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Global air quality change during the COVID-19 pandemic: Regionally different ozone pollution responses COVID-19

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ABSTRACT

The explosive spread of the 2019 novel coronavirus (COVID-19) provides a unique chance to rethink the relationship between human activity and air pollution. Though related studies have revealed substantial reductions in primary emissions, obvious differences do exist in the responses of secondary pollutants, like ozone (O3) pollution. However, the regional disparities of O3 responses and their causes have still not been fully investigated.

To better elucidate the interrelationship between anthropogenic emissions, chemical production, and meteorological conditions, O3 responses caused by lockdowns over different regions were comprehensively explored at a global scale. Observational signals of air-quality change were derived from multi-year surface measurements and satellite retrievals. With similar substantial drops in nitrogen dioxide (NO2), ozone shows rising signals in most areas of both East Asia and Europe, even up to ~14 ppb, while a non-negligible declining signal exists in North America, by about 2–4 ppb. Furthermore, the drivers behind the different O3 responses are discussed based on meteorological analysis and O3 sensitivity diagnosis. On the one hand, O3 responses to NO2 declines can be affected by the primary dependence on its precursors. On the other hand, it is also highly dependent on meteorological factors, especially temperature. Our study further highlights the great impact of taking into consideration both the regional disparities and synergistic effects of precursor reductions and meteorological influence for scientific mitigation of O3 pollution.

1. Introduction

Tropospheric ozone (O3), one of the most important air pollutants, has drawn increasing concern owing to exacerbated O3 pollution and increased knowledge about its climatic impacts and health hazards (Atkinson et al., 2016). It can create serious pollution events of great concern, but is also an invisible killer (Haagen-Smit, 1952). Robust evidence exists of higher mortality in association with exposure to O3 (Jerrett et al., 2009). In addition, tropospheric O3 is also the third largest greenhouse gas, contributing about 3%–7% of the greenhouse effect, and has a substantial impact on climate change (Chang et al., 2009). Moreover, O3 exposure also causes oxidation damage to crops, resulting in huge economic and ecological losses and posing great threats to food security (Peng et al., 2015).

As a typical secondary pollutant, surface O3 is mainly generated by volatile organic compounds (VOCs) and nitrogen oxides (NOx) through a series of photochemical reactions (Haagen-Smit, 1952; Wang et al., 2010). Its formation is driven by precursor emissions, chemical conversion, and weather with complicated mechanisms (Ding et al., 2008; Ding et al., 2013; Xue et al., 2014; Wang et al., 2017; Xu et al., 2018; Huang et al., 2020). The short-term daily changes in O3 are mainly affected by meteorological factors, while the long-term changes in O3 are affected by both climate and emissions (Gao et al., 2013; Zhu et al., 2015; Wang et al., 2019; Chen et al., 2020). Moreover, the nonlinear relationship...
between O3 production and its precursors further makes it challenging to understand the nature of O3 pollution and formulate specific control measures under different conditions (Sillman, 1999).

With the explosive spread of the 2019 novel coronavirus (COVID-19), the epidemic rapidly deteriorated into a global pandemic and kept escalating. Governments around the world imposed unconventional containments on economic activities and even restrictions on population mobility (lockdown), one after another (Cohen and Kupferschmidt, 2020). A near-complete standstill of social and economic activities occupied many countries, leading to large reductions in emissions, especially those from traffic and the manufacturing sector (Huang et al., 2020; Venter et al., 2020). However, despite such unprecedented decreases in primary pollution (Menut et al., 2020), obvious regional disparities still exist in global air-quality changes, especially with respect to O3 anomalies (Sicard et al., 2020). In China, large decreases in NOx emissions from transportation increased O3 and nighttime NOx radical formation, leading to the enhancement of atmospheric oxidizing capacity, which even made the secondary pollution offset the role of emissions reduction (Huang et al., 2020). On the contrary, O3 also shows declines together with nitrogen dioxide (NO2) in some regions like Canada and California (Adams, 2020; Connerton et al., 2020). Regionally different O3 pollution responses to NOx declines during the global pandemic may exist, owing to differences in emission reduction measures, natural conditions, and nonlinear O3 chemistry.

In this study, we integrated multi-year ground-based measurements of major pollutants, meteorological analysis, and satellite-retrieved atmospheric composition columns to explore the NOx and O3 pollution responses during the COVID-19 lockdown. Furthermore, regional disparities in O3 responses and the possible contributions from meteorological factors and emission changes are discussed, combining statistical analysis and O3 sensitivity diagnosis (Duncan et al., 2010; Souri et al., 2020). The interplay between emissions, atmospheric chemistry and meteorological conditions is assessed, with a focus on O3.

2. Data and methods

2.1. Ground-based observations and satellite retrievals

To analyze global air-quality changes during the COVID-19 lockdown, observational signals were extracted from surface air-quality observations and satellite-retrieved column amounts for three major regions, i.e., East Asia, Europe, and North America.

The ground-based air-quality observations were obtained from the World Air Quality Index platform (https://aqicn.org/data-platform/covid19/; last access: 31 July 2020) and originated from government-grade sources, mainly environmental protection agencies worldwide. The median of daily measurements at several stations was adopted for each major city. Only data with more than 70% valid temporal coverage were collected for further analysis. Moreover, outliers in the data with z-scores exceeding an absolute value of 3 (within 3 standard deviations from the mean) were removed for quality control (Cousineau and Chartier, 2010). Besides, the average of observations during the same period from 2015 to 2019 was inferred as the climatic normal level, to analyze from a second dimension apart from the comparison between the pre-COVID and COVID-lock periods.

To supplement surface observations, we also employed satellite data to illustrate the spatial pattern and temporal variation of air pollution. The Tropospheric Monitoring Instrument (TROPOMI) onboard the Copernicus Sentinel-5 Precursor satellite provides retrievals of tropospheric NO2 and formaldehyde (HCHO) column amounts. The Level-2 daily products, with an overlap time of around 1330 LST and a spatial resolution of 3.5 km latitude × 5.5 km longitude, were accessed (https://s5phub.copernicus.eu/dhus/#/home; last access: 31 July 2020). Measurements with a quality assurance value below 0.5 were omitted to reduce uncertainties resulting from processing errors, anomalously high signals, and sun glints. For NO2, the trajectory product was then regridded to a 0.25° × 0.25° spatial grid.

2.2. Meteorological analyses

The temperature at a height of 2 m, relative humidity, and solar radiation reaching the surface were taken from the NCEP FNL dataset (spatial resolution: 1° × 1°), which is updated every 6 h. The FNL product has integrated abundant observation and satellite retrievals, and has been widely used in research on weather and climate (Huang et al., 2016; Tang et al., 2020).

2.3. Ozone chemistry sensitivity diagnosis

The nonlinear chemical processes involved in O3 production have necessitated using proxy indicators to convey information about the primary dependence of O3 production on VOCs or NOx (Sillman, 1999; Souri et al., 2020). The space-based tropospheric column ratio of HCHO (a proxy for VOCs) to NOx has been widely used in previous studies as an indicator to qualitatively separate NOx-limited and NOx-saturated O3 formation regimes (Duncan et al., 2016; Choi et al., 2012; Jin and Holloway, 2015). Following these studies, data points with HCHO/NOx ratios below 1 are considered as an NOx-limited regime, those with HCHO/NOx ratios above 2 are considered as an NOx-limited regime, while those between 1 and 2 would fall into a transition regime. Indeed, Jin et al. (2017) also revealed that the column HCHO/NOx ratios marking the boundary between the NOx-saturated and transitional regimes are 0.9 from 2006 to 2012 for all three regions, and the thresholds are higher in the cold season than the warm season. Since the COVID-lock period defined in our research is mainly in the cold season, the adopted critical values in this study are relatively reasonable for qualitative differentiation. The TROPOMI NOx and HCHO products were also regridded to a 1° × 1° spatial grid, to calculate the ratio of HCHO/NOx and then diagnose O3 sensitivity regimes.

3. Results

3.1. Obvious NOx reduction caused by COVID-19 in the Northern Hemisphere

To obtain an overview of air-quality changes caused by the COVID-19 pandemic in the Northern Hemisphere, we compared the monthly average ground-based observed NOx concentration from January to March in 2020 with the climatic state, which is defined as the average of the same period in 2015–19 (Fig. S1). As shown, with the continuous expansion of the global pandemic, sharp decreases in NOx concentrations occurred in East Asia, Europe, and North America, successively. As the earliest epicenter of the pandemic, China was the first country to shut down commercial activities, restrict travel, and announce home quarantine, immediately after the Chinese Spring Festival in late January (Wang et al., 2020), reflecting the dramatic negative NOx anomalies in January and February (Fig. S1(a)). Then, European countries successively entered region-wide states of emergency and carried out measures with the ensuing outbreak in Europe, and NOx concentration started to decrease by ~10 ppb compared with the climatic state in February (Fig. S1(b)). As for North America, a large-scale stay-at-home order was finally implemented in late March. Prior to this, the NOx concentration had already showed scattered signals of decline.

Moreover, time series of daily average observations in 2020 and normal levels in the same period are compared, for the three regions, respectively (Fig. 1). For East Asia, the region-averaged NOx concentration shows a sharp decline of ~46% (~8 ppb), remarkably coincident with the start of lockdown, and remained at a low level for nearly two months after the outbreak of growth in newly confirmed COVID-19 cases. Prior studies have also revealed a significant drop of up to ~40% in the average NOx column over all Chinese cities relative to the same period
in 2019 (Bauwens et al., 2020). Unlike NO₂, O₃ sometimes shows an opposite rising signal, especially when NO₂ drops sharply (Zhao et al., 2020). As for Europe and North America, the downward trend of NO₂ and the upward trend of O₃ can on the one hand be partly attributed to seasonal changes, in terms of radiation and temperature (Fiore et al., 2002), while on the other hand the average ground-level NO₂ during the pandemic is ~25% and ~17% lower, respectively, than climatic normal levels even before the large-scale sudden emergence of the COVID-19 pandemic (Fig. 1(b-c)). Moreover, the global population-weighted concentration of ground-level NO₂ was indicated to have declined by ~60% (Venter et al., 2020).

Ozone in both East Asia and Europe during the pandemic is obviously higher than the climatic state, which is clearly opposite to the case for NO₂. Still, O₃ in North America shows an opposite signal (Fig. 1(c)): a decline from the climatic normal level in sync with NO₂ since March when some local governments started to call on people to segregate at home. Therefore, the pre-COVID and COVID-lock periods are selected for the three regions respectively, according to the approximate time node of the stay-at-home order and the changes in newly confirmed COVID-19 cases (Fig. 1). In addition, declines by almost ~18 ppb in satellite-retrieved tropospheric NO₂ column concentrations between the COVID-lock and pre-COVID period in 2020 further proves the sharp reductions in air pollutant emissions caused by lockdown (Fig. 1(d–f)).

3.2. Ozone response to emissions reduction and its regional disparity

To make a clearer comparison, regional statistics are counted based on ground-based observations for the four time periods, i.e. pre-COVID and COVID-lock in 2020 and 2015–19 respectively. In this case (Fig. 2), the average differences in 2015–19 between the same periods of pre-COVID and COVID-lock are considered as seasonal changes, while the differences between 2020 and the climatic state during the pre-COVID period are inferred as changes caused by meteorological factors and anthropogenic emission declines during the pandemic (Venter et al., 2020).

As illustrated in Fig. 2(a), regional average NO₂ concentrations reach an abnormally low value during the COVID-lock period in 2020 for all three regions, declining from climatic normal levels by ~7 ppb in East Asia, ~5 ppb in Europe, and ~3 ppb in North America. The values are much lower than the expected ones defined in Fig. 2, i.e., the magnitudes of decline are much larger than the difference between 2020 and the climatic state, indicating the existence of contributing factors other than interannual changes in emissions, especially in East Asia and Europe. With a declining NO₂, the regional average O₃ in Europe shows a significant increase (~5 ppb) from the climatic level, and ~4 ppb from the expected value, while there is a weak increase in East Asia and a moderate decline in North America. Apart from increased O₃ caused by seasonal changes (Fiore et al., 2002), the significantly increased O₃ in Europe and the moderately decreased value in North America are mainly caused by changes in anthropogenic emissions or meteorological conditions. Prior studies have also indicated that O₃ concentrations have increased differently in urban areas throughout western Europe during lockdown (Collivignarelli et al., 2020; Menut et al., 2020), while declines or little change are apparent in American cities like New York and Los Angeles (Connerton et al., 2020).

To elucidate the relationship between changes in NO₂ and O₃, ground-based observational changes are further analyzed for cities over the three regions, respectively (Fig. S2). Points of NO₂ and O₃ changes distribute evenly around zero before the pandemic in all three regions, while changes in NO₂ centralize in the negative area and can even be up to −14 ppb during the COVID-lock period. As for O₃ in East Asia and Europe, changes are more concentrated in the positive area than the neg-
Fig. 2. Ground-based station observations of NO₂ and O₃ in East Asia, Europe, and North America. The figure compares the average concentration level before the COVID-19 pandemic (2020-Pre), during the lockdown period (2020-Lock), and the five-year climatological level for 2015–19 in the same period. Panels (a) and (b) are for NO₂ and O₃, respectively. The dashed lines on 2020-Lock mark the expected value, defined as Norm-lock plus the difference between 2020-Pre and Norm-Pre.

3.3. Meteorological and chemical drivers behind the different O₃ responses

Tropospheric O₃ is primarily built by photochemical reactions under solar radiation, covering complex nonlinear photochemistry with multiple precursors including NOₓ, carbon monoxide, VOCs, and methane (Sillman, 1999). So, the primary dependence of O₃ production on its precursors, i.e., O₃ sensitivity, is an important factor for the O₃ responses in the face of NO₂ reduction. Here, the ratio of HCHO, a proxy to VOCs, to NO₂ columns has been applied to diagnose O₃ sensitivity regimes (Duncan et al., 2010; Choi et al., 2012) (see Section 2.3 for details).

The spatial distribution of the ratio of satellite-retrieved HCHO to NO₂ during the COVID-19 lockdown in 2020 is shown in Fig. 4. In East Asia, large areas with low HCHO/NO₂ values less than 1 are considered as an NOₓ-saturated regime (Souri et al., 2020) in eastern and southern China, especially in dense urban areas. Most cities in China would fall into the NOₓ-saturated regime owing to high NO₂ emissions, which means the O₃ is expected to increase with decreased NO₂ (Wang et al., 2019). The increased O₃ in eastern China can be explained to a certain extent; nevertheless, the observed O₃ anomalies in southern coastal areas still indicate the involvement of other factors like meteorological influences. As for Europe, the low ratio values over the northern cities show diagnoses of NOₓ-saturated regimes, fitting well with the observed O₃ anomaly, together with the high values over the Iberian Peninsula. As for North America, except for metropolitan areas, most areas are inclined toward NOₓ-limited regimes, with ratios even above 5, consistent with the transition from an NOₓ-saturated regime to an NOₓ-limited regime in North America, as revealed in prior studies (Choi et al., 2012; He et al., 2020). In addition, since the lockdown in North America almost fell in late spring, increased highly active VOC emissions from natural sources and the accelerated oxidation rate by the rising tem-
Fig. 3. Spatial distribution of changes in NO$_2$ and O$_3$ during the COVID-19 lockdown: (a, b) ground-based observational changes in NO$_2$ and O$_3$ for cities in East Asia during the COVID-19 lockdown in 2020 relative to the same period in 2019; (c, d) and (e, f) as in (a, b) but for Europe and North America, respectively.

Fig. 4. Ratio of satellite-retrieved HCHO to NO$_2$ during the COVID-19 lockdown: (a) spatial distribution of the ratio of HCHO to NO$_2$ in East Asia during the COVID-19 lockdown; (b, c) as in (a) but for Europe and North America, respectively.

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perature would make O$_3$ sensitivity tend toward a transitional regime or even an NO$_x$-limited regime (Jin and Holloway, 2015; Xu et al., 2021).

Besides, surface O$_3$ production is also strongly affected by meteorological factors like solar radiation fluxes, air temperature, and humidity (Ding et al., 2008; Pope et al., 2016; Lu et al., 2019). Fractional changes in meteorological conditions between the COVID-lock period in 2020 and the same period in 2015–19 are shown in Fig. 5. Air temperature is one of the most important drivers of tropospheric O$_3$ production, which can enhance the rate of photochemical production and promote its accumulation (Swackhamer 1991). During the COVID-lock period, temperatures were around 2°C warmer than the climatic state in eastern China and almost throughout Europe, contributing to O$_3$ formation (Fig. 5(a-b)). However, the effect of rising temperature can be partly offset by declines in solar radiation reaching the surface and increased relative humidity, which is mainly reflected in southern China and southern Europe (Fig. 5(d-i)), consistent with the barely changed O$_3$ in the Pearl River Delta and Iberian Peninsula regions (Fig. 3). For North America, due to substantially decreased temperatures and increased relative humidity, decreased O$_3$ shows in the southwestern coastal cities like California (Connerton et al., 2020). Though no significant changes in solar radiation exist, large increases of humidity by ~40% in the eastern coastal region of America reflects the sporadic signals of decreased O$_3$ (Fig. 5(f-i)). It was found that although O$_3$ responses to NO$_2$ declines can
be partly affected by chemical sensitivity, it is mainly dominated by meteorological factors, especially temperature and radiation. The drivers behind the O$_3$ responses further emphasize the importance of taking into consideration both the synergistic effects of precursor reductions and meteorological influences for refined O$_3$ pollution control over different regions.

4. Conclusion

The outbreak of COVID-19 raised a question about the relationship between anthropogenic emissions and air pollution, which has aroused heated discussion. Though research on air-quality changes caused by the lockdowns in different areas shows similar substantial reductions in primary emissions, obvious differences exist in the responses of secondary pollutants like O$_3$.

To better elucidate the reasons behind the regional differences in O$_3$ responses and the interplay between emissions, atmospheric chemistry, and meteorological conditions, global air-quality changes caused by COVID-19 lockdowns and regional specific O$_3$ responses to sharp NO$_2$ declines were explored. Observational signals of air-quality change were extracted from multi-year ground-based measurements of major pollutants and satellite-retrieved atmospheric composition columns. Ozone shows rising signals in most areas of both East Asia and Europe, while a non-negligible declining signal exists in North America, in the face of NO$_2$ reductions over the three regions, indicating significant differences in relations between NO$_2$ and O$_3$ changes.

Furthermore, meteorological and atmospheric chemical drivers behind the different O$_3$ responses were discussed based on analysis data and proxy indicators (HCHO/NO$_2$) for O$_3$ sensitivity diagnosis. Ozone responses to NO$_2$ declines can be affected by the primary dependence on its precursors to a certain extent, and the O$_3$ response in Europe fits particularly well with the O$_3$ sensitivity regimes. Meanwhile, meteorological factors are a rather important driver of the O$_3$ responses, especially air temperature and solar radiation. Apart from weakened titration effects caused by NO declines, increased O$_3$ in East Asia and Europe can be largely dominated by the climatologically warmer temperatures during the lockdowns in 2020. However, the contribution of rising temperature can be partly offset by a decline in solar radiation reaching the surface and an increase in relative humidity in southern China and southern Europe. For North America, declines in temperature and substantial increases in humidity can be important contributors to the decreased O$_3$ over the western coasts.

This study investigated the impact of meteorological conditions and chemical sensitivity under emission changes, which further emphasizes the great importance of taking into consideration the regional disparities and synergistic effects of precursor reductions and meteorological influences for scientific mitigation of O$_3$ pollution.
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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.aeolia.2020.100015.

References

Adams, M.D., 2020. Air pollution in Ontario, Canada during the COVID-19 state of emergency. Sci. Total Environ. 742, 410561. doi:10.1016/j.scitotenv.2020.10.1045.
Atkinson, R.W., Butland, B.K., Dimitrioupoloulos, C., Heal, M.R., Stedman, J.R., Carslaw, N., Jarvis, D., et al., 2016. Long-term exposure to ambient ozone and mortality: a quantitative systematic review and meta-analysis of evidence from cohort studies. BMJ Open 6 (2), e009493. doi:10.1136/bmjopen-2015-009493.
Baumwens, M., Compernolle, S., Stavralou, T., Müller, J.-F., Gent, J., Eikes, H., Levell, P.F., et al., 2020. Impact of coronavirus outbreak on NO2 pollution assessed using TROPOMI and OMI observations. Geophys. Res. Lett. 47 (11). doi:10.21002/glo87978.
Chang, W.Y., Liao, H., Wang, H.J., 2009. Climate responses to direct radiative forcing of anthropogenic aerosols, tropospheric ozone, and long-lived greenhouse gases in eastern China over 1951–2000. Adv. Atmos. Sci. 26 (4), 748–762. doi:10.1007/s00376-009-9032-4.
Chen, Z., Li, R., Chen, D., Zhuang, Y., Gao, B., Yang, L., Li, M., 2020. Understanding the causal influence of major meteorological factors on ground ozone concentrations across China. J. Clean. Prod. 242, 118498. doi:10.1016/j.jclepro.2019.118498.
Choi, Y., Kim, H., Tong, D., Lee, P., 2012. Summertime weekly cycles of observed and modeled NOx and O3 concentrations as a function of satellite-derived ozone production sensitivity and land use types over the Continental United States. Atmos. Phys. Chem. 12 (14), 6291–6307. doi:10.1016/j.atmoscp.2012.09.012.
Cohen, J., Kupferschmidt, K., 2020. Strategies shift as coronavirus pandemic looms. Science 367 (6481), 962–963. doi:10.1126/science.367.6481.962.
Colliander, M.C., Abba, A., Bertanza, G., Pedrazzani, R., Ricciardi, P., Miño, M.C., 2020. Lockdown for Covid-19 in Milan: what are the effects on air quality? Sci. Total Environ. 732, 139280. doi:10.1016/j.scitotenv.2020.139280.
Corner, P., Assunção, J.V.D., Miranda, R.M.D., Slovı, A.D., Pérez-Martínez, P.J., Ribeiro, H., 2020. Effects of COVID-19 in four megacities: lessons and challenges for public health. Int. J. Envir. Public Health 17 (14), 5067. doi:10.3390/ijerph17145067.
Courtois, D., Chartier, S., 2010. Outliers detection and treatment: a review. Int. J. Psychol. Res. Medellin 3 (1), 58–67. doi:10.21589/20110102048.444.
Ding, A.J., Fu, C.B., Yang, X.Q., Sun, J.N., Zheng, L.F., Xie, Y.N., Herrmann, E., et al., 2013. Ozone and fine particle in the western Yangtze River Delta: an overview of 1yr data at the SM08 station. Atmos. Chem. Phys. 13 (11), 5813–5830. doi:10.5194/acp-13-5813-2013.
Ding, A.J., Wang, T., Thouret, V., Cammas, J.P., Edels, P., 2008. Tropospheric ozone climatology over Beijing: analysis of aircraft data from the MOZAIK program. Atmos. Chem. Phys. 8, 1–13. doi:10.5194/acp-8-1-2008.
Duncan, B.N., Yoshida, Y., Olson, J.R., Silliman, S., Martin, R.V., Lamsal, L., Hu, Y., et al., 2010. Application of OMI observations to a space-based indicator of NOx and VOC controls on surface ozone formation. Atmos. Environ. 44 (18), 2213–2223. doi:10.1016/j.atmosenv.2010.03.010.
Feng, Z., Hu, E., Wang, X., Yang, J., Liu, L., Xiu, Y., 2015. Ground-level O3 pollution and its impacts on food crops in China: a review. Environ. Pollut. 199, 42–48. doi:10.1016/j.envpol.2015.01.016.
Fiore, A.M., Jacob, D.J., Yantosca, R.M., Field, B.D., Fusco, A.C., 2002. Background ozone over the United States in summer: origin, trend, and contribution to pollution episodes. J. Geophys. Res.: Atm., 107(D15),107(D15). doi:10.1029/2001jd0009982.
Gao, Y., Fu, J.S., Drake, J.B., Lamarque, J.F., Liu, Y., 2013. The impact of emissions from ozone in the United States under representative concentration pathways (RCPs). Atmos. Chem. Phys. 13 (18), 9607–9621. doi:10.5194/acp-13-9607-2013.