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Key Points:

- Climate models persistently do not simulate the observed planetary albedo symmetry
- However, they do agree in a reduction of Northern minus Southern hemispheric reflectance under CO₂ forcing
- Modeled bias and forced change of albedo asymmetry, as well as observed deviations from symmetry might be governed by surface temperature

Supporting Information:

Supporting Information may be found in the online version of this article.

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Connecting Hemispheric Asymmetries of Planetary Albedo and Surface Temperature

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Abstract Satellite measurements show that the Northern and Southern hemispheres reflect equal amounts of shortwave radiation (“albedo symmetry”), but no theory exists on if, how, and why the symmetry is established and maintained. Ambiguously, climate models are strongly biased in albedo symmetry but agree in the sign of the response to CO₂. We find that mean-state biases in albedo symmetry and hemispheric surface temperature asymmetry correlate negatively. Similarly, the response of albedo asymmetry to CO₂ forcing correlates negatively with the magnitude of the asymmetry in surface warming. This is true across many and within single climate model simulations: a too warm or stronger warming hemisphere is darker or darkens more than its counterpart. In the 21 years of observations we find the same tendency and hypothesize (a) albedo symmetry is a function of the current climate state and (b) we will observe an evolution toward albedo asymmetry in coming decades.

Plain Language Summary Observations indicate that the Northern and Southern Hemispheres reflect equal amounts of shortwave radiation. It is not understood whether this “albedo symmetry” is by chance or physically necessary in the current or across different climate states. Planetary albedo changes substantially under global warming and acts as a radiative feedback. Thus, it seems paramount to understand its dynamics. We are doing so by using climate models. They are not tuned for albedo symmetry and indeed show huge biases since three generations of models. We flesh out our understanding where these biases come from and further, find a robust evolution of the albedo symmetry in response to CO₂ forcing across model generations. Both, the models' bias and the forced change correlate well with the surface temperature difference between the hemispheres. Finally, we find this relation also present in the observed inter-annual deviations from albedo symmetry and surface temperatures. This implies that we might observe an evolution toward an albedo asymmetry in the next decades and symmetry depends on the climate state.

1. Motivation

At the top of the atmosphere (TOA), the Northern and Southern hemispheres reflect almost equal amounts of solar radiation, when averaged over several years (henceforth referred to as “albedo symmetry”). This phenomenon was first observed decades ago and confirmed with greater precision with the now 21-year long record of the Clouds and Earth's Radiant Energy System (Loeb et al., 2009; Vonder Haar & Suomi, 1971; Wielicki et al., 1996). Over the last 20 years, both hemispheres experienced exactly the same trend in planetary albedo (e.g., Hartmann & Ceppi, 2014; Jönsson & Bender, 2022; Raghuraman et al., 2021; Stephens et al., 2022; Stevens & Schwartz, 2012). Even after 50 years of research, we do not know whether and if so, how the climate system maintains this symmetry or whether it is a random product of the data record or a function of the current spatial patterns of surface albedo, clouds, aerosols, and changes therein over the last couple of decades. One mechanism of upholding albedo symmetry was introduced so far: The intertropical convergence zone shifts deeper into or toward the warmer hemisphere and hence brightens and cools it and increases the heat transport into the opposite hemisphere (Voigt et al., 2014). This mechanism is currently thought to not sufficiently explain albedo symmetry because the clouds compensating for the clear-sky asymmetry are mostly found at extra-tropical latitudes (Datseris & Stevens, 2021; Diamond et al., 2022; Jönsson & Bender, 2022; Stephens et al., 2015) and the interaction of the extra-tropics and tropics are very different in fully coupled models and likely the real world than in simulations with prescribed surface fluxes or surface temperature (e.g., Hawcroft et al., 2017; Kay et al., 2016; Kim et al., 2022). Several other papers proposed “ingredients” for a potential theory of albedo symmetry without spelling out actual mechanisms of “interhemispheric communication”: the marine cloud fraction and cloud phase partitioning (Bender et al., 2017), the subtropical and midlatitude clouds (Jönsson &

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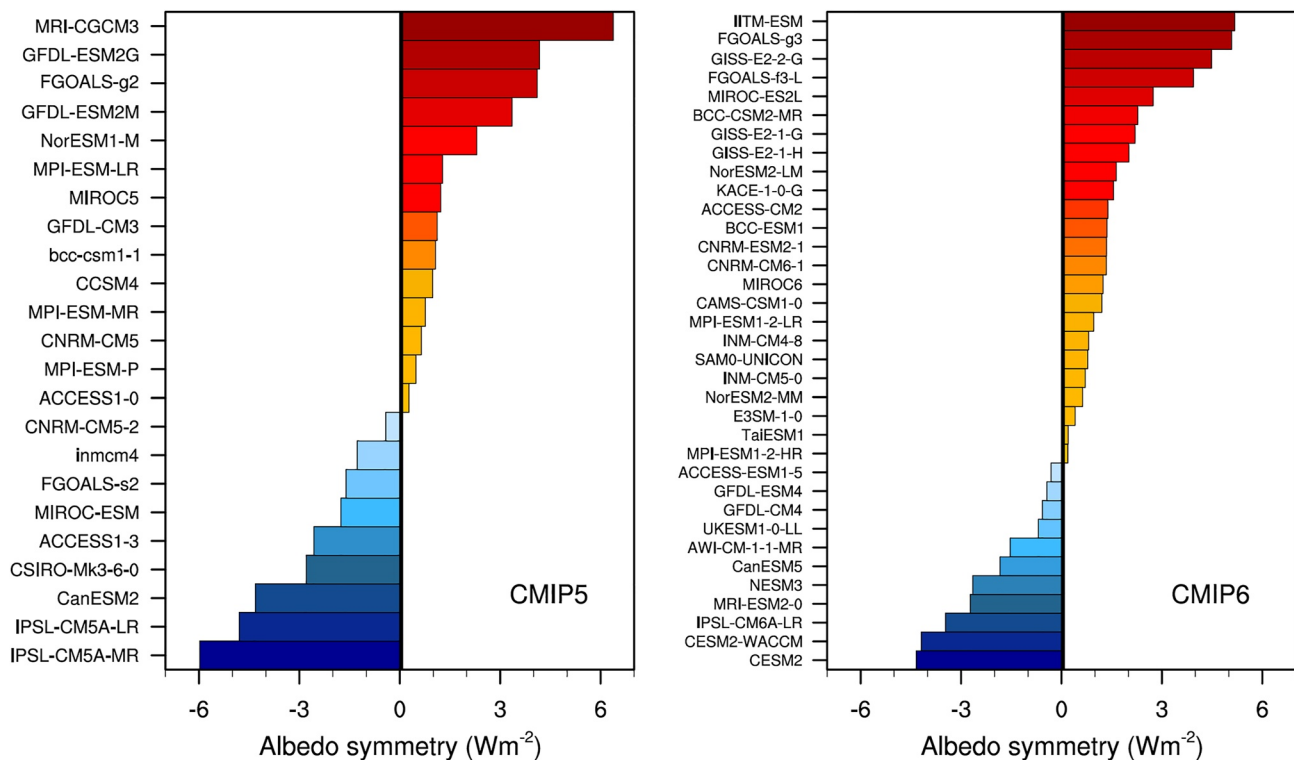


Figure 1. Albedo symmetry bias for CMIP5 and CMIP6 models. The black vertical line indicates the averaged observed value (see text for details on the calculation).

Bender, 2022), area-normalized cloudiness over oceans (Datseris & Stevens, 2021) set by storminess and the efficiency of cyclones to generate clouds (Hadas et al., 2023; Shaw et al., 2022), and the aerosol clear-sky forcing (Diamond et al., 2022).

Coupled climate models have long-standing and strong biases in global-mean albedo and albedo symmetry (Figure 1; see Bender et al. (2006), Bender (2011), and Voigt et al. (2013) for CMIP3-generation models). Hence, the question arises whether biased climate models can and should be used to increase physical understanding of the observations. If the observed hemispheric albedo symmetry is a fundamental property of the climate system, models should be able to reproduce symmetry in the mean-state and the magnitude of trends in each hemisphere—ideally without being tuned to these observations. The models might in principle simulate trends correctly even though their mean-state is biased, or vice versa. Understanding why models do not simulate albedo symmetry might help in understanding its drivers in the real world.

The goal of this paper is twofold: First, we show climate models to be useful for increasing understanding and generate hypotheses on processes not well understood in observations, in spite of and even due to their biases. Second, we introduce a new ingredient of a potential theory of albedo symmetry, the hemispheric asymmetry of surface temperature. We first document and flesh out our understanding of mean-state albedo symmetry biases and its CO₂-forced trends in coupled climate models (Section 3). We show that models project a robust and strong decrease in the hemispheric difference of planetary albedo—independent of their mean-state albedo symmetry. Both, the bias in mean-state albedo symmetry and the CO₂-forced change are correlated with a model's hemispheric surface temperature difference. We also find evidence for this relationship in observations. We hypothesize albedo symmetry to be dependent on the current climate state and that we will observe an evolution toward albedo asymmetry in response to asymmetric surface warming projected for the coming decades (Section 4). Finally, we assess our goals and discuss implications of our findings (Section 5).

2. Methods

We refer to the planetary shortwave reflected flux difference between the Northern and Southern hemispheric averages as “albedo symmetry” for the observations and as “albedo asymmetry” for the models. Our focus is not

on the exact differentiation of symmetry from asymmetry (e.g., Datseris & Stevens, 2021; Voigt et al., 2013) but on the robust disagreement between models and observations and the spread across models.

To calculate the observed annual-mean albedo symmetry, we follow the CERES EBAF Ed4.1 Data Quality Summary (2020) (see also, Wielicki et al., 1996; Loeb et al., 2009) in that we weight each month with the number of the days, including leap days, and use the provided geodetic latitudinal weights for area-averaging. We mostly use the 21-year average between January 2001 and December 2021, except in Figures 4c and 4d, where we use simulated and observed annual means of the same period. We derived observed surface temperatures from the HadCRUT5 data set for the same period, taking into account leap years and the length of months in time averages, but assuming a spherical earth and thus use cosine latitudinal weights (Morice et al., 2021).

We use all available models in the Coupled Model Intercomparison Projects CMIP5 and CMIP6 which provide variables “rsut” (reflected solar radiation at the TOA), “tas” (near-surface temperature), and “rsutcs” (reflected solar radiation at the TOA under clear-sky conditions) at monthly resolution (Figure 1; Taylor et al., 2011; Eyring et al., 2016, and SM text). To calculate the albedo asymmetry and surface temperature asymmetry we assume a spherical earth and all months having equal length and no leap years. For a 20-year average, taking the length of the months and leap years into account makes a difference for the albedo asymmetry of less than 0.1 Wm^{-2} , which is 1–2 orders of magnitudes lower than the values for the long-term model means we are discussing here. We refer to the average of 100 years of pre-industrial control simulations as “mean-state.” These simulations run with freely evolving ocean-atmosphere interactions but a repeated atmospheric composition of the year 1870 (CMIP5) or 1850 (CMIP6). We define a model bias as the difference between the models’ mean-state and the observed 21-year average, even though the former does not have a forced component. Alternatively, we could compare simulations of year 2001–2021 with the observations, however, scenarios switch during this time—from “historical” to “future” Representative Concentration Pathways (RCP, in 2005 for CMIP5) and Shared Socio-economic Pathways (SSP, in 2014 for CMIP6) –, the forcing includes uncertain aerosol and land-use changes, and fewer models provide the required fields. Figure S6 in Supporting Information S1 shows these more limited data from coupled historical simulations which are more noisy but confirm our findings laid out below. We further use idealized simulations of instantaneous CO_2 quadrupling which is held constant for 140 years. We refer to the difference between the average of year 121–140 to the averaged long control simulation as “change in abrupt4x.” These changes are quantitatively similar to the change at the end of the 21st century in strongly forced scenarios (RCP 8.5 and SSP585; Figure S6b in Supporting Information S1). We also use “amip” simulations, which prescribe observed sea surface temperature and sea ice patterns to atmosphere-land models for the period 1979–2005 (CMIP5) and 1979–2014 (CMIP6). We focus on the first-order, robust response to global, CO_2 -induced warming and not the comparably small changes in the last decades which are also influenced by aerosol forcing (e.g., Diamond et al., 2022; Irving et al., 2021; Jönsson & Bender, 2022; Lembo et al., 2019; Raghuraman et al., 2021; Stevens, 2015).

3. Mean-State and Change of Albedo Asymmetry

Models tend to be biased in their global-mean shortwave reflected flux—being either too dark or too bright in both hemispheres (models align along the 1:1 line in Figure 2a) and thus, even though a model might have a small bias in hemispheric albedo symmetry both its hemispheres might be roughly equally off. While many models are tuned for global-mean reflected flux values, for example, staying within $\pm 4 \text{ Wm}^{-2}$ compared to the observed value of $\approx 99 \text{ Wm}^{-2}$, we are not aware of modeling centers tuning for albedo symmetry (Hourdin et al., 2017; Schmidt et al., 2017; Wild, 2020). The biases in albedo symmetry are not related to the bias in global-mean reflected shortwave flux (Figure S1 in Supporting Information S1), dominated by cloud radiative effects in the tropics and the Southern Ocean region and clear-sky effects in the polar latitudes. Clouds contribute more to the net bias and large local model spread than clear-sky effects (Figure S2 in Supporting Information S1).

The change in asymmetry under CO_2 forcing is uncorrelated with the mean-state bias in asymmetry (compare color coding in Figures 2a and 2b; Figure S1 in Supporting Information S1 quantifies the effect with regression slopes of -0.01 and -0.16 and coefficients of determination of 0.00 and 0.1 for CMIP5 and CMIP6, respectively.). Some models get closer, while others move away from the observed albedo symmetry. Changes in the Northern and Southern hemispheres are of similar magnitude—up to 10% of the global mean-state reflected flux—but the change in the Northern hemisphere is consistently larger. Again, these changes in albedo asymmetry are

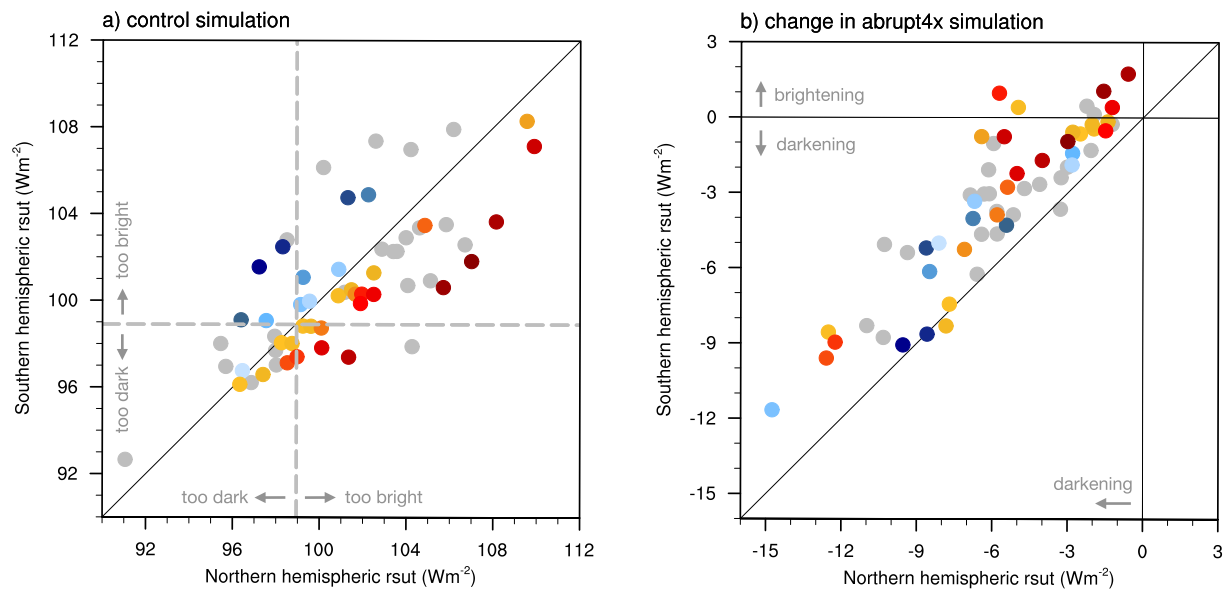


Figure 2. Southern versus Northern hemispheric reflected flux averaged over 100 years of the unforced control simulations with dashed lines showing the CERES average of 2001–2021 (a). Change in idealized climate model simulations (b, see text for details). CMIP6 models are colored as in Figure 1, CMIP5 are depicted in gray.

uncorrelated with the global mean-state bias in rsut or its change in a warmer world (Figure S1 in Supporting Information S1).

In the zonal mean, the models' mean-states spread around the observations with local biases of up to 20% of the mean-state value (Figure 3a). In some regions, the models have (more or less well studied) consistent biases, for example, in the Southern hemispheric tropics, around 40°–60° in both hemispheres, and in the Northern high

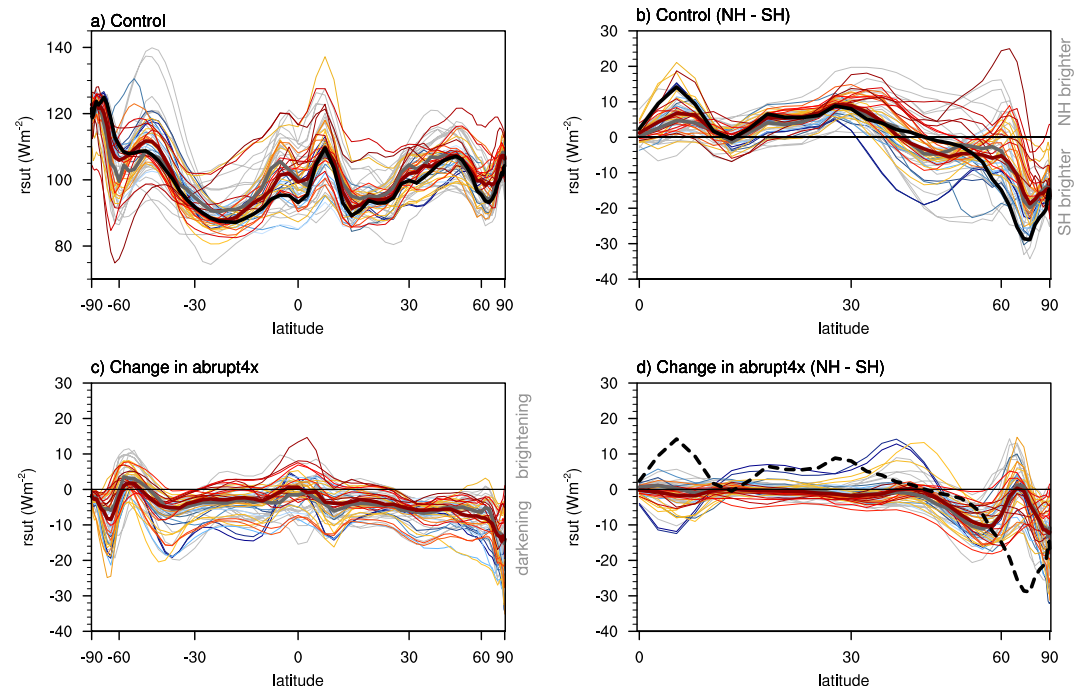


Figure 3. Zonal mean distribution of shortwave reflected flux (a) and albedo asymmetry for each latitude (b), and their changes with strong CO₂ forcing (c and d) for CMIP6 models in the same colors as Figure 1 (median in thick dark red) and CMIP5 in gray (median in thick gray). The CERES average over 2001–2021 is shown in solid black in panel a and b and as a dashed black line in panel d as reference. Figure S2 in Supporting Information S1 shows clear-sky and cloud radiative effects.

latitudes (e.g., Gettelman et al., 2020; Hawcroft et al., 2017; Haywood et al., 2016; Hwang & Frierson, 2013; Kay et al., 2016; Lembo et al., 2019; Notz & Community, 2020; Thackeray et al., 2019; Voigt et al., 2013). The albedo symmetry mean-state bias and spread tend to stem from mid- and high latitudes (Figure 3b; Bender et al., 2017; Jönsson and Bender, 2022), not the Tropics (Voigt et al., 2014). The Northern is brighter than the Southern hemisphere between the equator and around 50°, and vice versa between 50° and the poles. Models simulate this switch between 35° and 70°. We note again that we are comparing pre-industrial control simulations with observations averaged between 2001 and 2021 and hence do not expect a perfect match.

The robust tendency to darken (Figure 2b) stems from all latitudes, but is most pronounced in the mid- and high Northern hemispheric latitudes (Figure 3c). CMIP6 models show less strong brightening effects in Southern hemispheric mid-latitudes than CMIP5 models (Kay et al., 2016; Zelinka et al., 2020), but otherwise CMIP5 and CMIP6 do not differ systematically. The majority of models agree in a reduction of the asymmetry in the Tropics which works against their mean-state bias, comparatively little change in the subtropics, and a stronger Northern than Southern hemispheric darkening where the biases are also strongest (compare Figures 3b and 3d and e.g., Voigt et al., 2014; Hartmann & Ceppi, 2014).

4. Hemispheric Difference in Surface Temperature Might Force Albedo Asymmetry

In the mean-state, models with a large bias in albedo symmetry tend to also have a large bias in the hemispheric surface temperature asymmetry (Figure 4a). The warmer hemisphere also tends to be darker than its counterpart. This relationship stems to similar degree (around $1.2 \text{ Wm}^{-2} \text{ K}^{-1}$) from the clear-sky and cloud radiative effect, with more model agreement in the clear-sky than the cloud effect (Figure S3 in Supporting Information S1). We cannot easily differentiate between cause and effect since the shortwave TOA radiation and surface temperature can influence each other and may be tuned in tandem or not. There is no obviously expected dependence between the two at the hemispheric-mean level because the TOA longwave radiation and cross-equatorial heat transport also interact with the two fields.

However, we do at least approach causal inference when looking at CO₂-forced changes in albedo asymmetry, which are also well correlated with the change in surface temperature asymmetry (Figure 4b). For an un-equilibrated response to forcing, the Northern hemisphere should warm more than the Southern hemisphere because of its smaller ocean volume and heat capacity, larger continental area, and stronger polar amplification (e.g., Armour, 2017; Feulner et al., 2013; Friedman et al., 2013; Hu et al., 2022; Kang et al., 2014; Rugenstein et al., 2019; Salzmann, 2017; Senior & Mitchell, 2000). This response has to be dominated by the surface: TOA fluxes alone could not change the continental configuration or local ocean heat capacity. Ocean models forced with spatially homogeneous surface flux changes exhibit a hemispheric asymmetric warming (e.g., Marshall, Armour, et al., 2014; Marshall, Scott, et al., 2014). Hence, even though we are still concerned with the highly coupled system, we are confident that the differential hemispheric surface warming forces the albedo asymmetry, which in turn might reinforce the surface signal. The change in albedo asymmetry stems mostly from the robust clear-sky flux changes and to lesser degree (in CMIP6) or not at all (in CMIP5) from the hemispheric asymmetry in the cloud radiative effect (Figure S3 in Supporting Information S1).

Physically, the clear-sky part of the net shortwave effect for the mean-state and CO₂-forced change can be interpreted as follows (Figures S3 and S4 in Supporting Information S1): Within each hemisphere, sea ice, snow, and atmospheric absorption are robustly related to that hemisphere's surface temperature. The mean-state model differences and CO₂-forced changes in the Northern hemisphere are greater so that the hemispheric difference is asymmetric. The shortwave cloud effect counteracts the clear-sky effect locally, in high latitudes, but is not able to compensate it either locally or for the entire hemisphere. Unsurprisingly, cloud effects are less robust for the different model generations and conditions: In the mean-state within each hemisphere the cloud radiative effect is positively correlated with their hemispheric temperature, but interestingly, the hemispheric difference supports the all-sky relationship between surface temperature and TOA radiation. For the CO₂-forced changes within each hemisphere, the cloud radiative effect contributes more to the coupling of surface temperature and net shortwave TOA radiation than the clear-sky. However, counter to the mean-state situation, the change in the hemispheric difference of the cloud radiative effect is very weak, not robust across model generations and single models do not agree on the sign of the change. Both effects are expected, given the models' large spread and disagreement in sign of their global-mean shortwave cloud radiative feedbacks and the forcing adjustments which are usually larger than the global-mean shortwave clear-sky feedbacks (e.g., Kamae et al., 2015; Zelinka et al., 2020).

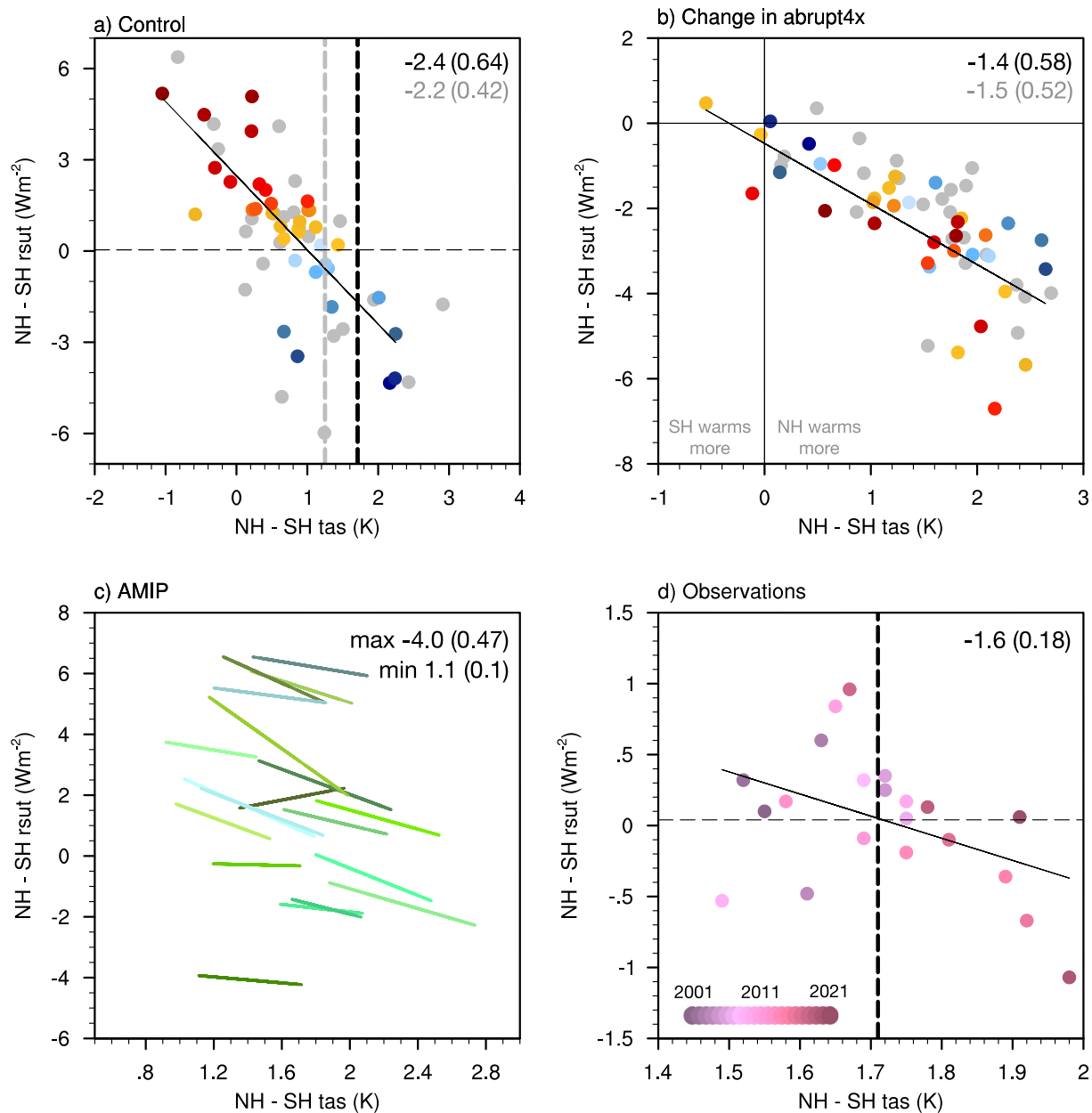


Figure 4. Climatological (a) and change (b) of albedo asymmetry versus climatology and change of surface temperature asymmetry *across* models, respectively. CMIP6 models are shown in the same colors as Figure 1; CMIP5 models in gray; CERES averages over 2001–2021 are shown as dashed horizontal line; HadCRUT5 averages of 1850–1900 and 2001–2021 in vertical dashed gray and black, respectively. Change of albedo and surface temperature asymmetry *within* simulations (c) and observations (d). Green lines in panel (c) are ordinary least square regressions of the years 1979–2005 (for CMIP5 models) and 1979–2014 (for CMIP6 models) in amip simulations (see Supporting Information S1 for model names.) All but one show a negative slope. See also Figure S5 in Supporting Information S1 for the regression within control and abrupt4x simulations. Panel d shows annual-means of observed 2001–2021 values. Text in all panels indicates the least square linear regression slope and coefficient of determination (R^2) values for CMIP6 in black and CMIP5 in gray.

We further confirm our relationship between the surface temperature and albedo asymmetry in several entirely different situations which are influenced to different degrees by internal variability and the forced response to CO₂ and other forcing agents: First, while until now we focused on the relationship across many models, the relationship also holds within the vast majority of single simulations across time (Figure S5 in Supporting Information S1). Second, we use amip simulations, which—by definition—are forced by the surface. This surface forcing is constructed from observations, which of course are also influenced by the TOA radiative imbalance but independent from what a specific coupled model would have produced based on its own processes, biases, and internal

variability (e.g., Loeb et al., 2020; Olonscheck et al., 2020; Raghuraman et al., 2021; Wills et al., 2022). We regress the asymmetry of albedo and surface temperature in all available years within each simulation (Figure 4c). In all but one model, we find the negative relationship confirmed. In amip simulations, the albedo asymmetry changed since 1979, and it remains an open question whether this indicates the observations from the 60ies and 70ies where imprecise and not perfectly hemispherically balanced, or whether the—most likely aerosol—forcing is wrong in the climate models. Importantly, the change in albedo asymmetry in the climate models is robust across models, model generations, tuning strategies, and independent of the mean-state bias. Third, coupled simulations with historical and assumed future forcings—including aerosols, land-use change, and other greenhouse gases—show the same relationship across models (Figure S6 in Supporting Information S1). Fourth, our relationship might be acting already in the observed record: The year-to-year deviations from albedo symmetry and magnitude of the surface temperature asymmetry in the last 21 years show that a warmer hemisphere is also darker (Figure 4d). This relationship is limited by the length of the record and might entirely be by chance. The p -value of the regression is 0.05 and does not improve when years with a high ENSO index are excluded (Jönsson & Bender, 2022; Loeb et al., 2018). Hence, put conservatively, the observations do not falsify our relationship (Popper, 1935/59).

5. Discussion, Conclusion, and Outlook

We explored the use of biased climate models to theorize observations which are not well explained. On one hand, the strong mean-state biases argue for entirely discarding coupled climate models from being useful to understand drivers of the observed albedo symmetry. If albedo symmetry is a fundamental property of the climate system with potential implications for large scale climate dynamics, climate models should be able to reproduce it. On the other hand, the fact that forced changes in albedo asymmetry occur in the vast majority of very different simulations, independent of their sign and magnitude of the mean-state bias, argues for the possibility that the observed symmetry is a function of the climate state and might change in coming decades. The disagreement of the models in the mean-state and their evolution under CO₂ forcing allowed us to develop a new, robust hypothesis for a controlling factor of hemispheric albedo symmetry or asymmetry. The surface forcing could play a role in upholding albedo symmetry (or a models' constant asymmetry): Within control simulations the warmer hemisphere is also darker on interannual timescales (Figure S5a in Supporting Information S1). The surface forcing could also imply that albedo symmetry is a function of the current climate state, including its hemispheric difference in surface temperature and warming rates as evident in Figure 4 and Figure S6 in Supporting Information S1. Hence, we expect an evolution toward albedo asymmetry in the coming decades as the hemispheric difference of surface warming increases in response to stronger CO₂ and weaker aerosol forcing. Figure 4d can be interpreted as evidence for this change to already take place. Aerosol effects on radiation and clouds might complicate or delay this effect, but also argue for a state dependence of albedo symmetry (Diamond et al., 2022). Alternatively, the simulated forced change of albedo asymmetry could be false, indicating that all models might have a common bias with the same sign in their shortwave radiative feedbacks. This would pose a serious problem for the projections of many climate variables. We conclude that in spite of their mean-state biases, climate models are a useful tool to generate hypotheses about the still unexplained observed albedo symmetry.

We speculate how the surface temperature asymmetry could connect the extra-tropical clear-sky (Northern Hemisphere) and cloud radiative (Southern Hemisphere) effects: Variations in ocean dynamics and ocean heat uptake modulate the meridional and cross-equatorial heat transport and its atmosphere-ocean partitioning, which in turn controls the local and remote (opposite hemisphere's) meridional temperature gradients, storminess, surface temperatures, and boundary layer structure which all are drivers of cloud cover and hence solar reflection.

Data Availability Statement

We acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. We thank the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF. All data used in this manuscript can be accessed freely from <https://esgf-node.llnl.gov/projects/cmip6/> for CMIP model output, <https://ceres.larc.nasa.gov/data/> for CERES-EABF, and <https://crudata.uea.ac.uk/cru/data/temperature/> for HadCRUT5. Processed data reflecting the steps laid out in the method section are available <https://doi.org/10.5061/dryad.v41ns1s1h>.

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