



From opportunity to continuity: a CubeSat implementation to enhance Earth's radiation budget observations from space

McKenzie A. Hawkins^{1,2}, Matthew Watwood^{1,2}, Mathew van den Heever^{1,3}, Peter Pilewskie^{1,2}, and Dave Harber¹

¹Laboratory for Atmospheric and Space Physics, Boulder, CO 80303, United States of America

²Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, CO 80303, United States of America

³Department of Aerospace Engineering, University of Colorado Boulder, Boulder, CO 80303, United States of America

Correspondence: McKenzie A. Hawkins (mckenzie.hawkins@lasp.colorado.edu)

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Abstract. Earth's radiation budget (ERB) is an essential climate variable, and its continuous observation from space is critical to understanding long-term climate change. The Clouds and Earth's Radiant Energy System (CERES) has maintained the longest continuous ERB record since 2000, with its follow-on mission, Libera, launching in 2027 with a 5-year prime mission lifetime. Beyond Libera, plans for ERB continuity remain uncertain, increasing the possibility of future gaps in the record. The Compact Total Irradiance Monitor (CTIM) was a 6U CubeSat developed under the NASA In-Space Validation of Earth Science Technologies (InVEST) program to measure total solar irradiance (TSI). Launched in July 2022 and operating until December 2023, CTIM collected climate-quality science data at an uncertainty of 0.017 %. During orbital eclipse, CTIM was pointed in the nadir direction to measure Earth's outgoing longwave emission, exploring the Earth-observing potential of an instrument designed for TSI. These measurements were compared to coincident CERES observations aboard Terra, Aqua, and NOAA-20. Additional adjustment factors for limb darkening were derived from radiative transfer simulations over a variety of scene types and atmospheric conditions and applied to CERES non-nadir viewing observations to better match the CTIM nadir observations and explain some of the variance exhibited between measurements. The resulting comparisons show an overall relative agreement of 1.2 %, within the respective instrument uncertainties. This study demonstrates that leveraging CubeSat technology could complement heritage ERB missions and reduce the risk of future observation gaps. The routine inclusion of Earth-viewing capabilities in future TSI instrument designs

represents a natural extension of this work, with the potential to meaningfully contribute to ERB observation continuity and reduce the risk of gaps in future ERB observations from space.

1 Introduction

The Earth's Radiation Budget (ERB) characterizes the flow of radiative energy from the Sun into the Earth system and out of the system as reflected solar (shortwave) and emitted terrestrial (longwave) radiation. The system is in equilibrium when the difference between incoming and reflected solar radiation, or absorbed solar radiation, is balanced by the emitted terrestrial radiation (Loeb et al., 2016; Stephens et al., 2012; von Schuckmann et al., 2016). Imbalances in the radiation budget arise due to climate forcings, feedback mechanisms, and internal variability (Forster et al., 2021; Loeb et al., 2024). The energy exchanges driven by these factors are represented in the ERB, making it a fundamental quantity for monitoring global climate change: when Earth absorbs more (less) energy than it emits over time, global mean surface temperature increases (decreases), as the climate system adjusts toward equilibrium (Loeb et al., 2018b; von Schuckmann et al., 2023). Larger departures from equilibrium trigger amplified responses to restore balance, and the resulting changes are manifested in the ERB on decadal-to-centennial timescales (Barkstrom and Smith, 1986; Dewitte and Clerbaux, 2018). Because the ERB responds over decadal-to-centennial timescales, accurate and continuous

monitoring of incoming and outgoing radiation is essential for understanding climate change. These long-term observations not only reveal the mechanisms driving climate shifts but also help inform mitigation strategies for managing future climate risks.

Both the Intergovernmental Panel on Climate Change (IPCC) (Forster et al., 2021) and the most recent Earth Decadal Survey (National Academies of Sciences, 2018) designate ERB observations as essential for determining the current energy imbalance and predicting future climate. Moreover, the ERB is designated as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS), operating under the coordination of the World Meteorological Organization (WMO), emphasizing the necessity for continuous, accurate monitoring of Earth's radiative energy (World Meteorological Organization, 2023).

Since the launch of Explorer 7 in 1959, the first satellite with a dedicated ERB instrument to provide usable measurements, satellite missions have provided essential observations of the ERB on a global scale (House et al., 1986; Vonder Haar et al., 2026). The Clouds and the Earth's Radiant Energy System (CERES) instruments began the longest continuous record of Earth's radiative energy system, extending from 2000 to the present (CERES first flew on Tropical Rainfall Measuring Mission in the late 1990s, without global coverage or data continuation through 2000; Loeb et al., 2024; Minnis et al., 2023). To ensure the continuation of the record, the National Aeronautics and Space Administration's (NASA) first Earth Venture Continuity mission, Libera, will provide seamless overlap and continuity of ERB observations with CERES in 2027 (Pilewskie et al., 2022).

Six CERES instruments aboard four satellites – Flight Model-1 (FM-1) and FM-2 on Terra, FM-3 and FM-4 on Aqua, FM-5 on Suomi-National Polar-Orbiting Partnership (S-NPP), and FM-6 on NOAA-20 – have collectively provided over 26 years of measurements of reflected solar radiation and emitted longwave radiation, delivering state-of-the-art, continuous observations of Earth's radiative energy budget (Priestley et al., 2018; Su et al., 2020). Despite this success, sustaining the ERB record faces increasing challenges. As the CERES instruments on Terra and Aqua near the end of their operational lives in 2027, and potentially CERES on S-NPP in 2026, it is likely that CERES FM-6 aboard NOAA-20 will be the only instrument to overlap with Libera when it launches on Joint Polar Satellite System-4 (JPSS-4) in late 2027 (Loeb et al., 2024). Libera reaches its prime mission end-of-lifetime by 2033, with no planned ERB missions to follow. From this operational timeline, Loeb et al. (2024) determine that as the number of ERB instruments decreases from four to one in just 6 years, the estimated probability of an ERB data gap reaches 33 % by 2028 and rises to 60 % by 2035 if Libera remains operational. Loeb et al. (2024) further show that the method for bridging an observational gap produces errors roughly four times larger than when successive missions overlap.

These projections highlight the urgency for next-generation ERB instruments and complementary observing strategies that are accurate, stable over time, and more cost effective than current designs. Without such innovations, gaps in the ERB record become increasingly likely, threatening the continuity required for reliable Climate Data Records (CDRs). Increasing overlap between successive missions and exploring complementary observing platforms, including emerging CubeSat platforms for ERB, offers practical strategies to mitigate these risks, providing redundancy, flexible launch opportunities, and enhanced intercalibration with larger missions (Gristey et al., 2017; Harber et al., 2019; Swartz et al., 2019).

Recognizing that CubeSats have the potential to mitigate gaps in measurements where continuity is critical and to enable new approaches to Earth observations, the National Academies of Sciences (2016) recommended that NASA increase its investment and coordination of CubeSat missions across science disciplines, a recommendation reflected in the growing number of NASA-funded CubeSat missions for Earth science, including ERB observations. This momentum extends internationally, with several recent missions collectively demonstrating the viability of small satellite platforms for ERB observations. The Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) 3U CubeSat, launched in 2016 under NASA's Earth Science Technology Office (ESTO) In-Space Validation of Earth Science Technologies (InVEST) program, was an early pathfinder demonstrating that broadband ERB observations of outgoing radiation could be made from a CubeSat platform, establishing an important benchmark for future CubeSat ERB constellation concepts (Swartz et al., 2019). NASA's Polar Radiant Energy in the Far-Infrared Experiment (PREFIRE), a pair of polar-orbiting CubeSats launched in 2024, addresses a long-standing gap in Earth-observing capability by providing the first systematic spectral measurements of far-infrared emissions at Earth's poles (Drouin et al., 2026). The French Uvsq-Sat nanosatellite, launched in 2021, and its sister satellite Inspire-Sat, launched in 2023, constitute the first European CubeSat constellation demonstrator dedicated to broadband wide-field-of-view (WFOV) measurements of Earth's outgoing radiation (Meftah et al., 2022, 2025). The follow-on Uvsq-Sat NG, a 6U CubeSat mission launched in 2025, aims to extend and improve the ERB record with enhanced measurement stability and capabilities (Meftah et al., 2023). The proposed Black Array of Broadband Absolute Radiometers Earth Radiation Imager (BABAR-ERI) 12U CubeSat similarly aims to demonstrate inexpensive, low-risk ERB measurements complementary to larger missions, further exemplifying the growing role of small satellite platforms in future ERB observing strategies (Coddington et al., 2025b).

This paper introduces one promising application to support continuity in the future ERB record by using Earth-viewing measurements from solar irradiance sensors, as demonstrated by the Compact Total Irradiance Monitor

(CTIM). CTIM (Fig. 1) was a 6U CubeSat built at the Laboratory for Atmospheric and Space Physics (LASP) and developed under the NASA ESTO InVEST program to measure total solar irradiance (TSI). CTIM was launched July 2022, collecting climate-quality solar irradiance data at an uncertainty of 0.017 % until end-of-mission in December 2023 (Flynn et al., 2024). During orbital eclipse (i.e., Earth nighttime), CTIM was pointed in the nadir direction to opportunistically measure Earth's outgoing longwave radiation. We leveraged this unique opportunity to evaluate the CTIM data against coincident CERES data.

This paper compares CTIM outgoing longwave radiance measured during orbital eclipse with coincident CERES observations to determine and utilize opportunistic CTIM Earth-observing applications for complementing future ERB missions. In doing so, we suggest that future implementations of this type can bridge gaps in ERB observations from space, extending and enhancing CDRs with additional ERB measurements that will deepen the understanding of the causes of climate change and predict future climate change more accurately. Section 2 provides an overview of the CERES and CTIM instruments. Section 3 introduces the preliminary analyses of CTIM longwave radiance observations that established the foundation for comparative analysis with CERES. Section 4 details the algorithm created to spatiotemporally match CTIM and CERES observations. Section 5 presents the adjustment factors created to reduce the spread in differences that resulted from viewing geometry differences. Section 6 provides results of the longwave radiance comparisons. Section 7 synthesizes the overall results of the study and discusses the future of complementary CubeSat observations for ERB record continuity.

2 Instrument Background

2.1 Clouds and Earth's Radiant Energy System (CERES)

Since 2000, the CERES instruments onboard the Terra, Aqua, S-NPP, and NOAA-20 satellites have provided the most spatially and temporally complete record of global shortwave and longwave top-of-atmosphere (TOA) radiative fluxes (Taylor et al., 2022). The CERES instruments have operated on satellites with sun-synchronous orbits: Terra operates with a Local Time of Descending Node (LTDN) of approximately 10:30, while Aqua, S-NPP, and NOAA-20 operate with a Local Time of Ascending Node (LTAN) of approximately 13:30 (NOAA Office of Satellite and Product Operations, 2025; Loeb et al., 2018a; Meftah et al., 2025). Terra and Aqua orbit at an altitude of 705 km, while S-NPP and NOAA-20 orbit at 824 km (Shankar et al., 2023). Each CERES instrument is a narrow field-of-view (NFOV) scanning broadband radiometer, which uses thermistor-based bolometers to acquire radiometric measurements (Wielicki

et al., 1996). CERES instruments aboard Terra, Aqua, and S-NPP measure broadband radiances at the TOA in three spectral regions: shortwave (0.3–5 μm), total (0.3–200 μm), and window (8–12 μm); broadband longwave radiation is estimated as the total minus the shortwave. The CERES FM-6 aboard NOAA-20 replaced the window channel with a longwave channel that measures from 5–35 μm (Thomas et al., 2024).

The CERES broadband radiances are converted to irradiances using scene-dependent inversion algorithms based on angular distribution models (ADMs). Before inversion, the radiances are spectrally “unfiltered” to remove the effects of the instrument's spectral response function (Loeb et al., 2001). The resulting irradiances provide a benchmark for quantifying the ERB and for constraining climate model simulations.

2.2 Compact Total Irradiance Monitor (CTIM)

On 2 July 2022, CTIM was launched into a 45° inclination, non-sun-synchronous orbit at an altitude of approximately 500 km with a 1-year mission lifetime goal to demonstrate next-generation technology for monitoring TSI. It returned science data beyond its mission lifetime goal until re-entry in early December 2023 (Flynn et al., 2024). CTIM used electrical substitution radiometers (ESRs) with a vertically aligned carbon nanotube (VACNT) absorber and a thermally integrated reflective dome to capture any remaining unabsorbed incident radiation. A 5 mm diameter precision aperture defined the TSI measurement area (Harber et al., 2019). CTIM accommodated two independent detector heads, each with four TSI channels. One primary channel on each of the detector heads received maximum solar exposure, while the remaining three were operated at varying cadences to track the detector degradation to maintain stability over time. The CTIM VACNT detectors were nearly ideal optical absorbers from the UV through the IR, with an effective absorptance (when used in tandem with the dome) exceeding 99.9 % (Harber et al., 2019; Tomlin et al., 2020). As a next-generation technology demonstration for TSI, CTIM successfully measured TSI within 0.04 % of the Total Irradiance Monitor (TIM) measurements from the Total and Spectral Solar Irradiance Sensor (TSIS-1) mission (Fig. 2). In addition, CTIM demonstrated measurements of TSI with long-term stability comparable to that of TSIS-1 TIM (Coddington et al., 2025a). Beyond the primary mission to measure TSI, the CTIM Earth-viewing observations provided ample data to explore its observational capabilities of Earth's outgoing radiation.

3 CTIM Earth-Viewing Observations

CTIM observed deep space every other eclipse to establish the instrument dark model (Harber et al., 2019). Dur-

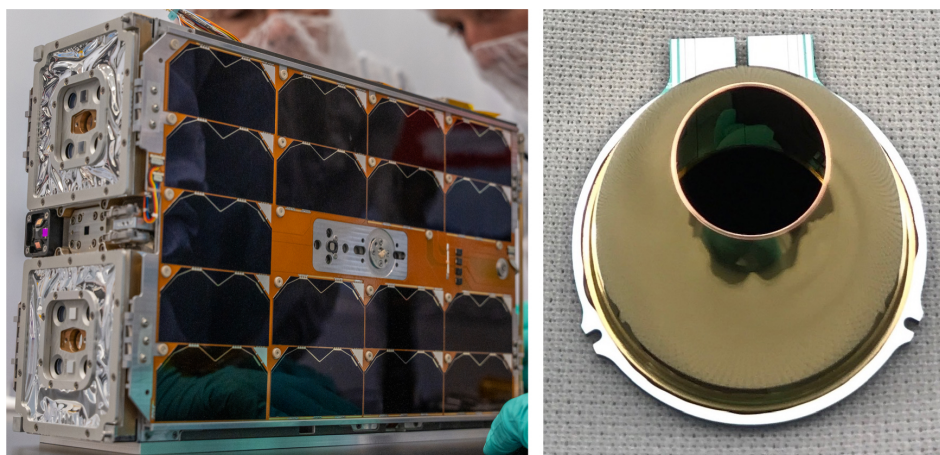


Figure 1. The Compact Total Irradiance Monitor prior to launch vehicle integration (left) and the detector (right).

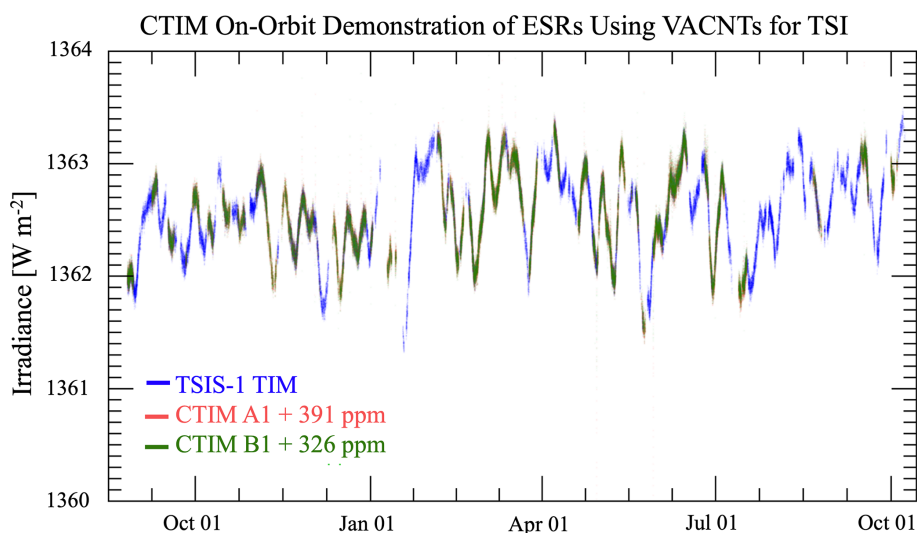


Figure 2. CTIM measured TSI from dual detector heads, A1 and B1, compared to the TSI measured by TSIS-1 TIM.

ing the other eclipse periods, the instrument was pointed at Earth nadir, collecting 28 321 observations of the outgoing terrestrial longwave radiance from 26 August 2022 through 18 November 2023. CTIM continued to acquire TSI measurements during the remainder of the orbit, while occasionally observing the sunlit Earth a total of 4633 times between 27 August 2022 and 24 August 2023. We converted the CTIM calibrated irradiance from the earth-viewing measurements to radiance (Sect. 3.1), separated the day and night observations (Sect. 3.2), and conducted preliminary longwave radiance analyses (Sect. 3.3), which became the groundwork for comparative analyses with CERES observations in this study.

3.1 CTIM Irradiance-to-Radiance Conversion

Because CTIM was designed to measure TSI, it was calibrated in irradiance, requiring a conversion to radiance for

comparing to the CERES directly measured radiance. The relationship between CTIM irradiance, F , and radiance, L , over the CTIM angular field-of-view (FOV) is given by:

$$F = \int_0^{2\pi} \int_0^{\pi/2} L(\theta, \varphi) r(\theta, \varphi) \sin\theta d\theta d\varphi \quad (1)$$

where $L(\theta, \varphi)$ is the directionally dependent radiance within the CTIM view, $r(\theta, \varphi)$ is the normalized CTIM angular response with respect to normal, and θ and φ are polar and azimuth angle, respectively.

Since r was azimuthally symmetric, we can rewrite Eq. (1):

$$F = \bar{L} \Omega_e \quad (2)$$

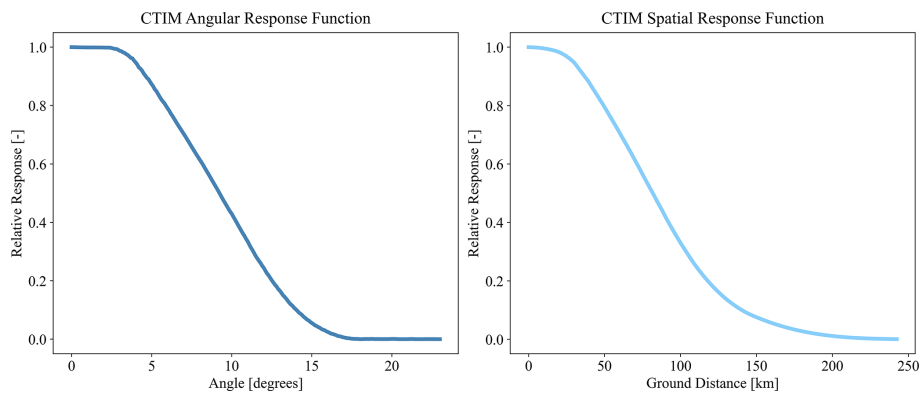


Figure 3. (Left) CTIM angular response function. The x axis shows the angle of incidence of incoming radiation, and the y axis shows the detector's normalized response. The angular response reached zero at 23° . (Right) CTIM spatial response function. The x axis shows the ground-distance equivalent of the angular response and the y axis shows the detector's normalized response. The spatial response (derived from a CTIM altitude of 453 km, accounting for along-track motion blurring) reached zero at 242 km, which was determined to be the CTIM footprint radius.

where,

$$\bar{L} = \frac{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} L(\theta, \varphi) r(\theta) \sin \theta d\theta d\varphi}{2\pi \int_0^{\frac{\pi}{2}} r(\theta) \sin \theta d\theta} \quad (3)$$

and *effective* solid angle, Ω_e , is

$$\Omega_e = 2\pi \int_0^{\frac{\pi}{2}} r(\theta) \sin \theta d\theta \quad (4)$$

Based on measurements conducted in lab, the CTIM off-normal angular response (Fig. 3, left) reached zero at 23° . Note that while the integration limits in Eqs. (1), (3), and (4) extend to $\pi/2$, the CTIM angular response $r(\theta)$ reached zero at approximately 23° . Numerical integration of Eq. (4) resulted in an effective CTIM solid angle of 0.0939 sr; substitution in Eq. (2) was used to compute mean radiance from the measured irradiance.

The relationship between the CTIM off-nadir angle (θ) and the cross-track ground distance (d) at nadir follows the equation:

$$d = h \cdot \tan(\theta) \quad (5)$$

where $h = 453$ km was the median CTIM orbital altitude across the analysis period (see Sect. 6 for a sensitivity analysis of the fixed-altitude assumption). Applying this relationship at the angle where the CTIM angular response reached zero (23°) yielded a cross-track ground distance of approximately 192 km. Because CTIM forward motion during each observation integration period introduced additional along-track blurring, the reported footprint radius of 242 km reflects the mean of the cross-track and along-track ground-distance extents.

3.2 Separation of Day and Night Observations

From August 2022 to November 2023, CTIM collected 32 954 observations of Earth. Of the two CTIM detector heads, A1 and B1, only observations from A1 were used in this analysis, since Earth radiance observational differences between the detectors were generally less than 0.3 %. The Earth-viewing observations were then separated into daytime and nighttime using the CTIM Sun-satellite angle and Fine Sun Sensor (FSS) data values. The CTIM Sun-satellite angle was measured between CTIM and the Sun when CTIM was pointed at Earth nadir, separate from TSI observation periods. Because Earth eclipsed the CTIM view of the Sun, the angle for nighttime observations was acute compared to daytime observations. The FSS was the reading from the fine sun sensor quadrant photodiodes. During eclipse, the FSS values were naturally very low. By examining the FSS read-out as a function of the Sun-satellite angle, we determined the Sun-satellite angle cutoff between night and day observations. Figure 4 shows a steep incline in CTIM FSS reading just above a CTIM Sun-satellite angle of 80° . This abrupt increase in signal represented the transition to daytime observations, so we used a Sun-satellite angle cutoff of 80° to separate eclipsed observations for longwave radiation analysis. This process resulted in 28 321 CTIM observations of Earth during orbital eclipse.

Figure 5 shows all the CTIM Earth observations, as well as the separated day and night observations resulting from the filtering process shown in Fig. 4. Daytime observations reached higher radiance values than nighttime observations, but nighttime observations occurred more frequently and dominated the CTIM Earth-viewing dataset. Since the CTIM primary mission was to measure TSI, the number of times it was pointed to Earth during the daytime was far less compared to observations during eclipse.

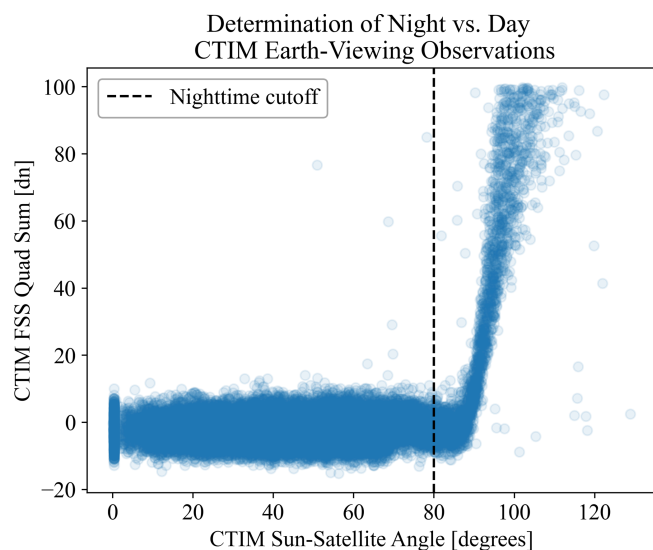


Figure 4. Determination of CTIM Earth-eclipsed observations from the CTIM FSS Quad Sum and CTIM Sun-Satellite Angle. Data-points accepted as eclipsed data had a Sun-satellite angle less than 80° .

3.3 Evaluation of CTIM Longwave Radiance Observations

The latitudinal variation of outgoing longwave radiation, known since the earliest ERB measurements from space (Vonder Haar and Suomi, 1971), was exhibited in CTIM data collected during orbital eclipse (Fig. 6). When averaged per degree of latitude, the CTIM radiances showed a local minimum over the tropics, indicating strong convective cloud cover in the inter-tropical convergence zone (ITCZ).

The spatially gridded variation of 15 months of CTIM longwave radiance data is shown in Fig. 7 and was qualitatively compared to 17 years of CERES data. Areas of local maxima and minima matched to similar features in the CERES average global outgoing longwave irradiance. Specifically, the highlighted areas of low radiative energy emission in equatorial regions in Fig. 7 aligned with the equatorial local minima in Fig. 6, both representative of high, cold clouds in the ITCZ. Compared to CERES outgoing longwave radiation (Fig. 7, bottom), some spatial artifacts are apparent in the CTIM longwave radiance (Fig. 7, top), attributable to the limited sampling of a single CubeSat over 15 months of nighttime eclipse observations compared to the multi-instrument, 17-year CERES average of both daytime and nighttime outgoing longwave radiation. The comparison here is qualitative, as the two datasets differed fundamentally in spatial sampling, temporal coverage, viewing geometry, and measurement period.

4 Matching Algorithm for CTIM and CERES

To conduct our comparative analysis between CTIM and CERES, we developed a four-step algorithm for matching the instruments' ground-projected footprints in space and time. CERES FM-1 and FM-2 on Terra, FM-3 and FM-4 on Aqua, and FM-6 on NOAA-20 were selected for comparison, while FM-5 on S-NPP was excluded as it was primarily operating in rotating azimuth plane scan (RAPS) mode during the CTIM lifetime. In RAPS mode, CERES scans in elevation while the scan plane continuously rotates around the satellite nadir axis, producing footprints with varying view zenith angles and continuously changing azimuth relative to the surface, resulting in far fewer collocations with nadir-viewing or cross-track instruments. For the CERES instruments aboard Terra, Aqua, and NOAA-20, we used CERES Single Scanning Footprint-Level 2 (SSF) Edition4A data products, which provide TOA shortwave and longwave radiances (Loeb et al., 2016).

There were fundamental differences in how CTIM and CERES viewed the Earth. CTIM acquired nadir observations with a line of sight perpendicular to Earth's surface with a footprint approximately 484 km in diameter. In contrast, the CERES instruments operated in cross-track scanning mode, sweeping from limb to limb, perpendicular to the satellite ground track. The CERES viewing zenith angles (VZAs) reached extrema of $\sim 66^\circ$ for Terra and Aqua, and $\sim 71^\circ$ for NOAA-20 (Su et al., 2020). Because CERES scans in a continuous sweep, the VZA varies for each footprint. The CERES footprint diameter is approximately 20 km at nadir for Terra and Aqua, and 24 km for NOAA-20 (Loeb et al., 2018b). Given the substantially larger CTIM footprint, each CTIM observation was populated with many CERES footprints. An algorithm was developed to spatiotemporally collocate CTIM and CERES observations.

Step 1. CERES footprints were selected based on spatial and temporal proximity to CTIM footprints within pre-defined parameters. The CTIM dataset included latitude, longitude, time, and radiance for each footprint. CERES SSF Level-2 data were pre-processed to retain only those footprints with a VZA of 20° or less, ensuring observations were near-nadir and consistent with the effective range of the CTIM angular response (at 20° the CTIM angular response reaches 0.0006, essentially zero) and thus, more directly comparable to the CTIM nadir observations. Using these CERES data, we applied a temporal constraint of ± 20 min relative to each CTIM footprint timestamp to avoid sampling across multiple CERES orbits. The Aqua and Terra orbital periods are approximately 99 min, and that of NOAA-20 is approximately 101 min (Parkinson et al., 2006; NOAA Office of Satellite and Product Operations, 2025). The ± 20 min window represents approximately 40 % of the CERES orbital periods, ensuring

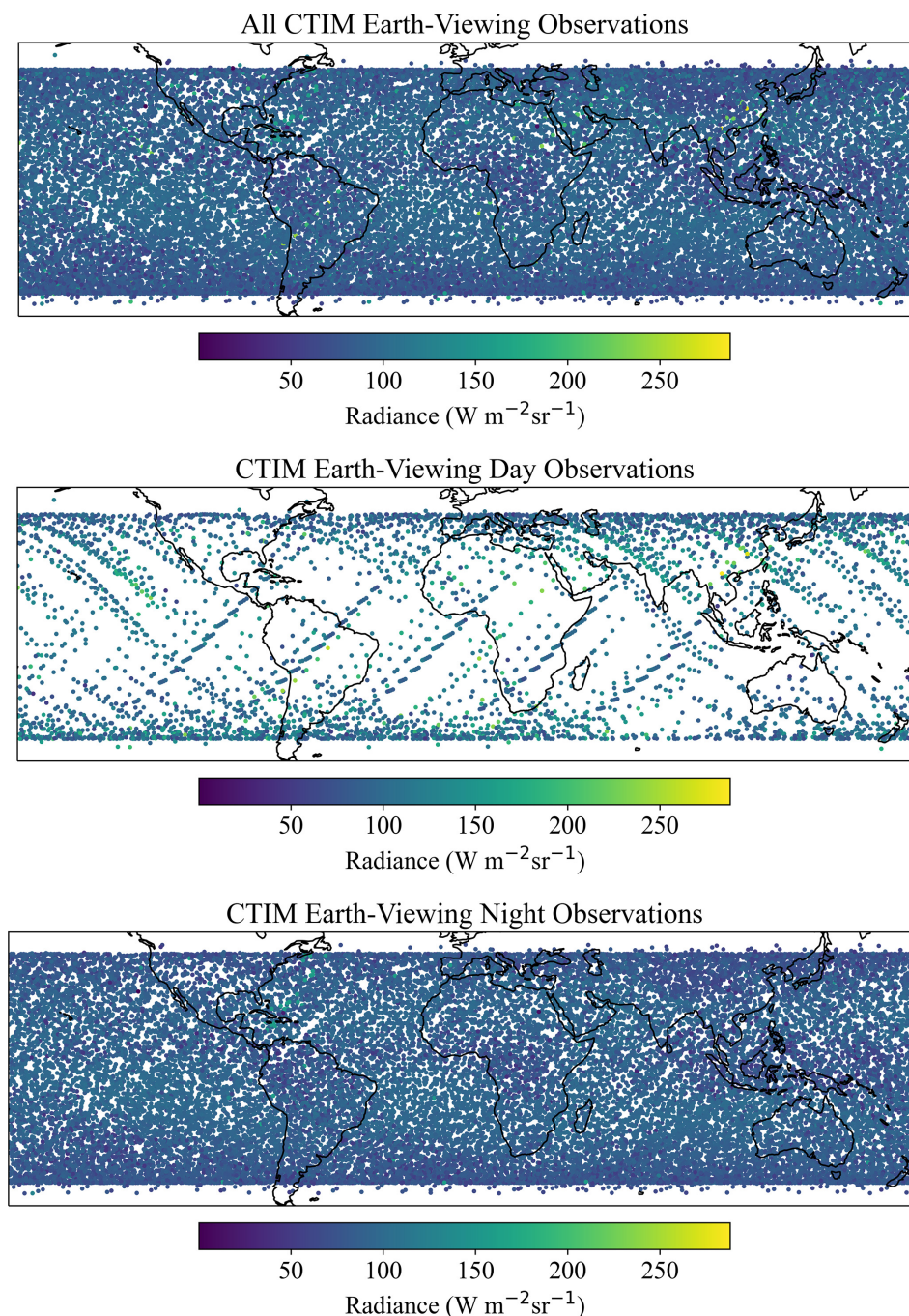


Figure 5. Global coverage of CTIM Earth-viewing observations. Top: all CTIM Earth-viewing observations including both daytime and nighttime observations. The separated day (middle) and night (bottom) observations resulted from the process shown in Fig. 4.

that only a single CERES overpass contributes to each CTIM match while remaining sufficiently long enough in time to maximize collocations. Given the CTIM footprint radius of 242 km, as determined by the CTIM spatial response function (Fig. 3, right) reaching zero at this ground distance, a spatial constraint of 242 km from the CTIM centroid was applied to maximize CERES

coverage within each footprint. We determined that a minimum threshold of 400 CERES samples within the CTIM footprint that met the time and VZA criteria was sufficient to optimize three objectives: maintain near-nadir observations for direct comparison with CTIM; ensure near-full CERES coverage over each CTIM footprint; and maximize the total number of CTIM–CERES

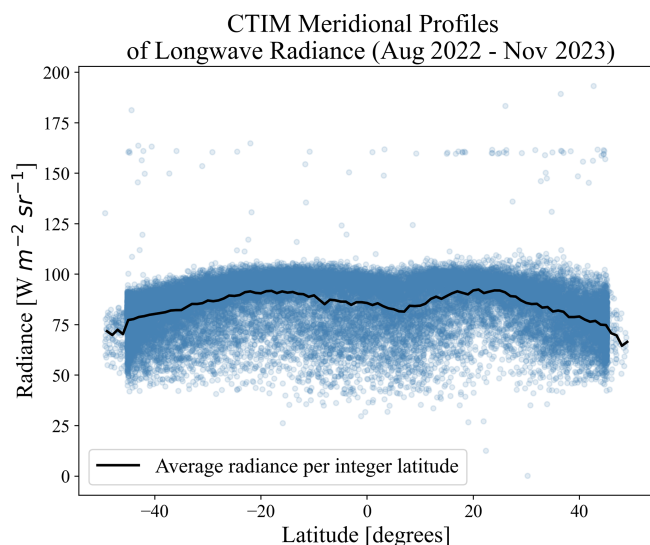


Figure 6. CTIM longwave radiance variation by latitude. Blue points represent individual CTIM radiances, and the black line represents the average radiance per degree latitude.

matches. Further quantitative rationale for the temporal and minimum footprint thresholds is discussed in the notes following Step 4. Each resulting CTIM–CERES “match” therefore consisted of at least 400 CERES footprints collocated within ± 20 min and 242 km of the CTIM footprint centroid, each with a VZA of 20° or less.

Step 2. For CTIM–CERES matches from Step 1 where spatial coverage was incomplete (i.e., areas within the CTIM footprint not sampled by footprints with VZA of 20° or less), additional CERES observations at any VZA within the same spatiotemporal constraints (± 20 min, 242 km radius) were included to fill these gaps. Although these supplemental CERES footprints could come from all VSAs (that could be as large as 71°), the geometry of CERES cross-track scanning naturally limited the maximum VZA to 29.86° within the 242 km radius around each CTIM footprint centroid. As shown in Fig. 8, only 6.93 % of all CERES observations in the dataset resulting from Steps (1) and (2) (approximately 33 supplementary CERES footprints per CTIM–CERES match on average within an average total of approximately 483 CERES footprints within each CTIM–CERES match) had a VZA greater than 20° . This procedure retained all 541 CTIM–CERES matches from Step 1, resulting in a total of 261 010 CERES footprints, with the vast majority representing near-nadir observations closely matching CTIM’s viewing geometry.

Step 3. CERES radiances were weighted by the CTIM spatial response function, the footprint area ratio as a function of VZA, and limb-darkening adjustment fac-

tors for clear-sky scenes (see Sect. 5). The CTIM spatial response function (the distance equivalence to the angular response) is shown in Fig. 3, right. To weight the CERES radiances with the CTIM spatial response, we first determined the distance each CERES footprint was from the centroid of the CTIM footprint, as given by each latitude and longitude. The weightings were determined from the distance from CTIM spatial response centroid for all CERES footprint radiances.

Step 4. The mean CERES weighted radiance for each CTIM footprint was determined with the weighted radiances from Step 3, such that each CTIM–CERES match provided a comparison between a CERES mean radiance and a CTIM radiance.

A flow diagram summarizing the algorithm is provided in Fig. 9.

Notes on parameter selection in Step 1

The temporal window of ± 20 min and minimum CERES footprint number threshold of 400 were selected based on sensitivity analyses in which each parameter was varied individually while all others were held at their baseline values described in Steps 1–4.

A temporal window of ± 10 min yielded only 263 CTIM–CERES matches, with a mean time difference of 4.81 min. Conversely, a ± 30 min window yielded 811 CTIM–CERES matches, but 32.0 % of all matching CERES footprints within a CTIM footprint were 20–30 min from the CTIM observations, increasing the potential for scene change between observations. The ± 20 min window balanced the need for ample matches and scene similarity between CTIM and CERES observations, yielding 541 CTIM–CERES matches with a mean time difference of 9.75 min (51.0 % of CERES footprints within 10 min of the CTIM observation). Thus, the selected ± 20 min window was conservative, sampling CERES observations close in time to CTIM while acquiring sufficient CTIM–CERES matches for statistically meaningful comparisons.

The minimum of 400 CERES footprints was selected to ensure adequate spatial sampling of the CTIM footprint by near-nadir CERES observations. This sensitivity analysis was conducted individually for each satellite (Terra, Aqua, and NOAA-20), since the orbits of the three satellites yield different numbers of CTIM–CERES matches. As the CERES footprint threshold increased from 350 to 450, the Terra match count fell from 302 to 146 while the fraction of footprints with VZA $> 20^\circ$ dropped from 11.8 % to 5.2 %; Aqua matches fell from 152 to 59 with VZA $> 20^\circ$ dropping from 12.9 % to 4.7 %; and NOAA-20 matches fell sharply from 289 to just 2, with VZA $> 20^\circ$ dropping from 6.3 % to 0.1 %. At the selected threshold of 400 footprints, Terra, Aqua, and NOAA-20 yielded 238, 109, and 194 CTIM–CERES matches, respectively (541 matches combined) with 8.9 %,

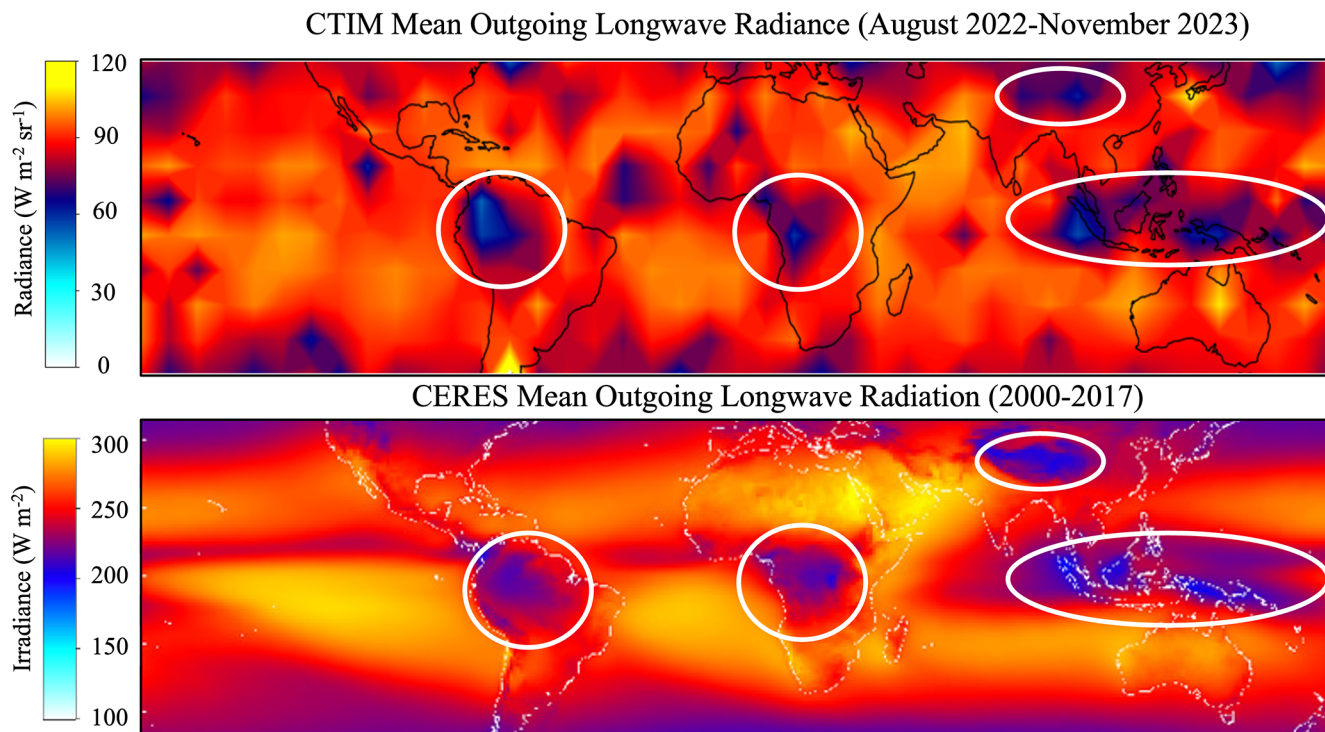


Figure 7. Global longwave radiation. Top: all CTIM longwave radiance from the A1 detector during orbital eclipse (nighttime observations) spatially gridded at $\sim 4^\circ$ resolution for 15 months of observations. All observed radiances within an approximate 4° bin were bin-averaged to determine the pixel radiance within the CTIM latitude range. Bottom: CERES all-sky outgoing longwave radiation (daytime and nighttime) averaged over seventeen years of observations from Terra and Aqua (adapted from Dewitte and Clerbaux, 2018). Yellow-red regions represent areas of high longwave radiation emission, and purple-blue regions represent areas of low longwave radiation emission. Note the CERES radiative energy is expressed in irradiance (W m^{-2}), and the CTIM radiative energy is expressed in radiance ($\text{W m}^{-2} \text{sr}^{-1}$). A direct quantitative comparison between the two is not straightforward, as converting radiance to irradiance requires assumptions about the angular distribution of emitted radiation that do not hold uniformly across all scene types. Despite the different units, localized concentrations of radiative energy are qualitatively similar, specifically low areas of radiative energy that are highlighted by the white circles.

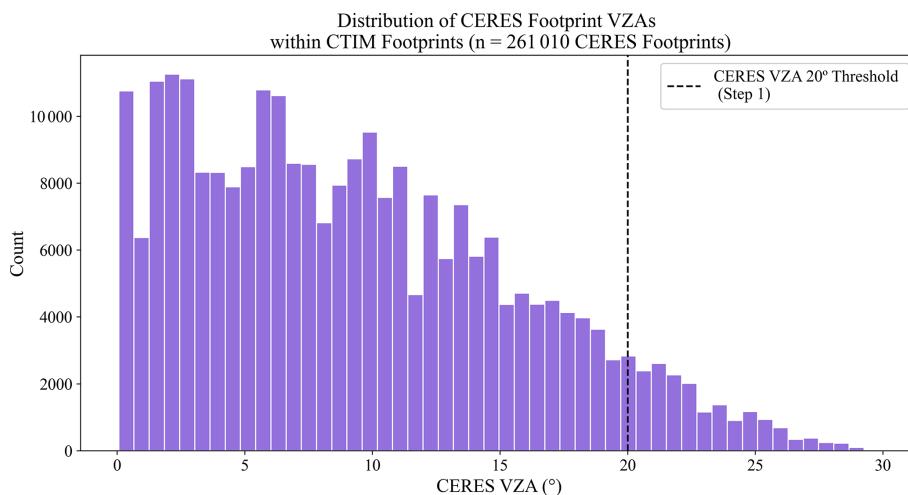


Figure 8. Distribution of CERES VZAs within CTIM footprints. The black line exhibits the VZA 20° threshold applied in Step 1 of the matching algorithm, showing the 6.93 % of CERES footprints with a VZA greater than 20° resulting from Step 2.

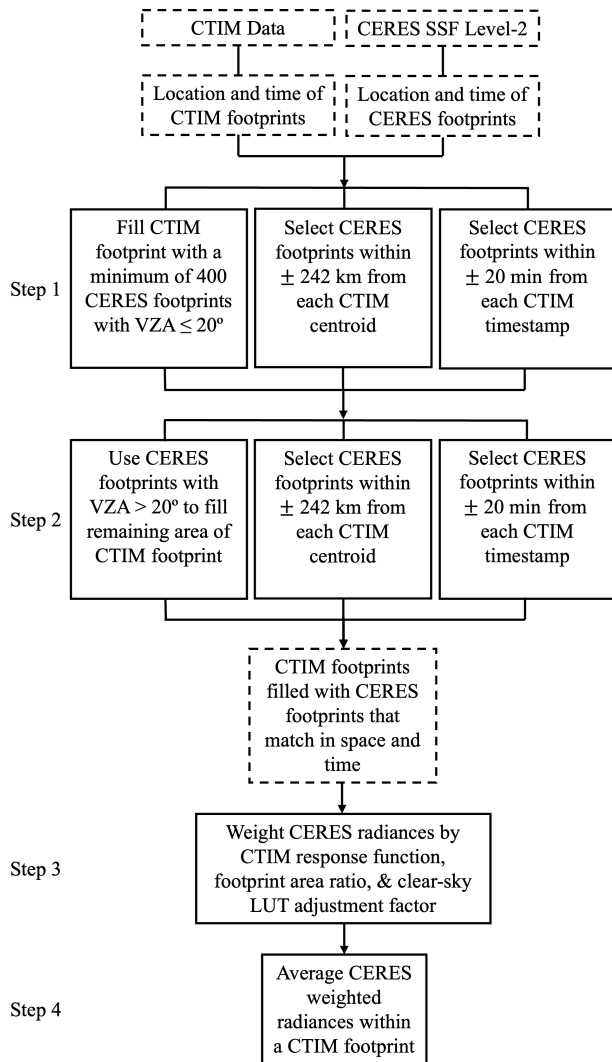


Figure 9. Processing flow for CTIM and CERES matching. Solid boxes were action steps and parameters. Dashed boxes were data inputs (outputs) for (from) steps.

9.0 %, and 2.9 % of CERES footprints having a VZA > 20° for each satellite (6.9 % collectively). This threshold ensured each CTIM footprint was predominantly filled with CERES observations within 20° of nadir for comparison with CTIM, while maintaining a statistically meaningful number of matches for all three satellites.

5 Adjustments for CERES VZA

5.1 Comparison Before Adjustments for CERES VZA

In initial comparisons, the algorithm outlined in Sect. 4 did not include adjustments for CERES viewing geometry. Before accounting for the CERES viewing geometry and only weighting the CERES radiances by the CTIM response function, the agreement between CTIM and CERES radiances

was within 1.21 % but with spread about the mean (standard deviation, σ , of the relative differences was 4.17 %) (Fig. 11). Since the negative bias was within the relative uncertainties of the two instruments (Sect. 6 and Table 4), we focused on reducing the spread in the statistical comparison. We hypothesized the spread was due, in part, to the different viewing geometries between CTIM and CERES. From this hypothesis, we first adjusted the CERES footprint area as a function of VZA (Sect. 5.2). In an effort to reduce the spread further, we considered adjusting CERES radiances due to limb darkening for off-nadir radiance. Therefore, we conducted radiative transfer simulations to examine limb-darkening effects of non-nadir viewing for CERES radiances to assess potential viewing geometry impacts on the comparison of radiances (Sect. 5.3–5.5).

5.2 VZA Influence on CERES Footprint Areas

Since CERES scans Earth in cross-track mode, the CERES pixel footprint projected at Earth's surface grows with increasing VZA (as illustrated in Fig. 10). The CERES footprint at nadir was approximated as a circular field of view (FOV) with a diameter of 20 km for Terra and Aqua and 24 km for NOAA-20. Although the instrument's physical field stop is hexagonal, the point spread function and optical blur produce an approximately elliptical footprint commonly represented as a circular “equivalent” at nadir, encompassing ~ 95 % of the PSF response (Green and Wielicki, 1997). As the cross-track scanner moves from nadir, the footprint semi-major axis increases with the slant range, and the footprint becomes elliptical. Due to Earth's rotation, the center points of the large VZA are displaced from the ground track. Smith et al. (1994) warranted no concern for such small displacements. Appropriate weighting was applied to account for biases that could arise from the variable footprint area for each CERES footprint off nadir.

The CERES VZA at the sensor (θ') was determined from the CERES VZA at the surface (θ) given by the SSF Level-2 data, following methods adapted from Jahani et al. (2022). The Earth was assumed to be spherical, and the law of sines was applied as shown in Fig. 12. Once θ' was determined, the cross-scan length of the CERES footprint ($l_{\text{cross-scan}}$; km) was approximated by first assuming the Earth to be flat on the CERES footprint scale and second, assuming the semi-major axis of the ellipse to be the average of l_1 and l_2 . The along-scan length was assumed to be constant at either 20 km for Terra and Aqua or 24 km for NOAA-20. Using the cross-scan and along-scan lengths, the CERES footprint areas were computed as a function of VZA. A footprint area ratio was determined by dividing the footprint area off nadir by the footprint area at nadir for all VZAs. The footprint area ratio for each satellite was used in the weighting process (Sect. 4, Step 3) to determine the mean CERES radiance in each CTIM footprint (Sect. 4, Step 4).

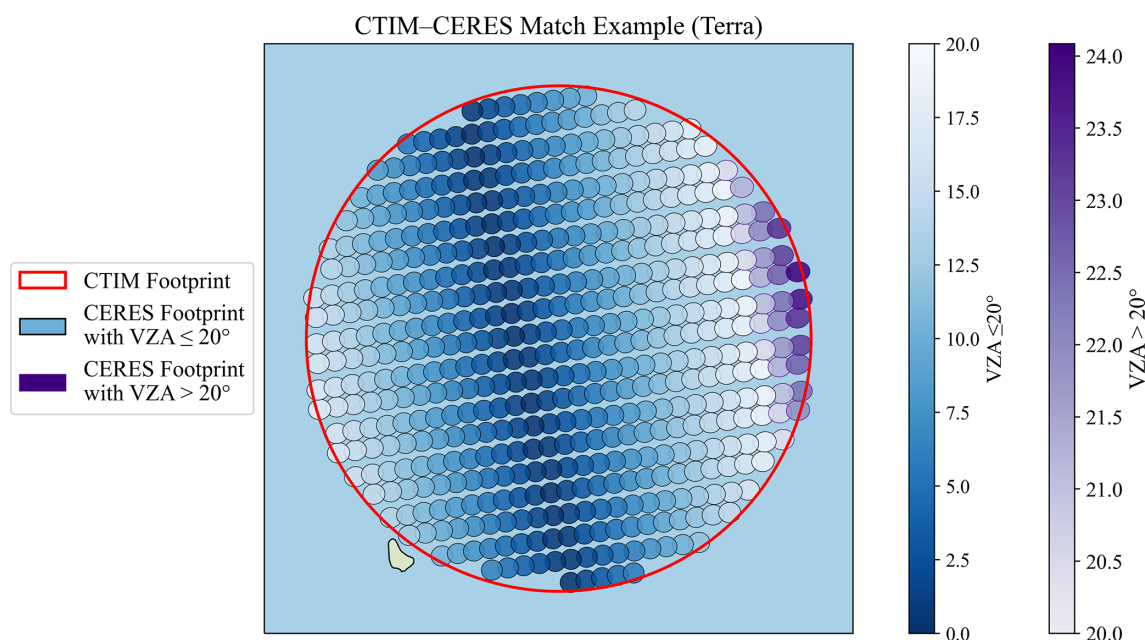


Figure 10. One resulting CTIM–CERES match from the matching algorithm. The CTIM footprint (large red circle) was populated with CERES footprints (small blue- and purple-filled circles and ellipses). Blue-filled CERES footprints represent all CERES footprints with a $VZA \leq 20^\circ$ (Step 1), where a darkening blue represents a VZA closer to nadir. Purple-filled CERES footprints resulted from Step 2, where the remaining CTIM area from Step 1 was populated with CERES footprints with a $VZA > 20^\circ$. Darkening purple represents a VZA increasing above 20° . CERES footprints become increasingly elliptical at larger VZAs, which is accounted for in Sect. 5.2.

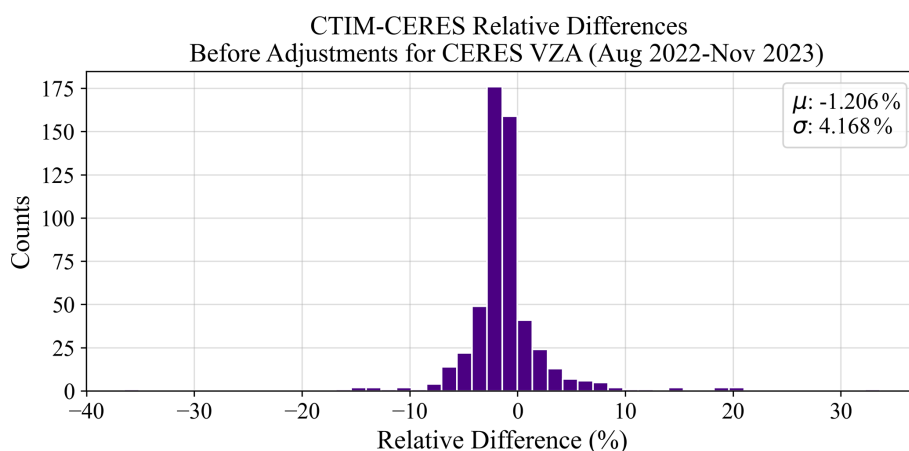


Figure 11. Distribution of relative differences (see Eq. 7) between CTIM and CERES before applying adjustments for CERES VZA. CERES radiances were only weighted by the CTIM response function.

5.3 VZA Influence on Limb Darkening

The radiance exiting at the TOA typically decreases in magnitude with increasing angle from nadir due to the increase in path length and the decrease in temperature with altitude. So-called *limb-darkening* models describe the variations in radiance with viewing angle (Smith et al., 1994). The MODerate spectral resolution TRANsmittance (MODTRAN) radiative transfer code was used to create lookup tables (LUTs) to derive limb-darkening adjustments to apply to CERES off-

nadir radiances as a function of scene type and atmospheric composition for clear-sky scenes.

To date, a limb-darkening adjustment has been developed only for cloud-free cases. Limb-darkening effects from clouds are often larger, particularly at large viewing angles for high-altitude cloud layers (Clerbaux et al., 2020; Loeb et al., 2005). The path through the clouds at oblique viewing angles reduces the radiance relative to nadir more than in clear-sky conditions, where emission is dominated by the surface and lower troposphere. In addition, each CERES SSF

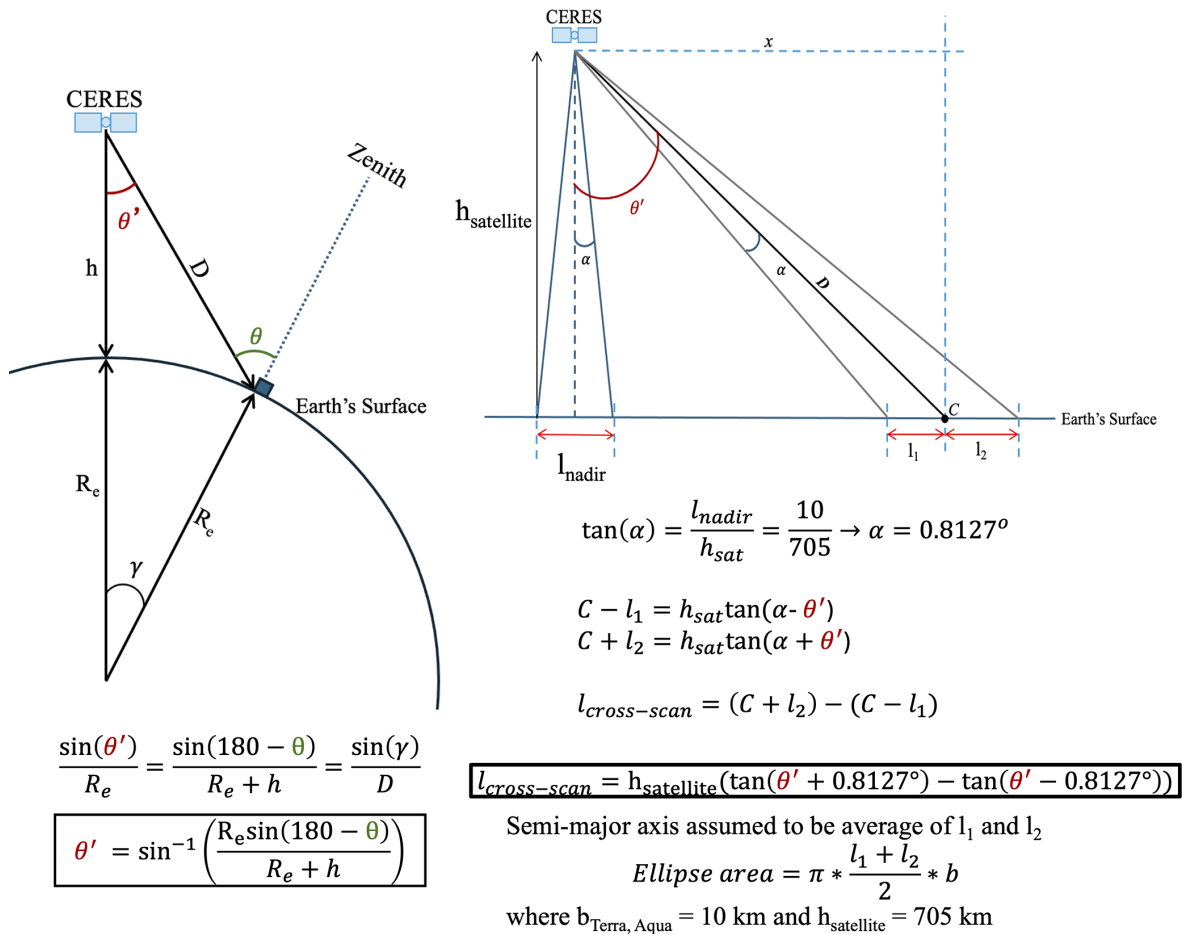


Figure 12. Geometry for determining the CERES footprint area as VZA increased off nadir (adapted from Jahani et al., 2022). Left: law of sines determined the VZA at the CERES sensor (θ'), given the CERES VZA at the surface (θ). Right: determination of the cross-scan width for Terra and Aqua as the VZA at the CERES sensor increased.

Level-2 footprint includes multiple cloud properties (such as cloud fraction, cloud optical depth, cloud top height, and vertical layer structure) that collectively modulate outgoing longwave radiance at different viewing angles. Accounting for all of these interactions substantially increases the complexity of radiative transfer calculations for limb-darkening adjustments for each CERES footprint, beyond the scope of the present study.

MODTRAN provides accurate and rapid simulations, computing line-of-sight atmospheric spectral transmittances and radiances for stratified, horizontally homogeneous atmospheres from the ultraviolet through the far-infrared spectrum (Berk et al., 2014). Because MODTRAN solves the radiative transfer equation along any line of sight, it was used to determine radiance changes with viewing angle for constructing limb-darkening adjustments for clear-sky scenes. The goal of these adjustments was to minimize the spread in the difference between CTIM and CERES radiances (Fig. 11), which we hypothesized might depend, in part, on the mismatches in VZA between CTIM and CERES.

5.4 Parameters for MODTRAN Simulations

To employ MODTRAN for clear-sky limb-darkening corrections, we varied four parameters: VZA, surface emissivity, surface temperature, and atmosphere model. Each CERES footprint included the SSF Level-2 data for surface emissivity, surface temperature, and VZA; the standard MODTRAN model atmospheres were determined by footprint latitude and date. This section details the selected parameters.

To determine the variations in radiance with viewing angle for the LUTs, the distribution of VZAs over all CERES footprints within our CTIM–CERES matches was used for determining the range of VZAs for MODTRAN simulations. While we constrained the CERES footprint criteria to 400 footprints with a VZA of 20° in Step 1 of our matching algorithm to best match CTIM nadir viewing, in order to fill the CTIM footprint, an additional 6.9 % of CERES footprints had a VZA greater than 20° with a maximum VZA of 29.86° (Fig. 8). From the CERES VZA distribution, we selected five VZAs for the MODTRAN simulations: 0, 8, 17, 25, and 30° .

MODTRAN provides six atmosphere base profiles of temperature, pressure, and molecular and aerosol composition. The three relevant atmosphere models applied in this study were tropical, mid-latitude summer, and mid-latitude winter, since CTIM covered approximately 40° N to 40° S. The MODTRAN tropical model simulates a tropical atmosphere between 15° latitude; the mid-latitude summer and winter atmosphere models are between 15–45° N and S latitude, respectively.

Surface emissivity and surface temperature determine the amount of radiation leaving the surface. Each surface type has a distinct emissivity. CERES uses the International Geosphere-Biosphere Programme (IGBP) surface type classification to determine surface broadband emissivity. The IGBP defines 18 distinct surface types (e.g., mixed forest, evergreen needleleaf) as a comprehensive system for organizing different Earth surface types for studying global environmental processes. For each CERES footprint, an IGBP surface type is determined in the SSF Level-2 data. From the 18 IGBP surface types, each surface type broadband emissivity ranges approximately between 0.890 and 1.0 (NASA Langley Research Center, 2025). Emissivity values, ϵ , were selected within this range to represent surface types in the MODTRAN simulations. In MODTRAN, the surface type was simulated by inputting the albedo ($1 - \epsilon$) for a Lambertian surface, with MODTRAN run in thermal-only mode (no solar source term) and a user-defined albedo (USDALB) = $1 - \epsilon$ for all ϵ : 0.89, 0.91, 0.93, 0.95, 0.97, 0.99, 1.00. We used a range of surface temperatures from 260 to 310 K for each of the seven surface emissivities. For the mid-latitude winter atmosphere, 240 and 250 K were additionally included to account for the colder surface temperatures observed in wintertime CERES footprints.

Using these parameters (listed in Table 1), 700 MODTRAN simulations were conducted to generate limb-darkening adjustment factors for clear-sky CERES radiances. An adjustment factor was calculated as in Eq. (6) for all simulated radiances. For example, the 8° VZA, 0.89 surface emissivity, 260 K surface temperature, mid-latitude summer atmosphere model radiance was compared to the 0° VZA, 0.89 surface emissivity, 260 K surface temperature, mid-latitude summer atmosphere model radiance to find the 8° VZA radiance relative difference to the 0° VZA.

$$\text{Adjustment Factor} = \frac{\text{Radiance}_{\text{nadir}}}{\text{Radiance}_{\text{off nadir}}} \quad (6)$$

The results of the mid-latitude summer atmosphere model simulation are shown in Fig. 13. As the VZA increased off nadir, the adjustment factor increased. Similarly, as surface temperature and surface emissivity increased, the adjustment factor increased. While the adjustment factor values changed slightly for each atmosphere model with the given variables, the trend remained the same for all three atmosphere models: As surface temperature increased, emissivity increased, and

Table 1. MODTRAN parameters used for simulating CERES long-wave radiance observations.

VZA (°)	Surface Emissivity	Surface Temperature (K)	Atmosphere Model
0	0.89	240*	Tropical
8	0.91	250*	Mid-latitude Summer
17	0.93	260	Mid-latitude Winter
25	0.95	270	
30	0.97	280	
	0.99	290	
	1.00	300	
		310	

* 240 and 250 K were modelled only for the Mid-latitude Winter atmosphere.

VZA increased, the simulated radiance decreased compared to the radiance at nadir. Though the adjustment factors were small in magnitude, we applied them to clear-sky scenes to ensure that CERES off-nadir radiances were consistent with CTIM nadir-viewing geometry, thereby enabling a more direct comparison between the datasets.

5.5 MODTRAN-Derived Limb-Darkening Corrections

To apply the clear-sky LUT adjustment factors to CERES-observed radiances, the SSF Level-2 clear-sky fraction data was used to determine clear-sky scenes for any CERES footprint within any CTIM footprint. Any CERES footprint that matched within any of the CTIM footprints with a clear-sky percentage of 95 % or greater was defined as a clear-sky scene. Of the 261 010 total CERES footprints across all 541 CTIM–CERES matches, 45 863 (17.6 %) met this criterion and received the limb-darkening adjustment. The remaining 82.4 % of CERES footprints were cloudy (Clear Sky $1 < 5$ %) and received no limb-darkening correction. Consequently, 409 of 541 CTIM–CERES scenes (75.6 %) had at least one corrected CERES footprint, while 132 CTIM–CERES scenes (24.4 %) were entirely uncorrected, as the majority of scenes contained non-negligible cloud cover.

The clear-sky CERES footprints were sorted into hemispheric regions: tropical, Northern Hemisphere, or Southern Hemisphere. Based on the date of observation and hemispheric region, the footprints were further sorted into tropical, summer, or winter seasons. Once sorted by season, each footprint was matched with a MODTRAN atmosphere model. As a result, all clear-sky CERES footprints within the CTIM–CERES matches were mapped onto one LUT adjustment factor value based on atmosphere model, surface emissivity and temperature, and VZA to interpolate an appropriate limb-darkening adjustment factor. The adjusted radiance was calculated by multiplying the observed CERES radiance by the adjustment factor (Eq. 6) in Step 3 of the matching algorithm described in Sect. 4. By adjusting the

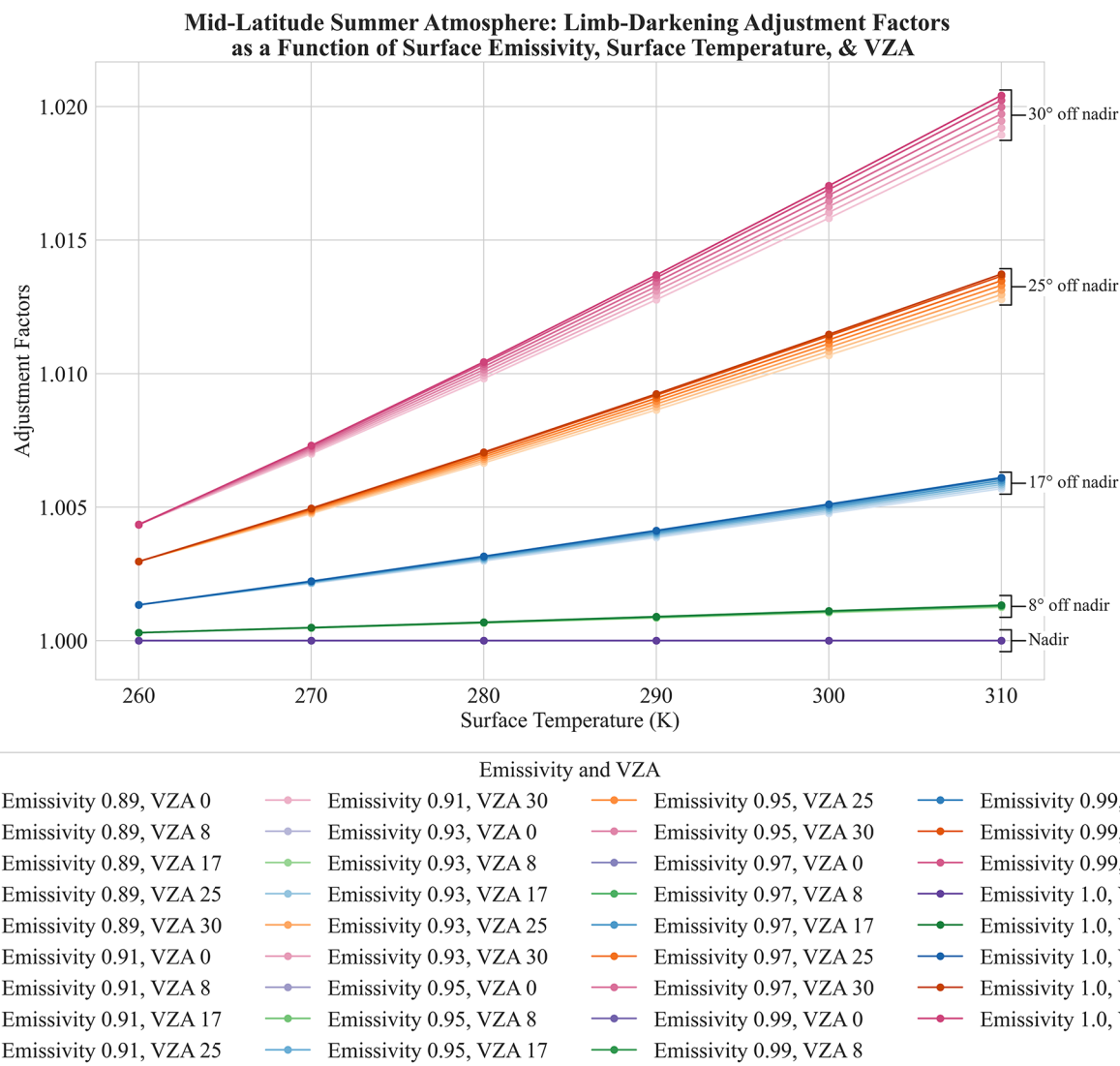


Figure 13. Limb-darkening adjustment factors based on surface temperature, emissivity, and degrees off nadir for a mid-latitude summer atmosphere. Each color represents a different value of VZA. Darkening color represents higher emissivity. The highest adjustment factor resulted from 30° off nadir, 1.0 emissivity, and 310 K surface temperature.

CERES radiances for off-nadir viewing, we accounted for limb-darkening effects in clear-sky scenes that influenced the radiance differences between CTIM and CERES.

6 Results

Using the matching algorithm detailed in Sect. 4, we found 541 matches between CTIM and CERES and applied the VZA adjustments discussed in Sect. 5. We grouped CERES instruments by their host satellite – FM-1 and FM-2 on Terra, FM-3 and FM-4 on Aqua, and FM-6 on NOAA-20 – and refer to each group by respective satellite name hereafter. From the grouping, we compared radiance measurements from each satellite’s CERES instruments individually, as well as

collectively, to those from CTIM. For our comparison, we determined relative difference as

$$\frac{\text{CERES Weighted Mean Radiance} - \text{CTIM Radiance}}{\text{CTIM Radiance}} \times 100\% \quad (7)$$

where for every match with CTIM, the CERES footprints within the CTIM footprint were adjusted for clear-sky limb darkening, weighted by the CTIM spatial response function and footprint area ratio, and averaged for a mean radiance, as described in Sect. 4.

Table 2 summarizes the incremental contribution of each correction (Sect. 4, Step 3) to the CERES–CTIM radiance comparison. Without any correction, the unweighted mean relative difference across all 541 matches was -0.877% with $\sigma = 5.378\%$ and $R^2 = 0.917$. The addition

Table 2. Incremental contribution of each adjustment to the CTIM–CERES radiance comparison for all 541 matches. For No Corrections, an unweighted mean of all CERES footprint radiances within each CTIM footprint was used. For CTIM Spatial Response Weighting, each CERES footprint radiance was weighted by the CTIM spatial response function based on the distance from the CERES footprint to the CTIM centroid. For CTIM Spatial Response and Footprint Area Weighting, the VZA-dependent CERES footprint area ratio was additionally applied. For the full adjustments, LUT-based limb-darkening adjustment factors were further applied to clear-sky CERES footprints (Clear Sky $\geq 95\%$), interpolated as a function of VZA, surface emissivity, surface temperature, and atmospheric season.

Weighting Step	Mean Relative Difference (%)	SD (%)	R^2
1. No Corrections	−0.877	5.378	0.917
2. CTIM Spatial Response Function Weighting	−1.206	4.168	0.948
3. CTIM Spatial Response Function Weighting & Footprint Area Ratio	−1.206	4.157	0.948
4. CTIM Spatial Response Function Weighting, Footprint Area Ratio, & Clear-Sky Limb-Darkening Adjustments	−1.186	4.159	0.948

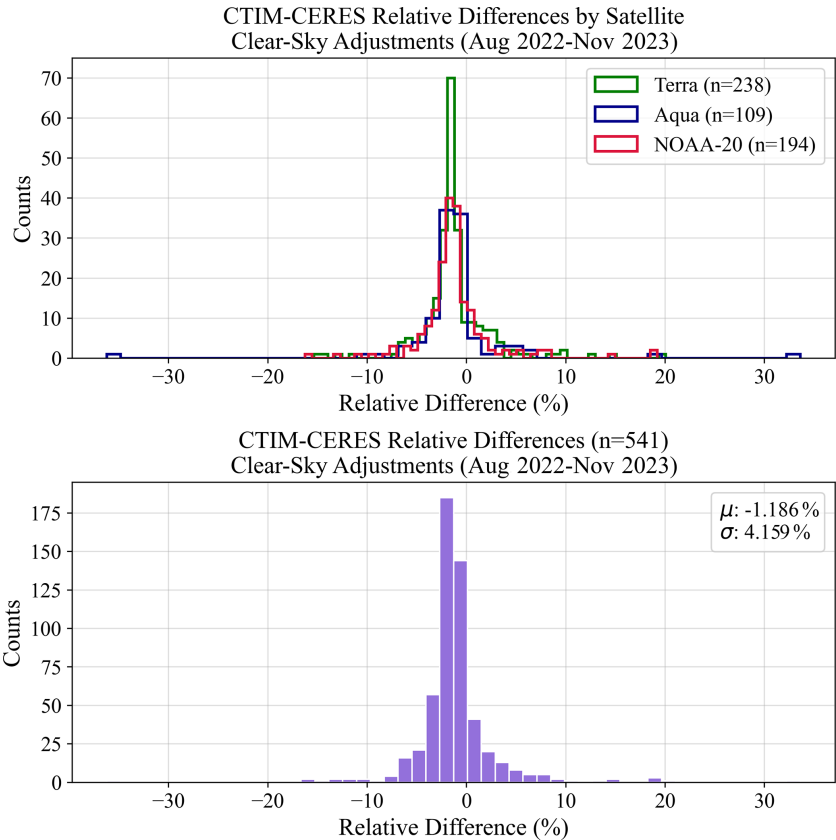


Figure 14. Relative difference histograms between CTIM and CERES measured longwave radiances for 541 matches. Top: relative differences between CTIM and CERES radiance measurements for Terra, Aqua, and NOAA-20. Bottom: relative differences between CTIM and CERES, where CERES represents the collective data from CERES aboard Terra, Aqua, and NOAA-20.

of CTIM spatial response function weighting shifted the mean slightly to -1.206% ($\sigma = 4.168\%$, $R^2 = 0.948$), reflecting the greater weight given to CERES footprints closer to the CTIM centroid. The further addition of the VZA-dependent footprint area ratio had negligible incremental effect (-1.206% , $\sigma = 4.157\%$, $R^2 = 0.948$). The full correction, which additionally applied the clear-sky LUT limb-darkening adjustment to CERES footprints with a clear-

sky fraction $\geq 95\%$, yielded a mean relative difference of -1.186% , $\sigma = 4.159\%$, and $R^2 = 0.948$, the values shown in Fig. 14 and reported throughout the remainder of this section.

Figure 14 shows the relative differences between CTIM and CERES on each satellite (top) and the relative differences between CTIM and all CERES instruments aboard all three satellites (bottom). Terra had 238 matches with CTIM

Table 3. Relative differences for each CERES satellite compared to CTIM, including the number of matching CTIM footprints per satellite based on our matching methods. The 95 % CI values are half-widths of bootstrapped confidence intervals on the mean (10,000 resamples). σ is the sample standard deviation of the individual relative differences.

Satellite	Mean Relative Difference	95 % CI (half-width)	SD (σ)	Matches with CTIM
Terra	−1.179 %	±0.449 %	3.556 %	238
Aqua	−1.207 %	±1.082 %	5.704 %	109
NOAA-20	−1.181 %	±0.532 %	3.829 %	194
CERES	−1.186 %	±0.345 %	4.159 %	541

Table 4. CTIM radiance standard uncertainties ($k = 1$). The uncertainty was dominated by the uncertainty in the solid angle and secondarily the reflectance. Both could be reduced for future instruments by implementing minor design changes and additional lab calibrations.

Source	Shortwave (%)	Longwave (%)
Detector reflectance	0.07	0.7
Detector power	0.008	0.008
Non-equivalence	0.13	0.13
Noise	0.15	0.15
Dark signal	0.19	0.19
Solid angle	1.63	1.63
Total	1.65	1.80

with a relative difference of $-1.18 \pm 0.45 \%$ and a standard deviation of $\sigma = 3.56 \%$. Aqua had 109 matches with a relative difference of $-1.21 \pm 1.08 \%$ ($\sigma = 5.70 \%$). NOAA-20 had 194 cases with a relative difference of $-1.18 \pm 0.53 \%$ ($\sigma = 3.83 \%$) (Table 3). It is important to note that the Aqua dataset was limited in time, as the SSF Level-2 data production stopped on 21 March 2023. Because of this, the Aqua data provided fewer matches than either Terra or NOAA-20. Both Terra and NOAA-20 individually provided data over the entire CTIM lifetime. Collectively (labelled CERES in Fig. 14 and in Table 3), the three satellites had 541 matches with CTIM with a mean relative difference of $-1.19 \pm 0.35 \%$ and a standard deviation of $\sigma = 4.16 \%$. Uncertainties represent the half-width of bootstrapped 95 % confidence intervals (10 000 resamples). The negative mean relative difference indicates that CTIM observed higher radiances than CERES on average. The limb-darkening adjustment was limited to the 17.6 % of CERES footprints that met the clear-sky criterion (Clear Sky 1 $\geq 95 \%$), and its overall impact on the mean relative difference and standard deviation was modest (Table 2), as also reflected in the small difference between the pre- and post-adjustment results shown in Figs. 11 and 14.

Linear regression of all 541 CTIM–CERES matching cases yielded a coefficient of determination of $R^2 = 0.948$

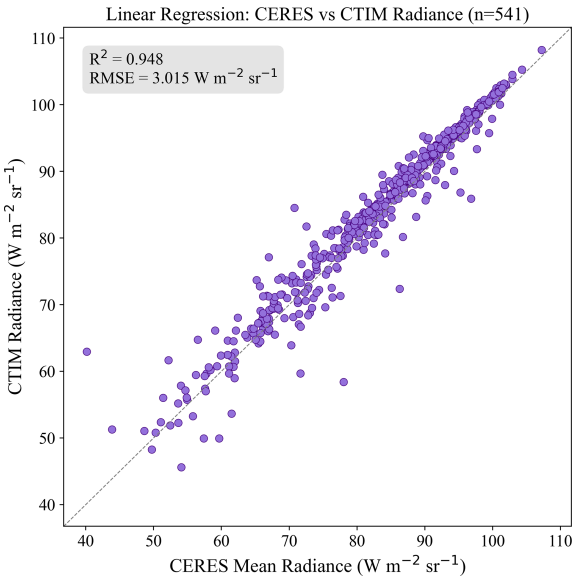


Figure 15. Linear regression of CERES (represented by Terra, Aqua, & NOAA-20) vs. CTIM radiances for 541 matches with clear-sky adjustments. The coefficient of determination ($R^2 = 0.948$) and root mean square error ($\text{RMSE} = 3.015 \text{ W m}^{-2} \text{ sr}^{-1}$) indicate a strong relationship between CTIM radiances and the CERES mean radiances for every CTIM–CERES match.

and a root mean square error (RMSE) of $3.02 \text{ W m}^{-2} \text{ sr}^{-1}$ (Fig. 15), indicating a high degree of correlation between CTIM radiances and CERES mean radiances. The observed spread ($\sigma = 4.16 \%$) was likely influenced by differences in viewing geometry and scene variability within the large CTIM footprint, rather than by instrument calibration uncertainty. For reference, CTIM measured TSI with an uncertainty of 0.017 % (Flynn, et al., 2024), and CERES longwave radiances are assumed to have a calibration uncertainty of 0.75 % ($k = 1$) (Loeb et al., 2018a). The CTIM radiance uncertainty budget (Table 4) shows total standard uncertainties of 1.65 % and 1.80 % ($k = 1$) for shortwave and longwave, respectively, dominated by solid angle uncertainty. Note that CTIM was designed for measuring solar irradiance with its narrow 0.5° divergence, at an uncertainty of less than 0.02 %.

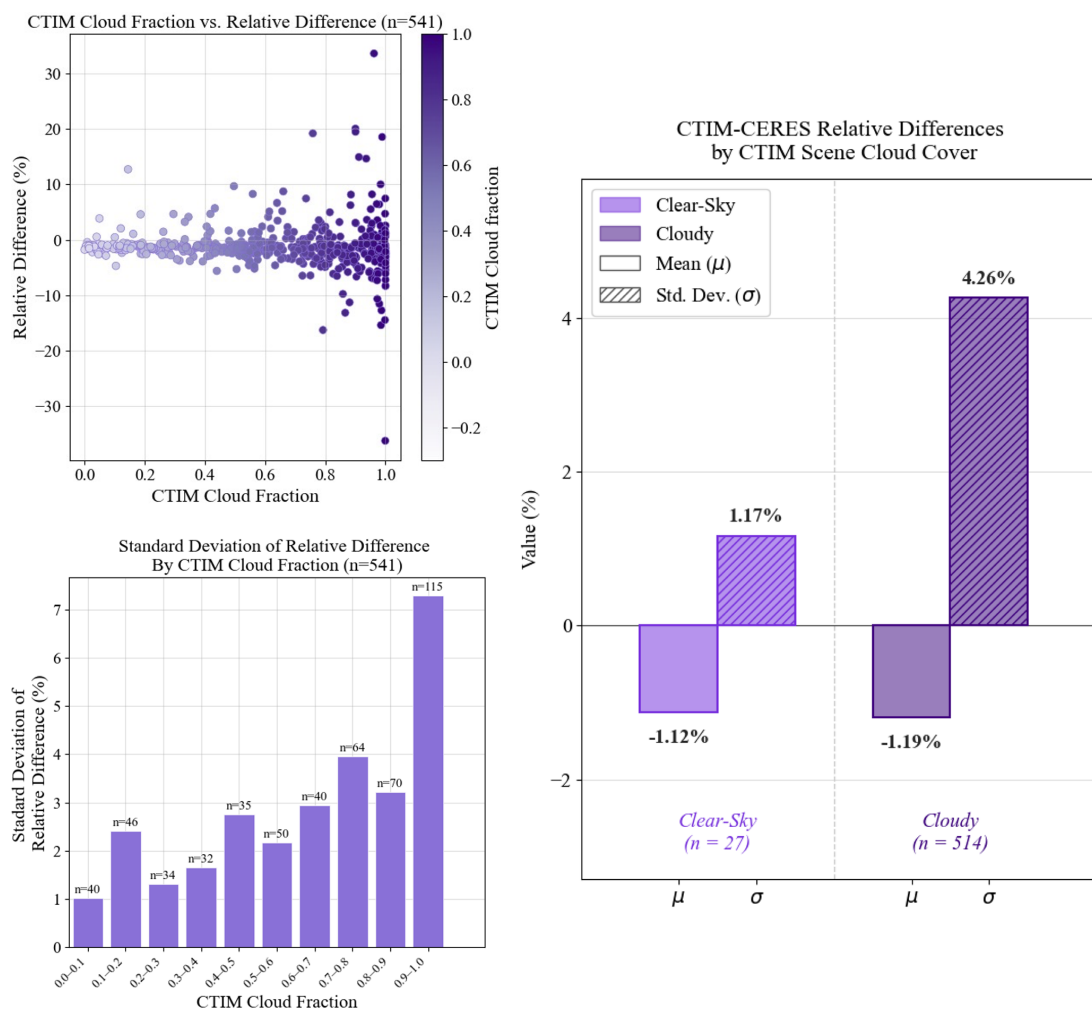


Figure 16. CTIM–CERES radiance relative differences as a function of CTIM scene cloud fraction for all 541 matches. Top left: scatter plot of relative difference versus CTIM scene cloud fraction, where cloud fraction represents the footprint-area-weighted mean of CERES SSF cloud fractions ($1 - \text{clear-sky fraction}$) within each CTIM footprint. Bottom left: Standard deviation of relative differences binned by CTIM scene cloud fraction. The standard deviation generally increases with cloud fraction, consistent with scene heterogeneity driven by cloud variability within the large CTIM footprint. Right: mean relative difference and standard deviation for clear-sky CTIM scenes (CTIM cloud fraction ≤ 0.05 , $n = 27$) and cloudy CTIM scenes (CTIM cloud fraction > 0.05 , $n = 514$). Clear-sky scenes yield a slightly reduced mean bias (-1.12% vs. -1.19%) and lower spread about the mean ($\sigma = 1.17\%$ vs. $\sigma = 4.26\%$), further suggesting that cloud presence was the dominant contributor to the overall $\sigma = 4.16\%$ observed across all 541 matches.

Intentionally designing the optical system to accommodate Earth-viewing with a larger spread in direction of outgoing radiation would substantially reduce uncertainty in future ERB radiance measurements. The comparisons in Fig. 14 and Table 3 show that CTIM and CERES agree to well within their respective uncertainties and that the Terra, Aqua, and NOAA-20 CERES instruments used in this study are statistically indistinguishable from one another.

Note that the spread in variation between CTIM and CERES decreased as the radiance values increased (Fig. 15). The spread in the lower radiance values could indicate the presence of clouds (colder scenes). Clouds may complicate CTIM–CERES comparisons because the CERES more

oblique viewing angles traverse longer paths through cloud layers than the CTIM nadir view. Although CTIM measures radiance over approximately 20° from nadir with decreasing weight at increasing angles, the two instruments still sample cloud layers along meaningfully different path lengths, introducing sensitivity to cloud optical depth, vertical structure, and temperature profile. Figure 16 supports the notion that clouds play a role in the spread in radiance in the CTIM–CERES matches. There is a greater spread in relative difference with increased CTIM scene cloud fraction, as determined by the footprint-area-weighted mean of the CERES SSF cloud fractions ($1 - \text{clear-sky fraction}$) within the CTIM footprint. The standard deviation of relative dif-

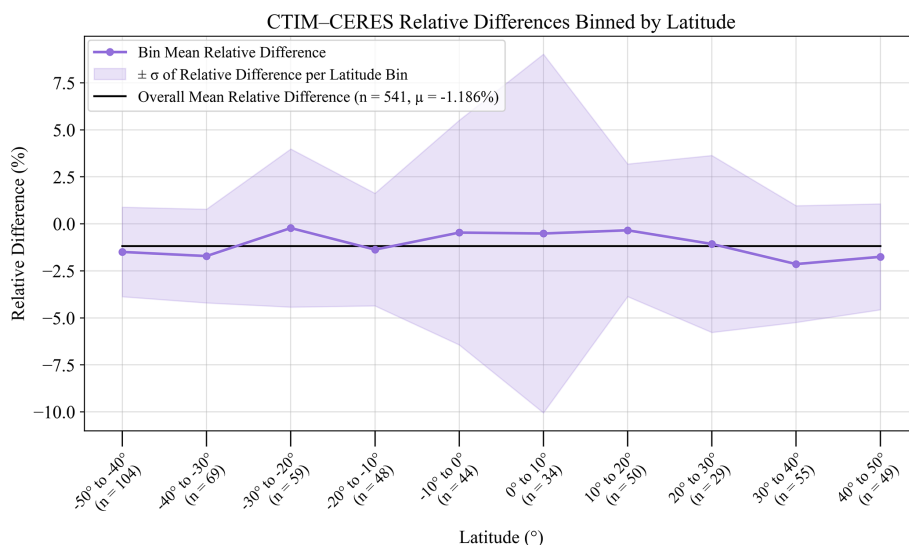


Figure 17. Mean CTIM–CERES relative difference and $\pm 1\sigma$ envelope binned by 10° latitude intervals for all 541 matches. The mean relative difference remains close to the overall mean of -1.19% across most latitude bins with no clear latitudinal trend. The two largest spreads occur in the -10 to 0° ($n = 44$, $\sigma = 5.97\%$) and 0 to 10° ($n = 34$, $\sigma = 9.54\%$) latitude bins, compared to all other bins ($\sigma = 2.38\%$ – 4.71%), consistent with the persistent deep convective cloud cover and enhanced scene heterogeneity of the ITCZ.

ference binned by CTIM cloud fraction (Fig. 16, bottom left) generally increases with cloud fraction, consistent with scene heterogeneity driven by cloud variability within the large CTIM footprint. To further quantify this effect, CTIM scenes were stratified into clear-sky (cloud fraction ≤ 0.05 , $n = 27$) and cloudy (cloud fraction > 0.05 , $n = 514$) subsets. Clear-sky scenes yield a mean relative difference of $\mu = -1.12\%$ and $\sigma = 1.17\%$, compared to $\mu = -1.19\%$ and $\sigma = 4.26\%$ for cloudy scenes (Fig. 16, right). The results shown in Fig. 16 support the hypothesis that the presence of clouds viewed at different geometries may be responsible, at least in part, for the spread in our results, which was only negligibly reduced after clear-sky limb-darkening adjustments (Fig. 14).

Figure 17 further examines the latitudinal dependence of the CTIM–CERES agreement by showing the mean relative difference and $\pm 1\sigma$ envelope binned by latitude. The mean relative difference remains close to the overall mean of -1.19% across most latitude bins, with no clear trend with latitude. However, the two largest spreads in relative difference occur in the -10 to 0° ($n = 44$, $\sigma = 5.97\%$) and 0 to 10° ($n = 34$, $\sigma = 9.54\%$) latitude bins, compared to all other bins ($\sigma = 2.38\%$ – 4.71%), consistent with the persistent deep convective clouds and enhanced cloud heterogeneity associated with the ITCZ. The large spread in these two latitude bins further supports the notion that clouds are the dominant contributor to the overall spread ($\sigma = 4.16\%$) in the relative difference between CTIM and CERES.

Notes on the fixed-altitude footprint geometry assumption

To evaluate the sensitivity of our results to the fixed 453 km altitude used in Sect 3.1, each CTIM footprint radius was recomputed using that observation's altitude in Eq. (5), excluding along-track motion blurring (a conservative approximation that yielded smaller footprints and therefore an upper bound on the expected sensitivity). Using the same 541 CTIM–CERES matches, the CERES footprints falling outside of the altitude-specific CTIM radius were excluded in the CERES mean radiance calculation. The resulting altitude-varying analysis yielded an overall mean relative difference of -1.20% ($\sigma = 4.17\%$), with per-match relative differences highly correlated between the two approaches ($R^2 = 0.998$). These results indicated that the fixed 453 km altitude did not introduce a meaningful bias in the reported CTIM–CERES comparisons.

7 Conclusions

Predicting Earth's future climate requires long-term continuous and accurate ERB observations (Dewitte and Clerbaux, 2018; Loeb et al., 2016, 2024; Su et al., 2020). Further, ensuring a seamless multidecadal CDR requires overlap between successive ERB instruments from space. Currently, sustaining the ERB record faces increasing challenges. The CERES instruments aboard the drifting Terra and Aqua satellites are scheduled to end science data collection in 2027 and S-NPP in 2026, leaving only NOAA-20 to overlap with Libera when it launches no earlier than September 2027. Loeb et al. (2024)

showed that probability of a data gap is less than 5 % through January 2027 but increases to 33 % in 2028 and to 60 % in 2035. The greatest reduction in data gap probability would likely result from launching a new ERB mission in addition to Libera. Emphasizing the significant value of a launch in the near term in addition to Libera in 2027, Loeb et al. (2024) concluded that launching an ERB mission in 2026 would limit the gap probability to 15 % through 2035, a launch in 2027 would raise this probability to 30 %, and a launch in 2030 would keep it below 41 % over the same period. Such projected gap probabilities highlight the value of supplementing the observational record with low-cost, rapidly deployable platforms like CubeSats, which could provide a buffer against future continuity losses.

Implementation of novel CubeSat technology for ERB observation will lower the gap risk in ERB records by increasing synergistic opportunities with complementary systems at lower costs. The compact dimensions of a CubeSat reduce launch costs, facilitating increased launch opportunities. While the design robustness (compared to large platforms) of CubeSats is limited by size, multiple independent instruments with lower individual reliability can collectively match the dependability of a single large, highly reliable platform. For example, three independent CubeSats with a three-year on-orbit survival probability of 63 % collectively raise the success probability to 95 % (Harber et al., 2019). Lower costs and risks for launch increase the possibility of low-cost operational missions that implement a constellation of independent instruments to complement large platforms. Gristey et al. (2017) demonstrated that a large, theoretical constellation of wide-field-of-view (WFOV) broadband radiometers could deliver unprecedented temporal and spatial sampling for improving ERB measurements. Wong et al. (2018), however, contend that achieving the necessary calibration and intercalibration across non-scanner (WFOV) instruments for climate-quality data remains a major challenge.

Still, the rapid advancement and miniaturization in technology and the rising accessibility of small satellite platforms create viable pathways for CubeSat constellations for ERB observations, complementary to larger missions. Missions such as RAVAN, PREFIRE, Uvsq-Sat, Inspire-Sat, and Uvsq-Sat NG collectively demonstrate the growing momentum toward small satellite ERB observations (Swartz et al., 2019; Drouin et al., 2026; Meftah et al., 2025). The proposed BABAR-ERI 12U CubeSat could further demonstrate inexpensive, low-risk ERB measurements in parallel with CERES and Libera (Coddington et al., 2025b). Similarly, CTIM demonstrates a potential pathway for CubeSat implementation in ERB observations from space.

We report opportunistic longwave radiance Earth observations from the CTIM CubeSat and compare them to Earth radiance observations from CERES, the instruments that have maintained the world's longest continuous ERB record. We created an algorithm for matching CTIM and CERES in space and time. We conducted MODTRAN simulations to

generate the limb-darkening adjustment factors for clear-sky scenes and accounted for CERES footprint areas off nadir. In the 15 months of CTIM Earth observations, we found the relative difference between CTIM and CERES longwave radiances to be -1.19 ± 0.35 % ($\sigma = 4.16$ %) with a coefficient of determination of 0.948 for 541 CTIM–CERES matches (containing 261 010 CERES footprints). These results show agreement between the two different platforms within their respective uncertainties. Notably, the CTIM optical system was not designed for Earth-viewing; an optical system designed specifically for Earth-viewing could reduce radiance uncertainty to within an order of magnitude of the solar irradiance uncertainty of 0.02 %.

This study suggests that leveraging novel CubeSat technology to demonstrate CTIM opportunistic Earth-observing applications may complement heritage ERB missions and reduce the risk of gaps in future ERB observations from space. Moreover, this work provides a potential pathway for the direct measurement of Earth's energy imbalance using the same systems for Earth and Sun measurements. While challenges remain, including long-term radiometric stability, absolute Earth-viewing calibration, and cloud anisotropy corrections, these could be directly addressed and improved through intentional design in future implementations. The routine inclusion of Earth-viewing capabilities in future TSI instrument designs emerges as a natural extension of this work, with the potential to meaningfully contribute to ERB observation continuity, maximize scientific utility, and strengthen the resilience of the ERB record by providing low-cost redundancy that complements rather than replaces dedicated large-scale missions. Additionally, CubeSat platforms could potentially fill gaps in the ERB record between successive missions in the future. It is worth noting that determining the absolute value of ERB and Earth's energy imbalance from space-borne instruments remains an extremely challenging measurement problem; while current satellite observations are better suited to monitoring ERB variability and long-term trends, improving absolute accuracy remains a critical goal – one that future intentionally designed Earth-viewing TSI CubeSats may help address.

Code and data availability. The algorithm developed for this paper is freely available on GitHub (<https://github.com/mckenziehawkins/CTIM-CERES>, last access: 25 August 2025, <https://doi.org/10.5281/zenodo.22879730>, Hawkins, 2026). The CERES SSF Level-2 data are available at <https://ceres.larc.nasa.gov/data/> (last access: 25 August 2025), and the CTIM data are found within the previously mentioned GitHub repository.

Author contributions. MH led the study, developed the matching algorithm, conducted the MODTRAN simulations, and prepared the manuscript. PP supervised the study and contributed to its conceptualization. MW contributed to the conceptualization and pre-

liminary work and assisted with algorithm development. DH served as principal investigator of the CTIM instrument, providing data and instrument expertise essential to the study. MvdH contributed to the conceptualization and preliminary work of the study. PP and DH contributed to the review and editing of the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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