
Title: Study on the life cycle of an ice cloud system over the Taklamakan desert using multi-source data

Corresponding authors: Haiyun Xia; hsia@ustc.edu.cn; University of Science and Technology of China

---

Dear Editors

On behalf of the co-authors, thank you for giving us an opportunity to revise the manuscript. We appreciate the great efforts and constructive comments from the reviewers, which improve the quality of the manuscript significantly. We have revised the manuscript carefully according to the reviewers' comments and suggestions. Our point-by-point responses are appended below. All changes made in the revised manuscript are marked in light blue. Attached please find the revised version of the manuscript, which we would like to submit for your kind consideration. We are looking forward to hearing from you!

Best regards!

Sincerely yours,

Haiyun Xia
School of Earth and Space Science
University of Science and Technology of China.
Hefei, Anhui, CHINA, 230026.

Reviewer #2:

Comments and Suggestions for Authors:

Major comments:

1. The study's strength lies in its multi-source data approach. However, a more thorough cross-validation and uncertainty quantification between different datasets (e.g., FY-4A, Himawari-8, CDWL) regarding key parameters like cloud phase and height would significantly enhance the robustness of the findings. For instance, beyond noting that FY-4A might misclassify some ice clouds as mixed-phase, quantifying the impact of such discrepancies on the defined life cycle stages would be valuable..

Response: We sincerely appreciate your positive feedback on our multi-source data approach and your highly valuable suggestion regarding cross-validation and uncertainty quantification. We completely agree that quantifying the uncertainties between datasets would significantly enhance the robustness of our findings. However, performing a strict pixel-level or quantitative cross-validation in this specific study is highly constrained by several objective factors:

(1) Spatiotemporal and Geographical Limitations of Himawari-8: The AHI sensor on Himawari-8 relies on visible bands to distinguish clouds and near-infrared bands to differentiate water and ice clouds, meaning its cloud type products are only available during the daytime (with a 10-minute temporal and 5 km spatial resolution). Considering the sunrise time at the study site (valid data available only after 10:00 LT) and observational errors, we have less than 1 hour of valid Himawari-8 data during the non-decomposed ice cloud phase (as shown in Fig. 5a). More importantly, the observation range of Himawari-8 is 60°S-60°N, 80°E-160°W. Our study site (37.06 °N, 82.69 °E) is located at the extreme outer edge of this detection region. Consequently, the cloud type parameter at the study site is frequently a null value, making phase identification heavily dependent on neighboring pixels.

(2) Observational Scale Discrepancies: FY-4A's AGRI sensor covers the entire study region with a 5-minute temporal and 4 km spatial resolution. Conversely, the CDWL utilizes a VAD scanning mode, which acts as a localized, single-point vertical observation. There is a significant scale discrepancy between the satellite's macroscopic grid and the lidar's localized point data.

(3) Inherent Algorithm Uncertainties: As pointed out by Lai et al. (2019), who used MODIS data as a benchmark to compare cloud property classifications between FY-4A and Himawari-8, the overall hit rates for cloud pixels by AHI and AGRI are 77% and 93%, respectively. For ice clouds, the recognition rates are comparable (80% for AHI and 81% for AGRI). However, AGRI's false hit rate for mixed-phase clouds increases to 75%, primarily because pixels classified as mixed-phase by MODIS algorithms are often interpreted as water or ice clouds by AGRI algorithms.

Regarding your perceptive question on how these discrepancies impact our defined life cycle stages, we acknowledge that relying solely on FY-4A might cause temporal shifts when defining the transition from Stage 3 to Stage 4 due to the aforementioned misclassifications. To mitigate this, our stage definition does *not* rely on a single satellite's phase classification. Instead, we use the high-resolution vertical probing of the CDWL (e.g., the descent of cloud base height and the dynamic characteristics of sinking ice virga) as the primary criteria for dividing the life cycle stages. Satellite data serve as a macroscopic evolutionary background to complement the radar data.

Change: Line 123-127. It is worth noting that the study site is located at the extreme western edge of the Himawari-8 detection range (80°E), and its cloud phase product relies on visible and near-infrared bands, resulting in sparse valid daytime data for the target ice cloud. Therefore, rather than absolute pixel-to-pixel validation, this study utilizes the temporal evolution trends and neighborhood spatial consensus from these multi-source datasets to comprehensively complement the CDWL point observations and define the ice cloud life cycle.

Reference:

Lai, R., Teng, S., Yi, B., Letu, H., Min, M., Tang, S., and Liu, C.: Comparison of Cloud Properties from Himawari-8 and FengYun-4A Geostationary Satellite Radiometers with MODIS Cloud Retrievals, Remote Sensing, 11, 1703, https://doi.org/10.3390/RS11141703, 2019.

2. While the paper provides a clear phenomenological description of the ice crystal cloud lifecycle, the discussion on the underlying physical mechanisms could be deepened. A more detailed analysis of processes such as the specific activation mechanisms of dust aerosols as ice nuclei and how turbulence precisely facilitates aerosol-supercooled water interaction, potentially supported by existing theories or model simulations, would strengthen the paper's scientific contribution.

Response: We fully agree that deepening the discussion on the underlying physical mechanisms significantly strengthens the scientific contribution of the paper.

In actual operation, we are faced with the constraint of extreme data volume. Due to the huge differences in the design, focus, and spatio-temporal resolution of multi-source observation instruments, the CDWL observation data volume of the complete ice cloud evolution process captured in this study is very small (less than 2 days). In contrast, other matching reanalysis datasets (such as ERA5, MERRA-2) have lower temporal resolution and fewer samples. This lack of data makes it very difficult to carry out direct statistical correlation discussions, and it also makes conventional numerical model simulations invalid due to the lack of sufficient initial values, boundary conditions, and verification data.

However, your suggestion pointed out the direction of breakthrough for us. We are currently using a 2-year long-term CDWL observation dataset, supplemented by deep learning methods, to systematically tackle this problem. We are introducing generative reconstruction techniques based on Denoising Diffusion Probabilistic Models (DDPM) and Denoising Diffusion Implicit Models (DDIM). We are combining ConvNeXt for large-receptive-field feature extraction and U-Net to solve the ill-posed inverse problem of ice crystal cloud image reconstruction caused by VAD scanning. We use a cross-attention mechanism to guide the high-precision reconstruction using local meteorological parameters, MERRA-2 dust data, and CDWL dynamic parameters to achieve end-to-end inversion from aerosol to ice cloud physical parameters.

To address your immediate concern in this phenomenological study, we have expanded our qualitative discussion in Section 3.2 based on classical theory to explicitly describe the deposition/immersion nucleation mechanisms of dust and the role of turbulence in enhancing collision-coalescence rates.

Change: Line 198-201. Physically, desert dust aerosols trigger glaciation via deposition or immersion freezing at -10 °C to -17.5 °C. The upward transport of these IN is strongly influenced by the PBLH (Holtslag and Boville, 1993). Within this layer, turbulent kinetic energy lifts the dust and generates micro-scale eddies, which accelerate the phase transition by enhancing dust-droplet collisions and local supersaturation.

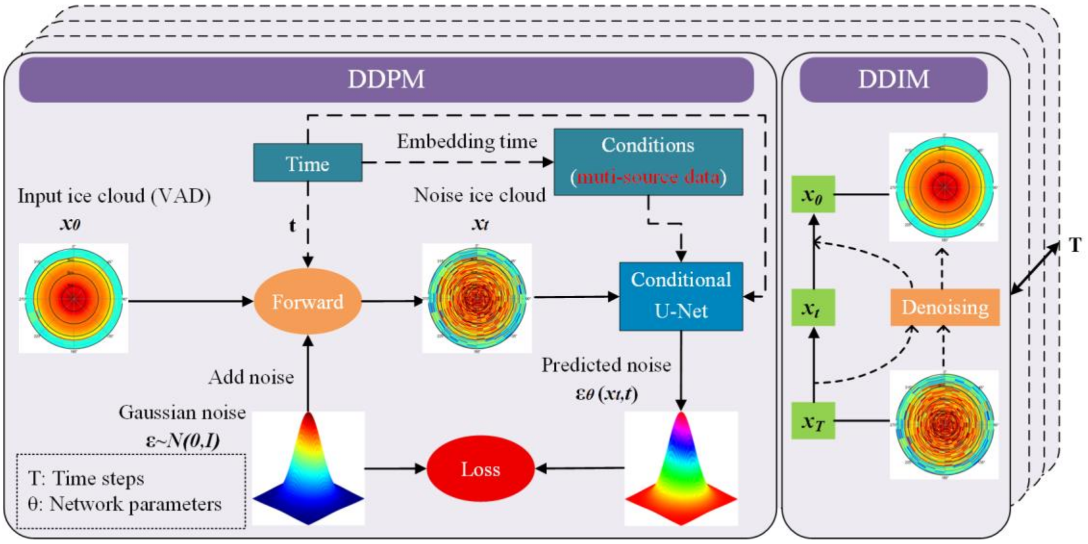

Figure 1. The DDPM+DDIM framework models cross-modal global dependencies between meteorological parameters and ice clouds, where DDPM handles model training and DDIM accelerates inference.

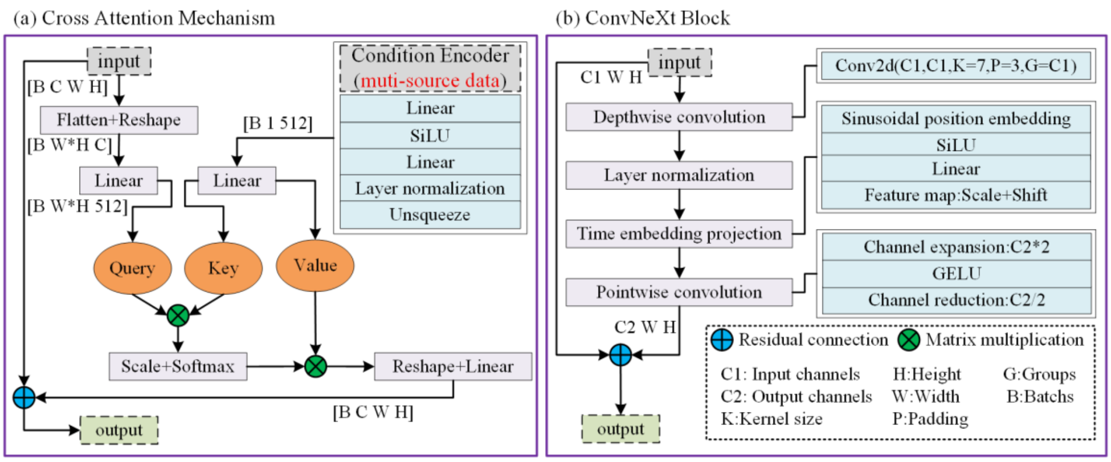

Figure 2. The Cross-Attention mechanism and ConvNeXt module. Cross-Attention captures cross-modal global dependencies between multi-source data and ice clouds; ConvNeXt enables large-receptive-field feature extraction to boost non-linear representation and generalization.

Reviewer #3:

Comments and Suggestions for Authors:

Study on the life cycle of ice crystal cloud over the Taklimakan desert using multi-source data" by Su et al. presents a case study of a cloud though four stages of existence as observed by stationary lidar, several satellite products, reanalysis data, and trajectory modeling. The paper excellently links signals in the data with meteorological phenomena at lead to the formation and dissipation of an ice cloud from dust. However, there is a lack of discussion regarding the advantages or disadvantages of this method compared to others. For example, could this multi-source method be used to demonstrate the life cycle of other ice clouds in the region? When comparing the case in the paper to others, are any of the data sources relatively unimportant? Because of this, I recommend this paper be accepted, though with potentially major revisions to address the questions above.

Response: We sincerely appreciate your positive evaluation of our data analysis and phenomenological descriptions. The three specific questions you raised are crucial for perfecting our methodological evaluation. Accordingly, we have supplemented the conclusion section of our revised manuscript.

1、Advantages and limitations: The core advantage lies in the perfect complementation between "vertical microscopic dynamics" and "horizontal macroscopic thermodynamics/phase states". The CDWL provides extremely high vertical spatiotemporal resolution, which is completely unattainable for meteorological satellites. Conversely, satellite and reanalysis data compensate for the CDWL's inability to directly acquire large-scale cloud phase states and three-dimensional thermodynamic fields. The disadvantage is that CDWL, as a fixed-point Eulerian observation method, relies heavily on large-scale cloud systems passing horizontally over the observation station. Additionally, CDWL cannot directly obtain cloud phase states and heavily relies on cross-validation from satellite observations.

2、Applicability to other ice clouds: This multi-source framework can definitely be used to demonstrate the life cycle of other ice clouds in the region. As described in Section 2.2, as long as the cloud system undergoes advection across the observation station, CDWL can record the spatial development characteristics of the cloud system at different times like a "slice". This method is particularly suitable for relatively enclosed topographies like the Taklamakan Desert where weather systems exhibit somewhat predictable movement patterns.

3、Relative importance of data sources: In this case and future similar studies, no single data source is completely "unimportant", but their relative importance changes significantly at different stages of the ice cloud life cycle. For instance, in the pre-formation stage (Stage 1-2), HYSPLIT trajectories and MERRA-2 reanalysis data are vital for tracing the source and climbing dust aerosols. The following table lists the irreplaceable functions of various types of data.

Table 1: Table of irreplaceable functions of various data

Data Source	Key Irreplaceable Functions
CDWL	Vertical structure, turbulence, cloud base height, ice virga detection
FY-4A/Himawari-8	Cloud phase, horizontal extent, cloud top temperature
ERA5	Temperature and humidity profiles, large-scale wind fields, ice water content
MERRA-2	Dust source regions, transport pathways, deposition amount
HYSPLIT	Trajectory verification, source region confirmation
Ground-based meteorological stations	Near-surface validation, visibility

Change: Line 290-298. To capture such complex interactions, this multi-source approach synergizes CDWL's high vertical resolution with satellites' broad horizontal coverage, capturing both microphysical dynamics and macro-scale thermodynamics. However, CDWL's fixed-point Eulerian nature requires clouds to advect overhead and relies on auxiliary data for phase classification. While applicable to other Taklamakan ice clouds, the importance of specific datasets shifts dynamically: HYSPLIT and MERRA-2 are crucial for initial dust tracking, whereas CDWL becomes essential later for observing localized ice virga evaporation. In view of this, our future research plans to integrate polarization lidar and weather radar (Ma et al., 2015; Yin et al., 2021; Wu et al., 2015; Yuan et al., 2022b). This will enable precise classification of clouds and aerosols, thereby deepening our understanding of ice cloud formation mechanisms in desert environments.

Minor/technical comments:

1、As far as I am aware, the name of the desert is typically romanized as "Taklamakan". "Ice crystal cloud" can simply be written as "ice cloud"

Response: The term 'ice cloud' is a more rigorous meteorological classification. Additionally, although both 'Taklamakan' and 'Taklimakan' are frequently used, 'Taklamakan' remains the most universally accepted English spelling. We have carefully revised the manuscript based on your valuable comments.

Change: Line 1-2. **Study on the life cycle of an ice cloud system over the Taklamakan desert using multi-source data**

Line 13. on the southern edge of the Taklamakan Desert**.**

…

2、There are several cases, such as in the title and abstract, where the indefinite article "an" is missing from before "ice crystal cloud".

Response: We deeply appreciate your meticulous review. Based on your feedback, several sentences have been modified to improve clarity.

Change: Line 1-2. **Study on the life cycle of an ice cloud system over the Taklamakan desert using multi-source data**

Line 12. and decomposition of an ice cloud event

…

3、In lines 80-85, references are given both in-text and parenthetically in each sentence. Only one of the two is necessary.

Response: Thank you for pointing this out. We have corrected the redundant citations in lines 80-85 in the revised manuscript.

Change: Line 79-84. To ensure the reliability of the data, the CDWL data with a CNR less than -17 dB were filtered out. Banakh et al. described the calculation method and error analysis of turbulent kinetic energy dissipation rate (TKEDR) (Banakh et al., 2017). Li et al. introduced the inversion of backscattering coefficient (BSC) in detail (Li et al., 2023). Wei et al. analyzed the error of wind speed and wind direction (Wei et al., 2019). The planetary boundary layer height (PBLH) is calculated by using the TKEDR method (Wang et al., 2021). Su et al. provided a detailed explanation of the parameter inversion method in the article (Su et al., 2024a).

4、In section 3.1.2, it is unclear how mixed phase is differentiated from a combination of ice, mixed, and supercooled. See Fig. 3 at -20 to -15 C, for example.

Response: Thank you for raising this critical point. To clarify, we detail the classification mechanism of the "mixed phase" from two distinct perspectives: the pixel-level algorithmic retrieval and the statistical meaning of the figure:

1、**Pixel-level retrieval mechanism:** The FY-4A cloud phase product identifies phases based on brightness temperature differences across multi-channel infrared bands (specifically 8.5, 10.8, and 12.0

μm). For a single 4-km spatial resolution pixel: if it exhibits solely the radiative signatures of ice crystals or supercooled water, it is classified as "Ice" or "Supercooled" phase, respectively. However, if the pixel contains the dual optical signals of both water and ice, the algorithm categorizes it as an independent "Mixed phase."

2、Statistical meaning of figure 3 (-20°C to -15°C): Figure 3 displays the temporal statistical probability of all pixels passing over the observation site during the entire study period (February 5-6), rather than a snapshot of the internal cloud profile at any single moment. Consequently, the co-occurrence of three phases within this temperature range signifies that, throughout the entire observation period, pure supercooled water pixels, mixed-phase pixels, and pure ice-phase pixels were independently recorded under these specific temperature conditions.

Change: Line 147-148. Fig. 3 shows the statistical probability distribution of these pre-classified cloud phase pixels.

Line 149-150. within the-10 °C to -17.5 °C, individual pixels of supercooled, mixed, and ice phases all occur statistically, indicating that the ice cloud is formed under relatively warm temperature conditions.

5、Line 175: The HYSPLIT results are in Fig. 7, not Fig. 6.

Response: Thank you for catching this error. We have corrected it in the revised manuscript.

Change: Line 181. Fig. 7 shows the 24 h HYSPLIT backward trajectory results of dust transport. Each stage of the ice cloud life cycle is analyzed as follows.

6、Line 188: Change "proves" to "supports".

Response: Thank you for catching this error. We have corrected it in the revised manuscript.

Change: Line 194. which supports that there is a dust layer here.

7、Line 200: The units of dust emission contain "ug" instead of "μg".

Response: Thank you for catching this error. We have corrected it in the revised manuscript.

Change: Line 207. Fig. S4k-l is also greater than 0.5 ug m^{-2} s^{-1}

8、Lines 215 - 216, 239: How can you be sure about this assertion? Generally, ice clouds formed from heterogeneous nucleation, as is the case here, have fewer crystals relative to those produced by homogeneous freezing. Is it not possible that there are actually a smaller number of crystals that are growing rapidly by vapor deposition to the point of precipitating? Collisions and aggregation would not be necessary, especially considering that the part of the cloud has dendritic growth zone conditions. Could the aggregation hypothesis be supported by the elevated TKEDR in the cloud, or perhaps by the Doppler velocity of the virga is higher than expected for individual crystals?.

Response: We deeply appreciate your insightful comments regarding the microphysical processes of the ice cloud. Your assertion is highly accurate; since the ice crystals in this case formed via heterogeneous nucleation, their number concentration is indeed likely lower than that produced by homogeneous freezing. We completely agree that in such an environment, especially within the dendritic growth zone conditions (-10°C to -17.5°C)—rapid growth via vapor deposition plays a dominant role in developing precipitating crystals. However, we still believe that collision and aggregation occurred simultaneously, and this hypothesis is directly supported by your excellent suggestion regarding the Doppler velocity. According to our CDWL observations, the maximum falling velocity of the ice virga reached 1.38 m/s. Individual pristine ice crystals (like dendrites) typically have much lower terminal velocities (around 0.3 to 0.5 m/s). The observed high fall speed of 1.38 m/s strongly indicates the presence of larger aggregates formed by collisions. Thank you for guiding us to look deeper into the Doppler velocity data. We have revised the manuscript to emphasize the primary role of vapor deposition while using the fall speed to justify the occurrence of aggregation.

Change: Line 239-241. the gradual thickening of the cloud layer provides a favorable environment for rapid crystal growth via vapor deposition, and simultaneously increases the probability of collision and aggregation of ice crystals, thus creating conditions for ice phase precipitation in Stage-4.

Line 394-402. t is obvious that the large-grained ice crystals, primarily grown by rapid vapor deposition and subsequent aggregation, rush down from 3 km to 1 km under the function of gravity conditions, forming an ice virga. The aggregation process is firmly supported by the maximum falling velocity of the ice virga (1.38 m/s), which significantly exceeds the typical terminal velocity of individual pristine ice crystals.

9、Figure 6: Perhaps it would be more useful to show the relative humidity with respect to ice in panel (h). Also, the caption refers to the figure as number 5 twice in line 229.

Response: We sincerely thank the reviewer for suggesting the use of Relative Humidity with respect to ice (RHi), which we agree is highly relevant for ice cloud microphysics.While we considered this conversion, ERA5 only provides a standard "Relative humidity" product. However, according to the ECMWF Integrated Forecasting System (IFS) documentation, the calculation of this standard ERA5 Relative humidity inherently accounts for the ice phase: the saturation vapor pressure is evaluated over liquid water for temperatures above 0 °C, over pure ice for temperatures below -23 °C, and uses a quadratic mixed-phase interpolation for temperatures between 0 °C and -23 °C. Since our studied cloud temperatures predominantly range from -10 °C to -35 °C (Fig. 6i), the native ERA5 product naturally reflects ice-phase thermodynamics. To maintain the dataset's thermodynamic consistency and avoid artifacts from manual empirical conversions, we retained the original product in Figure 6h.

Regarding the typographical error in the caption, we sincerely apologize for the oversight. We have corrected "Figs. 5a and 5b" to "Figs. 6a and 6b" as you correctly pointed out. Thank you again for enhancing the rigor of our manuscript.

Change:

Line 98-100. It should be noted that according to the ECMWF formulation, standard ERA5 relative humidity is calculated with respect to water above 0 °C, ice below -23 °C, and uses mixed-phase interpolation in between.

Line 217. In Figs.6a and 6b, the dotted boxes A and B represent the existing dust layer and the upward transport process of dust aerosol, respectively

10、Line 237: This is the first time virga is defined in the paper, but it was discussed earlier in the previous paragraph.

Response: Thank you for catching this. To ensure a better logical flow, we have removed the premature mention of 'virga' from the earlier paragraph. As a result, the term is now first introduced and immediately defined in Stage-4.

Change: Line 228. the laser beam does not penetrate the ice cloud (Wu and Yi, 2017; Cheng and Yi, 2020)

11、The header for the Conclusions section should be numbered 4.

Response: Thank you for pointing this out. We have corrected the section number for the Conclusions to 4 in the revised manuscript.

Change: Line 276. **4 Conclusions**