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NASA CERES Spurious Calibration Drifts Corrected by Lunar Scans to Show the Sun Is not Increasing Global Warming and Allow Immediate CRF Detection

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Abstract Orbital Earth Radiation Budget measurement comparisons to models, are critical for climate prediction confidence. Satellite systems must reduce calibration drifts for this purpose. NASA Clouds and the Earth’s Radiant Energy System (CERES) measures Earth albedo reductions that if correct, would increase solar forcing and suggest greater sunlight absorption is driving much of recent temperature increases. Such results are presented, alongside those from the Moon and Earth Radiation Budget Experiment (MERBE). MERBE uses constant lunar reflectivity for tracking and compensation of instrument telescope degradation, undetectable by CERES. MERBE finds Earth albedo constant compared to that of the Moon, because Arctic solar warming effects are balanced by solar cooling elsewhere, likely due to negative feedbacks. Contrary to NASA, this shows the Sun is not increasing warming and that CERES results are not as stable as claimed and assumed. Furthermore, MERBE can actually resolve Cloud Radiative Forcing (CRF) signals from the existing record, rather than in decades with official observations.

Plain Language Summary In contrast to NASA Clouds and the Earth’s Radiant Energy System results, this paper shows that the Earth reflectivity has not changed since the year 2000, by comparing the sunlight bouncing off it to that from the Moon. Disagreeing with NASA, this provides physical evidence that global warming is not being increased by the Sun. It also immediately brings data to the standard requested by the climate community for cloud forcing/feedback signal detection. The Moon and Earth Radiation Budget Experiment data is being staged for free on the FAIR compliant website Pangaea for climate scientists.

1. Introduction

There is still much uncertainty surrounding how the Earth will respond to the rapid recent warming that has been observed, due to significant anthropogenic greenhouse gas releases in the last 120 years. The resulting changes to clouds, often referred to as cloud radiative forcing/feedback or CRF (Bony et al., 2006), remains one of the largest unknowns. More specifically, it is unclear if the rapidly arriving warmer Earth will result in more, less, or simply different types of clouds, and whether changes to say their sunlight reflection will diminish or amplify warming (i.e., as a negative or positive climate feedback).

The time averaged solar flux of 1,361 Wm$^{-2}$ arriving at Earth is currently very stable on decadal length scales, with a slight negative trend of $-0.029\%$/decade in the 2000–2015 timeframe, so cannot by itself be responsible for current rapid surface temperature rises (see Figure 1, LASP, 2021). This work is therefore not an analysis of effects of variation in solar output on climate change (Haigh, 1996), but instead its focus is on changes to remaining planetary solar input after reflection from Earth, defined here as “albedo solar warming” (at first assuming the Solar output flux is completely constant over time). Albedo changes have the potential to be a primary driver of climate change, as they would alter the energy entering Earth from the currently stable Sun. For example, the rise in atmospheric reflectivity due to particulate aerosols emitted from the 1991 Pinatubo volcanic eruption (Soden et al., 2002), led to a temporary global cooling of around half a degree Celsius.

Climate scientists and economists estimated that the size of the CRF albedo solar warming/cooling climate signal trends being looked for, are no larger than just under 0.8 Wm$^{-2}$/decade in magnitude (Cooke et al., 2013; Wielicki et al., 2013). This is in terms of changes to fractional Earth reflectivity, multiplied with the incoming solar flux (that averages to 1,361 Wm$^{-2}$ with an overhead Sun). Solar flux is measured daily.
by orbiting electrical substitution radiometers, giving confidence that there are no false calibration drifts in such data sets, because no degrading optical components are used.

The only way to globally measure Earth albedo is from satellites in low polar Earth orbit. Such a process utilizes space-based focused telescopes and detectors that measure the Earth Radiation Budget or ERB (Ramanathan et al., 1989), a component of which is the broadband reflected solar flux leaving Earth. These scattered solar or Short Wave (SW) results between wavelengths 0.2 and 5 µm, divided by measurements of incoming solar flux, allow calculation of Earth's fractional albedo. Earlier analysis (Wielicki et al., 2005), examined the first five years of the worldwide ERB reflected SW measurements made by a NASA satellite program called Clouds and the Earth's Radiant Energy System (CERES (Wielicki et al., 1996)). It was concluded there that due to natural climate variability "noise," more data over at least a decadal time scale would be required to draw conclusions on any statistically significant albedo changes. Additionally, it was later assessed (Wielicki et al., 2013), that the calibration accuracy of CERES is not sufficient to detect the predicted 0.8 Wm⁻²/decade or less CRF change trends, for decades to come. Requests were made in both the 2007 & 2017 National Academies decadal surveys on science that advise the US government (NA, 2021), to develop an observing system with better accuracy and stability. These surveys included comments such as, "the single most critical issue for current climate change observations was their lack of accuracy and low confidence in observing the small climate change signals over long decade timescales."

Since that time, decadal length solar warming change measurements from CERES ERB devices have been presented (Dunn et al., 2020), similar to that shown here in Figure 2a. However, such results may be misleading due to the effects of un-monitored in-flight instrument degradation (Wielicki et al., 2013), which necessitates an alternative approach to instrument calibration such as that employed here. The new methodology in this work achieves stability and accuracy by fully compensating for Ultra-Violet (UV) “spectral darkening” to instrument optics (Matthews et al., 2006). It is a project called the Moon and Earth Radiation Budget Experiment (MERBE). Thousands of lunar scans by the instruments built for CERES are used by MERBE in Figure 2b. That allows tracking and compensation for in-flight telescope UV response reductions, which cannot be detected by NASA CERES on-orbit calibration techniques (Priestley et al., 2011). Such unmonitored instrument response changes caused the false negative albedo trends already found in early CERES albedo data (Wielicki et al., 2005).

Lunar albedo is constant to better than 10⁻⁷%/decade (Kiefer, 1997). The Moon therefore acts as a very low cost and useful calibration stability target for long term Earth observing orbital missions, including the highly stable but non-ERB and relatively narrowband SeaWIFS satellite (Barnes et al., 2004; Hooker et al., 1992). To first order, lunar calibration involves adjustment over time of instrument gain values in Wm⁻²Sr⁻¹/Volt, that convert detector signals to Earth and Moon radiance by multiplication (i.e., such that the Figure 2b MERBE lunar albedo plots all must have zero trends). In addition, lunar albedo can be used to bridge time and space gaps between different satellites as a constant radiometric standard. Ultimately the

![Figure 1.](image-url) Solar power flux arriving at the Top of Earth's atmosphere in the 2000–2015 period, showing a minor −0.029%/decade drop.
Moon’s reflectivity will also be fully SI traceable in the past, present, and future, since eventually it shall be accurately measured using missions in development (Fox et al., 2011; Goldin et al., 2019; Stone et al., 2020; Wielicki et al., 2013). Importantly, lunar calibration and its coming full SI traceability can be applied to existing MERBE data from 2002, when regular CERES orbital device Moon scans began.

It was previously shown that the primary and most used CERES Flight Model “CFM1” instrument, still has significant uncorrected false negative reflected SW calibration drifts in its latest NASA Edition 4.1 release.
These would amount to measuring around \(+0.4 \text{ Wm}^{-2}/\text{decade}\) of false solar warming under a constant Sun (Matthews, 2018b), due to the discussed UV degradation. MERBE has therefore completely recalibrated and regenerated all relevant instantaneous radiative flux data files from CERES devices. This was done using spectral characterization techniques and the Moon as a primary radiometric standard as documented previously (Matthews, 2008, 2009, 2018a, 2018b, 2018c; Matthews et al., 2006, 2007).

2. 2000-2015 NASA CERES Edition 4.1 EBAF Measured Global Albedo Solar Warming Change

ERB scanning instruments built for CERES measure from sun-synchronous US polar orbiting satellites (NASA, 2021), called “Terra” (March 2000\textarrow{\rightarrow}) and “Aqua” (July 2002\textarrow{\rightarrow}). Presently these space platforms have fixed day and night local equatorial crossing times of 10.30 and 13.30, but cover the entire Earth twice each day-night period. For full climate model science validation however, an estimate is needed of the mean radiation budget throughout the entire twenty-four-hour daily timespan. That requires accurate interpolation between these two fixed local time day and night instantaneous CERES flux measurements, stored in hourly files known as “Single Scanner Footprints” (SSF (Geier et al., 2002)). The NASA CERES personnel combine their Terra/Aqua SSF data with cross calibrated geostationary satellite results, for estimation of mean monthly fluxes that account for meteorological changes between the twice daily instantaneous SSF results. This leads to a final monthly averaged product called Energy Balanced and Filled (EBAF), placed in 1\textdegree\times 1\textdegree\ Lon/Lat bins by NASA, to become \(EBAF_{\text{CERES}}\) (Loeb et al., 2018).

Shown in Figure 2a is the anomalous de-seasonalized increase in the latest release of CERES Ed 4.1 EBAF global mean measured albedo solar warming, after weighting each EBAF pixel by its physical area on an Earth spheroid (i.e., from South to North Pole). Essentially this recreates a plot from other works up to 2015 (Dunn et al., 2020), except as previously stated, here it shows just the effects of the pure albedo change assuming the Sun is completely stable. That allows a direct trend comparison with the actual lunar albedo results of Figure 2b and removes the 11 years solar cycle auto-correlation effects, but the slight solar flux drop will also be addressed from now on. The clear Figure 2a positive trend wrongly suggests Earth reflectivity dropped between 2000 and 2015 to let more sunlight in. Numerically, with a global mean reflected SW flux of 99.2 \text{ Wm}^{-2}, the Figure 2a trend translates to an incorrect > 0.41 \text{ Wm}^{-2}/\text{decade} global heating increase rate in solar climate forcing from albedo change, under a constant Sun (and a final 0.38 \text{ Wm}^{-2}/\text{decade} value, with the actual slightly darkening Sun). The Equation 1 two-sigma trend error of \(\pm 0.226 \text{ Wm}^{-2}/\text{decade}\) from Figure 2a results, means according to NASA CERES there should be a very strong rejection of a null hypothesis that solar albedo did not decrease, at the >99.5% confidence level (i.e., in a one tail “t” test). That clearly and will soon be shown falsely suggests the Earth’s reflectivity was not remaining stable but rather decreasing over this period, to make solar albedo warming increase.

\[
\sigma^2 = \left( \frac{1 + \varepsilon}{1 - \varepsilon} \right) \frac{\sum (mt + c - H_t)^2}{(n - 2) \sum (t - \bar{t})^2} \tag{1}
\]

\(H_t\) is the heating rate found in month \(t\) (in decades) and \(m\) and \(c\) are the gradient and offset of the heating data slope over time. \(n\) is the number of months and \(\varepsilon\) is the auto-correlation value between successive data points to account for multiannual oscillations such as ENSO, when extracting a linear trend (i.e., \(H_{t+1} = \varepsilon H_t + \nu\)).

Earth’s temperature response to a change in solar input is complicated, however the Stefan Boltzmann law of physics for a celestial body in space requires that the temperature of that body will eventually adjust, such that its thermal emissions will meet the input from sunlight not reflected. The rapid response to the Pinatubo albedo increase suggests that the lag of Earth’s temperature change beyond a solar impulse can be very short on decadal scales. Some estimates of Earth’s lower troposphere temperature sensitivity to global mean solar input increases are 0.1–0.2\textdegree C/\text{Wm}^{-2}, in terms of changes to solar energy absorbed (Douglass & Clader, 2002; Schmidt, 2017). It is therefore possible that NASA CERES climate data if correct, would hence suggest there should have been a global mean surface temperature increase rate up to +0.074\textdegree C/\text{decade} occurring this century, indirectly due to the slightly dimming Sun. Furthermore if applied such, it would also
incorrectly find the Moon’s albedo to have dropped in the 2000–2015 period, if NASA CERES calibration coefficients were used in MERBE lunar processing.

3. 2000–2015 MERBE Edition 1.0 EBAF-Like Measured Global Albedo Solar Warming Change

Figure 2b shows the mentioned MERBE albedo data from the Moon, rather than the Earth albedo solar warming plots above and below. These two displayed separate Figure 2b results were taken by the most used CERES instruments called CFM1 on the EOS Terra satellite, and CFM3 on Aqua (although Terra’s CFM2 has been recalibrated by MERBE also (Matthews, 2018a)). A fundamental MERBE principal is that instrument calibration parameters used have to meet established NASA solar criteria (Priestley et al., 2011). At the same time though, they must additionally result in no statistically significant trends in final measured lunar albedo (Figure 2b).

As shown elsewhere, the first of these goals is achieved with an order of magnitude improvement in accuracy over NASA CERES (Matthews, 2018b). Random sampling errors are also reduced at least by a similar amount, using “Impulse Enhancement” of detector time constants (Matthews, 2018c), making remaining detector noise around 1/100%.

The second lunar calibration goal is reached with < ±0.104 Wm⁻²/decade two sigma stability error confidence for Terra, and ±0.147 Wm⁻²/decade for the newer Aqua satellite ((Matthews, 2018a), with values found also using Equation 1). These numbers can be compared to the two sigma ±0.3 Wm⁻²/decade stability figure, claimed by NASA over decadal periods and assumed for CERES by climatologists (Dessler, 2010; Loeb et al., 2007; Trenberth et al., 2014).

As mentioned, fixed time day and night instantaneous Terra/Aqua ERB flux measurements are stored in instantaneous hourly SSF files by NASA, 30 TB of which have had their ERB results completely recalibrated and regenerated by MERBE. Monthly means of both lunar calibrated MERBE SW SSF and CERES SW SSF (rather than EBAF) irradiances are collected by MERBE in the same 1° x 1° Lon/Lat bins, to become SSF_merbe and SSF_ceres. The NASA CERES specific EBAF_ceres / SSF_ceres ratio is multiplied with new MERBE SSF fluxes as in Equation 2. This includes the CERES estimates for the diurnal cycle between the twice daily instantaneous SSF results, but makes CERES calibration errors largely systematic in numerator and denominator.

Now, with the MERBE greater calibration accuracy and stability, a new version of NASA’s product is created called “EBAF–like,” independent of CERES calibration:

\[
\text{EBAF–like } = \text{SSF}_\text{merbe} \times \frac{\text{EBAF}_\text{ceres}}{\text{SSF}_\text{ceres}}
\] (2)

MERBE EBAF-like global net average solar heating change estimate results are displayed in Figure 2c. They show a very slight albedo solar forcing rise, amounting to a +0.054 Wm⁻²/decade albedo solar warming rate increase (representing +0.025 Wm⁻²/decade Earth solar warming for the real slightly dimming Sun). The MERBE plots of lunar albedo and pure Earth albedo heating in Figures 2b and 2c respectively, provide visual reassurance of the expected stability of the lunar albedo and the corresponding removal of the apparent CERES trend in the Earth albedo heating from Figure 2a. At less than a third the trend’s 95% confidence limit of ±0.189 Wm⁻²/decade from Equation 1, there is no statistical significance to the Figure 2c MERBE Earth trend, and very good confidence in accepting the null hypothesis of no albedo solar warming (one tail t test).

4. MERBE Data Impact on Cloud Feedback/Forcing Prediction Science

MERBE results disagree with those previously reported for NASA CERES, to show Earth albedo not to have changed between 2000 and 2015. These monthly mean MERBE EBAF-like incoming and reflected solar results can be downloaded on the EBAF 1° x 1° Lon/Lat grid, from a FAIR compliant site (Pan-gaea, 2021a, 2021b). The earlier quoted and higher CERES trend uncertainty of 0.226, versus 0.189 Wm⁻²/decade for MERBE, is likely because non-linear calibration artifacts exist in CERES results, as previously
shown (Matthews, 2018b). These act like false multi-year ENSO-like time cycle effects to cause a higher $\epsilon$ value in Equation 1, potentially steering climate model ENSO simulations in a wrong direction.

Spatial trend analysis can also be performed on the MERBE results as in Figure 3, to determine two sigma statistically significant heating and cooling regions purely from changes to Earth reflectivity (under a two-tail $t$ test). These trends are shown projected on an Authagrapth Earth map, to give equal visual area weighting for regions of solar warming and cooling in Wm$^{-2}$/decade. In this plot regions where there is a significant positive trend in solar forcing are shown in red and those with significant increasing trends in reflected shortwave are shown in blue, with regions with no significant trend remaining white. It can be seen from this figure that net rise in solar forcing in the warming Northern Arctic from melting sea ice is balanced by increases in reflectively elsewhere. The global result of these two competing effects as, perhaps a result of cloud feedbacks, is no net albedo change in the MERBE results in Figure 2c.

In further regard to the cloud forcing/feedback climate model prediction validation mentioned in the introduction, previous studies began by considering purely theoretical ERB instruments with perfect calibration (Wielicki et al., 2013), whose climate detection estimates are displayed in the left black curve of Figure 4a. This curve shows that due to natural variability by itself, even with zero errors in calibration, it would still take more than 12 years of continuous data to detect the maximum sized 0.8 Wm$^{-2}$/decade model predicted CRF signal. This would require the Figure 4a black curve crossing the threshold marked by the dashed horizontal green line. The same NASA statistical studies in addition found ways to combine this natural climate variability noise with various different levels of ERB calibration accuracy, as also shown in all curves of Figure 4a (credited to the same previous work (Wielicki et al., 2013)).

Figure 4b uses the Figure 4a curves above, but now plots against date accounting for the start of each mission. NASA made a 1.8% two sigma estimate of CERES data calibration accuracy beginning in March 2000. Assuming that is, correct, it would take at least a decade from 2021 for the NASA CERES solar climate observing system to even begin detecting any predicted CRF signals in albedo change warming/cooling (with 95% confidence). A proposed improved climate observing mission called CLARREO “Pathfinder” or CPF, is now underway and currently intended to be operated from the international space station by a target date of 2023 (Thome & Aytac, 2019). CPF will strive to achieve spectral resolution and a 0.6% absolute calibration accuracy with two sigma confidence, which might be transferred to ERB instruments like CERES in-flight (Goldin et al., 2019; Wielicki et al., 2013). However, if achieved as per the right red curve of Figure 4b, this CPF start date and the resulting improved climate observing system will not allow better model prediction validation to begin until after 2040 (i.e., nearly ten years after CERES, by NASA's own estimates).
For comparison and discussion in the final section, the same techniques produce the MERBE left blue curve also in Figure 4b, suggesting a potentially far earlier arrival of better model validation.

5. Summary and Conclusions

The Moon's constant albedo reflects light from the Sun containing UV where instrument degradation occurs, no wavelengths from which are emitted by CERES on board tungsten lamps, that NASA uses to update their SW calibration coefficients (Loeb et al., 2007). However, seeing a drop in raw signal from the Moon allowed MERBE to track telescope UV degradation, which would have been undetectable via the calibration techniques applied to the data by NASA. That made it possible to compensate for the largely negative CERES instrumental drifts found previously (Matthews, 2018b), by changing the radiometric instrument gain numbers.

CERES SW data that is, currently being used to steer climate models without such corrections therefore does not have the two sigma calibration stability of ±0.3 Wm⁻²/decade assumed by scientists (Dessler, 2010; Trenberth et al., 2014). More specifically this is because such NASA stability claims are based on no direct scientific physical evidence, using Top of Atmosphere (TOA) upwelling ERB result anti-correlations with largely modeled narrow-band ocean-only surface downwelling data only up to 2007 (Loeb et al., 2007, 2018).

The Figure 2a CERES albedo solar warming results presented here as stated have been shown in similar formats by other works, independent of this study (Dunn et al., 2020; Loeb et al., 2018, 2020). When analyzed statistically for trend errors, they would agree with these findings showing that the NASA CERES climate data set wrongly suggests with better than two sigma confidence, that the Earth global average reflectivity was not stable and decreased in the 15 years after 2000. This is equivalent to an albedo solar warming change rate around as large as +0.41 Wm⁻²/decade, which is close to the earlier +0.4 Wm⁻²/decade false calibration trend predicted (Matthews, 2018b). Climate models such as the CMIP series have been compared to CERES TOA fluxes for validation. This means those models overestimating recent warming, may be given higher weighting in scientific analysis, which could lead to a possibly incorrect “missing heat” finding. Hence also, that false CERES measured albedo drop might be enough to wrongly support the argument, that the Sun alone is responsible for close to half of the 0.3°C global temperature warming seen this century.

The fact of increasing CERES measured outgoing Infra-Red or LongWave (LW) fluxes between 5 and 200μm in the same period, is often used to explain and balance the net ERB with the albedo drop (Loeb et al., 2020). That however makes no difference to the false conclusion on rising Earth temperature, from blackbody physics. This warrants further investigation with the coming MERBE Edition 2 blackbody and lunar calibrated LW fluxes, past 2020.

In contrast to NASA CERES, MERBE finds no solar warming trend, showing that when referenced to a constant lunar albedo, the Earth albedo is also constant over time. This shows the Sun plays no part in current global warming.
Figure 3a spatially resolved MERBE results indicate that large increases in solar heating at the melting Northern Arctic, are balanced globally by increases in reflectivity elsewhere at lower latitudes, likely due to negative feedback cloud changes. The recently mentioned future MERBE data Edition 2 releases, will include the lunar stabilized LW global fluxes (Matthews, 2018a, 2018b). Then similar highly accurate spatial tracking like that of Figure 3 can be produced, for example, showing the needed measurements of ocean heat storage changes across the globe (Hansen et al., 2011). Also, large-scale oscillation studies can be performed over more than two decades, to validate simulations of their changes to cloud distributions etc. The 2000–2015 time frame encompasses multiple ENSO cycles, which themselves also need investigation in terms of multi-decadal CRF effects on long term trends, beyond the treatment here of adding their error effects with the Equation 1 auto-correlation “ε” factor.

As an update to NASA CLARREO findings (Wielicki et al., 2013), the equations that created Figure 4a were used to generate the blue lunar calibrated MERBE curve also shown in Figure 4b, as mentioned at the end of the last section. This was conservatively done using the root mean square MERBE lunar trend accuracy numbers also from Equation 1, which are themselves inflated by only 15 years of sampling noise (rather than the ultimate lunar albedo stability of 10⁻⁷%/decade). By NASA’s methodology, the suggestion is that the maximum CRF model predicted climate change signals could begin to be seen immediately in MERBE measurements after 2016. Furthermore, and again because it corrects data in the past, application of the same statistical techniques finds that in 2024, the coming MERBE Edition 2 could be capable of detecting a predicted CRF climate signal change of around 0.4 Wm⁻²/decade in size (Terra will currently de-orbit in 2026). MERBE may then aid in halving the greatest of climate model prediction uncertainties. Given CERES inaccuracy and a yet to be launched CPF, this will potentially be a quarter century sooner than any other official existing, or even proposed future ESA/NASA orbiting Earth observing missions could on their own. That must not detract from the importance of continuing ERB measurements, say with the new SI traceable CERES follow on currently named “Libera,” and spectrally resolving CLARREO-like endeavors. This is because as per the example mentioned, improved absolute accuracy is needed by MERBE to extend full SI traceability back to 2002, through the Moon.

In conclusion, the last two US National Academy of Science decadal survey reports and climate observation communities have been requesting a better orbital climate observing system for many years, to improve climate change prediction certainty. Use of independent ESA/NASA analysis, shows the newly available MERBE results to fulfill a large part of such requests today (Wielicki et al., 2013), rather than in decades time with official data. This is because it uses an existing stable source, the Moon, to uncover and correct drifts in records beginning 20 years ago, improving the stability and relative accuracy by an order of magnitude over existing techniques employed by NASA.

Data Availability Statement
MERBE EBAF-like Ed 1.0 incoming and reflected solar results are down-loadable at the FAIR compliant site (Pangaea, 2021a, 2021b).

References
Barnes, R. A., Eplee, R. E., Patt, F. S., Kieffer, H. H., Stone, T. C., Meister, G., et al. (2004). Comparison of seafwfs measurements of the moon with the U.S. geological survey lunar model. Applied Optics, 43(31), 5838–5854. https://doi.org/10.1364/ao.43.005838
Bony, S., Colman, R., Kattsov, V. M., Allan, R. P., Bretherton, C. S., Dufresne, J., et al. (2006). How well do we understand and evaluate climate change feedback processes? Journal of Climate, 19(15), 3445–3482. https://doi.org/10.1175/jcli3819.1
Cooke, R., Wielicki, B. A., Young, D. F., & Mlynczak, M. G. (2013). Value of information for climate observing systems. Environment Systems and Decisions, 34(1), 98–109. https://doi.org/10.1007/s10669-013-9451-8
Dessler, A. E. (2010). A determination of the cloud feedback from climate variations over the past decade. Science, 330, 1523–1527. https://doi.org/10.1126/science.1192546
Douglass, D. H., & Clader, B. D. (2002). Climate sensitivity of the earth to solar irradiance. Geophysical Research Letters, 29(16), 1–4. https://doi.org/10.1029/2002gl015345
Dunn, R. J. H., Staniski, D. M., Gobron, N., & Willett, K. M. (2020). State of the climate in 2019. Bulletin of American Meteorological Society, 101(8), S9–S128. https://doi.org/10.1175/2020bamsstateoftheclimate_intro.1
Fox, N., Kaiser-Weiss, A., Schmutz, W., Thome, K., Young, D., Wielicki, B. A., et al. (2011). Accurate radiometry from space: An essential tool for climate studies. Philosophical Transactions of the Royal Society A, 369, 4028–4063. https://doi.org/10.1098/rsta.2011.0246
Geier, E. B., Green, R. N., Kratz, D. P., & Minnis, P. (2002). Collection guide for single scanner footprint, toa and surface flux, clouds. Retrieved from https://ceres.larc.nasa.gov/documents/collect_guide/pdf/SSF_CG_R2V1.pdf

Acknowledgments
CERES instantaneous SSF and EBAF Ed 4.1 flux results were obtained from the NASA LaRC Atmospheric Science Data Center.
Goldin, D., Smith, G. L., Thomas, S., Cooper, D., Lee, R. B., Wallikainen, D., & Wilson, R. (2019). Claroero pathfinder/viirs intercalibration: Quantifying the polarization effects on reflectance and the intercalibration uncertainty. Remote Sensing, 11(16), 1914. https://doi.org/10.3390/rs11161914

Haigh, J. D. (1996). The impact of solar variability on climate. Science, 272(5264), 981–984. https://doi.org/10.1126/science.272.5264.981

Hansen, J., Sato, M., Kharecha, P., & Schuuckmann, K. (2011). Earth’s energy imbalance and implications. Atmospheric Chemistry and Physics, 11, 13421–13449. https://doi.org/10.5194/acp-11-13421-2011

Hooker, S. B., Essaias, W. E., Feldman, G. C., Gregg, W. W., & McClain, C. R. (1992). An overview of seafwfs and ocean color. In Seafwfs technical report series (Vol. 104566). NASA Goddard Space Flight Center.

Kiefer, H. H. (1997). Photometric stability of the lunar surface. Icarus, 130, 323–327. https://doi.org/10.1006/icar.1997.5822

LASP (2021). Solar radiation and climate experiment. Retrieved from http://lasp.colorado.edu/sorce/

Loeb, N., Wielicki, B. A., Duvel, J. P., Priestley, K. J., & Viollier, M. (2020). New generation of climate models track recent unprecedented changes in earth’s radiation budget observed by ceres. Geophysical Research Letters, 47(5), e2019GL086705. https://doi.org/10.1029/2019GL086705

Loeb, N. G., Doelling, D. R., Wang, H., Su, W., Nguyen, C., Corbett, J. G., et al. (2018). Clouds and the earth’s radiant energy system (ceres) energy balanced and filled (ebaf) top-of-atmosphere (toa) edition-4.0 data product. Journal of Climate, 31(2), 895–918. https://doi.org/10.1175/jcli-d-17-0208.1

Loeb, N. G., Wielicki, B. A., Su, W., Loukachine, K., Sun, W., Wong, T. M., & Davies, R. (2007). Multi-instrument comparison of top-of-atmosphere reflected solar radiation. Journal of Climate, 20(3), 575–591. https://doi.org/10.1175/jcli4018.1

Matthews, G. (2006). Celestial body irradiance determination from an under-filled satellite radiometer: Application to albedo and thermal emission measurements of the moon using ceres. Applied Optics, 47(28), 4981–4993. https://doi.org/10.1364/aao.47.004981

Matthews, G. (2009). In-flight spectral characterization and calibration stability estimates for the clouds and the earth’s radiant energy system (ceres). Journal of Atmospheric and Oceanic Technology, 26(9), 1635–1617. https://doi.org/10.1175/2009jtecha1243.1

Matthews, G. (2018a). First decadal lunar results from the moon and earth radiation budget experiment (merbe). Applied Optics, 57(7), 1594–1610. https://doi.org/10.1117/12.2000051

Matthews, G. (2018b). Real-time determination of earth radiation budget spectral signatures for non-linear un-filtering of results from merbe. Journal of Applied Meteorology and Climatology, 57(2), 273–294. https://doi.org/10.1175/jamc-d-16-0406.1

Matthews, G. (2018c). Signal processing enhancements to improve instantaneous accuracy of a scanning bolometer: Application to merbe. IEEE Transactions on Geoscience and Remote Sensing, 56(6), 3421–3431. https://doi.org/10.1109/tgrs.2018.2799823

Matthews, G., Priestley, K., Loeb, N. G., Loukachine, K., Thomas, S., Wallikainen, D., & Wielicki, B. A. (2006). Coloration determination of spectral darkening occurring on a broadband earth observing radiometer: Application to clouds and the earth’s radiant energy system (ceres). Proceedings of SPIE, 6296, 62960M. https://doi.org/10.1117/12.660884

Matthews, G., Priestley, K., & Thomas, S. (2007). Transfer of radiometric standards between multiple low earth orbit climate observing broadband radiometers: Application to ceres. Proceedings of SPIE, 6767, 67670U. https://doi.org/10.1117/12.734478

NA (2021). Decadal survey page. Retrieved from https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth

NASA. (2021). Earth observing system terra, aqua and npp. Retrieved from https://eospso.nasa.gov/current-missions

Pangaea (2021a). Merbe ed1.0 incoming solar data download. https://doi.org/10.1594/PANGAEA.931778

Pangaea (2021b). Merbe ed1.0 reflected solar data download. https://doi.org/10.1594/PANGAEA.931779

Priestley, K. J., Smith, G. L., Thomas, S., Cooper, D., Lee, R. B., Wallikainen, D., et al. (2011). Radiometric performance of the ceres earth radiation budget climate record sensors on the eos aqua and terra spacecraft through april 2007. Journal of Atmospheric and Oceanic Technology, 28(1), 3–21. https://doi.org/10.1175/2010jtech1521.1

Ramanathan, V., Cess, R. D., Harrison, E. F., Minnis, P., Barkstrom, B. R., Ahmad, E., & Hartmann, D. (1989). Cloud-radiative forcing and feedback by water vapor. Science, 243(4887), 57–63. https://doi.org/10.1126/science.243.4887.57

Schmidt, G. (2017). Why the sun is not responsible for recent climate change. Retrieved from https://www.carbonbrief.org/why-the-sun-is-not-responsible-for-recent-climate-change

Soden, B. J., Wetherald, R. T., Stenchikov, G. I., & Robock, A. (2002). Global cooling after the eruption of mount pinatubo: A test of climate feedback by water vapor. Science, 296(5568), 727–730. https://doi.org/10.1126/science.296.5568.727

Stone, T. C., Wielicki, B. A., Duvel, J. P., Priestley, K. J., & Viollier, M. (2020). The moon as a climate-quality radiometric calibration reference. Remote Sensing, 12(11), 1837. https://doi.org/10.3390/rs12111837

Thome, K., & Aytac, Y. (2019). Independent calibration approach for the claroero pathfinder mission. In Imaging spectrometry XXIII: Applications, sensors, and processing (pp. 11130). https://doi.org/10.1117/12.2529215

Trenberth, K. E., Fasullo, J. T., & Balmaseda, M. A. (2014). Earth’s energy imbalance. Journal of Climate, 27(9), 3129–3144. https://doi.org/10.1175/jcli-d-13-00294.1

Wielicki, B. A., Barkstrom, B. R., Harrison, E. F., Lee, R. B., Smith, G. L., & Cooper, J. E. (1996). Clouds and the earth’s radiant energy system (ceres): An earth observing experiment. Bulletin of American Meteorological Society, 77, 853–868. https://doi.org/10.1175/1520-0477(1996)077<0853:cate>2.0.co;2

Wielicki, B. A., Mlynczak, M. G., Thome, K., Leroy, S., Corliss, J., Anderson, J. G., et al. (2013). Achieving climate change absolute accuracy in orbit. Bulletin of American Meteorological Society, 94, 1519–1539. https://doi.org/10.1175/bams-d-12-00149.1

Wielicki, B. A., Wong, T. M., Loeb, N. G., Minnis, P., Priestley, K., & Kandel, R. (2005). Changes in earth’s albedo measured by satellite. Science, 308(5723), 825. https://doi.org/10.1126/science.1106484