

Why the Earth Exhibits Interhemispheric Albedo Symmetry

Erosion–formation asymmetry of low-cloud responses to circulation reorganization

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This manuscript is a non-peer-reviewed preprint submitted to EarthArXiv.

Abstract

Earth exhibits a striking near symmetry in interhemispheric mean albedo despite substantial asymmetries in surface properties, aerosols, and geography. Whether this symmetry is coincidental or dynamically constrained remains unresolved. Here we present a minimal theoretical framework showing that a moist atmosphere provides a physically constrained, but bounded, tendency to oppose interhemispheric albedo perturbations. A hemispherically asymmetric shortwave forcing induces cross-equatorial atmospheric energy transport, ITCZ displacement, and reorganization of the Hadley circulation. This response strengthens large-scale descent in the colder hemisphere and weakens it in the warmer hemisphere, generating an asymmetric humidity response. Enhanced descent drives transitions from cloud-permitted to cloud-forbidden regimes and robust erosion of reflective low clouds, whereas weakened descent does not guarantee new cloud formation because low-cloud maintenance is physically bounded. The resulting cloud adjustment produces a sign-definite shortwave response opposing the imposed albedo contrast, but with finite capacity. Interhemispheric albedo symmetry therefore emerges conditionally, when hemispheric forcings remain within the compensating capacity of low clouds and when the opposing cloud radiative responses in the two hemispheres are sufficiently matched in magnitude. Symmetry fails when that capacity or matching is exceeded.

Keywords

Inter-hemispheric albedo symmetry; shortwave radiative imbalance; cloud–radiative feedback; cloud-permitted and cloud-forbidden regimes; low clouds; Hadley circulation; Hadley circulation reorganization; ITCZ displacement; moist atmospheric dynamics; large-scale subsidence; cloud erosion; atmospheric energy transport.

1. Introduction

Earth exhibits a remarkable near symmetry in interhemispheric mean albedo and absorbed shortwave radiation despite pronounced hemispheric asymmetries in surface properties, aerosol distributions, and geography. Satellite observations show that the hemispheric-mean top-of-atmosphere (TOA) shortwave imbalance is small, of order 1 W m^{-2} or less in the climatological mean (Stephens et al., 2012; Loeb et al., 2009, 2018;

Donohoe et al., 2013; Datsleris and Stevens, 2021); Jönsson and Bender, 2022. The persistence of such a small hemispheric contrast, despite strong spatial heterogeneity and variability, raises a fundamental physical question: is interhemispheric albedo symmetry coincidental, or is it maintained by a constrained atmospheric response?

From an energetic perspective, interhemispheric asymmetries in absorbed shortwave radiation require compensation by cross-equatorial energy transport to maintain a steady climate (Trenberth and Stepaniak, 2003; Donohoe et al., 2013). Such hemispheric radiative imbalances are initially accommodated by the component of the climate system capable of responding on the shortest timescales. Because ocean heat uptake and cross-equatorial ocean transport require adjustment of the mixed layer and large-scale circulation and therefore act on seasonal to longer timescales, the atmosphere—able to respond within days to weeks through circulation and radiative adjustments—provides the primary initial compensation, inducing cross-equatorial energy transport, ITCZ displacement, and reorganization of the Hadley circulation (Held, 2001; Kang et al., 2008; Donohoe et al., 2013). Previous studies have shown that these adjustments are accompanied by asymmetric Hadley circulation responses, producing enhanced large-scale ascent in one hemisphere and enhanced subsidence in the other (Kang et al., 2008; Donohoe et al., 2013).

Clouds, particularly low clouds, exert a dominant control on planetary albedo through their shortwave radiative effects, owing to their high reflectivity and extensive spatial coverage (Hartmann et al., 1992; Klein and Hartmann, 1993; Stephens, 2005; Bony et al., 2006; Zelinka et al., 2016). On the other hand, empirical studies robustly relate low-cloud amount to local environmental conditions such as lower-tropospheric stability, inversion strength, subsidence, and surface thermodynamic properties (e.g., Klein and Hartmann, 1993; Wood and Bretherton, 2006). While these relationships successfully describe observed cloud variability, they do not by themselves explain whether cloud adjustments can systematically compensate hemispheric albedo perturbations, nor whether such compensation is guaranteed or bounded under circulation reorganization.

Here we develop a minimal theoretical framework linking hemispheric shortwave imbalance to cloud radiative adjustment through a physically constrained causal chain: energetic imbalance → atmospheric energy transport → ITCZ displacement → Hadley circulation reorganization → asymmetric large-scale descent → transitions between cloud-permitted and cloud-forbidden regimes. Strengthened descent in the colder hemisphere warms and dries the lower troposphere, enhances entrainment of dry air into the boundary layer, and suppresses the maintenance of low clouds, leading to efficient erosion of pre-existing cloud cover. In contrast, weakened descent in the warmer hemisphere expands regions where low clouds may persist but does not guarantee widespread cloud formation.

A central implication is that interhemispheric albedo symmetry is neither guaranteed nor coincidental. Cloud adjustments are physically necessary responses to circulation changes, but their hemispheric shortwave effect is finite and bounded. Albedo symmetry therefore emerges conditionally, when imposed hemispheric perturbations do not exceed

the cloud-mediated radiative adjustment accessible through circulation-driven changes in cloud regimes and when asymmetric cloud responses in both hemispheres quantitatively match to offset the imposed radiative imbalance.

In the following we frame interhemispheric albedo asymmetry as a shortwave energy imbalance, examine the induced circulation and cloud-regime transitions, and assess when their bounded radiative response yields interhemispheric symmetry.

2. Energetic constraint and fast atmospheric adjustment

Interhemispheric albedo asymmetry can be framed fundamentally as a hemispheric shortwave energy imbalance at the top of the atmosphere (TOA). Observations indicate that, despite substantial hemispheric differences in surface properties and aerosols, the climatological hemispheric-mean TOA shortwave imbalance is small, of order 1 W m^{-2} or less (Stephens et al., 2012; Loeb et al., 2009, 2018; Donohoe et al., 2013; Datsseris and Stevens, 2021; see Fig. 1). Any sustained imbalance of this kind must be compensated to maintain a statistically steady climate. Such persistence and variability of small hemispheric imbalances are well documented in CERES observations (Jönsson and Bender, 2022).

While the observational motivation is naturally framed in terms of Northern and Southern Hemispheres, the physical response to a hemispheric shortwave imbalance depends only on the sign of the energy anomaly, not on geographic orientation. In the following, we therefore adopt the more general terminology of warmer (energy-surplus) and colder (energy-deficit) hemispheres, which allows the framework to be expressed independently of hemisphere or planetary geography.

To formalize this energetic constraint, we define the interhemispheric albedo contrast as

$$\Delta\alpha = \alpha_N - \alpha_S$$

where α_N and α_S denote the hemispheric-mean planetary albedo of the Northern and Southern Hemispheres, respectively. A hemispheric albedo contrast produces a corresponding top-of-atmosphere shortwave radiative imbalance, which can be approximated as

$$\Delta R_{sw} \approx -S_0/4 \cdot \Delta\alpha$$

where S_0 is the solar constant and the factor $1/4$ accounts for the ratio between the Earth's cross-sectional area and its surface area. A positive $\Delta\alpha$ therefore corresponds to reduced shortwave absorption in the Northern Hemisphere relative to the Southern Hemisphere.

To maintain energetic balance, this hemispheric radiative imbalance induces cross-equatorial atmospheric energy transport H , such that $H \propto \Delta R_{sw}$. The resulting redistribution of energy shifts the latitude of maximum ascent and displaces the intertropical convergence zone (ITCZ), which we denote by a meridional displacement

yI, with $yI \propto H$ (Held, 2001; Kang et al., 2008; Frierson and Hwang, 2012; Donohoe et al., 2013; Bischoff and Schneider, 2014).

The resulting physically constrained causal sequence linking hemispheric shortwave imbalance to atmospheric energy transport, ITCZ displacement, Hadley circulation reorganization, and asymmetric large-scale descent is summarized schematically in Fig. 1.

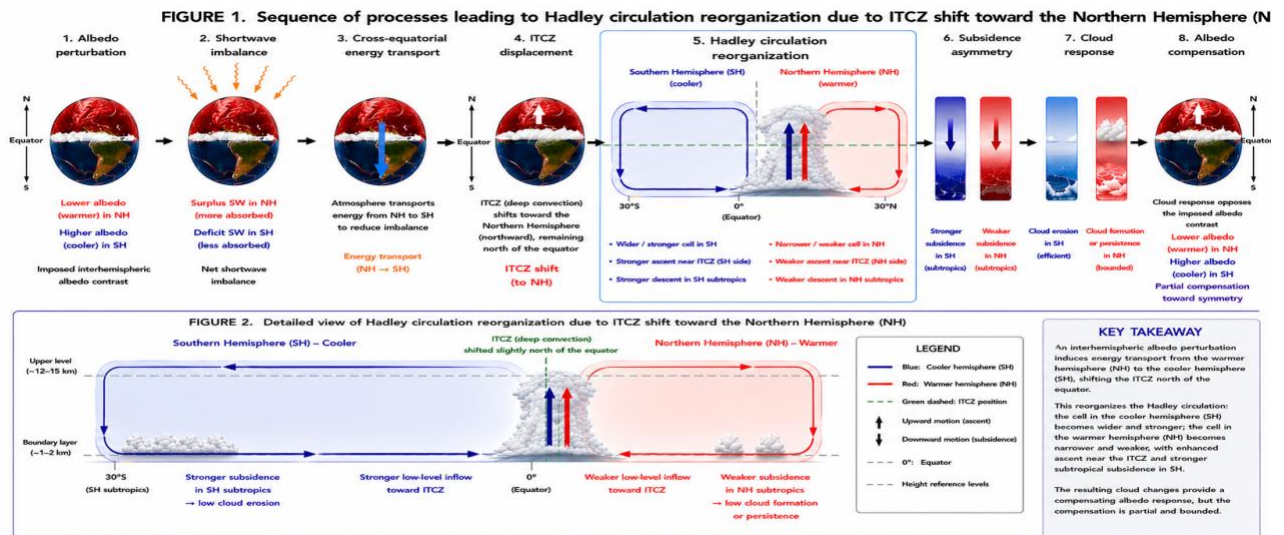


Figure 1. Conceptual mechanism linking hemispheric shortwave imbalance to cloud-mediated albedo compensation.

Panels 1-8 illustrate the causal chain. Panels 1 and 2: An imposed interhemispheric albedo contrast generates a hemispheric shortwave radiative imbalance. Panels 3 and 4: The resulting energy asymmetry induces cross-equatorial atmospheric energy transport and displacement of the Intertropical Convergence Zone (ITCZ) toward the warmer hemisphere. Panels 5 and 6: The ITCZ shift reorganizes the Hadley circulation, producing stronger ascent near the equator and stronger subtropical descent in the colder hemisphere, while ascent and descent weaken in the warmer hemisphere. Panels 7 and 8: This circulation asymmetry modifies lower-tropospheric humidity and cloud-supporting conditions, leading to efficient erosion of low clouds in the colder hemisphere and bounded cloud formation or persistence in the warmer hemisphere. The resulting cloud radiative response opposes the imposed hemispheric albedo contrast, providing a compensating but finite adjustment toward interhemispheric albedo symmetry.

Because the ocean adjusts to hemispheric radiative imbalances on much longer timescales through changes in heat storage and circulation, such imbalances initially require compensation by the atmosphere, which can rapidly transport energy across the equator through large-scale circulation adjustments (Held, 2001; Kang et al., 2008). The atmospheric response takes the form of enhanced cross-equatorial moist static energy

transport, which shifts the latitude of maximum ascent and displaces the intertropical convergence zone (ITCZ) toward the hemisphere receiving greater net energy input.

A displacement of the ITCZ necessarily entails a reorganization of the Hadley circulation. When the ITCZ shifts toward one hemisphere, the Hadley cell in that hemisphere weakens, while the opposing cell strengthens, producing an asymmetry in large-scale ascent and descent between hemispheres (Held, 2001; Kang et al., 2008). This circulation adjustment is a direct consequence of energy balance and angular momentum constraints and does not depend on cloud physics or surface properties.

Crucially, this dynamical response establishes the pathway through which hemispheric radiative imbalance can influence cloud fields. Changes in the strength and spatial extent of large-scale descent alter the thermodynamic and dynamical environment of the lower troposphere, particularly in subtropical regions where low clouds exert a strong control on planetary albedo (Klein and Hartmann, 1993; Wood and Bretherton, 2006; Wood, 2012; Stephens, 2005; Bony et al., 2015). The energetic constraint therefore links hemispheric shortwave imbalance to circulation reorganization, setting the stage for cloud-mediated radiative adjustments without assuming any specific cloud response a priori.

In the following section, we examine how the circulation asymmetry implied by this fast atmospheric adjustment translates into hemispheric differences in subsidence strength and structure, providing the dynamical basis for the cloud regime transitions analyzed subsequently.

3. Circulation Reorganization and Descent Asymmetry

The fast atmospheric adjustment to hemispheric shortwave imbalance necessarily entails a reorganization of the Hadley circulation, as established by energetic and angular momentum constraints (Held, 2001; Kang et al., 2008; Ceppi et al., 2013). A direct consequence of this reorganization is an asymmetry in large-scale subsidence between hemispheres. In the hemisphere opposite the displaced ITCZ—the colder, energy-deficient hemisphere—the strengthened Hadley cell produces enhanced descent over broad subtropical regions, while in the hemisphere toward which the ITCZ shifts, large-scale descent weakens and contracts. This hemispheric contrast in subsidence strength and structure is therefore a dynamically necessary outcome of the atmospheric energy balance response and does not depend on surface properties or cloud processes.

This subsidence asymmetry can be formalized in terms of the zonal-mean mass streamfunction, whose meridional gradients determine the strength and spatial extent of ascent and descent within the Hadley circulation. Strengthening of the overturning circulation in one hemisphere implies increased downward mass flux there, while weakening in the opposite hemisphere implies reduced downward mass flux. As a result, circulation reorganization alters not only the magnitude of subsidence but also the latitude bands over which descent dominates the lower troposphere.

For clarity, we characterize hemispheric subsidence using the large-scale vertical velocity, denoted by ω , with positive ω corresponding to downward motion in pressure coordinates. Let ω_c represent the characteristic subsidence strength in the colder hemisphere and ω_w that in the warmer hemisphere in their subtropical regions. The circulation response to hemispheric energy imbalance then satisfies

$$\Delta\omega = \omega_c - \omega_w > 0,$$

indicating systematically stronger descent in the colder hemisphere and weaker descent in the warmer hemisphere. This sign-definite subsidence asymmetry follows directly from the ITCZ displacement and Hadley circulation reorganization and is independent of cloud physics.

Because large-scale descent directly controls the thermodynamic structure of the lower troposphere, subsidence asymmetry provides a physically transparent link between circulation reorganization and environmental conditions relevant for cloud maintenance. Enhanced descent warms and dries the lower troposphere through adiabatic compression and increased entrainment of dry free-tropospheric air into the boundary layer, while weakened descent relaxes these effects. These changes are imposed by the circulation adjustment itself and occur prior to any cloud radiative feedback.

The significance of this result is that hemispheric radiative imbalance is translated, through fast atmospheric dynamics alone, into a hemispheric contrast in subsidence strength and structure. This establishes the dynamical precondition for asymmetric cloud responses without assuming how clouds behave. In the next section, we introduce a minimal representation of cloud-permitted and cloud-forbidden regimes to examine how this subsidence asymmetry impacts low-cloud maintenance and erosion.

4. Low-cloud-permitted and cloud-forbidden regimes

Large-scale subsidence exerts a primary control on the maintenance of low clouds by regulating the thermodynamic structure of the lower troposphere. Strengthened descent warms and dries the air above the boundary layer through adiabatic compression and enhanced entrainment of dry free-tropospheric air, reducing relative humidity within the cloud layer. When these effects become sufficiently strong, persistent low clouds cannot be maintained and existing cloud cover erodes on a short timescale. Conversely, weakened descent relaxes these constraints, allowing low clouds to persist where other necessary conditions are met.

To capture this behavior in a minimal and physically transparent way, we introduce a distinction between *cloud-permitted* and *cloud-forbidden* regimes. In cloud-forbidden regimes, environmental conditions imposed by large-scale descent preclude the maintenance of persistent low clouds. In cloud-permitted regimes, the environment does not prohibit low-cloud presence, although cloud formation and persistence are not guaranteed. This distinction reflects threshold-like behavior in low-cloud maintenance and does not assume a specific microphysical mechanism.

We formalize this distinction using relative humidity (RH) as the controlling thermodynamic variable. Relative humidity directly measures the proximity of air parcels to saturation and therefore determines whether cloud water can be maintained against entrainment drying. Crucially, large-scale subsidence acts monotonically on RH by warming and drying the lower troposphere, making RH the natural variable through which circulation reorganization constrains cloud existence. Other commonly used predictors of low-cloud variability, such as lower-tropospheric stability (LTS) or estimated inversion strength (EIS), act as empirical proxies for this thermodynamic control but embed Earth-specific calibrations that are not essential for the arguments developed here.

We define a critical relative humidity threshold, denoted RH_c representing the minimum humidity required for sustained low-cloud maintenance. The threshold RH_c is treated as a constant or weakly varying parameter, reflecting the fact that cloud-top radiative cooling and resistance to entrainment require a minimum moisture content but do not depend strongly on the instantaneous strength of subsidence. Using this threshold, we define a binary cloud-regime indicator $P(\phi)$, dependent on latitude ϕ as

$$P(\phi) = \begin{cases} 1, & RH(\phi) \geq RH_c \text{ (cloud-permitted),} \\ 0, & RH(\phi) < RH_c \text{ (cloud-forbidden).} \end{cases}$$

Here $RH(\phi)$ denotes the characteristic lower-tropospheric relative humidity at latitude ϕ . The indicator $P(\phi)$ classifies whether the local thermodynamic environment permits the maintenance of persistent low clouds; it does not represent cloud fraction or optical depth. The physical basis of the cloud-permitted and cloud-forbidden regimes, and the resulting asymmetry between cloud erosion under strengthened subsidence and bounded cloud formation under weakened subsidence, is illustrated schematically in Fig. 2.

Figure 2. Cloud-permitted and cloud-forbidden regimes controlled by large-scale subsidence

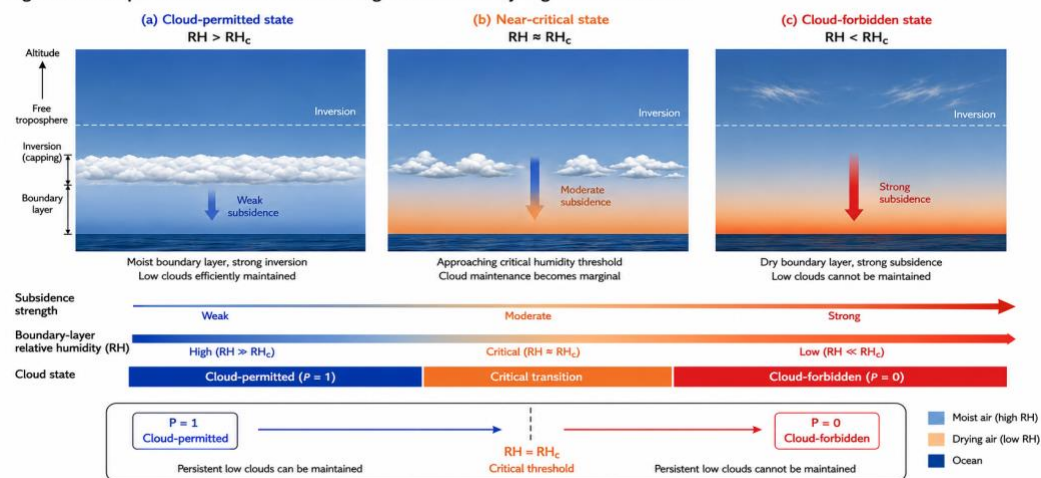


Figure 2. Cloud-permitted and cloud-forbidden regimes controlled by large-scale subsidence.

(a) Cloud-permitted state ($RH > RH_c$). A moist boundary layer beneath a strong inversion supports the maintenance of persistent low-cloud cover. Subsidence is weak and relative humidity remains above the critical threshold RH_c required for sustained low-cloud existence. (b) Near-critical state ($RH \approx RH_c$). Increasing subsidence reduces boundary-layer relative humidity and drives the system toward the critical threshold separating cloud-permitted and cloud-forbidden regimes. Low-cloud maintenance becomes marginal, and cloud cover becomes fragmented. (c) Cloud-forbidden state ($RH < RH_c$). Strong subsidence produces a dry boundary layer in which persistent low clouds can no longer be maintained. The transition from $RH > RH_c$ to $RH < RH_c$ therefore represents a transition from a cloud-permitted state ($P = 1$) to a cloud-forbidden state ($P = 0$). Increasing subsidence systematically decreases boundary-layer humidity and shifts the environment toward conditions unfavorable for persistent low-cloud maintenance.

A key asymmetry follows directly from this formulation. Transition from a cloud-permitted to a cloud-forbidden regime ($P(\phi) = 1 \rightarrow P(\phi) = 0$) constitutes a *sufficient* condition for cloud loss: when environmental humidity drops below RH_c , existing low clouds must erode. By contrast, remaining within a cloud-permitted regime ($P(\phi) = 1 \rightarrow P(\phi) = 1$) is only a *necessary* condition for cloud presence. A region may remain cloud-permitted without developing new cloud cover, because cloud formation and maintenance also require additional local boundary-layer processes—such as sufficient turbulence, surface moisture supply, and mesoscale organization—that are not directly imposed by large-scale subsidence. As a result, cloud erosion under strengthened subsidence is a more robust and efficient process than cloud formation under weakened subsidence.

This asymmetry is central to the hemispheric response. Following a hemispheric radiative perturbation, subsidence strengthens in the colder hemisphere and weakens in the warmer hemisphere (Section 3). In the colder hemisphere, regions driven across the threshold $RH = RH_c$ necessarily transition from cloud-permitted to cloud-forbidden states, producing systematic erosion of pre-existing low cloud cover. In the warmer hemisphere, regions that remain cloud-permitted are not required to generate new clouds; instead, existing cloud fractions persist to leading order.

Continuous adjustments may still occur within cloud-permitted regions, but these are secondary to the erosion mechanism emphasized here, because regime transitions eliminate cloud cover over finite areas, producing order-one local changes in shortwave reflectivity, whereas continuous variations within cloud-permitted regions modulate cloud properties around an existing state and yield comparatively smaller, often compensating radiative effects when aggregated hemispherically.

In the following section, we examine how the spatial integration of these local regime transitions translates into a net hemispheric shortwave cloud radiative response and determines the conditions under which interhemispheric albedo symmetry can be restored or must fail.

5. Net hemispheric low-cloud radiative response

The cloud-regime transitions described in Section 4 operate locally, but their climatic significance arises only through hemispheric aggregation. In this section, we quantify how asymmetric transitions between cloud-permitted and cloud-forbidden regimes translate into a net hemispheric shortwave cloud radiative response.

We denote by C the hemispheric-mean areal fraction of low-cloud cover. Changes in C arise from circulation-induced regime transitions that eliminate clouds where environmental conditions become cloud-forbidden and allow cloud persistence where conditions remain cloud-permitted. Let ΔC_c and ΔC_w represent the changes in hemispheric low-cloud fraction in the colder and warmer hemispheres, respectively, following a hemispheric radiative perturbation. Consistent with the regime logic developed in Section 4, ΔC_c is dominated by erosion of pre-existing clouds and is therefore negative, while ΔC_w reflects cloud persistence or limited formation and is small and weakly positive or near zero. As a result,

$$|\Delta C_c| > |\Delta C_w|.$$

The hemispheric-mean albedo changes due to low clouds, denoted $\Delta \alpha_{\text{cld}}$, can be written in minimal form as

$$\Delta \alpha_{\text{cld}} = \beta \cdot (\Delta C_w - \Delta C_c)$$

where $\beta > 0$ is a radiative efficiency factor converting changes in low-cloud areal fraction into changes in planetary albedo. The factor β encapsulates the mean shortwave reflectivity of low clouds and the relevant insolation geometry; its precise value is not required for the arguments developed here.

Because $\Delta C_c < 0$ and $|\Delta C_c| > |\Delta C_w|$, the cloud-mediated albedo response is sign-definite: erosion of reflective low clouds in the colder hemisphere reduces hemispheric albedo and increases absorbed shortwave radiation, opposing the imposed hemispheric shortwave deficit. In contrast, changes in low-cloud cover in the warmer hemisphere contribute a weaker and less systematic shortwave response. The net effect is a hemispheric cloud radiative adjustment that acts to reduce the imposed interhemispheric shortwave contrast.

Importantly, this result does not depend on detailed cloud microphysics or on the specific functional form of empirical cloud–environment relationships. It follows directly from (i) threshold-like behavior in low-cloud maintenance, (ii) the asymmetry between robust cloud erosion and contingent cloud formation, and (iii) hemispheric aggregation of local regime transitions. While the sign of the cloud radiative response is therefore robust, its magnitude depends on the spatial extent of regions driven across the cloud-permitted threshold and on the baseline distribution of low clouds.

This hemispheric formulation establishes the response whose limits are examined in the following section: the finite cloud-mediated shortwave adjustment capacity. In Section 6, we analyze how saturation of regime transitions and bounded circulation reorganization constrain the magnitude of $\Delta\alpha_{\text{old}}$ and determine when asymmetric cloud responses in the two hemispheres can quantitatively match the imposed radiative imbalance—or fail to do so.

6. Finite cloud response and conditional interhemispheric albedo symmetry

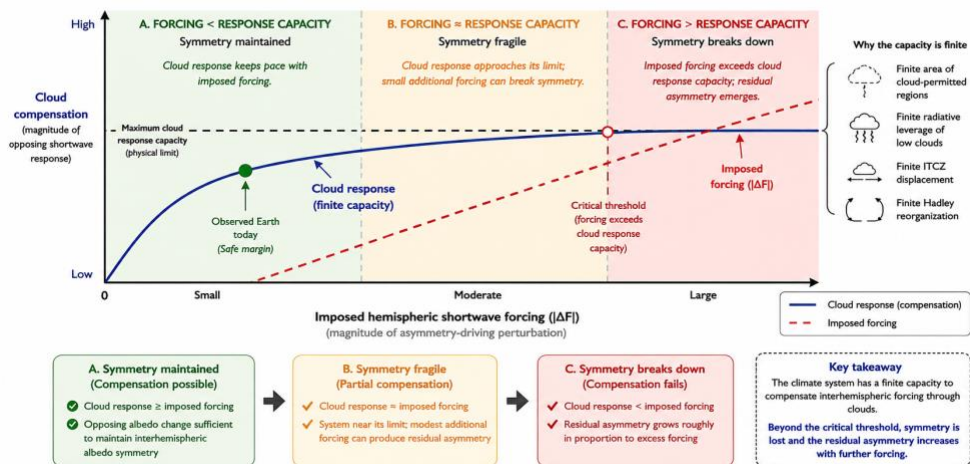
Circulation-driven cloud adjustments act systematically to oppose imposed hemispheric shortwave contrasts, but their compensating capacity is finite and operates through two distinct, bounded processes: cloud erosion in the colder hemisphere and cloud formation or enhancement in the warmer hemisphere. Interhemispheric albedo symmetry therefore emerges only under restricted physical conditions.

We define the cloud response capacity as the maximum hemispheric shortwave radiative adjustment achievable through circulation-induced changes in low-cloud extent and properties. This capacity is limited by three factors. First, the spatial extent of cloud-permitted regimes is finite: once large-scale subsidence renders regions cloud-forbidden, additional descent cannot erode further cloud cover in the colder hemisphere, while reduced subsidence in the warmer hemisphere can only promote cloud formation within regions that remain dynamically and thermodynamically favorable (Figure 3).

Second, the shortwave radiative leverage of low clouds is bounded, set by cloud optical depth, fractional coverage, and insolation geometry. Third, the circulation anomalies themselves are dynamically limited: ITCZ displacement and Hadley-cell reorganization saturate, constraining both the magnitude of subsidence-driven cloud erosion in the colder hemisphere and the compensating cloud formation in the warmer hemisphere (e.g., Kang and Held, 2012; Donohoe et al., 2013; Voigt et al., 2014).

Figure 3. Interhemispheric albedo symmetry is conditional: finite cloud response capacity

The climate system can only compensate a finite amount of imposed hemispheric shortwave forcing.



Note: IAFI is the magnitude of imposed interhemispheric shortwave forcing (e.g., due to aerosols, land-ocean contrasts, orbital forcing, volcanic forcing, etc.).

Figure 3. Finite cloud response capacity and the conditional nature of interhemispheric albedo symmetry.

The blue curve represents the magnitude of the cloud-mediated compensating response generated by atmospheric adjustment to an imposed hemispheric shortwave forcing ($|\Delta F|$). The response initially increases rapidly but approaches a finite upper limit owing to the bounded extent of cloud-permitted regions, finite radiative leverage of low clouds, finite ITCZ displacement, and finite Hadley circulation reorganization. The dashed red line represents the magnitude of the imposed forcing requiring compensation. Region A corresponds to forcings smaller than the available cloud response capacity, where interhemispheric albedo symmetry can be maintained. Region B represents a transitional regime in which the compensating response approaches its physical limit and symmetry becomes increasingly fragile. Region C corresponds to forcings exceeding the maximum cloud response capacity, where residual hemispheric asymmetry becomes unavoidable. The position of present-day Earth is shown schematically within Region A. The figure illustrates the central conclusion of this study: interhemispheric albedo symmetry is not guaranteed but emerges only when imposed hemispheric forcing remains within the finite compensating capacity of the cloud system.

Saturation implies a finite maximum compensating shortwave adjustment, but compensation remains possible as long as the imposed hemispheric radiative imbalance lies within that capacity. A residual asymmetry becomes unavoidable only when forcing exceeds capacity (e.g., via ITCZ/Hadley saturation and bounded cloud radiative leverage), even though the tendency remains compensating in sign on each side of the equator.

Exact restoration of hemispheric-mean albedo further imposes a quantitative matching condition between hemispheres. If an imposed perturbation increases the albedo of the colder hemisphere by $\Delta\alpha_{\text{aer}}$, exact compensation requires that the reduction of albedo by cloud erosion in that hemisphere, $\Delta\alpha_{\text{ers}}$, together with the increase of albedo due to cloud formation or enhancement in the warmer hemisphere, $\Delta\alpha_{\text{cf}}$, satisfy

$$\Delta\alpha_{\text{aer}} - \Delta\alpha_{\text{ers}} = \Delta\alpha_{\text{cf}}.$$

While cloud erosion under strengthened subsidence provides a robust reduction of the imposed contrast, cloud formation in the warmer hemisphere is contingent, spatially limited, and bounded by both cloud-permitted area and radiative saturation.

Near interhemispheric albedo symmetry thus reflects a conditional outcome: it arises only when imposed perturbations lie within the finite cloud response capacity and when the asymmetric but bounded cloud responses in both hemispheres quantitatively match. Outside this regime—under stronger forcings, different orbital configurations, or altered aerosol distributions—residual hemispheric albedo asymmetry should be expected.

7. Discussion

7.1 Relation to empirical cloud formulations

The framework developed here is complementary to existing empirical descriptions of low-cloud variability based on environmental predictors such as lower-tropospheric stability, inversion strength, subsidence, and surface thermodynamic conditions (e.g., Klein and Hartmann, 1993; Wood and Bretherton, 2006). Rather than replacing these relationships, we abstract their combined effect into a state-based distinction between cloud-permitted and cloud-forbidden regimes. This abstraction sacrifices local predictive detail in order to expose hemispheric-scale constraints, asymmetries, and bounds that empirical formulations alone do not address. Related observational and modeling analyses have examined how hemispheric albedo symmetry constrains shortwave cloud radiative feedbacks (Jönsson and Bender, 2023; Jönsson, 2024).

7.2 Why symmetry is conditional, not self-regulating

A central implication of the theory is that interhemispheric albedo symmetry is neither guaranteed nor self-regulating. Cloud responses do not “seek” symmetry; they respond necessarily to circulation changes imposed by hemispheric energy imbalance, as established in studies linking hemispheric forcing to ITCZ shifts and asymmetric Hadley circulation responses (Kang et al., 2008; Kang and Held, 2012; Donohoe et al., 2013).

Symmetry arises only when the magnitude of external forcing lies within the intrinsic limits of cloud-mediated radiative adjustment and when asymmetric cloud responses in both hemispheres quantitatively match to offset the imposed imbalance. The observed near-symmetry of Earth’s hemispheric albedo therefore reflects a contingent matching between forcing strength and response capacity, rather than an active stabilizing target of the climate system.

7.3 Scope and limitations

The theory focuses on low clouds because they dominate shortwave cloud radiative effects in subsiding regimes and exhibit strong sensitivity to large-scale descent and lower-tropospheric stability (Hartmann et al., 1992; Klein and Hartmann, 1993; Bony et al., 2006; Zelinka et al., 2016). Deep convective and high-level clouds, concentrated near the ITCZ, are not explicitly treated, as their primary radiative influence is longwave and their spatial extent is less directly tied to hemispheric subsidence asymmetry (Stephens, 2005; Bony et al., 2015). Including these cloud types is unlikely to alter the sign of the hemispheric shortwave response identified here but may modulate its magnitude.

The analysis is formulated as a fast atmospheric adjustment problem and does not address slower oceanic compensation processes. While ocean heat transport may modify hemispheric energy balance on longer timescales, it does not alter the immediate circulation–cloud pathway emphasized here (Held, 2001; Kang et al., 2008; Donohoe et al., 2013).

7.4 Predicted observational tests

The framework developed here yields several observationally testable predictions. First, periods characterized by anomalous ITCZ displacement should exhibit corresponding hemispheric asymmetries in subtropical subsidence, with strengthened descent in the colder hemisphere and weakened descent in the warmer hemisphere. These circulation anomalies should be detectable in reanalysis products through systematic changes in large-scale vertical velocity, lower-tropospheric humidity, and Hadley-cell strength.

Second, cloud responses should be asymmetric between hemispheres. Regions experiencing strengthened subsidence are predicted to exhibit efficient erosion of low-cloud cover, associated with reductions in cloud fraction and shortwave reflectivity. In contrast, regions experiencing weakened subsidence should display weaker and more variable cloud responses, dominated by cloud persistence and only limited cloud formation. Consequently, hemispheric cloud adjustments should be characterized by a stronger statistical relationship between subsidence anomalies and cloud loss than between reduced subsidence and cloud gain.

Third, the theory predicts the existence of a finite cloud response capacity. As hemispheric radiative forcing increases, the cloud-mediated compensating response should initially grow but eventually approach saturation as cloud-permitted regions become exhausted and circulation anomalies reach their dynamical limits. This prediction can be tested using climate-model experiments with progressively increasing hemispheric shortwave perturbations and by examining observational periods characterized by unusually large hemispheric radiative anomalies.

Finally, the framework predicts that interhemispheric albedo symmetry should become increasingly fragile as imposed hemispheric forcing approaches the limits of cloud compensation. Under sufficiently strong perturbations, residual hemispheric asymmetry should persist despite continued cloud adjustment. Detecting such departures from symmetry would provide direct evidence that cloud-mediated compensation is bounded rather than self-regulating.

8. Conclusions

We have presented a minimal theoretical framework addressing why Earth can exhibit near interhemispheric albedo symmetry despite substantial hemispheric asymmetries in surface properties, aerosols, and geography. The framework does not assume albedo symmetry *a priori*, nor does it invoke fine-tuned cloud behavior. Instead, it identifies a physically constrained sequence of processes linking hemispheric shortwave imbalance to cloud radiative adjustment through atmospheric energy transport, ITCZ displacement, Hadley circulation reorganization, and asymmetric large-scale descent.

Within this framework, low clouds respond to circulation changes primarily through regime transitions between cloud-permitted and cloud-forbidden states. Strengthened descent in the colder hemisphere robustly suppresses the maintenance of low clouds and erodes pre-existing cloud cover, while weakened descent in the warmer hemisphere expands regions where low clouds may persist but does not guarantee cloud formation. The resulting cloud response is therefore sign-definite in its opposition to imposed albedo contrasts, but asymmetric in efficiency between cloud erosion and cloud formation.

A key result is that cloud-mediated compensation is inherently finite. The cloud response capacity—the maximum hemispheric shortwave adjustment achievable through circulation-driven changes in low-cloud extent and properties—is constrained by the limited spatial extent of cloud-permitted regimes, finite cloud radiative leverage, and bounded circulation reorganization. As a consequence, interhemispheric albedo symmetry is not guaranteed. It emerges conditionally, when the magnitude of imposed hemispheric perturbations lies within the available cloud response capacity and when the asymmetric cloud responses in the two hemispheres quantitatively match to offset the imposed radiative imbalance. Symmetry fails when that capacity is exceeded.

This perspective clarifies that the observed near-symmetry of Earth's hemispheric albedo does not require clouds to “seek” symmetry, nor does it imply a universal or self-regulating outcome. Rather, cloud adjustments provide a physically necessary but bounded response to hemispheric forcing, while the existence of symmetry in the present climate reflects a contingent matching between the magnitude of external hemispheric perturbations and the intrinsic capacity of cloud-mediated radiative adjustment. Under different climatic or orbital conditions, this matching need not hold, and residual hemispheric asymmetry should be expected.

More broadly, the framework provides a transparent physical lens through which empirical cloud–environment relationships can be interpreted at the hemispheric scale, without reliance on Earth-specific parameter tuning. It yields falsifiable predictions regarding the sign, limits, and failure regimes of cloud compensation, offering a basis for future observational and modeling tests of hemispheric albedo adjustment.

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