Continuity of Earth Radiation Budget Measurements from Space

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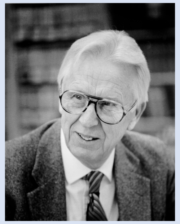
Bruce Wielicki, and Norman Loeb

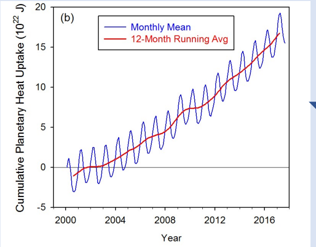
Continuity of ERB Measurements from Space

Commencement Thoughts

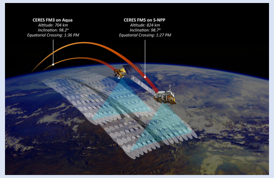


In the Beginning

Future Approaches

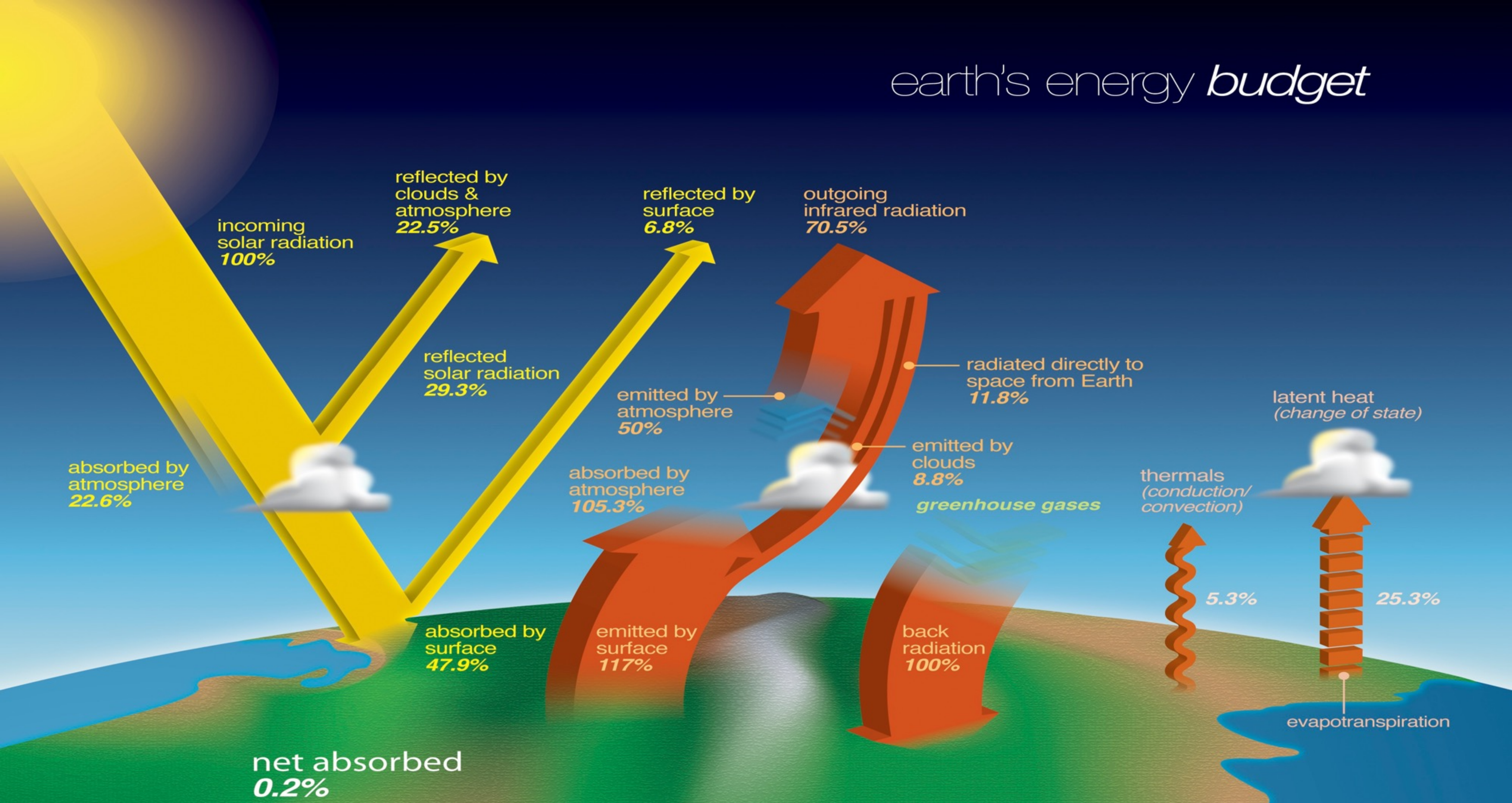


Need for ERB Continuity



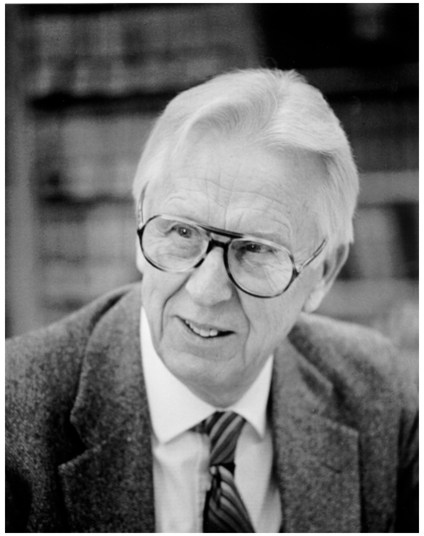
Scientific and Societal Impact

Path to Achieve Continuity


earth's energy budget
incoming solar radiation 100%
reflected by clouds & atmosphere 22.5%
reflected by surface 6.8%
outgoing infrared radiation 70.5%
reflected solar radiation 29.3%
radiated directly to space from Earth 11.8%
emitted by atmosphere 50%
latent heat (change of state)
emitted by clouds 8.8%
absorbed by atmosphere 22.6%
absorbed by atmosphere 105.3%
thermals (conduction/ convection)
greenhouse gases
5.3%
25.3%
absorbed by surface 47.9%
emitted by surface 117%
back radiation 100%
evapotranspiration
net absorbed 0.2%

The Hypothesis of Climate Change Science

For more than a century, we have been aware that changes in the composition of the atmosphere could affect its ability to trap the sun's energy for our benefit. We now have incontrovertible evidence that the atmosphere is indeed changing and that we ourselves contribute to that change. Atmospheric concentrations of carbon dioxide are steadily increasing, and these changes are linked with man's use of fossil fuels and exploitation of the land. Since carbon dioxide plays a significant role in the heat budget of the atmosphere, it is reasonable to suppose that continued increases would affect climate.



Verner E. Suomi

From "Carbon Dioxide and Climate: A Scientific Assessment," aka "The Charney Report", June, 1979

1.4. Determination of climatic trends—While radiation observations from satellites are presently not precise enough to determine the small globally-averaged variations that would correspond to climatic changes, the effort should be made to extend the accuracy so that these subtle variations can be observed. The requirements for this purpose are not well established, but accuracies of the order of ± 1 % *(or better)** for the radiation budget of the planet appear necessary. Furthermore, the system, with the required accuracy, will have to be maintained on a continuing basis for long periods (probably decades) in order to detect and verify any long-term climatic trends which may be present.

major problems in atmospheric radiation: an evaluation and recommendations for future efforts

Atmospheric Radiation Working Group (ARWG)

Bulletin of the American Meteorological Society
October, 1972

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* Kellog, W. W., *The Earth's Climate From Space*, Pergamon Press, ***1974***

Measurement of the Earth Radiation Budget

In the Beginning …

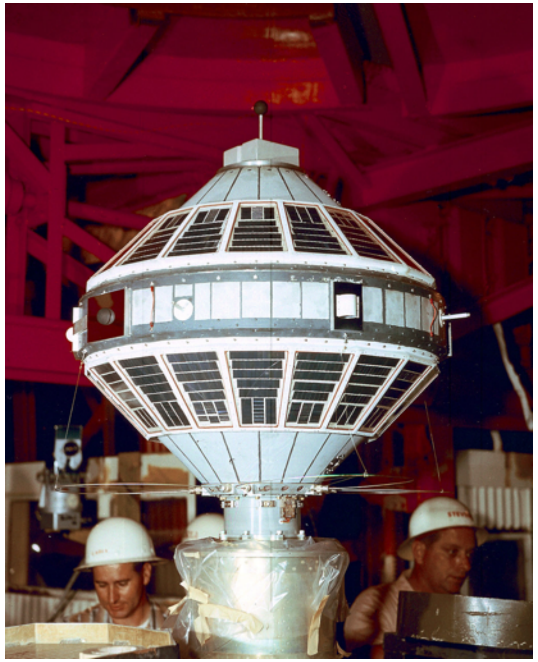
- The first measurements from space of the ERB were attempted in the 1950's, led by Verner Suomi of the Univ. of Wisconsin

- July 17, 1959, Suomi's first radiation budget instruments were on the Explorer satellite
  https://www.youtube.com/watch?v=K6sgMU6-pgc

- Suomi made it to orbit in October, 1959, Explorer VII satellite
  https://www.youtube.com/watch?v=AcsCtsWyPkY

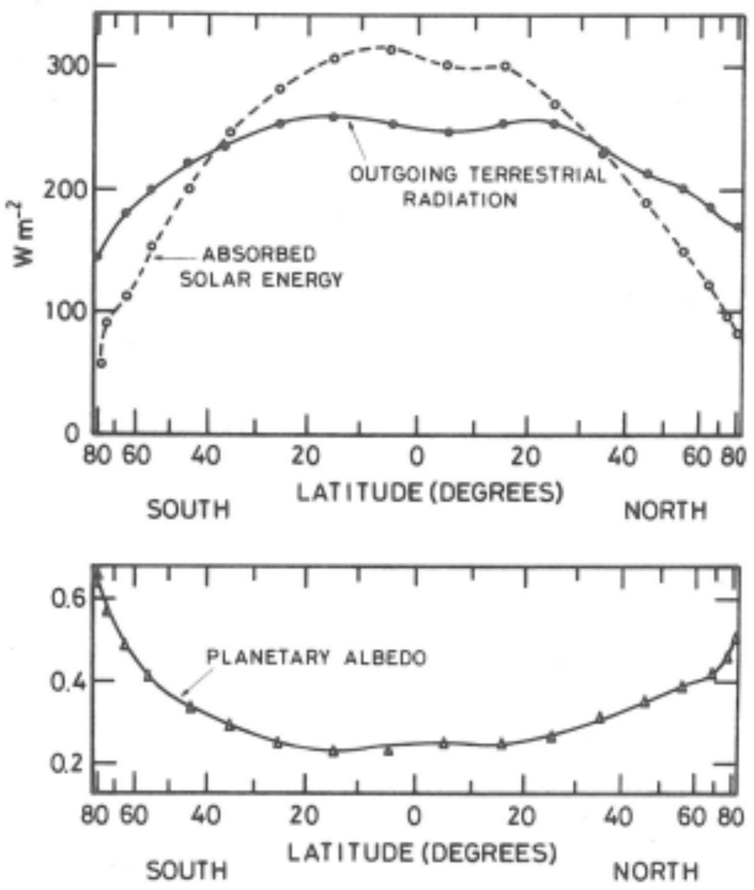
- ERB was the first Earth science measurement to be made from space

- Subsequent measurements over the 1960's provided stunning data on how the Earth is heated and cooled and transports energy from equator to pole



Seminal Results from Suomi's first ERB Observations

Mean meridional profiles of components of the Earth's radiation budget measured during the period 1962-1966.



VonderHaar and Suomi, 1971

Summary of Scanning and Geostationary Radiation Budget Instruments 1970's - present

Scanning

Period	Instrument
July-August 1975	ERB on Nimbus 6
1978–1980	ERB on Nimbus 7
1984–1989	ERBE on ERBS
1985–1987	ERBE on NOAA 9
1986–1989	ERBE on NOAA 10
1994–1995	ScaRaB-1 on Meteor-3 7
1997–1998	CERES on TRMM
1998–1999	ScaRaB-2 on Resurs-1
2000–present	CERES FM1 on Terra
2000–present	CERES FM2 on Terra
2003–present	CERES FM3 on Aqua
2003–present	CERES FM4 on Aqua
2008–2010	ERM on FY3A
2011–present	ScaRaB-3 on Megha-Tropiques
2011–present	CERES FM5 on Suomi NPP
2011	ERM on FY3B
2013–present	ERM on FY3C
2017 – present	CERES FM6 on NOAA-20

Dewitte and Clerbaux, *Remote Sensing*, 2017

Geostationary

Period	Instrument
2003–present	GERB2 on MSG1
2007–2012	GERB1 on MSG2
2012–present	GERB3 on MSG3
2015	GERB4 on MSG4

5.04 Top of Atmosphere Broadband Radiative Fluxes From Geostationary Satellite Observations

HE Brindley and JE Russell, Imperial College London, London, United Kingdom

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Also the Broadband Radiometer (BBR) instrument will be launched on EarthCARE in 2021!

Continuity of the Earth Radiation Budget from Space

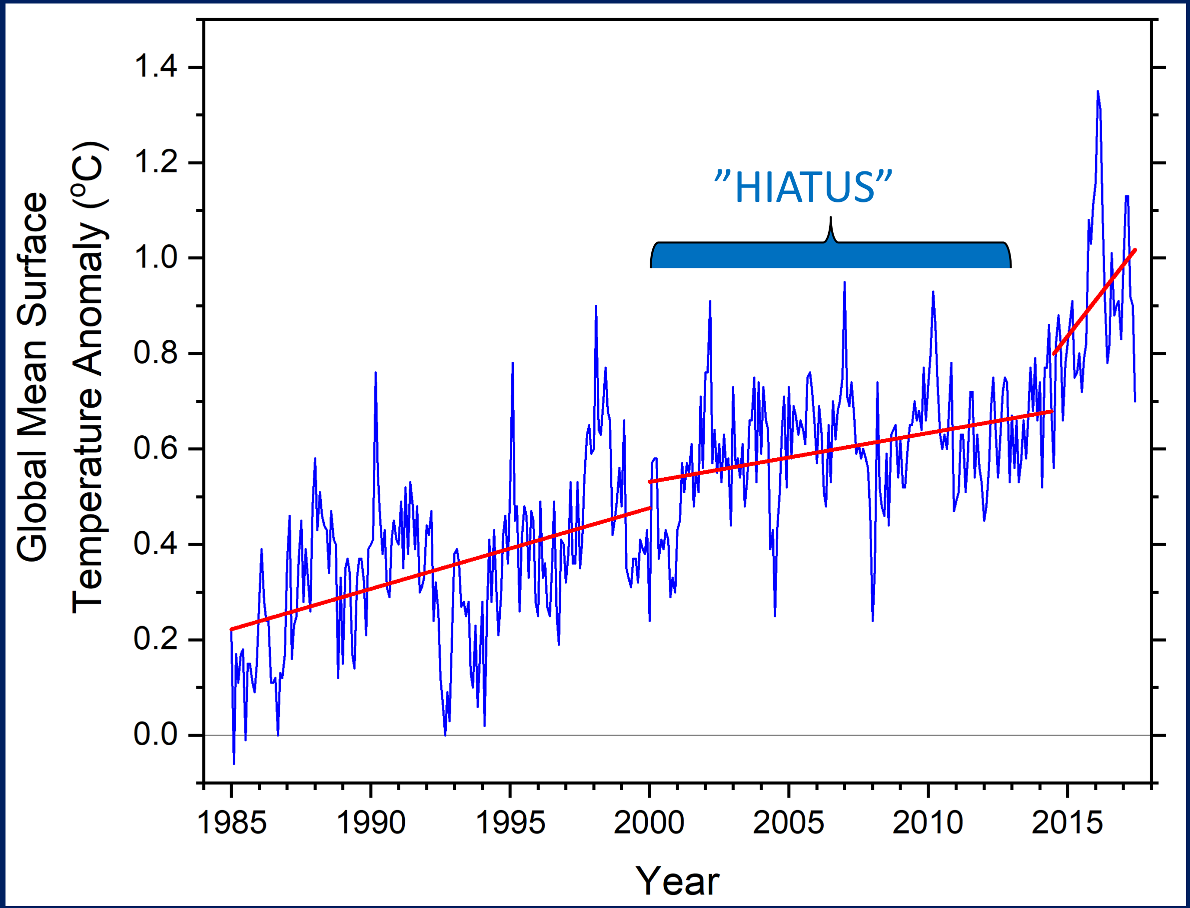
- ERB has been measured from space for nearly 60 years
- Continuous from LEO since 1999 (CERES) and GEO since 2003 (GERB)
- Continuity of the LEO record, due to its global extent, is essential to learning several key aspects of climate change including:
  - What is the magnitude of cloud radiative effect ?
  - How large is the Earth's energy imbalance ?
  - What is the magnitude of planetary energy uptake and ocean heat storage ?
  - Is the equator-to-pole energy transport changing ?

- These and related questions are often answered by looking for ***trends*** in parameters derived from the TOA ERB
- Natural variability in the ERB, coupled with the current accuracy of ERB sensors, requires ~ decadal measurements to see the trend
- This is longer than any single instrument can last – ***so continuity is essential!***

Example of Need for Continuity of ERB

Relationship of Surface Warming and ERB

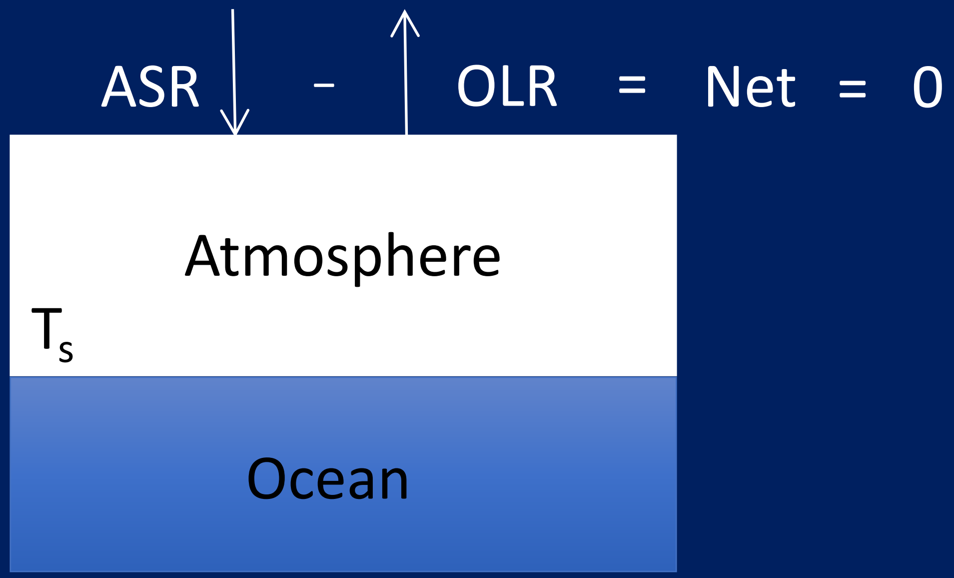
Global Mean Surface Temperature (GMST) Anomaly (Relative to 1951-1980)



- Global warming "hiatus" was a period in the 2000s in which the rate of increase in GMST slowed relative to the decades prior.

Loeb et al., 2018

Planetary Energy Budget and Surface Temperature



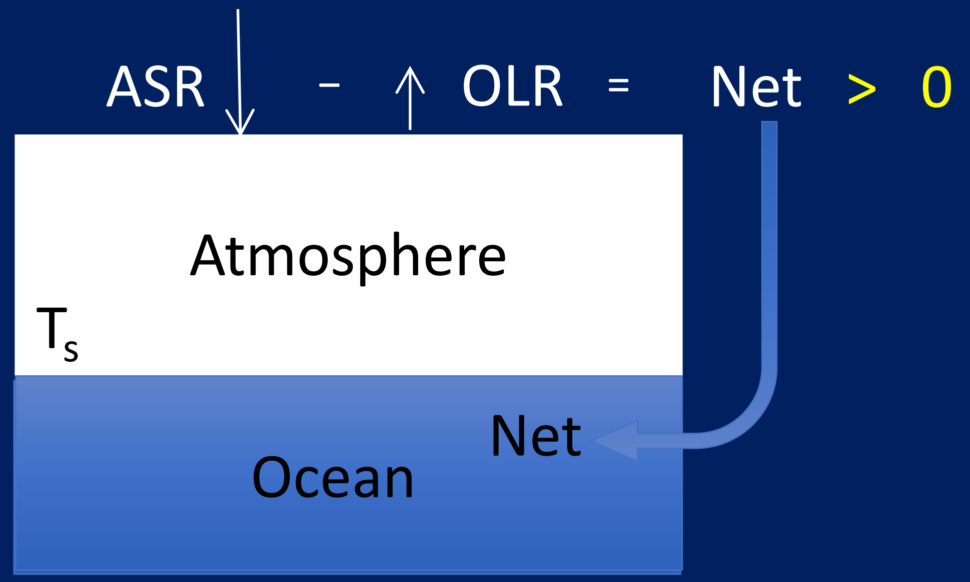
No External Forcing
(anthropogenic or natural)

- ASR = Absorbed solar radiation (observed by CERES)
- OLR = Emitted thermal radiation (observed by CERES)
- Net = Net top-of-atmosphere (TOA) radiation (observed by CERES)
- T_s = Surface temperature

T_s remains constant when averaged over a long time period

Planetary Energy Budget and Surface Temperature

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

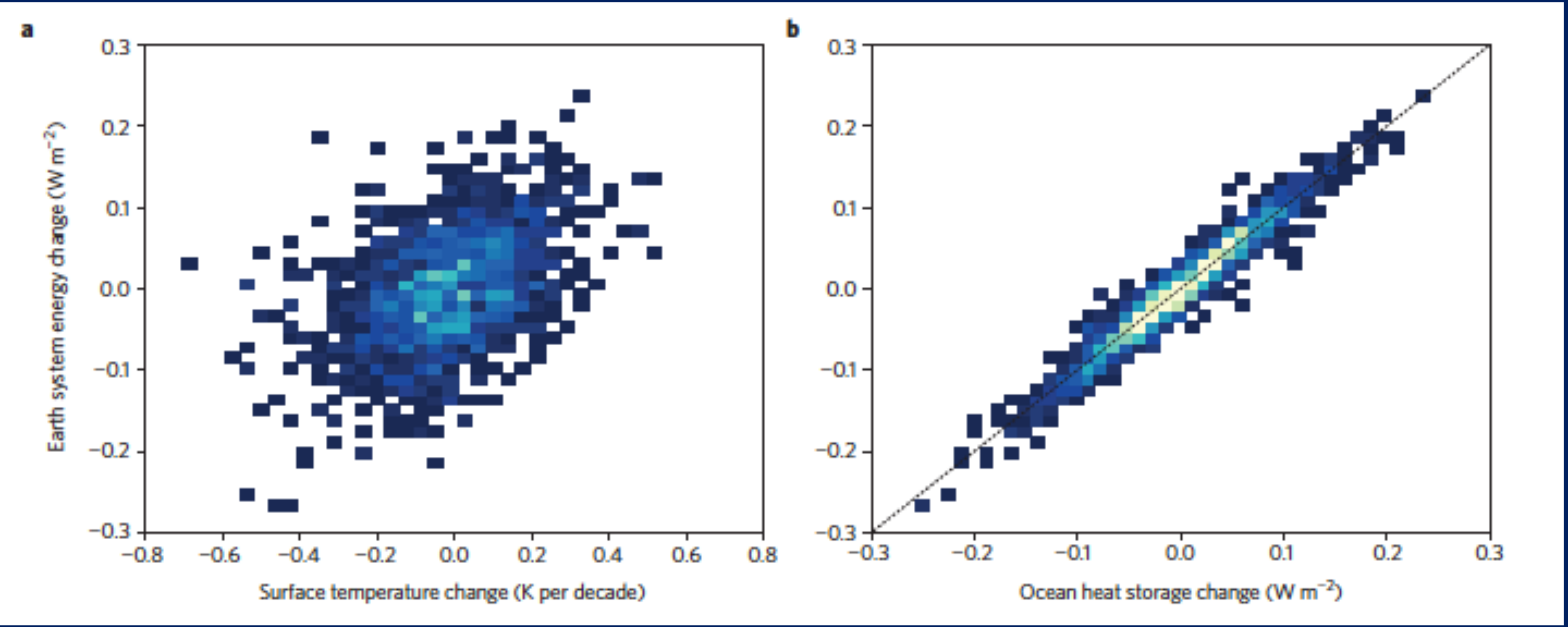


- Greenhouse gases trap emitted thermal radiation from surface, reducing ETR and heating Earth.
- 93% of the excess heat is stored in the ocean.
- Remainder warms atmosphere & land, melts snow and ice.

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.**

Earth System Energy Change relative to Surface Temperature Change and Ocean Heat Storage Change

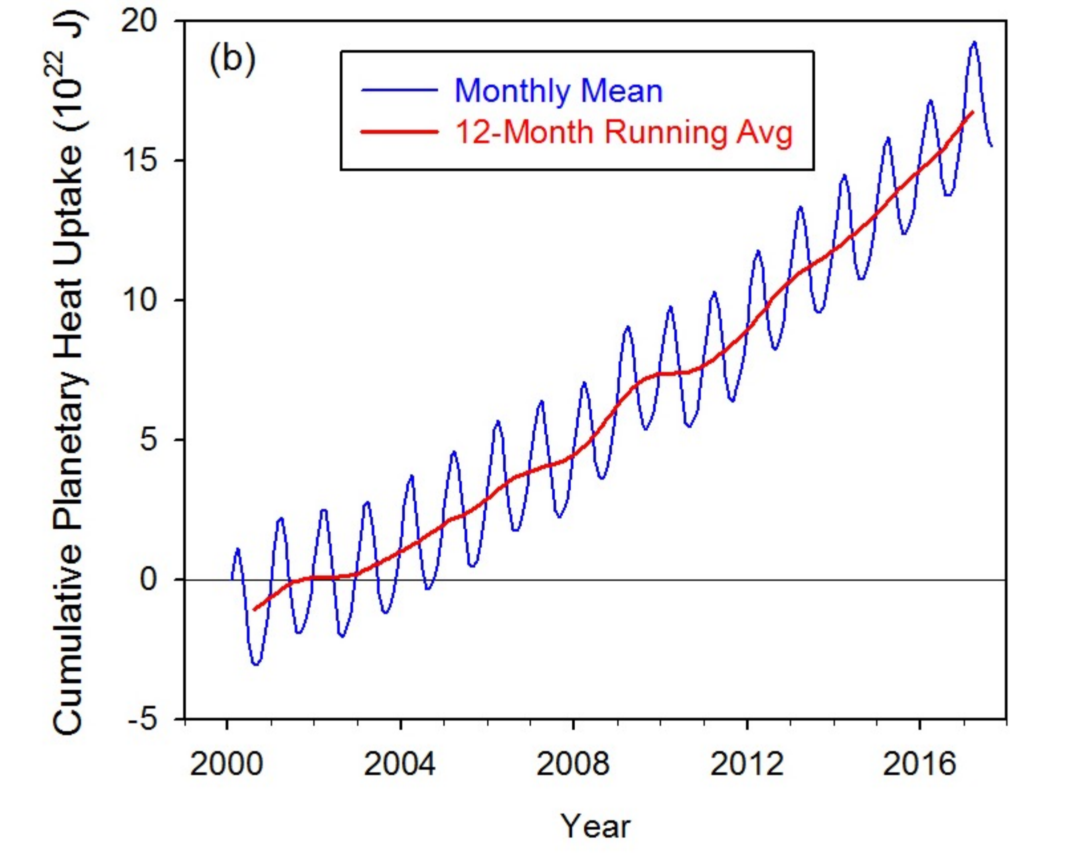


- Data from 14,000 years of combined control simulation from 24 CMIP5 models
- Strong correlation between ocean heat storage change and Earth system energy change
- Weak correlation between surface temperature change and Earth system energy change

(von Schuckmann et al., 2016)

Planetary Energy Budget During and After the Global Warming "Hiatus" from CERES Measurements

CERES Measurements of Planetary Heat Uptake



- **CERES observations show that there was no hiatus in planetary heat absorption. The "hiatus" was just a surface temperature phenomenon**
- **The change in planetary heat uptake provides a better indication of how Earth's climate is changing than surface temperature**
- **Continuity of ERB is essential to understanding how the planet is evolving as greenhouse gases increase**

(Loeb et al., 2018)

Continuity of the ERB from Space

- **Six CERES instruments in orbit now, continuous science since early 2000**
- **Some of these may be required to de-orbit by 2025**
- **A new instrument must be in orbit by ~ 2026/2027 to keep probability of a gap in the record below ~ 30%**

- **NASA just completed (July 26, 2019) the solicitation of mission proposals for continuity of the CERES record – selections in early 2020**

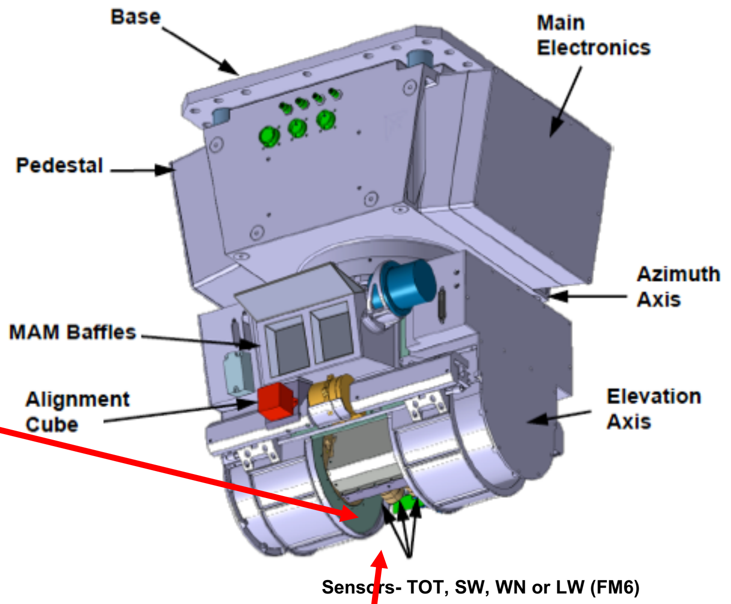
- **Examine now some of the critical requirements to achieve continuity of the ongoing CERES Earth Radiation Budget record**

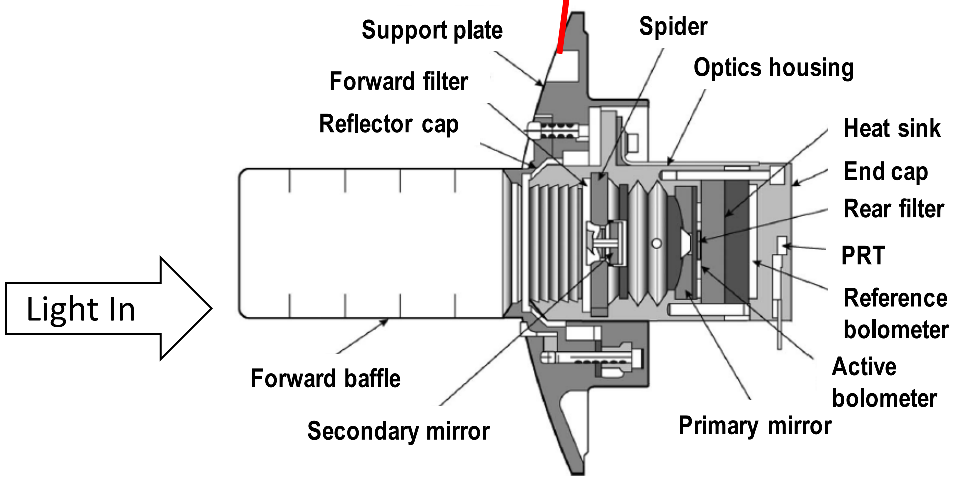
What is ERB Continuity?

- Continuity is the process of launching a new instrument and placing it on the same radiometric scale as its predecessors
- This is necessary because calibration accuracies are not at the “climate” level, e.g., 0.1 K 3-sigma for IR spectra (CLARREO Infrared)
- There is (not yet) a reference standard on orbit to calibrate extant and new sensors (CLARREO-PF; TRUTHS; CRABS)
- Continuity is more than temporal overlap between successive instruments
- Examine the following:
  - What are the necessary measurement characteristics?
  - Can there be a gap in ERB coverage and still derive accurate trends?
  - How long of an overlap period is needed?
  - The approach to tying a new sensor to its extant predecessors

The CERES Instrument

- **CERES measures radiation from the visible through far-infrared**
- **CERES has three sensor assemblies, each with Cassegrain telescopes and thermistor bolometer detectors, co-aligned and mounted on a spindle that rotates about the elevation axis**
- **Measurement Channels:**
  - ***Shortwave* sensor (SW): 0.3 – 5 µm**
  - ***Total* sensor (TOT): 0.3 – 100 µm**
  - **Longwave (LW): TOT minus SW (FM-1 to FM-5)**
  - ***Window* sensor (WN): 8 – 12 µm (FM-1 to FM-5)**
  - ***Longwave* sensor (LW) for FM6: 5 – 35 µm**
- **Measurement accuracy requirements: 0.5% for LW and 1.0% for SW (1-sigma)**



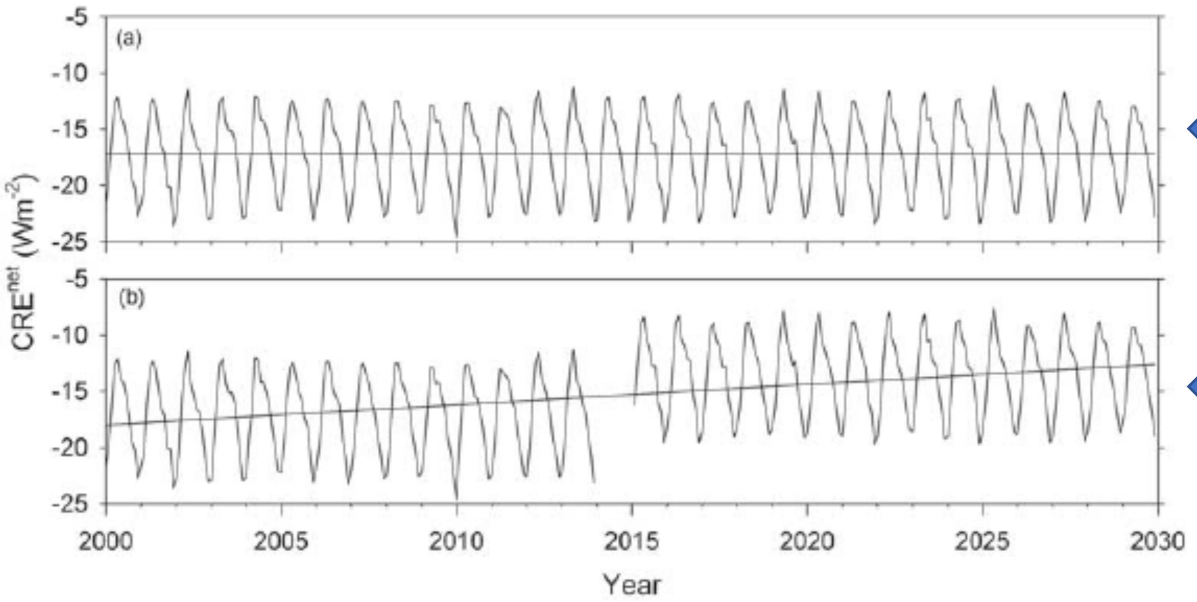


CERES Telescope Assembly

Top-Level Requirements to Achieve a Continuous ERB

- **Proper spatial, temporal, angular, spectral, and radiometric coverage**
- **Capable, agile sensors to execute a variety of on-orbit operations**
- **At current ERB accuracies, *no gaps* in the data (continuity)**
- **Concurrent imager to provide info on scene type**
- **5-year minimum lifetime**
- **Capable of global coverage in radiance measurements**
- **One year of overlap between a new and existing ERB sensor(s)**

Effect of a gap in data record on ERB accuracy



Simulated 30 year data record

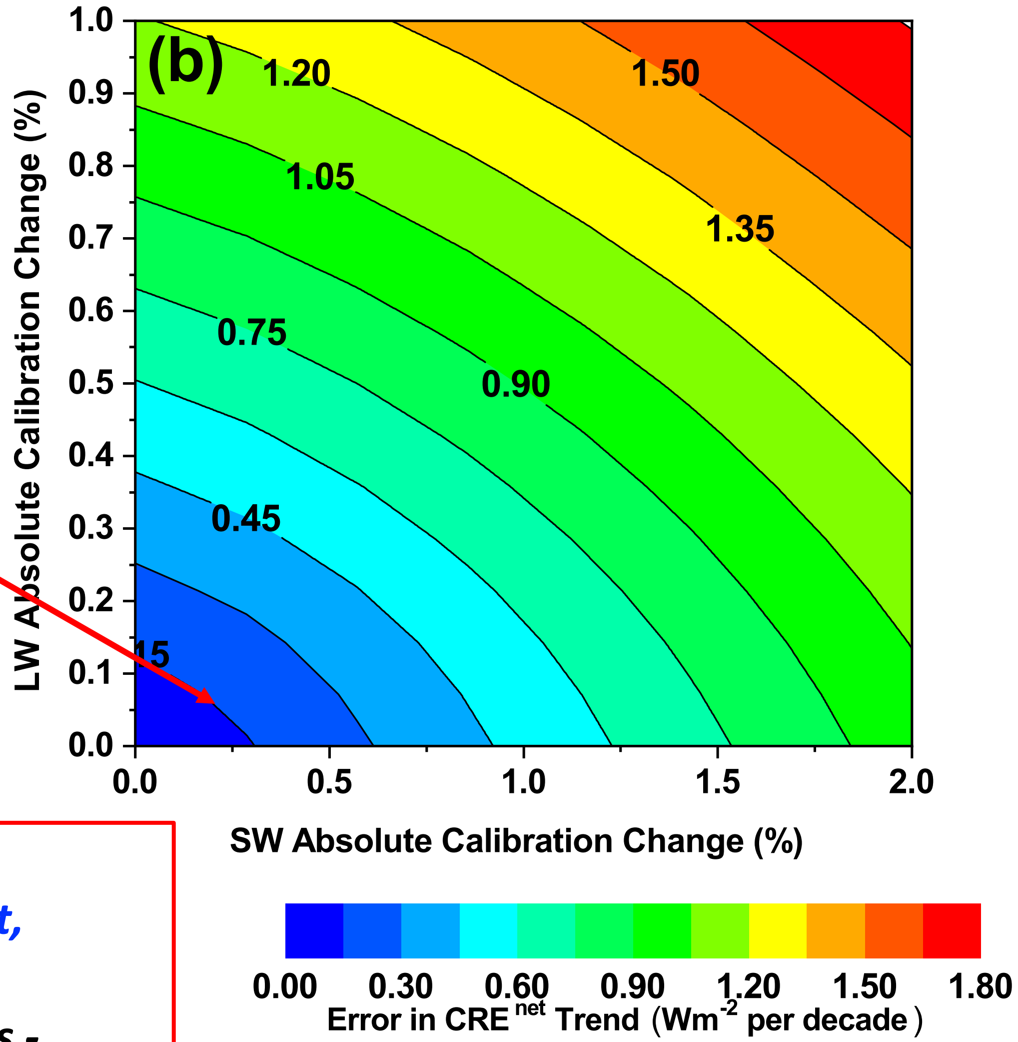
With 1 year gap and offset due to instrument calibration uncertainty

- Simulate 30 year record of CRE^{net} (CRE^{SW} + CRE^{LW}) based on CERES observations
- Add a gap, and place calibration errors on SW (2%) and LW (1%) fluxes post-gap
- Evaluate error in trend in CREnet based on gap length, date of occurrence of gap, and record length
- Require CRE^{net} trend error to be < 25% of trend in anthropogenic forcing
- Adjust adjust calibration errors downward until achieving desired CRE^{net} trend

Loeb et al., 2009

Effect of a gap in data record on ERB accuracy

- To obtain a CRE^{net} trend error < 25% of the decadal anthropogenic forcing (0.15 W/m²/decade), calibration change from one instrument to next is
  - < 0.3 % Short-Wave
  - < 0.1 % Long-Wave
- This is for a one-year gap 15 years into a 30 year record
- We are presently nearly 19 years into the CERES record begun on Terra (launch 12/1999)



Any gap in the record now, with extant instrument accuracies, and without a reference standard on orbit, would effectively require a restart of the record

- There can be no gap at current instrument accuracies -

Loeb et al., 2009

Approach to Overlap and Continuity

Q - How much overlap time is required to tie a new and existing instrument ?

A – Depends on their coincident temporal and spatial sampling

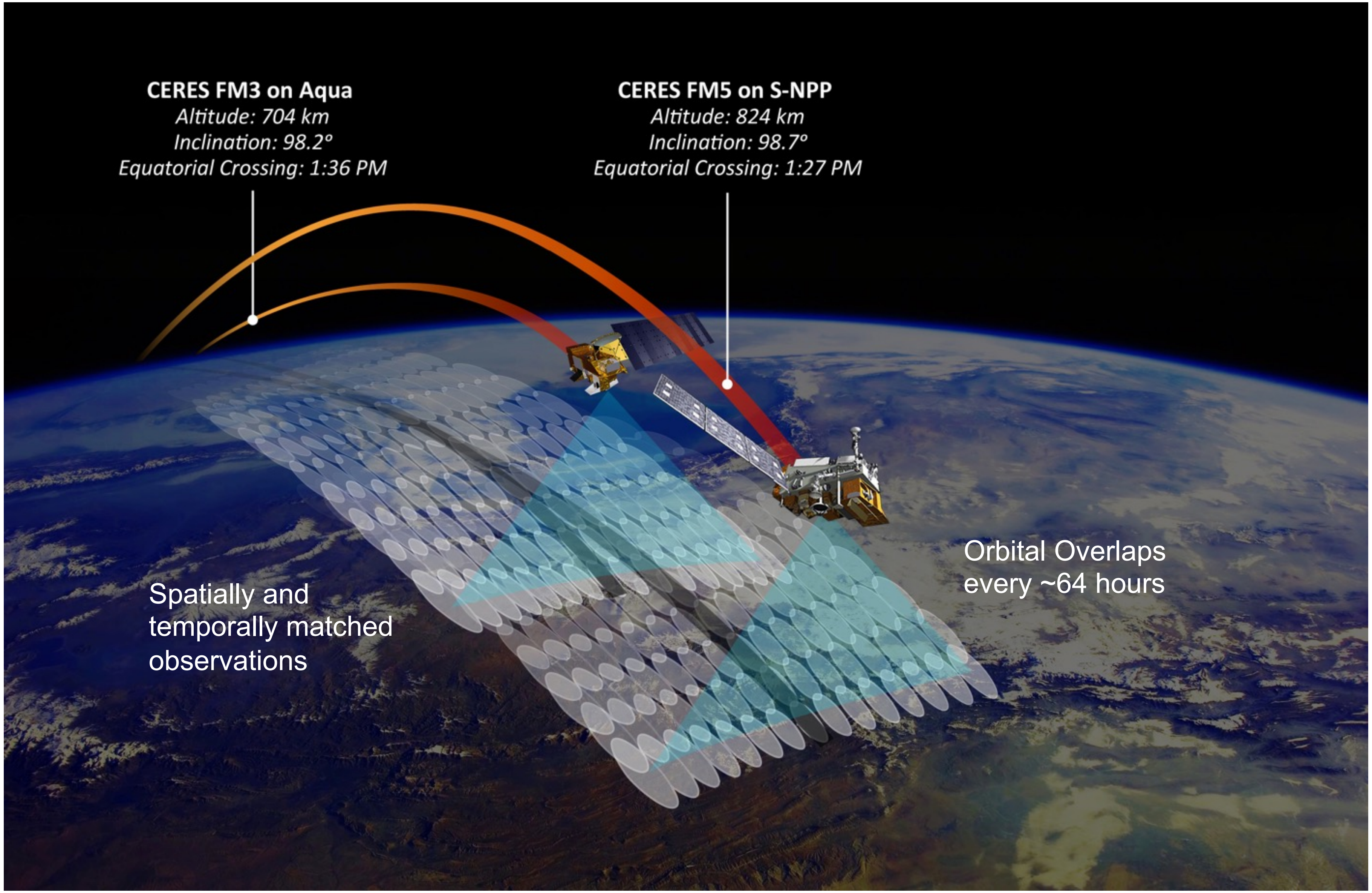
If identical, then the overlap time would be very short

- **Reality – temporal, spatial never 'identical' due to orbit plane, orbit altitude, etc.**
- **CERES is fortunate to have 6 instruments on orbit today and four of the six have overlapped with the first (on the Terra satellite) since launch (2002; 2011; 2017)**
- ***One year*** **is required for tropical overlap while six months for global data**

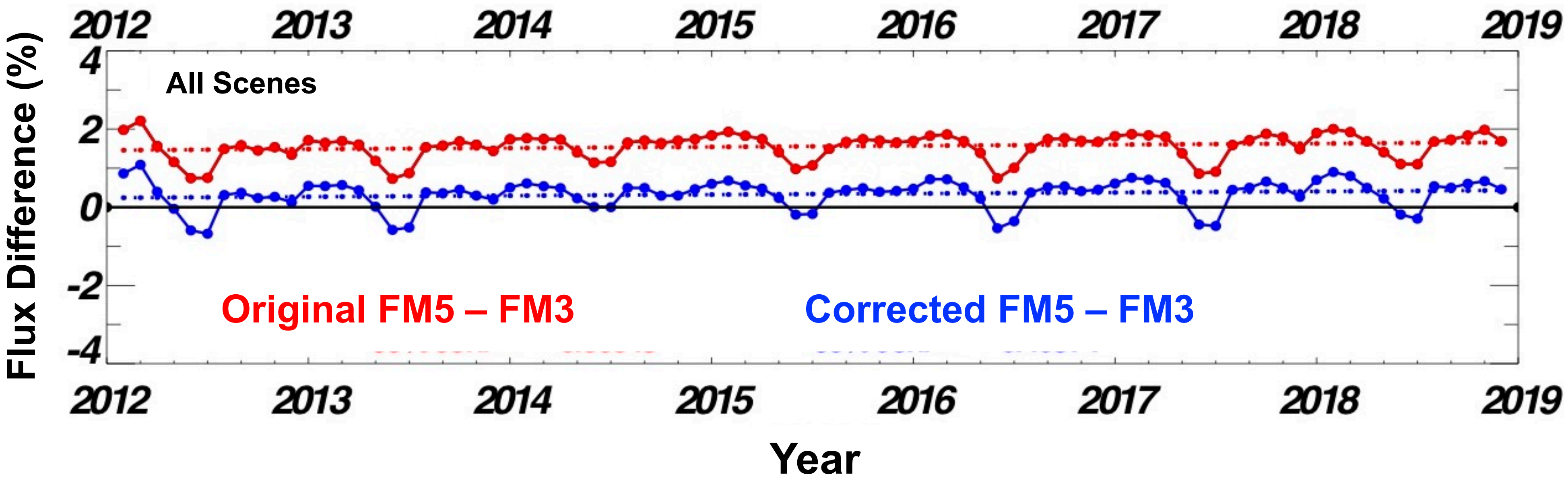
Continuity of Existing ERB CDR – Operational Example

- Tie new and and extant CERES instruments using Simultaneous Nadir Overpasses (SNO's)
  - Example of CERES FM-3 (Aqua, launched 2002) and FM-5 (SNPP, launched 2011)
  - Instruments built in the late 1990's
  - FM-3 and FM-5 agree to within 1-sigma uncertainties, with a small offset in the SW channel
  - Examine the approach to tie FM-5 to FM-3 – at the measured radiance level
- Examine an approach to the future when SNO's of different instruments may/will not be possible

Aqua (FM-3) and SNPP (FM-5) Orbital Tracks



Global All-sky TOA Flux Differences – SW channel



- **Slight offset exists (red curve) between FM-5 and FM-3 (launched 9 years apart)**
- **Offset may be spectrally dependent – can't assume it is just a gain adjustment**

Comparisons between FM5 and FM3 SW Reflectance

$$Reflectance = \frac{SW_{rad} * \pi}{F * \cos(SZA)}$$

$F = 1361\ W/m^2$

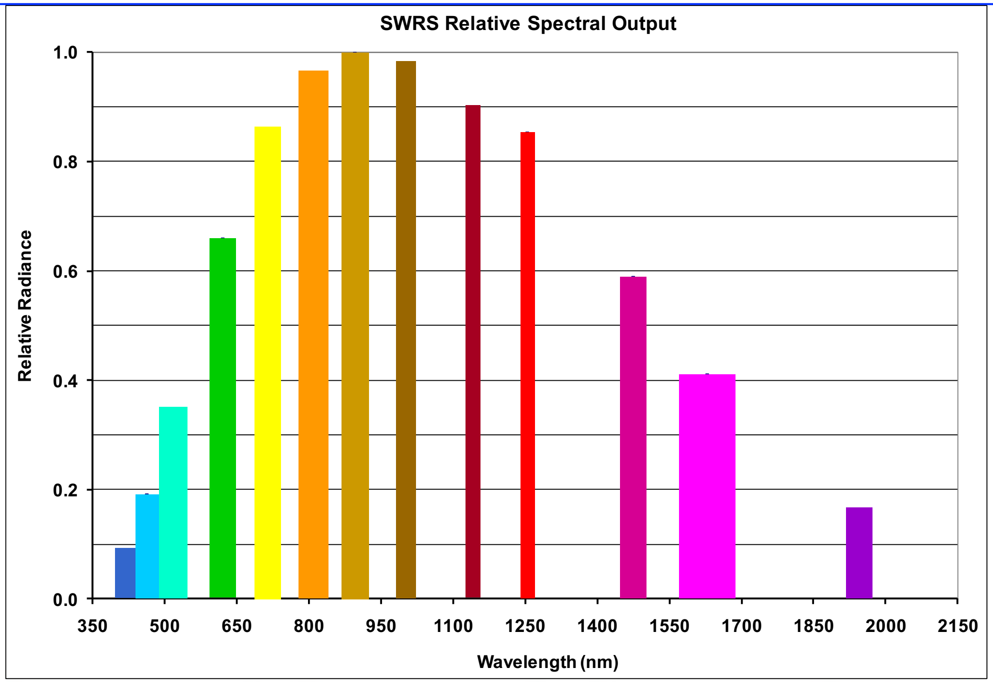
Global average for year 2014

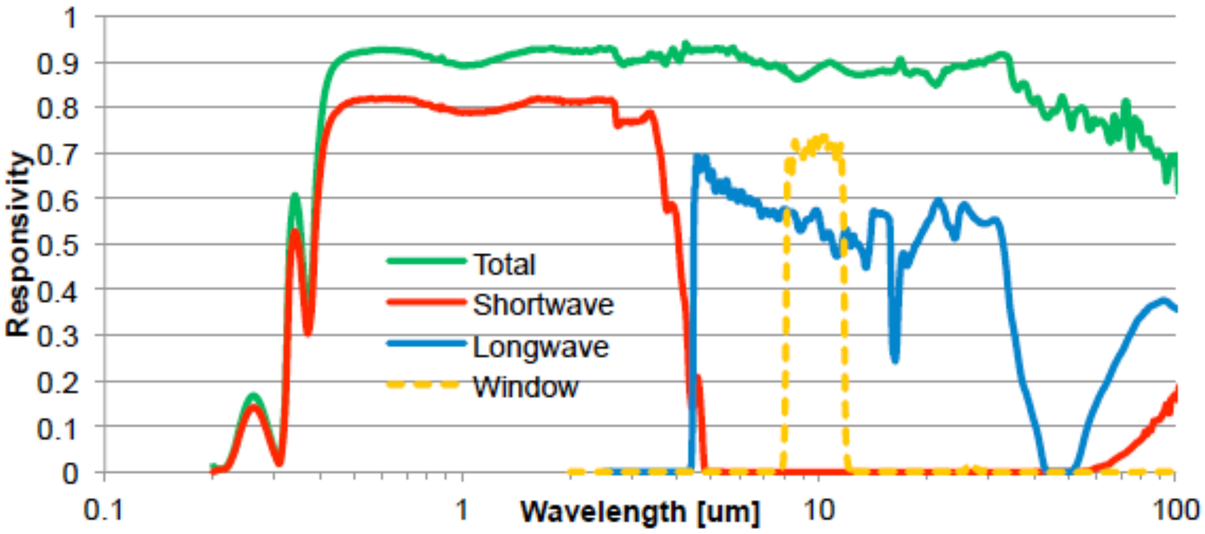
	N (days)	FM3 SW (Reflectance)	FM5 SW (Reflectance)	% Diff (FM5-FM3)
All-sky all scenes	144	0.2936	0.2947	**0.39**
All-sky ocean	123	0.0606	0.0611	**0.74**
All-sky land	79	0.2181	0.2184	**0.11**

- **Comparison of Reflectance (directly proportional to measured radiance) demonstrates the error is broadly spectrally dependent**
- **FM-5 is then tied to FM-3 by adjusting the FM-5 spectral response function to minimize differences in the SW radiance (reflectance)**

CERES Pre-launch Spectral Response Function Characterization

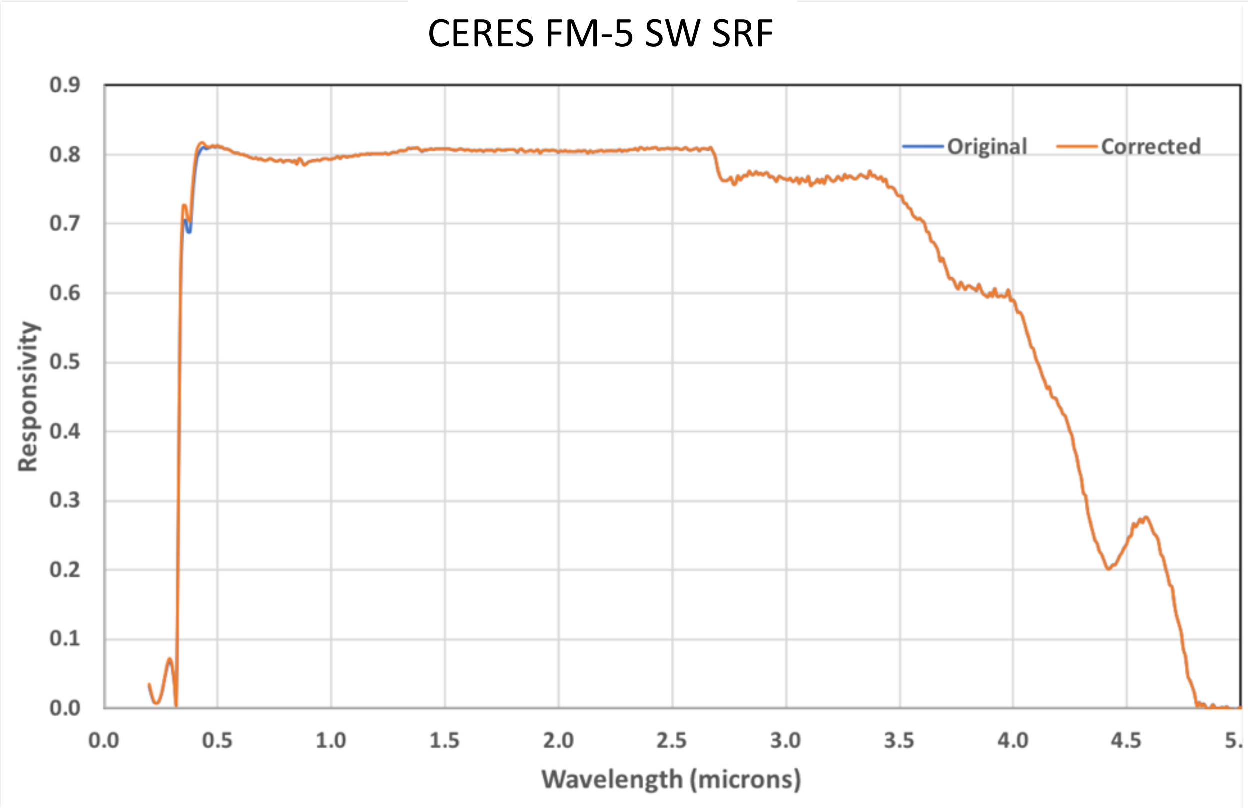
- Shortwave Reference Source (SWRS) uses a Quartz Tungsten Halogen lamp along with 13 narrow band filters to provide sources between 0.4 and 2.0µm
- A cryogenically cooled Transfer Active Cavity Radiometer (TACR) places these sources on the same radiometric scale as the NFBB (primary standard)
- CERES sensors (SW and TOT) and the TACR view the source alternatively
- The ratio of the CERES measurements to TACR measurements provides a spectral responsivity in each of the narrow spectral bands for both SW and SW portion of TOT
- Component spectral measurements complete the spectral response curve between the narrowband sources and extend the curve below 0.4µm

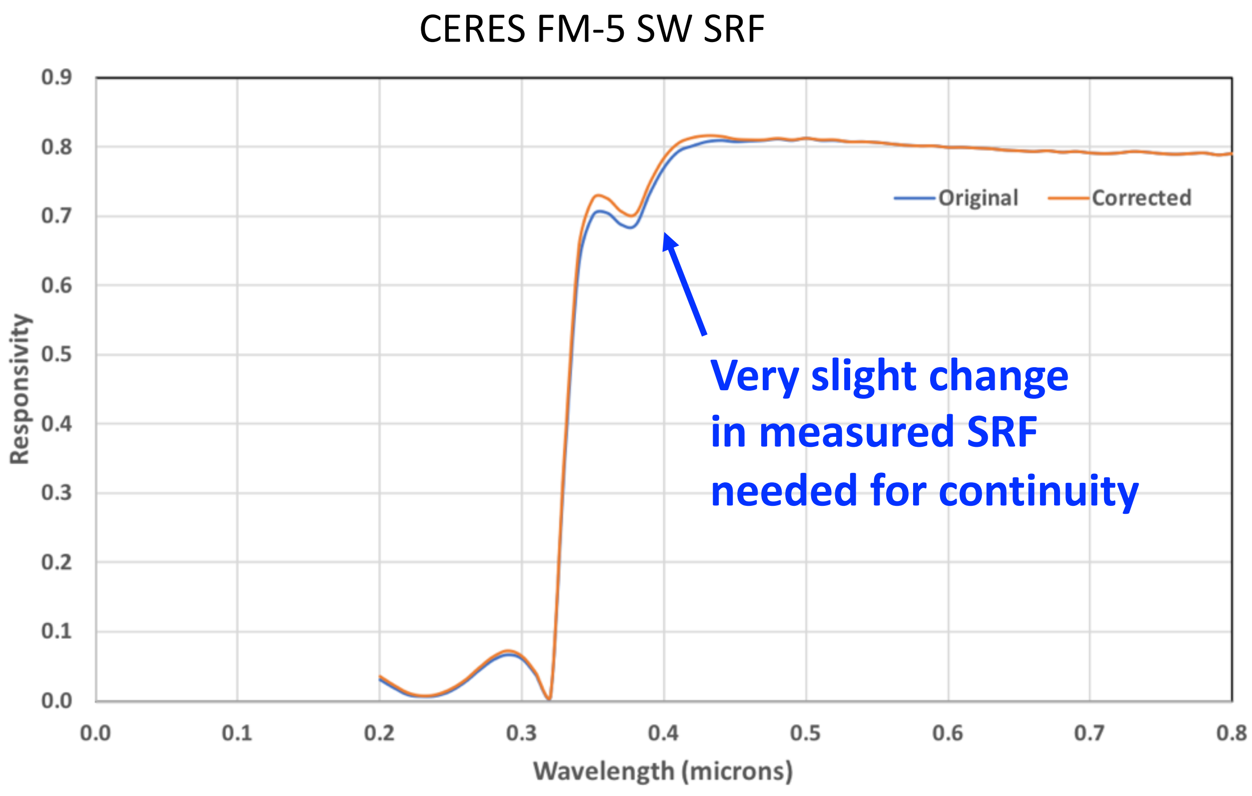




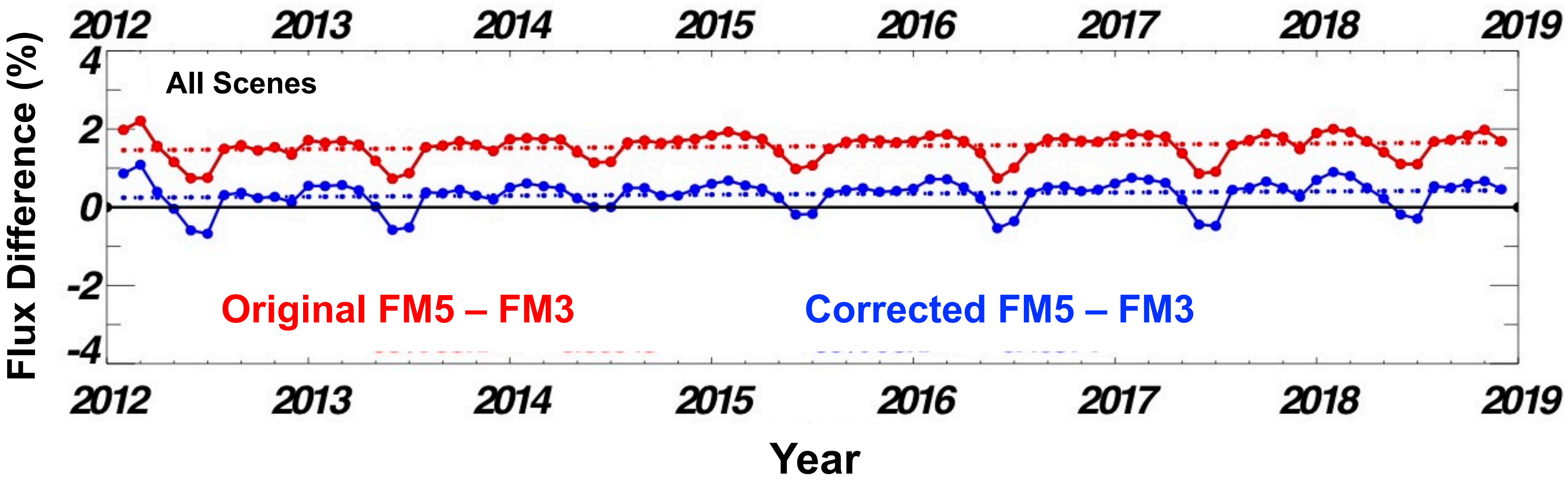
Adjusting the FM-5 SRF for Continuity with FM-3

- SRF adjusted by an objective constrained optimization algorithm using Lagrange multipliers
- All 13 spectral bands are used to adjust the SRF and
- The uncertainties of measured spectral responsivity constrain the optimization process





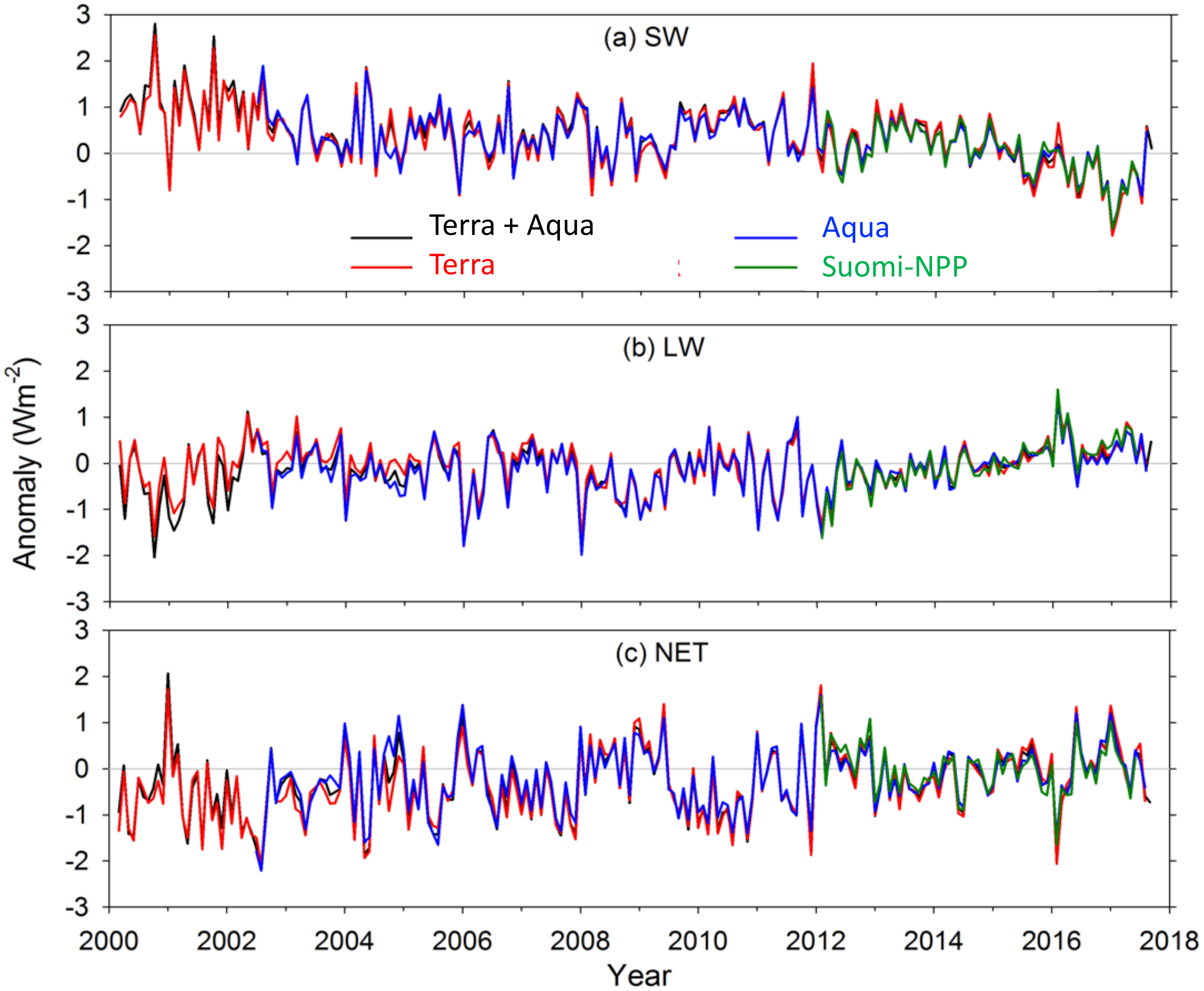
Global All-sky TOA Flux Differences – SW channel



Adjustment of the spectral response function places FM-5 on the same radiometric scale as FM-3

The Result – Continuity of 5 Instruments over Two Decades

The remarkable situation of five CERES instruments in simultaneous operation and with seamless continuity over nearly 20 years



Loeb et al., 2018

The mid-2020's
Achieving Continuity Without Satellite SNOs

- CERES has had the luxury (!) of having 6 instruments, of which 5 (so far) have lived well beyond their design lifetime – 80+ cumulative instrument years
- The orbit planes have been complementary to enable SNOs between the 5 instruments to do extensive cross-comparison for continuity and drift detection
- Sometime after 2021 Aqua and Terra may be de-commissioned and may not be in operation past 2025
- A new instrument will likely be on the JPSS-3 satellite ~ 2026
- All instruments (FM-5, -6 and '2026') will be in same orbit plane – No SNO's

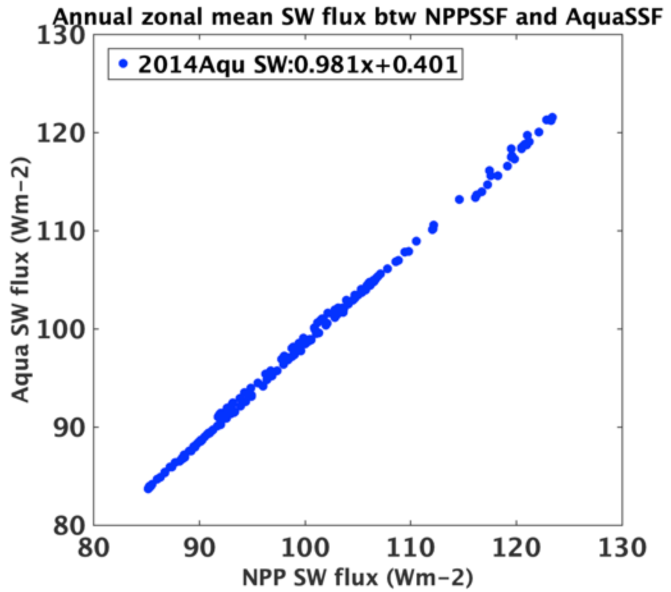
Q - How do we tie the record of FM-1, -2, -3, -4, -5, and -6 to a new CERES or CERES-like instrument without SNOs?
A – Regress monthly zonal mean fluxes (1-deg) of CERES against new instrument

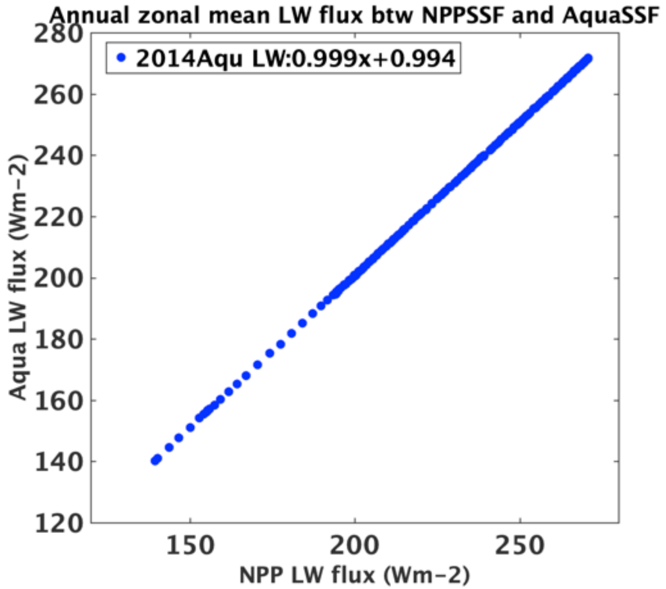
Demonstrate this approach now with CERES on Aqua and CERES on NPP

Use concurrent Aqua and NPP measurements to adjust NPP

- Regress Aqua 2014 SSF and NPP 2014 SSF fluxes
- Using the regression to adjust the 2014 NPP SSF data to be more Aqua-like
- Concurrent measurements provide much adjustment for NPP, compared with the adjustment when there is a gap between Aqua and NPP

	Global		Tropical	
SSF-1deg	SW	LW	SW	LW
Aqua	96.06	238.92	91.13	258.90
NPP	97.62	238.19	92.78	258.15
Aqua-like NPP	96.13	238.91	91.39	258.84





Climate Change and Scientific and Societal Relevance

Climate Change
Nobel-Caliber Research with Profound Scientific & Societal Impact

- **The detection of gravitational waves, the Higgs boson, and the signals of climate change all have similar attributes:**

1. **An ultimately testable hypothesis (V. Suomi; A. Einstein; P. Higgs)**
2. **Small signals requiring highly accurate measurements**
3. **Decades of development to arrive at the correct observational method**
4. **Need for broad, international cooperation and funding to sustain over long periods**
5. **Large teams to examine all the data, to test for, and to prevent false positives**
6. **Sufficiently high statistics to confirm existence either for acceptance of hypothesis or for justifying societal action (5-sigma Higgs boson; 3-sigma climate science)**

Recent Nobel Prizes in Physics

Gravitational Waves
Laser Interferometer Gravitational-Wave Observatory
LIGO

PRL 116, 061102 (2016) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

~ 1000 co-authors on this paper

Higgs Boson
Large Hadron Collider
LHC

Physics Letters B 716 (2012) 1–29

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ELSEVIER

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC[☆]

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

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ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

~ 2800 co-authors on this paper
Over 175 different institutions

Climate Change - Profound Societal Relevance

Bulletin of the Atomic Scientists

To: Leaders and citizens of the world
Re: A new abnormal: It is *still* two minutes to midnight
Date: January 24, 2019

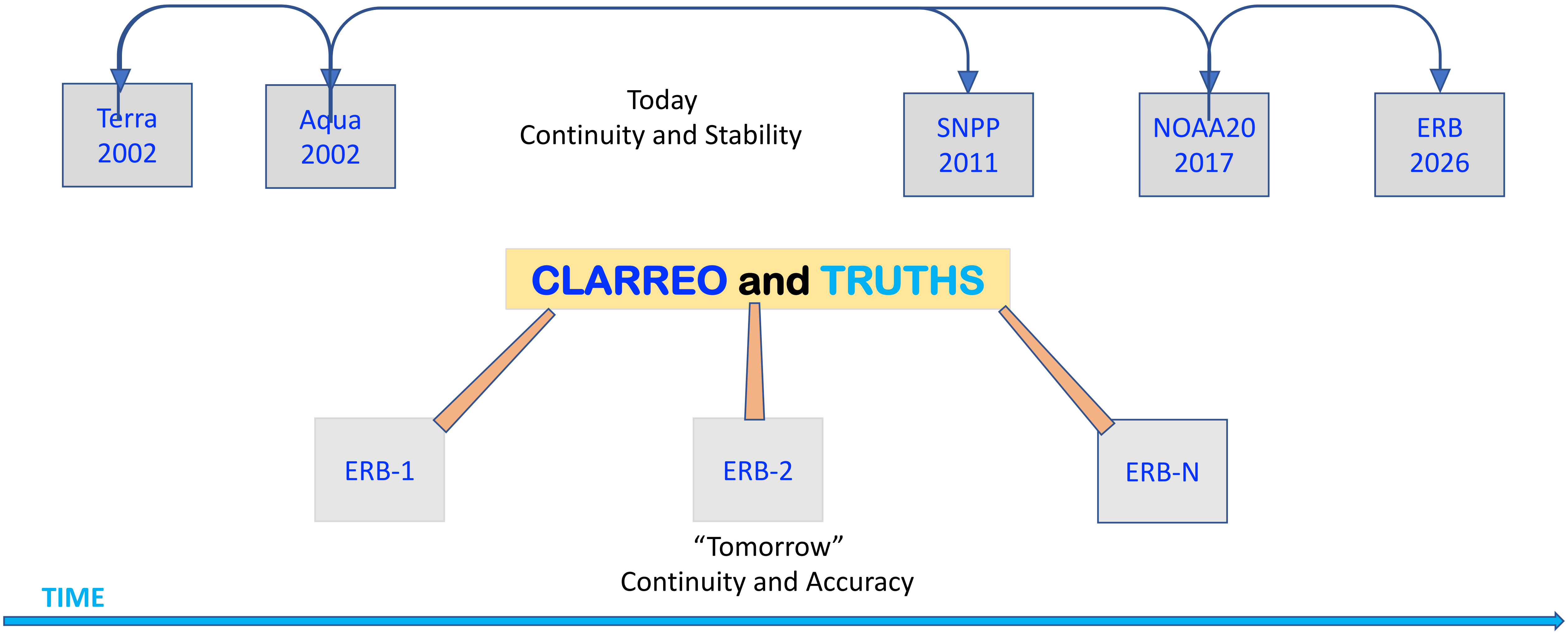
Humanity now faces two simultaneous existential threats, either of which would be cause for extreme concern and immediate attention. These major threats—nuclear weapons and climate change—were exacerbated this past year by the increased use of information warfare to undermine democracy around the world, amplifying risk from these and other threats and putting the future of civilization in extraordinary danger.

Excerpt from Bulletin of the Atomic Scientists 2019 Doomsday Clock Statement

https://thebulletin.org/doomsday-clock/current-time/#full-statement

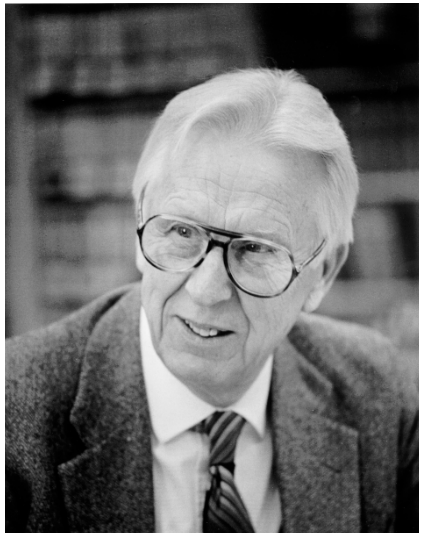
Path Forward and Summary

Current and Future Approaches to Continuity



Commencement Thoughts

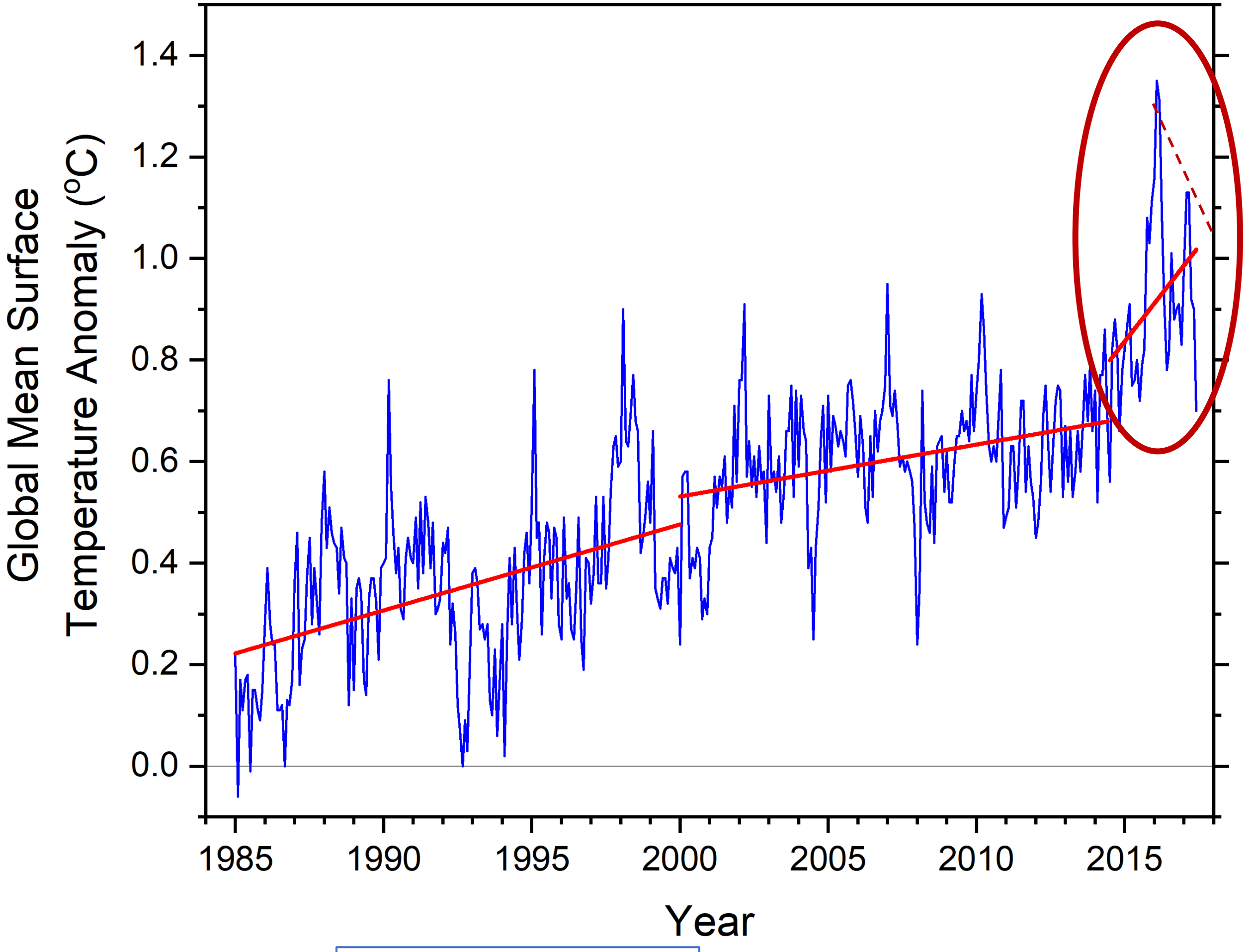
In order to address this question in its entirety, one would have to peer into the world of our grandchildren, the world of the twenty-first century. Between now and then, how much fuel will we burn, how many trees will we cut? How will the carbon thus released be distributed between the earth, ocean, and atmosphere? How would a changed climate affect the world society of a generation yet unborn? A complete assessment of all the issues will be a long and difficult task.



From "Carbon Dioxide and Climate: A Scientific Assessment," aka "The Charney Report", June, 1979

Backup Slides

Global Mean Surface Temperatures



Loeb et al., 2018

- **Skeptics have been pointing to the "decrease" in Earth surface temperature since 2016, an El-Niño year**
- **So much so that NASA put together a blog to correct this notion**
- **The real question is "What is happening to the Earth's energy budget? "**

https://climate.nasa.gov/blog/2893/nope-earth-isnt-cooling/

Results: Daytime LW radiance after SW SRF Correction

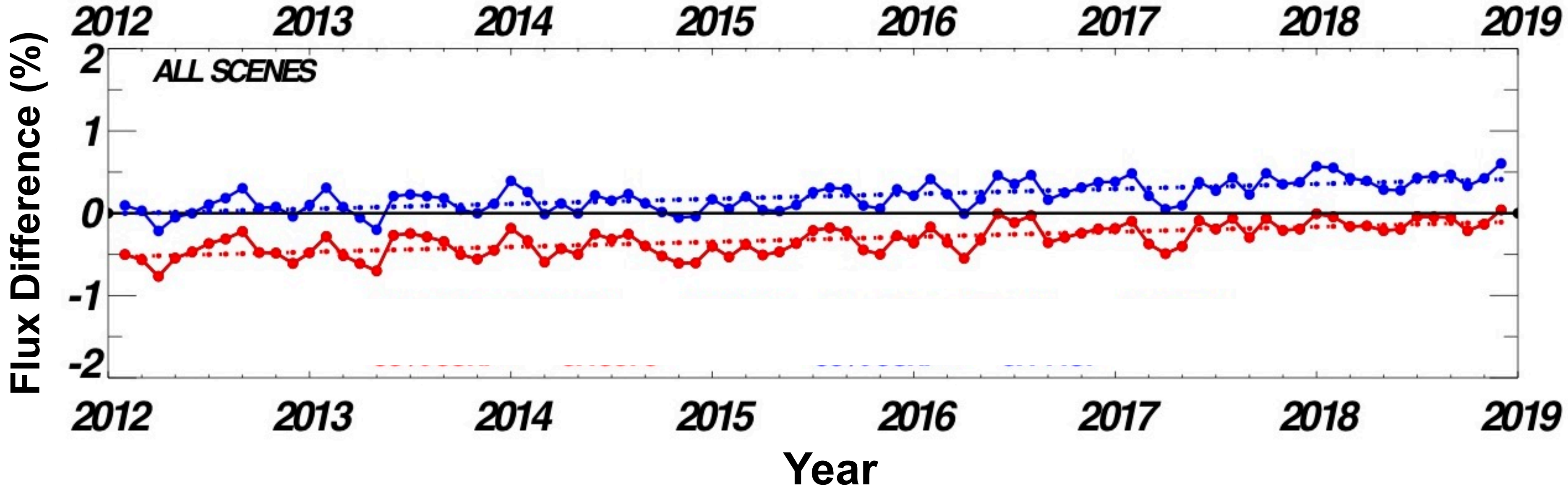
- **Daytime LW= TOT minus SW**

Global average for year 2014

	N (days)	FM3 Daytime LW (Radiance- $Wm^{-2}sr^{-1}$)	FM5 Daytime LW (Radiance- $Wm^{-2}sr^{-1}$)	% Diff (FM5-FM3)
All-sky all scenes	144	77.44	77.49	**0.07**
All-sky ocean	123	91.30	91.48	**0.20**
All-sky land	79	101.56	101.23	**-0.32**

- **No start of mission SRF adjustments necessary for TOT channel!**
- **FM-5 TOT channel agrees with FM-3 TOT channel, after SW adjustment, despite launching 9 years later**

Global All-sky Flux Differences- Daytime LW



- **Recall: LW = Total channel minus Shortwave**
- **Small correction to shortwave channel removes slight offset in LW TOA flux between CERES FM-5 and FM-3**

CERES Pre-launch Calibration

CERES Radiometric Calibration Facility

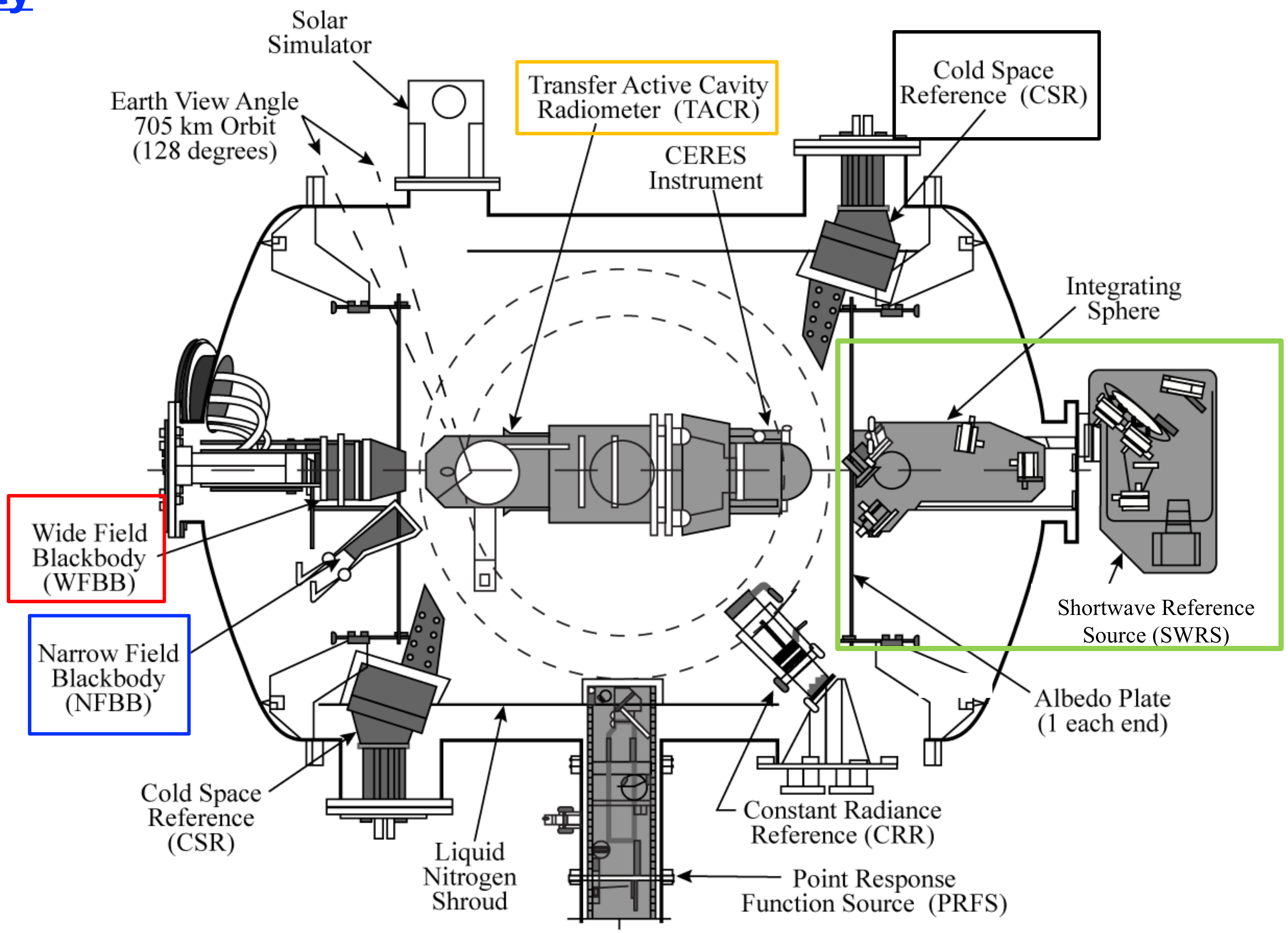
Thermal IR Bands

- Narrow Field of View Blackbody (NFBB) is primary standard (emissivity >0.9999)
- 12.5 cm Wide Field of View Blackbody (WFBB)
- Cold Space Reference (CSR) blackbodies

Reflected Solar Bands

- SW reference source (SWRS) with minimum LW variations and spectral characterization capability
- 13 discrete bands between 420 and 1960 nm
- 5 cm integrating sphere with associated optics

- Cryogenically cooled Transfer Active Cavity Radiometer (TACR)



Continuity of the Existing ERB CDR Instrument Requirements

- Spectral coverage
- Spatial Sampling (global coverage, cross-track scanning)
- Calibration accuracy and stability
- Cloud/scene identification for ADM used in R-to-F conversion
- FOV < 25 km
- Vicarious calibration
- Continuous operation
- Dynamic range

Note – still need to insert values for many of these

FM-3 and FM-5 SW reflectance after FM-5 SRF Adjustment

Global average for year 2014

	N (days)	FM3 SW (Reflectance)	FM5 SW (Reflectance)	% Diff (FM5-FM3)
All-sky all scenes	144	0.2936	0.2936	**0.00**
All-sky ocean	123	0.0606	0.0605	**-0.19**
All-sky land	79	0.2181	0.2176	**-0.23**

Summary

- Earth's Radiation Budget is perhaps the most fundamental measurement for understanding the processes and evolution of the climate system
- Rich history of measurements dating back 60 years
- Currently a continuous, global dataset from the CERES instruments approaches 20 years in length
- ERB data are essential to understanding energy flow within the climate system
- Ensuring continuity of the CERES measurements is critical to enabling a multi-decadal ERB CDR needed to assess climate change
- Climate science is Nobel-caliber and of profound societal relevance in 2019

Measurement of the TOA Earth Radiation Budget

- Measuring the ERB is a 9-dimensional sampling problem
- ERB, particularly the shortwave, is a function of
  - Location (latitude, longitude, altitude)
  - Solar zenith angle
  - View zenith angle and view azimuth angle
  - Wavelength
  - Time of Day
  - Calibration accuracy

- Uncertainties in any of these contribute to overall error in ERB

- Error in ERB measurement determines the time to detect trends against the noise of natural variability

Continuity of FM-5 and FM-3