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LETTER

Impact of dust-cloud-radiation interactions on surface albedo: a case study of ‘Tiramisu’ snow in Urumqi, China

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Abstract

Dust–cloud–surface radiation interactions are a complex nonlinear relation referring to the influences of both atmospheric dust and dust-on-snow on surface albedo. A ‘Tiramisu’ snow event occurred on 1 December 2018, in Urumqi, China, providing an excellent testbed for exploring the comprehensive effect induced by atmospheric dust and those deposited atop fresh snowpack on surface radiation. A detailed analysis indicates that the decrease of snow albedo by 0.17–0.26 (22%–34%) is contributed by the effects both the dust–cloud interactions and dust-on-snow at synoptic scale in this case. In particular, dust well mixed with ice clouds at altitudes of 2.5–5.5 km disrupted the ‘seeder–feeder’ structure of clouds and heterogeneous ice nucleation. Dust-induced changes in the low layer of ice clouds (3.3–5.5 km) under a lower temperature of −20 °C resulted in a 31.8% increase in the ice particle radius and 84.6% increase in the ice water path, which acted to indirectly buffer the incident solar radiation reaching the surface. Dust particles deposited on the snow surface further caused snow darkening since the snow albedo was found to decrease by 11.8%–23.3%. These findings underscore the importance of considering the comprehensive effect of dust–cloud–radiation interactions in the future.

1. Introduction

Dryland has expanded in semiarid regions and the warming rate over global dryland has been 20%–40% larger than that over humid regions since the 1960s, indicating dryland will suffer stronger warming risks such as desertification. Dust aerosols are mainly emitted by wind erosion over drylands (Kulkarni et al 2014, Chen et al 2018), and then modulate Earth’s radiative budget and hydrological cycle by direct and indirect effects (Gu et al 2012, Niemand et al 2012). This feedback mechanism is a complex nonlinear relation.

On the one hand, a large body of laboratory studies and numerical modelling since the 1950s has indicated that dust aerosols are the most effective ice nuclei (IN) and have a dramatic correlation with ice cloud formation in the middle and upper troposphere via heterogeneous ice nucleation (Sullivan et al 2010, Ansmann et al 2019, Zeng et al 2020, Wang et al 2021). Previous studies have shown that the ice cloud top temperature induced by dust is obviously higher than that without dust. For example, Saharan dust can cause a significantly higher amount of ice-containing cloud cover (25%–30%) with cloud top temperatures from −10 °C to −20 °C (Seifert et al 2010). Levin et al (2005) found that an increase in IN concentration induced by dust can reduce the collision efficiency between liquid droplets and further weaken cumulus precipitation in the Mediterranean region. Dust concentration within clouds, cloud type, cloud height and meteorological conditions lead to big changes and even mutations or reversals in dust–cloud interactions (Wielicki et al 1996, Zelinka et al 2014,
Zhao et al 2014, Fan et al 2016, Wang et al 2018, Liu et al 2019, Patel et al 2019). Moreover, under certain water vapour conditions, an increase in dust aerosols can reduce the effective radius of cloud droplets, increase the cloud albedo, change the cloud lifetime, and indirectly lead to the enhancement of reflected radiation and a decrease in surface temperature (Han et al 2008, Sun et al 2012).

On the other hand, dust-on-snow/ice is involved in complex processes of albedo feedback (Doherty et al 2013, Skiles et al 2018). Dust particles deposited on snow during long range transport can reduce snow/ice albedo and accelerate subsequent glacier melting under global warming background (Qian et al 2011, 2015, Dong et al 2014, Li et al 2016, Usha et al 2020). Observations and high-resolution modelling pointed out that the influence of snow darkening induced by dust is greater than that of black carbon above elevations of 4000 m in mountainous parts of Asia (Sarangi et al 2020). Dust deposited on snow has accelerated the melting of snow and ice over the Tibetan Plateau (TP) since 1990, then changing the radiation budget, especially for surface albedo, resulting in an increase in the surface temperature of 0.1 °C–0.5 °C in the southwestern TP and Kunlun Mountains in spring (Ji 2016, Wittmann et al 2017). Snow darkening further modulates summer monsoon circulation and hydrological cycles over East Asia and South Asia, effectively altering ecosystems, inducing additional carbon release, generating positive feedback, and thus accelerating climate warming (Yang et al 2010, Qian et al 2011). The previous studies emphasized the climate impacts of light-absorbing impurities (LAI) on snow albedo based on a community Earth system model. Few studies investigated the effects of dust on snow albedo from an observational perspective. Some studies have tried to analyse the influence of LAIs on snow albedo and snow melting through field experiments by sprinkling dust and BC on snow, ignoring the atmospheric aerosol and cloud effects on Earth’s system. These observations may provide inaccurate constraints on the modelling.

Overall, these studies have only been confined to the surface or the atmosphere, respectively, which cannot reflect the real aerosol physical process in weather and climate systems. For example, changes in cloud properties and precipitation efficiency induced by dust can further influence surface radiation (Zhang et al 2012). Therefore, it is necessary for considering the combined effect of both atmospheric dust and dust-in-snow based on observation facts. The study of dust–cloud–surface radiation interactions (DCRI) especially their impacts on surface albedo is important in deep understanding of aerosol impacts on Earth’s system (Douglas and L’Ecuyer 2019, Kant et al 2019, Cherian and Quaas 2020, Wang et al 2021).

On 1 December 2018, a rare weather event occurred in Urumqi, China. Strong winds and dust storms shrouded in Xinjiang after a sharp decrease in temperature accompanied by a heavy snow episode. The surface in Urumqi looked like ‘Tiramisu’ snow because of the accumulation of snow prior to the dust. Affected by the ‘Tiramisu’ snow, the international airport in Urumqi issued a yellow emergency alert. Three hundred and seven flights were cancelled, 34 flights delayed, and more than 4000 passengers were stranded. This weather event provides an excellent testbed for exploring DCRI. The study area and datasets are presented in section 2. Section 3.1 analyses the spatio-temporal distribution and cause of Tiramisu snow. Section 3.2 focuses on the influences of dust on ice cloud properties and of heterogeneous ice nucleation on the formation and development of ice clouds. In section 3.3, the effect of DCRI on the snow albedo is discussed. The conclusion and discussion are given in section 4.

2. Method

2.1. Study area

Urumqi (42.45°–44.08° N, 86.37°–88.58° E), the provincial seat of Xinjiang Uygur Autonomous Region, is located in the northern Tien Shan Mountains and the southern edge of the Junggar Basin, which is surrounded by vast desert areas, including the Taklamagan Desert to the south, the Gurbatunggut Desert to the north, and the Gobi Desert to the east. Due to the prevailing westerly circulation, dust particles from adjoining deserts are often carried to the Urumqi area from the northern Tianshan Mountains, resulting in frequent dust storms in this region (Li et al 2008, Dong et al 2010, 2011). Furthermore, the natural terrain barrier of the Tianshan Mountains also causes cold air to remain in the Junggar Basin during winter, which is conducive to the occurrence of snowfall and blizzards in Xinjiang.

2.2. In-situ measurement

The in-situ ground observation dataset are from regional automatic weather stations in Urumqi, including PM$_{10}$ concentration, temperature at 2 m, precipitation, snow depth and cloud cover. The dataset of solar shortwave radiation used include absorbed total solar radiation, scattered radiation and reflected radiation, which are provided by the State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences. Scattered radiation is identified as shortwave radiation scattered by atmospheric particles or reflected by clouds. Reflected radiation refers to the part reflected upward by the underlying surface after the incident solar radiation reaches the surface. Absorbed total solar radiation is the sum of direct solar radiation and scattered radiation. The surface albedo is defined as the ratio of
the all-wavelength solar radiation reflected by the surface to that incident upon it (Zhang 2005, Zhou et al 2020). The corresponding variables used in this study are shown in figure S1 (available online at stacks.iop.org/ERL/17/015001/mmedia).

2.3. CALIPSO and CERES
The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP/CALIPSO) is a two-wavelength, polarization-sensitive backscatter lidar that has strong sensitivity for the detection of aerosols and clouds and can therefore perform global profiling in the troposphere and lower stratosphere (Winker et al 2009). In this study, the classified particles from the Version 4 Level 2 CALIPSO lidar vertical feature mask (VFM) product are utilized to identify the vertical structure of dust, ice and liquid clouds (table S1).

Clouds and the Earth’s Radiant Energy System (CERES) is one of the highest priority scientific satellite instruments flying on several Earth Observing System (EOS) satellites and is used to examine the role of cloud and radiation feedback in the Earth’s climate system (Wielicki et al 1996). In this study, the 1-hourly SYN1deg_Ed4A product, with a resolution of 1° × 1°, is used to analyse cloud properties, including the ice water path (g m⁻²), ice particle radius (µm) and cloud top temperature (°C) (table S1).

2.4. MODIS
Moderate-Resolution Imaging Spectroradiometer (MODIS), on boarding on Terra and Aqua satellites, serves as one of the most widely used satellite remote sensing platforms for Earth science research (Justice et al 2002). Terra and Aqua satellites features with high spectral (36 channels), spatial (10 km) and temporal (5 min) resolution, wide spectral ranges (0.412–14.24 µm) and daily coverage at the global scale (Savchenko et al 2004). MODIS provides reliable and extensive results of aerosol and cloud for monitoring large-scale changes when it swept 2330 km wide viewing swat (Alexander et al 2018). The MODIS cloud product provides retrievals of cloud optical properties and other physical parameters, which are derived from solar reflected radiances that are remotely sensed infrared, visible and near infrared (Platnick and Meyer et al 2016). Moreover, compared with the dark target algorithm, the deep blue algorithm was developed to retrieve aerosols properties over bright surfaces, with its excellent performance in distinguishing dust storms and less uncertainties in the region where surface reflectance is much lower than in other longer visible bands.

2.5. MERRA-2
The second Modern-Era Retrospective analysis for Research and Applications (MERRA-2) is the latest atmospheric reanalysis of the modern satellite era produced by NASA’s Global Modeling and Assimilation Office. It begins in 1980 and uses an updated Goddard EOS model and assimilates more types of observations. All data collections from MERRA-2 are at the regular longitude-by-latitude grid of 0.625° × 0.5° (Molod et al 2015, Gelaro et al 2017). In MERRA-2, dust is simulated with the Goddard Chemistry, Aerosol, Radiation, and Transport model (Chin et al 2002) using a representation of dust sources from Ginoux et al (2001) and the dust emission scheme of Marticorena and Bergametti (1995). In this study, aerosol optical depth (AOD), mass fraction of cloud water (kg kg⁻¹), air temperature (°C), dust mixing ratio (kg kg⁻¹) of MERRA-2 are used in the study (table S1).

Numerous previous studies presented an evaluation of the MERRA-2 system with respect to non-assimilated aerosol properties (e.g. AOD, absorption, vertical profile, PM₂.₅) and cloud properties (e.g. ice cloud effective radius, liquid/ice cloud water path, cloud phase). They compared hourly AOD to AERONET observations at the global scale and found that at all stations, the MERRA-2 AOD better matches the observations, not only in terms of correlation but also in terms of more realistic variability and reduced root mean squared error (Buchard et al 2017, Randles et al 2017). Moreover, Wang et al (2018) found that MERRA-2 best captures the most of the observed cloud-radiation physics, and largely reproduces cloud properties compared with CERES. Posselt et al (2012) examines the representation of deep convective clouds in MERRA, comparing the liquid and ice clouds with deep convective cloud observed by the Tropical Rainfall Measuring Mission satellite retrievals. It showed that MERRA contains deep convective clouds in 98.1% of observations. We evaluate the MERRA2 datasets compared with AOD (figures 1(b) and S5) and the mass concentration of ice cloud and liquid cloud (figure S3) from MODIS retrievals. It is found that MERRA2 could well reproduce the spatial and temporal distributions of dust aerosol and cloud microscopic properties in this case, which is consistent with related studies by Xu et al (2020) and Gui et al (2021).

3. Results

3.1. Spatial and temporal distribution of Tiramisu snow
Tiramisu snow is a phenomenon of stratification with deposited dust in the upper layer and snow cover in the lower layer at the surface, which formed from strong winds, heavy snowfall, and dust storms successively in northern Xinjiang on 1 December 2018. Due to the influence of cold air (figure S1) and continuous water vapour transport (figures S2(a) and (b)), heavy snowfall occurred in northern Xinjiang (figure 1(a)). Strong winds resulted in the occurrence of dust storms and float dust at 17 meteorological observation stations in Xinjiang, among which nine
stations experienced dust storms, and strong dust storms occurred at five stations (figure S4). The dust index (DI), based on the frequency of floating dust, blowing dust and dust storms, well represents dust intensity (Wang et al. 2008). The strongest dusts with a DI between 11 and 20 appeared in Manas (85°40’–86°31’32”E, 43°21’21”–45°20’N) and Qitai (9°13’–91°22’E, 42°25’–45°29’N) in the southern edge of the Gurbantunggut Desert and Yanqi (85°13’19”–86°44’00”E, 41°45’31”–42°20’45”N) and Turpan (N44°1’2”–43°40’E, 88°16’–91°55’N) on the northern edge of the Tarim River (figure 1(a)). Dust aerosols in Urumqi originate mainly from external transport over the Gurbantunggut Desert. Dust concentrations greater than 500 µg m\(^{-3}\) were mainly concentrated below 3.3 km (figure S6). The PM\(_{10}\) concentration in Urumqi affected by the dust storm started relatively late at 6:00 local time (LT) and showed a three-peak structure in this day. The peak values appeared at 7:00, 12:00 and 16:00 LT, and the PM\(_{10}\) concentrations reached 2.33 \(\times\) \(10^3\), 4.38 \(\times\) \(10^3\), and 4.44 \(\times\) \(10^3\) µg m\(^{-3}\), respectively (figure 1(c)). The value of the first peak was the lowest due to wet deposition during this period. As indicated by MODIS composite images (figure 1(b)), AAOD soared to more than 0.3 and extended towards southeast of Xinjiang. Meanwhile, a well-developed cloud, that was partially within the thick dust layer and covered the whole domain where 12 h (0–12 Universal Time Coordinated (UTC)) cumulative precipitation was 10–17 mm, was observed by in-situ measurements (figure 1(c)).

The distribution of heavy snowfall was consistent with the strong DI in the Changji (86°24’–87°37’E, 43°06’–45°20’N) and Shihezi (84°58’–86°24’E, 43°26’–45°20’N) regions, especially in Urumqi. High values of snow depth, ranging from 15 to 22 cm, occurred in the Altai (86°53’–88°37’E, 47°27’–48°38’N) and Tacheng (82°41’–83°41’E, 46°21’–47°14’N), as well as Urumqi, Shihezi, and Changji along the Tian Shan Mountains. The main snowfall in Urumqi began at 5:00 local time (LT = UTC + 8 h) and ended at 12:00 LT, lasting for 7 h with the maximum hourly precipitation reaching 2.7 mm (figure 1(b)). Moreover, the upper air in Urumqi was almost completely covered by clouds from 1 to 2 December, and the cloud fraction reached approximately 85%–100% (figure S3(b)).

Why do dust storms occur during such heavy snowfall? Based on reanalysis data, in-situ measurements and satellite retrievals, the causes of the Tiramisu snow event are further discussed (see figure 1(d)). Overall, the European Plain and Lake Baikal region were controlled by high-pressure ridges, and the Western Siberian-Aral Sea area was controlled by a trough on 30 November (figure S2(a)). Since the strong cold air invaded southward to the Western Siberian region, a closed low vortex formed in the Western Siberian-Aral Sea area and transferred to a vertical pattern. Cold air from high latitudes invaded southward with northwesterly airstreams. The temperature at 2 m decreased from 10.9 °C to below −10 °C, and the lowest temperature reached −13 °C in Urumqi on 1 November 2018. A LLJ at 500 hPa was observed by satellite images (figure 1(b)). Since the strong cold air invaded southward with northwesterly airstreams. The temperature at 2 m decreased from 10.9 °C to below −10 °C, and the lowest temperature reached −13 °C in Urumqi on 1 November 2018. A LLJ at 500 hPa was observed by satellite images (figure 1(b)).
December (figure 1(c)). The cold outburst led to a dry and cold air mass from high latitudes that intensified rapidly in central Siberia (70°–90° E, 43°–65° N) and invaded low and middle latitudes, causing a sharp decrease in temperature and northerly gale weather in northern Xinjiang. Moreover, the water vapour belt in the northern edge of Xinjiang moved to lower altitude regions from 20:00 LT on 30 November (figure S2(a)) to 02:00 LT (figure S2(b)) on 1 December, and the water vapour flux from 1000 to 300 hPa reached $2.8 \times 10^4$ kg m$^{-1}$ s$^{-1}$. Strong northwesterly air-streams converged with warm wet mass near 45° N and resulted in heavy snowfall happening in the northern frontier region of Xinjiang on 1 December (figure 1(d)). Dust emission induced by intensified northerly gale in the western Gurbantunggut desert. A large amount of dust particles that were transported southward to the northern part of Xinjiang were blocked by the Tianshan Mountains, falling to the ground with the snowfall owing to wet deposition and continuously accumulating on snow. Thus, the ‘Tiramisu’ snow event was commonly caused by dust storms shortly after heavy snowfall.

3.2. The implications of dust effects on ice clouds

The ice cloud increased significantly in northern Xinjiang with a high cloud water path (170 g m$^{-2}$) and cloud top height (10 km), but the corresponding ice particle radius decreased to 24 µm at 14:45 LT (figure S3). In the vertical profile, the cloud system showed an uneven vertical structure, with pure ice clouds above 7 km, ice-phase clouds at 5–7 km, and liquid water clouds below 5 km in the central Xinjiang at 05:00 LT on 30 November based on CALIPSO, CERES, MODIS retrievals and MERRA2 reanalysis data. The vertical profile of ice water paths from CERES is consistent with that from MERRA2 (figure 2(c)). These clouds formed a typical ‘seeder–feeder’ structure (Hobbs and Locatelli 1978, Rutledge and Hobbs 1983). When water vapour and supercooled water droplets froze in the high layer (5.5–7 km), they grew into ice crystals through condensation and riming, forming the ‘seeder’ layer. The ice crystals that fell to the lower layer (3.3–5.5 km) grew rapidly through the Bergeron process, forming the ‘feeder’ layer. The interactions between the seeder layer and feeder layer led to snowfall in central Xinjiang, where snow depth varied from 5 to 7 cm on 30 November (figure S7).
Based on the VFM of CALIPSO, dust aerosols were found to be well mixed with ice clouds and a small number of liquid clouds at 2.5–5.5 km in central Xinjiang (85.4°–90° E, 38°–43° N) on 1 December (figure 2(a)). Dust was mainly concentrated in the low layer (3.3–5.5 km), and its concentration reached 469.5 µg m⁻³ at 17:00 LT (figure 2(c)). The increase in dust aerosols effectively initiated ice formation and resulted in the redistribution of ice clouds and liquid clouds by disrupting the original seed–feeder structure of clouds, which further modified snow cover and the content dust-on-snow by wet deposition (figure 2(c)). Although the dramatic increases of ice clouds also related with the decrease of temperature, dust aerosols were still one of the main reasons resulting in a change of ice cloud properties.

In the first stage, with the increase in the observed dust concentration from 06:00 to 12:00 LT, dust aerosols acted as ice nucleus accelerating the heterogeneous nucleation of ice clouds. Ice crystals from CERES retrievals located in the low layer (3.3–5.5 km) absorbed super-cooled water droplets and froze into larger particles with cloud top temperatures less than −20 °C. Dust aerosols was conducive to ice particles growing into a greater size with an adequate supply of water vapour and sustained low temperature before 12:00 LT on 1 December. The radii of ice particles grew from 24.3 to 38.7 µm (figure 2(c)), with a strong updrafts within deep convective clouds (with IWP > 300 g m⁻²). In the second stage, after 12:00 LT, the decrease in the temperature gradient weakened atmospheric circulation and cold air transport southward, and further resulted in a slight rising in air temperature. When the dust concentration exceeded 350 µg m⁻³, ice clouds induced by dust aerosols hardly increased to a greater size under limited water vapour transport conditions and relatively warmer conditions (figures S2(c) and (d)). Large amounts of dust particles rearranged the limited water vapour, which caused a significant decrease in the ice particle radius from 38.7 to 26.2 µm (figure 2(c)).

3.3. The impact of dust–cloud–surface radiation on snow albedo

Slight changes in snow albedo can significantly impact surface warming due to rapid feedbacks involving changes in snow morphology, sublimation, and melt rates (Bond et al. 2013, Liou et al. 2014, Li et al. 2018). Actually, the change in snow albedo was synthetically dominated by snow impurities, atmospheric dust, and clouds in this dust event, especially at the synoptic scale (figure 3). The radiation variations at the surface were closely related to PM₁₀ concentration and cloud mass fraction (figure 3(a)). Affected by Tiramisu snow, the solar radiation reaching the surface was at a minimum on 1 December, and the surface solar radiation, scattered radiation and reflected radiation reached 60, 58 and 34 W m⁻², respectively (figure 3(b)). The snow albedo decreased by 0.17 to 0.26 (approximately 22%–28%) on 1 December compared to the albedo of pure snow on 2 December. Simultaneously, the PM₁₀ concentration reached 4700 µg m⁻³ and the ice cloud concentration exceeded 80 mg kg⁻¹ on this day (figure 3(a)).

To investigate the influence of dust–cloud radiation on the snow albedo in light of the key factors influencing the snow albedo, cloud cover (100%), snow depth (12 cm) and dust concentration (0–40 µg m⁻³) in the case were used as constraining conditions (figures 3(c) and (d)). Four scenarios are compared with the Tiramisu snow case, and they are defined as follows. (a) The cloud cover is the same; the snow depth is 0; the event involves no dust; and the PM₁₀ concentration is less than 40 µg m⁻³. (b) The snow depth is the same; the cloud cover is 0; the event involves no dust; and the PM₁₀ concentration is less than 40 µg m⁻³. (c) The cloud cover and snow depth are the same; the event involves no dust; and the PM₁₀ concentration is less than 40 µg m⁻³. (d) The cloud cover and snow depth are 0; the event involves no dust; and the PM₁₀ concentrations are less than 40 µg m⁻³. It is found that the change of surface radiation induced by dust is not a linear superposition caused by dust aerosols in atmosphere and dust particles deposited on snow. It contributed to non-linear interactions of complex dust–cloud–radiation feedback especially at the synoptic scale. Thus, the classification of scenarios could determine the comprehensive impact of dust in the atmosphere and at the surface on surface radiation.

Statistics showed that the net surface solar radiation reached 260 W m⁻² and the surface albedo varied from 0.04 to 0.1 under clear sky conditions (green lines in figure 3(c)). Reflection from clouds significantly weakened the incident solar radiation. When the cloud cover was 100%, the solar radiation reaching the surface was 62.5 W m⁻², decreasing 75.6% compared to clear sky conditions (purple and green lines in figure 3(c)). The interception of incident solar radiation by snowfall was clearly weaker than that of cloud cover. When the accumulated snow depth was up to 12 cm, the solar radiation reaching the surface was 195.2 W m⁻², which was reduced by 23.8% (blue and green lines in figure 3(c)). Cloud cover and snowfall had a combined effect on the change in surface solar radiation ranging between 72.6 and 107.8 W m⁻², which were reduced by 57.8%–65.4% (black and green lines in figure 3(c)). In addition, the snow albedo was in the range of 0.6–0.85.

The influence of DCRI on snow albedo was more complex, especially when the dust concentration in the troposphere reached 200–600 µg m⁻³ (figure 2(c)). Dust aerosols strongly absorbed and scattered incident solar radiation, resulting in a rapid increase of the mass fraction of ice clouds rapidly increasing from 20 to 724.6 mg kg⁻¹.
Figure 3. (a) Evolution of surface solar radiation (black line), PM$_{10}$ concentration (yellow dots), snow albedo (red line) and ice cloud mass fraction (blue line) in Urumqi from 30 November to 3 December. (b) Variations in surface solar radiation (black line), scattered radiation (red line) and reflected radiation (blue line) in Urumqi. (c) Surface solar radiation (SSR) under different weather conditions, including dusty, snowy and cloudy weather on 1 December (red line); snowy and cloudy weather (black line); snowy weather without dust and cloud (blue line); cloudy weather without dust and snow (purple line), and clear sky (green line). Note that the snow depth in snowy weather was 12 cm, cloud cover in cloudy weather was 100%, and these values are consistent with the weather conditions on 1 December 2018. (d) Snow albedo under five different weather conditions.

The simultaneous increases in cloud cover, dust concentration and snowfall intensity caused the surface solar radiation to decrease to 22–60 W m$^{-2}$, which was reduced by 76.5%–85.5% compared to clear sky conditions (red lines in figure 3(c)). Moreover, dust particles deposited on the snowpack dominated snow darkening, which effectively weakened the strong reflection of solar radiation by snow cover, resulting in the reflected radiation varying between 20 and 34 W m$^{-2}$. The snow albedo decreased by 11.8%–23.3% (black and red lines in figure 3(c)), which may further accelerate the melting of snow.

4. Discussion and conclusion

Dust physical processes, including emission, transport and wet/dry deposition, is closely related to the atmosphere, hydrosphere and cryosphere. These feedback mechanisms have a complex nonlinear relation. However, previous studies always focused on dust effects only confined to the surface or the atmosphere including dust–cloud interactions and snow darkening induced by dust impurities in several decades. The research on DCRI is relatively insufficient. Heavy dust-storms and snowfall events occurring in Xinjiang on 1 December gives us an insight into the
dust–cloud–radiation interaction and its impacts on snow albedo. This study pointed out that the decrease of snow albedo is contributed by the integrated effect of both the dust in the atmosphere and dust-on-snow and underscores the importance of considering the comprehensive effect of dust–cloud–radiation interactions and dust-on-snow on snow albedo in a future study.

This case study occurred in Urumqi in the Xinjiang region during the winter. Due to the outbreak of cold waves, cold air from the western Siberian region rapidly invaded the northern Xinjiang. Accompanied by a continuous water vapour supply, heavy snowfall occurred in Urumqi under low temperatures of less than −10 °C. The PM$_{10}$ concentration reached $4.4 \times 10^3$ µg m$^{-3}$ due to the continuous transport of dust aerosols from the Gurbantunggut Desert. Therefore, the surface in Urumqi showed a stratification pattern like that of 'Tiramisu’ due to snowfall prior to the deposition of dust. It is noted that fresh snow is involved in more complex weather conditions compared with old snow, which has larger uncertainties in the change of snow albedo. Overall, Dust aerosols were well mixed with ice clouds in the low layer (3.3–5.5 km) in the case study. Dust aerosols acted as IN to effectively promote ice formation and prolong the ice cloud lifetime and increased the mass fraction of ice clouds to 724.6 mg kg$^{-1}$ when the dust concentration ranged between 200 and 600 µg m$^{-3}$, it indirectly decreased the incident solar radiation by 76.5%–85.5%. Moreover, dust particles deposited on snow during long range transport can reduce the snow/ice albedo by 11.8%–23.3% and accelerate subsequent snow melting (figure 4).

The study of DCRI is a challenging job. There is an urgent need to advance our understanding of DCRI physical properties and processes using a variety of new observational techniques, new model schemes and new theories. There are several uncertainties in this case study. Firstly, due to this sudden weather event, we did not have time to accurately capture the first-hand observations including cloud microphysical characteristics, aerosol vertical structure through field experiments. We used observations in the in-situ measurement and satellite retrievals and MERRA-2 reanalysis data in the study. To avoid errors in interpolation of datasets with different spatial resolutions, we did not re-map all the datasets to a consistent grid. It is noted that MERRA-2 could well capture the observed aerosol and cloud properties from MODIS and CERES retrievals. But the reanalysis fits the observations most closely for the largest class of convective systems, with performance generally decreasing with a transition to smaller convective systems.

Secondly, clouds are one of the largest uncertainty factor in predicting future climate change (Mark et al 2017). Although the influence of clouds on shortwave and longwave radiation has been well studied, the dominant role of cloud interactions with solar radiation is still uncertain (Liepert et al 2002, Yang et al 2015). In this case, we focused on the mixed phase cloud system with pure ice clouds above 7 km, ice-phase clouds at 5–7 km, and liquid water clouds below 5 km. The optical extinction of such clouds is much greater than that of clear sky and cirrus, which play an more important role in the DCRI. Further discussions on the impacts of different aerosol types on various cloud macroscopic properties (cloud

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Figure 4. Schematic diagram of dust–cloud–surface radiation interactions.
cover, cloud thickness and liquid water path, etc.), microscopic properties (ice crystal number concentration and size distributions) involved with thermodynamic, cloud microphysical process and chemical process should be investigated in detail in the study of DCRI.

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Data availability statement

No new data were created or analysed in this study.

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