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Enhanced formation of secondary organic aerosol from photochemical oxidation during the COVID-19 lockdown in a background site in Northwest China

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HIGHLIGHTS
• Gas-phase oxidized organic aerosol largely increased during COVID-19 lockdown in northwest China
• Aqueous-phase oxidized OA formation dominated in pollution periods under high aerosol liquid water content conditions
• The OA variations were widespread in northwest China during lockdown

ABSTRACT
The COVID-19 pandemic has drastically affected the economic and social activities, leading to large reductions in anthropogenic emissions on a global scale. Despite the reduction of primary emissions during the lockdown period, heavy haze pollution was observed unexpectedly in megacities in North and East China. In this study, we conducted online measurements of organic aerosol in a background site before and during the lockdown in Guanzhong basin, Northwest China. The oxygenated organic aerosol (OOA) increased from 24% of total OA (3.2 ± 1.6 μg m⁻³) before lockdown to 54% of total OA (4.5 ± 1.3 μg m⁻³) during lockdown, likely due to substantial decrease of NOₓ emissions during lockdown which resulted in large increase of O₃ and thus atmospheric oxidizing capacity. OOA showed higher mass concentrations and fractional contributions during lockdown than before lockdown, and increased with the increase of Ox in both periods. In comparison, aqueous secondary organic aerosol (aqSOA) showed high mass concentrations and fractional contributions in both polluted periods before and during lockdown with the increase of aerosol liquid water content (ALWC). The increase of aqSOA under high ALWC conditions is very likely the reason of pollution events during lockdown. Combined with trajectory analysis, the absence of Guanzhong cluster in polluted period during lockdown may play a key role in the OA variations between two polluted periods. In addition, when comparing the clusters from the same
transmission directions between before lockdown and during lockdown, the OA fractions showed similar variations during lockdown in all clusters, suggesting the OA variations are widespread in northwest China.

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1. Introduction

In December 2019, a novel coronavirus named officially as “COVID-19” by the World Health Organization (WHO) (Sohrabi et al., 2020), was globally pandemic and drastically affected the economy and daily life (Zhu et al., 2020; Tian et al., 2020; Wang et al., 2020a). In response to the lethality and infectivity of COVID-19, China’s central and local governments have implemented an extremely strict lockdown policy in the nation to quarantine COVID-19 outbreak since around 23/24 Jan 2020 (Tian et al., 2020; Wang et al., 2020b). The lockdown, on the other hand, has led to large reduction in anthropogenic emissions and therefore significant influence on air quality.

In contrast to the short-term and local emission control measures which have resulted in e.g., “Olympic Blue” in 2008 (Wang et al., 2010) and “APEC Blue” in 2014 (Huang et al., 2015) in Beijing, the COVID-19 lockdown has persistent and large-scale effects on air quality. During the COVID-19 lockdown, the energy demand and industrial output remained far below the average levels, for example, energy production by coal-fired power plants was reduced by one third compared to the same periods in preceding years (Chang et al., 2020). The on-road vehicles and domestic flights were reduced by more than 70% (Myllyvirta, 2020). Satellite observations showed approximate 40–70% and 90% reduction in NO2 concentrations in the nation and Wuhan, respectively (Bauwens et al., 2020; Le et al., 2020). Ground-based measurements also showed that surface NO2 decreased by approximate 60% during the lockdown period compared to that before lockdown in northern China (Shi and Brasseur, 2020). However, atmospheric oxidants, including ozone and nighttime NO3 radicals, showed an increase during the lockdown period due to the large reduction of NOx emission from transportation (Shi and Brasseur, 2020; Huang et al., 2020), which consequently increased the atmospheric oxidizing capacity and facilitates the formation of secondary inorganic aerosol (SIA, including SO42−, NO3− and NH4+ ) (Chang et al., 2020). The enhanced secondary formation could offset the reduction of primary emissions (Huang et al., 2020) and even caused unexpected severe air pollution in Northern China (Le et al., 2020; Sun et al., 2020; Huang et al., 2020). Nonetheless, the formation of secondary organic aerosol (SOA) and its contributions to fine particle during the lockdown period is not yet clear. SOA has been reported as a major fraction of particulate matter in recent studies (Huang et al., 2014). Therefore, understanding of the formation of SOA during the lockdown period is an invaluable opportunity to estimate the effect of emission control on atmospheric processes.

In this study, organic aerosol (OA) was measured online with a time-of-flight aerosol chemical speciation monitor (TOF-ACSM) at a background site in Guanzhong basin which is a part of the three top priority regions in China’s blue sky action as of 2019. The sources and atmospheric evolution of OA before and during COVID-19 lockdown are investigated, together with the effects of meteorological conditions (such as temperature and relative humidity) and air masses.

2. Experimental

2.1. Sampling site and instrumentation

Field measurements were carried out in the Qinling Station of Institute of Earth Environment, Chinese Academy of Sciences (34.07°N, 108.35°E, 689 m) from 23 Dec 2019 to 7 Feb 2020 (as shown in Fig. S1). It is located in the Qinling National Botanical Garden in the north of the Qinling Mountains, ~80 km southwest to Xi’an. The TOF-ACSM (Aerodyne Research Inc., Billerica, MA, US) was deployed for continuous measurements of non-refractory PM2.5 (NR-PM2.5) species including organics, sulphate, nitrate, ammonium, and chloride (Fröhlich et al., 2013). The time resolution was 20 min for the continuous measurements. Ambient air was drawn through a 3/8-in. stainless steel tube at a flow rate of 3 L min−1, and the coarse particles were removed by a cyclone (2.5 μm size cut, URG-2000-30ED) in the front of the sampling inlet. The sampled air was dried by a Nafion dryer system (MD 110-48S, Perma Pure, Inc., Lakewood, NJ, US) before entering into the ACSM. The aerosol beam was concentrated by a PM2.5 aerodynamic lens and transported to a vaporizer at 600 °C for evaporation, and then further ionized by electron impact and determined by a TOF mass spectrometer. Meanwhile, a scanning mobility particle sizer (SMPS, TSI model 3080) with a differential mobility analyzer and a condensation particle counter (CPC, TSI model 3772) were combined for regular calibration of the ionization efficiency (IE) and relative ionization efficiency (RIEs). The gaseous precursor data (including CO, SO2, NO2 and O3) and meteorological data (including temperature and relative humidity) were measured at the National Environmental Monitoring Station close to our measurement site and are available on the China National Environmental Monitoring Centre (http://www.cnemc.cn/).

2.2. Data analysis

The Acquity (v2.1.4, Tosotwerk AG, Thun, Switzerland) was used for data acquisition and Tofware (v2.5.13, Toswof AG, Thun, Switzerland) in Igor Pro 6.37 (WaveMetrics, Inc., Lake Oswego, Oregon, US) was used for ACSM data analysis and PMF matrices export. Organics, nitrate and chloride were analyzed using the standard RIEs which are 1.4, 1.1, and 1.3, respectively (Canagaratna et al., 2007). IE (258 ions pg−1), RIEs of ammonium (4.7) and sulphate (0.6) were estimated from IE and RIE calibrations. The composition dependent collection efficiency (CDCE) was calculated following the procedure described in Middlebrook et al. (2012).

The OA source apportionment was performed by positive matrix factorization (PMF, Paatero and Tapper, 1994; Paatero, 1997) and multilinear engine (ME-2, Paatero, 1999). PMF and ME-2 analysis were performed on the interface of SoFi (version 6.3, Canonaco et al., 2013), which have been widely used in previous studies (Ng et al., 2011; Duan et al., 2020). Briefly, PMF is a bilinear receptor model which separates the input data matrix to distinct source factors and their corresponding time-dependent concentrations. ME-2 provides a restriction method where a priori factor profile or time series is used to direct the apportionment results to minimize the rotational ambiguity from PMF, leading to environmentally meaningful results. The a value approach is applied to constrain one or more factor profiles by giving a constrained range to minimize the influence of non-local input profiles. The details of the factor-selection and constraining strategies using SoFi are presented in section S1 of the supplementary.

2.3. Trajectory analysis

The trajectory analysis was performed using the HYSPLIT model (Draxler and Hess, 1998) in Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT 4). Briefly, trajectories were calculated every 6 h from the air mass data which were downloaded from the National Oceanic and Atmospheric Administration (NOAA, ftp://arlftp,
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For model inputs, NH4 series are shown in Fig. 1. Two SOA sources, i.e., gas-phase oxidized tary Information Section S1. The pro were further resolved using PMF and ME-2 receptor models. Details of 1.5 μgm −1.5 to 74% of OA (6.8 ± 1.9 μgm −0.5 from the local National Environmental Monitoring Station. The measure- tion, and the particles were considered as deliquescent with no solid deliquescent with no solid formation (Fountoukis and Nenes, 2007).

2.4. Aerosol liquid water content

The aerosol liquid water content (ALWC) was calculated using the ISORROPIA-II model (Fountoukis and Nenes, 2007). ALWC was based on a NH4SO4−NO3−Cl−H2O system in thermodynamic equilibrium. For model inputs, NH4, SO42−, NO3−, and Cl− are from the TOF-ACSM measurements and the meteorological parameters (T and RH) are from the local National Environmental Monitoring Station. The “forward” mode and “metastable” mode were used in ISORROPIA-II calculation, and the particles were considered as deliquescent with no solid formation (Fountoukis and Nenes, 2007).

3. Results and discussion

3.1. OA variations during COVID-19 lockdown

The mass concentrations of NR-PM2.5 decreased from 29.6 ± 13.3 μg m−3 before lockdown to 13.8 ± 7.6 μg m−3 during lockdown. Over the entire campaign, OA consisted of 52% of NR-PM2.5. The average concentrations of OA decreased from 14.2 ± 3.8 μg m−3 before lock- down to 9.1 ± 3.8 μg m−3 during lockdown, while its mass fractions in- creased correspondingly from 48% to 64% of NR-PM2.5. The OA sources were further resolved using PMF and ME-2 receptor models. Details of PMF and ME-2 source apportionment are described in the Supplemen- tary Information Section S1. The profiles of OA sources and their time series are shown in Fig. 1. Two SOA sources, i.e., gas-phase oxidized OA (OOA) and aqueous-phase oxidized OA (aqSOA), and three primary organic aerosol (POA) sources, i.e., hydrocarbon-like OA (HOA), biomass burning OA (BBOA), and coal combustion OA (CCOA), were resolved. SOA (OOA + aqSOA) accounted for 67% of OA (9.2 ± 2.6 μg m−3), approximately twice higher than POA (34% of OA, 5.0 ± 1.5 μg m−3) before lockdown. During lockdown, SOA further increased to 74% of OA (6.8 ± 1.9 μg m−3) and POA decreased to 26% of OA (2.1 ± 0.5 μg m−3). The enhanced contribution of SOA during the lockdown period was likely caused by both an enhanced SOA formation and a con- siderable POA decrease. It should be noted that the two SOA factors show similar spectral patterns, yet their time series are largely different. O3 (O3 = O2 + NO2) and ALWC have been widely used as indicators for gas-phase reaction and aqueous-phase reaction, respectively (Sun et al., 2016; Xu et al., 2017; Gilardoni et al., 2016). As shown in Fig. 1, OOA was well correlated with the concentrations of O3 (r = 0.71), while aqSOA was corre-lated with the concentrations of SO42− (r = 0.79) and ALWC (r = 0.6). This suggests that OOA was mainly formed from gas-phase oxidation while the aqSOA formation was related to aqueous-phase processes. The concentrations of OOA increased from 3.2 ± 1.6 μg m−3 (24% of total OA) before lockdown to 4.5 ± 1.3 μg m−3 (54% of total OA) during lockdown (Fig. S3). Of note, OOA was the only OA factor that increased in both mass concentrations and propor- tions during lockdown. On the contrary, the mass concentrations of aqSOA decreased significantly from 5.8 ± 2.8 μg m−3 (43% of total OA) before lockdown to 1.5 ± 0.9 μg m−3 (17% of total OA) during lockdown, which was the largest decrease (74%) in all OA sources. The mass concentrations of HOA decreased from 0.9 ± 0.6 μg m−3 (7% of total OA) to 0.3 ± 0.3 μg m−3 (4% of total OA) with a reduction of 67%, which was the most significant decrease in POA. BBOA was the dominant POA source, consistent with those previous studies in the Guanzhong basin (Elser et al., 2016; Wang et al., 2017; Zhong et al., 2020). The mass con-centrations of BBOA decreased from 3.2 ± 0.7 μg m−3 (15% of total OA) before lockdown to 1.4 ± 0.4 μg m−3 (16% of total OA) during lockdown with a reduction of 56%. The mass concentrations of CCOA decreased slightly from 1.0 ± 0.3 μg m−3 (8% of total OA) before lockdown to 0.7 ± 0.2 μg m−3 (5% of total OA) during lockdown with a reduction of 30%. The reduction of POA during the lockdown was consistent with the study in Beijing (Sun et al., 2020), and was coincided with the reduction of gaseous species from direct emissions. NO2 decreased from 42.4 ± 18.1 μg m−3 before lockdown to 11.3 ± 8.2 μg m−3 during lockdown with a reduction of 73% and SO2 decreased from 7.6 ± 3.5 μg m−3 before lockdown to 4.5 ± 2.5 μg m−3 during lockdown with a reduction of 41%, similar to the results in other observation sites in China (Shi and Brasseur, 2020; Bauwens et al., 2020; Le et al., 2020; Huang et al., 2020). On the contrary, O3 showed a remarkable in- crease from 22.3 ± 20.4 μg m−3 before lockdown to 76.3 ± 26.8 μg m−3 during lockdown, which was much higher compared to the same period in 2019 (57.5 ± 27.4 μg m−3). The increase of O3 was likely due to the reduction of on-road vehicle and thus the reduction of NOx emissions because the reduction of NO alleviated O3 titration (Seinfeld and Pandis, 2016). Besides, considering the effect of aerosol sink for O3 pre-cursors (Li et al., 2018) and aerosol radiative effect on the O3 formation.

![Fig. 1. Profiles and time series of five OA factors. The external trace species, including NOx, Chloride, C2H4O2, O3, and ALWC are also shown for comparison.](image)
(Wu et al., 2020), the reduction of particles can also lead to an increase in O₃.

### 3.2. SOA formation before and during lockdown

We further investigated SOA formation in clean and polluted periods before and during lockdown (Fig. 2). The continuous periods with mass concentration of NR-PM₂.₅ < 15 μg m⁻³ were defined as clean periods (average of 13.5 ± 1.9 μg m⁻³ for pre-lockdown and 11.8 ± 2.3 μg m⁻³ for lockdown). The rest periods (average of 32.9 ± 12.9 μg m⁻³ for pre-lockdown and 27.1 ± 4.4 μg m⁻³ for lockdown) were defined as polluted periods. The mass concentrations and fractions of OA factors in four periods are shown in Fig. 2b and c. The fractional contributions of OOA and aqSOA were largely different between polluted period before lockdown and polluted period during lockdown.

During polluted period before lockdown, aqSOA was the dominant OA source, contributing to 48% of the total OA (6.7 ± 2.3 μg m⁻³), while its fractions decreased to 29% of the total OA (3.3 ± 1.9 μg m⁻³) in polluted period during lockdown. It was likely due to the decrease of the mass concentration of ALWC from 36.4 ± 38.4 μg m⁻³ in polluted period before lockdown to 22.6 ± 27.8 μg m⁻³ in polluted period during lockdown. In contrast, the OOA fractions increased from 18% of OA (2.5 ± 1.6 μg m⁻³) during polluted period before lockdown to 43% of OA (4.9 ± 1.4 μg m⁻³) during polluted period of lockdown, which was consistent with the enhanced formation of OOA during lockdown. However, during clean periods, regardless of lockdown, OOA was the dominant OA factor accounting for 41% of OA (3.9 ± 1.0 μg m⁻³) before lockdown and 59% of OA (4.6 ± 1.2 μg m⁻³) during lockdown, likely due to the extremely low mass concentrations of ALWC (2.6 ± 3.9 μg m⁻³ before lockdown and 2.2 ± 3.7 μg m⁻³ during lockdown).

Fig. 3 showed the relationships between OA and O₃ or ALWC during the four periods. Generally, the mass concentrations of OOA increased with the increase of O₃, while the mass concentrations of aqSOA increased with the increase of ALWC. OOA showed higher mass concentrations and fractional contributions during lockdown than before lockdown, and in both periods, they increased with the increase of O₃ (see Fig. 3). When comparing the two polluted periods, the OOA concentrations increased from 2.2–4.7 μg m⁻³ (17%–34% of total OA) before lockdown to 4.1–4.8 μg m⁻³ (38%–45% of total OA) during lockdown. For clean period, the OOA concentrations increased from 3.5–5 μg m⁻³ (34%–54% of total OA) before lockdown to 4.1–6 μg m⁻³ (53%–62% of total OA) during lockdown. In comparison, aqSOA showed high mass concentrations and fractional contributions in both polluted periods before and during lockdown with the increase of ALWC. In polluted periods, the aqSOA concentrations was 5.2–10.2 μg m⁻³ (41%–64% of total OA) before lockdown and 3.1–11.8 μg m⁻³ (25%–68% of total OA) during lockdown. It should be noted that the aqSOA concentrations and fractional contributions during lockdown were even higher than those before lockdown under high ALWC conditions. It is likely because more water-soluble organic species (e.g. glyoxal) were formed by enhanced gas-phase oxidation (Magneron et al., 2005; Volkamer et al., 2005) which were further oxidized to form aqSOA in aerosol liquid water (Kawamura and Gagosian, 1987; Carlton et al., 2007). This suggests that the polluted events during lockdown was very likely due to the increase of aqSOA under high ALWC conditions.

### 3.3. Trajectory comparison before and during lockdown

Fig. 4 shows the results of the cluster analysis of trajectory. During polluted period, there were three trajectory clusters before lockdown,
of which two were medium-distance transport (north cluster and south cluster) and the other one was short-distance transport (Guanzhong cluster). The concentrations of OA of Guanzhong cluster (14.8 ± 1.4 μg m⁻³) was the highest for these three clusters, followed by south cluster (14.7 ± 4.7 μg m⁻³) and north cluster (12.8 ± 1.7 μg m⁻³). Likewise, the concentrations of aqSOA were higher for the Guanzhong cluster (54% of OA, or 7.9 ± 1.3 μg m⁻³) than for the south cluster (45% of OA, or 6.6 ± 2.5 μg m⁻³) and the north cluster (44% of OA, or 5.6 ± 2.2 μg m⁻³). In comparison, the Guanzhong cluster was absent during lockdown period. The mass concentrations of OA were higher for the south cluster (12.3 ± 1.6 μg m⁻³) than for the north cluster (10.9 ± 1.4 μg m⁻³), also the concentrations of aqSOA were higher for the south cluster (36% of OA, or 4.4 ± 1.9 μg m⁻³) than for the north cluster (20% of OA, or 2.2 ± 1.8 μg m⁻³), similar with those before lockdown. The absence of Guanzhong cluster during lockdown may be an important reason of the OA variations between two periods because the Guanzhong cluster was the major air masses before lockdown (52% of measurement days) and it was characterized by relatively polluted air with high fractions of aqSOA.

As for clean periods, there was one cluster from northwest China, characterized by long-distance transport and relatively clean air before lockdown and during lockdown. The OA concentrations of the northwest cluster decreased from 9.5 ± 1.5 μg m⁻³ before lockdown to 7.8 ± 1.0 μg m⁻³ during lockdown, however, the average OOA concentrations increased correspondingly from 3.9 μg m⁻³ (41% of OA) to 4.6 μg m⁻³ (59% of OA). Of note, the comparison in the clusters from the same transmission directions between before lockdown and during lockdown showed that aqSOA fractions decreased while OOA fractions increased during lockdown in all clusters, suggesting the variations of OA fractions were widespread in northwest China.

Fig. 3. Variations of the mass concentrations five OA factors, and variations of the mass fractions of OOA, aqSOA and POA as a function of (a, b, c, d) Ox and (e, f, g, h) ALWC. The data are binned according to the Ox (5 ppb as increment) and ALWC (10 μg m⁻³ as increment for e, f, g, and 5 μg m⁻³ increment for h).

Fig. 4. The trajectories at 500 m height were calculated per 6 h using HYSPLIT model in Hysplit4. The air mass clusters (a) polluted period before lockdown (north, south, and Guanzhong), (b) clean period before lockdown (northwest), (c) polluted period before lockdown (north and south), (d) clean period before lockdown (northwest) are as shown, with the mass concentrations and fractions of OA factors in each cluster.
4. Conclusion

NR-PM$_{2.5}$ (Non-refractory Particulate Matter) were measured in near real-time by a Time-of-Flight Aerosol Chemical Speciation Monitor (TOF-ACSM) before and during the COVID-19 lockdown in a background site in northwest China. The mass concentrations of NR-PM$_{2.5}$ decreased from 29.6 ± 13.3 μg m$^{-3}$ before lockdown to 13.8 ± 7.6 μg m$^{-3}$ during lockdown. Two OOA were resolved using PMF and ME-2, which were gas-phase oxidized organic aerosol (OOA) and aqueous-phase oxidized organic aerosol (aqSOA). OOA increased in both mass concentrations and fractional contributions during the COVID-19 lockdown period, from 24% of OA before lockdown (3.2 ± 1.6 μg gm$^{-3}$) to 54% of OA during lockdown (4.5 ± 1.3 μg gm$^{-3}$). This suggests the formation of OOA was enhanced significantly by the enhanced atmospheric oxidizing capacity during the lockdown. aqSOA, on the contrary, decreased from 5.8 ± 2.8 μg gm$^{-3}$ (43% of OA) before lockdown to 1.5 ± 0.9 μg gm$^{-3}$ (17% of OA) during lockdown, likely due to the decrease of ALWC during lockdown. OOA showed consistently higher mass concentrations and fractional contributions during lockdown than those before lockdown, and they increased with the increase of Ox.H. However, the concentrations and fractional contributions of aqSOA during lockdown were even higher than those before lockdown under high ALWC conditions. Back trajectory analysis indicates that the absence of ALWC during lockdown is likely due to the increase of aqSOA under high ALWC concentrations. The transmission directions between before lockdown and during lockdown showed that aqSOA fractions decreased while OOA fractions increased during lockdown in all clusters, suggesting the variations of OA fractions are widespread in northwest China.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.144947.

References

Bauwens, M., Compèreolle, S., Stavrakou, T., Müller, J.-F., van Gent, J., Eske, H., Levent, F., van Sint Annaland, M., van Vuik, J.P., Vreeburg, J.P., Yli-Terentiev, J., Yu, H., Zhao, C., 2020. Impact of coronavirus outbreak on NO2 pollution assessed using TROPOMI and OMI observations. Geophys. Res. Lett. https://doi.org/10.1029/2020GL087798.

Canagaratna, M.R., Jayne, J.T., Jimenez, J.L., Allan, J.D., Alfarra, M.R., Zhang, Q., Onasch, T.B., Drewnick, F., Coe, H., Middlebrook, A., Delia, A., Williams, L.R., Trimborn, A.M., Northway, M.J., DeCarlo, P.F., Kolb, C.E., Davidovits, P., Worsham, D.R., 2007. Chemical and microphysical characterization of ambient aerosols with the aerodyne aerosol mass spectrometer. Mass Spectrom. Rev. 26 (2), 185–222.

Canzian, F., Crippa, M., Slowik, J.G., Baltensperger, U., Prévôt, A.S.H., 2013. Soft, an Igor based interface for the efficient use of the generalized multilinear engine (ME-2) for source apportionment: application to aerosol mass spectrometer data. Atmos. Meas. Tech. 6 (12), 3649–3661.

Carlton, A.G., Turpin, B.J., Aliferis, K.E., Seitzinger, S., Reff, A., Lin, H.-J., Ervens, B., 2007. Atmospheric oxalic acid and SOA production from glyoxal: results of aqueous photooxidation experiments. Atmos. Environ. 41 (35), 7588–7602.

Chang, Y., Huang, R.-J., Ge, X., Huang, X., Hu, J., Duan, Y., Zou, Z., Liu, X., Lehmann, M.F., 2020. Puzzling haze events in China during the coronavirus (COVID-19) shutdown. Atmos. Res. 222, 104655.

Draxler, R.R., Hess, G.D., 1998. An overview of the HYSPLIT_4 modelling system for trajectories, dispersion, and deposition. Aust. Meteorol. Mag. 47, 295–308.

Duan, J., Huang, R.-J., Li, Y., Chen, Q., Zheng, Y., Chen, Y., Liu, C., Ni, H., Wang, M., Ondracka, J., Geburins, D., Chen, C., Worsham, D.R., Hoffmann, T., O'Dowd, C., Cao, J., 2020. Summertime and wintertime atmospheric processes of secondary aerosol in Beijing. Atmos. Chem. Phys. 20 (6), 3793–3807.

Elser, M., Huang, R.-J., Wolf, R., Slowik, J.G., Wang, Q., Canonaco, F., Li, G., Bozzetti, C., Dallenbach, K.R., Huang, Y., Zhang, R., Li, Z., Cao, J., Baltensperger, U., El-Haddad, I., Prévôt, A.S.H., 2016. New insights into PM$_{2.5}$ chemical composition and sources in two major cities in China during extreme haze events using aerosol mass spectrometry. Atmos. Chem. Phys. 16 (5), 3207–3225.

Fountoukis, C., Nenes, A., 2007. ISORROPIA II: a computationally efficient thermodynamic equilibrium model for K$^+$−Ca$^{2+}$−Mg$^{2+}$−Na$^+$−SO$_4^{2−}$−NO$_3^{−}$−Cl$^{−}$−H$_2$O aerosols. Atmos. Chem. Phys. 7, 4639–4659.

Fröhlich, I., Cubison, M.J., Slowik, J.G., Bukowiecki, N., Prévôt, A.S.H., Baltensperger, U., Schneider, J., Kimmel, J.R., Gorin, M., Rohner, U., Worsham, D.R., Jayne, J.T., 2013. TheToF-ACSM: a portable aerosol chemical speciation monitor with TOFMS detection. Atmos. Meas. Tech. 6 (11), 3225–3241.

Gallionato, S., Mascelli, P., Paglione, M., Giulianelli, L., Barone, C., Rinaldi, M., Deesari, S., Sandrini, S., Costabile, F., Cobelli, G.P., Pietrogrande, M.C., Visentin, M., Scotto, F., Fuzzi, S., Facchini, M.C., 2016. Direct observation of aqueous secondary organic aerosol from biomass-burning emissions. Proc. Natl. Acad. Sci. 113 (36), 10013–10018.

Huang, R.-J., Zhang, Y.L., Bozzetti, C., Ho, K.F., Cao, J.J., Han, Y.M., Dallenbach, K.R., Slowik, J.G., Platt, S.M., Campanelli, F., Zofian, P., Wolf, R., Pieber, S.M., Brun, A., Crippa, M., Clarelle, G., Piazzalunga, A., Schwiikowski, M., Abadazadeh, C., Schmale, K., Zimmermann, R., An, Z., Sizidat, S., Baltensperger, U., El-Haddad, I., Prévôt, A.S.H., 2014. High secondary aerosol contribution to particulate pollution during haze events in China. Nature. 514 (7521), 218–222.

Huang, K., Zhang, X., Lin, Y., 2015. The “APEC Blue” phenomenon: regional emission control effects observed from space. Atmos. Res. 164–165, 65–75.

Huang, X., Ding, A., Cao, J., Zheng, B., Zhou, D., Qi, X., Tang, R., Wang, J., Ren, C., Nie, W., Chi, X., Xu, Z., Chen, L., Li, Y., Che, F., Pang, N., Wang, H., Tong, D., Qin, W., Cheng, W., Liu, W., Fu, Q., Liu, B., Chai, F., Davis, S.J., Zhang, Q., He, K., 2020. Enhanced aerosol pollution offset reduction of primary emissions due to COVID-19 lockdown in China. Nat. Sci. Rev. 0 (0), 1–9.

Kawamura, K., Cagosian, R.B., 1987. Implication of α-oxocarboxylic acids in the remote marine atmosphere for photo-oxidation of unsaturated fatty acids. Nature. 325, 330–332.

Le, T., Wang, Y., Liu, Y., Yang, Y., Li, G., Seinfeld, J.H., 2020. Unexpected air pollution with marked emission reductions during the COVID-19 outbreak in China. Sci. Rep. 10, 116, 422–427.

Magrenon, L., Melissiu, A., Lebras, G., Moortgat, G.K., Horowitz, A., Wirtz, K., 2005. Photolysis and OH-initiated oxidation of glycolaldehyde under atmospheric conditions. J. Phys. Chem. A 109 (20), 4552–4561.

Middlebrook, A.M., Bahreini, R., Jimenez, J.L., Canagaratna, M.R., 2012. Evaluation of composition-dependent collection efficiencies for the aerodyne aerosol mass spectrometer using field data. Aerosol Sci. Technol. 46 (3), 258–271.

Myllyvirta, L., 2020. Analysis: coronavirus temporarily reduced China’s CO2 emissions by a quarter. CarbonBrief. Available from: https://www.carbonbrief.org/analysis-coronavirus-temporarily-reduced-chinas-co2-emissions-by-a-quarter (Accessed 2 June 2020).

Ng, N.L., Canagaratna, M.R., Jimenez, J.L., Zhang, Q., Ulbrich, I.M., Worsnop, D.R., 2011. Real-time methods for estimating organic mass concentrations from aerosol mass spectrometer data. Environ. Sci. Technol. 45 (3), 910–916.
