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Long-term variation and evaluation of air quality across Hong Kong

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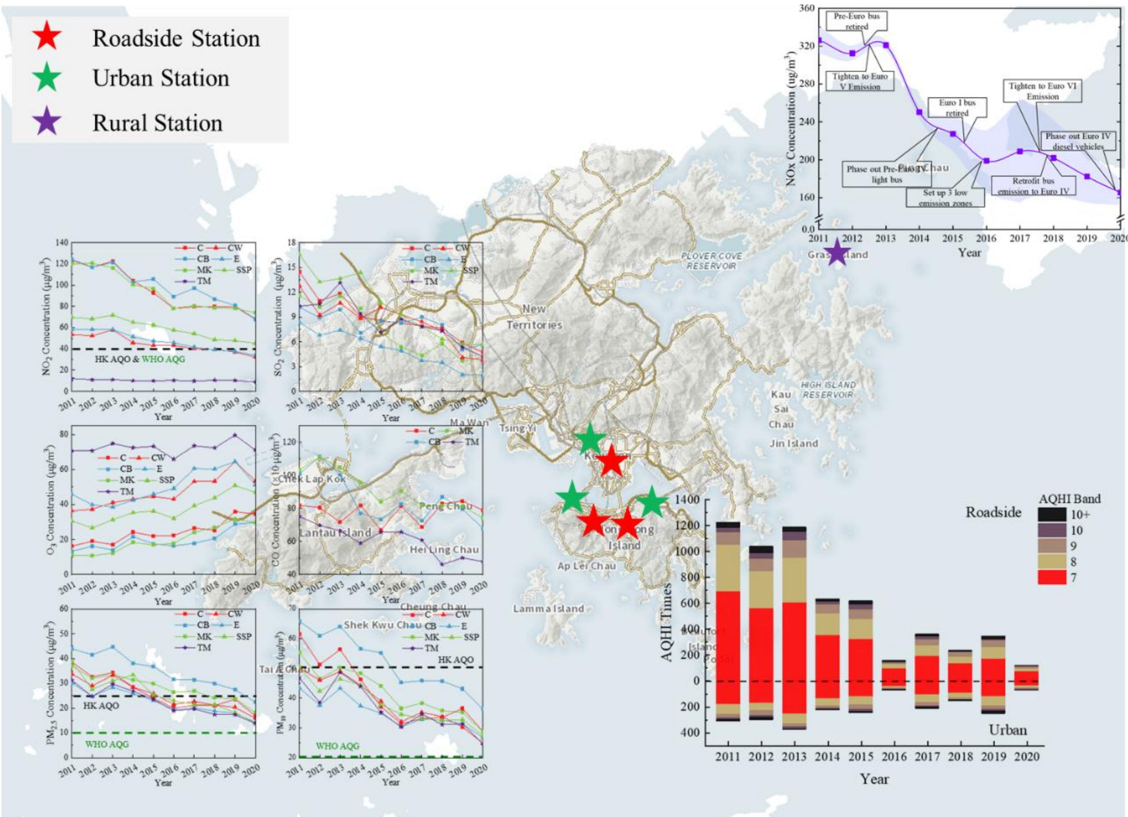
Graphical Abstract



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Abstract: Study of Air Quality Objectives (AQOs) and long-term changes of air pollution plays a decisive role in formulating and refining pollution control strategies. In this study, 10-year variations of six major air pollutants were analyzed at seven monitoring sites in Hong Kong. The continuous decrease of annual averaged concentrations of NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10} and numbers of days with severe pollution conditions validated the efficiency of the series of air pollution control schemes implemented by the Hong Kong government. However, there is still a big gap to meet the ultimate targets described by the World Health Organization. Besides, the concentration of O_3 at roadside and urban stations increased by 135 ± 25% and 37 ± 18% from 2011 to 2020, respectively, meanwhile the highest 8-hr averaged O_3 concentration was observed as 294 μg/m^3 at background station in 2020, which pointed out the increasing ozone pollution in Hong Kong. There was a great decrease in the annual times of air quality health index (AQHI) laying in “high”, “very high” and "serious" categories from 2011 to 2020 with the decrease rate of 89.70%, 91.30% and 89.74% at roadside stations, and 79.03%, 95.98% and 72.73% at urban stations, respectively. Nevertheless, the number of days categorized as "high" or above at roadside station was twice more than that in the urban station during the past ten years. Thus, more policies and attentions should be given to the roadside air quality and its adverse health effect to pedestrians on street.

Keywords:

Long-term variation

Roadside

Hong Kong air quality

Air Quality Objectives (AQO)

Air quality health index (AQHI)

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Introduction

Due to the rapid economic growth and urbanization, air pollution has drawn much more public attention over the past couple of years and has been a severe global environmental issue (Kim et al., 2015; Liu et al., 2019). Hong Kong is one of the most developed regions in the world and plays an essential role in Guangdong–Hong Kong–Macao Greater Bay Area (GBA) due to its special administrative status in China (Hui et al., 2020). The air quality in Hong Kong is affected by the intensive human activities and heavy traffic (more than 900,000 registered vehicles, at the end of 2020) (HKTD, 2021) owing to its large population (7.5 million residents, at the end of 2020) (HKC&SD, 2021). Vehicle emission has become the primary pollution source in the urban area of Hong Kong as the migration of most industrial factories from Hong Kong to Mainland China (Chan and Yao, 2008; Cui et al., 2018; Ho et al., 2013). For example, nitrogen oxides (NO_X) and carbon monoxide (CO), as the major significant vehicular gaseous pollutants, were generated from road transport emission for about 16% and 50% in Hong Kong in 2019, respectively (HKEPD, 2020). In addition, the distance of vehicle-kilometer-travelled, which was an important variable for evaluating transportation-related environmental issues, increased by 22% from 2011 to 2019. As more and more medias are reporting air pollution episodes and the severe poor-visibility effect, the public has taken notice of controlling the emissions of air pollutants and improving air quality in Hong Kong and the GBA (Ai et al., 2016; Brimblecombe, 2022; Hossain et al., 2021).

Ambient air quality objectives (AQOs), based on the causal link between air pollutions and environmental effects, were set up to standardize the requirements of good air quality and help to maintain the pollutants within the acceptable levels as far as possible (Angle, 2014). Hong Kong Air Quality Objectives (HK AQOs) were established by the Hong Kong government based on the methods from the United States in 1987, and it was reviewed at least once every five years. The requirements of HK AQOs and latest World Health Organization Air Quality Guidelines (WHO AQG) for different pollutants are listed in **Appendix A Table S1**. Besides, in order to address the critical air pollution situation and to provide the related information to the public on time, Hong Kong Environmental Protection Department (HKEPD) had set up the air pollution index (API), which was calculated by the concentration data of five types of major pollutants by a weighting system with the range from 0 to 500 and had been reported in real-time since 1995. Although API provides an assessable system for public to evaluate the air quality, a big shortcoming is that the calculation of the index ignores the joint effects from different air pollutants and only considers the deviation from the reference standard of one single pollutant. A multi-pollutant approach called air quality health index (AQHI) was pioneered in Canada (Stieb et al., 2008) to address the deficiency and to fill the gap between the rising concentration of pollutants and lag in reporting. Based on a multifaceted summary of health risks associated with individual pollutants, Wong et al. (2013) adapted the Canadian methods and developed the health-risk-related reporting system in Hong Kong to enhance the existing air quality indicators. The AQHI provides more information about the overall impact of mixed air pollutants to public, especially to the groups with high health risks and concerns (Chen et al., 2013; Li et al., 2017; Sun et al., 2016). The government of the Hong Kong Special Administrative Region (HKSAR) has implemented a wide range of measures targeting at different local emission sources including motor vehicles, power plants and vessels (HKEPD, 2015). A series of schemes were launched to upgrade the cleanliness of automotive exhausts, such as partial franchised buses were retired on May 2012 (for pre-Euro emission standards) and May 2015 (for Euro I emission standards), and the statutory vehicle emission standards were progressively tightened to Euro VI since June 2012. Besides, the Franchised Bus Low Emission Zones where a more restrictive vehicle emission-Euro V was established to further monitor and improve the air quality at designated roadside areas (HKEPD, 2015). In June 2021, the Clean Air Plan for Hong Kong 2035 was announced by the Environmental Bureau, which proposed the long-term goals and strategies for a better environment and aimed to build Hong Kong into a clean metropolis with great air quality by 2035 (HKSAR, 2021).

Although some achievements of air pollution control have been reported by HKEPD based on the reduction of the concentration of major air pollutants (Huang et al., 2015; Mason et al., 2019; Ng et al., 2013), detailed analysis of pollutants and their patterns in different monitoring stations was not conducted especially on a long-term basis. Hence, a 10-year continuous variation of air pollutants across roadside, urban and background sites in Hong Kong from 2010 to 2020 was analyzed in this study. The annual change of the major pollutants (NO_2, SO_2, O_3, CO, $PM_{2.5}$ and PM_{10}) and the comparisons with their relevant standards were presented. Moreover, the spatial differences of pollutants were illustrated, which thus can verify the impact of different geographical factors on pollution status and transformation and then determine any further measures that could be proposed and implemented in specific areas. The distribution of AQHI was calculated seriatim over the past ten years to investigate the improvement of air quality and provide a comprehensive assessment on human health and control measures in Hong Kong.

1 Materials and methods

1.1 Roadside pollutants concentrations retrieved from HKEPD

The HKEPD has set up the air pollution monitoring network comprising 18 fixed monitoring stations (15 general stations and 3 roadside stations) to continuously monitor the air pollution across Hong Kong and to forecast the air pollutants and health risks to the public. Three roadside air pollution monitoring stations located in the business area of Central (C), Causeway Bay (CB), and Mong Kok (MK) with heavy traffic and commercial buildings around are our main research targets. Besides, three general stations near the abovementioned roadside stations, which located in Central/Western (CW), Eastern (E), and Sham Shui Po (SSP) respectively, were also selected as urban sites. Moreover, a rural air pollution monitoring station situated in the island of Tap Mun (TM) with rare human activities was also introduced into this study as the background point for further analysis and comparison. These seven air monitoring stations were selected to study the roadside, urban and rural air pollution situations during the past ten years. The locations of the seven air quality monitoring stations are illustrated in **Fig. 1,** and the brief descriptions of the those monitoring stations are listed in **Table 1**.

The hourly averaged concentration data from the seven air quality monitoring stations was retrieved from HKEPD (https://cd.epic.epd.gov.hk/EPICDI/air/station/). The concentrations of both gaseous pollutants (CO, NO, NO_2, O_3, and SO_2) and particulate pollutants (fine suspended particulates (FSP), also named as $PM_{2.5}$ and respirable suspended particulates (RSP), also named as PM_{10}) were collected from January 2011 to December 2020. The concentration data of CO are not recorded at the three urban stations. The NO data is not provided at the E station, and the concentration of $PM_{2.5}$ is not available at CB station before March 2011 and CW station before August 2011, respectively. Other small amounts of discrete missing data are due to the on-site maintenance and calibration of equipment.

1.2 Calculation and banding of air quality health index (AQHI)

The AQHI, which replaced the air pollution index (API) in Hong Kong from 2013, is a short-term health-risk-based air pollution index (HKEPD, 2013). The AQHI considers the effect of multiple pollutants and is reported on a scale of 1 to 10 and 10+, which is further grouped into five health risk categories (as shown in **Table 2**).

The hourly AQHI is calculated from the sum of the percentage added health risk (*%AR*) of the 3-hr rolling average concentrations of four criteria air pollutants including nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and PM ($PM_{2.5}$ or PM_{10}, whichever poses a higher health risk) (Wong et al., 2013). The *%AR* was calculated by equations Eq. (1) and (2):

$$\%AR(X)=[\exp(\beta(X)\times C(X))-1]\times 100\% \qquad (1)$$

where X represents NO_2, SO_2, O_3, $PM_{2.5}$ and PM_{10}, $\%AR(X)$ is the added health risk of pollutant X, respectively, $C(X)$, is the 3-hr moving average concentration of the pollutants X in microgram per cubic meter (μg/m^3); and $\beta(X)$ is the added health risk in Hong Kong of the pollutant X.

$$\beta(NO_2)= 0.0004462559$$

$$\beta(SO_2)= 0.0001393235$$

$$\beta(O_3)= 0.0005116328$$

$$\beta(PM_{10})= 0.0002821751$$

$$\beta(PM_{2.5})= 0.0002180567$$

$$\%AR=\%AR(NO_2)+\%AR(SO_2)+\%AR(O_3)+\%AR(PM) \qquad (2)$$

where $\%AR(PM)=\%AR(PM_{10})$ *or* $\%AR(PM_{2.5})$, whichever is higher.

2 Results and discussion

2.1 Long- term variations of air quality

An overall temporal variation of the averaged concentrations of six pollutants in the seven air monitoring sites from 2011 to 2020 is illustrated in **Fig. 2**. It is obvious that the concentration level for most of the pollutants (except for O_3) was gradually decreasing during the past 10 years, which should be attributed to the updating and tightening of the policies and requirements for on-road vehicles and their emissions launched by the HKSAR government. Though the air quality was threatened by the increase of total registered vehicles and the annually travelled vehicle-kilometers in recent years, the improvement of air quality in Hong Kong indicates that the measures implemented by the government are effective (HKTD, 2019).

Table 3 lists the variation rates of air pollutants at the seven stations from 2011 to 2020 in order to clearly express the changes. The descent rates of NO_2 at the seven air monitoring stations range from 27.18% (TM) to 45.34% (CB). TM shows the lowest overall concentration of NO_2 and it is the only station that achieves the annual requirements of both HK AQO and WHO AQG among the studied stations (**Fig. 2a**), as TM is a rural station without vehicular emission sources nearby. For other sites, although the concentrations of NO_2 showed a definite tendency to gradually decrease**,** they still exceeded the annual standard of both HK AQO and WHO AQG most of the time, which is 40 $\mu g/m^3$. Only two urban stations, CW and E, met the annual standard of HK AQO and WHO AQG after 2017.

SO_2 (**Fig. 2b**) and CO (**Fig. 2d**) presented an overall decrease trend with slight fluctuations in the annual averaged concentrations from 2011 to 2020, which ranged from 44.3% (CB) to 76.33% (E) for SO_2 and from 36.3% (TM) to 3.63% (C) for CO, respectively. There was no annual air quality objective for the pollutants of SO_2 and CO. The concentration of SO_2 at TM was higher than many roadside and urban stations, although TM is deemed as a background station with lowest concentration of NO_2, CO, $PM_{2.5}$ and PM_{10}. Ship emission was one of the major sources of SO_2 pollution in Hong Kong, which contributed about 36% of ambient SO_2 concentrations (Ng et al., 2013; Yau et al., 2012). TM is not close to any shipping ports in Hong Kong but is close to several ports based in mainland China (Ng et al., 2013), where there is no strict regulation on the emission from marine vessels (Mason et al., 2019). Besides, the highest CO concentration was recorded at MK station. As CO is generally a stable chemical in the atmosphere and mainly comes from the incomplete combustion of fuels from traffic vehicles' engines (Han and Naeher, 2006), the highest concentration at MK is due to its highest traffic intensity among the three roadside stations (shown in the **Appendix A Test S1** and **Fig. S1**).

Undoubtedly, particle pollution ($PM_{2.5}$ and PM_{10}) level showed an evident decreasing tendency over the past 10 years, which is demonstrated in **Fig. 2e** and **Fig. 2f**, respectively. In general, the concentration of $PM_{2.5}$ decreased by 48.99% (CB) to 64.20% (SSP), while the concentration of PM_{10} concentration decreased by 38.28% (E) to 53.15% (C). In addition, with the implementation of a series of control policies, the concentrations of PM_{10} met the HK AQO at all the seven stations from 2016 to 2020. However, the annual concentrations are still beyond the ultimate targets of the WHO AQG, which are 10 $\mu g/m^3$ for $PM_{2.5}$ and 20 $\mu g/m^3$ for PM_{10}.

Contrary to other pollutants, O_3 showed a continuous increase from 2011 to 2019 and a slight decline in 2020 (**Fig. 2c**). As a secondary pollutant formed from the process of photochemical reactions, the concentration of O_3 is largely influenced by its precursors and meteorological conditions such as VOCs and NO_X under sunlight irradiation (Chen et al., 2020; Tan et al., 2021; Wang et al., 2021). Due to a series of social distancing and lockdown actions implemented in 2020 to reduce the transmission of COVID-19 in Hong Kong and GBA, both the emissions and transportations of various O_3 precursors were reduced (Le et al., 2020). Owing to the noticeable decrease of VOCs and NO_X, the O_3 generated through the abovementioned photochemical reactions declined significantly at urban and rural stations, and the overall rates of decrease were 17% (CW), 20% (E), 8% (SSP) and 10% (TM), respectively. However, the drop of O_3 concentration was not obvious at the three roadside stations and the potential reasons for spatial variability of O_3 will be discussed in Section 2.3. Furthermore, the peak concentration of the daily highest 8-hr average concentration of O_3 was measured at TM in 2020, which was 294 μg/m^3. The worsening situation of O_3 pollution has drawn much attention in Hong Kong in the last decade and many O_3 episode days have been reported (Chen et al., 2020; Wang et al., 2017, 2001).

2.2 Exceedance of Air Quality Standard

To further evaluate the air quality at the seven mentioned air quality monitoring stations, the frequencies of exceedance for 24-hr $PM_{2.5}$, 24-hr $PM_{10,}$ 8-hr O_3 and 1-hr NO_2 were calculated every year in **Appendix A Table S3**, which are defined as the ratio of the numbers of days or hours (1-hr NO_2) when the calculated concentrations exceed their corresponding standards (referred to the HK AQO shown in **Appendix A Table S1**) to the total numbers of days or hours in that year. There were great improvements of air pollution situations for both $PM_{2.5}$ and PM_{10} during the past ten years. Their frequencies of exceedance decreased from 2011 to 2020 and no excessive day was observed at all stations in the year 2020. There was also a noticeable decline of the frequency of exceedance for 1-hr NO_2, especially for the three roadside stations, which changed from 9.44% to 0.46 % (C), 8.34% to 0.26% (CB) and 6.72% to 0.42 (MK), receptively. Conversely, the frequency of exceedance for 8-hr O_3 demonstrated an unexpected increase and it should be noticed that the frequency at urban sites was greater than that at roadside sites. However, the worst situation was observed at the rural site and the frequency of exceedance ranged from 4.37% to 12.88%. Besides, an unusual large in quantity of the days with O_3 concentrations exceeding the 8-hr standard was spotted in 2019, and the exceeding days were 47 for rural station (TM) and 21 for urban station (CW).

2.3 Spatial variability of air quality

As discussed in section 2.1, it can be observed that there are obvious disparities of concentrations of pollutants regarding to their different station types and locations. The annual averaged concentrations of all pollutants in the three types of stations are shown in **Fig. 3**. In general, roadside stations had the worst air quality with the highest concentration of NO_2, CO, $PM_{2.5}$ and PM_{10}. It was facile to conclude that concentrations of NO_2, CO, $PM_{2.5}$ and PM_{10} at roadside stations were higher than those at the nearby urban stations as the latter stations are placed far away from the main road and normally located on the higher roof of the buildings, while roadside stations are located at the main traffic streets or even at intersections where are the busiest commercial districts in Hong Kong as well. The heavy traffic motions with large amount of vehicle exhausts and dusts on road would lead to these severe pollutions. Background station showed the significant low concentrations of NO_2 (**Fig. 3a**) and CO (**Fig. 3d**) compared with the other six roadside and urban stations for its rare vehicle emissions nearby. The annual variations of $PM_{2.5}$ and PM_{10} at three different stations are shown in **Fig. 3e** and **Fig. 3f**. It was not surprising that the roadside concentrations of $PM_{2.5}$ and PM_{10} were the highest due to its heavy traffic and there was apparent consistence in annual changes compared with other sites from 2011 to 2020.

However, as illustrated in **Fig. 3b**, the SO_2 concentration at the background station was as high as other sites and was even the highest among the three types of stations in 2013 and 2016 to 2019, which could be explained by the following reasons. As discussed before, ship emission is the major contributor of SO_2 at coastal areas (Lau et al., 2005; Ng et al., 2013), especially for the place like Hong Kong, which is a major hub port for South Asian Pacific region and mainland China and serves as the fourth busiest shipping port in the world (Mason et al., 2019). Moreover, the concentration of SO_2 at TM station was further influenced by the neighboring shipping ports in mainland China (Mason et al., 2019; Ng et al., 2013).

As a major constituent of photochemical smog, O_3 is not considered as a direct-emitted pollutant, while it is formed by photochemical reactions between NOx and volatile organic compounds (VOCs) under sunlight radiations (Cheung and Wang, 2001; Xu et al., 2011).As shown in **Fig. 3c**, background station owned the highest O_3 concentration level among all types of stations with the 10-year averaged concentration of 70.61

μg/m^3, while the concentrations were 21.33 μg/m^3 and 44.75 μg/m^3 for roadside stations and urban stations, respectively. One reason for the O_3 trend among different types of sites should be the titration role of NO, which should exhibit highest concentration on roadsides, then urban sites, resulting in the relatively low concentration of O_3 compared with the rural site. However, the annual average ozone concentrations at the roadside and urban stations increased by 56.82% and 25.53% from 2011 to 2020, respectively, while only 0.75% increase was recorded at the rural station. The huge growth of O_3 pollution at roadside and urban site was mainly due to the reduction of local NOx emissions from vehicles. O_3 formation was limited by VOCs in urban areas of Hong Kong (Chen et al., 2020; Cui et al., 2018; Liao et al., 2021; Tan et al., 2021), and the reduction of NOx does not guarantee a decrease in ozone in VOC-limited regions due to the nonlinear relationship between NOx and O_3 (Atkinson-Palombo et al., 2006; Marr and Harley, 2002; Sillman et al., 1990). The lessened NOx-titration effect caused by the reduction of NO will result in more ozone remaining in the atmosphere and lead to a large increase in measured ozone concentrations (Tonse et al., 2008), which has been reported in Hong Kong and PRD regions (Li et al., 2013; Xue et al., 2014; Zhang et al., 2021). The generation of O_3 in the remote area was affected by many factors, such as biomass burning, long-range transportation of ozone precursor, i.e., methane, CO, NO_X, volatile organic compounds (VOCs), and atmospheric circulation (Wang et al., 2009). Therefore, the background station exhibited both regional and super-regional characteristics and the concentration of O_3 became the highest at background station due to the regional chemical processes and transportation of urban plumes (So and Wang, 2003; Zheng et al., 2010, 2009). In conclusion, it seems to be a long-term project to reduce the peak ozone concentration in Hong Kong by only controlling NOx emissions, in other words, VOC control should also be considered (HKSAR, 2020; Li et al., 2013).

2.4 Evaluation of the effectiveness of air pollution control measures and NO_X

Pollution source control is often considered to be the most practical and effective way to deal with air pollution. A wide range of policies were successively implemented by the government of Hong Kong for the control of vehicular emissions (HKEPD, 2015). **Appendix A Table S4** tabulates the control measures and regulations for vehicles and their emissions suggested and enforced by HKEPD since 2011. As roadside NOx concentration is immensely affected by the emissions from on-road vehicles (Pandey et al., 2008), it would be helpful to use its variations to understand how policy could affect the emission of pollutants. **Fig. 4** visualizes the annual averaged NO_X concentration from three roadside stations with the milestones marking the implementation of different control measures. The annual concentration of NO_X dramatically decreased from 312.47 ± 14.40 $\mu g/m^3$ in 2012 to 250.24 ± 6.10 $\mu g/m^3$ in 2014, which was attributed to the retirement of pre-Euro buses and tightening to Euro V Emission standard during that period. With a series of subsequent control measures for commercial vehicles such as phasing out Pre-Euro IV light buses and stopping using Euro I buses, the emission of NO_X reduced progressively. After a slight increase of NO_X in 2017, another incentive policy was proposed to tighten the first registered vehicles to Euro VI emission standard. Moreover, more than 8 thousand of highly-polluted diesel-fueled vehicles were required to be obsolete or upgraded to meet the Euro VI standard by the end of 2019. Another critical measure was that all the buses need to be retrofitted to meet the standard of Euro IV. Under the support of these control measures in Hong Kong, the concentration of NO_X was decreased conspicuously by nearly 50% from 320.16 ± 14.4 $\mu g/m^3$ in 2011 to 165.36 ± 13.73 $\mu g/m^3$ in 2020, which indicated that the implementation of appropriate measures was an effective way to control vehicle emissions and improve pollution situation of roadside NO_X (Ai et al., 2016; Tian et al., 2011).

2.5 Evaluation of AQHI

As the AQHI is a reporting system that estimates short-term health risk based on air pollutions and helps to take precautionary measures to protect human health (Wong et al., 2013), it is therefore reasonable to exclude the background station TM for further evaluation, where few people may stay. According to the recommended cut-points for different bands of AQHI and their corresponding health risk categories, the frequencies of each AQHI band are calculated and recorded. The specific times when the averaged AQHI is at band 7 or above (which belong to “high”, “very high” and “serious” categories) at roadside and urban stations from 2011 to 2020 are demonstrated in **Fig. 5**. In general, with the implementation of a series of air pollution control measures, the times of AQHI at “high”, “very high” and “serious” categories from 2011 to 2020 went through a sharp reduce with the rates of 89.70%, 91.30% and 89.74% at roadside stations, and 79.03%, 95.98% and 72.73% at urban stations, respectively. Besides, the number of times with high-risk or above at roadside was much higher than that in the urban stations. Over the past 10 years, the statistic times of AQHI laying in “high”, “very high” and “serious” categories at roadside stations were 2.45 times, 2.89 times and 2.30 times higher than those at urban stations, respectively, which indicated that additional precautions should be taken for the public on roads and sidewalks.

However, it should be noted that the unexpected fluctuations and rises were observed from 2017 to 2019. The possible reason was the increased concentrations of O_3 at both roadside and urban stations. As shown in Eq. (1), the AQHI was calculated from the summation of $\%AR$, which was calculated by using the concentrations of four pollutants, NO_2, SO_2, O_3, and PM_{10} in this study. The respective regression coefficients $\beta(O_3)$ owned the highest value among these four pollutions, which indicated the highest potential risk to human. Although the long-term evolution conveyed by the AQHI system shows an improved air quality in Hong Kong, the trend of the increasing concentration of O_3 should not be neglected for human health risk.

3 Conclusions

A long-term variation of air pollutions was analyzed to evaluate the air quality in Hong Kong from 2011 to 2020. The annual averaged concentrations of the major air pollutants (NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10}) decreased in the past ten years due to a series of control strategies implemented by the Hong Kong government. The annual averaged concentrations of particulate matters all met their related requirements of HK AQO in 2020. However, the ever-increasing concentration of O_3 was observed at all the monitoring stations. The O_3 concentration at the background site was 3.31 times and 1.58 times greater than the averaged concentrations at roadside sites and urban sites, respectively. However, huge growths of O_3 concentration at roadside stations were observed with growth rates of 112% (C), 123% (CB) and 170% (MK). The regional chemical processes (dominant O_3-forming precursors) and less transportation effects may jointly contribute to the increase of O_3 concentration at background station, while the reason for its increase at roadside stations was the reduction of NOx-titration effect. The increased concentrations of O_3 also lead to unexpected fluctuations and rises of the frequency of high AQHI from 2017 to 2019, which may pose threats to human health. The AQHI categorized as “high” or above at roadside stations ranked at the first place indicating that more attentions should be taken for the public who often expose to the street environment. At the same time, distinct and positive effects on air quality improvement in Hong Kong were achieved by the current policies, especially for the control of NO_X and particulate matters. In addition, customized and regionalized control strategies for effectively reduction of O_3 are urgently needed and intercity corporations for policy making and pollution control are expected.

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Appendix A Supplementary data

Supplementary data associated with this article can be found in the online version at.

References

Ai, Z.T., Mak, C.M., Lee, H.C., 2016. Roadside air quality and implications for control measures: A case study of Hong Kong. Atmos. Environ. 137, 6–16.

Angle, R.P., 2014. Ambient air quality objectives, in: Air Quality Management: Canadian Perspectives on a Global Issue. Springer, Dordrecht. 289–301.

Atkinson-Palombo, C.M., Miller, J.A., Balling, R.C., 2006. Quantifying the ozone “weekend effect” at various locations in Phoenix, Arizona. Atmos. Environ. 40, 7644–7658.

Brimblecombe, P., 2022. Trends in secondary inorganic particles in Hong Kong, 1995–2020. Atmos. Environ. 268, 118801.

Chan, C.K., Yao, X., 2008. Air pollution in mega cities in China. Atmos. Environ. 42, 1–42.

Chen, R.J., Wang, X., Meng, X., Hua, J., Zhou, Z.J., Chen, B.H., et al., 2013. Communicating air pollution-related health risks to the public: An application of the Air Quality Health Index in Shanghai, China. Environ. Int. 51, 168–173.

Chen, Y.P., Yan, H., Yao, Y.J., Zeng, C.L., Gao, P., Zhuang, L.Y., et al., 2020. Relationships of ozone formation sensitivity with precursors emissions, meteorology and land use types, in Guangdong-Hong Kong-Macao Greater Bay Area, China. J. Environ. Sci. 94, 1–13.

Cheung, V.T.F., Wang, T., 2001. Observational study of ozone pollution at a rural site in the Yangtze Delta of China. Atmos. Environ. 35, 4947–4958.

Cui, L., Wang, X.L., Ho, K.F., Gao, Y., Liu, C., Hang Ho, S.S., et al., 2018. Decrease of VOC emissions from vehicular emissions in Hong Kong from 2003 to 2015: Results from a tunnel study. Atmos. Environ. 177, 64–74.

Han, X., Naeher, L.P., 2006. A review of traffic-related air pollution exposure assessment studies in the developing world. Environ. Int. 32, 106–120.

HKC&SD (Hong Kong Census and Statistics Department), 2021. Population Estimates. Available: https://www.censtatd.gov.hk/en/scode150.html Accessed December 8, 2021.

HKEPD (Hong Kong Environmental Protection Department), 2020. AIR QUALITY in Hong Kong 2019. Available: https://www.aqhi.gov.hk/api_history/english/report/files/AQR2019e_final.pdf Accessed April 10, 2022.

HKEPD (Hong Kong Environmental Protection Department), 2015. Air Pollution Control Strategies. Available: https://www.epd.gov.hk/epd/english/environmentinhk/air/prob_solutions/strategies_apc.html Accessed June 12, 2021.

HKEPD (Hong Kong Environmental Protection Department), 2013. About AQHI. Available: https://www.aqhi.gov.hk/en/what-is-aqhi/about-aqhi.html Accessed April 21, 2021.

HKSAR (the Hong Kong Special Administrative Region), 2021. Clean Air Plan for Hong Kong 2035. Available: https://www.enb.gov.hk/sites/default/files/pdf/Clean_Air_Plan_2035_eng.pdf Accessed December 15, 2021.

HKSAR (the Hong Kong Special Administrative Region), 2020. Concentration of ozone in air. Available: https://www.info.gov.hk/gia/general/202005/20/P2020052000485.htm?fontSize=2 Accessed May 30, 2021.

HKTD (Hong Kong Transport Department), 2021. Annual Transport Digest 2021. Available: https://www.td.gov.hk/mini_site/atd/2021/en/index.html Accessed

December 8, 2021.
HKTD (Hong Kong Transport Department), 2019. THE ANNUAL TRAFFIC CENSUS-2019. Available: https://www.td.gov.hk/filemanager/en/content_5018/annual traffic census 2019.pdf Accessed May 31, 2021.
Ho, K.F., Ho, S.S.H., Lee, S.C., Louie, P.K.K., Cao, J., Deng, W., 2013. Volatile organic compounds in roadside environment of Hong Kong. Aerosol Air Qual. Res. 13, 1331–1347.
Hossain, M.S., Frey, H.C., Louie, P.K.K., Lau, A.K.H., 2021. Combined effects of increased O_3 and reduced NO_2 concentrations on short-term air pollution health risks in Hong Kong. Environ. Pollut. 270, 116280.
Huang, Y., Ling, Z.H., Lee, S.C., Ho, S.S.H., Cao, J.J., Blake, D.R., et al., 2015. Characterization of volatile organic compounds at a roadside environment in Hong Kong: An investigation of influences after air pollution control strategies. Atmos. Environ. 122, 809–818.
Hui, E.C.M., Li, X., Chen, T., Lang, W., 2020. Deciphering the spatial structure of China's megacity region: A new bay area—The Guangdong-Hong Kong-Macao Greater Bay Area in the making. Cities. 105, 102168.
Kim, K.H., Kabir, E., Kabir, S., 2015. A review on the human health impact of airborne particulate matter. Environ. Int. 74, 136–143.
Lau, K.-H., Wu, W.M., Fung, J.C.H., Henry, R.C., Barron, B., 2005. Significant Marine Source for SO_2 levels in Hong Kong. Civic-exchange Environmental and Conservation reports, Hong Kong.
Le, T.H., Wang, Y., Liu, L., Yang, J.N., Yung, Y.L., Li, G.H, et al., 2020. Unexpected air pollution with marked emission reductions during the COVID-19 outbreak in China. Science. 369, 702–706.
Li, X., Xiao, J.P., Lin, H.L., Liu, T., Qian, Z.M., Zeng, W.L., et al., 2017. The construction and validity analysis of AQHI based on mortality risk: A case study

in Guangzhou, China. Environ. Pollut. 220, 487–494.

Li, Y., Lau, A.K.H., Fung, J.C.H., Zheng, J., Liu, S., 2013. Importance of NOx control for peak ozone reduction in the Pearl River Delta region. J. Geophys. Res. Atmos. 118, 9428–9443.

Liao, Z.H., Ling, Z.H., Gao, M., Sun, J.R., Zhao, W., Ma, P.K., et al., 2021. Tropospheric Ozone Variability Over Hong Kong Based on Recent 20 years (2000–2019) Ozonesonde Observation. J. Geophys. Res. Atmos. 126, e2020JD033054.

Liu, Z.R., Hu, B., Ji, D.S., Cheng, M.T., Gao, W.K., Shi, S.Z., et al., 2019. Characteristics of fine particle explosive growth events in Beijing, China: Seasonal variation, chemical evolution pattern and formation mechanism. Sci. Total Environ. 687, 1073–1086.

Marr, L.C., Harley, R.A., 2002. Spectral analysis of weekday-weekend differences in ambient ozone, nitrogen oxide, and non-methane hydrocarbon time series in California. Atmos. Environ. 36, 2327–2335.

Mason, T.G., Chan, K.P., Schooling, C.M., Sun, S., Yang, A., Yang, Y., et al., 2019. Air quality changes after Hong Kong shipping emission policy: An accountability study. Chemosphere. 226, 616–624.

Ng, S.K.W., Loh, C., Lin, C., Booth, V., Chan, J.W.M., Yip, A.C.K., et al., 2013. Policy change driven by an AIS-assisted marine emission inventory in Hong Kong and the Pearl River Delta. Atmos. Environ. 76, 102–112.

Pandey, S.K., Kim, K.H., Chung, S.Y., Cho, S.J., Kim, M.Y., Shon, Z.H., 2008. Long-term study of NOx behavior at urban roadside and background locations in Seoul, Korea. Atmos. Environ. 42, 607–622.

Sillman, S., Logan, J.A., Wofsy, S.C., 1990. The sensitivity of ozone to nitrogen oxides and hydrocarbons in regional ozone episodes. J. Geophys. Res. 95, 1837–1851.

So, K.L., Wang, T., 2003. On the local and regional influence on ground-level ozone concentrations in Hong Kong. Environ. Pollut. 123, 307–317.

Stieb, D.M., Burnett, R.T., Smith-Doiron, M., Brion, O., Shin, H., Economou, V., et al., 2008. A New Multipollutant, No-Threshold Air Quality Health Index Based on Short-Term Associations Observed in Daily Time-Series Analyses. J. Air Waste Manage. Assoc. 58, 435–450.

Sun, L., Wong, K.C., Wei, P., Ye, S., Huang, H., Yang, F.H., et al., 2016. Development and Application of a Next Generation Air Sensor Network for the Hong Kong Marathon 2015 Air Quality Monitoring. Sensors. 16 (2), 211.

Tan, Y., Han, S.W., Chen, Y., Zhang, Z.Z., Li, H.W., Li, W.Q., et al., 2021. Characteristics and source apportionment of volatile organic compounds (VOCs) at a coastal site in Hong Kong. Sci. Total Environ. 777, 146241.

Tian, L., Hossain, S.R., Lin, H., Ho, K.F., Lee, S.C., Yu, I.T.S., 2011. Increasing trend of primary NO_2 exhaust emission fraction in Hong Kong. Environ. Geochem. Health. 33, 623–630.

Tonse, S.R., Brown, N.J., Harley, R.A., Jin, L., 2008. A process-analysis based study of the ozone weekend effect. Atmos. Environ. 42, 7728–7736.

Wang, H.L., Wu, K., Liu, Y.M., Sheng, B.S., Lu, X., He, Y.P., et al., 2021. Role of Heat Wave-Induced Biogenic VOC Enhancements in Persistent Ozone Episodes Formation in Pearl River Delta. J. Geophys. Res. Atmos. 126, e2020JD034317.

Wang, T., Cheung, V.T.F., Anson, M., Li, Y.S., 2001. Ozone and related gaseous pollutants in the boundary layer of eastern China: Overview of the recent measurements at a rural site. Geophys. Res. Lett. 28, 2373–2376.

Wang, T., Wei, X.L., Ding, A.J., Poon, C.N., Lam, K.S., Li, Y.S., et al., 2009. Increasing surface ozone concentrations in the background atmosphere of Southern China, 1994-2007. Atmos. Chem. Phys. 9, 6217–6227.

Wang, T., Xue, L.K., Brimblecombe, P., Lam, Y.F., Li, L., Zhang, L., 2017. Ozone pollution in China: A review of concentrations, meteorological influences, chemical precursors, and effects. Sci. Total Environ. 575, 1582–1596.

Wong, T.W., Tam, W.W.S., Yu, I.T.S., Lau, A.K.H., Pang, S.W., Wong, A.H.S., 2013.

Developing a risk-based air quality health index. Atmos. Environ. 76, 52–58.

Xu, J., Ma, J.Z., Zhang, X.L., Xu, X.B., Xu, X.F., Lin, W.L., et al., 2011. Measurements of ozone and its precursors in Beijing during summertime: Impact of urban plumes on ozone pollution in downwind rural areas. Atmos. Chem. Phys. 11, 12241–12252.

Xue, L.K., Wang, T., Louie, P.K.K., Luk, C.W.Y., Blake, D.R., Xu, Z., 2014. Increasing external effects negate local efforts to control ozone air pollution: A case study of Hong Kong and implications for other chinese cities. Environ. Sci. Technol. 48, 10769–10775.

Yau, P.S., Lee, S.C., Corbett, J.J., Wang, C., Cheng, Y., Ho, K.F., 2012. Estimation of exhaust emission from ocean-going vessels in Hong Kong. Sci. Total Environ. 431, 299–306.

Zhang, X., Fung, J.C.H., Lau, A.K.H., Hossain, M.S., Louie, P.K.K., Huang, W., 2021. Air quality and synergistic health effects of ozone and nitrogen oxides in response to China's integrated air quality control policies during 2015–2019. Chemosphere. 268, 129385.

Zheng, J.Y., Shao, M., Che, W.W., Zhang, L.J., Zhong, L.J., Zhang, Y.H., et al., 2009. Speciated VOC emission inventory and spatial patterns of ozone formation potential in the Pearl River Delta, China. Environ. Sci. Technol. 43, 8580–8586.

Zheng, J.Y., Zhong, L.J., Wang, T., Louie, P.K.K., Li, Z.C., 2010. Ground-level ozone in the Pearl River Delta region: Analysis of data from a recently established regional air quality monitoring network. Atmos. Environ. 44, 814–823.

Figure

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List of figures

Fig. 1 The locations and appearances of seven air quality monitoring stations. Red color represents the roadside stations, green color represents the urban stations, and yellow color represent the background station.

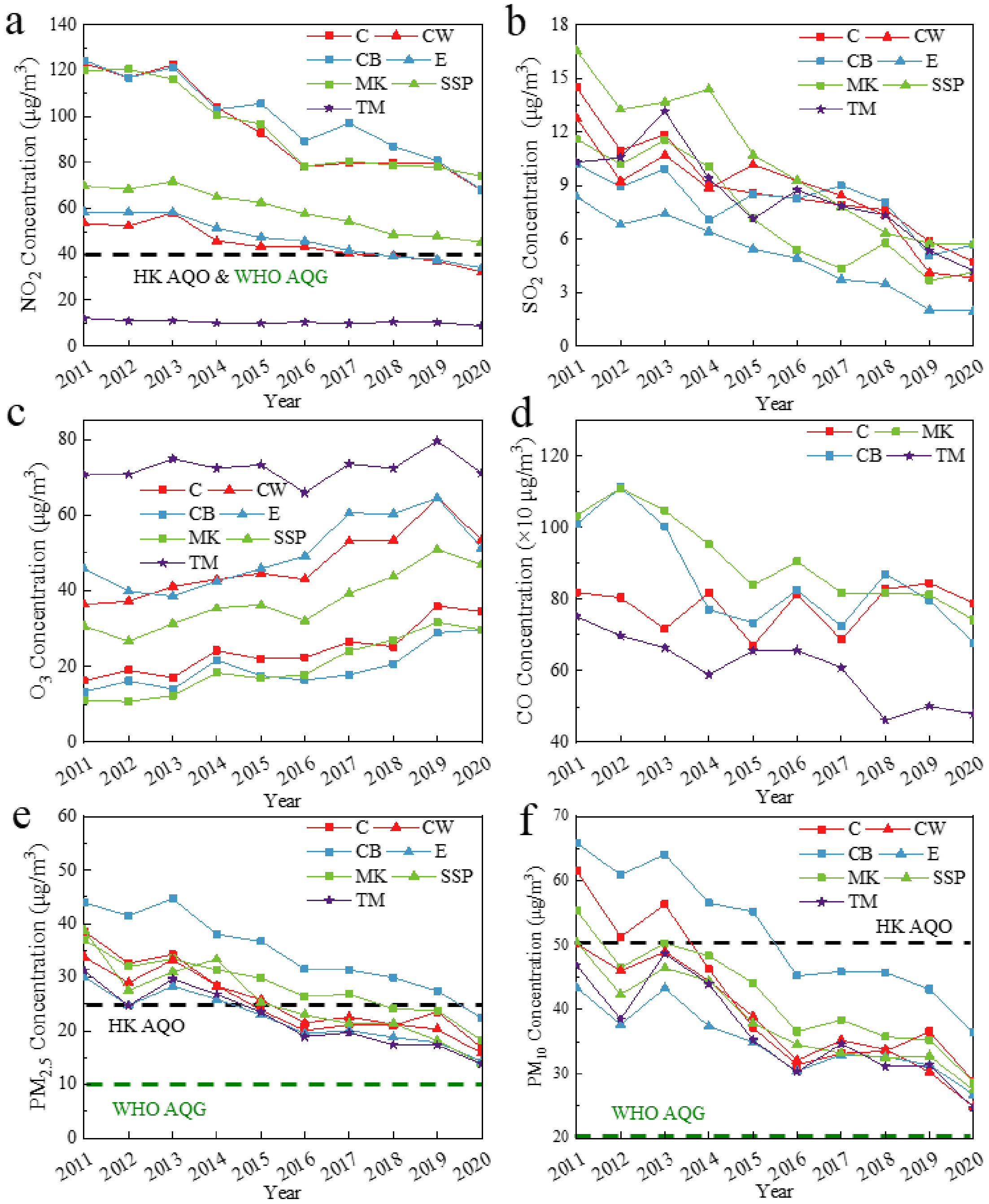

Fig. 2 Annual concentration of (a) NO_2, (b) SO_2, (c) O_3, (d) CO, (e) $PM_{2.5}$ and (f) PM_{10} from 2011 to 2020 at seven air quality monitoring stations (Detailed data was listed in **Appendix A Table S2**). The black dotted lines marked as new annual Hong Kong Air Quality Objectives (HK AQO) and blackish green dotted lines marked as the ultimate targets according to World Health Organization's Air Quality Guidelines (WHO AQG), respectively.

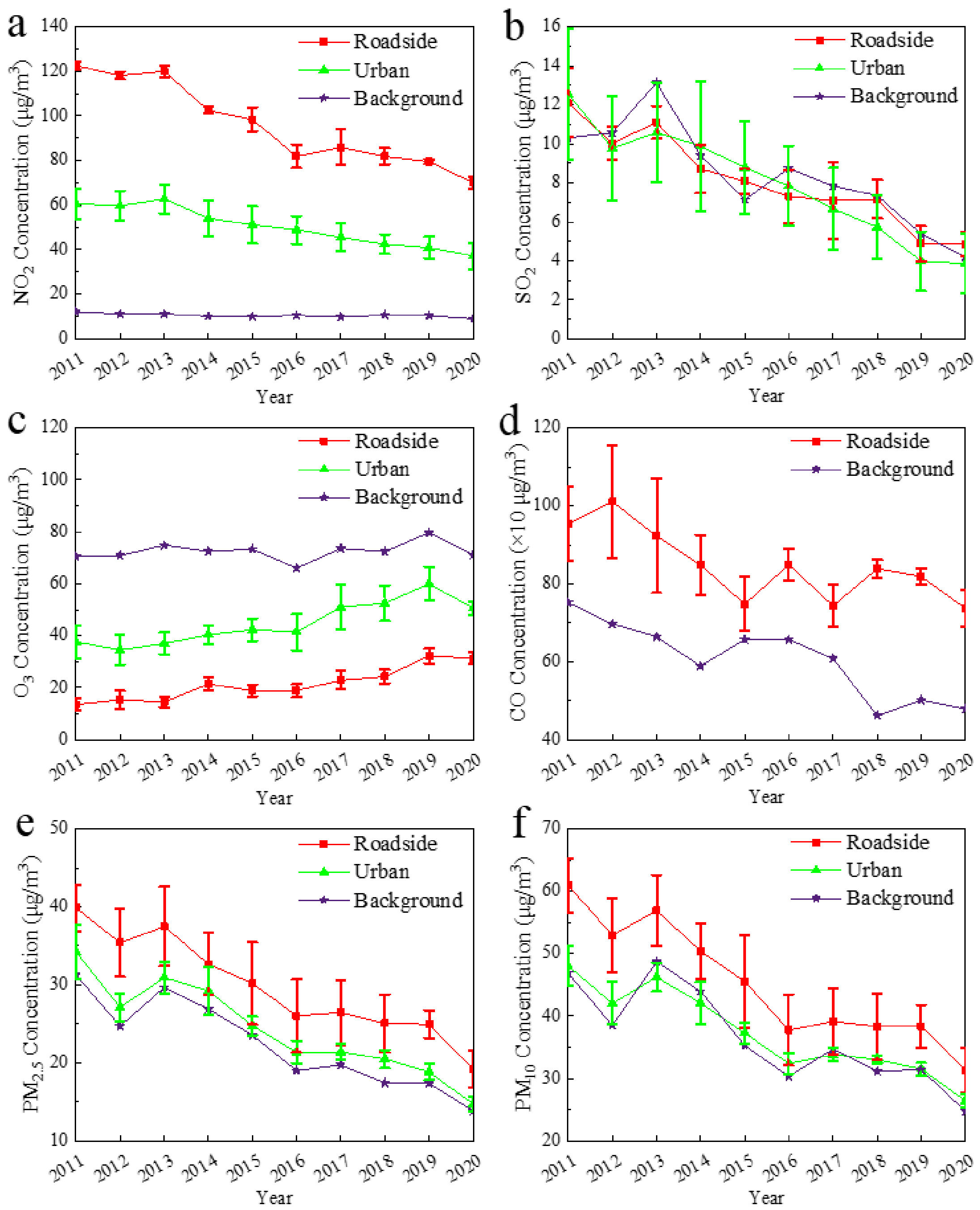

Fig. 3 Spatial variations of (a) NO_2, (b) SO_2, (c) O_3, (d) CO, (e) $PM_{2.5}$ and (f) PM_{10} between roadside, urban and background stations from 2011 to 2020. The red squares are the average concentration of three roadside stations; the green squares are the average concentration of three urban stations; the whiskers are standard deviation.

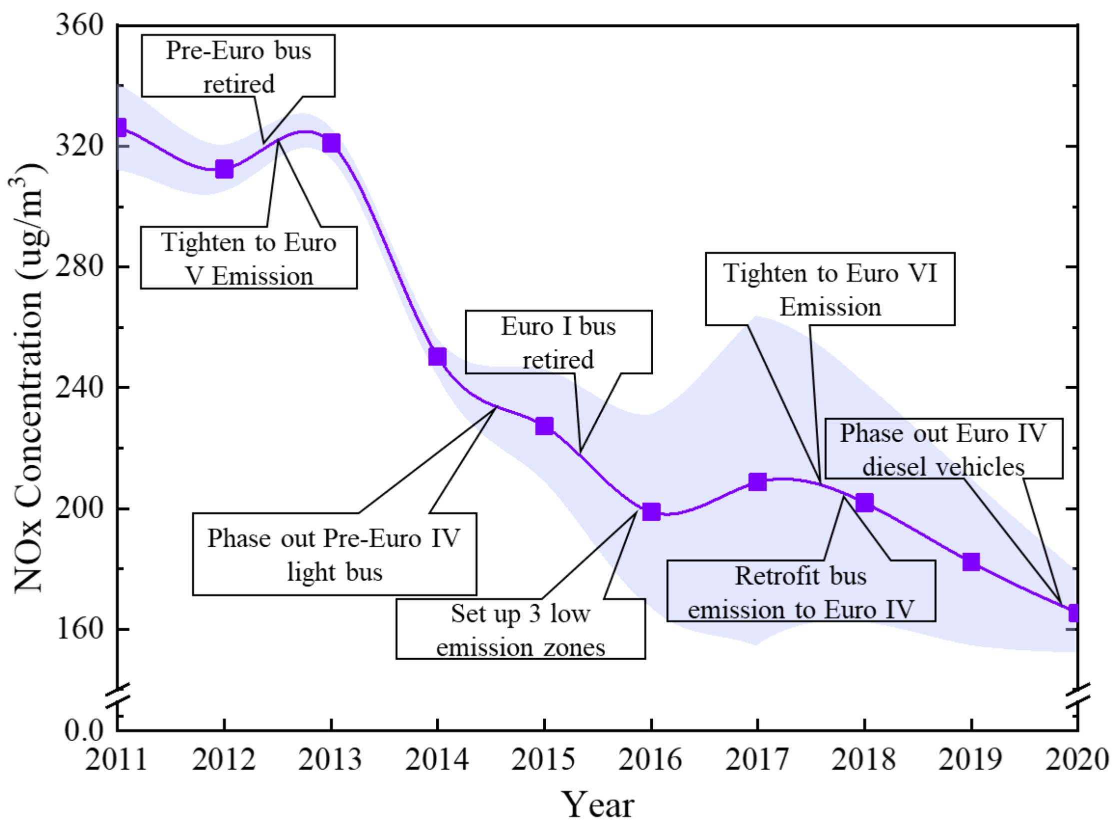

Fig. 4 Temporal variation of NO_X concentration at roadside with the timeline of implementation of air pollution control measures from 2011 to 2020. The solid squares are the average concentration of three roadside stations; the shaded areas are standard deviation; air pollution control measures are listed in text box.

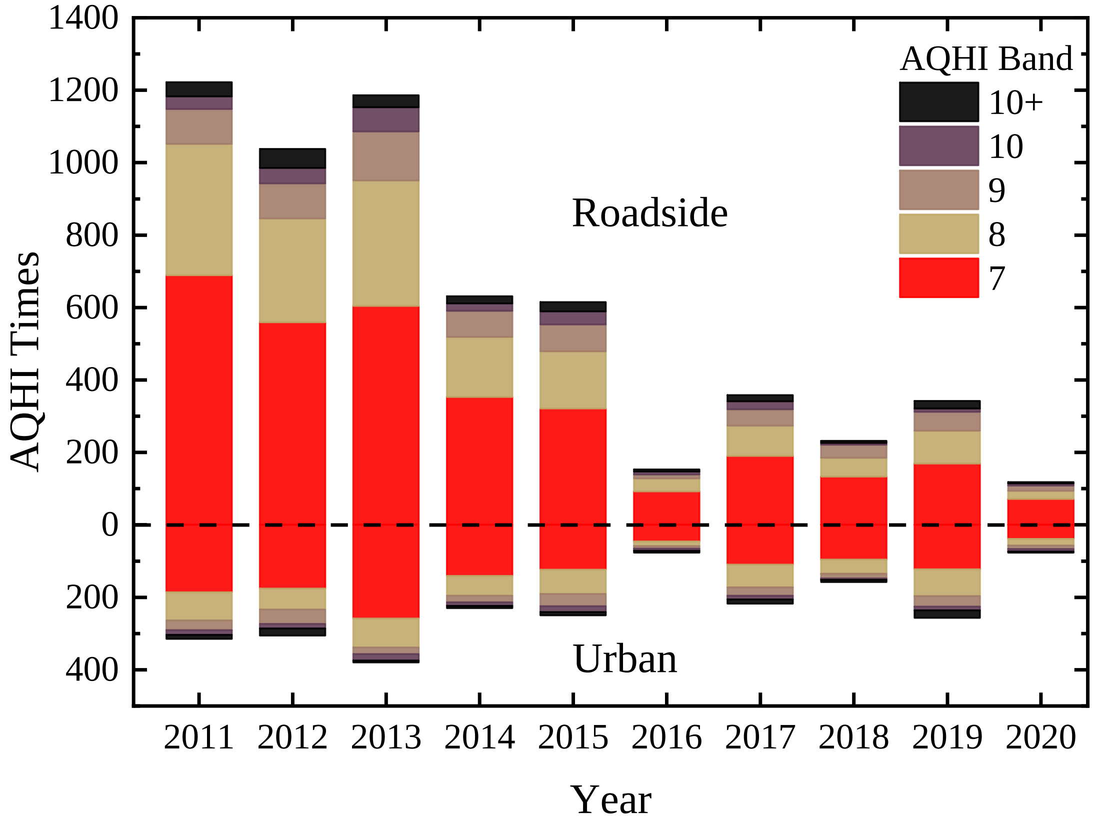

Fig. 5 Distribution of the times of different AQHI bands at roadside and urban stations from 2011 to 2020. The recommended health risk categories are: high (7); very high (8,9,10) and serious (10+).

List of tables

Table 1 Summary and characteristics of air quality monitoring stations

Type	Name	Abbreviation	Description	Sampling Height (m)	Remark
Roadside	Causeway Bay	CB	At the roadside of Yee Wo Street with the most bus stations nearby among the 3 roadside stations, a busy commercial and shopping area surrounded by tall buildings and high mansions	3	
Roadside	Central	C	At the intersection of Chater Road and Des Voeux Road with very busy traffic in Central	4.5	
Roadside	Mong Kok	MK	At the joint point between Nathan Road and Lai Chi Kok Road with heavy traffic throughout the day, the most densely populated districts in Hong Kong	3	
Urban	Eastern	E	On the rooftop inside the Sai Wan Ho Fire Station, adjacent to Taikoo Shing	15	Nearest to CB
Urban	Central/Western	CW	On the roof of Sai Ying Pun Community Complex and close to the MTR Sai Ying Pun Station	16	Nearest to C
Urban	Sham Shui Po	SSP	Inside the Sham Shui Po police station, locates at the center of Sham Shui Po District	17	Nearest to MK
Background	Tap Mun	TM	In the northeastern island of Hong Kong, inside Tap Mun Police Post, least human activities nearby	11	Rural

Table 2 Summary of health risk category and Air Quality Health Index (AQHI)

Health Risk Category	AQHI	Added Health Risk (%AR)	Remark
Low	1	0 - 1.88	
	2	>1.88 - 3.76	
	3	>3.76 - 5.64	
Moderate	4	>5.64 - 7.52	%AR of 5.64: 0.5 × threshold for people who are sensitive to air pollution (%AR of 11.29) to take precautionary actions
	5	>7.52 - 9.41	
	6	>9.41 - 11.29	
High	7	>11.29 - 12.91	%AR of 11.29: threshold for people who are sensitive to air pollution to take precautionary actions
Very High	8	>12.91 - 15.07	%AR of 12.91: threshold for the general public to take precautionary actions
	9	>15.07 - 17.22	
	10	>17.22 - 19.37	
Serious	10+	>19.37	%AR of 19.37: 1.5 × threshold for the general public (%AR of 12.91) to take precautionary actions

Table 3 Rate of change (%) of air pollutants at seven stations from 2011 to 2020

Stations	NO_2	SO_2	O_3	CO	$PM_{2.5}$	PM_{10}
C	-44.82	-67.29	112	-3.63	-56.28	-53.15
CB	-45.34	-44.33	123	-32.86	-48.99	-44.77
MK	-38.44	-64.43	170	-28.22	-50.59	-48.12
CW	-39.88	-69.99	47	N.A.	-53.04	-50.46
E	-41.85	-76.33	12	N.A.	-52.38	-38.28
SSP	-34.99	-65.31	53	N.A.	-64.20	-45.51
TM	-27.18	-59.19	1	-36.30	-55.71	-47.24

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Supplementary Material
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