Urban air quality in Xinjiang and snow chemistry of Urumqi Glacier No. 1 during COVID-19’s restrictions

Feiteng Wang1 · Xin Zhang1 · Fanglong Wang1 · Mengyuan Song1 · Zhongqin Li1 · Jing Ming2

Received: 18 December 2021 / Accepted: 25 May 2022 / Published online: 4 June 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract
The unprecedented COVID-19 outbreak impacted the world in many aspects. Air pollutants were largely reduced in cities worldwide in 2020. Using samples from two snow pits dug separately in 2019 and 2020 in Urumqi Glacier No. 1 (UG1) in the Xinjiang Uygur Autonomous Region (Xinjiang), China, we measured water-stable isotopes, soluble ions, and black and organic carbon (BC and OC). Both carbon types show no significant variations in the snow-pit profiles dated from 2018 through 2020. The deposition of anthropogenically induced soluble ions (K+, Cl−, SO42−, and NO3−) in the snow decreased to 20–40% of their respective concentrations between 2019 and 2020; however, they increased 2- to fourfold from 2018 to 2019. We studied the daily concentrations of SO2 (2019–2020), NO2 (2015–2020), CO (2019–2020), and PM2.5 (2019–2020) measured in the sixteen major cities and towns across Xinjiang. The variabilities in these air pollutants were supposed to illustrate the air quality in the urban area and represent the change in the source area. The NO2 decreased in response to mobility restrictions imposed by local governments, while SO2, CO, and PM2.5 did not consistently correspond. This difference indicates that the restriction measures primarily affected traffic. The increases in chemical species in the snow from 2018 to 2019 and the subsequent decreases from 2019 to 2020 were consistent with the variations in SO2 and NO2 measured in urban air and estimated by MERRA-2 model. Therefore, the pandemic could possibly have an impact on snow chemistry of the Tien-Shan glaciers via reduced traffic and industrial intensity; more evidence would be obtained from ice cores, tree rings, and other archives in the future.

Keywords COVID-19 · Snow chemistry · Urumqi Glacier No. 1 · Air pollutants

Introduction
At the end of 2019, a novel virus known as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was first reported in Wuhan, China and spread worldwide in the following months (WHO 2020). The proliferation of the coronavirus disease 2019 (COVID-19) cases caused by SARS-CoV-2 urged the World Health Organization (WHO) to declare it a pandemic on 11 March 2020 (WHO 2021). At the time of this writing, COVID-19 has infected over 510 million people in almost every country on earth and caused 6.2 million deaths with infection cases in almost every country on earth (WHO 2022). In response, governments worldwide have enacted restriction policies when necessary to slow the viral spread (Han et al. 2020). Coinciding with these restriction measures, emissions (e.g. CO2, SO2, NO2, and other air pollutants) from anthropogenic activities (industry, tourism, transportation, agriculture, etc.) have dramatically declined (Friedlingstein et al. 2020).

Another study concluded that the reduction in greenhouse gases and air pollutants emissions reduced future warming by 0.3 °C by 2050 (Forster et al. 2020), although no near-future (2020–2024) impact on surface temperature was detected by Jones et al. (2021). During the global-scale lockdown (March to May 2020), PM2.5 and NO2 concentrations decreased by 16% and 46%, respectively, compared to the...
same period during 2015–2019 (He et al. 2021). In Somerville, MA, USA, a nearly 2-month measurement showed that ultrafine particle number concentration and black carbon (BC) concentration during lockdown were 60–68% and 22–46% lower than pre-pandemic levels (Hudda et al. 2020). In Milan, Italy, the mandated lockdown during February 2020 caused significant reductions in PM$_{2.5}$, BC, CO, and NO$_x$ (Collivignarelli et al. 2020). In São Paulo, Brazil, the late March 2020 lockdown also decreased NO$_x$ and CO concentrations in the atmosphere by over 50% (Nakada &Urban 2020). In China, the average NO$_x$ load in the atmospheric column over all cities dropped 40% in January–April 2020 compared with the same period in 2019, according to satellite measurements (Bauwens et al. 2020). However, a modelling study independent from the direct measurements estimated that the emissions of SO$_2$, NO$_x$, CO, non-methane volatile organic compounds (NMVOCs), and primary PM$_{2.5}$ decreased by 27%, 36%, 28%, 31%, and 24%, respectively, in February 2020 compared with those in February 2019 (Zheng et al. 2021).

Because chemical transformations in the atmosphere also have various roles in air quality, the reduction in the primary pollutants did not necessarily lead to air quality improvement but demonstrated complex chemical effects (Kroll et al. 2020). In the populous areas of eastern and northern China, the dramatic decrease in primary pollutants, specifically NO$_x$, facilitated the formation of ozone and night-time NO$_3$ radicals, which in turn fuelled the formation of secondary pollutants. Consequently, these secondary pollutants may have offset the effects of the decreased primary pollutants on air quality. This explains why unexpected haze events still occurred during the lockdown periods (Huang et al. 2020; Le et al. 2020).

The Xinjiang Uygur Autonomous Region (hereafter “Xinjiang”) spans over 1.6 million km$^2$, which is one-sixth of China’s total land area, and has ~25 million inhabitants (SBX 2020). With such a large area and relatively small population, the population density of Xinjiang is approximately 1/15 of the national average and is highly concentrated in the major cities in each prefecture-level administrative district (Mao et al. 2016; Wu et al. 2015). Relatively small urban populations in Xinjiang differ in air pollution features from those of the more populated eastern China. For example, a recent 3-year measurement reported that the concentrations of black carbon (BC) in Jimunai, a small town on the Kazakhstan-China border, were comparable to Beijing and increasing dramatically (Wang et al. 2021). An investigation into the air quality in 16 major cities in Xinjiang revealed that the daily mean PM$_{2.5}$ concentrations were ~8–54 times higher than the WHO guideline (Rupakheti et al. 2021).

Following the lockdown that began on 23 January 2020 in Wuhan, the Xinjiang government quickly launched a level-1 Public Health Emergencies Response (PHER) in 2 days (January 25) (GUXARC 2020). In the following months, Xinjiang lifted these restrictions gradually to level-2, 3, 4, and normal from February 25 (SCC 2020), March 7 (Xnews 2020b), March 21 (Xnews 2020c), and September 1 (Pdaily 2020) onward, respectively (refer to Table S1 about PHER in the Supporting Information). The distribution of chimney-aliike pollution sources within the vast and relatively lightly polluted background of Xinjiang drives us to study the effects of the lockdown controls employed by the local government on the air quality in the major cities during the pandemic.

The pollutants dispersed from sources would be transported over adjacent mountain glaciers and received by them via dry deposition and (or) wet scavenging. The glaciochemistry information preserved in snow and ice through air-snow exchange process (Elias 2021; Harder et al. 2000, Kreutz &Koffman 2013) provides an excellent archive to study the relationship between the reduced anthropogenic activities and the nearby glaciers records. For example, non-sea-salt sulphate in air and snow samples was measured to estimate the tropospheric residence time at the South Pole (Harder et al. 2000); Aerosol and fresh snow samples collected near Mt. Qomolangma (Everest) were measured for major ions to calculate their scavenging ratios (Ming et al. 2007); the seasonal variations of sulphate and methane sulfonic acid (MSA) in aerosol and snow at two sites of the Greenland Ice Sheet indicated a much less accumulation of winter snow at the summit (Jaffrezo et al. 1994). All above studies demonstrate the close relationship between air and snow chemistry and suggest the snow or glacio-chemistry can reflect the local or regional atmospheric environment.

In the early stages of the COVID-19 outbreak, a few reports predicted that the pandemic would likely leave traces in the future snow-and-ice records (Goyal 2020; NSF 2020). A recent remote-sensing work suggested a 30% reduction in the deposition of light-absorbing particles (BC, dust, etc.) in the Indus River Basin snow during the spring and summer of 2020 (Bair et al. 2021). However, a sole field measurement reported no change in BC levels on a Peruvian glacier before and during the pandemic (Sanchez-Rodriguez 2020). Xinjiang is a major area of mountain-glacier development in China (Aizen et al. 2007, Liu &Liu 2015, Liu et al. 2016). We suppose a possible perturbance in the glaciochemistry record in Xinjiang’s glaciers resulting from the pandemic in Xinjiang’s glaciers. In this study, we investigated glaciochemical-record abnormalities due to the COVID-19 pandemic in Urumqi Glacier No. 1 (UG1) (43.08°N, 86.80°E, ~3750–4500 m a.s.l.), at Tian-Shan Mountain, as it has conventional long-term snow-pit sampling (Fig. 1).
Material and methods

Snow sampling in UG1

The UG1 is a well-known mountain glacier and hosts a long-term conventional observation project. Each summer, research staff routinely dig snow pits and sample snow to study mass balance and snow physics and chemistry on the glacier. On 14 Jun 2019 and 18 Jun 2020, we dug a 180 cm deep snow pit and a 200 cm deep snow pit, respectively, at the equilibrium line altitude (4000 m above sea level) of the glacier, respectively. We sampled snow using Whirl–Pak® bags at a 10 cm interval alongside a ruler (see Fig. S1 in the Supporting Information). A scale was used to measure the snow density of each layer in the pits after sampling with a snow cutter. The samples were packed into the bags and transported at \(-15 \text{ °C}\) to the State Key Laboratory of Cryospheric Science in Lanzhou for further analysis. In the laboratory, snow samples were placed in a room-temperature cleanroom until melted entirely.

Measuring the snow chemistry in the laboratory

Measurements of oxygen-18, deuterium, and soluble ions

We used a liquid water isotope analyser (Model LWIA DLT-100, Los Gatos Research Inc, USA) to measure the oxygen-18 and deuterium isotope ratios (\(\delta^{18}O\) and \(\delta D\)) in our snow samples. The \(\delta^{18}O\) and \(\delta D\) values are relative to their counterparts in the Vienna Standard Mean Ocean Water (V-SMOW), referencing the work of Craig (1961). Before analysing the samples, we measured the standards four times. Each sample was measured six times, but only the last four measurements were recorded to minimize the effects of cross-contamination between each standard and sample. The measurement errors for \(\delta^{18}O\) and \(\delta D\) were better than \(+0.25 \text{ ‰}\) and \(+1 \text{ ‰}\) (Lagura & Urbino 2011), respectively. We used an ion chromatography system (Model DX-320, Thermo Scientific Dionex™, USA) with an IonPac™ CS12A IC column to measure \(\text{K}^+, \text{Ca}^{2+}, \text{Na}^+, \text{Mg}^{2+}\), and \(\text{NH}_4^+\) and another model (ICS-1500, Thermo Scientific Dionex™, USA) with an IonPac™ AS11-HC column to measure \(\text{SO}_4^{2-}, \text{NO}_3^-, \text{and Cl}^-\). The detection limits and standard deviations of the measured snow samples are shown in Table S3, in the Supporting Information.

Measurements of BC, organic carbon, and dust

We used quartz-fibre filters (Tissuquartz® 2500QAT-UP 47 mm, Pall™) to filter the samples. A vacuum pump was used to accelerate filtering, and the Whirl–Pak® bags and filter devices were flushed with deionized water to increase particle capture. We weighed the filters before and after filtering each sample and calculated the difference between the weights, which was considered the weight of retained mineral dust. The filters loaded with samples were dried.
in laminar-air flow conditions. A total of 0.5 cm$^2$ sections was punched from the sample filters. We then used a multi-wavelength thermal-optical reflectance carbon analyser (DRI Model 2015, Magee Scientific Inc., USA) to measure BC and organic carbon (OC). The software of this analyser integrates the Interagency Monitoring of Protected Visual Environments protocol (IMPROVE) and the thermal-optical reflectance method (Chow et al. 2001). A detailed description of this instrument, including its working principles and technical features, can be found in Chen et al. (2015).

**Air-pollutant data in Xinjiang**

We selected the capital cities of the sixteen prefecture-level administrative subregions in Xinjiang (Fig. 1 and Table S2 in the Supporting Information) to compare air quality before and during the pandemic. The daily average concentrations of four pollutants, SO$_2$ (2019–2020), NO$_3$ (2015–2020), CO (2019–2020), and PM$_{2.5}$ (2019–2020), whose formations are closely related to human activities, were obtained from the daily reports of the China National Environmental Monitoring Centre (2021) (http://www.cnemc.cn/ or http://106.37.208.233:20003/, last accessed: 10 July 2021). The monitoring of SO$_2$, NO$_3$, CO, and PM$_{2.5}$ complied with the technical specifications for the operation and quality control of ambient air quality continuous automated monitoring systems under the guidance of the China National Environment Protection Standards (HJ 818–2018 and HJ 93–2013). The measuring stations were located in individual counties, and the data from each county within a prefecture were averaged together to obtain the prefecture-level values.

**Results and discussion**

**Glaciochemistry in the snow pits of UG1**

We dated the snow pits by inspecting seasonal variability in the $\delta^{18}$O, $\delta^D$, dust layers, and net mass-accumulation records in the snow-pit profiles. In the Tien-Shan glaciers, $\delta^{18}$O and $\delta^D$ have shown significantly positive correlations with air temperatures (Yao et al. 2013), with less negative values during warmer seasons and more negative values during cooler seasons (Wang et al. 2017). This seasonality delineated the layers in the snow-pit profiles (Fig. 2a and b). The late spring dust layers were indicated by a horizon in the dust profile formed by intense ablation and scarce snowfalls on UG1 (Fig. 2a), which helped to identify the melting season (May–August) (Fig. 2b). Net mass accumulation measurements by the Tien-Shan Glaciers Observation Station (2021) were referenced when dating the snow layers. Thus, the ages of the snow pits were quite refined to a monthly level of detail.

A previous study suggested that primarily regional (within Xinjiang) air masses ended at the UG1 (46–87% seasonally) with few from farther sources (Zhang et al. 2020). Therefore, we anticipated that the deposition of air pollutants onto the Xinjiang glaciers would decrease due to the pandemic. We did not detect significant variations in BC, OC, and insoluble dust before and after the pandemic outbreak in the two snow-pit profiles (~2017–2020) (Fig. 2a and b). However, the soluble ion fluxes in the 2020 snow pit, especially K$^+$, Cl$^-$, SO$_4^{2-}$, and NO$_3^-$, which are usually linked with industries, traffic, and agriculture, uniformly show a decrease in average deposition from 2019 to (Fig. 2a). In the 2019 snow pit, those ions consistently increased from 2017 to 2019 (Fig. 2b), possibly owing to increased regional emissions before the pandemic (Li et al. 2017; Wang et al. 2021). For more information, we included the concentration profiles in Fig. S2, which does not show significant differences from Fig. 2.

To better illustrate the variations in deposition flux for K$^+$, Cl$^-$, SO$_4^{2-}$, NO$_3^-$, and BC recorded in the snow profiles during 2018–2020, Fig. 3a, b, and c show their average yearly concentrations. From 2019 to 2020, K$^+$, Cl$^-$, SO$_4^{2-}$, and NO$_3^-$ significantly decreased, while from 2018 to 2019, they increased. However, there were no significant differences in BC before and after the COVID-19 outbreak, and only a marginal decrease from 2019 to 2020 (Fig. 3c), which was similar to the BC records reported in some Peruvian glaciers (Sanchez-Rodriguez 2020). Various studies have reported that BC and OC in the surface snow of some mountain glaciers were used to congregating in the dust layer with magnitudes of concentrations higher than other layers in a snowpit profile (Ming et al. 2009; Xu et al. 2012). The decreasing signals of BC and OC due to the reduced emissions were compromised by their high concentrations in the dust layers. The mean concentrations of K$^+$, Cl$^-$, SO$_4^{2-}$, and NO$_3^-$ increased 2- to 4-folders from 2018 to 2019, but in 2020, shrank to 0.2–0.4 times their 2019 values (Fig. 3d).

**Air pollutants in Xinjiang before and during COVID-19**

With mobility restrictions adopted worldwide, air pollution in cities varied from normal to non-uniform decreases (Baldasano 2020; Higham et al. 2020; Otmani et al. 2020; Venter et al. 2020). For example, during the first 100 days of lockdown in the UK, which began on 23 March 2020, NO$_2$ levels halved, but SO$_2$ doubled (Higham et al. 2020). Previous studies suggested that gaseous air pollutants in Xinjiang resulted primarily from local emissions (e.g. powerplants, industry, and traffic) (Mamtimin & Meixner 2011, Petracchini et al. 2016), and backward air mass trajectory analysis suggested limited transboundary transport of pollutants, but not dominantly (Ming et al. 2009; Zhang et al. 2020). In
Xinjiang’s sixteen prefectures, pollutant concentrations (CO, NO$_2$, PM$_{2.5}$, and SO$_2$) in 2020 showed non-uniform shifts from 2019 to 2020 with some complex changes throughout this period (see Fig. S4 and the conclusions drawn from it in Table 1). Among the four pollutants, NO$_2$ dropped periodically in 15 out of the 16 prefectures (with Tacheng as the exception). PM$_{2.5}$ and SO$_2$ decreased separately in eight cities, and CO decreased in only five prefectures. The measured PM$_{2.5}$ in concentration showed heterogeneous variations (both increasing and decreasing) at different sites in Xinjiang between 2019 and 2020 (Hammer et al. 2021). An independent modelling study also showed dramatic decreases in the emissions of SO$_2$, NO$_x$, and PM$_{2.5}$ in Xinjiang during the January–April period between 2019 and 2020 (Zheng et al. 2021).

NO$_2$ in the atmosphere has been strongly linked with traffic and industries that burn fossil fuels (Degraeuwe et al. 2019). Major cities worldwide showed consistent declines in their NO$_2$ concentrations due to lockdowns or mobility restrictions (Gao et al. 2021; Higham et al. 2020; Shi et al. 2021). In Xinjiang, most prefectures show two significant dips in NO$_2$ during February–March and July–August of 2020, compared to those periods in 2019 (Fig. S4). Because of the consistency in NO$_2$ variations among the prefectures in Xinjiang after the activity restrictions, we further examined NO$_2$. We averaged the NO$_2$ data of the sixteen prefectures as shown in Fig. 4. There was no significant difference in NO$_2$ variations between the periods of 2015 to 2019 and 2019 to the pandemic. Two decreases in NO$_2$ appear in February–March and July of 2020, which deviated from both 2015 to 2019 and 2019 (Fig. 2a and b). After the mobility restriction stage I began, the NO$_2$ began to deviate from its previous-year track (2015–2019 in Fig. 4a or 2019 in Fig. 4b) in early February of 2020, and this deviation continued into a relatively loose restriction stage (IV) in Xinjiang. However, in mid-July 2020, new cases erupted in Urumqi after a nearly 5 months rest with no new cases in Xinjiang. The Urumqi authorities announced a citywide “wartime-state” period on 16 July 2020 (Xnews 2020a), equivalent to the strictest mobility restrictions, i.e. absolute lockdown. Besides Urumqi, no other prefectures were reported publicly to impose lockdown measures. The concentration of

Fig. 2 The water-stable isotope ratios ($\delta^{18}$O and $\delta$D), the deposition flux of BC, OC, and soluble ions (μg cm$^{-2}$.= concentration×snow density×layer depth), and snow density (g cm$^{-3}$) in the layers of the snow pits dug in Urumqi Glacier No. 1 on 18 June 2020, and 14 June 2019, respectively. The coloured shades (in a) and horizontally dashed lines (in b) illustrate the layers in the snow pits corresponding to the ages annotated on the right. The vertical dashed lines mark the average concentrations of the respective species in the layers dated to the most current year and previous years when the snow pits were sampled. The mineral ions (e.g. Ca$^{2+}$ and Mg$^{2+}$) were more associated with background crust weathering (dust) in the UG1 area (Li et al. 2006)
NO₂ plunged in response to the lockdown (Figs. 4 and S2), suggesting that it was applied not only in Urumqi but also throughout Xinjiang. Thus, we scrutinized the openly accessible information released in websites for the Xinjiang government, newspapers (Renmin Daily, Xinhua Daily, etc.), and other information sources during the lockdown period. The application of the total lockdown throughout Xinjiang in July was later partially verified by private consultations with local officials. In contrast to NO₂, no significantly abnormal CO, SO₂, and PM₂.₅ values were observed in most prefectures during the same periods (Fig. 4S). The sensitivity of NO₂ to mobility suggests that NO₂ can be monitored in cities as an indicator of population mobility.

As the precursors of SO₄²⁻ and NO₃⁻ in the snow, SO₂ and NO₂ in the air were used to test if the glaciochemistry in UG1 varied consistently with their airborne counterparts.

Table 1 Number of prefectures with decreased air pollutants and percent decreases in the sixteen prefectures

| Subject | CO | NO₂ | PM₂.₅ | SO₂ |
|---------|----|-----|-------|-----|
| Prefectures where pollutants significantly decreased | Bortala, Hami, Shihezi, and Urumqi | All except Tacheng | Korla, Bortala, Changji, Karamay, Shihezi, Tacheng, Urumqi, and Wujiacheng | Korla, Changji, Ili, Kashgar, Kyrgyz, Shihezi, Tacheng, and Turpan |
| Number | 5  | 15  | 8     | 8   |
| %     | 31 | 94  | 50    | 50  |

We created the yearly maps of SO₂ surface mass concentrations in the study area from 2018 to 2020 via NASA’s Giovanni web-server (https://giovanni.gsfc.nasa.gov/giovanni/) (Global Modelling Assimilation Office 2015) (Fig. 5a, b, and c). The patterns show that the central and northwest areas were more likely to impact the snow chemistry in UG1 due to the relatively high SO₂ concentrations and regional transport by the climatological westerlies (Ming et al. 2009). The yearly area-averaged SO₂ increased marginally from 1.17 μg m⁻³ in 2018 to 1.19 μg m⁻³ in 2019 and then decreased to 1.16 μg m⁻³ in 2020 (Fig. 5d). The variations in average NO₂ from 2018 to 2020 showed similar changes (Fig. 5e). The urban air pollutants in the study area and glaciochemistry in UG1 (Figs. 2 and 3) are consistent; therefore the reduced industry, traffic, and other anthropogenic activities due to the pandemic restrictions suppressed the...
concentrations of pollutants in the atmosphere and reduced their deposition in UG1.

**Conclusions**

In Xinjiang, from late January 2020 through late August 2020 when the government imposed stringent restrictions, the primary air pollutants (SO$_2$, CO, PM$_{2.5}$, and NO$_2$) were reduced in the major cities and towns throughout all sixteen prefectures. Compared to SO$_2$, CO, and PM$_{2.5}$, NO$_2$ was the most sensitive air pollutant to the mobility restriction measures. During February–March 2020, when the highest level of restriction was imposed, NO$_2$ concentrations notably decreased compared to the same period in 2019. In late July–August 2020, when Urumqi entered a “wartime” state, a similar decline in NO$_2$ occurred throughout Xinjiang. We confirmed that the mobility restrictions were not only implemented in Urumqi but also throughout Xinjiang by examining government reports, consulting with local officials in private, and analysing local observations of atmospheric components.

The pandemic might also leave its marks on the UG1, which is a Tien-Shan glacier. The concentrations of species linked to anthropogenic activity showed dramatic decreases in the snow from 2019 to 2020, whereas they had increased from 2018 (and earlier) to 2019. The variations in SO$_4^{2-}$ and NO$_3^-$ deposited on the surface of UG1 were consistent with their precursors, SO$_2$ and NO$_2$, in the study area. These variations were likely due to the mobility restriction measures that were enacted to prevent the spread of COVID-19. Additionally, over the last two decades, the emissions of BC from central Asian regions have increased greatly (Wang et al. 2021). We expected that mobility restriction measures around Xinjiang would significantly reduce the deposition of BC onto the glaciers. However, we did not observe significant variation in BC in the snow of UG1 from 2018 to 2020. The differences between the variations in BC and soluble ions recorded in UG1 deserve to be further studied in the future.
Acknowledgements  The authors thank the field and laboratory staff for helping with the sampling and measurements.

Author contribution  FTW, XZ, FLW, MS, ZL, and JM drafted the manuscript; XZ, MS, and FLW processed the data and helped with the graphics; FTW, ZL, and JM conceived the main idea; FTW designed the experiment and completed the work and JM supervised the whole study.

Funding  This research is supported by the State Key Laboratory of Cryospheric Science (SKLCS-ZZ-2022), the National Key Research and Development Program of China (2020YFF0304400), the National Natural Science Foundation of China (42001066), and the Second Tibetan Plateau Scientific Expedition and Research (STEP) program (2019QZKK0201).

Data availability  All data generated or analysed during this study are included in this published article [and its supplementary information files].

Declarations

Ethics approval  Not applicable.

Consent to participate  Not applicable.

Consent for publication  Not applicable.

Competing interests  The authors declare no competing interests.

References

Aizen VB, Aizen EM, Kuzmichonok VA (2007) Glaciers and hydrological changes in the Tien Shan: simulation and prediction. Environ Res Lett 2:045019
Bair E, Stillinger T, Rittger K, Skiles M (2021): COVID-19 lockdowns show reduced pollution on snow and ice in the Indus River Basin. Proc Natl Acad Sci U S A 118
Baldasano JM (2020) COVID-19 lockdown effects on air quality by NO2 in the cities of Barcelona and Madrid (Spain). Sci Total Environ 741:140353
Bauwens M, Compernolle S, Stavrakou T, Muller JF, van Gent J, Eskes H, Levelt PF, van der AR, Veefkind J, Yu H, Zehner C (2020): Impact of coronavirus outbreak on NO2 pollution assessed using TROPOMI and OMI observations. Geophys Res Lett, e2020GL087978
Chen L, Chow J, Wang X, Robles J, Sumlin B, Lowenthal D, Zimmermann R, Watson J (2015) Multi-wavelength optical measurement to enhance thermal/optical analysis for carbonaceous aerosol. Atmos Meas Tech 8:451–461

Fig. 5  Map of the yearly averaged SO2 surface mass concentrations derived from the MERRA-2 model (data accessed from https://giovanni.gsfc.nasa.gov/giovanni/ on 15 August 2021) for the study area (35°–50°N, 70°–100°E) in (a) 2018, (b) 2019, and (c) 2020, respectively; (d) the area-averaged yearly SO2 (μg m−3) from 2018 to 2020 derived from the data in (a), (b), and (c); (e) the average yearly NO2 (μg m−3) measured in 16 major cities of Xinjiang from 2018 to 2020. The black circles indicate the area where the UG1 resides. The text on the top of (a–c) is “Time Averaged Map of SO2 Surface Mass Concentration (ENSEMBLE), time average hourly 0.5°×0.625 deg...” for the specific year and this study area, respectively, with which the images are directly saved from the online model outputs (https://giovanni.gsfc.nasa.gov/giovanni/) and not editable.
Jaffrezo J-L, Davidson CI, Legrand M, Dibb JE (1994) Sulfate and Hudda N, Simon MC, Patton AP, Durant JL (2020) Reductions in traffic-related black carbon and ultrafine particle number concentrations in an urban neighborhood during the COVID-19 pandemic. Sci Total Environ 742:140931

Jaffrezo J-L, Davidson CI, Legrand M, Dibb JE (1994) Sulfate and MSA in the air and snow on the Greenland Ice Sheet. Journal of Geophysical Research: Atmospheres 99:1241–1253

Jones CD et al. (2021): The climate response to emissions reductions due to COVID-19: initial results from CovidMIP. Geophys Res Lett 48, e2020GL091883

Kreutz KJ, Koffman BG (2013): ICE CORE METHODS | Glaciochemistry, Encyclopedia of Quaternary Science, pp. 326–333

Kroll JH, Heald CL, Cappa CD, Farmer DK, Fry JL, Murphy JG, Steiner AL (2020) The complex chemical effects of COVID-19 shutdowns on air quality. Nat Chem 12:777–779

Lagura CF, Urbino GA (2011): Liquid water isotope analyzer (LWIA) equipment and method validation and its application to hydrology. Integrated Chemists of the Philippines, Philippines

Le Quéré C, Jackson RB, Jones MW, Smith AJP, Abenethy S, Andrew RM, De-Gol AJ, Willis DR, Shan Y, Canadell JG, Friedlingstein P, Creutzig F, Peters GP (2020) Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat Clim Change 10:647–653

Le T, Wang Y, Liu L, Yang J, Yung YL, Li G, Seinfeld JH (2020): Unexpected air pollution with marked emission reductions during the COVID-19 outbreak in China. Science, eab7431

Li C, Martin RV, van Donkelaar A, Boys BL, Hammer MS, Xu JW, Marais EA, Reff A, Strum M, Ridley DA, Crippa M, Brauer M, Zhang Q (2017) Trends in chemical composition of global and regional population-weighted fine particulate matter estimated for 25 years. Environ Sci Technol 51:11185–11195

Li Z, Edwards R, Mosley-Thompson E, Wang F, Dong Z, You X, Li H, Li C, Zhu Y (2006) Seasonal variability of ionic concentrations in surface snow and elution processes in snow–firn packs at the PGPI site on Ürümqi glacier No. 1, eastern Tien Shan. China Annals of Glaciology 43:250–256

Liu Q, Liu S (2015) Response of glacier mass balance to climate change in the Tianshan Mountains during the second half of the twentieth century. Clim Dyn 46:303–316

Liu S, Zhang Y, Liu Q, Sun M (2016): Impacts and risks of climate change — climate change impact and risk study on glaciers. Climate Change Impacts and Risks in Key Areas Series. Science Press, Beijing, 237 pp

Mantimbin B, Meixner FX (2011) Air pollution and meteorological processes in the growing dryland city of Urumqi (Xinjiang, China). Sci Total Environ 409:1277–1290

Mao Q, Long Y, Wu K (2016): Spatio-temporal changes of population density and urbanization pattern in China (2000–2010). China City Planning Review 25

Ming J, Zhang DQ, Kang LC, Tian WS (2007): Aerosol and fresh snow chemistry in the East Rongbuk Glacier on the northern slope of Mt. Qomolangma (Everest). J Geophys Res-Atmos 112

Ming J, Xiao C, Cachier H, Qin D, Qin X, Li Z, Pu J (2009) Black carbon (BC) in the snow of glaciers in west China and its potential effects on albedos. Atmos Res 92:114–123

Nakada LYK, Urban RC (2020) COVID-19 pandemic: impacts on the air quality during the partial lockdown in São Paulo state. Brazilian Sci Total Environ 730:139087

NSF (2020): Glacial ice will likely hold records of the COVID-19 pandemic, researchers say

Otman A, Benchirf A, Tahri M, Bouanakha M, Chakir EM, El Bouch Meixner FX, Paolini V, Cecinato A (2016) Gaseous pollutants in the city of Salé City (Morocco). Sci Total Environ 545:461–468
Rupakheti D, Yin X, Rupakheti M, Zhang Q, Li P, Rai M, Kang S (2021) Spatio-temporal characteristics of air pollutants over Xinjiang, northwestern China. Environ Pollut 268:115907
Sanchez-Rodriguez W (2020): No change in black carbon levels on Peruvian glaciers, despite pandemic quarantine
SBX (2020): 2019 Xinjiang Statistic National Data. Statistics Bureau of Xinjiang, Urumqi
SCC (2020): Xinjiang pandemic prevention and control emergency response adjusted to level-2. Government of China, Xinjiang
Shi Z, Song C, Liu B, Lu G, Xu J, Van Vu T, Elliott RJR, Li W, Bloss WJ, Harrison RM (2021): Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns. Science Advances 7, eabd6696
Tien-Shan Glaciers Observation Station (2021): Mass balance observation data of glacier no. 1 at the headwaters of Urumqi River, Tianshan Mountains
Venter ZS, Aunan K, Chowdhury S, Lelieveld J (2020) COVID-19 lockdowns cause global air pollution declines. Proc Natl Acad Sci 117:18984
Wang L, Zhang X, Ming J (2021) Aerosol optical properties measured using a PAX in Central Asia from 2016 to 2019 and the climatic and environmental outlooks. ACS Earth and Space Chemistry 5:95–105
Wang S, Zhang M, Crawford J, Hughes CE, Du M, Liu X (2017) The effect of moisture source and synoptic conditions on precipitation isotopes in arid central Asia. Journal of Geophysical Research: Atmospheres 122:2667–2682
WHO 2020b: Coronavirus disease 2019 (COVID-19): situation report – 82
WHO (2021): Timeline: WHO’s COVID-19 response
WHO (2022) WHO coronavirus disease (COVID-19) dashboard.
Wu K, Long Y, Mao Q, Liu X (2015) Featured graphic. Mushrooming Jiedaos, growing cities: an alternative perspective on urbanizing China. Environ Plan A 47:1–2
Xnews (2020a): Urumqi entered the pandemic prevention and control “wartime” state
Xnews (2020b): Xinjiang (including the Corps) new Covid-19 outbreak prevention and control emergency response level adjusted to a level-3 response. Government of China, Xinjiang
Xnews (2020c): Xinjiang’s new Covid-19 outbreak prevention and control emergency response level adjusted to level-4. Government of China, Xinjiang
Xu B, Cao J, Joswiak DR, Liu X, Zhao H, He J (2012) Post-depositional enrichment of black soot in snow-pack and accelerated melting of Tibetan glaciers. Environ Res Lett 7:014022
Yao T, Masson-Delmotte V, Gao J, Yu W, Yang X, Risi C, Sturm C, Werner M, Zhao H, He Y, Ren W, Tian L, Shi C, Hou S (2013) A review of climatic controls on δ18O in precipitation over the Tibetan Plateau: observations and simulations. Rev Geophys 51:525–548
Zhang X, Li Z, Ming J, Wang F (2020): One-year measurements of equivalent black carbon, optical properties, and sources in the Urumqi River Valley, Tien Shan, China. Atmosphere-Basel 11
Zheng B, Zhang Q, Geng G, Chen C, Shi Q, Cui M, Lei Y, He K (2021) Changes in China’s anthropogenic emissions and air quality during the COVID-19 pandemic in 2020. Earth System Science Data 13:2895–2907

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.