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. R1 (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. R1 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.

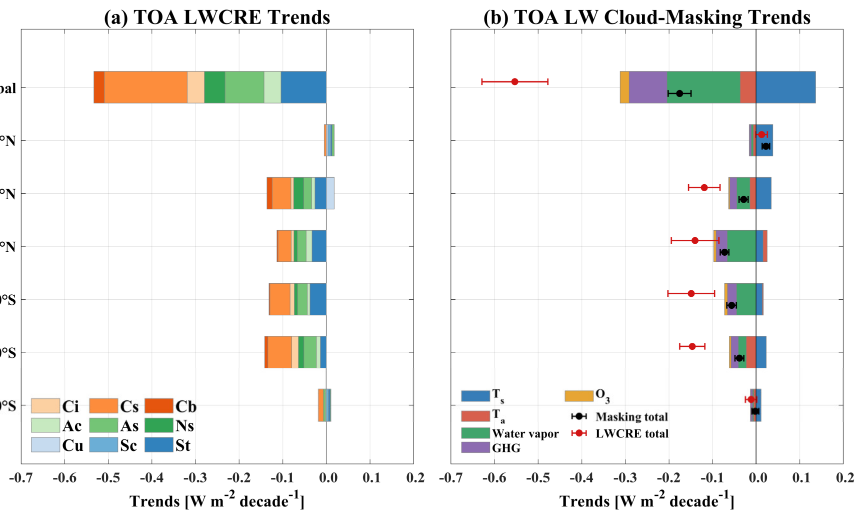

Figure R1 (same as Figure S10 in the revised manuscript). Contributions associated with cloud types and longwave cloud masking to the TOA LWCRE trend from July 2002 to December 2020. (a) Conventional LWCRE trends associated with nine cloud types. Only cloud-type trends significant at the 95% confidence 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

$$\Delta \mathrm{LWCRE}_{\mathrm{mask}} = \sum_{x} (\Delta OLR_x^{clear} - \Delta OLR_x^{all}) \tag{22}$$

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. R2, 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.

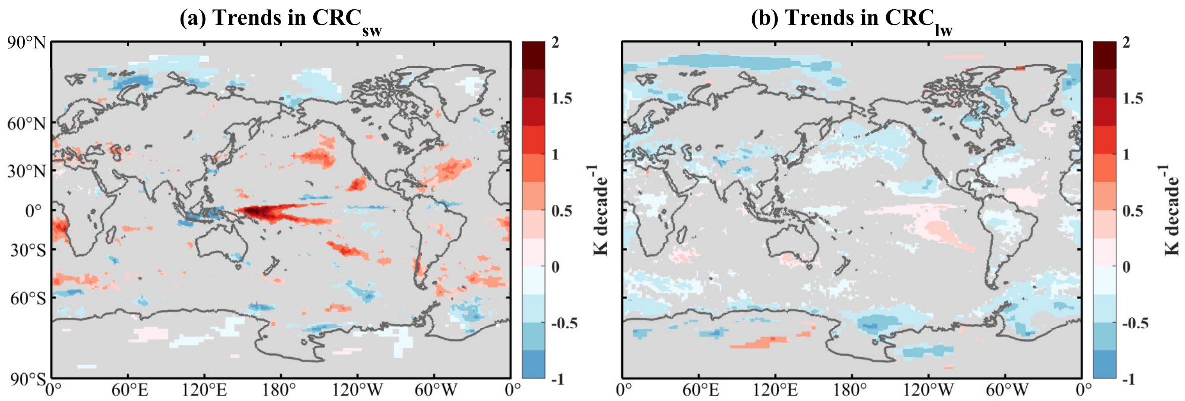

Figure R2. Spatial distributions of trends in the surface-temperature contributions associated with (a) shortwave and (b) longwave cloud-radiative changes (CRC_{sw} and CRC_{lw}) from July 2002 to February 2023. Units are K decade^{-1}. Only trends significant at the 95% confidence level are shown.

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. R3, 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.

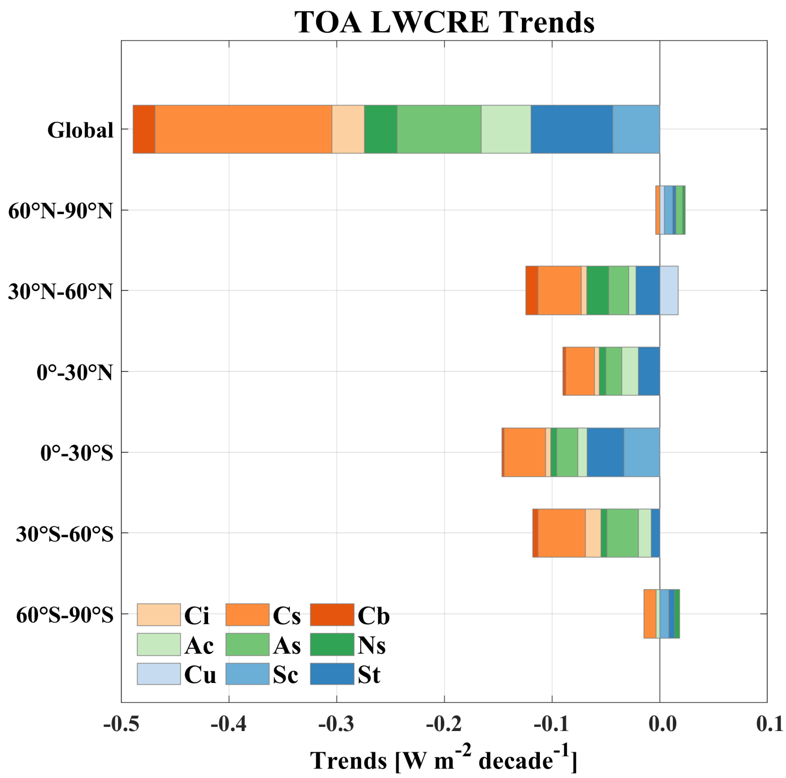

Figure R3 (same as Figure S9 in the revised manuscript). Latitude-zone and global averaged trends (July 2002 to February 2023) for top-of-atmosphere longwave cloud radiative effect (LWCRE). The latitude-zone values are area-weighted to represent their contributions to the global mean. Only trends significant 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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