Response to Reviewer #1's Comments:

Ruixue Li et al. (Authors)

We are very grateful for Reviewer #1's careful reading and constructive comments and suggestions. The Reviewer raised two important concerns, which we fully agree with and have addressed in detail:

1. **Physical interpretation of cloud changes in the context of large-scale circulation.**

   The reviewer noted that some of our explanations referred too generally to "large-scale circulation changes" without identifying the relevant circulation systems. We have therefore revised these sections to discuss specific circulation features, including shifts in the ITCZ and changes in the Hadley circulation. Supported by previous studies, we explain how these circulation changes may be related to the observed cloud changes. We have also revised the wording throughout the manuscript to distinguish statistical relationships identified by our analysis from causal physical processes.

2. **Connection with previous studies.**

   The reviewer noted that our results were not sufficiently discussed in the context of existing research. We have expanded the discussion and added references on large-scale circulation, aerosol–cloud interactions, changes in emissions and aerosol loading, and observed cloud and radiation trends. These revisions clarify how our results agree with or add detail to previous findings.

In addition, we have reorganized parts of the Methods and Supplement, revised several figures and tables to improve their clarity, and corrected wording and formatting issues throughout the manuscript. We believe that these changes have improved both the physical interpretation and presentation of our results.

Please see our point-by-point reply to comments. All revisions are shown in the revised manuscript by using track changes. The line numbers involved in the response correspond to the clear version of the manuscript.

General comments

Comment: The manuscript provides a very informative breakdown of cloud contributions to warming in a succinct framework, and the results comprise a valuable estimation of recent observed trends that provides further evidence and detail on the recent evolution climate feedbacks. While the results are not novel, they will have value for the fields of Earth's energy budget and albedo studies and contribute to a growing body of literature detailing meteorological drivers of global warming. In general, the manuscript is very well written, using clear, easily read language. However, I feel that two weaknesses compromise the manuscript's efficacy in communicating these results: one, the analysis is at times overly simplistic and lacking physical rigor in explaining results using arguments from dynamical and general circulation changes under global warming, and; two, the results and conclusions on changes in radiation balances are not discussed in the context of other publications that have either discovered or arrived at the same results. Therefore, I suggest that minor revisions be made before considering the manuscript for publication. For these concerns, reframing and more thoroughly referencing and relating the findings to the existing literature about dynamical/circulation, emissions, and aerosol evolution, which is mostly in agreement with the study's findings, would help.

Response: We sincerely thank the reviewer for this balanced and constructive assessment of our manuscript. We appreciate the reviewer's recognition of the value and clarity of our analysis. We agree that the original manuscript did not always connect the statistical results clearly enough to specific large-scale circulation changes and did not provide sufficient discussion of related studies. In response, we have revised the relevant sections to place the cloud changes within a clearer dynamical context, while distinguishing statistical associations from causal interpretations. We have also expanded the discussion and references concerning circulation changes, aerosol and emission trends, and changes in the Earth's radiation balance. The specific revisions are described in our point-by-point responses below.

Major comments

Especially since the manuscript uses a combined Results and Discussion format, the body requires more referencing to remain fair to the existing literature. Without this, the study risks framing findings as new rather than as complementary evidence confirming or clarifying previous findings.

Response: We agree with this concern. We have revised the Results and Discussion section to make the connection with previous work more explicit. We also adjusted the tone so that established findings are described as being consistent with or supported by our results rather than presented as newly discovered.

1. **Comment:** L331: This is a very good thing to point out but I think it requires more references, as it is not a new finding and has been shown in previous studies. For example, it aligns nicely with conclusions of Sledd and L'ecuyer (2020).

   Response: We thank the reviewer for this helpful suggestion. We agree that the moderating influence of clouds on the radiative response to polar sea-ice loss has been documented previously and requires broader acknowledgement. We have added studies addressing cloud responses to sea-ice retreat, cloud masking of surface-albedo changes, and the resulting modification of the ice–albedo feedback (Kay and Gettelman, 2009; Alkama et al., 2020; Sledd and L'Ecuyer, 2021).

   Revised manuscript text (L380-383): In contrast, at high latitudes, the effects combine, as both cloud shortwave and longwave effects contribute to negative T_s trends, indicating that cloud changes partially mitigate polar warming (Kay and Gettelman, 2009; Alkama et al., 2020; Sledd and L'Ecuyer, 2021).

2. **Comment:** L355-356: The supplementary figure only shows the trends in downwelling SW flux at the surface, but no causal evidence for aerosol- and water vapor-driven extinction are shown in the manuscript. The authors could say that it offsets a reduction in downwelling SW radiation at the surface, but provide more references in addition to Li et al. (2024b). Also, Fig. S3a should be referenced before and separately from the references supporting the explanation for drivers.

   Response: We thank the reviewer for this important clarification. We agree that Fig. S3 shows only the observed trends in surface downwelling shortwave radiation and does not provide causal evidence attributing these trends to aerosol extinction or water-vapor absorption. We have therefore revised this paragraph to distinguish the observational result from its possible physical interpretation. We now first cite Fig. S3a when describing the absence of a significant trend in all-sky surface downwelling shortwave radiation and cite Fig. S3b separately when referring to the reduction under clear-sky conditions. We then state that aerosol extinction and atmospheric water-vapor absorption are possible contributors to the clear-sky reduction, based on previous studies, rather than presenting them as drivers demonstrated by our analysis. We have also added further references supporting these potential influences.

Revised manuscript text (L403-412): Differently, in 30–60°S, despite no significant trend in $SW_{all}^{\downarrow}$ (Fig. 1b, Fig. S3a), clouds exhibit a substantially positive shortwave contribution to the T_s trend (Fig. 1a). This is because a decrease in RSR_{cloud} dominated by reduced CR contributes to an increase in solar radiation reaching the surface, which offsets the concurrent reduction in clear-sky surface downwelling solar radiation (Fig. S3b). This clear-sky reduction may reflect increased atmospheric attenuation associated with greater aerosol extinction and stronger water-vapor absorption (Haywood and Boucher, 2000; Wild, 2009; Trenberth et al., 2009; Li et al., 2024b). Therefore, clouds exert a positive shortwave contribution to T_s trends by counteracting the observed clear-sky reduction.

3. **Comment:** L386-389: This needs some further references to other studies explaining the effect. If speculative explanations are discussed, these should be placed in the context of current literature, and formulated clearly framing them as possible explanations.

Response: We thank the reviewer for this comment. We agree that the proposed explanation linking the longwave trend to changes in cloud vertical distribution was insufficiently supported. We have added references showing that surface downwelling longwave radiation depends strongly on cloud-base height and temperature, and we now frame the concurrent decrease in low-level clouds and increase in high-level clouds as a possible explanation based on previous studies.

Revised manuscript text (L437-446): However, in the NH high latitudes, despite a significant increase in total CF, the cloud-induced change in surface downward longwave radiation shows a decreasing trend (Fig. 2c). One possible explanation is the observed redistribution of cloud vertical structure. Because cloud-base temperature generally decreases with increasing cloud-base height, lower and warmer clouds typically emit more longwave radiation toward the surface than higher and colder clouds (Intrieri et al., 2002; Shupe and Intrieri, 2004; Viúdez-Mora et al., 2015). Consequently, the concurrent decrease in low-level clouds and increase in high-level clouds may contribute to the reduction in cloud-related surface downwelling longwave radiation.

4. **Comment:** L475-476: The authors are implicating CF-AOD coupling and show neat results clearly substantiating the importance of aerosol impacts on cloud lifetime. This should be explicitly stated and referred to other studies (e.g. Twomey, 1974, 1977 and more recent; perhaps also the SLCF chapter of IPCC AR6, Szopa et al., 2023).

   Response: We thank the reviewer for this constructive suggestion. We agree that our results on the CF–AOD coupling provide evidence for aerosol impacts on cloud lifetime, and that this should be stated more explicitly. We have revised the text to clearly identify this as a manifestation of the cloud lifetime effect (Albrecht, 1989), and have added more related references, including Twomey (1974, 1977), Rosenfeld et al., (2019), Bellouin et al., (2020), and the IPCC AR6 Chapter 6 on Short-Lived Climate Forcers (Szopa et al., 2023).

   Revised manuscript text (L523-533): The CF decline of St and Sc, which contribute most to the reduction in RSR_{cloud}, is largely statistically explained by rising T_s and decreasing AOD (Fig. 5, Fig. 6). The warming-induced suppression of low clouds is consistent with the positive cloud–temperature feedback mechanisms (Klein et al., 2017; Myers et al., 2018). Meanwhile, the tight coupling between CF reduction and AOD decline explicitly highlights the impact of aerosols on cloud lifetime (Albrecht, 1989). The reduction in aerosol loading may decrease cloud condensation nuclei (CCN) and cloud droplet number concentrations (CDNC), favoring larger droplets and more efficient collision–coalescence and precipitation, which may in turn reduce cloud persistence and fractional coverage (Twomey, 1974, 1977; Albrecht, 1989; Rosenfeld et al., 2019; Bellouin et al., 2020; Szopa et al., 2023).

5. **Comment:** L509-512: This is perhaps one of the most critical instances where discussion and referencing previous literature is needed. Why is this not discussed in the context of Hadley circulation and the large amount of literature from research into ITCZ dynamics and cloud adjustments? Neither the ITCZ or Hadley circulation are mentioned anywhere in the text. This is essentially phrasing the shift of the ITCZ as a result of dynamical CCF changes in a very disconnected way, not providing any link to the very clear general circulation argument that we know has a strong control on clouds in this region. Citations are needed to show that this result is in agreement with many others showing the migration of the ITCZ northward (e.g., Guo et al., 2026; Shrestha, Soden & He, 2026; Loeb et al., 2025), which explains the changes in dynamical CCFs shown here.

Response: We appreciate this important suggestion. We agree that the original paragraph treated the tropical dynamical changes too locally and did not connect them to the broader circulation literature. We have revised the paragraph and added references to clarify that these dynamical CCF changes may represent a large-scale migration or reorganization of tropical ascent. In particular, reduced ascent and moisture supply over 0–30°S are consistent with a northward displacement of the zonal-mean ITCZ and a corresponding adjustment of the ascending branch of the Hadley circulation, which would reduce deep convection and Cb occurrence south of the equator.

Revised manuscript text (L566-573): Taken together, the decline in Cb over 0-30°S is accompanied by reduced ascent and moisture supply and by upper-tropospheric warming and drying (Fig. 5 and Fig. 6), which may reflect a broader reorganization of tropical circulation. Their overall sign is consistent with a northward shift of the zonal-mean Intertropical Convergence Zone (ITCZ) and a corresponding adjustment of the ascending branch of the Hadley circulation (Schneider et al., 2014; Loeb et al., 2025; Guo et al., 2026; Shrestha et al., 2026), which would reduce deep convection and Cb occurrence south of the equator.

6. **Comment:** L525-527: Again, since potential explanations are given without any new evidence, this needs citation directly after the claim. The discussion in the rest of the paragraph is good.

   Response: We thank the reviewer for pointing out that this interpretation required direct literature support. We have added references in the revised manuscript. These studies document recent reductions in anthropogenic and shipping-related aerosol emissions and their associated effects on aerosol loading and cloud microphysical properties.

   Revised manuscript text (L601-607): In addition, the decline in CR in the NH mid-latitudes coincides with a decreasing AOD trend (Fig. 5), which is potentially linked to controls on industrial and shipping sulfur emissions (Bai et al., 2020; Cao et al., 2023; Hodnebrog et al., 2024; Yuan et al., 2024; von Salzen et al., 2025). The aerosol decline may lead to decreased CCN, decreased CDNC, and larger effective droplet radii (Fig. 7b), thereby lowering cloud albedo (Twomey, 1974, 1977; Li et al., 2018; Cao et al., 2023; Hodnebrog et al., 2024; Yuan et al., 2024; Li et al., 2025a).

7. **Comment:** L606-613: Hadas et al. (2023) showed this as well. The compensation here is not clear in the formulation; I am not sure whether the authors are talking about compensation for PA reductions, or to spatial distributions in PA, as in maintaining the hemispheric albedo symmetry (on which there is a whole body of work). Could the authors rephrase to clarify what compensations they are referring to, and refer to previous literature on compensation pathways?

   Response: We thank the reviewer for pointing out that the meaning of "compensation" was unclear. Here, we refer specifically to the cloud compensation that contributes to hemispheric planetary albedo symmetry: the higher clear-sky albedo of the NH is climatologically offset by greater cloud reflection in the SH mid-latitudes. We have revised the text to define this compensation pathway explicitly and cite Hadas et al. (2023), who related the hemispheric cloud-albedo contrast to differences in mid-latitude baroclinic activity. We then distinguish this climatological relationship from dynamic changes during our study period. Our results show that the larger reduction in cloud-reflected solar radiation over the NH mid-latitudes was not balanced by SH mid-latitude cloud changes, suggesting that this pathway did not fully compensate for the emerging hemispheric contrast on the observed short timescale. This interpretation is consistent with Diamond et al. (2024) and Loeb et al. (2025).

   Revised manuscript text (L718-729): Regionally, both cloud changes and the relative CF and CR contributions exhibit hemispheric differences. In 30–60°N, the RSR_{cloud} decline stems mainly from reduced CF (especially St, Sc, Ns, and Cb), which is consistent with rising SSTs, reduced AOD, and mid-tropospheric drying. In contrast, in 30–60°S, it is mainly driven by reduced CR, partially mitigated by increased Sc and Cs resulting from enhanced atmospheric stability. Climatologically, greater cloud reflection in the SH mid-latitudes compensates for the higher clear-sky albedo of the NH, helping maintain hemispheric PA symmetry (Bender et al., 2017; Datseris and Stevens, 2021; Jönsson and Bender, 2023; Hadas et al., 2023). During the study period, however, the larger reduction in RSR_{cloud} over the NH mid-latitudes is not balanced by the SH mid-latitude cloud changes, suggesting that this compensation pathway did not fully operate on the observed short timescale (Diamond et al., 2024; Loeb et al., 2025).

8. **Comment:** L620-621: There is a large amount of literature on the declining PA beyond Li et al. (2015). Please cite additional references from this body of work.

   Response: Thank you for this suggestion. We have expanded the references on recent PA decline.

   Revised manuscript text (L736-738): The observed reductions in CF and CR are consistent with the long-term decline in global PA reported over recent decades (Loeb et al., 2021; Goessling et al., 2025; Hodnebrog et al., 2024; Loeb et al., 2024; Li et al., 2024b; Li et al., 2025b).

Minor comments

1. **Comment:** L35: Grammar: "while also" -> "and".

   Response: Thank you. We have revised the sentence for grammar and clarity.

   Revised manuscript text (L33-35): Over the past two decades, the Earth is experiencing unprecedented warming, which exacerbates global heatwaves, wildfires, droughts, and glacier melt, and poses increasing threats to human health and life (Ripple et al., 2024; Gould et al., 2025).

2. **Comment:** L42-43: This makes it seem like the paper is framed for identifying causes rather than feedbacks, which are the focus of the study and manuscript.

   Response: We thank the reviewer for this helpful comment. We agree that the phrase "identify the underlying reasons" incorrectly suggested a causal attribution study. Cloud feedbacks provide an important motivation for this work; however, as also noted by Reviewer #2, the observed cloud-radiative trends over 2002–2023 may contain contributions from aerosol-driven adjustments, rapid adjustments to greenhouse-gas forcing, internal climate variability, and temperature-mediated cloud feedbacks. Our analysis does not uniquely separate these components and therefore should not be described as a formal diagnosis of cloud feedback. We have revised the sentence to frame the study more accurately as an observation-based assessment of recent cloud-radiative changes and their contributions to surface warming.

Revised manuscript text (L42-44): This motivates a quantitative assessment of how observed radiative changes have accompanied and modulated the recent persistent global warming.

3. **Comment:** L90: While it is true that surface fluxes are computed, I would use "modeled" instead, as computed may imply a lack of assumptions. This would better reflect that they must be taken with respective considerations in mind.

   Response: Thank you. We agree that 'modeled' better reflects the nature of the CERES EBAF surface fluxes. We have revised the wording accordingly.

   Revised manuscript text (L90-93): We use monthly mean observed incoming solar radiation (ISR) and reflected shortwave radiation (RSR) at the top of atmosphere (TOA), alongside modeled surface upwelling and downwelling shortwave and longwave radiation fluxes at 1° resolution from EBAF (Wielicki et al., 1996; Kato et al., 2018; Loeb et al., 2018).

4. **Comment:** Table 1: I think this table could be organized better for readability, and more comprehensive to prevent the need for the reader to dig in the manuscript in order to proceed and understand the text – it might benefit from including some of the information from Table A1 here instead. The listing of variables in sentence form also makes it difficult to read, and I would suggest giving each variable a row. The name might benefit from being split into two columns, one column for the short/variable and one for the long name/brief description. Furthermore, an extra column with an example reference citing a study on the use of this variable, or review, could be really useful and make this table a more pedagogically developed tool for the purposes of the study. If this makes it too cumbersome, it may also be better to list some of the variables in the methods text with their brief descriptions and citations (where applicable), as their appearance without naming in the text is a bit jarring.

   Response: We agree that the previous Table 1 was too compressed. We have reorganized Table 1 so that each variable appears on a separate row with its cloud category, short variable name, description, physical role, and example reference. Detailed formulas and calculation methods remain in Appendix A to avoid making the main table too large.

   Revised manuscript text

   (Table 1 in the revised manuscript):

Table 1. Cloud controlling factors for low, middle, and high clouds.

Cloud Category	Variable (Unit)	Full name	Physical Mechanism	Example reference
Low clouds (Cu, Sc, St)	T_s (K)	Surface skin temperature	Modulates boundary-layer thermal structure and cloud-top entrainment rate.	Klein et al. (2017)
	EIS (K)	Estimated inversion strength	Measures lower-tropospheric stability. See Eq. (A1) for details.	Klein et al. (2017)
	ω_{850} (positive downward; Pa s^{-1})	850 hPa vertical velocity	Represents large-scale subsidence/upwelling in the lower troposphere.	Klein et al. (2017)
	ST_{adv} (K s^{-1})	Surface temperature advection	Modulates lower-tropospheric stability via horizontal temperature advection. See Eq. (A2) for details.	Klein et al. (2017)
	$Wind_{10}$ (m s^{-1})	10 m wind speed	Regulates surface turbulent fluxes affecting cloud formation.	Klein et al. (2017)
	SHF (W m^{-2})	Sensible heat flux	Contributes to boundary-layer heat budget and turbulent mixing.	Andersen et al. (2023)
	RH_{700} (%)	Relative humidity at 700 hPa	Modulates dry-air entrainment at cloud top.	Klein et al. (2017)
	M (K)	M parameter	The potential temperature difference between surface and 800 hPa. Indicates boundary-layer instability and cold-air advection.	Naud et al. (2023)
	AOD	Aerosol optical depth	Serves as a proxy for column aerosol loading and potential aerosol–cloud microphysical adjustments.	Li et al. (2018)
Middle clouds (Ac, As, Ns)	ω_{500} (Pa s^{-1})	500 hPa vertical velocity	Represents large-scale vertical motion in the mid-troposphere.	Li et al. (2014)
	RH_{700} (%)	Relative humidity at 700 hPa	Characterizes lower-to-mid-tropospheric humidity.	Inoue and Kamahori (2001)
	CAPE (J kg^{-1})	Convective available potential energy	Reflects convective instability.	This study; Walters et al. (2019)
	VPD_{500} (kPa)	500 hPa vapor pressure	Measures mid-level dryness controlling cloud dissipation. See Eq. (A3) for details.	This study; Bony and Emanuel (2001)

		deficit		
	MTS (K)	Mid-tropospheric static stability	The potential temperature difference between 500 hPa and 700 hPa, representing mid-tropospheric static stability.	This study; Li et al. (2014)
	MFC_{700} (kg kg^{-1} s^{-1})	700 hPa moisture flux convergence	Quantifies horizontal moisture transport convergence. See Eq. (A5) for details.	This study; Wong et al. (2018)
	$T_{adv,700}$ (K s^{-1})	700 hPa temperature advection	Represents thermal advection affecting cloud development. See Eq. (A6) for details.	This study; Grise and Tselioudis (2024)
	AOD	Aerosol optical depth	Serves as a proxy for column aerosol loading and potential aerosol–cloud microphysical adjustments.	Han et al. (2025)
High clouds (Ci, Cs, Cb)	T_s (K)	Surface skin temperature	Influences deep convection and upper-level cloud formation.	Wilson Kemsley et al. (2024)
	ω_{300} (Pa s^{-1})	300 hPa vertical velocity	Represents upper-tropospheric dynamical forcing.	Wilson Kemsley et al. (2024)
	RH_{700} (%)	Relative humidity at 700 hPa	Low-to-mid tropospheric moisture modulates convective initiation.	Wilson Kemsley et al. (2024)
	UTRH (%)	Upper-tropospheric relative humidity	Defined as the vertically averaged relative humidity within the 200 hPa layer below the tropopause. Indicates upper-tropospheric moisture availability.	Wilson Kemsley et al. (2024)
	SUT (K km^{-1})	Upper-tropospheric static stability	Represents upper-tropospheric static stability. See Eq. (A7) for details.	Wilson Kemsley et al. (2024)
	ΔU_{300}	300-hPa zonal wind shear	300 hPa zonal wind shear affects upper-level cloud organization. See Eq. (A8) for details.	Wilson Kemsley et al. (2024)
	CAPE (J kg^{-1})	Convective available potential energy	Controls deep convective intensity.	Wilson Kemsley et al. (2024)
	T_{trop} (K)	Tropopause temperature	Sets upper bound on convective cloud top height and cirrus formation.	Li et al. (2014)
	Thick (m)	300–700 hPa	Calculated as the difference in geopotential height between 300	This study

	thickness	and 700 hPa; indicative of tropospheric mean temperature and thermal expansion.	
AOD	Aerosol optical depth	Serves as a proxy for column aerosol loading and potential aerosol–cloud microphysical adjustments.	Han et al. (2025)

Note: Factors labeled “This study” were not adopted directly from an established cloud-controlling-factor framework but were selected based on their expected dynamical or thermodynamic relevance to the corresponding cloud category. The accompanying references support the physical basis of the factor, although they may not use the identical variable definition or pressure level adopted here.

5. **Comment:** L277: Typeset "k" in "k-th" in math mode.

   Response: Thank you. We have corrected the typesetting.

   Revised manuscript text (L286-287): This quantity represents the model-estimated contribution statistically associated with variations in the k-th meteorological factor.

6. **Comment:** Figure 1: There are a few spacing issues in subplot and axis labels; make sure there is a space after the subplot label “(a)”, “K” in the x axis label of (a), and “Trend” in the x axis label of (d).

   Response:

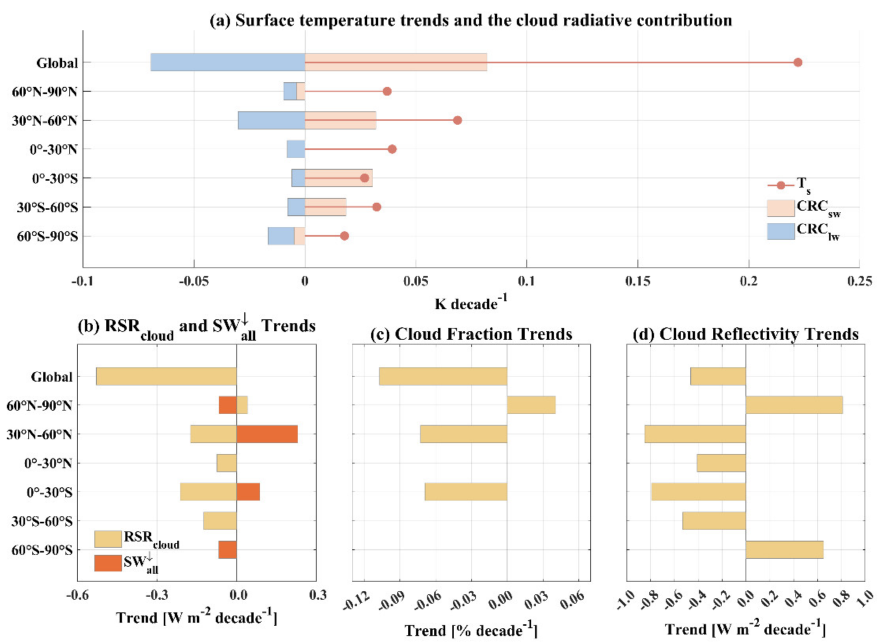

Figure R1 (Same as Figure 1 in the revised manuscript). (a) ERA5 T_s trends from July 2002 to February 2023 and the T_s trends caused by changes in surface shortwave and longwave cloud radiative forcing (CRC_{sw} and CRC_{lw}) (methodology detailed in Section 2.3). (b)Global and latitude-zone averaged trends in the all-sky surface downward shortwave radiation fluxes ($SW_{all}^{\downarrow}$)and the cloud component of TOA RSR (RSR_{cloud}), (c) CF, and (d) CR. Note that the latitudinal-mean trends in (a)-(c) are weighted by their area to account for their contributions to the global mean; the sum of the zonal trends approximately equals the global trend. Only trends significant at the 95% confidence level are shown.

Thank you for catching these figure-label issues. We have corrected the subplot and axis-label spacing in Figure 1 (As shown in Fig. R1). In addition, we have carefully checked all other figures in the manuscript and corrected any similar spacing inconsistencies to ensure a consistent and professional appearance throughout.

7. **Comment:** L392-393: "TOA longwave cloud radiation effect: use the previously defined acronym/variable for ease of reading and consistency.

   Response: We have revised this sentence to use the previously defined acronym consistently.

   Revised manuscript text (L446-449): Over 30–60°N and 0–30°S, the reduction in CF allows more longwave radiation to escape to space, resulting in an increase in outgoing longwave radiation, corresponding to a negative TOA LWCRE trend.

8. **Comment:** L394-396: I do not think that sufficient detail and evidence has been given up to this point for claiming that cloud vertical distribution is clearly linked to the observed trends; this comes in the next section. Thus, this appears rather out of nowhere.

   Response: We thank the reviewer for pointing out this logical issue. We have revised this sentence to provide a smoother transition to the following section and to avoid making a claim about cloud vertical distribution before the relevant cloud-type evidence is presented.

   Revised manuscript text (L451-453): Overall, the changes in cloud amount and reflectivity are both relevant to the contrasting shortwave and longwave cloud contributions. The cloud-type analysis below evaluates these contributions more directly.

9. **Comment:** L420-423: Here comes the root and substantiation for the observed LW CRE changes mentioned before. I would also be careful to call this a regime change; the processes driving low-, mid-, and high-level clouds of the typologies included in the study are very different from those driving intra-cloud type variation, thus the regime shift is more of an entire circulation regime change rather than a cloud regime change. This may be important to

differentiate since it is possible to talk about e.g. Sc-Cu regime changes, but not Sc-Ci changes, and the reader must be aware that the authors mean climate/atmospheric circulation regimes.

Response: We thank the reviewer for this important clarification. We agree that the term "cloud regime change" was imprecise and could misleadingly imply a direct physical transition between cloud types, analogous to the well-known Sc–Cu regime transition within the boundary layer. Our analysis identifies concurrent changes in the occurrence and characteristics of distinct cloud types across different altitude categories; it does not demonstrate a direct transition from one cloud type to another. In particular, opposing trends in low-level and high-level clouds should not be interpreted in the same sense as a physically connected Sc–Cu regime transition. We have therefore replaced "cloud regime change/transition" in the Results and Conclusions with "redistribution of cloud occurrence across cloud types and vertical levels associated with large-scale atmospheric circulation and thermodynamic changes."

To avoid ambiguity, we have also revised this statement throughout the manuscript. Expressions such as "cloud regime change" or "cloud transition" have been replaced by descriptions of cloud type changes. Meanwhile, we describe these changes as statistically consistent with thermodynamic and dynamical changes accompanying large-scale atmospheric circulation adjustments. This wording distinguishes large-scale atmospheric changes from transitions between individual cloud regimes and avoids implying direct conversion between cloud types. We have also revised the title to: Planetary Albedo Change Exacerbates Surface Warming: A Perspective on Cloud-Type Changes.

Revised manuscript text (L469-478): The CF contribution reflects concurrent decreases in low-level (St and Cu), mid-level, and Cb clouds, which are partly offset by increases in optically thin high clouds (Cs and Ci). This redistribution among distinct cloud types and altitude categories is associated with broader changes in atmospheric circulation and thermodynamic conditions. As a result, the negative RSR_{cloud} contributions from the displaced low-level, mid-level, and Cb clouds are partially offset by the positive contributions from the increasing high-level optically thin clouds. This change would also reduce the downwelling longwave emission from clouds to the surface, thereby confirming the observed longwave cooling contribution of clouds to the T_s trend (Fig. 1a).

10. **Comment:** L443-446: I would not describe or refer to figure elements in the main text by their appearance; the circle key explanation should be left to the figure caption, and any references in the text should be to the physical quantity, not the markers. That is, try to reformulate to something like, "the close agreement between observed CF trend and the sum of all CCF contributions indicates …".

    Response: We thank the reviewer for this careful suggestion. We have rewritten this sentence to refer directly to the physical quantities rather than the markers in the figure.

    Revised manuscript text (L494-497): Figure 6 shows the area-weighted contributions of individual factors to the CF trend across nine cloud types and six latitude zones. The close agreement between the observed CF trend and the sum of all CCF contributions indicates that the model captures a reasonable portion of the trends.

11. **Comment:** Figure 6: The label text is rather small for the large size of this figure.

    Response: Thank you. We have increased the label and axis-text size in Figure 6 to improve readability.

    Revised figure:

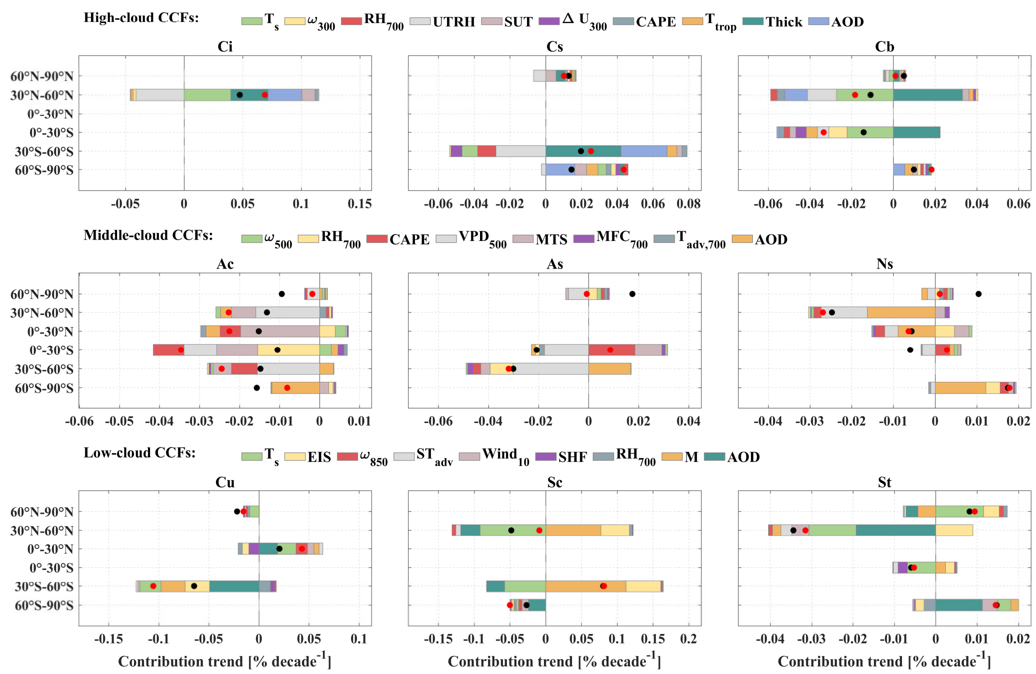

Figure R2 (Same as Figure 6 in the revised manuscript). Contributions of meteorological factors to CF trends (% decade^{-1}) for nine cloud types across six latitude zones, sorted in descending order of magnitude. Black dots indicate the observed significant CF trend, while red dots denote the sum of factor contributions. Latitudinal means are area-weighted to account for their contributions to the global mean. Only trends significant at the 95% confidence level are highlighted.

12. **Comment:** L479-480: Here a citation is needed. I am also not sure if it isn't warranted to regress against CR as well, because now we have nothing to compare to here. Is it not interesting to have a directly comparable metric, so we can judge if your results indicate whether aerosol impacts on cloud lifetime are more important than on cloud albedo?

    Response: We thank the reviewer for this constructive suggestion. Firstly, we have added citations for the aerosol-cloud interpretation. Next, we fully agree that regressing cloud reflectivity (CR) against meteorological factors, in parallel with our cloud fraction (CF) analysis, would yield valuable insight. In response, we conducted such an analysis for low clouds as an illustrative example.

    Because CF and CR describe different cloud properties, we did not assume that they are controlled by an identical set of cloud-controlling factors. CF is a macrophysical measure of cloud occurrence and coverage, whereas CR depends more directly on cloud optical and microphysical properties, including cloud droplet number, droplet size, and liquid water content, while also responding to the surrounding thermodynamic and dynamical environment. We therefore selected different sets of controlling factors for the two variables. For low-cloud CF, we retained the predictors used in the main manuscript (see Table 1). For low-cloud CR, we drew on previous studies (Jian et al., 2021; Wall et al., 2022; Zhang et al., 2025) and selected a suite of physically relevant predictors, including relative humidity at 950 hPa (RH_{950}), relative humidity at 700 hPa (RH_{700}), vertical velocity at 900 hPa (ω_{900}), vertical velocity at 700 hPa (ω_{700}), estimated inversion strength (EIS), aerosol optical depth (AOD), latent heat flux (LHF), and surface temperature advection (ST_{adv}). These variables represent boundary-layer and lower-tropospheric moisture, vertical motion, inversion strength, aerosol loading, surface moisture supply, and horizontal thermal advection.

    We note that Jian et al. (2021) used the mass concentrations of several aerosol species near cloud level, including hydrophilic black carbon, organic carbon, sulfate, sulfur dioxide, dust, and sea salt, whereas our analysis uses column-integrated AOD. Moreover, Jian et al. (2021) investigated the factors associated with the long-term monthly variability of marine stratocumulus albedo rather than attributing its linear trend. We retained AOD in the exploratory CR analysis to maintain consistency with the aerosol proxy used in our CF regression analysis. AOD has also been widely used to examine statistical relationships between aerosol loading and cloud fraction, including analyses that account for meteorological covariability (Engström and Ekman, 2010; Grandey et al., 2013; Gryspeerdt et al., 2016; Andersen et al., 2023). Nevertheless, we recognize that the choice of aerosol proxy introduces substantial uncertainty. AOD is a column-integrated optical quantity and does not directly represent CCN concentrations near cloud base. Jia et al. (2026) systematically compared several commonly used CCN proxies and demonstrated that their performance differs substantially, with AOD producing considerably larger biases than surface CCN, aerosol index, and several other proxies. This evidence reinforces the need for caution when interpreting the AOD contribution as a direct microphysical aerosol effect.

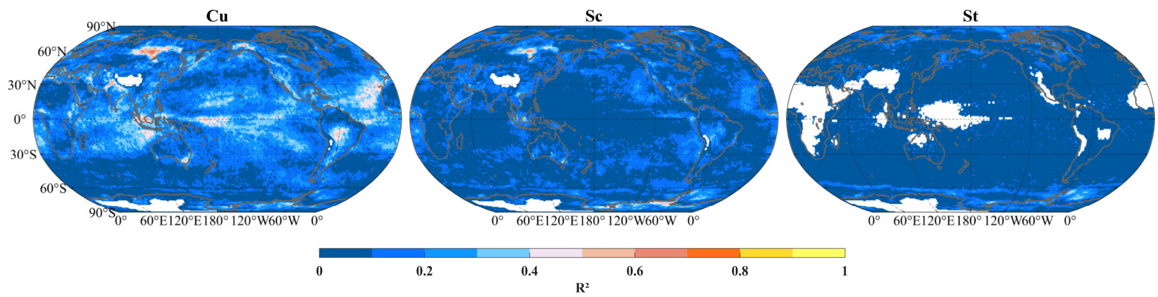

Figure R3. Spatial distributions of the coefficient of determination (R^2) obtained from the stepwise multiple linear regression of cloud reflectivity (CR) for low-level clouds during July 2002–February 2023.

The stepwise multiple linear regression for CR, however, yields poor performance, with grid-cell R^2 values generally below 0.4 (Fig. R3), and the CR trends reconstructed from the summed factor contributions differ substantially from the observed trends (Fig. R4). These diagnostics indicate that the selected controlling factors do not provide a sufficiently reliable basis for attributing the observed CR trends. The limited regression skill may reflect the dependence of CR on cloud microphysical and optical variability that is not fully represented by monthly reanalysis fields, together with uncertainties in using AOD as a proxy for cloud condensation nuclei. This result further underscores the need for improved observational constraints on cloud microphysical processes. This limitation is also why we use the satellite-observed changes in cloud optical thickness and effective particle radius to interpret the CR changes qualitatively, rather than attributing them quantitatively through the regression model.

Furthermore, the AOD contributions from the CF and CR regressions are not directly comparable because the two models use different predictor sets and represent different cloud properties. We consequently cannot determine from the present analysis whether aerosol effects on the cloud lifetime are more important than their effects on cloud reflectivity. We provide the exploratory results in Figs. R3 and R4, but have not included this poorly constrained attribution in the revised manuscript.

Nevertheless, we fully agree with the reviewer that this is a highly important and thought-provoking question, which provides a valuable direction for future work.

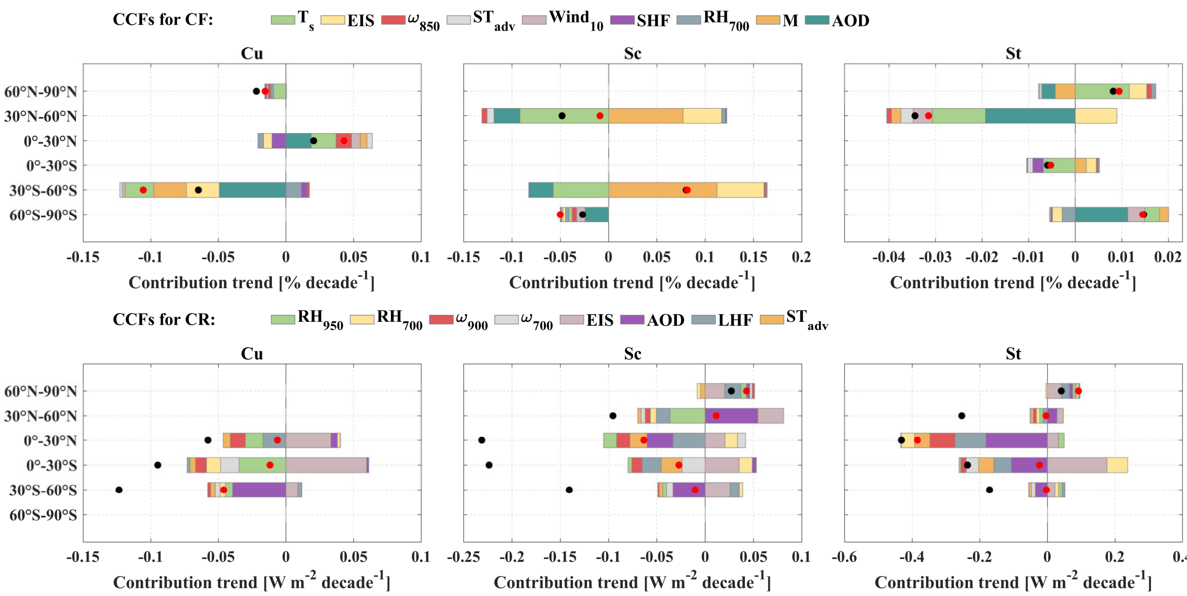

Figure R4. Contributions of meteorological factors to CF (upper row) and CR (lower row) trends for low clouds across six latitude zones, sorted in descending order of magnitude. Black dots indicate the observed significant trend, while red dots denote the sum of factor contributions. Latitudinal means are area-weighted to account for their contributions to the global mean. Only trends significant at the 95% confidence level are highlighted.

Revised manuscript text (L526-533): Meanwhile, the tight coupling between CF reduction and AOD decline explicitly highlights the impact of aerosols on cloud lifetime (Albrecht, 1989). The reduction in aerosol loading may decrease cloud condensation nuclei (CCN) and cloud droplet number concentrations (CDNC), favoring larger droplets and more efficient collision–coalescence and precipitation, which may in turn reduce cloud persistence and fractional coverage (Twomey, 1974, 1977; Albrecht, 1989; Rosenfeld et al., 2019; Bellouin et al., 2020; Szopa et al., 2023).

13. **Comment:** L479-480: Less important than before, but here some citation is also needed. I am also not sure if it isn't warranted to regress against CR as well, because now we have nothing to compare to here. Would it be interesting to have a directly comparable metric, so we can judge if the authors' results indicate whether aerosol impacts on cloud lifetime are more important than (non-lifetime) on cloud albedo?

    Response: Thank you. This concern has been addressed in our response to Comment 12.

14. **Comment:** L492-494: "... implying cloud reductions": it would be more correct to say that reduced storm track activity does not imply cloud reductions, it directly causes them.

    Response: We thank the reviewer for this clarification. We have revised the sentence to describe the established physical consequence of reduced storm-track activity more accurately.

    Revised manuscript text (L546-548): As a result, the frequency and intensity of mid-latitude cyclones are expected to diminish, thereby weakening large-scale ascent and directly reducing storm-associated cloud occurrence.

15. **Comment:** L503-506: Can this spatial correlation map be included in the supplement to substantiate the claim? One like Fig. S5 would be sufficient.

    Response: We thank the reviewer for this constructive suggestion. We have added Fig. S8, which shows the spatial distributions of the ω_{300}–Cb regression coefficient, the standardized ω_{300} trend, and the resulting contribution of ω_{300} to the Cb trend (Please see Fig. R5).

    The new figure shows that the negative zonal-mean ω_{300} trend in Fig. 5 does not represent the local trend in the regions that dominate the Cb contribution. Over the western equatorial Pacific, negative ω_{300}–Cb coefficients coincide with significant positive trends in ω_{300}. Because positive pressure-velocity trends indicate weakened ascent, their spatial correspondence produces a negative contribution to the Cb trend. This regional contribution dominates the negative zonal-mean contribution shown in Fig. 6 in the revised manuscript. We have revised the manuscript to clarify that the discrepancy arises because the contributions are calculated grid by grid before spatial averaging, rather than from the product of zonal-mean coefficients and zonal-mean factor trends.

In addition, we noticed that a similar argument in the previous manuscript (L485–488) was not sufficiently supported by visual evidence. To address this, we have prepared another supplementary figure (Fig. S7 in the revised manuscript) to support the corresponding discussion in L489–492 of the revised manuscript. (Revised manuscript text: Although the zonal-mean attribution suggests a substantial contribution from T_s (Fig. 6), this relationship is primarily evident over land (Fig. S7b), whereas the dominant decrease in Cb occurs over oceanic regions (Fig. 3, Fig.S7a). Therefore, increasing T_s does not explain the principal oceanic Cb reduction.)

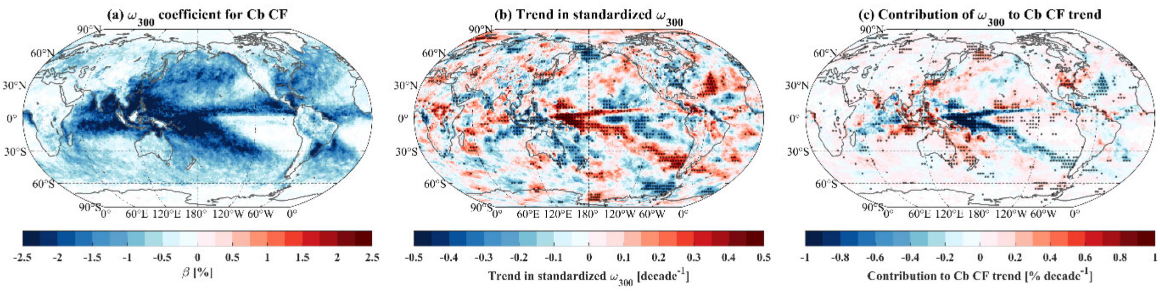

Figure R5 (Same as Figure S8 in the revised manuscript). Spatial distributions of (a) the standardized regression coefficient relating 300-hPa pressure vertical velocity (ω_{300}) to Cb cloud fraction, (b) the decadal trend in standardized ω_{300}, and (c) the resulting contribution of ω_{300} to the Cb cloud-fraction trend. Coefficients and contributions are shown where ω_{300} was retained by the stepwise regression. Black dots in (b) and (c) indicate trends significant at the 95% confidence level. Positive ω_{300} trends indicate weakened ascent, whereas negative trends indicate strengthened ascent.

Revised manuscript text (L556-566): Moreover, although standardized ω_{300} exhibits a negative zonal-mean trend over 0–30°S (Fig. 5), this zonal mean does not directly determine its contribution to the Cb trend because the contributions are calculated at each grid point before spatial averaging. The spatial distributions in Fig. S8 show that the negative ω_{300}–Cb regression coefficients over the western equatorial Pacific coincide with significant positive local trends in ω_{300}, indicating weakened ascent. This spatial correspondence produces a negative contribution of ω_{300} to the Cb trend in this region (Fig. S8c), which dominates the negative zonal-mean contribution shown in Fig. 6. This may be associated with a weakening of the Walker circulation (Wu et al., 2021) over the western equatorial Pacific, which suppresses convective development and moisture uplift, limiting the formation of these clouds.

16. **Comment:** L512-514: Which cloud types' contributions to CF are smaller in the SH than NH, and in which direction? There are opposing signs of contributions; the contributions by cloud type need to be specified here, otherwise it is difficult to interpret the claim. While the logic is hard to follow because of the opposite total signs of contributions in each hemisphere, the claim seems to be focused on Sc contributions, but I am not sure. It is also difficult to differentiate between e.g. Sc and Cu in Fig. 4 due to the very small contribution bars.

    Response: We apologize for the ambiguity in the original wording. Our intended point was about the net total CF contribution in the two midlatitude bands, rather than the contribution of a single cloud type. We agree that the direction of the contribution and the relevant cloud types should be stated explicitly.

    As shown in Fig. 1b and Fig. 4, RSR_{cloud} decreases in both the Northern and Southern Hemisphere midlatitudes. In the NH midlatitudes, the total CF contribution is negative and accounts for approximately -0.12 W m^{-2} $decade^{-1}$ of the RSR_{cloud} decrease. This negative CF contribution is mainly associated with decreases in St, Sc, Ns, and Cb. In contrast, in the SH midlatitudes, the net CF contribution is positive (0.03 W m^{-2} $decade^{-1}$), meaning that CF changes partly offset, rather than enhance, the CR-driven decrease in RSR_{cloud}. This positive CF contribution mainly reflects increased Sc, which compensates for the negative contributions from reduced mid-level clouds. We have revised the text to clarify the sign, hemispheric contrast, and cloud-type contributions.

    Revised manuscript text (L585-594): Notably, the net contribution of total CF changes to the RSR_{cloud} trend differs in sign between the two mid-latitude zones (Fig. 4). In 30–60°N, CF changes contribute approximately −0.12 W m^{-2} $decade^{-1}$, reinforcing the decrease in RSR_{cloud}; this negative contribution arises mainly from decreases in St, Sc, Ns, and Cb. By contrast, in 30–60°S, the net CF contribution is positive (approximately 0.03 W m^{-2} $decade^{-1}$) and therefore partly offsets the CR-driven decrease in RSR_{cloud}. This positive contribution can be attributed to an increase in more reflective Sc, which compensates for the RSR_{cloud} decrease caused by reduced Cu and mid-level clouds. As shown in Fig. 6, the increasing EIS trend and decreasing instability (M parameter) trend suppress convective Cu while favoring the formation of the more stable Sc.

17. **Comment:** L544-545: Missing specification about where the rise in RSR_cloud occurs in contrast to low and midlatitudes; do the authors mean in the high latitudes?

Response: Thank you. We have revised the sentence to specify that this contrast occurs at high latitudes.

Revised manuscript text (L621-623): In contrast to the low- to mid-latitudes, increased CF and enhanced CR have led to a rise in RSR_{cloud} at high latitudes in both hemispheres, thereby mitigating regional warming (Fig. 4a, b).

18. **Comment:** L547-548: I do not think that the claim that physical processes are captured can be made, because the study focuses on statistical modeling. I advise to omit this sentence or reformulate to a more physically sound description of what the statistical model is yielding.

Response: We thank the reviewer for pointing out that our original wording overstated what can be inferred from a statistical model. We agree that the model cannot be considered to capture the underlying physical processes, particularly given its relatively limited explanatory power at high latitudes. Our intention was to indicate that, despite this limitation, the statistical relationships still provide useful information about the environmental factors associated with the observed high-latitude cloud trends. We have therefore reformulated the sentence to distinguish statistical associations from a physical representation of the processes.

Revised manuscript text (L624-638): Although the model performance is relatively limited at high latitudes (Fig. S5), the regression still captures part of the statistical relationship between CF anomalies and the selected environmental factors. They should, however, be interpreted as statistical indications rather than as evidence that the underlying physical processes are fully represented by the model.

19. **Comment:** L596: "Driven by the ongoing climate crisis, …": This is a bit odd wording; the study is driven by the ongoing climate crisis? Perhaps it needs to be rephrased as motivation.

Response: Thank you. We have rephrased the opening sentence of the conclusion so that the climate crisis is presented as motivation rather than as the literal driver of the study.

Revised manuscript text (L706-709): Motivated by the rapid recent warming, ongoing climate crisis, and the need to understand cloud changes, this study quantifies the cloud radiative contribution to surface warming over 2002-2023 using CERES data and a surface energy balance framework.

20. **Comment:** L597: "surface energy balance equation": I would describe this as a model or framework, rather than an equation.

    Response: We agree and have revised this terminology throughout the relevant text.

    Revised manuscript text (L706-709): Motivated by the rapid recent warming, ongoing climate crisis, and the need to understand cloud changes, this study quantifies the cloud radiative contribution to surface warming over 2002-2023 using CERES data and a surface energy balance framework.

21. **Comment:** L606: As in before, the term "the mechanisms" implies physical and mechanistic explanations, but the study is focused on statistical modeling and relationships between quantities. I would suggest replacing these words with "cloud behaviors/changes" or similar.

    Response: We agree that the term "mechanisms" implied a level of physical and causal interpretation that is not fully supported by our statistical analysis. Our intention was to emphasize that the hemispheric contrast involves not only different cloud changes, but also different relative contributions from cloud fraction and cloud reflectivity, together with different environmental factors statistically associated with these changes. We have replaced this wording with a more cautious description of cloud behaviors and statistical relationships.

    Revised manuscript text (L718-719): Regionally, both cloud changes and the relative CF and CR contributions exhibit hemispheric differences.

22. **Comment:** Table A1: Typesetting/kerning issues in right column of table.

    Response: We thank the reviewer for identifying this typesetting issue. Following the suggestion in the preceding comment (Comment 4), we have incorporated the contents of Table A1 into the reorganized Table 1 and removed Table A1 from the Appendix. We have corrected the typesetting and spacing in Table 1 to improve its consistency and readability.

23. **Comment:** Eq. A2: STadv is sometimes written as a text and at other times in math mode, with subscript "adv". Please ensure all variables are consistent throughout the manuscript.

Response: Thank you for identifying this inconsistency. We have standardized the notation of this variable as "ST_{adv}" throughout the main text, equations, tables, and Appendix, with "adv" consistently formatted as a subscript.

24. **Comment:** L699-702: These are not very clear/standard descriptions of tasks/roles. What is the difference between organizing and writing? What does "modifying the paper" mean compared to reviewing and revising? I suggest using something more standardized, transparent, and easily understood, like the widely used CREdiT system (https://credit.niso.org/).

    Response: We agree that the previous author-contribution statement was not sufficiently transparent. We have revised it using the CRediT taxonomy.

    Revised manuscript text: Author contributions. R.L.: Methodology, Formal analysis, Visualization, Writing - original draft. J.M.L.: Conceptualization, Supervision, Writing - review and editing. B.J.: Methodology, Writing - review and editing. L.Z.: Validation, Writing - review and editing. J.Y.L.: Investigation, Writing - review and editing. All authors contributed to interpretation of the results and approved the submitted manuscript.

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Response to Reviewer #2's Comments:

Ruixue Li et al. (Authors)

We are sincerely grateful to Reviewer #2 for the careful and critical evaluation of our manuscript. The reviewer raised a fundamental concern regarding our inaccurate characterization of cloud feedback in the original manuscript, together with important questions about longwave cloud masking, the presentation of spatial variability, and the quantitative connection between cloud-type changes and longwave radiative trends. We agree that the original manuscript did not define these boundaries with sufficient care. In response, we have substantially revised the framing and terminology of the study, clarified the diagnostic and statistical nature of our analysis, and conducted additional spatial and cloud-type-resolved analyses. These comments have helped us define the scope, evidence, and limitations of the study more accurately.

Please see our point-by-point reply to comments. All revisions are shown in the revised manuscript by using track changes. The line numbers involved in the response correspond to the clear version of the manuscript.

General comments

Comment: In this paper, Li et al. quantify the contribution of cloud radiative changes to decadal surface temperature trends over 2002–2023 using CERES radiation data with a surface energy-balance framework, and aim to establish a direct observational link between cloud transitions, planetary albedo decline, and spatially heterogeneous warming. The authors suggest that cloud changes strongly modulate the spatial pattern of surface warming by enhancing warming in low- and mid-latitudes while mitigating warming at high latitudes. The abstract claims that the work provides a constraint on cloud feedbacks in recent climate change.

However, the work fails to attribute cloud radiative changes during 2002–2023 to different forcing and feedback processes, and the work could not be used to constrain cloud feedbacks in recent climate change, as is claimed in the last sentence of the abstract. Therefore, substantial revisions are required before the paper be accepted for publication.

Response: We sincerely thank the reviewer for this careful assessment and for identifying an important overstatement in our original framing. We apologize that our previous wording was imprecise and could have led readers to interpret the observed cloud-radiative trends as a direct constraint on cloud feedback. Our analysis cannot uniquely separate the contributions of external forcing, including aerosol–cloud interactions, rapid adjustments to greenhouse-gas forcing, internal climate variability, and temperature-mediated cloud feedback. We have therefore removed the claim that our results constrain cloud feedback from the Abstract and revised similar statements throughout the manuscript. The study is now framed as an observation-based assessment of recent cloud-radiative and cloud-type changes and their associations with surface-temperature trends, rather than as a formal constraint on cloud feedback.

We have also revised causal and mechanistic language, clarified that the regression analysis identifies statistical relationships rather than uniquely attributable physical causes, and explicitly discussed the different processes that may contribute to the observed trends. In addition, we quantified the contribution of longwave cloud masking, clarified that our principal results describe zonal rather than spatial patterns, and evaluated the relationship between cloud-type changes and longwave radiative trends. These revisions and additional analyses are described in detail in our point-by-point responses below.

Specific comments

1. **Comment:** The trend of cloud radiative effect is not affected by cloud feedback alone, so the trend analyses in work could not provide a constraint on cloud feedbacks in recent climate change. The trend of CRE is affected by: (1) Cloud-aerosol interactions. (2) Rapid adjustment to changes in the concentration of greenhouse gases. (3) Effect of decadal and interdecadal oscillations. (4) Cloud feedback on global warming. Most of the meteorological factors listed in Fig. 6 are affected by all of these four factors, so the current trend analyses are not sufficient to constrain cloud feedback.

   Response: We fully agree with the reviewer’s central point. The original manuscript used the term “cloud feedback” too broadly and did not adequately distinguish a trend in cloud radiative effect from a temperature-mediated cloud-feedback response. As the reviewer notes, the observed cloud-radiative trends during 2002–2023 may contain contributions from aerosol–cloud interactions, rapid adjustments to greenhouse-gas forcing, decadal and interdecadal variability, and cloud feedbacks associated with warming. Moreover, the meteorological factors used in our regression are not uniquely associated with any one of these processes.

Their trends may themselves reflect a combination of forced responses and internal variability. Consequently, the regression cannot provide a process-level separation of these four contributions.

To address this concern, we have revised the language of the manuscript in three ways. First, we have removed the statement that our analysis provides a constraint on cloud feedbacks and have replaced it with a more accurate description of the study as an observational diagnosis of recent cloud-radiative changes. Second, we now describe the relationships in Fig. 6 as statistical associations between cloud-fraction anomalies and the selected cloud-controlling factors, rather than as a causal attribution of the physical processes responsible for the trends. Third, we have added an explicit limitation explaining that the present observational and regression framework cannot isolate aerosol-driven adjustments, greenhouse-gas rapid adjustments, internal variability, and the forced cloud-feedback component. We appreciate this comment because it has led us to define the contribution and limitations of the study much more precisely.

Revised manuscript text (L26-28): Our results establish a direct observational link between cloud-type changes, planetary albedo decline, and zonally contrasting warming, characterizing the cloud-radiative changes in recent climate change.

Revised manuscript text (L80-82): This observation-based assessment provides a benchmark for evaluating the representation of cloud radiative effects in climate models and offers new insights into the cloud type changes that influence recent warming trends.

Revised manuscript text (L261-268): Importantly, the observed CF trends and associated cloud-radiative changes may reflect a combination of aerosol-driven cloud adjustments (Bellouin et al., 2020), rapid adjustments to greenhouse-gas forcing and temperature-mediated cloud feedbacks (Zelinka et al., 2013; Sherwood et al., 2015), and internal climate variability (Zhou et al., 2016). Because each predictor may respond to more than one of these processes, the regression quantifies statistical relationships and trend contributions but does not uniquely attribute the observed trends to individual forcing, adjustment, internal-variability, or feedback components.

2. **Comment:** The longwave component of the masking effect has not been removed, although the shortwave component of the masking effect has been removed according to Eq. (15). Under global warming, the masking effect have an important impact on LWCRE trends.

   Response: We sincerely thank the reviewer for this important and constructive comment. We agree that the conventional longwave cloud radiative effect (LWCRE), calculated as the difference between clear-sky and all-sky outgoing longwave radiation (OLR), does not represent the radiative effect of cloud-property changes alone. Changes in non-cloud properties can affect clear-sky and all-sky OLR differently because clouds partly mask the radiative effects of the atmosphere and surface below them. Consequently, an LWCRE trend can be decomposed into a component associated with changes in cloud properties and a cloud-masking component associated with changes in non-cloud properties, including water vapor (H_2O), well-mixed greenhouse gases (GHGs), ozone (O_3), surface temperature (T_s), and atmospheric temperature (T_a) (Soden et al., 2004, 2008; Raghuraman et al., 2023).

   Unlike the simplified treatment of shortwave masking in Eq. (15), longwave cloud masking cannot be reliably estimated using a similarly simplified radiative-transfer formulation. Its magnitude depends on vertically resolved temperature, humidity, and trace-gas profiles, as well as their spectrally overlapping absorption and emission with clouds at different altitudes. We therefore used the publicly available ERA5 partial radiation perturbation (ERA5–PRP) dataset developed by Raghuraman et al. (2023). These data were generated by applying a two-sided partial radiation perturbation method with the offline Rapid Radiative Transfer Model for General Circulation Model Applications–Parallel (RRTMGP). The PRP experiments quantify the effects of individual variables on clear-sky and all-sky TOA radiation, allowing the masking contribution from each non-cloud variable to be calculated from the difference between its clear-sky and all-sky radiative perturbations.

   Because the ERA5–PRP dataset ends in December 2020, we evaluated longwave cloud masking over the common period from July 2002 to December 2020. We calculated the trends associated with T_s, T_a, H_2O, GHGs, and O_3 at the global scale and within the six latitude zones used in our main analysis. The results are presented together with the cloud-type-resolved and total LWCRE trends in Fig. R6 (same as Figure S10 in the revised manuscript).

The analysis shows that the global-mean TOA longwave cloud-masking trend is negative and accounts for approximately 32% of the magnitude of the observed negative LWCRE trend over July 2002–December 2020. Thus, cloud masking constitutes a substantial part of the observed LWCRE change and cannot be neglected when interpreting the trend.

The ERA5–PRP dataset does not resolve cloud masking separately for the nine cloud types considered in our study. We therefore do not subtract the aggregate masking estimate from each individual cloud-type contribution, as such an allocation would not be physically justified. Instead, Fig. R6 presents the cloud-type-resolved conventional LWCRE trends alongside the independently estimated masking components and the total LWCRE trend. We have also revised the manuscript to clarify that the cloud-type results represent cloud-type-associated LWCRE changes rather than radiative changes caused solely by intrinsic cloud-property variations.

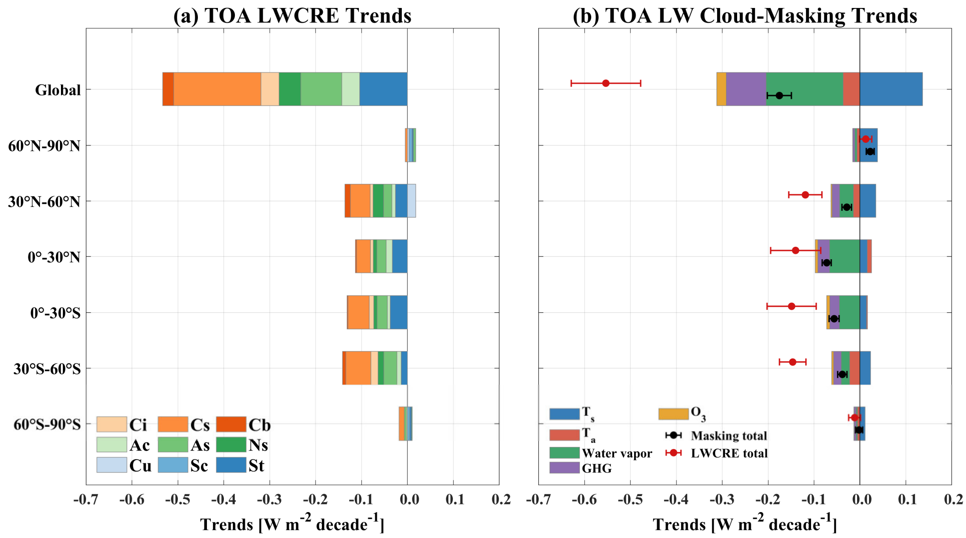

Figure R6 (same as Figure S10 in the revised manuscript). Contributions associated with cloud types and longwave cloud masking to the TOA LWCRE trend from July 2002 to December 2020. (a) Conventional LWCRE trends associated with nine cloud types. Only cloud-type trends significant at the 95% confidence level are shown. (b) Contributions of surface temperature (T_s), atmospheric temperature (T_a), water vapor, well-mixed greenhouse gases (GHGs), and ozone (O_3) to the TOA longwave cloud-masking trend estimated using the ERA5-PRP experiments. Black and red circles denote the total cloud-masking and total LWCRE trends, respectively, with error bars indicating their 95% confidence intervals. Values for the six latitude zones are area-weighted contributions to the global mean, whereas the Global row represents the global-mean trend. Positive values indicate contributions toward increasing LWCRE, and negative values indicate contributions toward decreasing LWCRE.

We acknowledge that the masking assessment ends 26 months earlier than the main study period, which extends to February 2023. We therefore use this common-period analysis to demonstrate the magnitude and importance of longwave cloud masking, rather than treating it as an exact correction for the full July 2002–February 2023 record. We have added the data and methodology, the new supplementary figure, and a discussion of this limitation and its implications for interpreting the cloud-type-resolved LWCRE trends.

Revised manuscript text (L292-332):

2.6 Quantification of TOA longwave cloud masking

The conventional TOA longwave cloud radiative effect (LWCRE) is defined as the difference between clear-sky and all-sky outgoing longwave radiation.

$$\mathrm{LWCRE_{TOA}} = \mathrm{OLR_{clr}} - \mathrm{OLR_{all}} \tag{19}$$

It can also be partitioned among the nine cloud types. For cloud type *c*, its contribution is calculated as

$$\mathrm{LWCRE_{TOA,c}} = \mathrm{CF_c} \times (\mathrm{OLR_{clr}} - \mathrm{OLR_c}) \tag{20}$$

where $\mathrm{OLR_c}$ is the overcast outgoing longwave radiation for cloud type *c*, $\mathrm{OLR_{clr}}$ is the corresponding clear-sky outgoing longwave radiation, and $\mathrm{CF_c}$ is the fractional coverage of that cloud type. Summing $\mathrm{LWCRE_{TOA,c}}$ across the nine cloud types gives the total $\mathrm{LWCRE_{TOA}}$.

Changes in LWCRE do not arise exclusively from changes in cloud properties. Clouds modify the TOA radiative response to changes in non-cloud variables. For example, the radiative effects of changes in surface and atmospheric temperature, water vapor, greenhouse-gas concentrations, and ozone generally differ between clear-sky and cloudy conditions because clouds partly obscure longwave emission from the surface and lower atmosphere. Consequently, changes in these non-cloud variables can produce a change in LWCRE even if the clouds themselves remain unchanged. This contribution is referred to as the cloud-masking effect (Soden et al., 2004, 2008).

An LWCRE anomaly can therefore be expressed as

$$\Delta\mathrm{LWCRE_{TOA}} = \Delta\mathrm{LWCRE_{cloud}} + \Delta\mathrm{LWCRE_{mask}} \tag{21}$$

where the longwave cloud-masking component is

$$\Delta \mathrm{LWCRE_{mask}} = \sum_x (\Delta OLR_x^{clear} - \Delta OLR_x^{all}) \tag{22}$$

and x represents surface temperature (T_s), atmospheric temperature (T_a), water vapor (H_2O), well-mixed greenhouse gases (GHGs, including CO_2, CH_4, N_2O, CFCs, and HFCs), and ozone (O_3). We quantified these components using the publicly available ERA5 partial radiation perturbation (ERA5–PRP) dataset (Raghuraman et al., 2023b), following the methodology described by Raghuraman et al. (2023a). The dataset was generated using a two-sided PRP method with ERA5 monthly atmospheric fields, observed greenhouse-gas concentrations, and the offline RRTMGP radiative-transfer model. For each non-cloud variable, its cloud-masking contribution was calculated as the difference between its clear-sky and all-sky TOA longwave radiative perturbations.

As the ERA5–PRP dataset is available only through December 2020, this analysis covers the common period from July 2002 to December 2020, rather than the full July 2002–February 2023 period used in the main analysis. We use this overlapping period to demonstrate the magnitude and importance of longwave cloud masking rather than to extend the masking estimate over the full study period. The cloud-type decomposition is therefore interpreted as the observed LWCRE associated with each cloud category, which includes both cloud-property changes and cloud-masking contributions.

Revised manuscript text (L679-704): We further examined the cloud-type-resolved trends in TOA LWCRE (Fig. S9). Across the low and middle latitudes, nearly all statistically significant cloud-type contributions show decreasing LWCRE trends, except for a small positive Cu contribution in the NH midlatitudes. For several cloud types, particularly the low- and mid-level clouds and Cb over the NH midlatitudes and SH tropics, the negative LWCRE trends coincide with decreases in CF (Fig. S4a). However, the correspondence is not one-to-one. For example, Cs occurrence increases globally, and both Cs and Sc increase over 30–60°S, whereas their associated LWCRE trends remain negative. These contrasting signs demonstrate that changes in cloud amount alone cannot explain the LWCRE trends. The concurrent decreases in cloud reflectivity for many cloud types, especially over the SH midlatitudes (Fig. S4b), suggest accompanying changes in cloud optical properties, although shortwave reflectivity does not directly constrain longwave emissivity. At a given cloud amount, LWCRE can also vary with cloud-top altitude and temperature, as well as cloud optical depth and emissivity (Zelinka et al., 2012; Raghuraman et al., 2024). Because these cloud-property contributions are not explicitly separated here, they are considered possible explanations rather than quantitatively attributed drivers. Moreover, conventional LWCRE includes the masking of changes in non-cloud properties by clouds (Soden et al., 2004, 2008; Raghuraman et al., 2023). Using the ERA5–PRP dataset, we quantified the masking effects of surface temperature, atmospheric temperature, water vapor, well-mixed greenhouse gases, and ozone over the common period from July 2002 to December 2020 (Fig. S10). The global longwave cloud-masking trend is negative, with major negative contributions from water vapor and well-mixed greenhouse gases partly offset by the surface-temperature contribution, and accounts for approximately 32% of the magnitude of the total negative LWCRE trend. Although this assessment ends 26 months earlier than the main analysis period, it demonstrates that longwave cloud masking is substantial.

3. **Comment:** The spatial pattern of cloud-induced warming is emphasized in the abstract. However, there is no figure showing the spatial pattern of cloud-induced warming in the paper. All figures show the trends in 6 zonal belts, but the phrase "spatial pattern" usually include information in both zonal and meridional directions.

   Response: We thank the reviewer for pointing out this imprecision. We agree that the phrase "spatial pattern" conventionally implies two-dimensional regional structure, whereas the principal quantitative comparisons in our manuscript are organized across six latitudinal zones. We have therefore replaced "spatial pattern" with "zonal pattern" in the Abstract and the relevant sections of the manuscript. This wording more accurately reflects the scale at which our main results are presented.

   In addition, we examined the gridded trends in the shortwave and longwave cloud-radiative contributions to surface-temperature trends. As shown in Fig. R7, the global maps support the broad zonal contrast identified from the latitude-band averages, while also showing substantial regional variability within individual latitude zones. We note that a trend need not be statistically significant at every individual grid cell for the corresponding area-weighted zonal-mean trend to be significant. The significance of each zonal-mean trend is evaluated from its area-weighted zonal-mean time series and is therefore distinct from the pointwise significance shown on the maps. Nevertheless, because the main analysis does not provide a comprehensive assessment of all two-dimensional regional structures, we have revised the terminology to avoid implying that the manuscript provides a complete analysis of all regional structures.

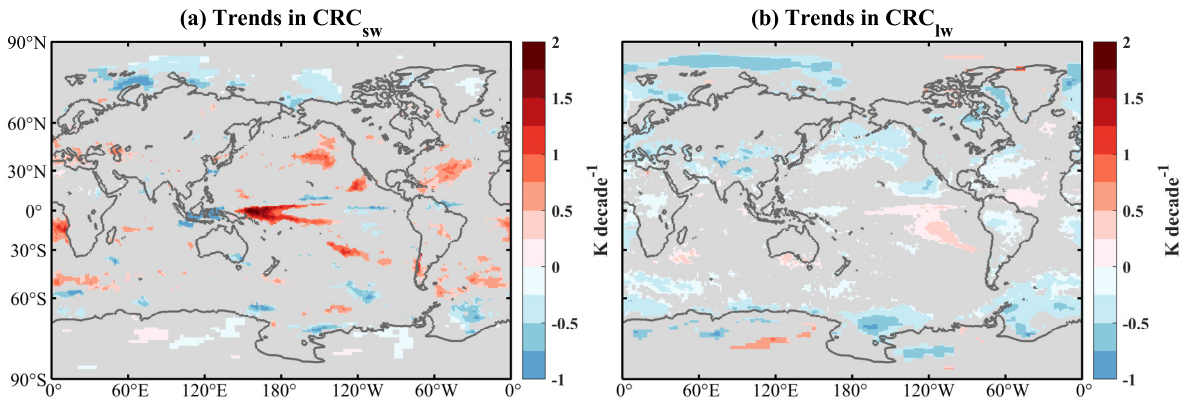

Figure R7. Spatial distributions of trends in the surface-temperature contributions associated with (a) shortwave and (b) longwave cloud-radiative changes (CRC_{sw} and CRC_{lw}) from July 2002 to February 2023. Units are K decade^{-1}. Only trends significant at the 95% confidence level are shown.

Revised manuscript text (L11-14): Cloud changes exert a weak net effect on global mean warming due to near-cancellation between shortwave warming and longwave cooling, but strongly modulate its zonal pattern. Specifically, clouds enhance warming in low- and mid-latitudes while mitigating warming at high latitudes.

4. **Comment:** The systematic transitions from low-/mid- to high-level clouds, which have already been identified in previous studies, was not quantitatively linked to the trend of LW cloud radiative changes in this study.

Response: We thank the reviewer for identifying this important gap. We agree that the original manuscript discussed the concurrent decrease in low- and middle-level clouds and increase in high-level clouds, but did not directly quantify how individual cloud types contributed to the observed LWCRE trend.

To address this concern, we have now calculated the TOA LWCRE trend separately for each of the nine CERES FBCT cloud types (Cu, Sc, St, Ac, As, Ns, Ci, Cs, and Cb). We then derived the area-weighted contribution from each cloud type within the six latitude zones, together with the corresponding global-mean trends (Fig. R8, same as Figure S9 in the revised manuscript).

We have also revised the terminology used in the manuscript. Because the observations do not demonstrate a direct conversion of one cloud type into another, we no longer describe these changes as a systematic low-/mid- to high-cloud transition. Instead, we refer to a redistribution of cloud occurrence and longwave radiative contributions across cloud types and vertical levels. The new quantitative analysis has been included in the revised Supplement and discussed in the manuscript.

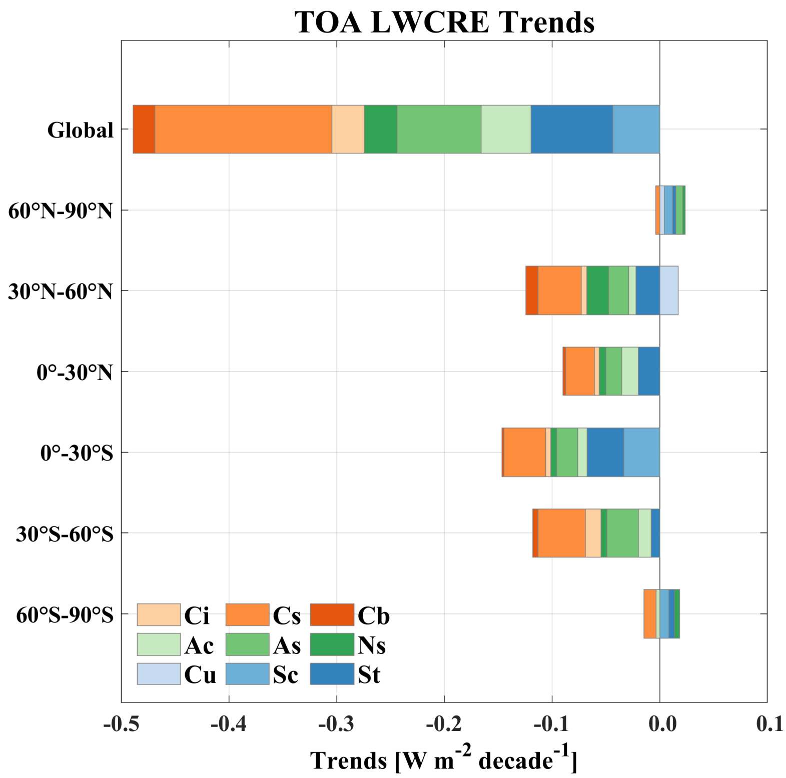

Figure R8 (same as Figure S9 in the revised manuscript). Latitude-zone and global averaged trends (July 2002 to February 2023) for top-of-atmosphere longwave cloud radiative effect (LWCRE). The latitude-zone values are area-weighted to represent their contributions to the global mean. Only trends significant at the 95% confidence level are shown.

Revised manuscript text (L679-704): We further examined the cloud-type-resolved trends in TOA LWCRE (Fig. S9). Across the low and middle latitudes, nearly all statistically significant cloud-type contributions show decreasing LWCRE trends, except for a small positive Cu contribution in the NH midlatitudes. For several cloud types, particularly the low- and mid-level clouds and Cb over the NH midlatitudes and SH tropics, the negative LWCRE trends coincide with decreases in CF (Fig. S4a). However, the correspondence is not one-to-one. For example, Cs occurrence increases globally, and both Cs and Sc increase over 30–60°S, whereas their associated LWCRE trends remain negative. These contrasting signs demonstrate that changes in cloud amount alone cannot explain the LWCRE trends. The concurrent decreases in cloud reflectivity for many cloud types, especially over the SH midlatitudes (Fig. S4b), suggest accompanying changes in cloud optical properties, although shortwave reflectivity does not directly constrain longwave emissivity. At a given cloud amount, LWCRE can also vary with cloud-top altitude and temperature, as well as cloud optical depth and emissivity (Zelinka et al., 2012; Raghuraman et al., 2024). Because these cloud-property contributions are not explicitly separated here, they are considered possible explanations rather than quantitatively attributed drivers. Moreover, conventional LWCRE includes the masking of changes in non-cloud properties by clouds (Soden et al., 2004, 2008; Raghuraman et al., 2023). Using the ERA5–PRP dataset, we quantified the masking effects of surface temperature, atmospheric temperature, water vapor, well-mixed greenhouse gases, and ozone over the common period from July 2002 to December 2020 (Fig. S10). The global longwave cloud-masking trend is negative, with major negative contributions from water vapor and well-mixed greenhouse gases partly offset by the surface-temperature contribution, and accounts for approximately 32% of the magnitude of the total negative LWCRE trend. Although this assessment ends 26 months earlier than the main analysis period, it demonstrates that longwave cloud masking is substantial.

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