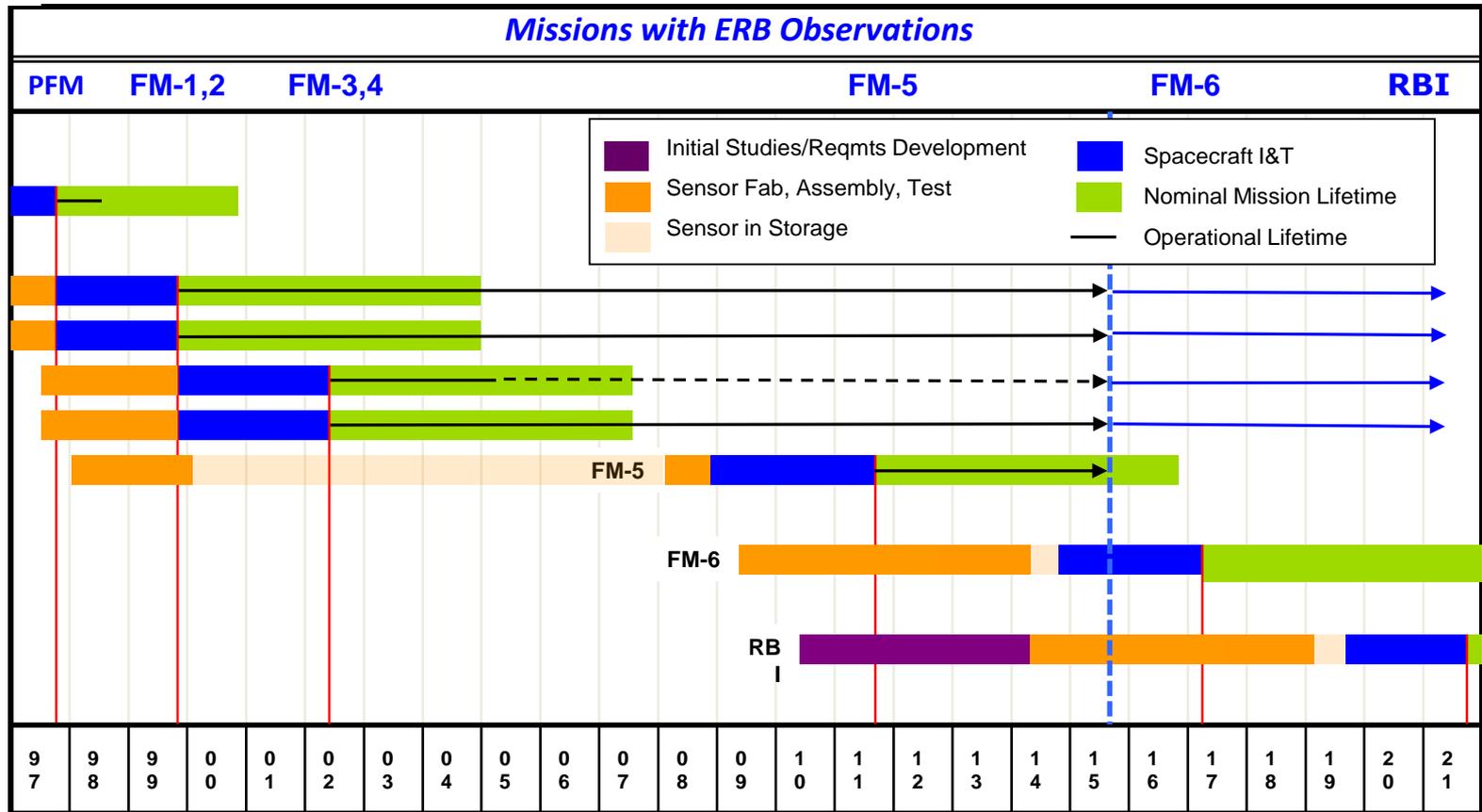
CERES Instruments

- 6 instruments on 4 satellites (TRMM, Terra, Aqua, SNPP) for diurnal and angular sampling.
- FM6 to be flown on JPSS-1. RBI on JPSS-2.
- Narrow field-of-view scanning radiometer with nadir footprint size of 10 km (TRMM); 20 km (Terra, Aqua, SNPP, JPSS-1).
- 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.



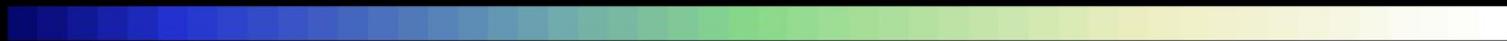
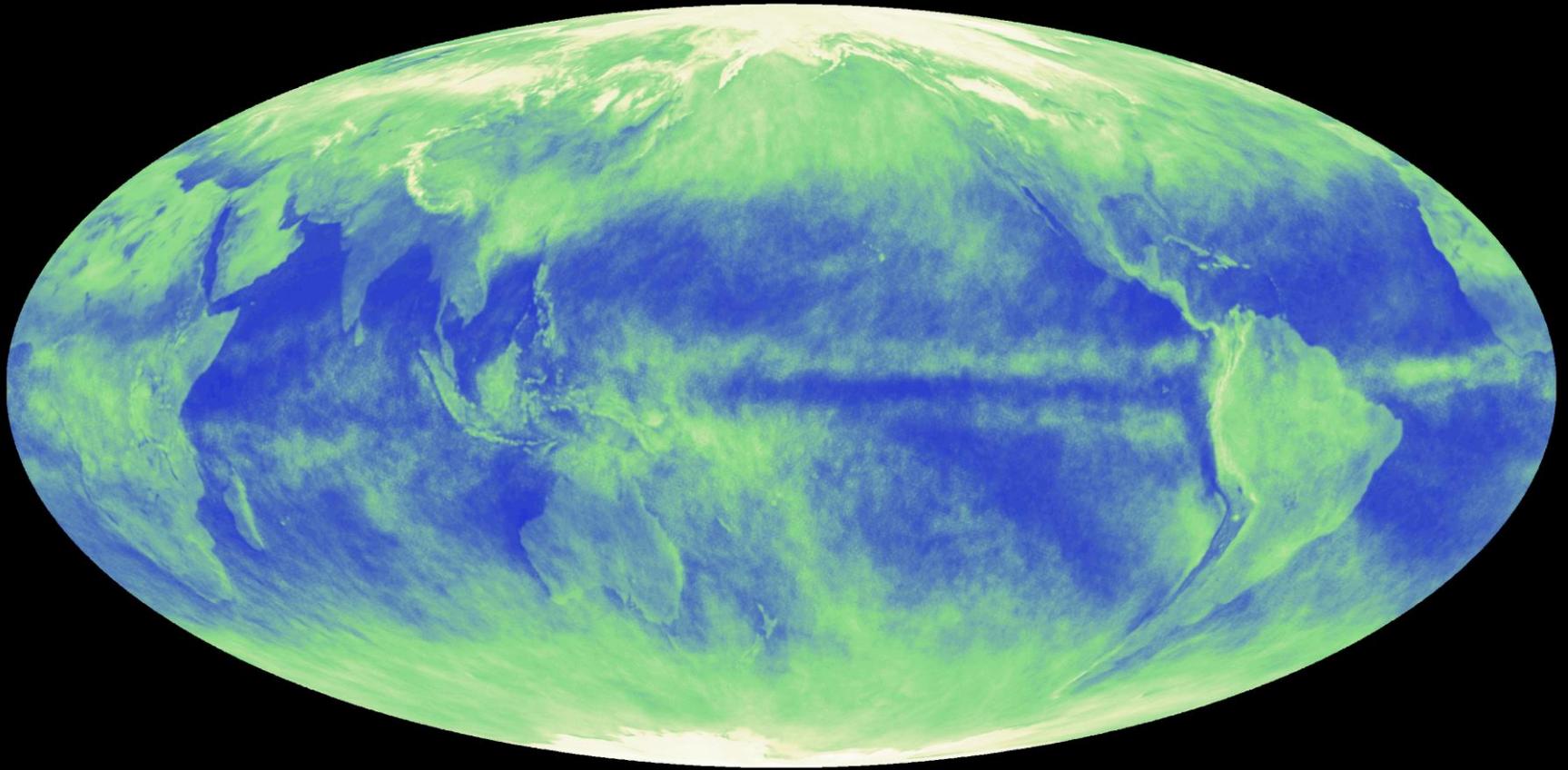


CERES & RBI Flight Schedules



- Currently, 5 CERES instruments fly on 3 satellites: Terra (L1999), Aqua (L2002) and SNPP(L2011).
- CERES FM6 will fly on JPSS-1 in FY17 (2nd Qtr). The CERES follow-on instrument (Radiation Budget Instrument, or RBI) will fly on JPSS-2 in FY21 (4th Qtr).

Planetary Albedo from CERES (March 2013)



0
0.75

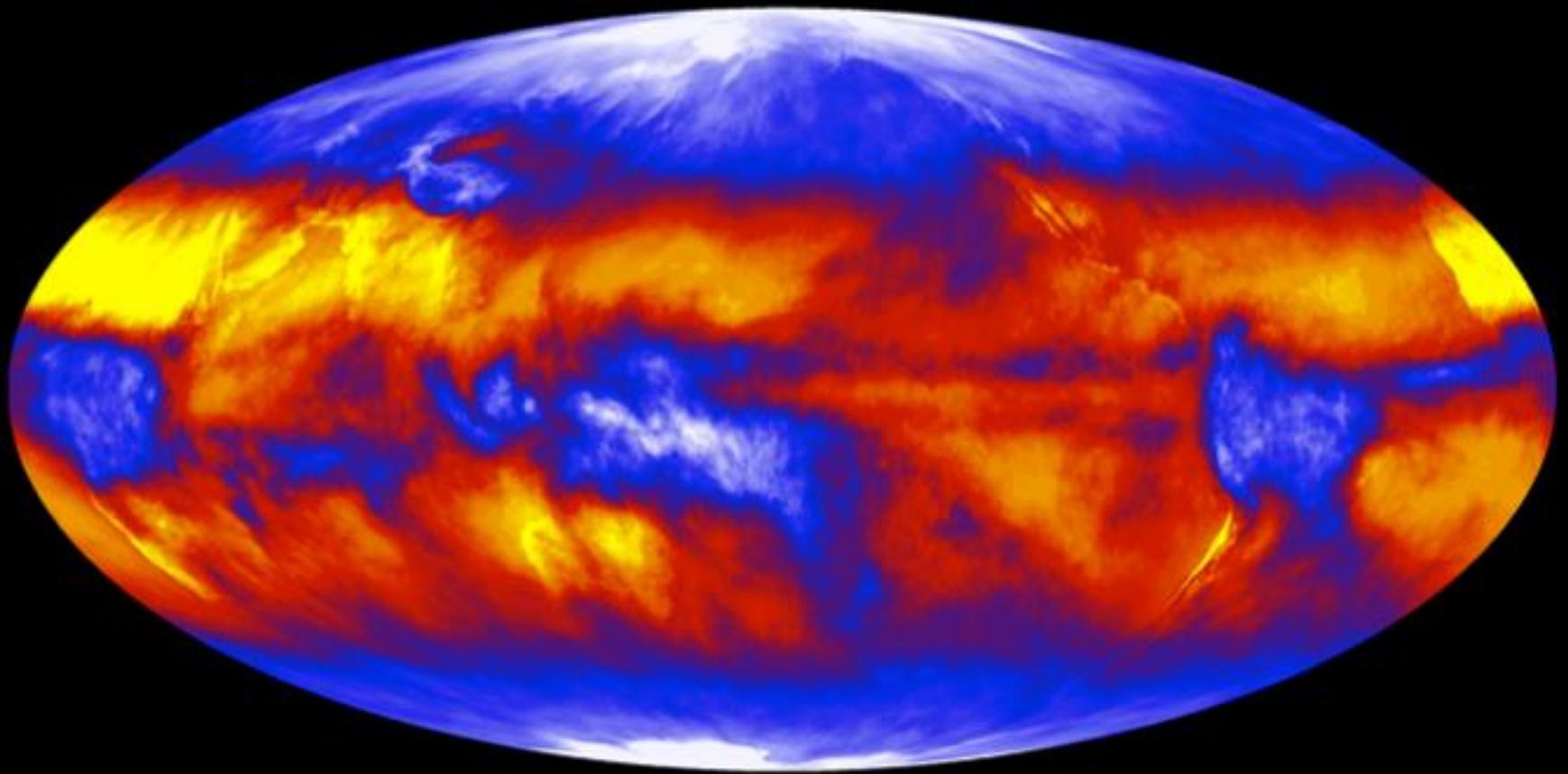
0.188

0.375

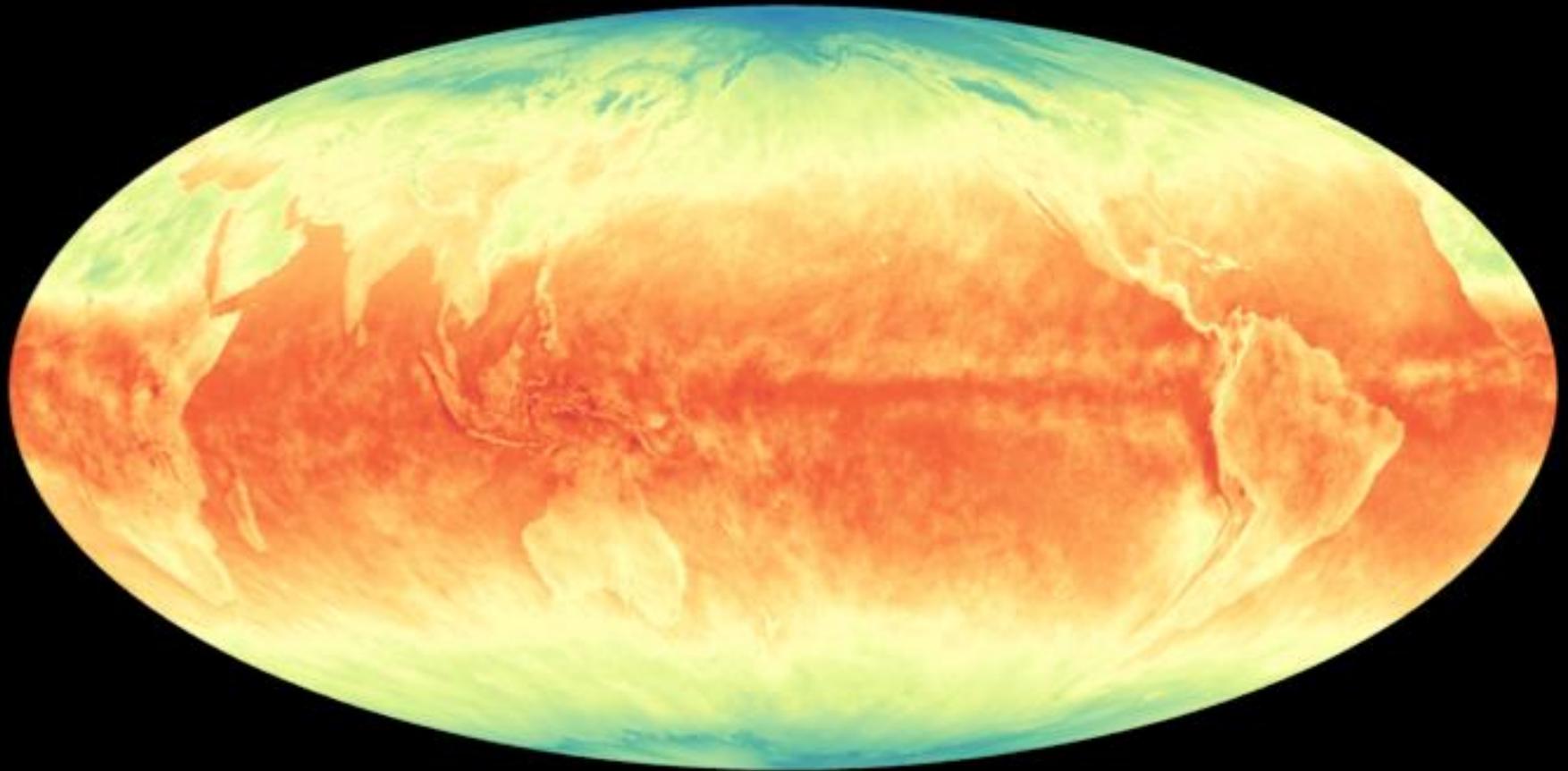
0.563

Albedo

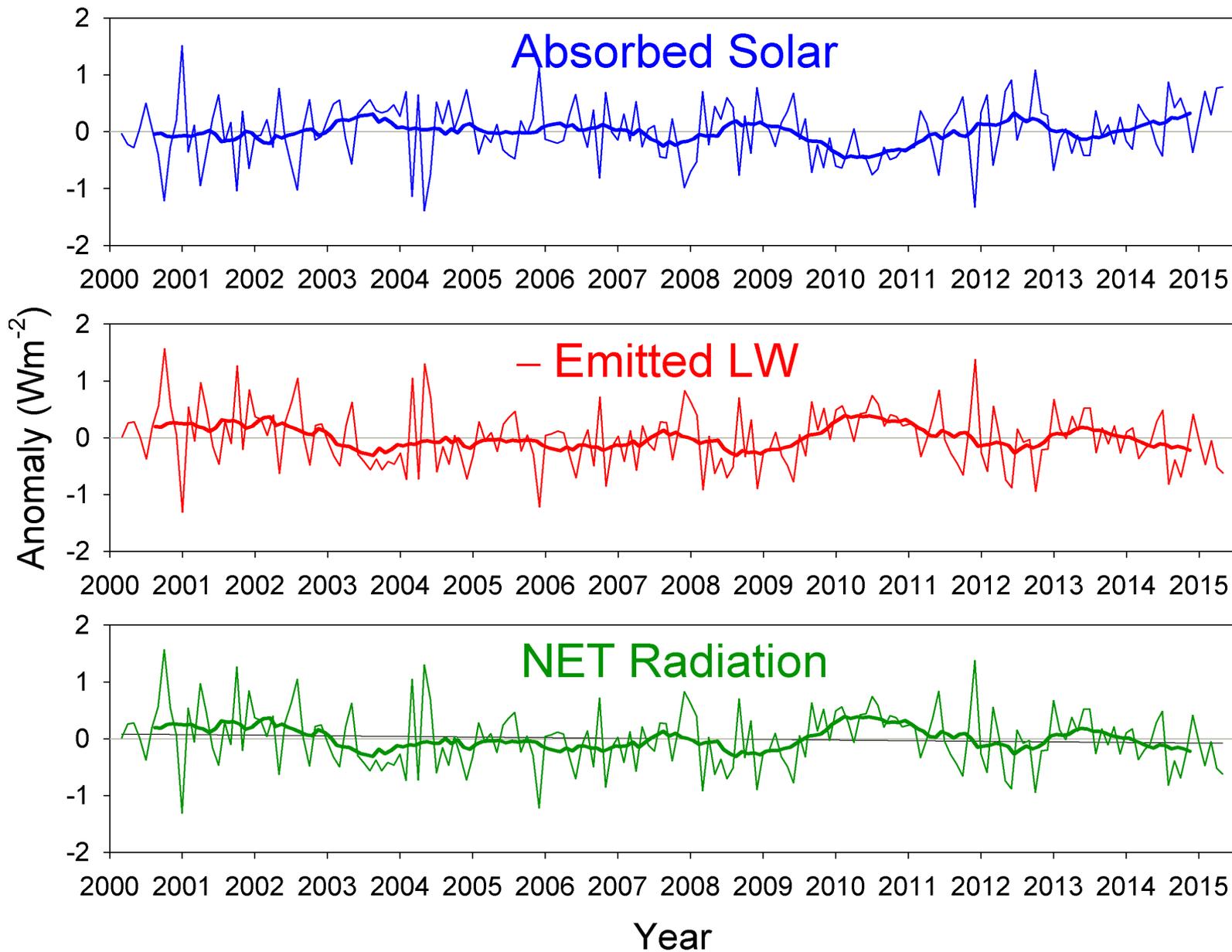
Emitted Thermal Radiation (March 2013)



Net TOA Radiation (March 2013)

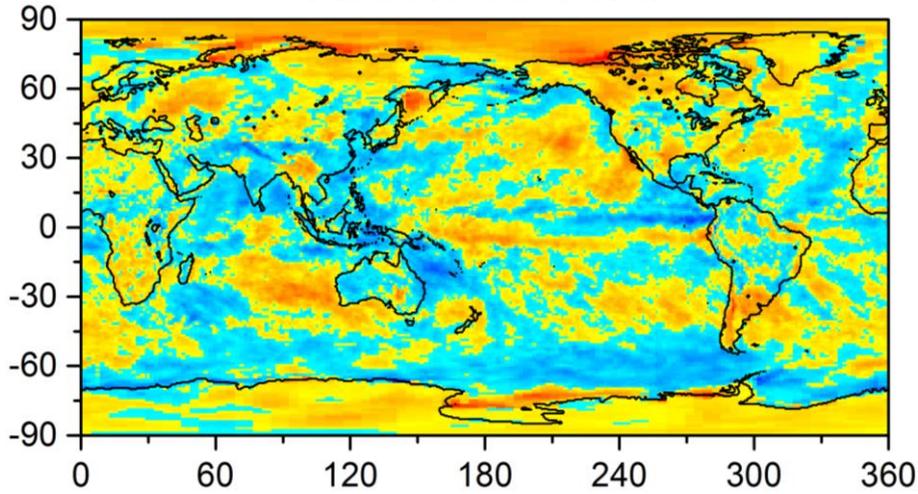


Global TOA All-Sky Radiation Anomalies (CERES_EBAF_Ed2.8; 03/2000 – 05/2015)

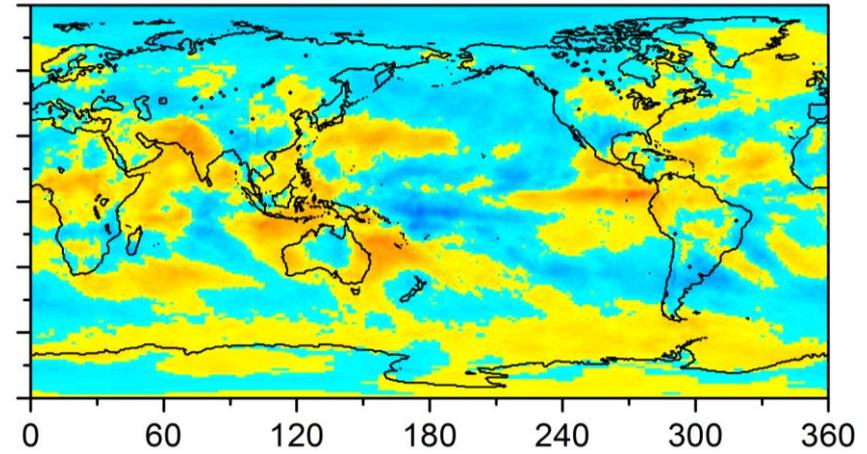


TOA Radiation Changes (March 2000 – May 2015)

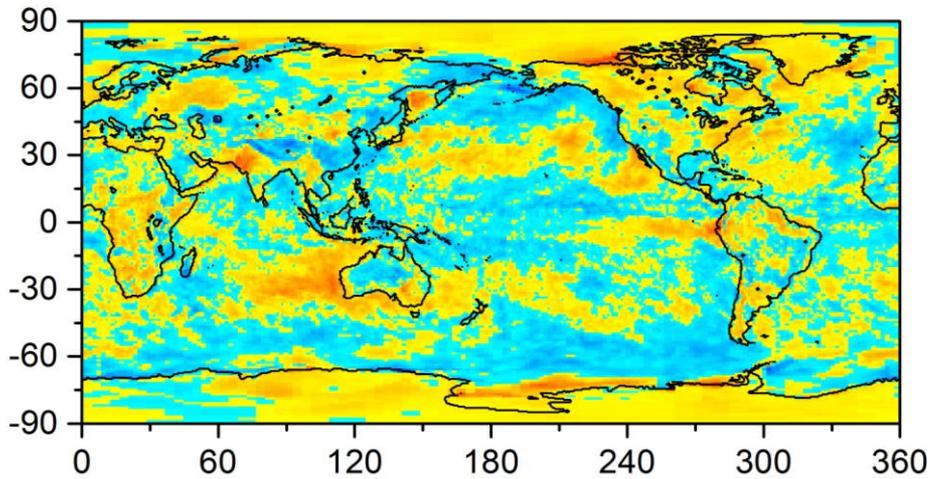
Absorbed Solar



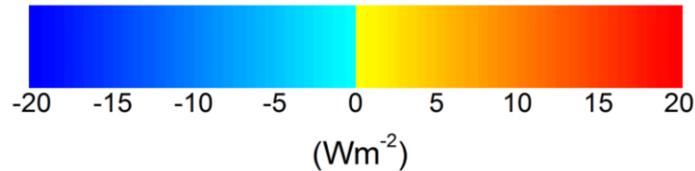
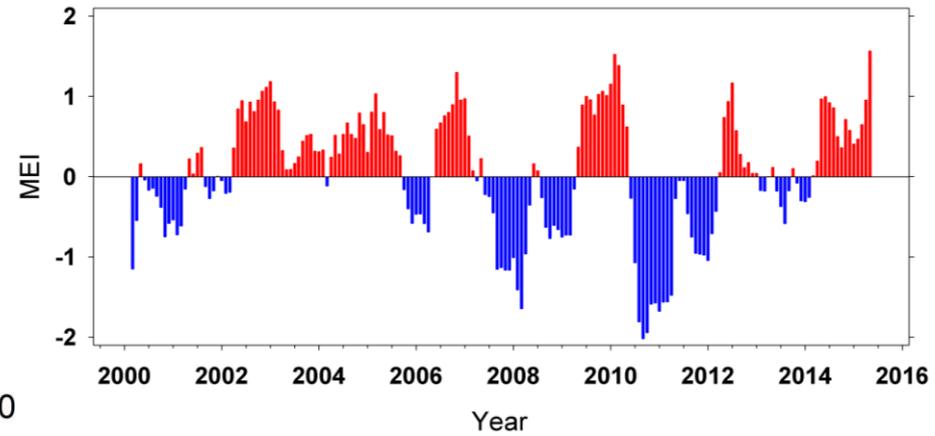
-Emitted LW



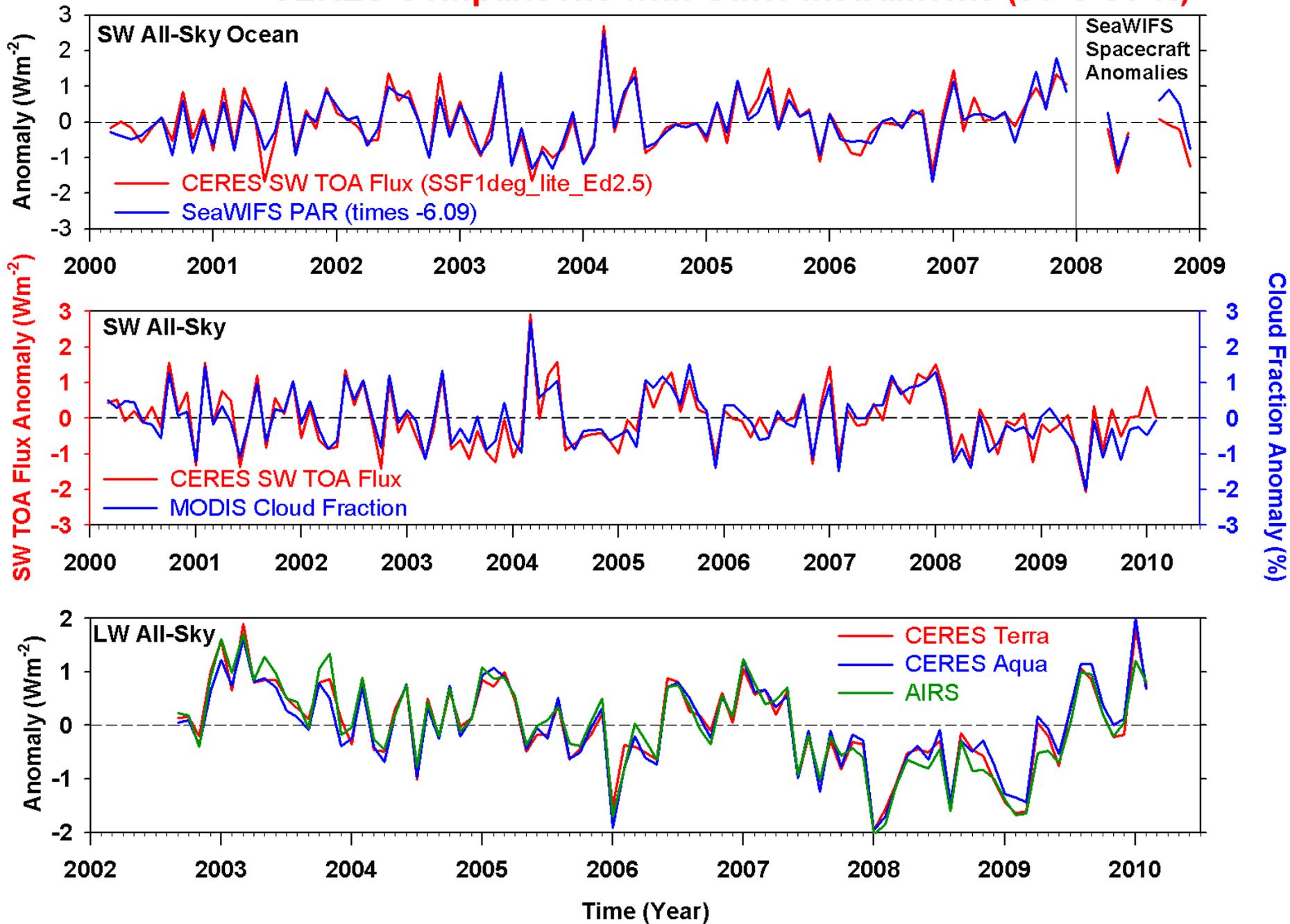
Net Radiation



Multivariate ENSO Index



CERES Comparisons with Other Instruments (30°S-30°N)



Net Radiation from Satellite Instruments

- Requires measuring incoming solar radiation (S_0), reflected solar radiation (F^{SW}) and outgoing longwave radiation (F^{LW}).
- Incoming and total outgoing radiation are $\approx 340 \text{ Wm}^{-2}$, while net imbalance is of order 0.5 Wm^{-2} , or **0.15%** of the incoming/total outgoing radiation.
- Constraining N to 50% of its mean, or 0.25 Wm^{-2} , is incredibly challenging: absolute uncertainty in S_0 alone is 0.13 Wm^{-2}
 $\Rightarrow (F^{SW} + F^{LW})$ needs to be known to 0.2 Wm^{-2} or 0.06% of the incoming/total outgoing radiation.
- Satellite instruments provide excellent spatial and temporal sampling, but thus far have yet to achieve this level of accuracy.
- Satellite instruments are more radiometrically stable than they are absolutely accurate.
 \Rightarrow Satellites are better suited for tracking short-term (interannual) variations in net radiation than determining the absolute value.

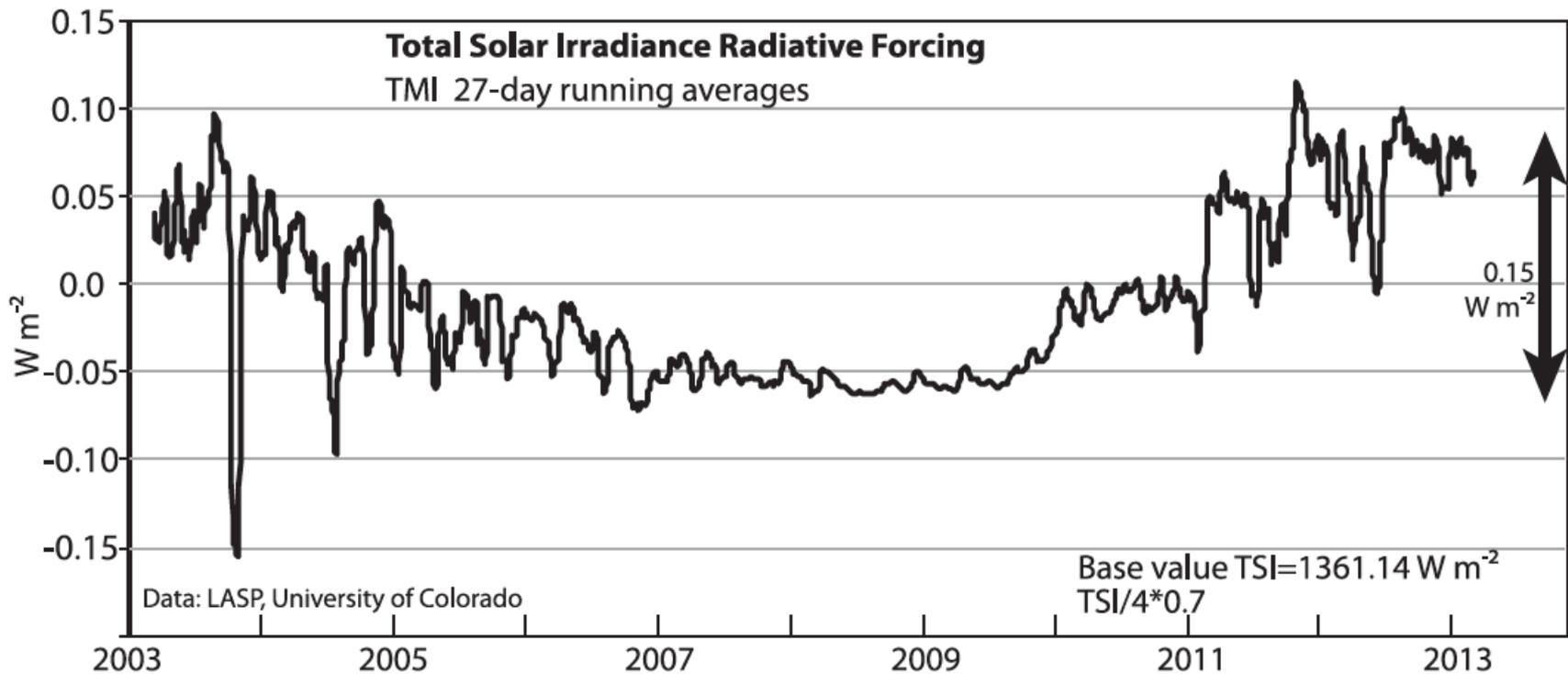
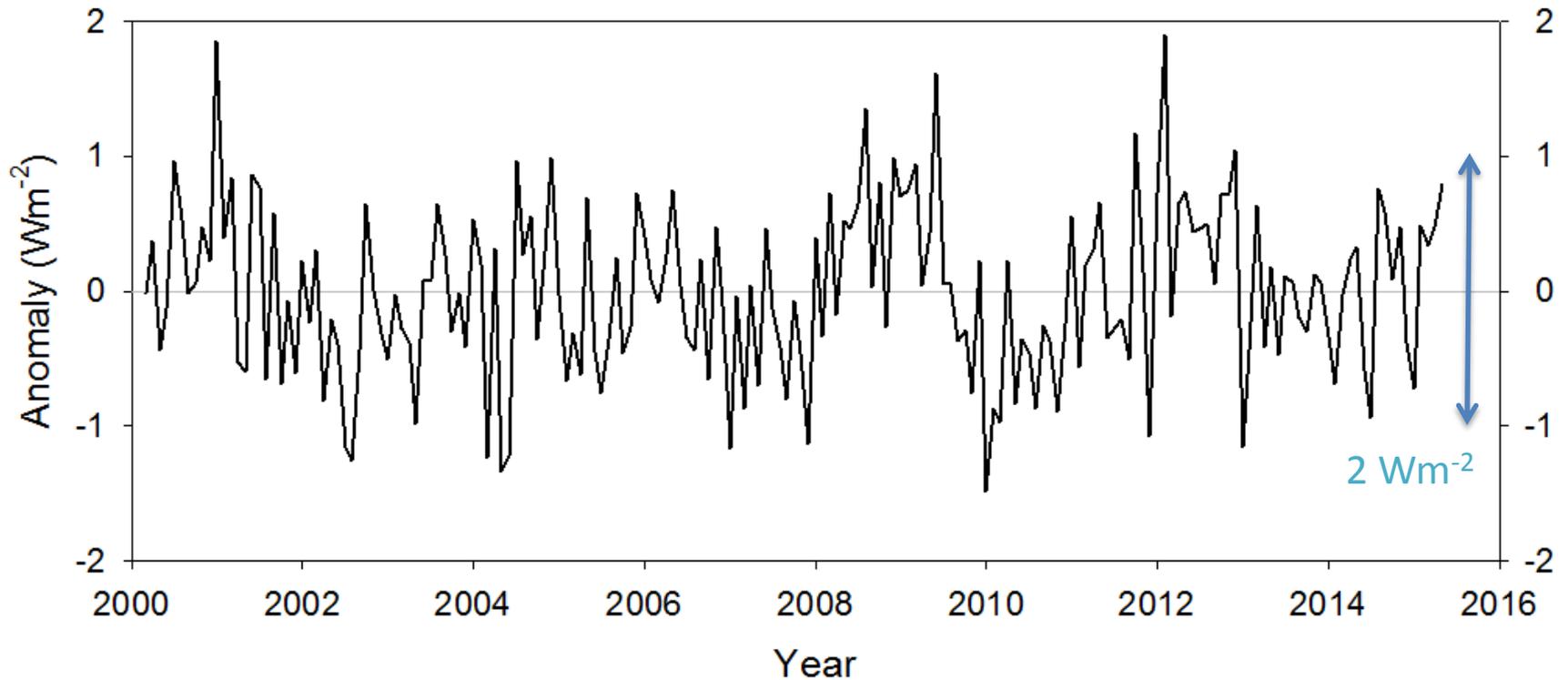


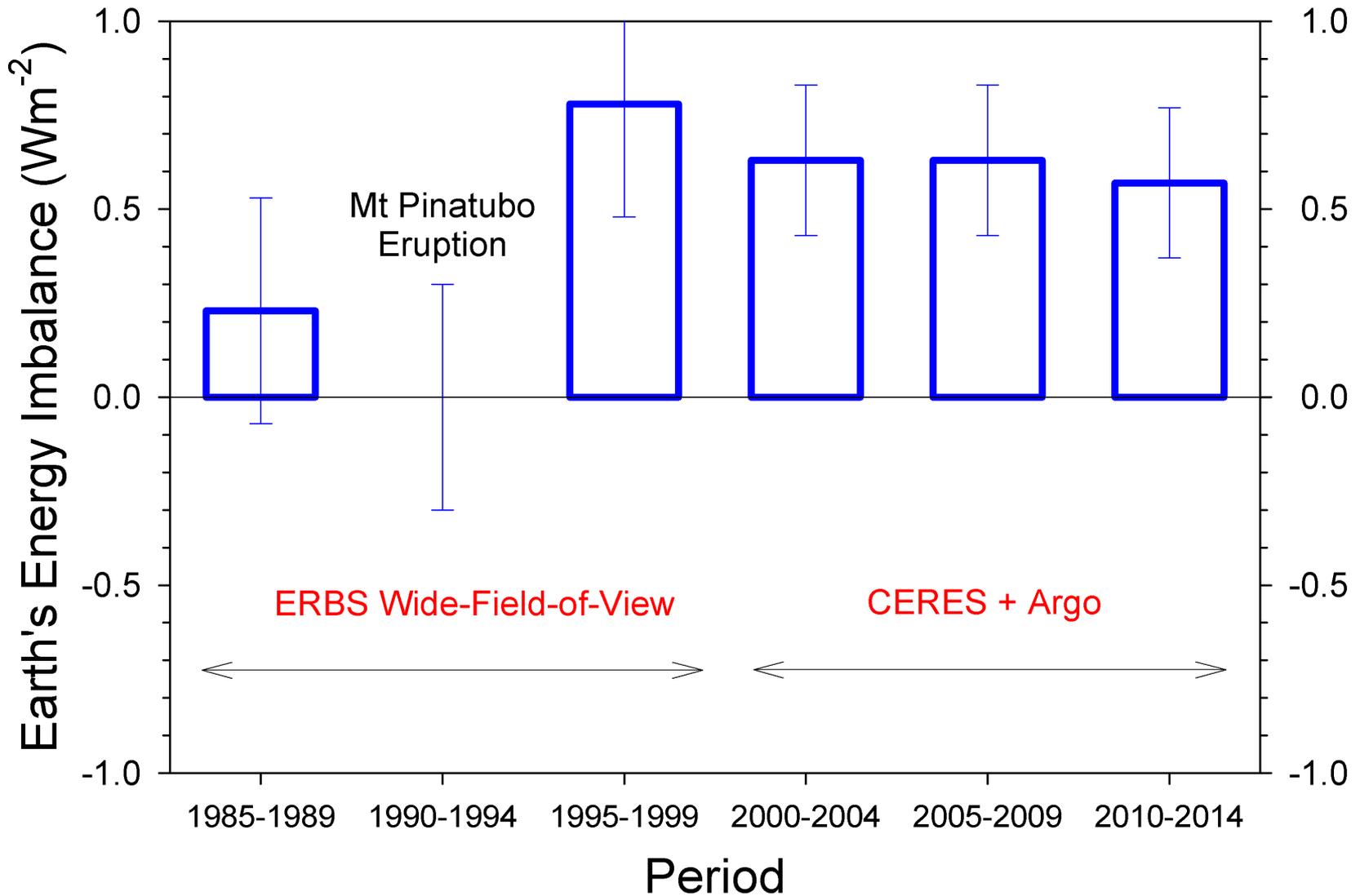
FIG. 2. Radiative forcing (W m^{-2}) from changes in total solar irradiance from the TIM instrument relative to a base value of TSI of 1361.14 W m^{-2} as 27-day running averages. The double arrow at right shows the range of 0.15 W m^{-2} .

Global TOA Net Flux Anomaly (CERES EBAF Ed2.8; 03/2000-05/2015)



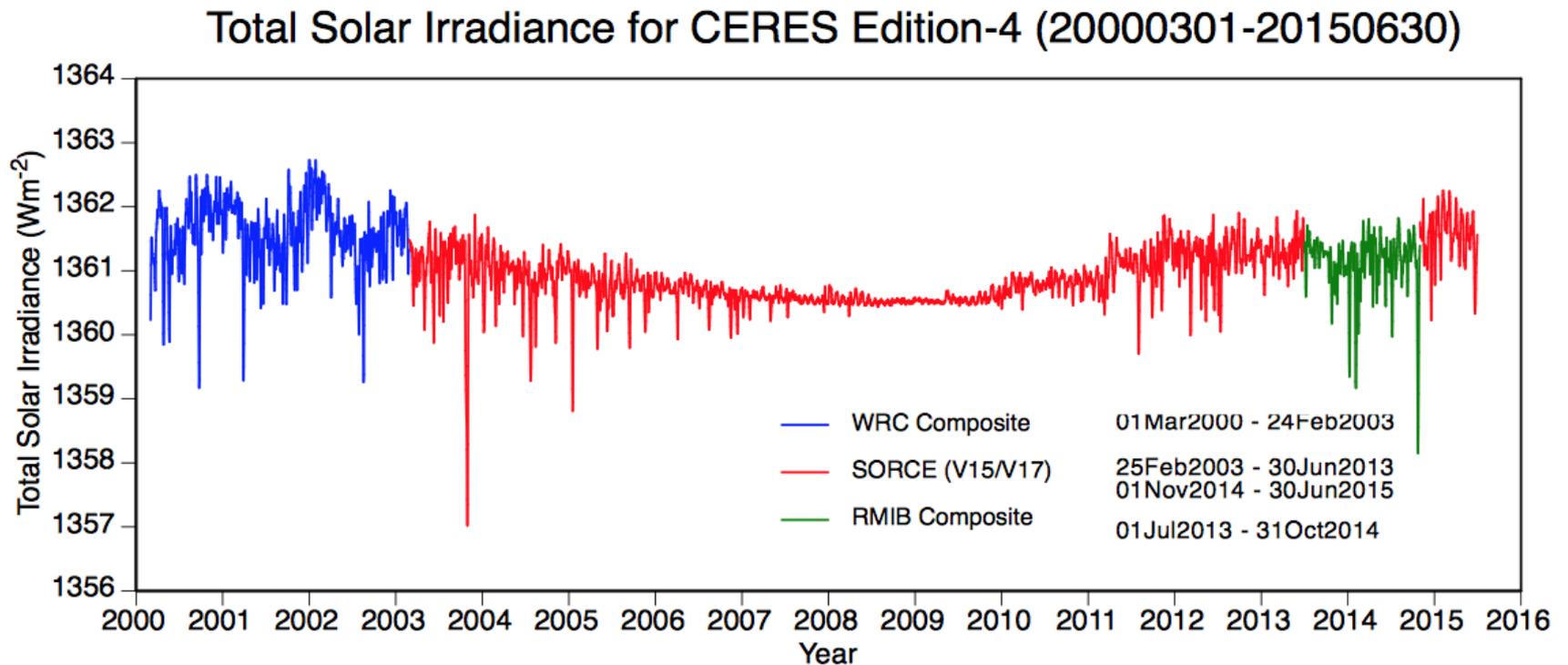
- The global mean net downward radiation exhibits substantial internal variability mainly associated with ENSO.

Satellite & Argo Based Changes in Earth's Energy Imbalance



- The planet's EEI imbalance has been fairly stable since 1995.

TSI composite data from WRC, SORCE(V15) and RMIB for the Timeframe of CERES Terra, Aqua & NPP



For CERES Ed4, all TSI data are offset to match SORCE TSI Version 15

Conclusions

- EEI is a fundamental metric defining the status of global climate change.
 - => EEI is in many ways a more basic measure of the climate system than global mean surface temperature.
- Tracking and understanding EEI and where the energy added ends up is essential to improving seasonal-to-decadal climate predictions and projections on longer timescales.
- There is a much better understanding of EEI thanks to new satellite data (CERES, SORCE) and network of ocean in-situ measurements (Argo).
- Still more work to be done both on the analysis side and in-situ measurements (e.g., deep ocean coverage, marginal seas, high latitudes).