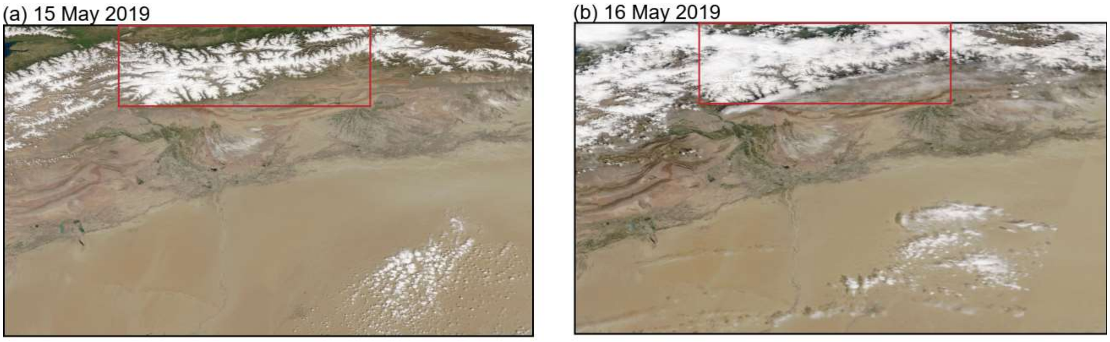
Response to Anonymous Referee #1

Your work is very interesting, but I have a serious concern. You haven't discussed the potential uncertainties and how they might influence your conclusions.

R: Thank you for your interest and constructive comments. We have supplemented the discussion on potential uncertainties in the revision. In response to the review comments, we have submitted a revised manuscript with track changes enabled to clearly indicate the modifications made. The followings are our point-by-point responses to the comments. Our responses start with "R:".

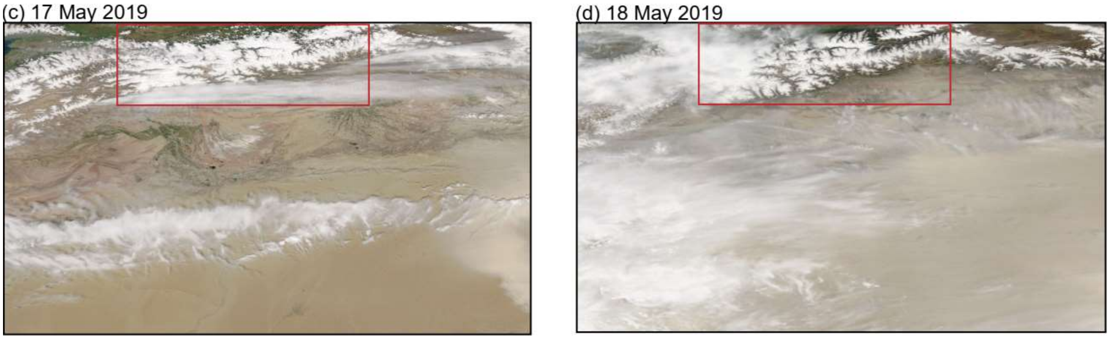
Convincing dust-induced snow-darkening within three days using MODIS/CALIOP daily snapshots is quite tricky.

R: Daily images have been added to illustrate the entire period of snow darkening events occurring from 15 May to 22 May 2019, 23 August to 6 September 2019, and 1 November to 4 November 2012 in the Tien Shan, Kunlun, and Qilian Mountains (Figures S2, S7, S10). However, due to the impact of cloud on MODIS image and LAPs retrieval, three representative MODIS images which captured before, during, and after dust events were selected to elucidate the effects of dust events on snow darkening, consistent with the study of Pu et al. (2021).



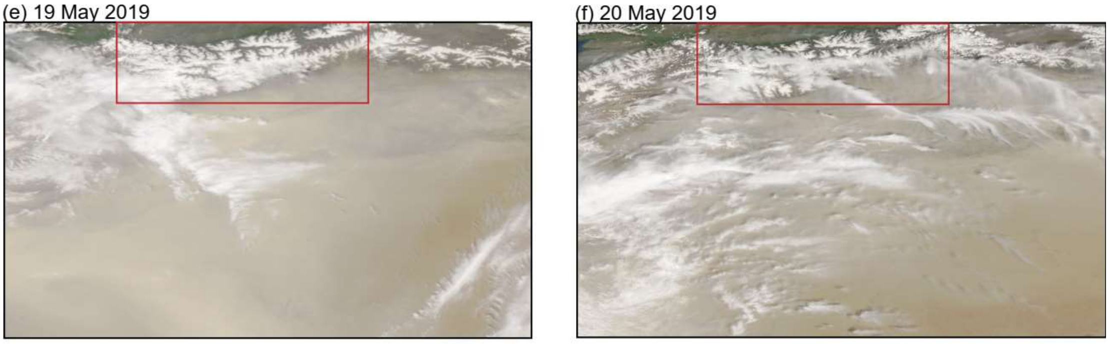
(a) 15 May 2019

(b) 16 May 2019



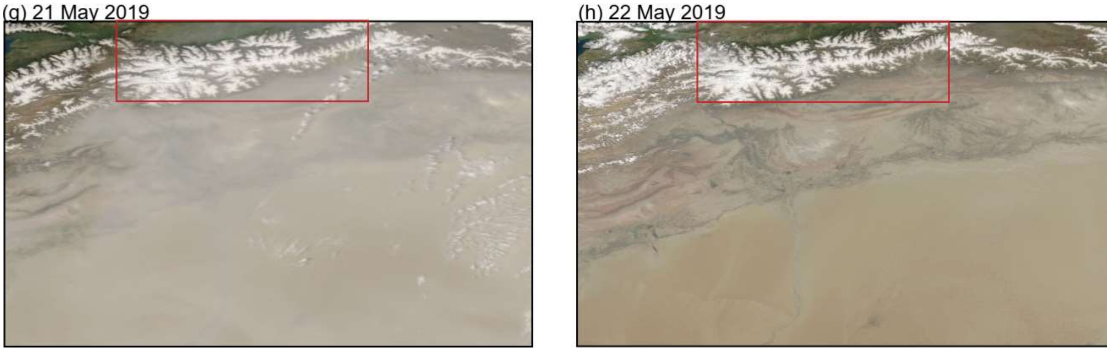
(c) 17 May 2019

(d) 18 May 2019



(e) 19 May 2019

(f) 20 May 2019



(g) 21 May 2019

(h) 22 May 2019

Figure S2. Satellite observations during the 15–22 May 2019 severe dust event across the Tien Shan (a-h).

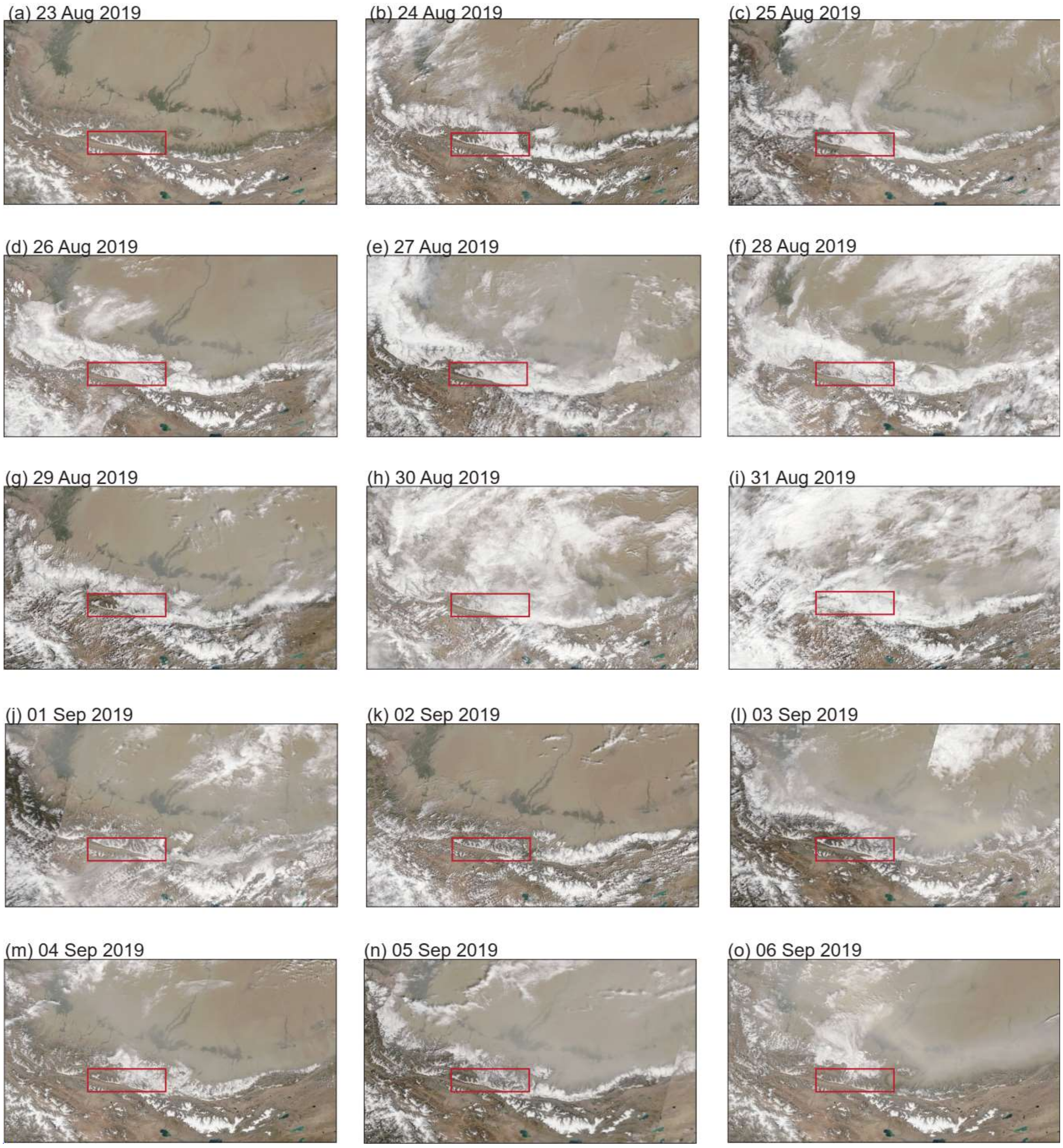

(a) 23 Aug 2019
(b) 24 Aug 2019
(c) 25 Aug 2019
(d) 26 Aug 2019
(e) 27 Aug 2019
(f) 28 Aug 2019
(g) 29 Aug 2019
(h) 30 Aug 2019
(i) 31 Aug 2019
(j) 01 Sep 2019
(k) 02 Sep 2019
(l) 03 Sep 2019
(m) 04 Sep 2019
(n) 05 Sep 2019
(o) 06 Sep 2019

Figure S7. Satellite observations during the 23 August to 06 September 2019 severe dust event across the Kunlun Mountains (a-o).

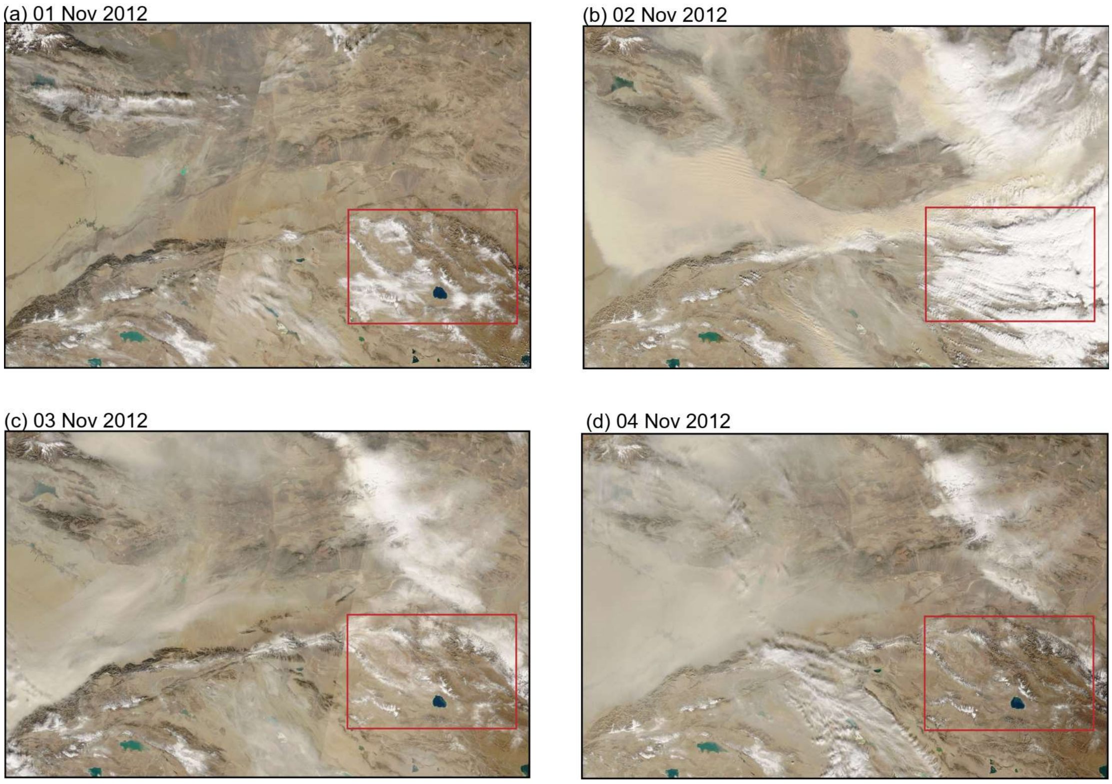


Figure S10. Satellite observations during the 01–04 November 2012 severe dust event across the Qilian Mountains (a-d).

Wouldn't the diurnal variabilities that MODIS misses cause significant biases?

R: The diurnal variations missing in MODIS images does not result in significant biases. LAPs and the associated albedo reductions, retrieved at 10:30 AM local time (coinciding with the MODIS Terra satellite overpass), were used as proxies for daily averages, in accordance with Painter et al. (2012). This approximation was reasonable, given that the content of LAPs exhibited little variation over a diurnal cycle (Painter et al., 2009; Zege et al., 2011). Daily snow albedo variation is primarily due to changes in the solar zenith angle (Figure S1). Given that the solar zenith angle mainly affects snow albedo in NIR, with little impact on the VIS, the diurnal variation in LAPs-induced snow albedo reduction was also considered limited. The revised content has been added to the manuscript. (Lines 310-318)

Could the dust in the atmosphere introduce biases in the MODIS view of the surface?

R: Thank you for the insightful comments. The dust in the atmosphere can lead to biases in the retrieval results. The uncertainty analysis added to the manuscript includes the uncertainties caused by atmospheric dust. Cui et al. (2021) verified a similar retrieval method across the Northern Hemisphere, and we referenced their work to update the discussion on atmospheric dust uncertainty. The related analysis has been added in Lines 294-309 in revised manuscript as follow:

"Cui et al. (2021) verified a similar retrieval method across the Northern Hemisphere. They considered that the accuracy of MODIS surface reflectance is typically ± (0.005 + 0.05 × reflectance) under conditions where aerosol optical depth (AOD) is less than 5.0, and solar zenith angle is less than 75°, as stated in the MODIS Surface Reflectance user's guide (Collection 6; https://modis.gsfc.nasa.gov/data/dataprod/mod09.php, last access: 19 January, 2024). In addition, the bias for snow grain size retrieval was assumed to be 30 % according to the studies of Pu et al. (2019) and Wang et al. (2017). These biases led to an overall uncertainty ranging from 10% to 110% in the retrieval of LAPs across the Northern Hemisphere. The study revealed that uncertainty decreased as LAPs concentration increased, with reported uncertainties dropping to below approximately 30% in regions of high pollution, such as Northeast China. In our study, the snowpack was also significantly polluted due to severe dust depositions, leading us to consider a retrieval uncertainty of 30% for LAPs, in alignment with the findings of Cui et al. (2021). Then, the overall lower bound and upper bound of the uncertainty value of snow albedo reduction retrieval was calculated and will be discussed in the following section."

The overall lower bound and upper bound of the uncertainty value of snow albedo reduction retrieval has been added in Figure 5b, Figure 7b, Figure 9b, and Figure S5.

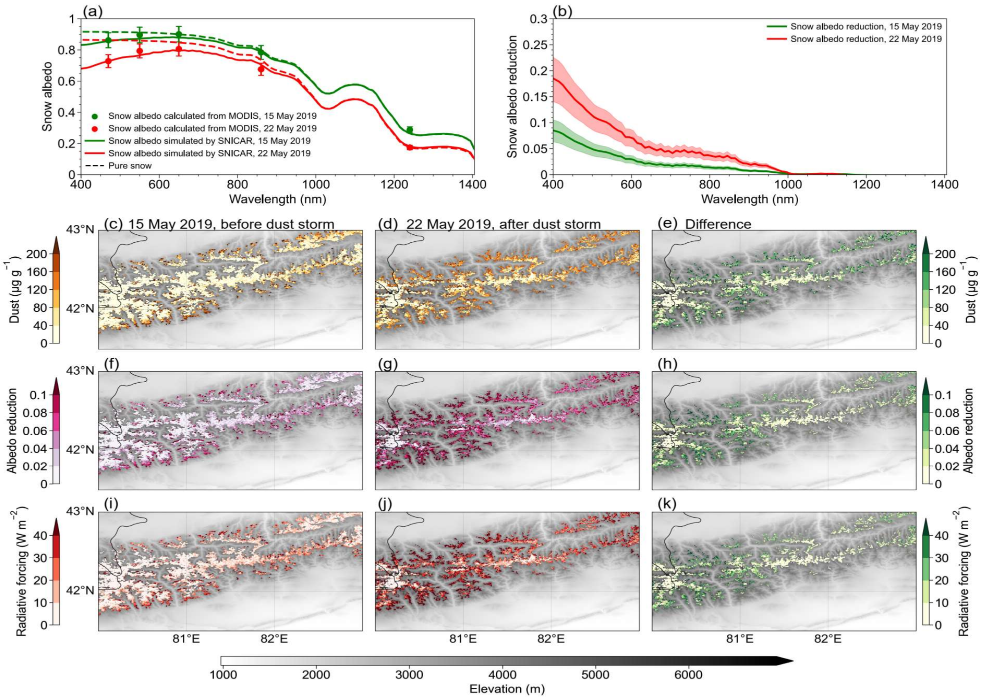


Figure 5. (a) Averaged SNICAR-simulated spectral snow albedo (solid lines) and MODIS-derived 5-band snow albedo (dots) for the region across the Tien Shan impacted by the 18–22 May 2019 severe dust event. (b) Snow albedo reduction on 15 May 2019 (green) and 22 May 2019 (red). Shadows indicate the retrieval uncertainty. Spatial distributions of the average (c, d) dust, (f, g) albedo reduction, and (i, j) radiative forcing on 15 and 22 May 2019, respectively. Spatial distributions of the differences in (e) dust, (h) albedo reduction, and (k) radiative forcing between 15 and 22 May 2019. The background image in (c–k) is a grayscale topographic map of the Tien Shan.

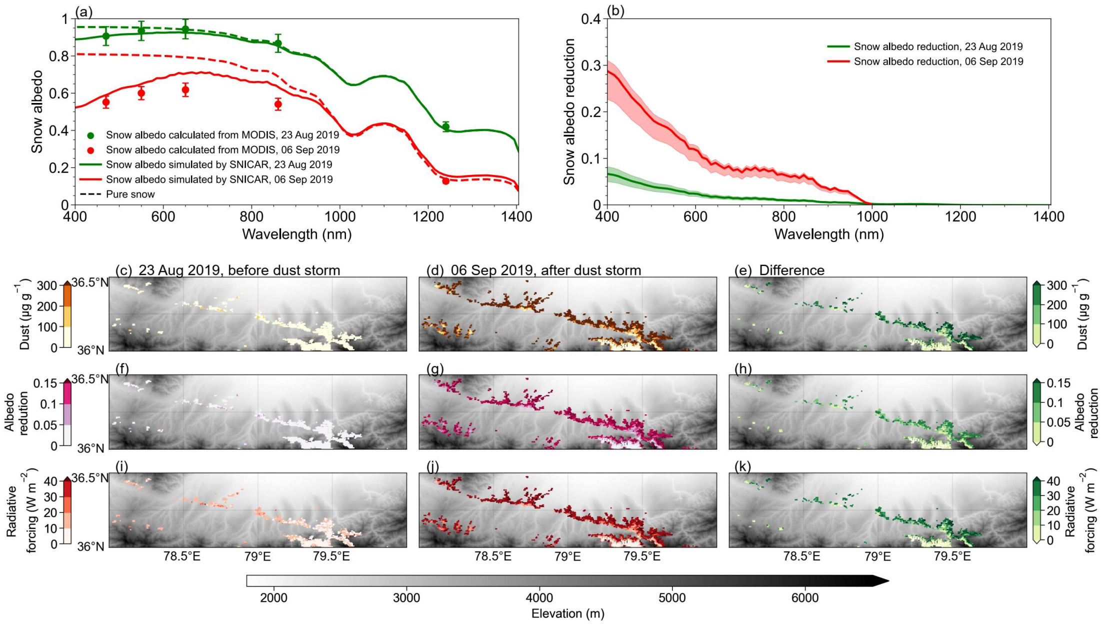


Figure 7. (a) Averaged SNICAR-simulated spectral snow albedo (solid lines) and MODIS-derived 5-band snow albedo (dots) for the region across the Kunlun Mountains impacted by the 26 Aug to 08 Sep 2019 severe dust event. (b) Snow albedo reductions on 23 Aug 2019 (green) and 06 Sep 2019 (red). Shadows indicate the retrieval uncertainty. Spatial distributions of the average (c, d) dust, (f, g) albedo reduction, and (i, j) radiative forcing on 23 Aug and 06 Sep 2019, respectively. Spatial distributions of the differences in (e) dust, (h) albedo reduction, and (k) radiative forcing between 23 Aug and 06 Sep 2019. The background image in (c–k) is a grayscale topographic map of the Kunlun Mountains.

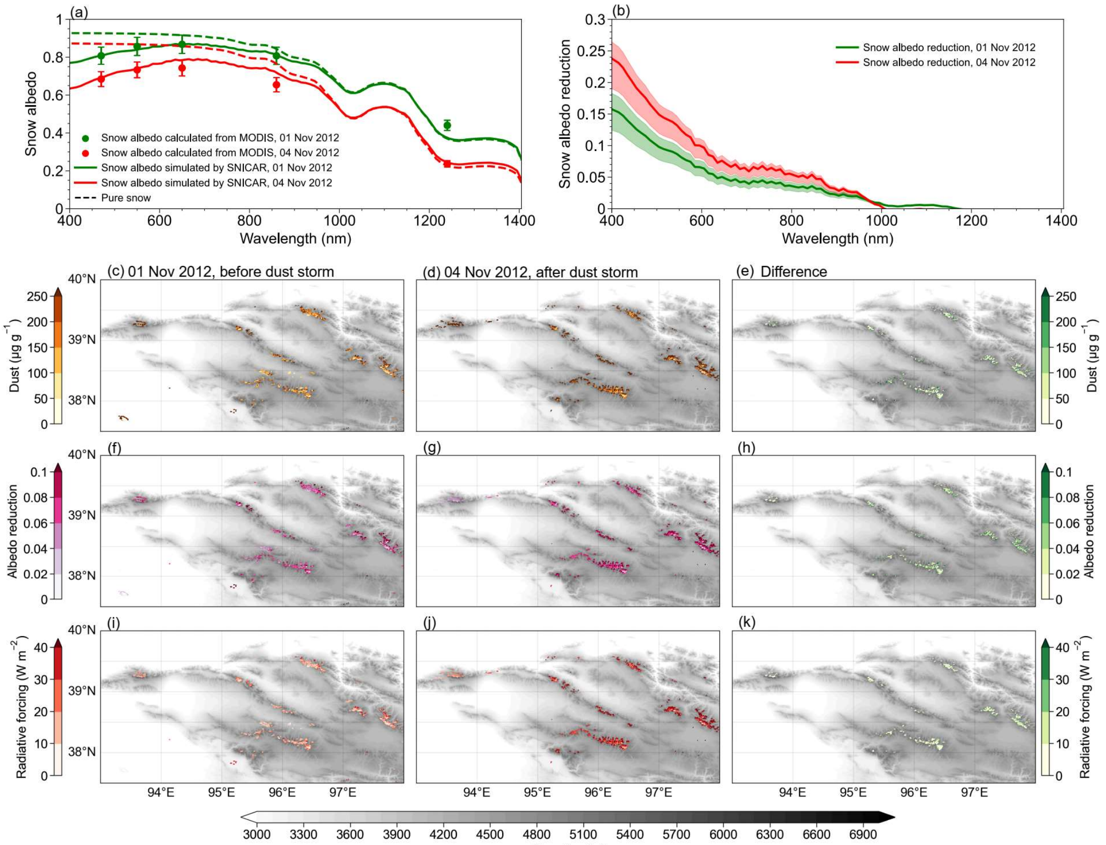


Figure 9. (a) Averaged SNICAR-simulated spectral snow albedo (solid lines) and MODIS-derived 5-band snow albedo (dots) for the region across the Qilian Mountains impacted by the 02–04 Nov 2012 severe dust event. (b) Snow albedo reductions on 01 Nov 2012 (green) and 04 Nov 2012 (red). Shadows indicate the retrieval uncertainty. Spatial distributions of the average (c, d) dust, (f, g) albedo reduction, and (i, j) radiative forcing on 01 and 04 Nov 2012, respectively. Spatial distributions of the differences in (e) dust, (h) albedo reduction, and (k) radiative forcing between 01 and 04 Nov 2012.

The background image in (c–k) is a grayscale image of the Qilian Mountains.

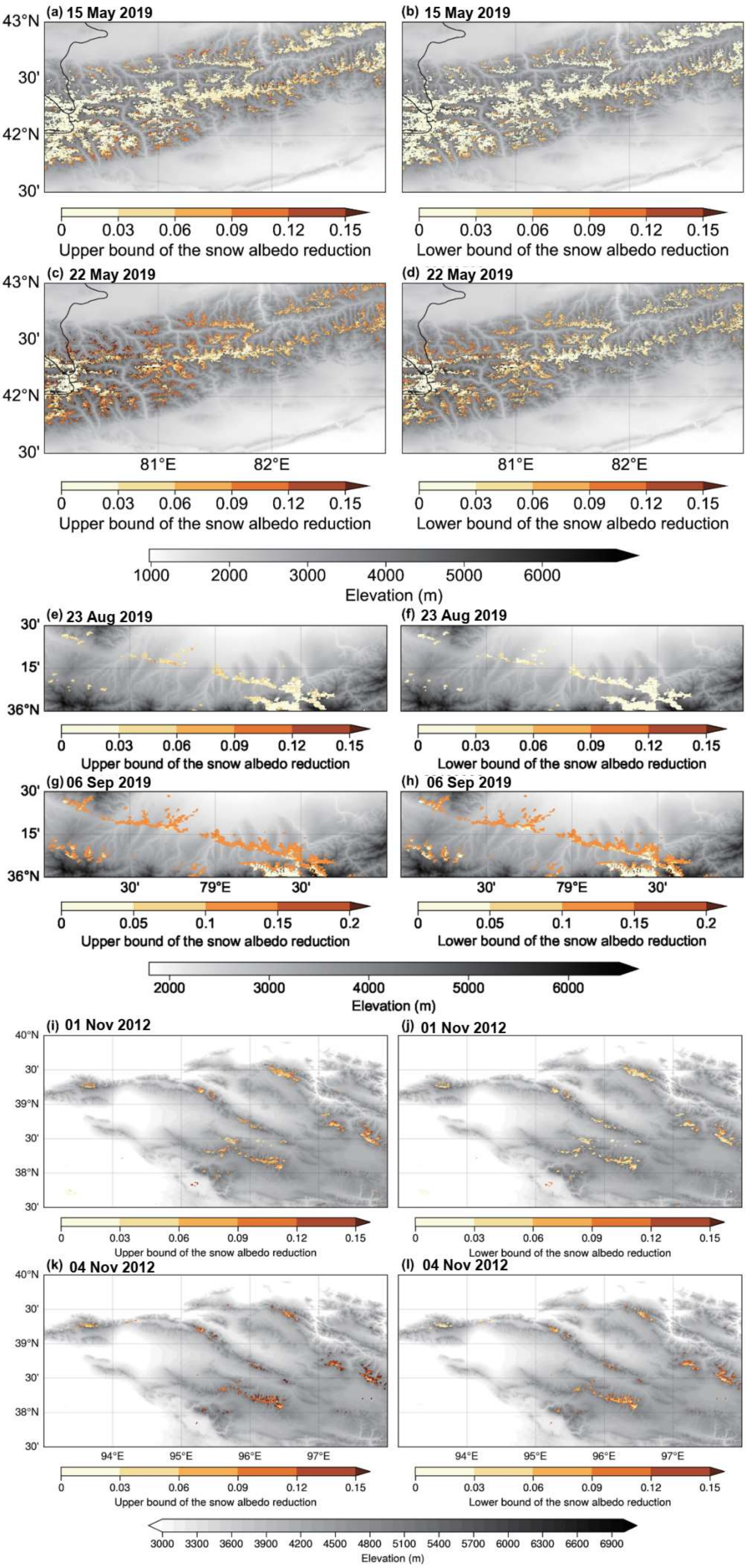

(a) 15 May 2019
(b) 15 May 2019
43°N
30'
42°N
30'
0 0.03 0.06 0.09 0.12 0.15
Upper bound of the snow albedo reduction
Lower bound of the snow albedo reduction
(c) 22 May 2019
(d) 22 May 2019
81°E
82°E
1000 2000 3000 4000 5000 6000
Elevation (m)
(e) 23 Aug 2019
(f) 23 Aug 2019
30'
15'
36°N
(g) 06 Sep 2019
(h) 06 Sep 2019
30'
79°E
30'
0 0.05 0.1 0.15 0.2
2000 3000 4000 5000 6000
Elevation (m)
(i) 01 Nov 2012
(j) 01 Nov 2012
40°N
30'
39°N
30'
38°N
30'
(k) 04 Nov 2012
(l) 04 Nov 2012
94°E
95°E
96°E
97°E
3000 3300 3600 3900 4200 4500 4800 5100 5400 5700 6000 6300 6600 6900
Elevation (m)

Figure S5. The overall lower bound and upper bound of the uncertainty value of snow albedo reduction retrieval due to atmospheric correction in Tien Shan (a-d), Kunlun Mountains (e-h) and Qilian Mountains (i-l).

Considering that CALIOP's track is merely a line over a MODIS granule, might assuming vertical profiles and aerosol types along the CALIOP track for the entire MODIS domain introduce biases in your analysis?

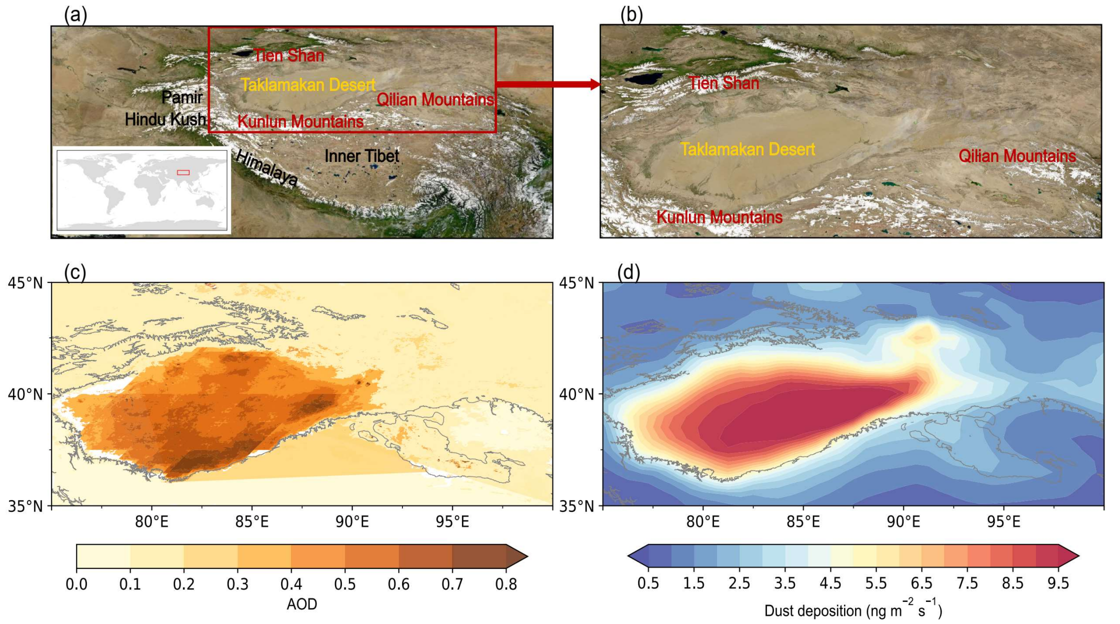
R: We used MODIS images to show the process of dust events. CALIOP solely tracked the dust height and was not involved in the retrieval process, thus it will not bring potential biases to the retrieval results. Additionally, Rohde et al. (2023) highlighted that aerosols in dust events predominantly consist of dust, as opposed to other aerosol types.

It would be helpful if you could add a section summarizing, and if possible, quantifying these uncertainties.

R: Thank you for your constructive comments. We have quantified the potential uncertainties in Section 2.6 and analyzed the overall lower bound and upper bound of the uncertainty value of snow albedo reduction retrieval in Section 3.1. Please refer to the revised manuscript for details.

1. Consider adding a map to indicate the regions you are referring to, especially in the introduction part. You could perhaps zoom out Figure 2(a).

R: Thank you for the good suggestion! We have added a map to indicate the region.



2. Good job listing a comprehensive set of references.

R: Thanks for your encouragement.

3. Since MODIS observes only once or twice per day, are you using simulations to minimize biases due to such sparse observations? (It seems like you're using models to "retrieve the dust content of the snowpack.")

R: Simulations were not employed; rather, LAPs and their associated albedo reductions, retrieved at 10:30 AM local time (MODIS Terra satellite overpass), served as proxy for daily averages in accordance with Painter et al. (2012). The reasonableness of this simplification has been discussed in the revised manuscript.

4. How significant is the diurnal variation of snow albedo for your estimations? It's possible that dust-induced darkening exhibits robust diurnal variability, which could introduce significant biases into your estimations.

R: The diurnal variations missing in MODIS images does not result in significant biases. LAPs and the associated albedo reductions, retrieved at 10:30 AM local time (coinciding with the MODIS Terra satellite overpass), were used as proxies for daily averages, in accordance with Painter et al. (2012). This approximation was reasonable, given that the content of LAPs exhibited little variation over a diurnal cycle (Painter et al., 2009; Zege et al., 2011). Daily snow albedo variation is primarily due to changes in the solar zenith angle (Figure S1). Given that the solar zenith angle mainly affects snow albedo in NIR, with little impact on the VIS, the diurnal variation in LAPs-induced snow albedo reduction was also considered limited. The revised content has been added to the manuscript. (Lines 310-318)

5. Regarding CALIOP, it's important to clarify if you assumed the type of aerosol and its vertical profile to be the same across the entire MODIS image.

R: We used MODIS images to show the process of dust events. CALIOP solely tracked the dust height and was not involved in the retrieval process, thus it will not bring potential biases to the retrieval results. Additionally, Rohde et al. (2023) highlighted that aerosols in dust events predominantly consist of dust, as opposed to other aerosol types.

6. In the section discussing the radiative transfer models, you mention two models: one for obtaining contaminated snow and the other for simulating atmospheric radiative transfer. However, you don't explain how these two models are used or combined. This section needs more clarity.

R: To clarify the whole retrieval process, a flowchart delineating the step-by-step derivation of dust content, including snow albedo reduction and radiative forcing, has been incorporated as Figure 2. Eq. (8) integrates two models to compute dust-induced broadband albedo reduction, drawing on spectral snow albedo from SNICAR and spectral solar irradiance from SBDART simulations. It is consistent with Pu et al. (2019) and Cui et al. (2021). We have refined this content in Section 2.6 for improved clarity and augmented it with additional details on the spectral solar irradiance simulations using SBDART.

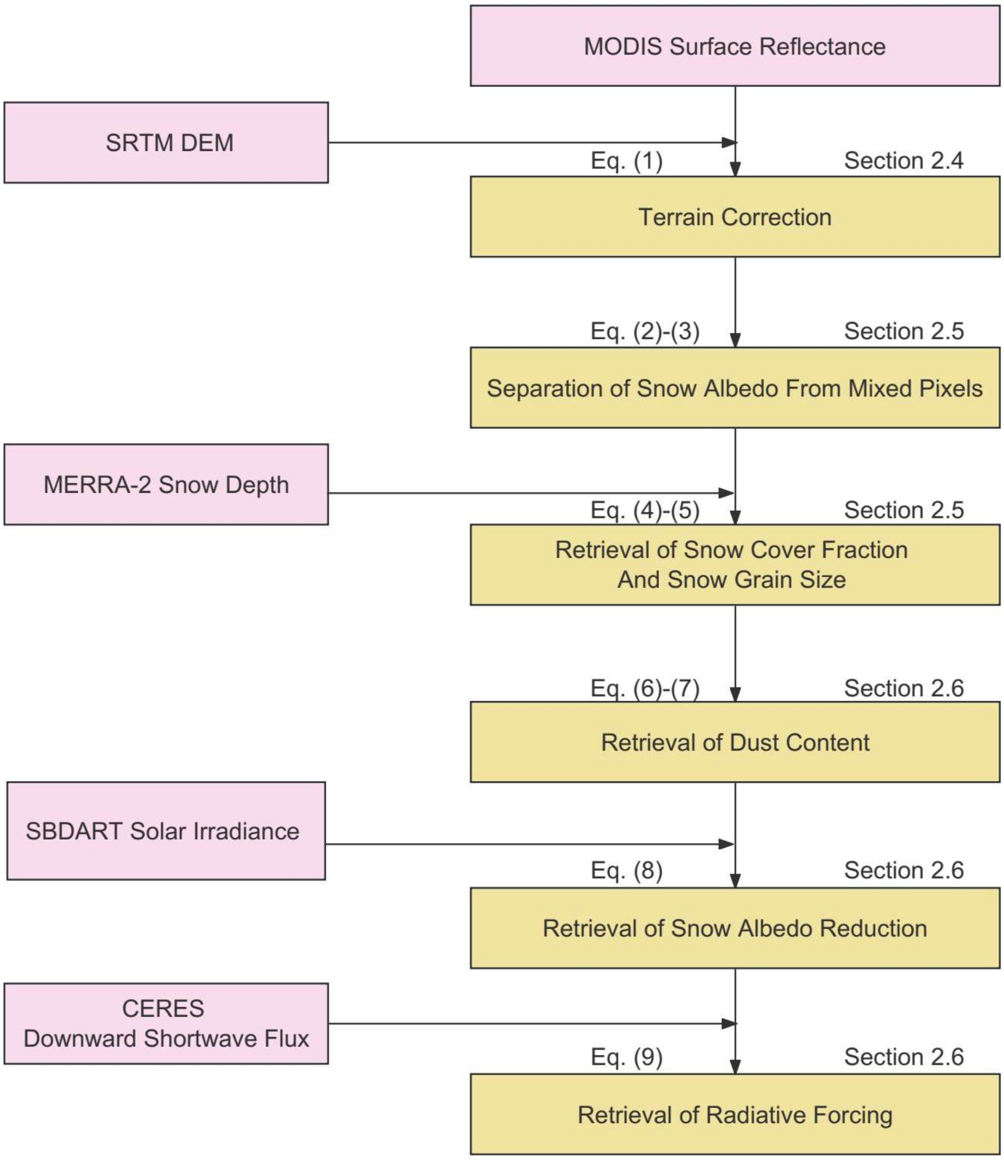


Figure 2. Flowchart illustrating the step-by-step retrieval of dust content and the associated snow albedo reduction and radiative forcing: the pink boxes denote the external input data, while the yellow boxes are used for calculations in this study.

7. Lines 161-163 mention that the SNICAR model provides spectral albedo, but lines 190-192 suggest you used the same model to derive snow grain size and dust content. This is confusing and should be clarified.

R: Sorry for the coarse description. To clarify the whole retrieval process, a flowchart illustrating the step-by-step derivation of dust content and the associated snow albedo reduction and radiative forcing has been added (Figure 2). We fit the SNICAR-simulated snow reflectance to the MODIS-derived snow reflectance to retrieve snow grain size and dust content. According to Eq. (4)-(7), snow grain size is initially retrieved using MODIS reflectance in Bands 2 and 5. Subsequently, dust content is determined using MODIS reflectance in Bands 3 and 4. Finally, we use SNICAR to simulate spectral albedo across 350-2500 nm, utilizing the previously retrieved snow grain size and dust content.

8. In general, the radiative transfer part of your work lacks clarity and should be improved. In Section 3.1.1 (Figure 3) (and also in the other 2 examples), you aim to demonstrate dust-induced snow-darkening within three days using MODIS/CALIOP snapshots. It's important to address whether the surface reflectance product in MODIS could be affected by dust aerosols. Consider checking and showing CALIOP feature curtains (similar to your Figure 3j) for all three days to ensure that the darkening isn't due to atmospheric dust particles but rather snow-darkening.

R: Thank you for the insightful comment. We have improved the radiative transfer part of this work. We fully agree with your concern about the potential impact of atmospheric dust on the uncertainty of satellite retrieval results. We have updated the discussion on the uncertainty of snow albedo reduction, taking into account the effect of atmospheric dust on MODIS surface reflectance. Furthermore, in response to your comments, a comprehensive examination of all three-day CALIPSO images was conducted. However, it was found that, apart from the CALIPSO images already presented in our paper, the CALIPSO satellite did not pass over the study area during three dust events.

9. Line 23: Why >2100, >600,… km^2? Why can't put the approximated area?

R: We have revised as suggestion.

10. Line 35: 'Through' -> 'From'

R: We have revised as suggestion.

11. Line 48: satellite- -> satellite

R: We have revised as suggestion.

12. Line 56: I am not quite sure what ‘imbalance’ you are referring to here

R: Observational evidence and model projections that describe an imbalance in the Asian water tower caused by accelerated transformation of ice and snow into liquid water (Yao et al., 2022). In addition to climate change, light-absorbing particle deposition can also accelerate this process (Kang et al., 2020). We have revised the related content in the manuscript to clarify the expression.

Reference

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