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Air pollutants in Xinjiang during the COVID-19 pandemic and glaciochemical records of a Tien-Shan glacier

Feiteng Wang[1], Xin Zhang[1], Fanglong Wang[1], Mengyuan Song[1], Zhongqin Li[1], Jing Ming[2]

[1]State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, 730000, China
[2]Beacon Science & Consulting, Malvern, 5061, Australia

Correspondence to: Jing Ming (petermingjing@hotmail.com)

Abstract. The outbreak of COVID-19 unprecedently impacts the world in many aspects. Air pollutants have been largely reduced in cities worldwide, as reported by numerous studies. We investigated the daily concentrations of SO_2, NO_2, CO and $PM_{2.5}$ monitored across the Xinjiang Uygur Autonomous Region (Xinjiang), China, from 2019 through 2020. The variation in NO_2 showed responding dips when the local governments imposed mobility restriction measures, while SO_2, CO and $PM_{2.5}$ did not consistently correspond to NO_2. This difference indicates that the restriction measures targeted traffic majorly. Sampling from two snow pits separately dug in 2019 and 2020 in Urumqi No.1 (UG1), we analysed water-stable isotopes, soluble ions, black and organic carbon (BC and OC). BC and OC show no differences in the snow-pit profiles dated from 2018 to 2020. The concentrations of human activity induced soluble ions (K^+, Cl^-, SO_4^{2-} and NO_3^-) in the snow shrank to 20% – 30% in 2020 of their respective concentrations in 2019, while they increased 2 – 3.5-fold in 2019 from before 2018. We suggest that the pandemic has already left marks in the cryosphere and outlook that more evidence would be exposed in ice cores, tree rings, and other archives in the future.

1 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 started spreading worldwide in the next 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 Mar 11, 2020 (WHO, 2021a). By the time preparing this writing, COVID-19 has affected over 158 million cases and caused nearly 3.3 million deaths with infection cases in almost every country on earth (WHO, 2021b). Responding to the escalated severity of COVID-19, global governments have been placing restriction policy when necessary to slow the virus spread (Han et al., 2020). Along with various restriction measures taken due to the pandemic, the byproducts (e.g., CO_2, SO_2, NO_2 and other air pollutants) from anthropogenic activities (industry, tourism, transportation, agriculture, etc.) has dramatically declined (Friedlingstein et al., 2020).
The annual global CO_2 emission was estimated to reduce by 4% to 7% comparing 2020 with 2019, derived from the government policies and activity data (Le Quéré et al., 2020); by another independent investigation, the reduction of GHGs and air pollutants emissions could avoid future warming of 0.3 °C by 2050 (Forster et al., 2020). In Somerville (MA, USA), a nearly two-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 (Hudda et al., 2020). In Italy's Milan, the lockdown mandated from February 2020 determined significant reductions of $PM_{2.5}$, BC, CO and NO_x (Collivignarelli et al., 2020). In

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São Paulo of Brazil, the late March lockdown in 2020 also decreased NO_x and CO concentrations in the atmosphere by over 50% (Nakada and Urban, 2020). In China, the average NO_2 load in the atmospheric column over all cities measured by satellites dropped 40% in Jan–Apr 2020 compared with the same time in 2019 (Bauwens et al., 2020). However, because chemical transformations in the atmosphere also share roles in air quality varying besides emissions and meteorology, such reduction in the primary pollutants did not necessarily lead to air quality improvement but demonstrated complex chemical effects (Kroll et al., 2020). For example, in the populated eastern and northern China, the dramatic decreasing of the primary pollutants, e.g., NO_x, facilitates forming ozone and night-time NO_3 radical which fuel the formation of secondary pollutants; the consequently formed secondary pollutants may have offset the effect of decreased primary pollutants on air quality; and this explains why there were still unexpected haze events even 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, one sixth of China's total land area, and is populated with ~ 25 million inhabitants (SBX, 2020). With such a large area and relatively small population, Xinjiang has a population density around 1/15 of the China's average, and its populations are highly concentrated in the major cities in each prefecture-level administrative district (Mao et al., 2016; Wu et al., 2015). City-concentrated populations with relatively small total size may differ in the air pollution features of Xinjiang from more populated eastern China. For example, a recent three-year measurement reported that the air concentrations of black carbon (BC) in Jimunai, a small Kazakhstan-China border town, were comparable to Beijing, China's capital and increasing at a dramatic rate (Wang et al., 2021). An investigation into the air quality in 16 major cities of Xinjiang reveals that the daily mean concentrations of $PM_{2.5}$ were ~ 8–54 times as high as the WHO guideline (Rupakheti et al., 2021).

Following the lockdown put into practice in Wuhan on Jan 23 2020, the Xinjiang government quickly launched the Level-1 Public Health Emergencies Response (PHER; Table S1) in two days (Jan 25) (GXUARC, 2020). In the following months, Xinjiang lifted its restriction gradually to Level-2, 3, 4 and normal from Feb 25 (SCC, 2020), Mar 7 (Xnews, 2020b), Mar 21 (Xnews, 2020c) and Sep 1 (Pdaily, 2020) on, respectively (refer to Table S1 about PHER in the Supporting Information). The chimney-alike distribution of pollutant sources within a vast and relatively slightly polluted background (Xinjiang) drives us to study the shutoff effect of employing lockdown controls by the local governments on the air quality in the major cities during the pandemic.

In the early-stage outbreak of the Covid-19, a few reports supposed that the pandemic would likely leave traces in the future snow-and-ice records (Goyal, 2020; NSF, 2020). However, a unique field measurement found no change in black carbon levels on the Peruvian glaciers before and during the pandemic (Sanchez-Rodriguez, 2020). Xinjiang is a dominant area of mountain-glaciers development in China (Aizen et al., 2007; Liu and Liu, 2015; Liu et al., 2016). We suppose the possibility of records from the pandemic in the snow of Xinjiang's glaciers. In this study, we try to find records of the Covid-19 pandemic in a Tien-shan glacier, Urumqi Glacier No. 1 (UG1), for it has the conventional snow-pit sampling for the long term (Figure 1).

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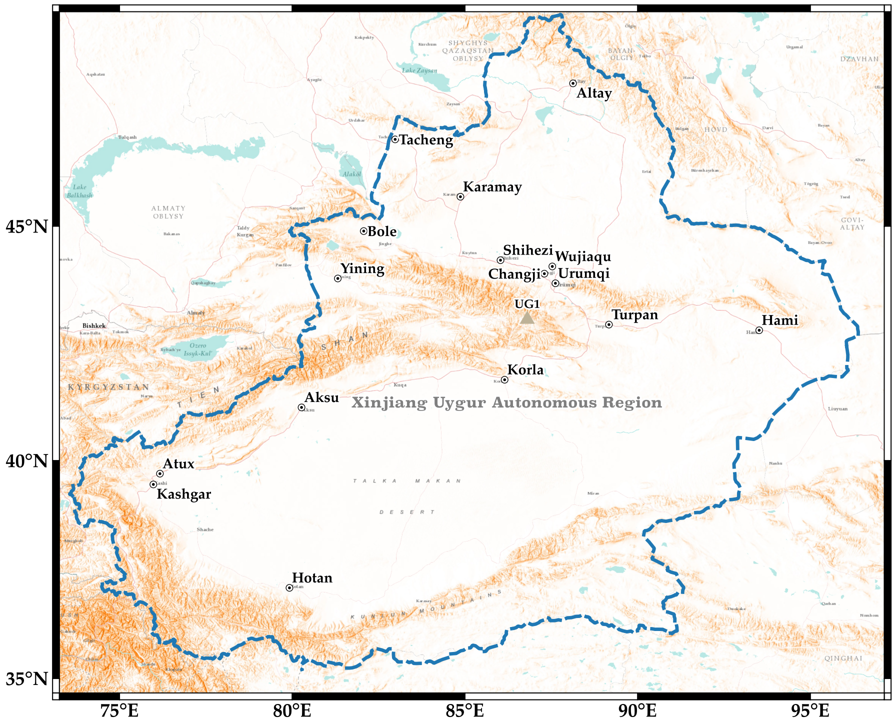

Figure 1. The study area, where the boundary of the Xinjiang Uygur Autonomous Region of China (Xinjiang), the prefecture-level cities and Urumqi Glacier No. 1 (UG1) are annotated individually. The World Hillshade image and the terrain and other labels in the map are provided by the ArcGIS Map Service and the ESRI Reference Overlay tool, respectively, implanted in the software QGIS (Qgis.Org, 2021).

2 Experiments and methods

2.1 Xinjiang and Air-pollutant's data

We selected the capital cities of the sixteen prefecture-level administrative subregions in Xinjiang as our study objects (Figure 1 and Table S2 in the supporting information) to investigate the variation in air quality before and during the pandemic. The daily averaged concentrations of four pollutants, SO_2, NO_2, CO and $PM_{2.5}$ whose formations are closely related to human activities, were collected from the China National Environmental Monitoring Centre daily reports (http://www.cnemc.cn/) (China National Environmental Monitoring Centre, 2021) from Jan 1, 2019 through Dec 31, 2021. The monitoring of SO_2, NO_2, CO and $PM_{2.5}$ comply with the technical specifications for operation and quality control of ambient air quality continuous automated monitoring system under the guidance of China National Environment Protection Standards (HJ 818-2018 and HJ 93-2013). The pollutants were measured by the stations located in the individual counties administratively inferior to the prefectures, and the data were averaged from the county-level measurements and counted as the prefecture-level averages.

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2.2 Snow sampling in Urumqi Glacier No. 1

Urumqi Glacier No. 1 is a well-known mountain glacier and hosts a long-term conventional observation of the glacier. Each summer, research staffs will routinely dig snow pits and sample snow to study mass balance, snow physics and chemistry on the glacier. On Jun 14 of 2019 and Jun 18 of 2020, we dug a 180-cm-deep snow pit and a 200-cm-deep snow pit at the equilibrium line altitude (4000 m a.s.l.) of the glacier, respectively. We sampled snow with Whirl-Pak® bags at a 10-cm step alongside a ruler (refer to Figure S1 in the Supporting Information). The samples packed in the bags were transported in the −15 °C condition back to the laboratory until further analysis.

2.3 Laboratory experiments: measuring species in snow

2.3.1 Measurements of Oxygen-18, D (2H) and soluble ions

We used the liquid water isotope analyzer (Model LWIA DLT-100, Los Gatos Research Inc, USA) to measure $\delta^{18}O$ and δD in our snow samples. The values of $\delta^{18}O$ and δD are relative to their counterparts in the Vienna Standard Mean Ocean Water (V-SMOW), details of which refer to Craig's early work (Craig, 1961). Before submitting samples, we measured the standards four times. Each sample would be measured six times but kept the last four measurements to minimize the cross-contamination effect between the submissions of standards and samples. The errors of measurements of $\delta^{18}O$ and δD were reported better than ± 0.25 ‰ and ± 1 ‰ (Lagura and Urbino, 2011), respectively. We used the Ion Chromatography System (Model DX-320, Thermo Scientific Dionex™, USA) to measure K^+, Ca^{2+}, Na^+, Mg^{2+} and NH_4^+ and another model (ICS-1500, Thermo Scientific Dionex™, USA) to measure SO_4^{2-}, NO_3^- and Cl^-. The detection limits and standard deviations of the measured snow samples are shown in Table S3, Supporting Information.

2.3.2 Measurements of BC, organic carbon (OC) and dust

In the laboratory, snow samples were placed at room temperature and melted completely in a clean room. We then 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 to calculate the differences between the weights, which were taken as the weights of mineral dust on the filters. The filters loaded with samples would be let dry in laminar-air condition. The 0.5-cm^2 filter chips with samples were punched off the original 47-mm filters. We used a multi-wavelength thermal-optical reflectance carbon analyzer (DRI Model 2015, Magee Scientific Inc., USA) to measure BC and OC. DRI Model 2015 is an improved model on basis of the earlier widely used DRI 2001. This analyzer's software integrated the Interagency Monitoring of Protected Visual Environments (IMPROVE_A) protocol and the thermal-optical reflectance (TOR) method (Chow et al., 2001). The detailed description of this instrument, including its working principle and technique features can be referred to in Chen et al. (2015).

3 Results and discussion

3.1 Air pollutants in Xinjiang from 2019 to 2020

With mobility restrictions adopted worldwide, air pollutants around cities across the world were reported to largely vary from normal and show non-uniform dropping (Baldasano,

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2020; Higham et al., 2020; Otmani et al., 2020; Venter et al., 2020). For example, the first 100 days of lockdown in the UK since Mar 23, 2020, came with NO_2 halved, but SO_2 doubled (Higham et al., 2020). In Xinjiang's sixteen prefectures, the concentrations of air pollutants (CO, NO_2, $PM_{2.5}$ and SO_2) in 2020 also show non-uniform shifts from 2019 with some tangles in some time throughout the days of 2019 and 2020 (Figure S2). Among the four pollutants, NO_2 dropped periodically in 15 out of all 16 cities, $PM_{2.5}$ and SO_2 decreased separately in eight cities, and CO only showed dropping in five cities (Table 1 visually concluded from Figure S2).

Table 1. Number of cities with obviously dropping in air pollutants and their percentages in the sixteen cities

Subject	CO	NO_2	$PM_{2.5}$	SO_2
City number with obviously dropping in air pollutants	5	15	8	8
%	31	94	50	50

NO_2 in the atmosphere is strongly linked with traffic and industries that burn fossil fuels (Degraeuwe et al., 2019). Global major cities showed consistent declines in their NO_2 concentrations due to lockdown or mobility restrictions (Gao et al., 2021; Higham et al., 2020; Shi et al., 2021). Here in Xinjiang, most prefectures show two significant dips in NO_2 during the periods Feb – Mar and Jul – Aug of 2020, respectively, compared to 2019 (Figure S2). Because of the consistency of NO_2 variations among the prefectures in Xinjiang after the activity restrictions, we take more discussion on NO_2. We averaged the NO_2 data of the sixteen prefectures and showed them in Figure 2. After commencing the mobility restriction stage I, the NO_2 started to deviate from its 2019 track in early Feb of 2020, and this deviation did not stop until going into a relatively loose restriction stage (IV) in Xinjiang. However, into mid-July 2020, new cases disrupted majorly in Urumqi after a nearly five month's rest with no new cases in Xinjiang. The Urumqi city was announced into a "wartime-state" period on Jul 16, 2020 (Xnews, 2020a), which is equal to the most strict mobility restriction, i.e. absolute lockdown. Besides Urumqi, no other prefectures were reported publicly to impose lockdown measures. The concentration of NO_2 plunged responding to the lockdown (Figure 2 and S2), implying that the lockdown was not only applied in Urumqi but all other prefectures of Xinjiang. In contrast with NO_2, no significantly abnormal CO, SO_2 and $PM_{2.5}$ from 2019 to 2020 were observed in most prefectures during the same period (Figure 2S). The sensitivity of NO_2 to mobility suggests that monitored NO_2 in cities can be used as an indicator of population mobility in the future.

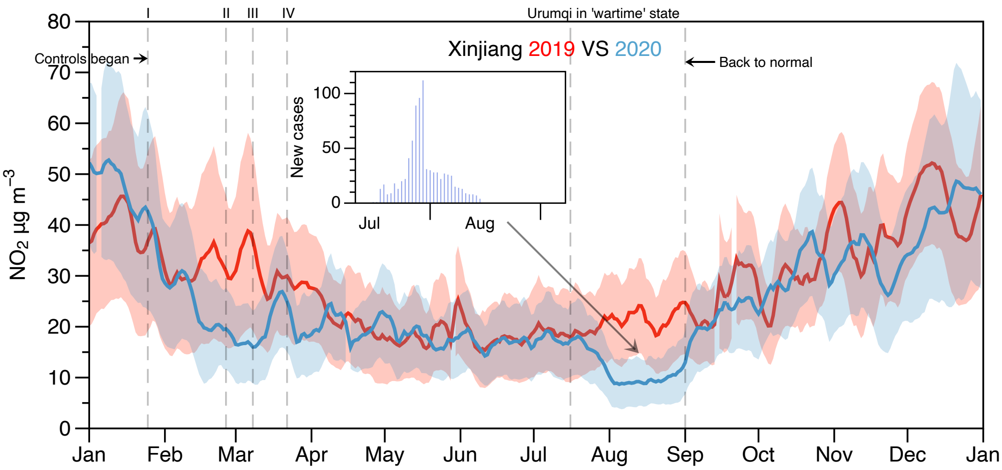

Figure 2. The seven-day smoothed concentrations of NO_2 averaged from the sixteen prefectures in Xinjiang, in which the red and blue lines with the corresponding ± 1× standard-deviation shades are representing 2019 and 2020, respectively. The four stages of restriction released by the Xinjiang government are marked with dashed lines and Roman numbers. The smaller histogram depicts the daily new cases in Xinjiang with the majority in Urumqi during mid-Jul to mid-Aug of 2020 when Urumqi announced to be in a "wartime-state" period (Xnews, 2020a). From Sep 1, 2020 on, the government announced back to normal.

3.2 Glaciochemical records in the snow pits

We dated the snow pits roughly to month by inspecting seasonality of the oxygen-18 and deuterium isotope ratios ($\delta^{18}O$ and δD), dust layers and net mass-accumulation records in the snow-pit profiles. In the Tien-Shan glaciers, $\delta^{18}O$ and δD showed significantly positive correlations with air temperatures (Yao et al., 2013). $\delta^{18}O$ and δD would be less negative in warmer seasons and more negative in cooler seasons (Wang et al., 2017). There would also be dust layers illustrated by a horizon in the dust profile formed from intense ablation and scare snowfalls in Urumqi Glacier No. 1 in late spring. The net mass accumulations were referred to the annual data report released by the Tien-Shan Glaciers Observation Station (Tien-Shan Glaciers Observation Station, 2021).

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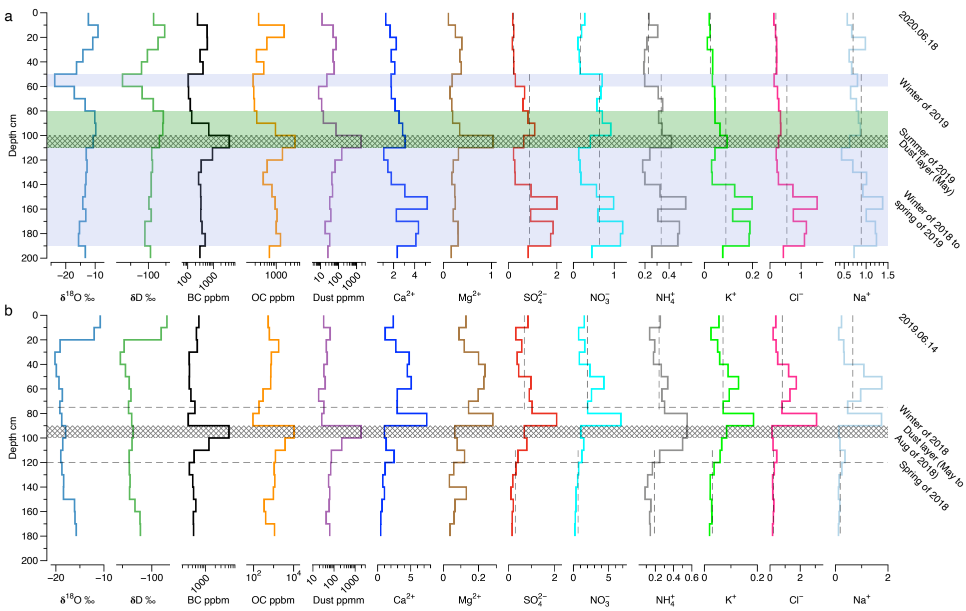

Figure 3. The water-stable isotope ratios ($\delta^{18}O$ and δD), BC, OC and soluble ions (mg kg^{-1}) recorded in the layers of the snow pits dug in Urumqi Glacier No. 1 on a) Jun 18, 2020, and b) Jun 14, 2019, respectively. The coloured shades (in a) and horizontally dashed lines (in b) illustrate the layers in the snow pits with best estimated time 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.

Except in the dust layers, we could not determine whether there were significant variations of BC, OC and insoluble dust before and after the pandemic outbreak in the two snow-pit profiles (~ 2017 – 2020) (Figure 3a&b). However, the soluble ions, especially K^+, Cl^-, SO_4^{2-}, NO_3^- lined with industries, traffic and agriculture in the snowpit dug in 2020 uniformly show diving in 2020 compared with 2019, determined by the levels of their average concentrations (Figure 3a). While in the snowpit dug in 2019, those ions show consistently increasing from 2017 – 2018 to 2019 (Figure 3b), possibly attributed to increasingly intense emissions before the pandemic.

To better illustrate the average-concentration variations of K^+, Cl^-, SO_4^{2-}, NO_3^- and BC recorded in the snow-profiles in the last three years, we show their average concentrations of the individual years in Figure 4a, b and c. From 2019 to 2020 there were significantly decreasing in K^+, Cl^-, SO_4^{2-} and NO_3^-, while these species kept their increasing from 2018 to 2019 in the snow. For BC, there was no apparent differences after and before the outbreak of Covid-19 (Figure 4c), which was similar to the BC records reported in some Peruvian glaciers (Sanchez-Rodriguez, 2020). From 2018 to 2019, the mean concentrations of K^+, Cl^-, SO_4^{2-} and NO_3^- increased by 2 – 3.5 folders of 2018 in 2019, while shrank to 0.2 – 0.3 of 2019 in 2020 (Figure 4d).

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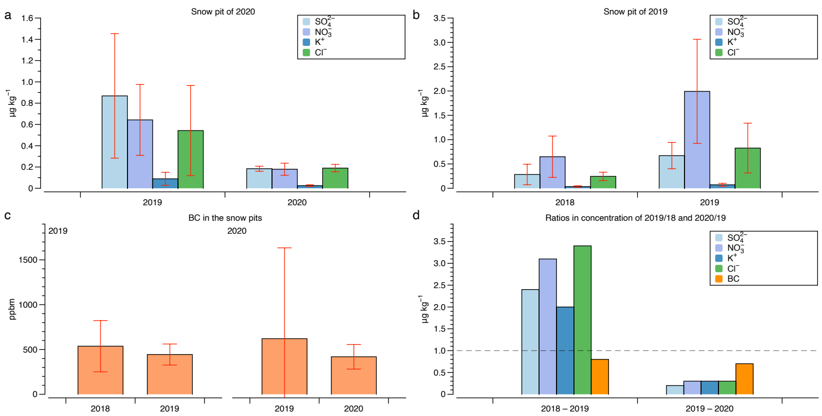

Figure 4. a) The average concentrations of SO_4^{2-}, NO_3^-, K^+ and Cl^- in the layers dated to 2019 and 2020 in the snow pit dug on Jun 18, 2020, respectively; b) the same dated to 2018 and 2019 in the snow pit dug on Jun 14, 2019, respectively; c) the average concentrations of BC in the snow layers dated to 2018, 2019 and 2020 in the above two snow-pit profiles; d) the ratios in the concentrations of the respective species of 2019 to 2018 and 2020 to 2019. The error bars mark the ± 1× standard deviation.

4 Summary and outlook

The unprecedented Covid-19 has been shocking the world in many aspects. The episodes of significant reduction in air pollution owing to strict mobility restrictions implemented in many cities across the world is one of them. In Xinjiang of China, the government imposed stringent restrictions from late Jan 2020 through late Aug 2020. The main air pollutants were depressed at a time around all sixteen prefectures. Compared to SO_2, CO and $PM_{2.5}$, NO_2 is the most sensitive air pollutant to the mobility restriction measures. Its concentration during Feb – Mar 2020 when imposed the highest level of restriction, displayed a notable dip compared to that in the same period of 2019. In late Jul – August 2020, when Urumqi proclaimed to enter a "wartime" state, the similar dive in NO_2 show the second time derived from all Xinjiang's average; and we suppose mobility restrictions were not only implemented in Urumqi but in the whole Xinjiang region.
The pandemic also leaves its marks on a Tien-Shan glacier, Urumqi Glacier No. 1. The concentrations of anthropogenic activity induced species recorded in the snow showed dramatically decreases from 2019 to 2020, while they did increase by times from before 2018 to 2019. The overturned records of these ions are probably owing to the mobility restriction measures to prevent the spread of Covid-19. Over the last two decades, the emissions of BC from central Asian regions have increased dramatically (Wang et al., 2021). We expected mobility restriction measures around Xinjiang could significantly reduce the deposition of BC onto the glaciers. However, we did not measure BC's significant variation in the snow of UG1 from 2018 to 2020. The case is not alone because a similar circumstance of BC was observed in some Peruvian glaciers (Sanchez-Rodriguez, 2020). The differences between the variations of BC and soluble ions recorded in the snow of UG1 deserve to be further studied in the future.
The pandemic is yet close to an end but ongoing. The influence would be expected in many aspects of nature and the environment. We have not investigated other glaciers than UG1 in Xinjiang to further study if air-pollutant emissions are reduced due to imposed mobility restriction measures. The highly susceptible SARS-CoV-2 virus is not as limited to climate as

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various viruses previously met by human societies (Baker et al., 2021) and almost demonstrates new cases in every country and region on earth. We suppose there may be similar records in the snow to be found in more glaciers worldwide. It is reasonable to foresee the hiatus on records created by this pandemic in some archives with the high temporal resolution, e.g., firn snow, ice cores, tree rings, etc., in the future.

Data availability

All data are available at zenodo.org, https://doi.org/10.5281/zenodo.4708792.

Author contribution

Conceptualization: FTW, JM
Methodology: FTW, XZ, FLW, MS, ZL, JM
Investigation: FTW, XZ, FLW, MS
Visualization: FTW, JM
Supervision: JM
Writing—original draft: FTW, XZ, FLW, MS, ZL, JM
Writing—review & editing: FTW, JM

Competing interest

Authors declare that they have no competing interests.

Supplementary material

Refer to an independent supplementary document.

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Appendix: the acronyms and full names of some institutions shown in the in-text citations and bibliography

Acronym	Full name
GXUARC	Government of Xinjiang Uygur Autonomous Region, China
NSF	National Science Foundation
Pdaily	People's Daily
SCC	State Council, China
WHO	World Health Organization
SBX	Statistics Bureau of Xinjiang
Xnews	Xinhua News

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