Response to Reviewer 1 Comments

Thank you for your letter commenting on our manuscript entitled "***Innovative Cloud Quantification: Deep Learning Classification and Finite Sector Clustering for Ground-Based All Sky Imaging***" (MS No.: egusphere-2024-678). These comments are valuable and very helpful for the revision and improvement of our paper. We have carefully studied and made corrections, and hope to get your approval. The main changes of the paper and the responses to the review comments are as follows.

Comments 1: *By proposing this topic, the authors should know that the definition of clouds is challenging and observations of clouds from different instruments vary a lot, making cloud information uncertain. This brings a serious issue: how could the authors provide the true information for the training? Note that this question is general for all cloud identification studies.*

Response 1: Thank you very much for raising the issues of uncertainty in cloud definition and the potentially large differences in cloud information obtained by different observational instruments. In this study, we are fully aware of the difficulties posed by cloud definition and observation consistency, and have taken a number of measures to minimize the resulting uncertainties:

1. Data source and instrument calibration: The cloud observations we use come from ground-based all-sky imagers that have been rigorously calibrated to ensure the reliability and consistency of the underlying data. Meanwhile, we refer to the cloud classification standard of the International Meteorological Organization (WMO) to ensure that the definition of cloud types is accurate.

2. Multi-source data fusion and cross-validation: Although there may be errors in single instrument observations, we try to integrate data from different time periods and multiple observation platforms to reduce the bias caused by a single source through cross-validation, and strive to build a high-quality training set that contains a variety of typical cloud features.

3. Expert labeling and manual review: We invited meteorological experts to participate in the labeling process of cloud images to ensure that the training samples are accurately labeled. Meanwhile, the model prediction results were manually reviewed to further confirm the consistency between the cloud features learned by the model and the actual cloud patterns.

4. Adaptive and robust model design: To cope with changes in cloud morphology and lighting conditions, we developed adaptive segmentation and classification strategies and introduced image enhancement algorithms to ensure stable model performance in complex environments and minimize the impact of observational uncertainty on recognition results.

5. Validation and Comparison: Through comparison tests with the publicly

available dataset TCI, we confirm that the proposed method achieves a level higher than 98% in cloud classification accuracy, which indirectly verifies the validity and accuracy of the training data and the model we provided.

Thank you again for your valuable comments, which are extremely important guidance for our research.

Comments 2: *Regarding the importance of clouds, particularly on the radiation balance via its radiative forcing, a recent review study by Zhao et al. (2023, doi: 10.1016/j.atmosres.2023.106899) is worthy to mention here.*

Response 2: Thank you very much for your valuable comments and recommended literature, as you pointed out that the relevant studies on the importance of clouds in the radiative balance, especially through their radiative forcing, recently published in "Atmospheric Research" by Zhao et al. (2023, DOI: 10.1016/ j.atmosres.2023.106899) provides us with the latest research results and insights. Based on your suggestion, we have added the following to the Introduction's section on the background and significance of the study:

"It is noteworthy that the critical role of clouds in the Earth's radiation balance has been further emphasized and empirically demonstrated in recent years. For example, Zhao et al. in their recent review explored in detail the impact of clouds on the global climate system through radiative forcing mechanisms, revealing how clouds act as a dynamic feedback system that can have a significant impact on the global radiation balance by playing a cooling role through blocking solar shortwave radiation as well as bringing a warming effect by absorbing and re-emitting longwave radiation (Zhao et al. 2023), this study reinforces the importance of quantitative cloud analysis for understanding and predicting climate change."

Thank you again for your review and suggestions, which certainly enhanced the academic rigor and relevance of this paper.

Comments 3: *For sentence "In essence, clouds serve as an important "sunshade" to maintain the balance of the greenhouse effect and prevent overheating of the Earth": while the sentence is definitely correct, it is fair to mention the net cooling effect of clouds globally.*

Response 3: Thank you for your valuable suggestion that the issue of the net cooling effect of clouds should be mentioned, and we recognize that this point should be fully and accurately expressed. In order to improve the description of the article, we have revised the corresponding part of the original article as follows:

Original sentence, "Essentially, clouds act as a key 'sunshade' that maintains the balance of the greenhouse effect and prevents the Earth from overheating."

Revised Sentence: "Clouds act as an important barrier in regulating the Earth's energy balance on a global scale, helping to prevent the Earth's surface from overheating, while also acting as a significant net cooling effect due to their nature of reflecting, absorbing, and emitting solar radiation, playing an integral role in the overall temperature regulation of the planet."

In subsequent discussions, we will further elucidate this net cooling effect produced by clouds under different circumstances, as well as their complex interactions on the global climate and radiation balance, to ensure that readers gain a more comprehensive understanding.

Comments 4: *For sentence "For instance, high-level cirrus clouds mainly contribute to reflection and scattering, while low-level stratus and cumulus clouds more so cause the greenhouse effect": This is wrong, since high cirrus clouds play warming (greenhouse) effect and low clouds play cooling effect.*

Response 4: Thank you very much for catching the inaccuracies in my presentation of the effect of clouds on the Earth's radiation balance during your review. You are correct in pointing out that high altitude cirrus clouds actually exert a greenhouse effect, while lower stratus and cumulus clouds exert more of a cooling effect. Due to an oversight on my part that resulted in the description of these two cloud effects in the original article not matching the actual situation, we have corrected the corresponding sentence in the paper and the new formulation is as follows:

Original sentence: "For example, high-level cirrus clouds affect the radiative balance mainly through reflection and scattering effects, while low-level stratocumulus and cumulus clouds contribute more to the greenhouse effect."

Revised Sentence: "For example, high altitude cirrus clouds actually contribute to the warming (greenhouse) effect on the Earth's radiation balance due to their stronger absorption and re-emission properties of longwave radiation, whereas low level stratus and cumulus clouds usually exhibit a cooling effect due to their good reflection and shading of solar shortwave radiation."

Thank you again for your careful review and valuable comments, which play a vital role in improving the quality of the paper, and we will take this as an opportunity to more carefully check every scientific statement in the text to ensure the accuracy and completeness of the content. If you have any other comments or suggestions, please feel free to continue to put forward, so that we can further improve the paper.

Comments 5: *For sentence "Moreover, there are considerable regional disparities in cloud amount, and pronounced differences exist in regional climate characteristics": There are many studies regarding the regional variations of clouds which are worthy to refer here, such as a most recent study by Chi et al. (2024, doi: 10.1016/j.atmosres.2024.107316).*

Response 5: Your professional comments on the presentation of the paper regarding regional variability in cloud cover and its relationship with climate characteristics are sincerely appreciated. You pointed out that more studies on regional cloud amount variability should be cited to support this argument, especially the recent study by Chi et al. (2024) published in the journal (Atmospheric Research) (doi: 10.1016/j.atmosres.2024.107316). Based on your suggestion, we have revised the relevant sections and added the important research results of Chi et al. as references. Here is the revised sentence:

Revised sentence: "There are large differences in cloudiness among different locations and significant differences in regional climatic characteristics, Globally, clouds over the oceans occur more frequently than over land, but the situation is reversed for cloud systems with more than two layers; seasonal variations in the global mean total cloud fraction are small but large among different latitudinal zones (Chi et al. 2024)."

In addition, we will cite the Chi et al. study in detail at the appropriate places in the text, summarizing and discussing their findings in order to flesh out and strengthen the strength of the argument in this section.

Comments 6: *For image processing techniques used for cloud detection, previous studies should be introduced and cited, to identify the creativity of this study.*

Response 6: Thank you very much for your valuable suggestions. In the revised manuscript, we have fully recognized the importance of citing previous research to highlight the innovativeness of this study and have provided a detailed description and literature references of existing image processing techniques for ground cloud detection. The following is an overview of what we have added to the article:

"In the field of meteorology and remote sensing, cloud detection and identification have been the core and challenge of research. The current mainstream ground-based cloud detection methods mainly include two categories: traditional image processing techniques and deep learning-based techniques (Hensel et al., 2021). Traditional threshold segmentation and texture analysis methods rely on manually extracted features that are less adaptable in dealing with atypical situations; while deep learning methods are able to automatically learn features for superior performance."

Our research falls into the latter category and highlights the following innovations in particular: designing an adaptive segmentation strategy for different cloud types, which improves partitioning accuracy by extracting representative features by setting the segmentation parameters according to the cloud morphology; introducing an adaptive image enhancement algorithm, which significantly improves the detection results, especially in the regions near the sun where the light influence is strong, and outperforms the traditional Normalized Differential Reflectance (NRBR) segmentation method; the use of multilevel refinement technique improves the ability to capture the details of the edges and bottoms of various types of clouds, and enhances the adaptability to a wide range of cloud types under complex illumination conditions. We have not sufficiently discussed some specific image processing techniques used in previous studies and their limitations before, to compensate for this, in the subsequent revisions, we will compare and cite related studies in detail in order to further clarify the contribution of this study to the technological innovation of cloud detection. For example, the performance and limitations of methods such as the traditional threshold analysis method in specific scenarios will be described in detail, and the specific improvement measures and innovations of this study in terms of precise quantification of cloud amount and enhancement of classification accuracy will be clarified in comparison with the YOLOv8 model, adaptive segmentation strategy, and the cloud detection process combining the finite sector technique and k-means clustering adopted in this study.

Thank you again for your professional guidance, and we will incorporate the above additions when revising the paper to ensure that both the originality and innovativeness of this research work are reflected, and that research results in existing fields are fully respected and referenced.

Comments 7: *There are multiple previous cloud classification methods, including the machine learning algorithm, texture feature extraction, and so on, most recent studies should be mentioned or referred.*

Response 7: Thank you for your valuable suggestions on the scope of references to cloud classification methods in our study. In order to better highlight the innovation and rigor of this research, we have carefully reviewed and updated the descriptions and references to previous cloud classification methods in the text to reflect the latest research results and technological advances.

Based on the original text, we have highlighted the applications of machine learning algorithms in cloud classification in recent years. In particular, it is pointed out that Convolutional Neural Networks (CNNs) excel due to their ability to learn increasingly complex patterns and cloud texture properties from large-scale pre-training datasets, which addresses the shortcomings of traditional methods in characterizing and extracting cloud texture features. CNNs are able to capture the subtle textures of clouds, such as edges and shapes, using their hierarchical feature extraction framework, which leads to the effective classification of complex cloud patterning (Citation: Yu et al., 2020).

We also detail the wide application of unsupervised learning methods, especially k-means clustering, in cloud segmentation and recognition tasks. Several studies have utilized k-means models to rapidly cluster and identify clouds and clear-sky regions in all-weather imagery, significantly improving the speed and efficiency of cloud computation (Citation: Krauz et al., 2020). These unsupervised learning techniques simplify the workflow of cloud image analysis by autonomously discovering data category structure without manual annotation. In this study, we take full advantage of deep learning to realize the classification of four typical cloud types for the whole year of 2020 at the Yangbajing Observatory on the Tibetan Plateau with an accuracy of more than 95% through a customized version of the YOLOv8 architecture. Moreover, we innovatively designed a set of adaptive segmentation strategies for different cloud types, which significantly improved the performance of cloud classification and quantification under complex lighting environments by setting the segmentation parameters according to the cloud body morphology as well as eliminating the sunlight interference with an adaptive image enhancement algorithm.

In light of your suggestion, we further enhance the citations of recent related studies, including but not limited to Zhang et al. (2018), Li et al. (2022b), Ma et al. (2021), Zhu et al. (2022), Gyasi and Swarnalatha. (2023), Li et al. (2017), He et al. (2018), Rumi et al. (2015), and Wu et al. (2021) on cloud classification, covering methods such as manual identification, threshold segmentation, texture feature extraction, and satellite remote sensing, etc., and analyzing in detail the strengths and limitations of the respective methods, so as to enable readers to better understand the role of the present study in solving the problem of climate scientific research in addressing the need for large number of fine cloud datasets with unique value and technological innovation.

We will continue to monitor the latest progress in this field and add and update the corresponding literature citations in the final manuscript to ensure that the current state of the art in cloud classification technology and the unique contributions of this study are fully presented.

Comments 8: *Laser radar does not necessarily have large equipment size.*

Response 8: With regard to your reference to the fact that LIDAR does not necessarily have the dimensions of a large-scale device, we fully share your viewpoint. In the original presentation, the general characteristics of LIDAR systems may have been described in too general a manner, ignoring the development trend and technological progress of individual miniaturized or portable LIDARs. Therefore, we will clarify and correct the dimensions and forms of LIDAR in the corresponding section to ensure the accuracy of the presentation.

Original: "Laser radar emits sequenced laser pulses and estimates cloud vertical structure and optical depth from the backscatter to directly quantify cloud amount, but has large equipment size, high costs, limited coverage area, and cannot produce cloud distribution maps."

Revised sentence: "Lidar can directly quantify cloud amount by emitting sequential pulsed lasers and estimating cloud vertical structure and optical thickness from the backscatter information. While miniaturized or even portable Lidar equipment exists in the market, these instruments have high costs and limited coverage area in the all-sky cloud image recognition method involved in this study."

Thank you again for your efforts to improve the quality of the paper, and we will make sure that the amended text reflects more objectively and fairly the characteristics and development of LiDAR technology.

Comments 9: *"with relatively good air quality and low atmospheric pollution levels": I think using "with relatively good air quality" is enough.*

Response 9: Dear reviewer, regarding the descriptive problem you pointed out, you think that the expression "relatively good air quality" is sufficient to express "the region has relatively good air quality", and there is no need to mention the additional phrase "low air pollution levels". There is no need to refer to "low levels of air pollution". We agree that this is a more concise and clearer expression that can directly convey the key message. Therefore, we have revised the original draft as follows:

Revised sentence: "The Yangbajing area is far away from industries and cities, and the air quality is relatively good, which can reduce the impact of atmospheric pollution on cloud observation"

Thank you again for your careful guidance, which has helped to improve the quality of our paper.

Comments 10: *Table 1: "Measure cloud distance" is better as "Measurable cloud distance"*

Response 10: Thank you very much for your careful review of the table in the manuscript and your valuable suggestions. In response to your suggestion, we fully accept it and change the title of the column "Measure cloud distance" to "Measurable cloud distance" to more accurately reflect the actual meaning of the indicator, i.e., the maximum distance range of cloud cover that can be measured by the equipment. The column heading of "Measure cloud distance" will be changed to "Measurable cloud distance" to more accurately reflect the actual meaning of the indicator, i.e., the maximum range of cloud distance that can be measured by the device. The revised table is shown below:

Function	Description
Measurable cloud distance	0~10Km
Measuring range	Elevation angle above 15°
Observation periods	Observe every 10 minutes
Horizontal visibility	≥2km
Operating temperature	-40°~50°
Sensor	CMOS
Image resolution	4288 × 2848
Operational durability	24 h operation
Ingress protection	IP65

We value your review comments and have revised the manuscript accordingly, as appropriate, to enhance the rigor and accuracy of its presentation.

Comments 11: *3.2.3: Have similar indicators been used by other studies? If have, a few reference could be helpful.*

Response 11: Thank you very much for your valuable comments on the use of evaluation metrics in Section 3.2.3. Comparison and citation of similar evaluation metrics used in similar studies is essential to validate the reliability and validity of the methodology of this study. During the cloud classification performance evaluation process, we did adopt the industry widely recognized metrics of Precision, Recall and F1 score, which have been used in several previous studies to measure the performance of cloud classification systems, e.g., studies such as (Dev et al., 2017; Guo et al., 2024) have used similar evaluation system. In the revised manuscript, we will explicitly point this out and cite relevant literature to support the rationality of our choice of these metrics, demonstrating the consistency and comparability of this study with existing work.

The following are examples of some of the reference citations that are planned to be included:

1. Dev, S., Lee, Y. H., and Winkler, S.: Color-Based Segmentation of Sky/Cloud Images From Ground-Based Cameras, IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., 10, 231-242, 10.1109/JSTARS.2016.2558474, 2017. Precision, recall were also used as one of the criteria for evaluating the performance of cloud segmentation algorithms in that study.

2. Guo, B., Zhang, F., Li, W., and Zhao, Z.: Cloud Classification by Machine Learning for Geostationary Radiation Imager, IEEE Trans. Geosci. Remote Sens. . , 62, 1-14, 10.1109/tgrs.2024.3353373, 2024. where metrics of precision, recall, and F1 score are used to evaluate cloud classification models.

Through literature citation and illustration, we believe that we can better demonstrate that the evaluation metrics chosen in this study are consistent with peer studies and facilitate readers in understanding and evaluating the results of this study in the cloud classification task.

Comments 12: *3.4: As indicated, a proper K value is important for K-means method. How do the authors choose their K values?*

Response 12: Thank you very much for your attention and guidance in submitting the paper on the issue of K-value selection in K-mean clustering methods. In Section 3.4, we indeed did not fully elaborate the process of determining the K-value, for which we apologize and will add and improve it in the revised manuscript with the following modifications:

After obtaining the cloud type adaptive segmented images, for the K-mean clustering within each sector, we executed several trials to determine the optimal K-value. The specific selection process is as follows:

(1) Initial estimation: a preliminary K-value setting is performed based on the complexity of the observed data and the expected number of clustering categories (e.g., sky, cloud, and background).

(2) Iterative optimization: By implementing the K-mean algorithm and observing the clustering results, the K-value is adjusted according to the actual clustering effect until the clustering results are stable, i.e., the clustering centers are no longer significantly changed between several adjacent iterations (Dinc et al., 2022).

(3) Evaluation indexes: using clustering effectiveness indexes such as contour coefficient, Calinski-Harabasz index, Davis-Boulding index, etc., the clustering results under different K-values are evaluated, and the K-values that make the evaluation indexes optimal are selected.

(4) Evaluation index: Combining the knowledge and practical experience of meteorological experts, the selected K-values are tested for their rationality to ensure that they are in line with the principles of meteorology and actual observation.

In this study, for the task of cloud quantification and classification of all-sky images in the Yangbajing area, we chose k=5 as the hyperparameter of the clustering algorithm, which is based on a series of rigorous experimental analyses and the conclusion of practical effect evaluation. Through the trial and error and cross-validation of a large number of sample data, we found that when k is set to 5, the clustering results can most effectively distinguish the blue sky, the white cloud layer, the transition zone and possible ground or near-ground occlusions, thus achieving the desired segmentation effect. We also draw on the a priori knowledge in the field about the identification of cloud amount and cloud features, and combine it with the field observation data to ensure that the selected k value matches the actual physical phenomena. The clustering strategy is able to maintain a high level of robustness and identification effectiveness under a variety of lighting dynamics in the Yangbajing area, where the lighting conditions are complex and changeable.

In the revised manuscript, we will document and clearly articulate this selection process for readers and peer reviewers.