Persistence and Variability of Earth's Interhemispheric Albedo Symmetry in 19 Years of CERES EBAF Observations

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ABSTRACT: Despite the unequal partitioning of land and aerosol sources between the hemispheres, Earth's albedo is observed to be persistently symmetric about the equator. This symmetry is determined by the compensation of clouds to the clear-sky albedo. Here, the variability of this interhemispheric albedo symmetry is explored by decomposing observed radiative fluxes in the CERES EBAF satellite data record into components reflected by the atmosphere, clouds, and the surface. We find that the degree of interhemispheric albedo symmetry has not changed significantly throughout the observational record. The variability of the interhemispheric difference in reflected solar radiation (asymmetry) is strongly determined by tropical and subtropical cloud cover, particularly those related to nonneutral phases of El Niño–Southern Oscillation (ENSO). As ENSO is the most significant source of interannual variability in reflected radiation on a global scale, this underscores the interhemispheric albedo symmetry as a robust feature of Earth's current annual mean climate. Comparing this feature in observations with simulations from coupled models reveals that the degree of modeled albedo symmetry is mostly dependent on biases in reflected radiation in the midlatitudes, and that models that overestimate its variability the most have larger biases in reflected radiation in the tropics. The degree of model albedo symmetry is improved when driven with historical sea surface temperatures, indicating that the degree of symmetry in Earth's albedo is dependent on the representation of cloud responses to coupled ocean–atmosphere processes.

SIGNIFICANCE STATEMENT: Although the Northern Hemisphere contains more landmass and aerosol sources than the Southern Hemisphere, making it more reflective during clear-sky conditions, each hemisphere reflects the same amount of solar radiation because the Southern Hemisphere has more cloud cover. This symmetry of reflectivity has remained persistent for the entire modern satellite record despite global trends in reflectivity. We find that observed variations in this symmetry correspond to the main modes of variability of weather and climate and not to recent variations in Earth's total energy budget. Understanding how this symmetry varies with time can aid understanding of how clouds will continue to respond to forced changes in Earth's climate, thus addressing one of the fundamental uncertainties in future projections of climate change.

KEYWORDS: Cloud cover; Albedo; Shortwave radiation

1. Introduction

The first satellite-borne observations of Earth's radiative balance in the 1960s brought the observation that Earth reflects nearly the same amount of shortwave (SW) radiation in both hemispheres (Vonder Haar and Suomi 1971). This symmetry exists despite the higher clear-sky reflectivity in the Northern Hemisphere (NH) than in the Southern Hemisphere (SH) that exists due to the distribution of land surface and aerosol sources because of compensation by the mean cloud cover. Pointing out that this interhemispheric albedo symmetry exists in more recent satellite records, Voigt et al. (2013) partitioned Earth into pairs of random halves and measured the difference in mean reflected radiation in each pair, finding that only 3% of pairs exhibit the degree of symmetry observed in Earth's reflected radiation. This suggests that the observed symmetry and spatial distribution of albedo does not result from a high

number of spatial degrees of freedom (i.e., that the albedo field is not free to vary arbitrarily in all directions). With longer records of Earth's radiative balance, it was possible to test and reconfirm the interhemispheric albedo symmetry (Stephens et al. 2015). Bender et al. (2017) detailed the interhemispheric asymmetries in both cloud cover and cloud properties that compensate for the clear-sky albedo asymmetry between hemispheres: despite tropical cloud albedo and fraction being higher in the NH than in the SH, reinforcing the clear-sky asymmetry, higher SH subtropical cloud fraction and SH midlatitude cloud albedo contribute to the total cloud compensation to the clear-sky asymmetry.

Cloud amount and cloud albedo in SH midlatitudes are systematically underestimated in global climate models, leading to too much absorption of solar radiation in SH midlatitudes in the mean state across models; together with too much radiation being reflected over the tropics, poleward heat transport and thus eddy activity in the SH extratropics are too low in models, further suppressing the presence of clouds

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(Trenberth and Fasullo 2010). Other considerations contributing to this bias include model microphysics, as a lack of ice-nucleating particles in atmospheric models has been shown to lead to inefficient cloud droplet growth in low clouds over the Southern Ocean, reducing cloud albedo (Vergara-Temprado et al. 2018). Underestimated reflected SW radiation over SH midlatitudes due to the lower cloud albedo in models has also been suggested to contribute to disagreement in cloud radiative effects in response to increased greenhouse gas emissions (Grise and Polvani 2014), as well as to a double intertropical convergence zone (ITCZ) bias in models (Hwang and Frierson 2013). However, more recent work has reported that improving Southern Ocean albedo biases in coupled models does not improve model accuracy of the ITCZ or tropical climate (primarily because most of the energy transport occurs in the ocean) but increases poleward heat transport, particularly in the SH (Kay et al. 2016b; Hawcroft et al. 2017).

Meridional heat transport results from meridional differences in net energy input into Earth; for a hemispherically asymmetric profile of net radiative energy input, a cross-equatorial energy transport would result (Marshall et al. 2014). However, many configurations of Earth's climate exist that would allow for asymmetries in both absorption of solar radiation and outgoing longwave radiation (OLR) with no cross-equatorial energy transport, or for cross-equatorial energy transport to be balanced by a contrast in net energy input between the hemispheres. This confounds the search for mechanisms in the climate system that would compensate for an interhemispheric difference in albedo and for a physical explanation using energetic considerations. One theorized mechanism that would minimize interhemispheric differences in heat input is the meridional migration of the ITCZ, which has been proposed to act as a compensation mechanism to interhemispheric differences in albedo (Voigt et al. 2013, 2014a,b; Stephens et al. 2015). This tropical band of convergence on which the rising branch of the Hadley cells is located shifts with the latitude of maximum energy input into the atmosphere, occurring in the warmer hemisphere (Kang and Held 2012; Schneider et al. 2014; Bischoff and Schneider 2016). This enables a net energy transport across the equator into the cooler hemisphere, due to the higher moist static energy in the poleward branch aloft than in the lower, equatorward branch. The tropical maximum in cloudiness follows with the rising branches of Hadley circulation, introducing feedbacks in the ITCZ migrations (Voigt et al. 2014a). The relation of the ITCZ position to Earth's radiative energy balance has been studied in detail (e.g., Kang et al. 2008; Seo et al. 2014).

While suggested theoretical responses to asymmetries in albedo between the hemispheres would impact global circulation and cloud cover patterns, no explanation that would account for the degree of compensation to interhemispheric asymmetry in clear-sky albedo accomplished by clouds that is present in observations has been given. Previous studies have found that models do not reproduce the interhemispheric albedo symmetry and disagree over which hemisphere is brighter (Voigt et al. 2013; Stephens et al. 2015). Variability currently observed in the climate, such as meridional shifts in midlatitude storm track clouds (Bender et al. 2012) and the

midlatitude jet stream (Grise and Medeiros 2016), or interhemispheric differences in changes in extratropical poleward eddy heat fluxes (Chemke and Polvani 2020), make it relevant to investigate the temporal evolution of the interhemispheric albedo symmetry. Doing so can help to fill gaps in theory that would explain global responses in atmospheric and ocean circulation to meridionally asymmetric properties of planetary albedo, as well as to characterize a future climate response to changes thereof.

Loeb et al. (2018a) found that global mean outgoing longwave radiation and reflected SW radiation in CERES EBAF are correlated from 2000 until roughly 2014, when the means of each diverged and the global mean net radiation began to increase. At the same time, global mean sea surface temperatures (SSTs) increased, leading to an overall reduction in marine stratocumulus cloud cover due to decreased marine boundary layer stability. The anomalous behavior of Earth's radiation balance also occurs in a series of atmospheric model simulations forced with historical SSTs over the same time period (Loeb et al. 2020). A pertinent question to be raised is whether this affects the interhemispheric albedo symmetry. This change in the behavior of Earth's radiation balance occurs in concert with the cessation of an alleged "pause" or "hiatus" in globally warming temperatures, the boundary of which Loeb et al. (2018a) notes is also marked by a change from balance between heat loss to the deep ocean and the net radiation at the top of the atmosphere (TOA), to a net heating from the radiative imbalance exceeding the heat fluxes into the deep ocean. Because the differences in surface temperature tendencies between the hiatus and posthiatus periods are debated (Lewandowsky et al. 2015), we do not seek to characterize these two periods or to discuss the existence of a hiatus in global temperature increase, but rather to test the stability of the interhemispheric albedo symmetry following the marked changes in radiative balance outlined in Loeb et al. (2018a).

Further motivating a test of the interhemispheric albedo symmetry, there is evidence of global, decadal variations in reflected SW radiation at the TOA. A decrease of downwelling SW radiation was measured at the surface from the mid- to late twentieth century, followed by an increase from the late twentieth century onward (Wild 2009). This "dimming" and subsequent "brightening" (at the surface) may have been caused by an increase in SW absorption in the atmosphere, as the observed changes in downwelling SW radiation at surface measurement sites are not equal in magnitude to the changes in upwelling SW radiation at the TOA observed by satellites, which would be the case if there had been changes in the reflective and scattering properties of the atmosphere (Schwarz et al. 2020). Other studies confirm a trend in declining reflected SW radiation at the TOA in satellite observations covering the twenty-first century that cannot be explained by internal variability alone (Kramer et al. 2021; Loeb et al. 2021; Raghuraman et al. 2021). Raghuraman et al. (2021) offer the explanation that changes in clouds following rising global mean temperatures have caused a decrease in planetary albedo. These ongoing changes make investigating their impact on the spatial distribution of albedo a relevant question in understanding Earth's energy balance and climate.

Here, we aim to resample the observed symmetry of Earth's albedo using now nearly two decades worth of satellite measurements of Earth's radiative balance, opening up the possibility of studying effects on the interhemispheric albedo symmetry by variations in the ocean–atmosphere system occurring on the interdecadal time scale. We also seek to motivate closer study of cloud contributions to Earth's interhemispheric albedo symmetry as a global rather than a tropical feature, which would provide insight into both observed and modeled behavior in global cloud cover. As clouds are intimately connected with Earth's climate via feedback mechanisms with radiation and dynamics (Stephens 2005; Boucher et al. 2013; Voigt et al. 2021), the observed interhemispheric albedo symmetry presents an opportunity to find new determinants of and constraints on cloud cover. Discovering fundamental mechanisms in the climate system that maintain Earth's observed interhemispheric albedo symmetry can provide additional understanding of how characteristics of global cloud cover would differ in past or future climates.

2. Data and methods

To quantify the degree of interhemispheric albedo symmetry, we define *asymmetry* to be the difference in area-weighted mean reflected radiation $F_{\text{TOA}}^{\uparrow}$ between the hemispheres (NH minus SH). Reflected SW radiation at TOA is decomposed into components reflected by the atmosphere and by the surface. These fluxes are then used to compare the asymmetry and interhemispheric differences in reflected flux components between the periods March 2013–February 2019 [the post-hiatus period (PH period)] and March 2000–February 2013 [the hiatus period (H period)], following Loeb et al. (2018a). Another primary function of the distinction between these two periods is to reassess the conclusions of Stephens et al. (2015), which were based on data covered here by the H period. We construct a time series of the total asymmetry as well as of interhemispheric differences in mean decomposed flux contributions thereto. We also use time series of mean interhemispheric differences of decomposed reflected SW flux contributions in latitudinal bands covering the tropics, subtropics, midlatitudes, and polar latitudes. These are compared with the total asymmetry time series to estimate to what degree variations of reflected radiation at different latitudes determine the variability of the total asymmetry.

Using the time series for the total asymmetry, we construct composites of periods during which the symmetry is highly perturbed toward one hemisphere reflecting more than the other. This allows us to identify contributing factors that strongly perturb the observed interhemispheric albedo symmetry and relate them to variability in features of Earth's climate system (e.g., patterns of SSTs or atmospheric oscillations). We then analyze common modes of variability in monthly mean reflected radiation by calculating empirical orthogonal functions (EOFs) for the entire record; EOFs are statistical tools useful for identifying persistent spatial patterns in data, in addition to their explanatory power for the variability of the field. These results are used to interpret any changes in reflected radiation between the PH and H periods in order to identify persisting or anomalous changes outside of the common modes of variability.

Last, we compare the asymmetry and the variability thereof in coupled models and identify possible sources of bias by comparing the time evolution of asymmetry as well as meridional profiles of reflected SW radiation. We also address the ability of models to reproduce the historical evolution of the asymmetry in extended atmospheric simulations using prescribed, observed SSTs and sea ice concentration, which cover most of the satellite observation record. This allows us to investigate atmospheric responses in models to the forcing induced by historical SST patterns, and whether this produces a more or less realistic degree and variability of asymmetry.

a. Data

We use CERES EBAF, edition 4.1 (Loeb et al. 2018b), for monthly mean radiative fluxes (incoming solar radiation, upwelling SW radiation and OLR at TOA, and both upwelling and downwelling SW radiation at the surface) during all-sky and clear-sky conditions between March 2000 and September 2019 (19 full years) on a $1^{\circ} \times 1^{\circ}$ resolution grid. Clear-sky fluxes that were calculated by sampling only cloud-free pixels were used. The CERES EBAF dataset has been adjusted within uncertainty ranges in order to correct for discrepancies between net TOA fluxes and changes in upper ocean heat content from in situ observations, making it ideal for use in studies of Earth's radiative balance. The uncertainties in CERES EBAF edition-4.1 fluxes (which are included in appendix A and can be found in the CERES EBAF data quality summary) and for Solar Radiation and Climate Experiment Total Irradiance Monitor (SORCE TIM) measurements of solar irradiance (Kopp and Lean 2011) are used to estimate uncertainties in our calculations, as detailed in the appendix. The time evolution of the total asymmetry and mean contributions are also compared with the NOAA multivariate ENSO index (MEI), version 2 (Wolter and Timlin 2011).

b. Model output

We use historical and preindustrial (PI) control simulation output from 11 models from phase 6 of the Coupled Model Intercomparison Project (CMIP6) (Eyring et al. 2016). For PI control conditions, we use 450 years of simulation. Only models with at least three realizations of the historical simulations were selected, and the model time period used covers the years shared with CERES EBAF (2000–14). We also complement the historical model output with extended datasets from the Atmospheric Model Intercomparison Project (AMIP) experiment within the CMIP6 framework, used and presented in Loeb et al. (2020), to investigate how reflected radiation in atmospheric models compares to CERES EBAF when the ocean–atmosphere interactions are fixed in accordance with the observed ocean states. These atmospheric simulations are extensions of the historical simulations through 2017, thus capturing several of the PH years; the simulations were run with prescribed, observed historical SSTs and sea ice concentration, as well as emissions data used for CMIP6 historical experiments (however, after 2014, emissions in the extended simulations were held at 2014 levels). Some models in Loeb et al. (2020) are also covered in the coupled model section (CanESM5, CESM2, IPSL-CM6A-LR) or

TABLE 1. Models used in the model comparison. Coupled historical simulations are denoted by “Historical,” and coupled simulations of preindustrial control conditions are given by “PI control.” Models with atmospheric simulations using historical SSTs are denoted by “AMIP.”

Model	Simulations	Resolution	Reference
ACCESS-ESM1.5	Historical, PI control	$1.88^\circ \times 1.24^\circ$	Ziehn et al. (2019)
BCC-ESM1	Historical, PI control	$2.8^\circ \times 2.8^\circ$	Zhang et al. (2018)
CanESM5	Historical, PI control, AMIP	$2.8^\circ \times 2.8^\circ$	Swart et al. (2019b); Swart et al. (2019a)
CESM2	Historical, PI control, AMIP	$1.25^\circ \times 0.94^\circ$	Danabasoglu (2019); Danabasoglu (2020)
ECHAM6.3	AMIP	$1.88^\circ \times 1.86^\circ$	Wieners et al. (2019a)
EC-Earth3	Historical; PI control	$0.7^\circ \times 0.7^\circ$	EC-Earth Consortium (2019a)
EC-Earth3-Veg	AMIP	$0.7^\circ \times 0.7^\circ$	EC-Earth Consortium (2019b)
GFDL-AM4	AMIP	$1.25^\circ \times 1.0^\circ$	Zhao et al. (2018)
HadGEM3	AMIP	$1.88^\circ \times 1.25^\circ$	Ridley et al. (2019)
IPSL-CM6A-LR	Historical; PI control; AMIP	$2.5^\circ \times 1.27^\circ$	Boucher et al. (2018b); Boucher et al. (2018a)
MIROC6	Historical; PI control	$1.41^\circ \times 1.41^\circ$	Tatebe and Watanabe (2018)
MPI-ESM1-2-LR	Historical; PI control	$1.88^\circ \times 1.86^\circ$	Wieners et al. (2019b)
MRI-ESM2-0	Historical; PI control	$1.88^\circ \times 1.88^\circ$	Yukimoto et al. (2019)
NorESM2-MM	Historical; PI control	$1.25^\circ \times 0.94^\circ$	Bentsen et al. (2019)

share components with the coupled models (EC-Earth3 and EC-Earth3-Veg, ECHAM6.3, and MPI-ESM1-2-LR). The models used in this study, as well as their sources, are listed in Table 1.

c. Methods of calculation

1) DECOMPOSITION OF REFLECTED FLUXES

We use a decomposition of reflected SW radiation at TOA into contributions by the surface and the atmospheric components to the planetary reflectivity, derived from a simple set of radiative transfer equations (Stephens et al. 2015). The system reflectivity (or planetary albedo) R of Earth is defined as

$$R = \frac{F_{\text{TOA}}^\uparrow}{S}, \quad (1)$$

where $F_{\text{TOA}}^\uparrow$ is the upwelling SW radiation at the top of the atmosphere and S is the incoming solar radiation. The system transmissivity T is defined as

$$T = \frac{F_S^\downarrow}{S}, \quad (2)$$

where $F_S^\downarrow$ is the downwelling SW radiation at the surface. We also define the surface albedo α as

$$\alpha = \frac{F_S^\uparrow}{F_S^\downarrow}, \quad (3)$$

where $F_S^\uparrow$ is the upwelling SW radiation at the surface. The term $F_S^\downarrow$ can be expressed as

$$F_S^\downarrow = tS + rF_S^\uparrow, \quad (4)$$

where r and t are the intrinsic reflectivity and transmissivity, respectively, of the atmosphere. This accounts for the amount of solar radiation transmitted through the atmospheric column and reaching the surface, as well as the amount reflected toward the surface by the atmosphere. Note that t and r are

calculated independently in this model so that absorption and forward scattering processes are included in transmissivity values. Similarly, $F_{\text{TOA}}^\uparrow$ can be expressed as

$$F_{\text{TOA}}^\uparrow = rS + tF_S^\uparrow. \quad (5)$$

Combining these equations give expressions for R and T in terms of r , t , and α :

$$R = r + \frac{\alpha t^2}{1 - r\alpha} \quad \text{and} \quad (6)$$

$$T = \frac{t}{1 - r\alpha}. \quad (7)$$

From these, the reflectivity and transmissivity of the atmosphere can be obtained:

$$r = R - \alpha T \quad \text{and} \quad (8)$$

$$t = T \frac{1 - \alpha R}{1 - \alpha^2 R^2}. \quad (9)$$

The system reflectivity R as expressed in Eq. (6) is composed of two components: the atmospheric contribution r and the surface contribution $(\alpha t^2)/(1 - r\alpha)$. The product of each of these with the incoming solar radiation S give their respective contributions to the reflected SW radiation at the TOA, $F_{\text{atm}}^\uparrow$ and $F_{\text{surf}}^\uparrow$, in terms of radiative fluxes in watts per meter squared:

$$F_{\text{atm}}^\uparrow \equiv Sr \quad \text{and} \quad (10)$$

$$F_{\text{surf}}^\uparrow \equiv S \frac{\alpha t^2}{1 - r\alpha}. \quad (11)$$

The difference between the all-sky atmospheric contribution $F_{\text{atm}}^\uparrow$ and the clear-sky atmospheric contribution $F_{\text{atm,clear-sky}}^\uparrow$ is the cloud contribution to reflected fluxes $F_{\text{cloud}}^\uparrow$:

$$F_{\text{TOA}}^\uparrow = F_{\text{atm}}^\uparrow + F_{\text{surf}}^\uparrow = F_{\text{cloud}}^\uparrow + F_{\text{atm,clear}}^\uparrow + F_{\text{surf}}^\uparrow \quad (12)$$

Here, S , $F_{\text{TOA}}^\uparrow$, $F_S^\uparrow$, and $F_S^\downarrow$ are obtained from CERES EBAF to calculate the atmospheric and surface contributions $F_{\text{atm}}^\uparrow$ and $F_{\text{surf}}^\uparrow$, respectively, to TOA reflected SW radiation for both all-sky and clear-sky conditions. For mean contributions over time, we use only complete years beginning in March and ending in February.

2) TIME EVOLUTION OF ASYMMETRY

Total asymmetry time series are given as the 12-month running-mean difference between NH and SH mean $F_{\text{TOA}}^\uparrow$, as the interhemispheric albedo symmetry is a feature of annual mean climate. We also use and present the difference between NH and SH mean deseasonalized monthly anomalies $F_{\text{TOA}}^\uparrow$; since the 12-month running mean does not capture the variability that determines asymmetry due to smoothing, this allows us to diagnose events on the monthly time scale that contribute to the degree of asymmetry in a given 12-month period. Interhemispheric differences of decomposed reflected fluxes are also computed using area-weighted means for the tropics (0° – 20°), the subtropics (20° – 40°), the midlatitudes (40° – 60°), and the polar regions ($>60^\circ$). Comparisons presented in the results are of interhemispheric differences in monthly anomalies of decomposed reflected fluxes in these meridional sections, which are then compared with the total asymmetry using linear regressions. All deseasonalized monthly anomalies are denoted with Δ .

3) COMPOSITE ANALYSIS

To investigate patterns of variability that appear in times of perturbed symmetry, we use a composite analysis approach by using the interhemispheric mean asymmetry time series to identify states of high asymmetry in either direction. We construct an “SH brighter” composite with months below the 10th percentile in the distribution of asymmetries and “NH brighter” composite with the months exceeding the 90th percentile. Differences between the composite records and the entire CERES EBAF records were tested for significance using a Welch’s t test.

4) EOF ANALYSIS

The principal components (PCs) and EOFs of the CERES EBAF dataset are computed numerically using singular value decomposition (Dawson 2016). This method lends expedience, since singular values of the two-dimensional matrix (all spatial dimensions are stored as one dimension; the other is time) are computed using linear algebra methods with a lower computational cost than solving for large covariance matrices.

3. Results

a. CERES EBAF

1) TIME EVOLUTION OF ASYMMETRY

The time evolution of the asymmetry as well as contributions to this asymmetry are shown in Fig. 1. Along with the asymmetry time series, the interhemispheric differences in monthly anomalies of reflected radiation $F_{\text{TOA}}^\uparrow$ are presented in Fig. 1a. Months with high asymmetry on the monthly time scale do not

necessarily affect the running-mean asymmetry; clusters of anomalous months that affect the 12-month running mean do not appear with seasonality or regularity. Figure 1b presents the interhemispheric differences of individual contributions to reflected radiation, which illustrates that the total interhemispheric albedo symmetry is determined by the compensation of surface contributions $F_{\text{surf}}^\uparrow$ (a mean NH–SH difference of $+2.11 \text{ W m}^{-2}$ between 2000 and 2019) by atmospheric contributions $F_{\text{atm}}^\uparrow$ (a mean NH–SH difference of -2.12 W m^{-2}). Further breaking this down, the interhemispheric difference in clear-sky atmospheric contributions $F_{\text{atm,clear}}^\uparrow$ strengthen the clear-sky asymmetry toward a brighter NH, and the sum of the interhemispheric differences in $F_{\text{atm,clear}}^\uparrow$ and $F_{\text{surf}}^\uparrow$ is compensated by the interhemispheric difference in cloud contributions to reflected fluxes, $F_{\text{cloud}}^\uparrow$ [following Eq. (12)]. It can be seen that, because of the magnitude of its contribution to planetary albedo, the variability of $F_{\text{cloud}}^\uparrow$ primarily controls the variability of asymmetry.

As would be expected from increased atmospheric absorption of SW radiation (Schwarz et al. 2020), the mean values of $F_{\text{TOA}}^\uparrow$ in both the NH and SH have a trend of roughly -0.79 and -0.73 W m^{-2} per decade, respectively, over the entire record (Fig. 1a); however, the interhemispheric differences in clear-sky $F_{\text{atm}}^\uparrow$ exhibit no trend (Fig. 1b), indicating that the increased atmospheric SW absorptivity is distributed evenly between the hemispheres. The interhemispheric differences in mean reflected radiation remain symmetrical to the same degree.

The time evolution of the interhemispheric difference in 12-month running-mean net radiative fluxes (Fig. 1b), here defined as absorbed solar radiation minus OLR (positive upward at TOA) so that a positive value corresponds to energy input into the hemisphere, is anticorrelated with the asymmetry ($R = -0.43$). This implies that when one hemisphere is reflecting less incoming solar radiation than the other, it is also receiving more net energy input than the average interhemispheric difference in net radiation, despite competing effects of clouds on shortwave and longwave radiation. The 12-month running-mean OLR is also anticorrelated with the asymmetry ($R = -0.55$); when clouds are reflecting more SW radiation, they are also reducing OLR.

The time mean interhemispheric difference in net radiation is -1.75 W m^{-2} , made up by the interhemispheric difference in OLR (a time mean of $+1.19 \text{ W m}^{-2}$) and absorbed solar radiation, -0.56 W m^{-2} . This implies that despite the SH absorbing more solar radiation, the NH is warmer because of a net cross-equatorial transport, which is consistent with previous studies on the interhemispheric difference in energy input (Kang et al. 2015). Although the mean interhemispheric difference in absorbed solar radiation is significant, it is on the same order as the mean interhemispheric difference in incoming solar radiation (-0.64 W m^{-2}) caused by Earth’s elliptical orbit; the difference in planetary albedo between the NH and SH is only 0.03% of the global mean planetary albedo.

Regressions of interhemispheric differences (NH minus SH) in zonal-mean contributions to reflected radiation in latitudinal bands, depicted in Fig. 2, give a picture of how strongly contributions at each range of latitudes impact the

FIG. 1. (a) Left axis: the time evolution of the asymmetry (interhemispheric differences in 12-month running-mean $F_{TOA}^\uparrow$; solid black line) and interhemispheric differences in monthly mean anomalies $\Delta F_{TOA}^\uparrow$ (dashed black line). The blue and red ticks along the time axis denote months with anomaly asymmetries that are respectively lower than the 10th and higher than the 90th percentile in the time evolution and make up the “SH brighter” and “NH brighter” composites, respectively. Right axis: the 12-month running-mean $F_{TOA}^\uparrow$ in the NH (blue line) and SH (yellow line). (b) Time evolution of interhemispheric differences in 12-month running-mean $F_{TOA}^\uparrow$ and contributions thereto ($F_{atm}^\uparrow$ and $F_{atm,clear}^\uparrow$: all-sky and clear-sky atmospheric, respectively; $F_{surf}^\uparrow$: surface, and $F_{cloud}^\uparrow$: cloud), OLR, and net radiation (NET). OLR is defined as positive outward at TOA, and NET is defined as positive for a net energy input into Earth.

total asymmetry. The results of linear regressions against the total asymmetry reveal that deviations in the asymmetry are most strongly influenced by deviations in the interhemispheric difference of atmospheric contributions to reflected radiation in the tropics and subtropics, where the correlation coefficients with monthly asymmetry deviations are 0.69 and 0.62, respectively. These are almost entirely determined by interhemispheric differences in cloud contributions to reflected radiation, which have correlation coefficients of 0.71 and 0.59 (for the tropics and subtropics, respectively) with the total asymmetry deviations. The correlation between the clear-sky atmospheric contribution is less strong, although deviations in the interhemispheric differences in subtropical clear-sky contributions correlate more strongly with the total asymmetry deviations ($R = 0.38$) than the tropics ($R = 0.22$) and the midlatitudes ($R = 0.28$); this may be because the subtropics are less cloudy than the tropics and midlatitudes, where clouds mask the

effect of clear-sky variations in reflectivity. However, clear-sky fluxes in CERES EBAF are inherently more uncertain due to the variable availability of clear-sky observations (see appendix). Furthermore, deviations in clear-sky contributions to reflectivity are not independent of deviations in all-sky contributions because aerosols interact both directly with radiation and indirectly by their interactions with clouds (Boucher et al. 2013). The influence of $F_{cloud}^\uparrow$ on the overall asymmetry drops sharply poleward of the subtropics, indicating that clouds beyond the subtropics do not contribute to strong variations in asymmetry. Surface contributions are weakly anticorrelated to the overall asymmetry in the tropics and subtropics, and there is virtually no correlation in the midlatitudes and poles. This indicates that variability in surface albedo does not affect the total asymmetry as much as variability in atmospheric reflectivity. Furthermore, interhemispheric differences in tropical and subtropical surface albedo impacts the total asymmetry more than the midlatitudes

FIG. 2. Regression plots for interhemispheric differences in monthly mean anomalies of contributions to reflected fluxes for (top) all-sky atmospheric, (top middle) clear-sky atmospheric, (middle) cloud, and (bottom middle) surface, divided into (columns) regions, against the interhemispheric difference in monthly mean anomalies in upwelling SW radiation at TOA. (bottom) The sum of all-sky contributions ($\Sigma\Delta F$); for the total interhemispheric difference (bottom-left plot), this should be a 1:1 relation by definition. Red lines are lines of best fit from linear regression; colored circles in the upper left of each plot include the correlation coefficient R , and the slope m is included in the lower right.

and polar regions; this is as expected because there is more incident radiation there.

2) PERSISTENCE OF THE SYMMETRY

In Fig. 3a, we present the interhemispheric differences in contributions to reflected solar radiation following the decomposition of TOA fluxes for the entire CERES EBAF record as well as for the PH and H periods. We find no significant difference in the total asymmetry or in interhemispheric differences in each contribution to reflected radiation between the hiatus and post-hiatus periods described by Loeb

et al. (2018a), illustrating the robust persistence of the interhemispheric albedo symmetry throughout CERES EBAF. While the mean difference for the post-hiatus is $+0.45 \pm 0.42 \text{ W m}^{-2}$, indicating that the NH is likely more reflective than the SH during the PH period, this range overlaps with the uncertainty ranges of the asymmetry of both the H period and of the entire time record (i.e., there is no evidence that the mean values for asymmetry are different in either period in CERES EBAF).

Figure 3b presents the differences in $F_{\text{atm}}^{\uparrow}$ between the PH and H periods. The areas in which the differences test as

FIG. 3. (a) Differences between hemispheric means (NH minus SH) of reflected fluxes and the atmospheric and surface contributions to the reflected fluxes for the entire 2000–19 record, and during the H (2000–13) and PH (2013–19) periods. Error bars indicate estimated uncertainties for the mean values, derived from CERES EBAF errors (see [appendix A](#)). (b) Differences in atmospheric contributions to reflected SW radiative fluxes $F_{\text{atm}}^{\uparrow}$ between the PH and H periods; differences not exceeding the uncertainty ranges (as calculated in the appendix) are removed (white space), and stippling indicates a significant difference in $F_{\text{atm}}^{\uparrow}$ distributions at that grid cell between the two time periods with 95% confidence.

significant at 95% confidence are localized to the equatorial western Pacific warm pool (WPWP), the NH eastern Pacific subtropics, and the North Atlantic subtropics. Reduced cloudiness near the WPWP is a signature of reduced Walker circulation, where the convective region shifts from the WPWP to the central Pacific in the pattern associated with positive ENSO (El Niño) conditions (the mean MEI during the PH period is +0.12) ([Pinker et al. 2017](#)). In the eastern Pacific, reduced reflected radiation can be accounted for by reduced low cloud cover over the subtropical region during the positive phase of the Pacific decadal oscillation (PDO)

([Loeb et al. 2018a, 2020](#)); the higher SST deepens and decreases the stability of the marine boundary layer (MBL), shifting it away from the ocean surface and reducing available moisture ([Wood 2012](#)). While not significant, an increase in $F_{\text{atm}}^{\uparrow}$ over the central Pacific (as is expected with El Niño conditions) is evident, as well as an increase in $F_{\text{atm}}^{\uparrow}$ over most of the Arctic. The latter only partially masks a decrease in $F_{\text{surf}}^{\uparrow}$ (not shown; north of 60°N, there is an area-weighted mean decrease of -0.57 W m^{-2} between the PH and H periods), leaving an area-weighted mean decrease in $F_{\text{TOA}}^{\uparrow}$ north of 60°N of -0.41 W m^{-2} between the PH and H periods. This

FIG. 4. Composite mean monthly anomalies in reflected solar radiation $\Delta F_{\text{TOA}}^{\uparrow}$ in the states of high asymmetry for (a) SH brighter and (b) NH brighter. Stippling indicates that composite $\Delta F_{\text{TOA}}^{\uparrow}$ differs from the entire distribution of $\Delta F_{\text{TOA}}^{\uparrow}$ in CERES EBAF at that grid cell with 95% confidence.

is consistent with observations that suggest no changes in Arctic clouds during summer but increasing cloud cover during fall (Kay et al. 2016a).

3) COMPOSITE ANALYSIS

Both the asymmetry as differences in 12-month running hemispheric means and the differences in hemispheric mean monthly anomalies were used to make composite records of months with high asymmetry; while both showed similar results, composite $F_{\text{TOA}}^{\uparrow}$ fields using 12-month running-mean asymmetry showed no significant differences from the entire CERES EBAF record. As the annual cycle of interhemispheric differences in mean $F_{\text{TOA}}^{\uparrow}$ shows little variability, the characterization of interhemispheric differences in monthly anomalies is used here as a diagnostic tool to identify contributing variations that determine the asymmetry seen in Fig. 1a. Figure 4 presents the composite mean fields for monthly mean reflected solar radiation anomalies $F_{\text{TOA}}^{\uparrow}$ in the SH-brighter and NH-brighter cases based on interhemispheric asymmetry in $F_{\text{TOA}}^{\uparrow}$. In regions where composite $F_{\text{TOA}}^{\uparrow}$ tested as significantly different from the full record, the signal of ENSO can be seen: in the SH-brighter composite, $F_{\text{TOA}}^{\uparrow}$ is decreased over the Maritime Continent and over the central subtropical Pacific [typical of El Niño conditions (Yang et al. 2016)], and in the NH-brighter composite, $F_{\text{TOA}}^{\uparrow}$ is decreased over the WPWP (typical of La Niña conditions). The mean MEI value is +0.11 and −0.55 for the SH-brighter and NH-brighter composites, respectively. Furthermore, it is worth noting the interhemispheric difference in monthly mean net radiation anomalies in the composites: this is +0.27 and −0.26 W m^{-2} for the SH-brighter and NH-brighter composites, respectively. The pattern and strength of El Niño-like anomalies in the SH-brighter composite are not as strong as the La Niña-like anomalies seen in the NH-brighter composite. This may be due to higher spatial variability in SH $F_{\text{TOA}}^{\uparrow}$ than in the NH, since marine cloud cover has a higher control over $F_{\text{TOA}}^{\uparrow}$ due to the extent of ocean area coverage.

The results of the composite analysis hint that extreme variations in the symmetry are strongly determined by variations in tropical cloud cover, particularly with opposing

phases of ENSO, and to a lesser degree, subtropical cloud variability.

Other signals that may also contribute to the SH-brighter asymmetry include higher reflected radiation due to the South American monsoon system primarily over the South Atlantic convergence zone as well as an eastward extension of the South Pacific convergence zone, with the latter tending to occur more often during El Niño conditions (Salinger et al. 2014).

4) EOF ANALYSIS

The first four EOFs of reflected radiation (presented in appendix B) consist of annual and semiannual cycles. This agrees with previous results from EOF analysis performed on earlier absorbed solar radiation data from Earth radiation budget instruments aboard Nimbus satellites (Smith et al. 1990). The fifth EOF of monthly mean $F_{\text{TOA}}^{\uparrow}$ and the first EOF of deseasonalized monthly anomalies of reflected radiation $F_{\text{TOA}}^{\uparrow}$, along with the percentage of the total variance that they can explain, are shown in Fig. 5. We find that the variation beyond annual and semiannual cycles is slightly higher in CERES EBAF than in previous measurements; the percentage of the variance explained by annual and semiannual cycles in CERES EBAF is 93.8%, while Smith et al. (1990) give an estimate of 97.6%. For interannual variations, the dominant EOF is that corresponding to the ENSO signal (Fig. 5). The signal is similar to that of results from more robust multivariate EOF analysis of the pattern of the ENSO on reflected radiation (Pinker et al. 2017).

The spatial imprint of ENSO on reflected SW radiation due to changes in cloud cover is asymmetric between the hemispheres. To illustrate this, the covariance field from EOF5 of $F_{\text{TOA}}^{\uparrow}$ (EOF1 of $F_{\text{TOA}}^{\uparrow}$) has a ratio of mean values between the NH and SH of 0.79 (0.74); that is, the covariance of reflected radiation with the EOF corresponding to the ENSO phase in the SH is stronger than in the NH. This implies that ENSO has a larger impact on reflected radiation in the SH than in the NH, impacting the asymmetry during nonneutral ENSO conditions.

To test the strength of the ENSO signal in the composite analysis, we regress the composite mean $F_{\text{TOA}}^{\uparrow}$ fields against the

FIG. 5. (a) The fifth EOF of $F_{\text{TOA}}^{\uparrow}$ and (b) the first EOF for deseasonalized monthly anomalies in reflected radiation $\Delta F_{\text{TOA}}^{\uparrow}$ in CERES EBAF. The percentage of variance explained (PVE) by each EOF is also listed. The signs of EOFs and PCs are arbitrary and have therefore been made consistent for ease of interpretation.

covariance field of $F_{\text{TOA}}^{\uparrow}$ in EOF1, limited to the tropics (20°S to 20°N) and with the sign normalized to ENSO phase convention. This yields a correlation strength of $R = 0.47$ and -0.54 for the SH-brighter and NH-brighter composites, respectively. This indicates that El Niño and La Niña phases do explain a part of the spatial variability in the tropics in SH-brighter and NH-brighter mean composite $F_{\text{TOA}}^{\uparrow}$ fields, respectively. Taken together with the results of the composite analysis, we find that states of high asymmetry in CERES EBAF also correspond with the dominant mode of interannual variability in reflected radiation.

b. Models

Time series and measures of model asymmetry in historical and PI control simulations during the period overlapping with CERES EBAF are presented in Fig. 6. Figure 6a illustrates that models have a large spread in asymmetry, and that modeled asymmetries have higher variability in single realizations (as in the error bars for PI control and AMIP simulations) than is observed; this variability is reduced and becomes comparable to the variability in CERES EBAF asymmetry only when averaging across three realizations (as in the error bars for coupled model simulations—the intermodel mean standard deviation of the detrended ensemble asymmetry time series is then 0.36 W m^{-2} , while that of CERES EBAF is 0.41 W m^{-2}). Few models exhibit significantly perturbed mean asymmetry in the 2000–14 period relative to PI control simulations outside of the range of internal variability in PI control simulations; those that do tend toward NH brightening relative to the SH in comparison with PI control asymmetries (CanESM5, MRI-ESM2.0, and BCC-ESM1).

The variability within a single realization for PI control simulations is comparable to the single-realization variability in coupled model historical simulations (the intermodel mean standard deviations of the detrended asymmetry time series in single realizations of PI control and coupled model historical simulations are 0.60 and 0.57 W m^{-2} , respectively), indicating that the interhemispheric difference in albedo remains stable over long time periods. Moreover, for all 15-yr windows in PI control simulations in all models, model asymmetry varies little

(not shown; the intermodel mean standard deviation of 15-yr mean asymmetry is 0.23 W m^{-2}). In other words, observing the model in any given 15-yr window in an unperturbed climate is likely to produce a mean interhemispheric albedo difference that is well within 1% of the total mean interhemispheric albedo difference. Across all simulations, the interhemispheric difference in mean midlatitude $F_{\text{TOA}}^{\uparrow}$ (over 40°–60° only) is the primary determinant of the degree of model asymmetry, with a correlation coefficient of 0.90 (Fig. 6b).

Model asymmetry for simulations in the AMIP configuration is generally closer to the symmetry seen in CERES EBAF (Fig. 6a) than the asymmetry of coupled models, underlining the importance of spatial variations in surface temperature for determining cloud distributions. Model for model, the variability of the asymmetry time series in a single realization do not differ significantly or consistently between coupled and atmospheric models in historical simulations, indicating that modeled atmospheric and cloud responses to surface temperature variability drive the overestimated variability in interhemispheric albedo differences.

Meridional profiles of zonal-mean $F_{\text{TOA}}^{\uparrow}$ (Fig. 7a) show that models mostly disagree with CERES EBAF over the SH mid-latitudes and the tropics, as has been noted with previous phases of CMIP (Trenberth and Fasullo 2010; Hwang and Frierson 2013; Grise and Polvani 2014). Most models overestimate interannual variability in $F_{\text{TOA}}^{\uparrow}$, except for in the Arctic, as is evident from the standard deviations in zonal-mean monthly anomalies of reflected radiation $F_{\text{TOA}}^{\uparrow}$ (Fig. 7b). While the variability of $F_{\text{TOA}}^{\uparrow}$ in the SH midlatitudes across models is generally in agreement with CERES EBAF, the magnitude is not.

Interestingly, most models have trends in the asymmetry time series over the overlapping period, which is not observed in CERES EBAF (Fig. 7d). The 95% confidence interval for the estimated trend in CERES EBAF asymmetry includes zero trend—that is, the albedo symmetry persists—while the intermodel mean trend across three realizations is -0.66 W m^{-2} per decade, with most models agreeing with the sign of the trend. Trends in zonal-mean reflected radiation (Fig. 7c) reveal that models with higher negative trends in asymmetry (Fig. 7d) over the period overlapping with CERES EBAF have asymmetric

FIG. 6. Characteristics of asymmetry in 2000–14 in coupled (plus signs) and atmospheric (times signs) models, as well as in 450 years of PI control simulations in coupled models (filled triangles). For coupled models in historical simulations, output is averaged across three realizations, whereas output from one realization is used for PI control simulations and historical simulations in atmospheric models. (a) Time mean asymmetry; error bars denote standard deviations in 12-month running-mean asymmetry. (b) Interhemispheric differences of midlatitude (40°–60°) mean $F_{TOA}^{\uparrow}$ plotted against mean asymmetry in CERES EBAF and in models. (c) Time evolution of the 12-month running-mean asymmetry in CERES EBAF and in historical simulations from coupled (solid lines) and atmospheric (dashed lines) models. Error bars depict standard deviations between realizations for the coupled models.

trends in tropical reflected radiation near the equator, where NH (SH) tropical $F_{TOA}^{\uparrow}$ is decreasing (increasing) over the time period in all models. This trend is reduced in AMIP simulations, but models in the AMIP configuration also exhibit a larger increase, as well as greater variability, in SH midlatitude zonal-mean $F_{TOA}^{\uparrow}$ over 2000–14.

To compare with the results of the EOF analysis performed on CERES EBAF, we present the first EOF of monthly mean reflected solar radiation anomalies $F_{TOA}^{\uparrow}$ from each coupled model (using all monthly data from three realizations) as well as the variance explained by the corresponding PC in Figs. 8a–k. The models generally reproduce the spatial signal of the ENSO evident in the first EOF of $F_{TOA}^{\uparrow}$ in CERES EBAF, albeit with a wide spread of signal strengths. The three models in which the ENSO signal explains more variability than is seen in CERES EBAF (CESM2, MIROC6, and MRI-ESM2-0) also overestimate the variability of the degree of asymmetry. The model with the weakest first EOF of $F_{TOA}^{\uparrow}$, BCC-ESM1, does not reproduce the extent of the spatial pattern of the ENSO despite the variance being in the regions where cloud cover

would be impacted (the central and western Pacific); the variability of the asymmetry in BCC-ESM1 instead comes from the overestimated midlatitude $F_{TOA}^{\uparrow}$ variability (Fig. 7d).

The first EOF of model $F_{TOA}^{\uparrow}$ in the AMIP configuration is also shown in Figs. 8l–q. The variance of total reflected SW radiation explained by the corresponding EOF agrees with that of CERES EBAF more than in coupled models, and the extent of the spatial pattern of reflected SW radiation related to the ENSO is more accurately reproduced. For CanESM5 and ECHAM6 (the atmospheric component of MPI-ESM1-2-LR), the percentage of variance explained by the corresponding EOF agrees more with CERES EBAF with prescribed SSTs, indicating that while the fully coupled configuration does not resolve the ENSO phenomenon in these models, the atmospheric response to ENSO variation in SSTs is realistic.

We also present in Fig. 9 the composites of mean anomalies $\Delta F_{TOA}^{\uparrow}$ (using all monthly data from three realizations) for each model for the SH-brighter months where asymmetry, calculated as the interhemispheric difference in mean anomalies $\Delta F_{TOA}^{\uparrow}$, is below the 10th percentile of mean anomalies and for

FIG. 7. Meridional profiles of (a) mean $F_{TOA}^{\dagger}$, (b) standard deviation of zonal-mean monthly anomalies of reflected solar radiation $\Delta F_{TOA}^{\dagger}$, and (c) trends in zonal-mean $F_{TOA}^{\dagger}$ estimated by linear regression over 2000–14. (d) Changes in the asymmetry estimated by linear regression over 2000–14 in coupled (plus signs) and atmospheric (times signs) models. Error bars for CERES EBAF depict the 95% confidence interval for the trend's slope, and models for which the slope's 95% confidence range includes zero (likely no trend) are circled.

the NH-brighter months where the same asymmetry is above the 90th percentile to compare with composites of high asymmetry in CERES EBAF. Models disagree with CERES EBAF over common patterns during states of high asymmetry; there is an overall, global “smearing” of $\Delta F_{TOA}^{\dagger}$, indicating that specific, regional patterns of $F_{TOA}^{\dagger}$ variability that contribute to the variability of the asymmetry are not as persistent in models. Of the regional patterns that the models do exhibit, several models (CESM2, CanESM5, MIROC6, MRI-ESM2-0, and NorESM2-MM) include the El Niño signal seen in the corresponding EOF as well as in the CERES EBAF composite during SH-brighter conditions, but not necessarily the La Niña signal in the NH-brighter conditions. These models also have larger reflected radiation anomalies under these conditions than in CERES EBAF, contributing to overestimated variability presented in Fig. 7. In the NH-brighter composites, few models exhibit the signals seen in CERES EBAF; only increased reflectivity over the WPWP (in CESM2, IPSL-CM6A-LR, ACCESS-ESM1-5, MRI-ESM2-0, EC-Earth3, and NorESM2-MM) and decreased reflectivity over the Indian Ocean (CESM2, MRI-ESM2-0, and EC-Earth3) is shared. In EC-Earth3, opposing modes of increased and decreased $F_{TOA}^{\dagger}$ can respectively be seen in the SH-brighter and NH-brighter composites over the Indian Ocean.

4. Discussion

Relating the time evolution of the total asymmetry to that of interhemispheric differences in decomposed contributions to reflected fluxes at different latitudes reveals that variations in the degree of asymmetry are most strongly determined by

variability in cloud cover at low latitudes. Anomalous patterns of reflected radiation during months with high asymmetry found in the composite analysis are also related to modes of variability in the tropics and subtropics, but the resulting asymmetry on the annual time scale is perturbed only to within $1 Wm^{-2}$ (Fig. 1a). This albedo symmetry remains persistent despite changes in global mean net radiation since about 2014 (Loeb et al. 2018a) and despite a global decline in reflected SW radiation (Schwarz et al. 2020). This illustrates that Earth's interhemispheric albedo symmetry is a feature that remains robust throughout distinct changes in Earth's radiative balance.

The strength of model bias in asymmetry relative to observations is an indicator of persistent biases in planetary albedo in localized regions. The SH midlatitudes have been notoriously difficult to accurately model (Trenberth and Fasullo 2010), with far-reaching consequences for modeled circulation and climate (Hwang and Frierson 2013; Haywood et al. 2016); this continues to be a source of error in CMIP6 models, as is evident in our model comparison. These sources of bias are persistent over the simulation time period. The high variability of model asymmetry in single simulations relative to CERES EBAF is most likely due to overestimated modeled variability of zonal-mean reflected radiation over the tropics (Fig. 7d). Moreover, models disagree with CERES EBAF over both the amount and the meridional distribution of zonal-mean reflected radiation in the tropics; observed $F_{TOA}^{\dagger}$ is higher in the NH than in the SH in the tropics, primarily due to cloud cover resulting from the mean position of the ITCZ (Bender et al. 2017), while models tend toward a more meridionally

FIG. 8. The first EOF of deseasonalized monthly anomalies of reflected radiation $\Delta F_{\text{TOA}}^{\uparrow}$ in (a) CERES EBAF, (b)–(k) CMIP6 models in the coupled configuration, and (l)–(q) CMIP6 models in the AMIP configuration. The PVE by the PC corresponding to the first EOF is included for each model. The signs of PCs and EOFs are arbitrary and have therefore been made consistent for ease of interpretation.

symmetric distribution of $F_{\text{TOA}}^{\uparrow}$ in the tropics. While asymmetry biases are still present, atmospheric simulations using historical SSTs come closer to the symmetry observed in CERES EBAF coupled models; this points to the importance of surface temperature distributions in determining the placement of clouds and thus the spatial distribution of planetary albedo in models.

To illustrate the application of this feature, we consider the evolution of the asymmetry seen in CMIP6 models. Most model simulations exhibit an interhemispherically asymmetric change in reflected radiation over the tropics (Fig. 7c) over the period overlapping with CERES EBAF. This is most likely due to a southward shift in the zonal-mean position of the ITCZ in historical simulations in coupled models that is not seen over the same time period in CERES EBAF. This agrees with Zanits et al. (2020); the southward ITCZ migration seen in CMIP6 historical simulations is likely a response to aerosol forcing that is higher in the NH than in the SH, inducing the previously described mechanisms of adjustment in the position of

the ITCZ (Bischoff and Schneider 2016; Schneider et al. 2014; Voigt et al. 2014b, 2017). Meanwhile, models agree on average on the sign of changes in $F_{\text{TOA}}^{\uparrow}$ in the SH midlatitudes, strengthening the negative asymmetry trend tendency. This is most likely due to model responses in SH midlatitude cloud cover and cloud properties to historical forcings, which has been linked to both ozone-consuming emissions (Gillett and Thompson 2003; Polvani et al. 2011; Grise et al. 2013) and greenhouse gas emissions (Kushner et al. 2001; Barnes and Polvani 2013; Yin 2005; Grise and Polvani 2014). While a poleward shift in SH extratropical storm track clouds is indeed seen in observations (Bender et al. 2012), the net effect on Earth's radiation balance is suspected to be small or zero, as the reduction in radiation reflected by midlatitude clouds is balanced by increased low cloud cover following an increased stability of the MBL equatorward of the jet (Grise and Medeiros 2016).

The difference between model asymmetry in historical and PI control simulations reveals that it is possible to perturb the mean degree of interhemispheric albedo symmetry in a model,

FIG. 9. SH-brighter composite mean monthly anomalies in reflected radiation $\Delta F_{\text{TOA}}^{\uparrow}$ for (a) CERES EBAF and (b)–(k) CMIP6 member models, and NH-brighter composite mean $\Delta F_{\text{TOA}}^{\uparrow}$ for (l) CERES EBAF and (m)–(v) CMIP6 member models. CMIP6 member model composites are taken from ensembles with three realizations.

but most models' asymmetry remains within the range of interannual variability in PI control simulations. This shows that despite known responses in modeled cloud cover to historical forcings (Mamalakis et al. 2021), changes in modeled asymmetry are minimal over the historical period. That model mean asymmetry is mostly determined by interhemispheric differences in midlatitude albedo (Fig. 6b) in both coupled models and simulations with prescribed SSTs shows that the ability of models to reproduce the interhemispheric albedo symmetry is strongly dependent on the ability of the model to accurately simulate midlatitude clouds, a long-standing problem in GCMs (Hwang and Frierson 2013; Vergara-Temprado et al. 2018; Kay et al. 2016b; Bender et al. 2017).

Our results show that any recent changes to the atmospheric contribution to reflected radiation (Fig. 3b) (Schwarz et al. 2020; Kramer et al. 2021; Loeb et al. 2021; Raghuraman et al. 2021) during the period covered by satellite observation do not impact the evolution of the asymmetry in CERES EBAF. This brings the aforementioned meridionally asymmetric pattern in the evolution of $F_{\text{TOA}}^{\uparrow}$ in response to historical forcings seen in models into question. Averaging trends across model realizations yields interdecadal asymmetry trends that are not present in CERES EBAF. While the short length of the time period covered by CERES EBAF makes it difficult to determine the robustness of trends in observations, Raghuraman et al. (2021) also conclude that trends in reflected SW radiation over the

same time period are roughly the same in both hemispheres, and furthermore, are well above the range of internal variability in magnitude.

Areas where reflected radiation is significantly different from the entire CERES EBAF record during the months of high asymmetry show signals of opposing phases of the ENSO; in the SH-brighter composite, an El Niño signal can be seen, and in the NH-brighter composite, a La Niña signal can be seen. The spatial impact of the ENSO on reflected SW radiation is asymmetrical itself, as is evident from the results of the EOF analysis. We thus believe that the ENSO is a source of the variability of the asymmetry in CERES EBAF, which has been shown to be the primary source of interannual variability in the global mean net radiation balance (Trenberth et al. 2014). The results of EOF analysis of reflected radiation in coupled models reveal that models disagree over the strength or spatial extent of the ENSO signal therein, thus impacting the ability of models to accurately represent the evolution of asymmetry.

It has been suggested that an interhemispherically asymmetric albedo could impact Earth's climate (Voigt et al. 2013, 2014b; Stephens et al. 2015); a contrast in radiative heating between the hemispheres has consequences for circulation, and the ocean–atmosphere system may respond so as to minimize the required cross-equatorial heat transport. Such an adjustment to asymmetric heating can drive interannual variability in e.g., tropical precipitation through the mechanisms that would adjust to the interhemispheric contrast in heating (Kang et al. 2008; Marshall et al. 2014; Schneider et al. 2014). A change in cloud cover away from the equator such as in patterns seen in the composites of anomalously high asymmetries may cause downwelling water in subtropical cells to be asymmetrically heated, and thus change the meridional temperature gradient across the equator as the temperature of upwelling water increases, as outlined in Burls and Fedorov (2014) and Barreiro and Philander (2008). This would translate to a shift in the position of the ITCZ due to the resulting changes in the surface heat fluxes between the ocean and atmosphere as proposed by Marshall et al. (2014) and Schneider et al. (2014), illustrating how asymmetries in Earth's reflective properties may trigger theorized responses. These short-term responses of the ITCZ and Hadley circulation to asymmetric heating may be studied using other data and methods, and have previously been shown to correlate with ENSO phases (Oort and Yienger 1996; Nguyen et al. 2013; Hieronymus and Nycander 2020).

5. Conclusions

With nearly two decades of continuous observation with consistent instrumentation made available by the CERES climate data record, we seek to test whether the observation that Earth's Northern and Southern Hemispheres reflect the same amount of solar radiation, as noted in previous generations of satellite observations (Vonder Haar and Suomi 1971) and in more recent years (Voigt et al. 2013; Stephens et al. 2015), holds true. We conclude that the planetary albedo remains symmetrical about the equator to the same degree as in previous observations and studies. This feature persists even given

anomalous changes in the net radiation budget over recent years during predominantly positive ENSO and PDO phases (Loeb et al. 2018a, 2020) as well as a global declining trend in reflected radiation at TOA (Schwarz et al. 2020; Kramer et al. 2021; Loeb et al. 2021; Raghuraman et al. 2021). Hence, we do not find enough evidence to falsify the hypothesis that the interhemispheric albedo symmetry is a distinct and fundamental feature of Earth's climate system maintained by compensating mechanisms. This would imply that such a compensation occurs over relatively short time scales (less than a decade), as the declining trend in global mean reflected SW radiation is present over the entirety of CERES EBAF.

We find that variability in tropical cloud cover on the monthly time scale most strongly determines variability in the interhemispheric albedo symmetry. Extratropical clouds have increasingly weaker control over variability in the albedo symmetry toward the poles. Statistically significant signals of opposing phases of the ENSO are found in months of high asymmetry: in the most extreme cases of asymmetry where the SH or NH is brighter than the other hemisphere, the spatial pattern of El Niño or La Niña is respectively present, and the mean MEI is correspondingly positive or negative, respectively, during these months. This indicates that ENSO conditions tend toward nonneutral during states of high asymmetry. In addition, we replicate tests of the overall, global variability of reflected radiation in CERES EBAF using EOF analysis, confirming that the interannual variability is most strongly controlled by ENSO, in agreement with studies based on data from previous Earth radiation budget experiments (Smith et al. 1990). Taken together, we find that the ENSO strongly controls the variability of the observed interhemispheric albedo symmetry. This is most likely due to the hemispherically asymmetric impact of nonneutral ENSO phases on cloud cover between the hemispheres, in combination with the availability of more incoming solar radiation along the equator yielding larger anomalies in hemispheric mean values of reflected radiation.

Member models of CMIP6 have a large spread of bias in asymmetry, the degree of which is best explained by the degree of interhemispheric differences in midlatitude $F_{\text{TOA}}^{\uparrow}$, which is a symptom of the difficulties in accurately representing midlatitude clouds in models (Hwang and Frierson 2013; Vergara-Temprado et al. 2018). Models also tend to overestimate the interannual variability of reflected radiation in the tropics, resulting in a time evolution of model-specific asymmetry that is too variable. This variability is removed with averaging across more realizations; sources of overestimated variability in model asymmetry include biases in cloud properties (e.g., tropical clouds that reflect too much radiation lead to larger asymmetry variations for a given cloud distribution) and a smoothing of the ENSO signal, which in several models account for too much of the overall variability of reflected radiation. Models where the EOF corresponding to the ENSO explains less variability also tend to underestimate the variability of model asymmetry in single realizations. Model asymmetry in historical simulations with atmospheric models given SST fields consistent with observations agree more closely with CERES EBAF than their coupled model

counterparts, showing that atmospheric and cloud responses to surface temperature variations are important in determining the interhemispheric difference in albedo.

Both coupled models and models with prescribed SSTs exhibit a declining trend in asymmetry over the historical period—that is, the NH is reflecting less over time and the SH is reflecting more over time, a feature that is not present in CERES EBAF during the years shared (2000–14). In almost all models, zonal-mean trends reveal a decline and rise in NH and SH, respectively, reflected radiation near the equator over the historical period. These asymmetry trends become weaker with averaging across more realizations, but most models agree in sign and zonal-mean patterns of tropical albedo changes.

That the variability present in the degree of asymmetry on the interannual time scale arises mainly from internal variability illustrates that the interhemispheric albedo symmetry is robust as a feature of the Earth and its mean annual climate. Here, comparisons of model asymmetry and variability thereof with observations show where modeled climate impacts the ability to reproduce Earth's interhemispheric albedo symmetry. Further studies to elucidate the consequences of interannual variations in asymmetry, such as responses in the ocean–atmosphere system to hemispherically asymmetric heating, would help in understanding the interhemispheric albedo symmetry as a characteristic of Earth maintained by its climate system.

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APPENDIX A

Propagating Uncertainties in CERES EBAF Fluxes

Uncertainty for contributions to reflected fluxes must be derived from each formulation in the decomposition of the fluxes used in this study, as outlined in Stephens et al. (2015). Although the variables are not independent, they are here assumed to be independent for simplicity and thus we neglect covariances. Uncertainties used as input in the error propagation are listed in Loeb et al. (2018b), and the uncertainty in incoming solar radiation from SORCE TIM measurements is listed in Kopp and Lean (2011); these values are shown in Table A1.

TABLE A1. Uncertainties (W m^{-2}) in CERES EBAF monthly mean fluxes $F_{\text{TOA}}^{\uparrow}$, S , $F_S^{\uparrow}$, and $F_S^{\downarrow}$. Values are as reported in the CERES EBAF edition-4.1 data quality summary except for uncertainties in S , which are estimated from uncertainties in SORCE TIM daily measurements of solar irradiance.

Flux	All sky	Clear sky
$F_{\text{TOA}}^{\uparrow}$	2.5	5.4
S	0.12	0.12
$F_S^{\uparrow}$	11	11
$F_S^{\downarrow}$	14	6

Variables here are expressed with the form $X = \bar{X} \pm \delta X$, where $\bar{X}$ is the mean value of the variable and δX is the uncertainty. We begin with the uncertainty of the system reflectivity R , estimated using Gaussian error propagation:

$$\delta R = \bar{R} \sqrt{\left(\frac{\delta F_{\text{TOA}}^{\uparrow}}{F_{\text{TOA}}^{\uparrow}}\right)^2 + \left(\frac{\delta S}{S}\right)^2}. \quad (\text{A1})$$

The uncertainty of the system transmissivity T is

$$\delta T = \bar{T} \sqrt{\left(\frac{\delta F_S^{\downarrow}}{F_S^{\downarrow}}\right)^2 + \left(\frac{\delta S}{S}\right)^2}. \quad (\text{A2})$$

The uncertainty of the surface albedo α is

$$\delta \alpha = \bar{\alpha} \sqrt{\left(\frac{\delta F_S^{\uparrow}}{F_S^{\uparrow}}\right)^2 + \left(\frac{\delta F_S^{\downarrow}}{F_S^{\downarrow}}\right)^2}. \quad (\text{A3})$$

An uncertainty for the intrinsic transmissivity of the atmosphere t as expressed in Eq. (9) can then be estimated using Gaussian error propagation, also neglecting covariances:

$$\delta t = \sqrt{\left|\frac{\partial t}{\partial T}\right|^2 \delta T^2 + \left|\frac{\partial t}{\partial \alpha}\right|^2 \delta \alpha^2 + \left|\frac{\partial t}{\partial R}\right|^2 \delta R^2}, \quad (\text{A4})$$

where

$$\begin{aligned} \frac{\partial t}{\partial T} &= \frac{1 - \alpha R}{1 - \alpha^2 R^2}, \\ \frac{\partial t}{\partial \alpha} &= \frac{RT - 2\alpha R^2}{\alpha^4 R^4 - 2\alpha^2 R^2 + 1}, \quad \text{and} \\ \frac{\partial t}{\partial R} &= \frac{\alpha T - 2R\alpha^2}{\alpha^4 R^4 - 2\alpha^2 R^2 + 1}. \end{aligned}$$

The partial derivatives in Eq. (A4) are evaluated using mean values $\bar{R}$, $\bar{T}$, $\bar{\alpha}$, and $\bar{t}$. We estimate the uncertainty for the intrinsic reflectivity of the atmosphere $r = R - t\alpha T$ in a similar way:

$$\delta r = \sqrt{\delta R^2 + |-\alpha T|^2 \delta t^2 + |-tT|^2 \delta \alpha^2 + |-\alpha t|^2 \delta T^2}, \quad (\text{A5})$$

which is again evaluated using mean values $\bar{t}$, $\bar{\alpha}$, and $\bar{T}$. Mean values for R , T , α , t , and r as well as their respective uncertainties

FIG. B1. (a)–(d) The first four EOFs, respectively, of reflected solar radiation $F_{\text{TOA}}^{\uparrow}$. The PVE by each EOF is also listed. (e) The mean annual cycle of the PC strengths corresponding to the first four EOFs.

in Eqs. (A1)–(A5) are then used to calculate uncertainties in the decomposed contributions to reflected SW fluxes. The uncertainty of the atmospheric contribution to reflected fluxes $F_{\text{atm}}^{\uparrow} = S r$ is

$$\delta F_{\text{atm}}^{\uparrow} = \bar{F}_{\text{atm}}^{\uparrow} \sqrt{\left(\frac{\delta S}{\bar{S}}\right)^2 + \left(\frac{\delta r}{\bar{r}}\right)^2}. \quad (\text{A6})$$

The uncertainty of the surface contribution $F_{\text{surf}}^{\uparrow} = S(\alpha t^2)/(1 - r\alpha)$ is also estimated with Gaussian error propagation, again neglecting the contribution by the uncertainty of S :

$$\delta F_{\text{surf}}^{\uparrow} = \sqrt{\left|\frac{\partial F_{\text{surf}}^{\uparrow}}{\partial S}\right|^2 \delta S^2 + \left|\frac{\partial F_{\text{surf}}^{\uparrow}}{\partial \alpha}\right|^2 \delta \alpha^2 + \left|\frac{\partial F_{\text{surf}}^{\uparrow}}{\partial t}\right|^2 \delta t^2 + \left|\frac{\partial F_{\text{surf}}^{\uparrow}}{\partial r}\right|^2 \delta r^2}, \quad (\text{A7})$$

where

$$\frac{\partial F_{\text{surf}}^{\uparrow}}{\partial S} = \frac{\alpha t^2}{(1 - r\alpha)^2},$$

$$\frac{\partial F_{\text{surf}}^{\uparrow}}{\partial \alpha} = \frac{S t^2}{(1 - r\alpha)^2},$$

$$\frac{\partial F_{\text{surf}}^{\uparrow}}{\partial t} = \frac{2S\alpha t}{1 - r\alpha}, \quad \text{and}$$

$$\frac{\partial F_{\text{surf}}^{\uparrow}}{\partial r} = -\frac{S\alpha^2 t^2}{(1 - r\alpha)^2},$$

with the partial derivatives in Eq. (A7) evaluated using the mean values $\bar{S}$, $\bar{\alpha}$, $\bar{t}$, and $\bar{r}$. Keeping in mind that the uncertainties in all-sky and clear-sky fluxes differ, the uncertainty of the cloud contribution to reflected fluxes is thus

$$\delta F_{\text{cloud}}^{\uparrow} = \sqrt{\delta F_{\text{atm,all-sky}}^{\uparrow 2} + \delta F_{\text{atm,clear-sky}}^{\uparrow 2}}. \quad (\text{A8})$$

The uncertainties of time means of any variable over a period of N months are scaled by a factor of $N^{-1/2}$. For regional means, the uncertainty of the area-weighted mean ΔX_H of any variable X is calculated using

$$\delta X_H = \frac{1}{\sum_j w_j} \sqrt{\sum_j (w_j \delta X_j)^2}, \quad (\text{A9})$$

where w_j is the weight corresponding to the grid cell area for each cell j and δX_j is the uncertainty for that cell, keeping in mind that each grid cell may have different uncertainties due to scaling by that cell's mean. Differences of regional means have uncertainty $\delta(X_{\text{NH}} - X_{\text{SH}})$, which is the sum of each regional mean's uncertainty (δX_{NH} and δX_{SH}) in quadrature:

$$\delta(X_{\text{NH}} - X_{\text{SH}}) = \sqrt{\delta X_{\text{NH}}^2 + \delta X_{\text{SH}}^2}. \quad (\text{A10})$$

APPENDIX B

EOFs of Annual and Semiannual Cycles

The first four EOFs of reflected solar radiation $F_{\text{TOA}}^\dagger$ are presented in Fig. B1. The mean annual cycles of the PC strengths are depicted in Fig. B1e and show that EOFs 1 and 3 are of annual cycles (the PC strengths for EOFs 1 and 2 have peaks in June and August, respectively) and EOFs 2 and 4 are of semiannual cycles (the PC strength for EOF2 has peaks in December and June, and that of EOF4 has peaks in February and July). EOF1 is the annual cycle of insolation, and EOF2 is the seasonal migration of the ITCZ. EOFs 2 and 4 include albedo variability related to monsoon systems, particularly the East Asian and Pacific monsoon systems (He 2009; Ha et al. 2012). These results agree with prior studies of the variability of shortwave irradiance using EOF analysis (Smith et al. 1990).

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