Maintenance of Earth's hemispheric albedo symmetry despite changes in aerosol and ice cover during the twenty-first century

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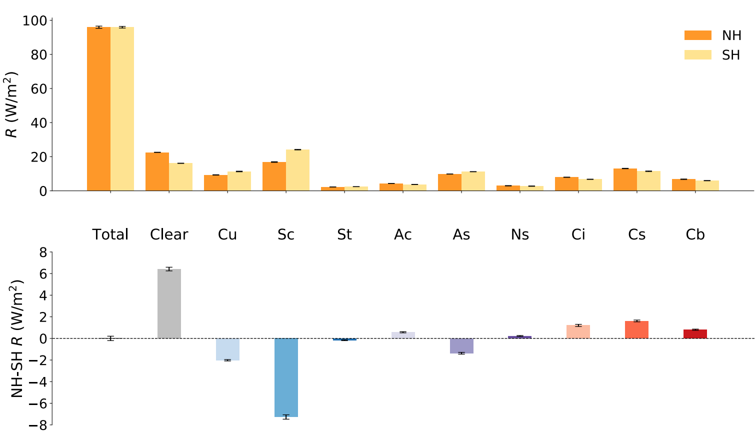
Introduction

One striking feature of the observed Earth system is its **hemispheric albedo symmetry** — that is, the amount of sunlight reflected (***R***) in any given year from the Northern Hemisphere (**NH**) is essentially equal to that reflected from the Southern Hemisphere (**SH**). This is surprising for at least two reasons: 1) Because land surfaces are brighter than ocean surfaces in general, the Northern Hemisphere has a much larger surface albedo (reflectivity) than does the Southern Hemisphere; and 2) state-of-the-art global climate models generally do not simulate this hemispheric symmetry. Differences in cloudiness between the hemispheres compensate for the clear-sky asymmetry. **Figure 1** shows this phenomenon for each hemisphere separately (*top*) and their difference (*bottom*) for the total amount of sunlight reflected (*first column*) as well as components related to reflection in cloud-free "clear" skies and by different cloud types (see below for definitions of each type). Error bars represent two standard errors of the mean.



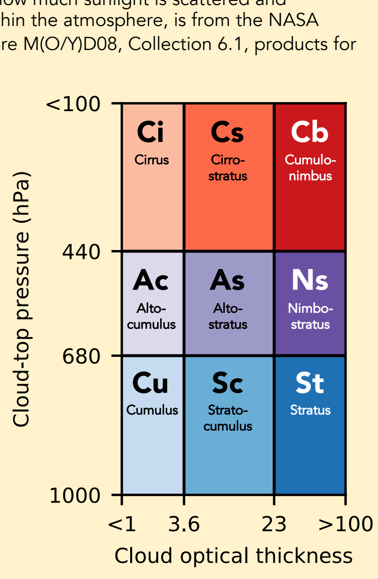
Data & Methods

Data sources

- All data is publicly available (see Acknowledgements at bottom of poster)
- Radiative properties for different cloud types, clear-sky scenes, and the total Earth system come from the NASA CERES monthly FluxByCldTyp, Edition 4A, product for July 2002 to June 2020
    - **Figure 2** shows how each cloud type is defined based on its cloud-top pressure (i.e., altitude) and its cloud optical thickness (how bright the cloud is)
- Sea ice coverage (C_{ice}) is from the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 3, for January 2003 to December 2019
- Snow cover (C_{snow}) is from the NASA MODIS Terra & Aqua monthly Snow Cover M(O/Y)D10CM , Collection 6.1, products for January 2003 to December 2019
- Aerosol optical depth (τ_a) at 550 nm, or how much sunlight is scattered and absorbed by tiny particles suspended within the atmosphere, is from the NASA MODIS Terra & Aqua monthly Atmosphere M(O/Y)D08, Collection 6.1, products for January 2003 to December 2019

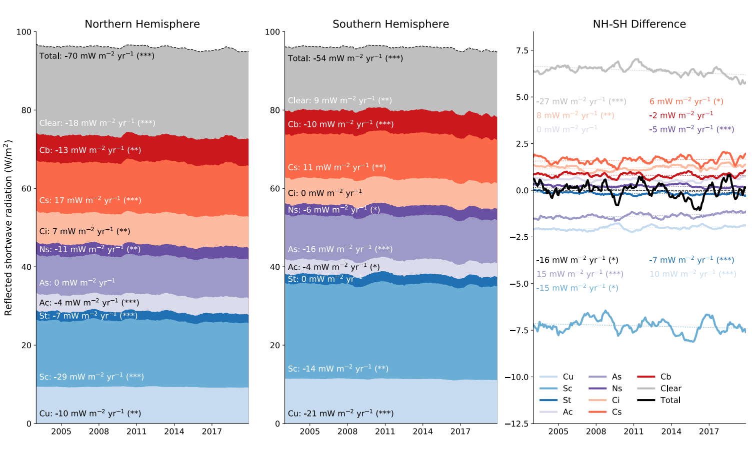
Processing & statistics

- CERES cloud types are created by averaging the appropriate pressure/optical thickness bins weighted by cloud fraction
- CERES data are averaged with a 12-month running mean weighted by days per month
- Geospatial averages are taken assuming spherical geometry
- Linear trends are calculated for the CERES data using a least-squares method (scipy.optimize.curve_fit)
- Trend significance is assessed using a two-tailed Student's t-test with the degree of freedom for each time series calculated assuming red noise
- Significance values are adjusted for multiple hypothesis testing using a Benjamini-Hochberg correction



Trends in reflected sunlight

Figure 3 shows how much sunlight was reflected overall (*dashed lines*) and by each component (*shaded areas*) from 2003-2019 for the Northern Hemisphere (*leftmost column*) and Southern Hemisphere (*center column*). Hemispheric differences are also shown (*rightmost column*). Trends are presented (*text and dotted lines*) with adjusted p-values below 0.1, 0.01, and 0.001 demarcated by one, two, or three asterisks, respectively. Overall, both hemispheres have been reflecting less sunlight to space over time, driven in large part by reductions in low-altitude cumuliform and stratiform cloudiness. The largest change in the hemispheric differences comes from the clear-sky component, which is decreasing strongly in the Northern Hemisphere while increasing in the Southern Hemisphere.

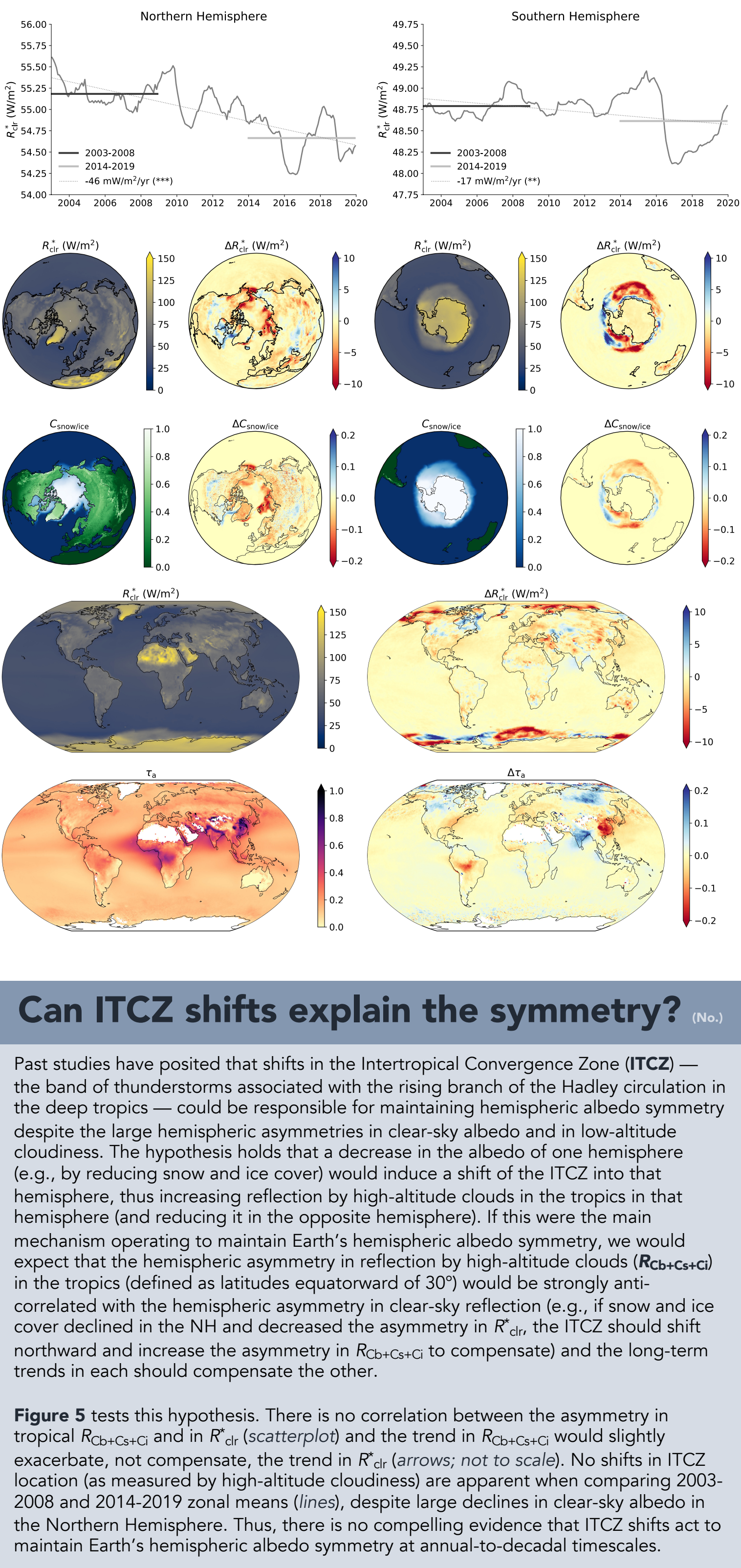


Trends in snow, ice, & aerosol

Figure 4 shows trends in the amount of sunlight that would be reflected if clear-sky (cloud-free) conditions prevailed all year long, designated R^*_{clr}. This is a better measure of the surface albedo than the R_{clr} measure shown above, which is affected by both the surface brightness as well as the amount of clouds (because "clear-skies" don't reflect any sunlight when the skies aren't clear!). R^*_{clr} has declined much more rapidly than R_{clr} in the Northern Hemisphere (*top left*) and the trend flips from positive to negative in the Southern Hemisphere (*top right*), although the trend in hemispheric asymmetry is similar for both R^*_{clr} and R_{clr}. The Southern Hemisphere values are driven strongly by non-linear sea ice variations, so the linear trend should be interpreted cautiously.

Loss of snow and ice cover during the twenty-first century, especially in the Arctic, can explain a large portion of the clear-sky reflectance trends (*middle rows*). Changes are measured as the difference (Δ) between the 2014-2019 and 2003-2008 averages.

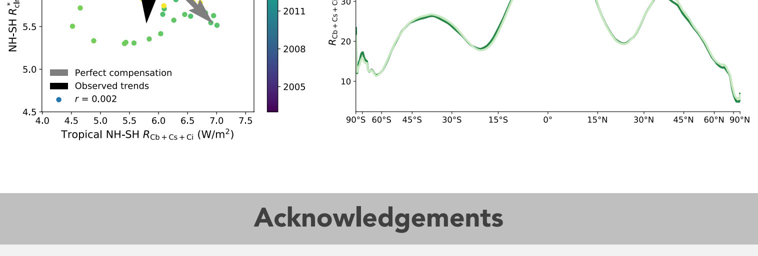
Aerosol changes (*bottom rows*) also played a role in the clear-sky trends. In the Northern Hemisphere, however, large reductions in aerosol from eastern Asia have been balanced by large increases in southern Asia.



Can ITCZ shifts explain the symmetry? (No.)

Past studies have posited that shifts in the Intertropical Convergence Zone (**ITCZ**) — the band of thunderstorms associated with the rising branch of the Hadley circulation in the deep tropics — could be responsible for maintaining hemispheric albedo symmetry despite the large hemispheric asymmetries in clear-sky albedo and in low-altitude cloudiness. The hypothesis holds that a decrease in the albedo of one hemisphere (e.g., by reducing snow and ice cover) would induce a shift of the ITCZ into that hemisphere, thus increasing reflection by high-altitude clouds in the tropics in that hemisphere (and reducing it in the opposite hemisphere). If this were the main mechanism operating to maintain Earth's hemispheric albedo symmetry, we would expect that the hemispheric asymmetry in reflection by high-altitude clouds ($R_{Cb+Cs+Ci}$) in the tropics (defined as latitudes equatorward of 30°) would be strongly anti-correlated with the hemispheric asymmetry in clear-sky reflection (e.g., if snow and ice cover declined in the NH and decreased the asymmetry in R^*_{clr}, the ITCZ should shift northward and increase the asymmetry in $R_{Cb+Cs+Ci}$ to compensate) and the long-term trends in each should compensate the other.

Figure 5 tests this hypothesis. There is no correlation between the asymmetry in tropical $R_{Cb+Cs+Ci}$ and in R^*_{clr} (*scatterplot*) and the trend in $R_{Cb+Cs+Ci}$ would slightly exacerbate, not compensate, the trend in R^*_{clr} (*arrows; not to scale*). No shifts in ITCZ location (as measured by high-altitude cloudiness) are apparent when comparing 2003-2008 and 2014-2019 zonal means (*lines*), despite large declines in clear-sky albedo in the Northern Hemisphere. Thus, there is no compelling evidence that ITCZ shifts act to maintain Earth's hemispheric albedo symmetry at annual-to-decadal timescales.



Acknowledgements

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CERES FluxByCldTyp data are available at https://ceres.larc.nasa.gov/data/#fluxbycldtyp-level-3. Sea ice and snow cover data are available from the National Snow and Ice Data Center (https://nsidc.org/). MODIS aerosol optical depth data are available from the NASA LAADS Distributed Active Archive Center (https://ladsweb.modaps.eosdis.nasa.gov/).