We sincerely appreciate the reviewer's thoughtful and constructive comments. We have carefully considered each comment and revised the manuscript accordingly. Our point-by-point responses are provided below in bold.

Reviewer 1

This manuscript uses the 2B-CLDCLASS-LIDAR product (based on both CALIOP/CALIPSO and CPR/CloudSat) to classify mixed-phase cloud properties by "cloud types" defined by the satellite product during the period 2006-2010. Some of their key findings are: 1) in the tropics, Ac and Ns + DC clouds shift with the location of the storm tracks and ITCZ whereas 2) mid-latitude and polar Sc + St clouds are affected by atmosphere-ocean coupling, and 3) Cu cloud types are driven primarily by orographic convection. There is great value in classifying clouds by "cloud type" and the authors have carried out and presented a detailed analysis. The authors have also done a great job explaining most of the features they present and are quite careful to address uncertainty in their analysis as well. Mixed-phase clouds are challenging to observe and represent in models of all scales, and few analyses focus on "cloud type" classifications of mixed-phase clouds, especially on a global scale. This study is thus very valuable to the cloud and climate community. I only have a few suggestions regarding the manuscript: 1) though detailed, some of the written descriptions explaining the features of the plots are redundant and could be shortened to be more concise, 2) their explanation of features mostly focus on meteorological influences and do not say much about the role of aerosols, 3) the implications of their work can be strengthened. Overall, I recommend relatively minor revisions.

Reply: We thank the reviewer for the assessment of our study and for the constructive suggestions. In response, we have shortened several descriptive passages to improve conciseness, added discussion of potential aerosol influences where relevant, and strengthened the discussion of the broader implications of the cloud-type-dependent climatology for model evaluation. We have also made several additional revisions to clarify the methodology and presentation throughout the manuscript according to specific reviewer comments.

Specific comments:

- It may be worth clarifying what "cloud type" means in the manuscript. It clearly follows the 2B-CLDCLASS-LIDAR classification, what worth explicitly defining that in the manuscript, and also how that contrasts with other definitions in the literature, e.g. "cloud regimes" defined by Cho et al. 2021 (https://journals.ametsoc.org/view/journals/apme/60/7/JAMC-D-20-0247.1.xml) using the MODIS dataset but also "weather states" defined by Tselioudis et al. 2021 (https://journals.ametsoc.org/view/journals/clim/34/17/JCLI-D-21-0076.1.xml). Are the cloud types in distinct updraft (e.g. omega500) categories?

Reply: We thank the reviewer for this suggestion. We have clarified the meaning of "cloud type" by adding the following text in Sect. 2.1. We have also revised the terminology throughout the manuscript to use "cloud type" consistently for the 2B-CLDCLASS-LIDAR categories and to reserve "cloud regime" and "weather state" for the distinct grid-box-based classifications derived from MODIS and ISCCP observations, respectively.

"The product identifies eight cloud types: cirrus (Ci), altostratus (As), altocumulus (Ac), stratus (St), stratocumulus (Sc), cumulus (Cu), nimbostratus (Ns), and deep convection (DC). These categories are based on traditional meteorological cloud-type nomenclature and are assigned to individual cloud layers by the 2B-CLDCLASS-LIDAR classification. This definition differs from the Moderate Resolution Imaging Spectroradiometer (MODIS) "cloud regimes" and the International Satellite Cloud Climatology Project (ISCCP) "weather states," which characterize cloud fields at the grid-box scale by clustering joint histograms of cloud top pressure and cloud optical thickness (Cho et al., 2021; Tselioudis et al., 2021). Consequently, a cloud regime may contain multiple cloud types, and a given cloud type may occur within multiple regimes (Oreopoulos et al., 2014)."

Different cloud types are also expected to be associated with different large-scale dynamical environments (e.g. omega500). However, omega500 is not an input to the 2B-CLDCLASS-LIDAR classification, and its distribution among cloud types is not explicitly evaluated in the present study. Examining the relationship between cloud type and large-scale vertical motion would be useful future work.

- Lines 38-46: This information is outdated. Many CMIP6 models tend to overestimate supercooled liquid in mixed-phase clouds. See e.g. Tan et al. (2025) https://www.nature.com/articles/s41612-025-00948-7

  Reply: We thank the reviewer for pointing this out. We have revised this part as follows:

  "Earlier generations of climate models, including many models participating in Phase 5 of the Coupled Model Intercomparison Project (CMIP5) tended to glaciate mixed-phase clouds prematurely, resulting in an underestimation of supercooled liquid water and biases in associated shortwave cloud radiative effects, particularly over the Southern Ocean and other mid-to-high latitude regions (Klein et al., 2009; Cesana et al., 2015; McCoy et al., 2016). The Phase 6 of the Coupled Model Intercomparison Project (CMIP6) multi-model mean liquid-to-ice transition temperature is closer to satellite observations than CMIP5 multi-model mean (Tan et al. 2025). However, the transition temperature still exhibits an inter-model spread of approximately 30 °C, with individual models simulating either too much or too little supercooled liquid water. For example, Tan et al. (2025) found that 18 CMIP6 models overestimated and 17 underestimated the

extratropical supercooled liquid fraction relative to observations. Thus, despite continued progress in cloud microphysical parameterizations, including treatments of ice nucleation and other mixed-phase cloud processes, substantial uncertainty remains in simulated cloud phase partitioning and its associated radiative effects and feedbacks (Tan et al., 2016; Zelinka et al., 2020).”

- Lines 70-72: Another application of satellite observations to study mixed-phase clouds is to study their phase heterogeneity which is of great interest for accurately modelling their radiation and longevity (e.g. Coopman & Tan (2023) satellite mixed-phase cloud heterogeneity characterization (DARDAR) based grid cells classified as “stratiform” using MODIS cloud regimes https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023GL104977)

  Reply: We thank the reviewer for pointing out this additional application of satellite observations and the relevant study by Coopman and Tan (2023). We have added the following text to acknowledge this important application:

  “Satellite observations have also been used to characterize the spatial distribution of thermodynamic phase within mixed-phase clouds. For example, Coopman and Tan (2023) used DARDAR observations to quantify the spatial homogeneity of liquid and ice within mixed-phase clouds and examined their relationships with meteorological and aerosol conditions. The degree of phase homogeneity is relevant to mixed-phase cloud microphysical processes, radiative effects, and lifetime. Nevertheless, systematic global comparisons of mixed-phase cloud occurrence and properties among cloud types remain limited.”

- Line 155: What months does the dataset start and end during the years 2006-2010?

  Reply: The analysis period is June 2006 through December 2010, beginning with the first month of available CloudSat observations and ending before the 2011 battery anomaly and subsequent daytime only sampling. We have clarified the exact temporal coverage in the revised manuscript as follows:

  “The analysis is based on CloudSat observations from June 2006 through December 2010.”

  As a sensitivity check, we also repeated the analysis using only the complete calendar years 2007–2010 and found nearly identical global mean occurrence and spatial patterns. Specifically, the global mean identified mixed-phase cloud occurrence changed only from 18.46% to 18.45%, corresponding to a relative difference of approximately 0.05%. We therefore retain the June 2006–December 2010 period.

- It was stated that MODIS daytime LWP values were used in the analysis. But what if MODIS and 2B-CLDCLASS-LIDAR do not agree on the cloud phase? How do the authors determine which cloud phase is correct or do they reject that data point and exclude it from the analysis?

  Reply: We thank the reviewer for raising this issue. We do not reconcile the MODIS and 2B-CLDCLASS-LIDAR phase classifications because they serve different roles in this analysis. Cloud phase and cloud type are determined solely from the 2B-CLDCLASS-LIDAR product, whereas the MODIS phase classification is used only to screen the LWP retrievals shown in Fig. 3 column 2. Specifically, MODIS cloud water path is retained as LWP only when the MODIS optical-properties phase flag classifies the collocated pixel as liquid and the water-path retrieval is valid. This phase flag does not include a mixed-phase category. Therefore, when a CloudSat/CALIPSO mixed-phase cloud is classified as ice or undetermined by MODIS, the MODIS water-path retrieval is excluded from the LWP statistics, but the cloud remains classified as mixed phase and is retained in the CloudSat/CALIPSO occurrence and cloud-geometry analyses. Consequently, the MODIS LWP values in Fig. 3 column 2 represent a conditional subset of the CloudSat/CALIPSO mixed-phase cloud population.

  We have added the following text in Sect. 2.2 to clarify:

  "For the LWP analysis, only single-layer daytime mixed-phase profiles are retained to reduce ambiguity in interpreting MODIS LWP retrievals under multilayer cloud conditions. MODIS cloud water path is retained as LWP only when the MODIS optical-properties phase flag classifies the collocated pixel as liquid and the water-path retrieval is valid. The MODIS phase classification is used only to screen the LWP retrieval and does not alter the cloud phase or cloud type determined from 2B-CLDCLASS-LIDAR."

  We have also expanded the discussion of Fig. 3 column 2 to clarify the resulting sampling and retrieval limitations of the MODIS LWP statistics.

- Figure 1: The "potential" mixed-phase cloud definition based simply on temperature range does not seem useful to show

  Reply: We thank the reviewer for this comment. We originally included the "potential" mixed-phase cloud panel as a thermodynamic reference to illustrate that the population of clouds occurring within the −40 to 0 °C temperature range is substantially larger than the population in which mixed phase is actually identified, emphasizing the complexity of cloud phase within this temperature range. However, we agree that this temperature-based diagnostic is not central to the subsequent cloud-type-dependent analyses in this study. To keep the manuscript focused and avoid potential confusion, we have removed this panel from Fig. 1 and the associated discussion.

- Passage describing Figure 8: this is somewhat redundant with previous passages. Can this be condensed to be more concise especially since the word length is somewhat long (main text well exceed 700 lines)?

  Reply: We agree with the reviewer that the original discussion of old Fig. 8 (now Fig. 7) was somewhat redundant with parts of the discussion of Figs. 5 and 6. We have substantially condensed this passage, retaining primarily the information that is complementary to the preceding analyses, particularly the land/open-ocean contrasts and differences in the seasonal cycle of integrated occurrence among cloud types.

- Methods and uncertainty: What is the penetration depth of both lidar and radar? Can the authors provide statistics on what percentage of clouds were multilayer and how retrievals were treated in their analysis? Were any quality control flags considered and filtered out in their analysis?

  Reply: We thank the reviewer for raising these methodological questions.

  Neither CALIOP nor the CloudSat CPR has a fixed geometric penetration depth, since penetration depends on cloud optical and microphysical properties. For CALIOP, the lidar signal is typically fully attenuated after approximately five optical depths from cloud top (Mace and Zhang, 2014). In contrast, the 94 GHz CPR generally penetrates optically thick clouds much more effectively, although attenuation can become substantial in strongly precipitating clouds. The complementary radar and lidar observations therefore provide more complete information on cloud vertical structure than either sensor alone, including multilayer clouds, although some underlying cloud layers may still be missed. We added the following sentence in Sect. 2.4: "The CALIOP signal is typically fully attenuated after approximately five optical depths from cloud top (Mace and Zhang, 2014)."

  Multilayer cloud profiles are retained in the CloudSat/CALIPSO analyses, with their treatment depending on the type of analysis. To quantify the prevalence of multilayer clouds in our dataset, we have added the following text to the discussion of Fig. 1: "Multilayer clouds constitute a substantial fraction of the identified mixed-phase cloud population: 43.5 % of profiles containing mixed-phase clouds contain multiple detected cloud layers. For profiles containing mixed-phase As, Ac, St+Sc, Cu, and Ns+DC, the fractions that contain multiple detected cloud layers are 57.3 %, 63.8 %, 33.5 %, 57.6 %, and 33.5 %, respectively." We have also clarified their treatment in Sect. 2.3: "For spatial distributions of mixed-phase cloud occurrence, occurrence is calculated at the profile level as the number of CloudSat profiles containing at least one mixed-phase cloud layer divided by the total number of observed profiles within a given bin. Each profile is counted at most once for the overall mixed-phase cloud occurrence and at most once for

each cloud-type category, regardless of the number of mixed-phase layers of that type within the profile. Thus, a profile containing more than one mixed-phase cloud type may contribute to multiple cloud-type categories. For cloud geometry and vertically resolved mixed-phase occurrence, the analysis is performed at the layer level. Individual mixed-phase cloud layers within multilayer profiles are retained according to their cloud type and vertical extent, while non-mixed-phase layers within the same profile do not contribute to the mixed-phase cloud statistics."

We have also clarified the treatment of multilayer clouds for the MODIS LWP analysis in Sect. 2.2 by adding: "For the LWP analysis, only single-layer daytime mixed-phase profiles are retained to reduce ambiguity in interpreting MODIS LWP retrievals under multilayer cloud conditions."

Regarding quality control, the analysis excludes invalid or missing values required for the corresponding calculations but does not apply additional screening based on the confidence field provided in 2B-CLDCLASS-LIDAR. We have clarified this in Sect. 2.3 by adding: "Invalid or missing cloud type, cloud phase, cloud top and base height, and ancillary values required for the corresponding analyses are excluded. No additional screening based on the 2B-CLDCLASS-LIDAR confidence field is applied."

- Line 315: I do not consider IWP a cloud "microphysical" property. It's a macrophysical property.

  Reply: We agree with the reviewer. We have replaced the term "microphysical" to "macrophysical" when it refers to IWP and LWP. We have revised this sentence to: "Macrophysical differences are also evident in LWP and IWP."

- Figure 3: Why do Cu clouds consistency have similar LWP as Ns + DC clouds (a2, b2, c2)? I would expect Cu clouds to have much lower LWP than those of Ns + DC clouds.

  Reply: We thank the reviewer for raising this point. The expectation that Cu should generally have lower LWP than Ns+DC is reasonable when considering the full populations of these cloud types. However, the LWP values shown in Fig. 3 represent subsets of the CloudSat/CALIPSO mixed-phase cloud populations. MODIS LWP is retained only for single-layer daytime mixed-phase clouds for which the collocated MODIS pixel is classified as liquid and has a valid cloud-water-path retrieval.

  For vertically extensive Ns+DC clouds, this selection is particularly restrictive because many have ice-dominated cloud tops. Only approximately 19.8% of the single-layer daytime mixed-phase Ns+DC population has a valid MODIS LWP retrieval, so the Ns+DC LWP statistics represent a limited liquid-retrievable subset rather than the full Ns+DC population. Furthermore, MODIS LWP is inferred from retrieved cloud optical

thickness and effective radius under a single-phase retrieval framework, introducing additional uncertainty for vertically heterogeneous mixed-phase clouds. The MODIS optical-property retrieval also reports cloud optical thickness only up to 150, which could further constrain retrieved LWP for very optically thick Ns+DC clouds; however, we have not explicitly evaluated how frequently this limit is reached in our dataset.

The 2B-CLDCLASS-LIDAR Cu category includes shallow cumulus and cumulus congestus. The Cu included in this study must extend into the mixed-phase temperature range. They can therefore be substantially deeper and contain more condensate than typical shallow Cu. These sampling characteristics and retrieval limitations may help explain why Cu and Ns+DC show similar MODIS LWP in Fig. 3.

We have added a concise clarification to the discussion of Fig. 3:

"The relatively similar MODIS LWP of Cu and Ns+DC should be interpreted cautiously because both statistics represent conditionally sampled subsets. Both are subject to the MODIS liquid-phase screening; in addition, the mixed-phase Cu sample is restricted to Cu extending into subfreezing temperatures and can include cumulus congestus, whereas the liquid-phase screening is particularly restrictive for Ns+DC with ice-dominated cloud tops."

- 332-333: Could the higher IWP in the NH compared to SH be due to the presence of INPs? See e.g. the satellite study of Tan et al. 2014 (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013JD021333) on temperature vs aerosol (INP) effects. "Surface-type" and "aerosol loading" on line 335 are mentioned, but that can also be connected to not only aerosol loading but also aerosol type (whether they act as CCN or INPs).

  Reply: We thank the reviewer for this suggestion. We agree that aerosol type and ice-nucleating ability, rather than aerosol loading alone, may be relevant to the hemispheric differences. Tan et al. (2014) found that temperature has the dominant influence on supercooled liquid cloud fraction, but that at fixed mixed-phase temperatures, higher frequencies of dust and polluted dust are associated with lower supercooled cloud fractions, consistent with a role of these aerosol types in ice nucleation. This suggests a plausible pathway through which differences in INP sources could contribute to the hemispheric contrasts observed here. We have revised the corresponding text as follows:

  "These hemispheric contrasts may be influenced by differences in surface-type distribution (more land in the NH versus more open ocean in the SH), aerosol abundance and type, including their ability to act as cloud condensation nuclei (CCN) or ice-nucleating particles (INPs), and large-scale dynamical environments, although they are generally smaller than the variations among cloud types. In particular, the greater continental influence in the NH may provide more sources of efficient INPs, such as

mineral dust, which could influence ice production and contribute to the observed IWP differences (Tan et al., 2014).”

- Lines 450-453: This summary only addresses meteorological effects on cloud type formation but not aerosol effects. Please also consider aerosol effects as well.

  Reply: We thank the reviewer for this suggestion. We agree that the original summary emphasized meteorological controls and did not sufficiently acknowledge potential aerosol influences. Previous studies have shown that aerosol abundance and type can affect mixed-phase clouds through their roles in droplet activation and ice nucleation. Tan et al. (2014) found that, although temperature is the dominant influence on supercooled cloud fraction, at fixed mixed-phase temperatures, higher frequencies of dust and polluted dust are associated with lower supercooled cloud fractions. Stauffer et al. (2025) found that meteorological conditions largely control properties of Arctic mixed-phase stratiform clouds, while aerosol influences are important for understanding differences in the responses of liquid and ice water. We have added the following text:

  “Aerosol abundance and type may also modulate these cloud-type-dependent patterns through their roles as CCN and INPs, affecting droplet activation, ice nucleation, phase partitioning, and cloud persistence (Tan et al., 2014; Stauffer et al., 2025). Because aerosol properties are not explicitly analyzed here, their contribution to the observed seasonal patterns cannot be separated from the meteorological influences considered above.”

- Figure 4: I found this plot confusing not only because of how the double x-axes should be interpreted in relation to each other but also because I am unsure why only As + Ac and St + Sc were arbitrarily selected for the “fraction” axis and the other categories ignored or not grouped together.

  Reply: We thank the reviewer for this comment. The phase-fraction curves were originally included as an illustrative comparison between mid-level stratiform clouds (As+Ac) and low-level stratiform clouds (St+Sc). We focused on these two stratiform categories because their phase partitioning relative to cloud-top temperature is more straightforward to interpret than for Cu and Ns+DC, for which cloud-top temperature may be less representative of the vertical distribution of liquid and ice. However, we agree that displaying only these two grouped categories, together with a second x-axis, complicates the figure and can make the selection appear arbitrary. Because a detailed phase-partitioning analysis is not central to the present study, we have removed the phase-fraction curves and the corresponding top x-axis from Fig. 4, as well as the

associated discussion. Figure 4 now focuses on the phase-resolved cloud occurrence as a function of cloud-top temperature for all five cloud types using a single x-axis.

- In Figures 4, 6, 8, and 9 I recommend replacing "T" with "CTT" so that the reader is clear that this is cloud-top temperature and not the mean cloud layer temperature at the resolution of the satellite product.

  Reply: We thank the reviewer for the suggestion and have replaced "T" with "CTT" for the relevant figures.

- Line 577-579: Are these MCAO clouds?

  Reply: We thank the reviewer for pointing this out. We agree that MCAOs are likely an important contributor to the strong cold-season open-ocean St+Sc occurrence, although MCAO events are not explicitly identified in our analysis. We have clarified this point in the revised manuscript:

  "The much stronger cold-season oceanic occurrence is consistent with an important contribution from marine cold-air outbreaks (MCAOs), during which cold air moving over relatively warm ocean generates strong surface sensible and latent heat fluxes that promote marine boundary-layer cloud formation (Fletcher et al., 2016; Murray-Watson et al., 2023)."

- In my opinion, Figure 7 does not add much more novel/interesting information to the analysis/manuscript and recommend moving it to the Supporting Information.

  Reply: We agree with the reviewer that Fig. 7 provides complementary rather than central information relative to the cloud top temperature analysis in Fig. 6. We have therefore moved this figure to Appendix A as Fig. A1 and substantially condensed the associated discussion. In the main text, we now retain only a brief reference to the height coordinate analysis and its main complementary interpretation:

  "Corresponding distributions in cloud-top-height coordinates are shown in Appendix A (Fig. A1). These results generally support the cloud-type-dependent vertical structures inferred from Fig. 6 and indicate that some hemispheric differences in cloud top temperature reflect differences in background thermal structure rather than corresponding differences in cloud top height"

- Figure 9 caption: It would be clearer and more concise to write that the caption here is the same as that for Figure 8 except for 45S-75S.

Reply: We agree with the reviewer. We have shortened the figure caption to "Same as Fig. 8, but for 45°S–75°S latitude band; columns 1 and 2 show results over open ocean and sea ice, respectively."

- Line 724-730: The implications of the results are discussed here, though the information it draw on is perhaps outdated about the cloud phase bias in global climate models, but also does not address novel ways that the dataset can be used. One example is a new method that was developed to diagnose how changing cloud types/regimes/weather states influence cloud feedback that can be applied to evaluate climate models as well (Zelinka et al. 2023 https://link.springer.com/article/10.1007/s00382-022-06488-7 and Tan et al. 2024 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023JD040540)

  Reply: We thank the reviewer for this suggestion. We agree that the discussion should reflect recent progress in the representation of mixed-phase clouds in climate models and better highlight potential applications of the cloud-type-dependent climatology developed here. We have revised this discussion accordingly and incorporated the regime-based cloud-feedback approaches of Zelinka et al. (2023) and Tan et al. (2024).

  We revised the corresponding discussion as follows:

  "The results also have implications for model evaluation. Although the representation of cloud phase partitioning has improved from CMIP5 to CMIP6, substantial intermodel spread remains in simulated phase partitioning and its associated radiative effects. The cloud-type-dependent differences identified here provide an additional dimension for model evaluation beyond bulk or temperature-dependent phase statistics. Recent regime-based approaches separate cloud feedback into contributions from changes in cloud properties within individual regimes and changes in the frequency of occurrence of different regimes (Zelinka et al., 2023; Tan et al., 2024). Such an approach could be extended to cloud-type-resolved model analyses to distinguish changes in mixed-phase properties within individual cloud types from changes in their frequency of occurrence. The climatology developed here provides observational benchmarks for the occurrence and properties of these cloud types, which can support evaluation of their representation in climate models."

- Can the authors comment on future satellite missions such as VIIRS/EarthCARE in the context of extending their record or what the newer generation of satellites can reveal in terms of cloud type-based analyses of mixed-phase cloud properties?

  Reply: We thank the reviewer for the suggestion. We have added a discussion of how VIIRS and EarthCARE could contribute to extending and advancing cloud type-based analyses of mixed-phase clouds.

“New and continuing satellite observations provide complementary opportunities to extend and advance this analysis. The NASA MODIS–Visible Infrared Imaging Radiometer Suite (VIIRS) Continuity Cloud Properties products apply a common retrieval framework to Aqua MODIS and Suomi National Polar-orbiting Partnership (SNPP) VIIRS observations, providing continuity for passive cloud properties such as cloud phase, optical thickness, effective radius, and cloud water path (Platnick et al., 2021). These products can help extend the passive cloud-property record relevant to the present analysis. The Earth Cloud, Aerosol and Radiation Explorer (EarthCARE) provides a new generation of active radar-lidar observations following CloudSat/CALIPSO, with a 94 GHz CPR and a 355 nm high-spectral-resolution Atmospheric Lidar (ATLID) (Illingworth et al., 2015; Wehr et al., 2023). EarthCARE observations therefore provide an opportunity to continue and extend cloud-type-dependent analyses of mixed-phase clouds, although differences in sensor characteristics and retrieval and classification methods need to be considered. In addition, the Doppler capability of the EarthCARE CPR provides information on the vertical motion of cloud and precipitation particles. Together with other CPR measurements and retrievals, this capability could allow cloud-type-dependent mixed-phase cloud structure to be examined in relation to dynamical and precipitation characteristics.”

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