Response to Reviewers' Comments

Reviewer #1

Zhao et al. presented a detailed study on investigating the transport routes of Asian dust to the Arctic, the variation of aerosol properties during the long-range transport, and the impact of particle deposition on the surface albedo. Dust has been recognized as an important natural contributor to the global aerosol budget while its climate forcing is highly uncertain. Zhao et al. found that Asian dust has high probability reaching the Arctic and two typical transport events are well verified by various methods. The variations of the aerosol optical properties between the two events are compared, suggesting the importance of transport routes in modifying the aerosol properties. At last, the reduction of surface albedo due to the deposition of particles is demonstrated significant, which could be a crucial factor of the aerosol indirect climatic effect in the Arctic region.

Overall, this study is a nice work as it expands the current understanding of the Arctic haze. Hence, I recommend this manuscript for publication after the following comments have been addressed.

We sincerely thank for the reviewer's positive comments and helpful suggestions on this manuscript. Based on the specific comments, we have responded to all the comments point-by-point and made corresponding changes in the manuscript as highlighted in red color. Please check the detailed responses to all the comments as below.

Major comments:

In the identification of dust particles by using the Lidar observation (e.g., Figure 6 and Figure 8), high extinctions aloft can be seen. How to differentiate the extinction between dust and clouds?

Thanks for the comment. Clouds and dust can be mixed together under some conditions as the reviewer mentioned. Usually, the detection of very high extinctions could be caused by the existence of clouds. Also, the clouds (for example high clouds) usually showed discontinuity from the vertical profiles of aerosols. Based on these criteria, clouds can be identified, e.g., the blank areas on April 17 in Figure 6. As for Figure 8, no obvious clouds are observed.

In the revised manuscript, the sentence "Clouds are screened and represented by the blank pixels." is added in the caption of Figure 6.

In Figure 10, the analyzed periods of AOD and AE are not consistent. Please state the reason. Also, in Figure 10c, why AOD in the source region is even lower than the downwind regions?

Thanks for the comment. The AE products are not available over the ocean while most of the analyzed periods covered the ocean. That's why the analyzed periods of AOD and AE were not consistent.
As shown in Figure S1b, the AOD hotspots were observed on March 8 and 9, showing the eastward movement of aerosol plume. This probably indicates the dust plume has already drifted away from the dust source region on March 7. This explains the relatively low AOD in the source region lower than the downwind regions.
In Line 490 - 494, the paragraph is revised as "AOD was relatively low over the Gobi Desert on March 7 while the mean AOD even increased to 0.56 - 0.68 from March 8 to 11. As shown in Figure S1b, the eastward movement of aerosol plume was evident. This probably indicated the dust plume had already drifted away from the dust source region, which explained the lower AOD in the source region than the downwind regions.".

In Section 3.7.1, it is feasible to use the calculated ratio of the particulate matter in the snow versus that in the atmosphere. However, this ratio is derived based on the measurement of black carbon in snow and in the atmosphere. The authors should clarify how can be this ratio used for the estimation of dust in snow.

Thanks for the comment. As the simultaneous measurement of dust in the air and snow was not available, the calculated ratio was also applied for dust. The assumption was based on that dust and black carbon could be sufficiently mixed due to the fact that each long-range transport event took several days. In this regard, the deposition behavior of dust and black carbon could be similar in the targeted remote Arctic region.
In Line 548 - 551, the sentence is revised as "This ratio was then applied to estimate the concentrations of dust and elemental carbon in snow during the two cases based on the assumption that particulate dust and elemental carbon could be well mixed under the sufficiently long transport duration.".

Other comments:
Line 36: "This study implied that the dust long transport from China to the Arctic was ubiquitous and may be a potential contributor to the Arctic regional climate and ecosystem." The term "ecosystem" is suggested omitted.

Thanks for the suggestion. The word "ecosystem" is deleted in the revised submission.

Line 47 – 48: "origin of aerosol, transport, and deposition". This expression is confusing and not clear.

This sentence is revised as "The magnitudes of direct radiative forcing of Arctic aerosols were closely related to the origin of aerosol and its transport and deposition (Quinn et al., 2008)."

Section2., how was the aerosol absorption measured?

Aerosol absorption was measured by a filter absorption photometer. The aerosol absorption coefficients were obtained at three wavelength of 467, 530, and 660nm. The measurement results at 530nm were used.
In the revised Section 2, the description about aerosol absorption is added in Line 147 – 150.

Line 153: "height resolution" should be "vertical resolution".
It is corrected as suggested.

Line 154 – 165: relevant references about the satellite sensors should be cited.

The relevant references are added as below.

Levy, R. C., L. A. Remer, S. Mattoo, E. F. Vermote, and Y. J. Kaufman (2007), Second-generation operational algorithm: Retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance, J. Geophys. Res.,112, D13211, doi:10.1029/2006JD007811.

Hsu, N. C., M.-J. Jeong, C. Bettenhausen, A. M. Sayer, R. Hansell, C. S. Seftor, J. Huang, and S.-C. Tsay (2013), Enhanced Deep Blue aerosol retrieval algorithm: The second generation, J. Geophys. Res. Atmos.,118, 9296–9315,doi:10.1002/jgrd.50712.

Omar, A. H., et al. (2009), The CALIPSO automated aerosol classification and lidar ratio selection algorithm, J. Atmos. Oceanic Technol.,26,1994–2014, doi:10.1175/2009JTECHA1231.1.

Line 255-257: The writing "the presence of a low pressure system over northern Japan in spring" needs more evidence.

Thanks for the comment. This sentence is a general statement. In section 3.4, more details about the low pressure system are presented in both CASE I and CASE II.
In the revised submission (Line 266 - 267), one sentence is added as "In Section 3.4, more details about the low-pressure system will be presented based on case analysis.".

Line 279: the expression of time and date should be consistent throughout the paper.
As for the geopotential height fields that are used in Figure 4 and Figure 5, it is not clear which pressure level data is used.

"11:00, March 14" is changed as "11:00 on March 14". The pressure level of the geopotential height fields is 500hPa. In the caption of Figure 4 and Figure 5, this

information is added.

Line 344: “particle spheric information” should be “particle morphology information”.

Thanks for pointing it out. It is corrected.

Line 358: When Angström exponent first appears here, its wavelength range should be provided.

The value of Angström exponent is calculated in the wavelength range of 440-870nm. It is added when it first appears. Also, the wavelength range is added in the caption of Figure 6 and Figure 8.

As for the aerosol types observed by CALIPSO, the visualization is not clear enough to be determined in Figure 7 and 9.

The font size of aerosol types is enlarged in the revised Figure 7 and Figure 9.

Line 468 – 470: Please provide more supporting information on this statement.

One reference is added to support this statement.
Xu, L., Fukushima, S., Sobanska, S., Murata, K., Naganuma, A., Liu, L., Wang, Y., Niu, H., Shi, Z., Kojima, T., Zhang, D., and Li, W.: Tracing the evolution of morphology and mixing state of soot particles along with the movement of an Asian dust storm, *Atmos. Chem. Phys*., 20, 14321-14332, 10.5194/acp-20-14321-2020, 2020.

Reviewer #2:
This manuscript presents an interesting study to reveal the transport pathway of wind-blown dust from East Asia to the Arctic, and evaluate snow surface albedo change due dust and elemental carbon. The manuscript focused on an important topic as it's necessary to understand how the rest of the world affect the Arctic due to its vulnerable environment and ecosystem. The authors applied multiple tools including the trajectory modeling, reanalysis data, and several observational database to investigated dust events during 2011-2015, with sufficient details demonstrated and in-depth discussions made. The manuscript presented a very interesting integrated data analysis with observations from different platforms but focused on one same event. In general the manuscript is well organized with solid method and clear description of the analysis and conclusions. Therefore I would recommend this manuscript to be accepted with a few minor revisions, if the following comments could be properly addressed.

We sincerely thank for the reviewer's positive comments and helpful suggestions on this manuscript. Based on the specific comments, we have responded to all the comments point-by-point and made corresponding changes in the manuscript as highlighted in red color. Please check the detailed responses to all the comments as below.

Comment#1. Fresh dust particles will gradually go through aging process during the long-range transport, which may result in a different optical property of aged dust particles. Therefore I would recommend to include a brief discussion regarding how this may affect the conclusion about dust impact on snow albedo.

Thanks for the comment. We quite agree with the reviewer that the aging process of dust particles would affect the change of snow albedo. This effect is not considered in this study as it may require information about more detailed microphysical properties of the evolved dust particles. In the conclusion section of the revised submission, a paragraph is added to state the shortcomings of this study.
Line 656 – 667: It has to be noted that the simulation of surface albedo due to the transport of dust particles was subject to large uncertainties. The concentrations of impurities in snow were estimated by empirical equations but not in-situ measurement data. As a result, the cumulative effect of impurities in reducing the surface albedo was not considered. Also, the evolution of dust microphysical properties was not accounted in the model simulation. The atmospheric aging processes, i.e., dust particles coated with various type of aerosols during the long-range transport, could further enhance the reduction of snow albedo. The dust particle refractive index is regarded as an important factor for dust absorption in snowpack (He, 2022). To reduce the uncertainties of snow albedo simulation, simultaneous in-situ measurements of particle composition and optical properties in both the air and snowpack are essentially needed in the future Arctic studies.

Reference:

He, C.: Modelling light-absorbing particle–snow–radiation interactions and impacts on snow albedo: fundamentals, recent advances and future directions, Environmental Chemistry, 10.1071/EN22013, 2022.

Comment#2. line98-102. These two sentences have the same meaning as aerosol loading is surely equivalent to the instantaneous forcing. Therefore I would recommend remove either one to be concise.

Thanks for the suggestion. This sentence is revised as "Zwaaftink et al. (2016) combined a Lagrangian particle dispersion model FLEXPART (FLEXible PARTicle dispersion model) and surface particle concentration observations to simulate the global dust emissions. It was found that the instantaneous radiative forcing in the Arctic caused by dust was also dominated by Asia and Africa."

Comment#3. line102."the deposition of dust … for almost all of the bottom of … forcing" unclear description, please consider rephrase it.

Thanks for pointing out this unclear writing. It is revised as "In addition, the deposition of dust on snow was responsible for almost all the instantaneous radiative forcing at the bottom of the atmosphere (Kylling et al., 2018)."

Comment#4. line108. "dust from China" Part of Gobi desert was outside China, I would recommend to mention dust from East Asia or dust from Taklamakan and Gobi deserts.

Thanks for the suggestion. This term is now revised as "dust from East Asia".

Comment#5. sec2.1. Is there any judgement why these two sites are selected but not other sites?

We select these two sites mainly from two aspects. Firstly, these two sites are almost the most northern sites in the Arctic Circle. They are located in the remote regions where human activities are negligible. Thus, the long-range transported particles can be more easily discerned. Secondly, these two Arctic sites have long-term measurement data and the observations there are continuing. In this study, only two typical cases are selected and analyzed. For researchers who want to look into this topic from different perspectives, they can use the long-term measurement data at these two sites.
In the revision (Line 119 - 121), we have added the paragraph "They are almost the most northern sites in the Arctic Circle and located in the remote regions where human activities are negligible. Thus, the long-range transported particles can be easily discerned." in Section 2.1.

Comment#6. line197. “Cma” should be ”CMA”

It is corrected in the revised submission.

Comment#7. sec3.1. Dust in East Asia has shown a significant decreasing trend during the past decade, so is this study period 2011-2015 representative for this study?

Thanks for the comment. It is true that the dust in East Asia has shown a significant decreasing trend during the past decade. As shown in Table 2, the total number of dust events during 2011-2015 reached 50 and included various types of dust events. We believe the number is statistically meaningful and thus representative of this study.

Comment#8. “Shaanxi” is this a typo?

We have double checked that it is not a typo. Shaanxi is a province adjacent to Gansu province. We didn’t mean Shanxi province which is not usually regarded as a dust source region.

Comment#9. line227. Please explain why the forward trajectory were computed at three specific height (500, 1000, 1500m)?

Dust can be lifted at a wide range of heights. The 500m height can be used to represent the lifted dust in the boundary layer. The 1000m height can be used to represent the lifted dust at around the top of the boundary layer. And the 1500m height can be used to represent the lifted dust in the free troposphere. Thus, we used these three heights to represent the typical heights of lifted dust in the dust source region.
In the revised submission (Line 236 - 237), the sentence is revised as “10-15 days forward trajectories starting at typical altitudes of lifted dust (500m, 1000m, and 1500m) were computed for each dust event in China during 2011-2015.”

Comment#10. Sec3.2. It is necessary to briefly mention that the air mass traveling from desert carry along dust particles will be discussed later in sec3.5.

Thanks for the suggestion. The sentence “More explicit characterizations of the transport pathways from the dust source regions to the Arctic will be discussed later in Section 3.5.” is added in the revision (Line 267 - 268).

Comment#11. line301. The Barrow observation site is at ground surface, please explain why configure the backward trajectory at 6km?

Thanks for the comment. For Asian dust that can reach the Arctic region via the long-range transport, dust mostly travelled in the free troposphere. Thus the backward air mass was simulated at a high altitude. In the meantime, dust particles were subject to

deposit during the transport. This could be observed by the aerosol vertical profiles that the dust plumes extend from high altitudes to the near surface. Thus, even at a ground-based site, the intrusion of dust could still be observed.

Comment#12. lin468-470. Is it possible the AOD change was due to variations in an existing source (e.g., anthropogenic emission), rather than due to the mixing of dust and other particles?

Thanks for the comment. It is very likely the decreasing AOD could be also ascribed to the decrease of anthropogenic aerosols. A number of studies have shown that the dust transport had a cleansing effect on the local air pollutions via the strong diffusion effect. In the revised submission (Line 484 - 485), we have added a sentence that "In the meantime, local air pollutants could be reduced by the strongly invaded dust (Wang et al., 2018a).".

Wang, Q., Dong, X., Fu, J. S., Xu, J., Deng, C., Jiang, Y., Fu, Q., Lin, Y., Huang, K., Zhuang, G.: Environmentally dependent dust chemistry of a super Asian dust storm in March 2010: observation and simulation, Atmos. Chem. Phys., https://doi.org/10.5194/acp-18-3505-2018, 2018.

Comment#13. 523-525. Particles in snow should be cumulative increasing through deposition even airborne concentration is decreasing, please briefly explain the judgement for the ratio used in this section.

Thanks for the comment. We quite agree with the reviewer that particles in snow could be cumulative increasing through deposition. Thus, the modeling of surface albedo reduction depended on various factors other then the ratio of ambient particle concentration vs. particle concentration in snow. In this regard, we define the simulated albedo as an instantaneous value.
In Section 3.7.1 (Line 551 - 554), we added a statement that "Since the cumulative effect of impurities in reducing the surface albedo was not considered in this study, the simulation result by the SNICAR model was considered as the instantaneous surface albedo in the following discussions."
In the conclusion section, we also add some discussions on the shortcomings of this study.
Line 656 – 667: It has to be noted that the simulation of surface albedo due to the transport of dust particles was subject to large uncertainties. The concentrations of impurities in snow were estimated by empirical equations but not in-situ measurement data. As a result, the cumulative effect of impurities in reducing the surface albedo was not considered. Also, the evolution of dust microphysical properties was not accounted in the model simulation. The atmospheric aging processes, i.e., dust particles coated with various type of aerosols during the long-range transport, could further enhance the reduction of snow albedo. The dust particle refractive index is regarded as an important

factor for dust absorption in snowpack (He, 2022). To reduce the uncertainties of snow albedo simulation, simultaneous in-situ measurements of particle composition and optical properties in both the air and snowpack are essentially needed in the future Arctic studies.