Ozone and its variability in Hong Kong

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Abstract

In recent years, the rapid development of industry and economy, has resulted in increasingly severe and frequent air quality problems. With the deepening of air pollution research, ozone pollution has received more and more attention. Nowadays, the current concentration of ozone in the troposphere has been significantly exceeded, as a significant pollutant, has a major threat to the human living environment, and has aroused the great attention of the international community.

This present paper studies the variation of ozone concentration in Hong Kong and analyzes the causes based on the actual situation. This present paper selects and analyzes data from four sites in Hong Kong. The ozone concentration has a significant diurnal variation, with two peaks, one in the morning and one in the afternoon. The ozone concentration is inversely proportional to the amount of precipitation and the amount of cloud cover, but is proportional to the amount of radiation. Seasonally, Hong Kong has the highest average ozone concentration in autumn and the lowest ozone concentration in summer. The degree of dispersion of summer pollution is the smallest, and the degree of dispersion is the largest in autumn. Suburban ozone concentration in Hong Kong is higher than the city center. Ozone levels in Hong Kong are generally acceptable, but still, need to be improved.

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1. Introduction

1.1 What is ozone?

Ozone is composed of an oxygen atom and an oxygen molecule, the chemical formula is O_3Ozone can also be called superoxide. Due to the unstable structure of ozone, it is highly reactive with oxygen molecules under certain conditions. So, the content of ozone in the air can change within a certain range.

Atmospheric ozone is formed when energy in the form of solar radiation causes the oxygen molecules break down into two oxygen atoms. Then the individual oxygen atoms combine with the intact oxygen molecules to form ozone.

Ozone decomposes slowly at room temperature and rapidly decomposes at 200℃. At room temperature and normal pressure, the decomposition half-life of ozone (content of less than 1%) is about 20 to 30 minutes. With the increase of temperature, the decomposition speed is accelerated. When the temperature exceeds 100℃, the decomposition is very intense. When reaching a high temperature of 270℃, ozone can be immediately converted to oxygen. The decomposition rate of ozone in water is faster than in air. Ozone can be rapidly decomposed into oxygen in an aqueous solution containing impurities. But in pure water, the decomposition rate is slower, such as in distilled water or tap water, the ozone half-life is about 20min (at 20℃). If the water temperature is close to 0℃, the ozone will become more stable. Ozone is extremely stable in the ice, and its half-life is 2000 years.[1]

Ozone is an important trace component of the natural atmosphere, but its distribution in the atmosphere is very uneven. The ozone content is very low in the troposphere, where only about 10% of atmospheric O_3 is found. Ninety percent of atmospheric O_3 is found in the stratosphere, 20-50 km from the Earth's surface.[2][3]

Ozone is insoluble in liquid oxygen, carbon tetrachloride, and so forth, but is soluble in water and has a greater solubility than oxygen in the water. Ozone oxidation is very strong, stronger than oxygen. Ozone also oxidizes organic compounds, allowing organic pigments to decolorize. Ozone can also corrode rubber and can oxidize unsaturated organic compounds. [4]

1.2 Reasons to measure ozone

The presence of ozone in the stratosphere is critical to life on Earth. The ozone layer can absorb ultraviolet light, of which wavelength is less than 306.3nm. The ozone layer mainly absorbs a portion of UV-B (wavelengths: 290-300nm) and all UV-C (wavelength<290 nm). The ozone layer protects plants and animals on the Earth from short-wave UV damage. Only long-wave UV-A and a small amount of UV-B can radiate to the ground. Long-wave ultraviolet radiation damage to biological cells is much lighter than that of the medium-wave ultraviolet light. So, the ozone layer, as a protective umbrella, is protecting the living creatures on the earth to survive and multiply.

Ozone absorbs ultraviolet light in the sun and converts it into heat to heat the atmosphere. As a result of this effect, the atmospheric temperature structure has a peak at a height of about 50 km, and there is a temperature rising layer at about 15 to 50 km above the earth. It is because of the presence of ozone there is a stratosphere. And on the planet outside of the earth, there is no stratosphere because there is no ozone and oxygen. The atmospheric temperature structure has an important effect on the circulation of the atmosphere, and the cause of this phenomenon also comes from the vertical distribution of ozone.[5]

Studies have shown that UV-B can destroy biological proteins and genetic material deoxyribonucleic acid (DNA), causing cell death; increase the incidence of eight types of skin cancer; damage the eyes leading to cataracts and blindness, and inhibit plant growth vegetables. Moreover, UV-B radiation can penetrate the 10m deep layer of water killing phytoplankton and microbes, thus endangering the biological food chain and the source of free oxygen, affecting the ecological balance and water self-purification capacity. Therefore, the ozone layer has become the protective layer of the Earth's life system.[6][7]

Ozone in the atmosphere can be consumed and destroyed by reacting with many substances. Among all substances that react with ozone, the simplest and most active chemical substances containing carbon, hydrogen, chlorine, and nitrogen, such as nitrous oxide (N_2O), water vapor (H_2O), tetra chlorinated carbon (CCl_4), methane (CH_4) and now the most valued chlorofluorocarbons (CFCs). These substances are stable in the lower atmosphere, but after UV activation they become ozone-depleting substances in the stratosphere. This reaction consumes ozone in the stratosphere, breaking the balance of ozone, resulting in increased ground ultraviolet radiation, which brings a series of problems to the Earth's ecology.

Ozone is fragile because ozone has its own special nature and is susceptible to various factors. Satellite observations show that since the 1970s, the global total ozone has decreased significantly, and the global total ozone has been reduced by 3% between 1979 and 1990. Near the Antarctic, ozone reduction is particularly serious, there has been "Antarctic ozone hole." Antarctic ozone is less than about 30% to 40% of the global ozone average. Recently, the data released from detectors mounted on Russian and American satellites were informed that the "Antarctic Ozone Hole" had an area of 2,400 square kilometers and the thinnest was only 100 dobson (equivalent to 1 mm thickness).[8]

The thinning of the ozone layer will also cause the ground photochemical reaction to intensify, so that the troposphere ozone concentration increases, but also make photochemical smog pollution increased. Photochemical reactions in the environment are mainly due to the exposure to sunlight, pollutants absorb photons and make the material molecules in an electron excited state, and cause chemical reactions with other substances. Ozone also absorbs visible light and 9-10 microns of infrared light, which can heat the atmosphere. Therefore, changes in ozone concentrations not only affect the stratospheric atmosphere temperature and movement but also influence the global heat balance and global climate change.[9]

In the natural atmosphere, ozone in the lower atmosphere determines the OH^- and NO_3^- generation, which itself is also an important oxidant, can remove a lot of natural and man-made pollutants. In the troposphere, ozone is a precursor of hydroxide ions and nitrate ions. During the day, ozone produces OH^- by photolysis. At night, ozone reacts with nitroxides to produce NO_3^-. If there is no ozone, a lot of natural and human-made pollutants such as CH_4, CO, and NO_x will accumulate in the atmosphere. So, ozone can be used as an important indicator of atmospheric oxidation capacity.[10]

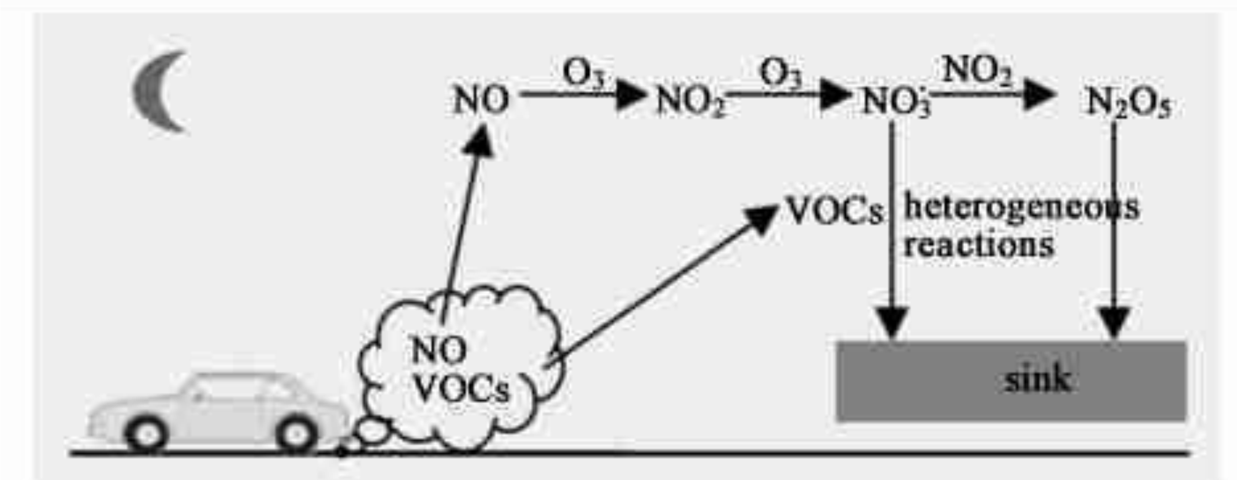

Figure 1. The integral role of ozone in nighttime chemistry. (Source: Jia et al. 2006)

Although ozone has many benefits to humanity, its harm cannot be ignored. Its high oxidation has obvious injuries, especially for human health systems, all kinds of building materials and soil plants. Ozone belongs to harmful gases. When the concentration reaches 0.3mg/L, the eyes, nose, throat will feel very uncomfortable. When the concentration reaches 3-30mg/L, people will feel a headache, and the respiratory organs will be paralyzed. When the concentration reaches 15-60mg/L, the ozone will be harmful to the human body. The degree of the toxicity is related to the length of the contact time. As long as the ozone concentration stays below 20ppm and contact lasts no more than 2 hours, the body will not have permanent damage.

Ozone toxicity is mainly due to its strong oxidizing properties. Ozone can damage the cell wall, so the hazards are acute. The primary harm to the human body is the impact on the respiratory system, easy to produce acute lung injury, such as emphysema. There are also increasing asthma in recent years, which may be related to ozone pollution.[11][12] In addition, the strong oxidative nature of ozone is corrosive, and ozone can react chemically with organic compounds containing unsaturated carbon-carbon bonds. Therefore, ozone will cause corrosion of many buildings, industry, chemical materials, resulting in shorter construction life, car tire aging. High concentrations of ozone can affect the soil fertility, but also reduce the leaf chlorophyll content, thereby reducing plant photosynthesis. Plants not only cannot absorb enough nutrients from the soil but also cannot produce enough nutrients through photosynthesis.[13][14][15]

Nowadays, the current concentration of ozone in the troposphere has been significantly exceeded, as a significant pollutant, has a major threat to the human living environment, and has aroused the great attention of the international community.[10]

1.3 Measurement of ozone

The Hong Kong Observatory began to release an ozonesonde to measure ozone in Hong Kong in 1993. The ozonesonde operated by the Observatory consists of an electrochemical cell ozone sensor (Science Pump Corporation Model ECC 6AB), an electronic interface board, a gas sampling pump, and a radiosonde. At present, model RS92-SGPD radiosonde of Vaisala is used. The ozonesonde contains two platinum electrodes immersed in the cathode and the anode chamber at a concentration of 1% potassium iodide (KI) solution. As the air is continuously pumped into the cathode chamber the ozone reacts with the KI solution to generate current. The amount of current produced is directly related to the ozone concentration in the air so that the ozone partial pressure can be deduced. The ozonesonde, attached to a 1.5 kg rubber balloon, usually reaches the stratosphere before the balloon bursts, with an average ascent speed of 5 m/s and a sampling rate of every 2 seconds. Therefore, the vertical resolution of the profiles is about 10 meters.[16]

1.4 Meteorological Factors that affect ozone concentration

There is a correlation between solar radiation and the daily variation of ozone hourly average concentration. The solar radiation intensity is gradually increased from 5 am to 12 pm, and gradually decreases after 12 pm. Ozone concentration is generally gradually increased from 5 am to 2 pm, and after 2 pm gradually weakened. The maximum value of solar radiation appears at 12 pm, and the highest value of ozone concentration in the day appears at 2 pm. The ozone concentration is delayed by two hours compared to the maximum solar radiation. (Figure 1) This indicates that ozone production is closely related to solar radiation.[17] Ozone is a secondary pollutant formed by solar radiation.[18]

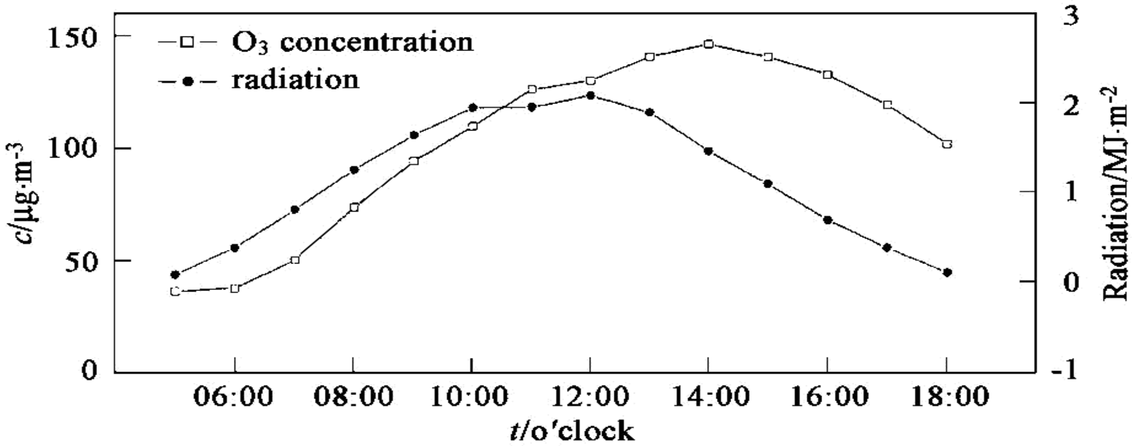

Figure 2. Diurnal variation of solar radiation and ozone hourly average concentration. (Source: Yin et al. 2004)

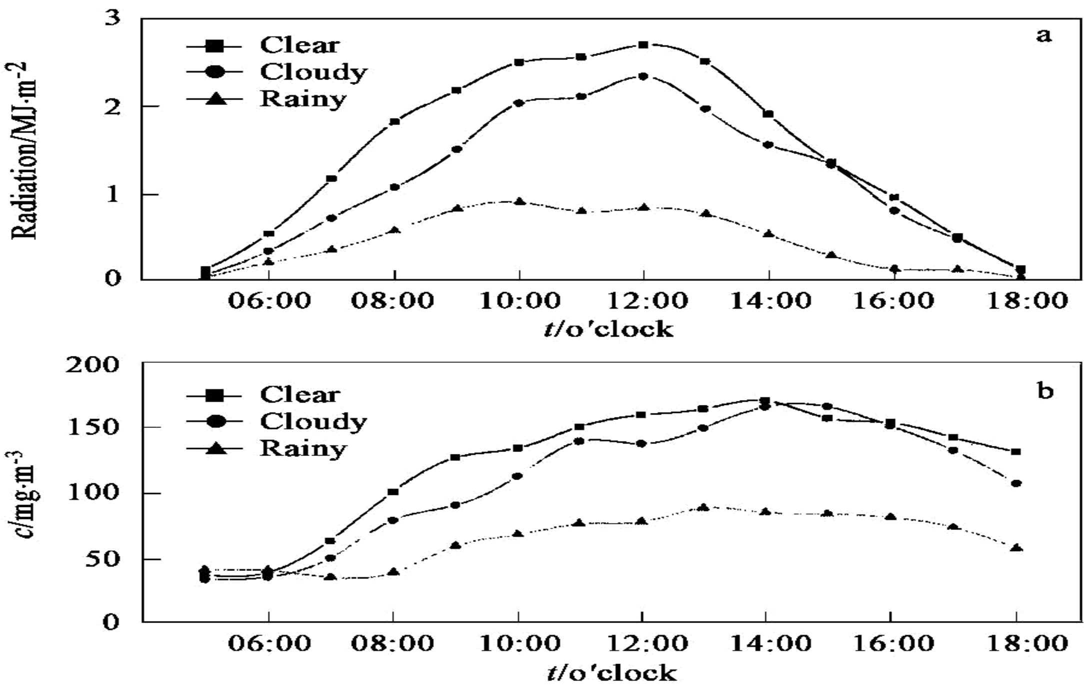

Figure 3. Diurnal variation of solar radiation and ozone hourly average concentration in different weather conditions. (Source: Yin et al. 2004)

The solar radiation changes with time in three weather conditions and the ozone concentration also show similar changes with time.[17] In sunny days, solar radiation is the strongest, and ozone concentration is also the highest. This indicates that on sunny days, strong solar radiation is conducive to the generation of ozone. In the cloudy or rainy days, the solar radiation is relatively weak, which is not conducive to the generation of ozone, so the ozone concentration is relatively low. (Figure 2)

month	Temperature(K)	Solar radiation(MJ/m^2)	Number of observation	Concentration range(μg/m^3)	Average value(μg/m^3)	Over-limit ratio (%)
May	294.95	19.26	456	2.40-256.36	108.87	7.68
June	299.45	18.80	624	7.34-621.71	131.44	8.91
July	300.85	15.68	672	3.22-292.64	80.04	3.72
August	299.45	14.31	696	0.10-253.71	68.99	2.01
Sep	295.55	12.45	600	0.84-226.96	68.19	0.17
Oct	289.35	10.35	720	1.69-158.65	51.81	0.00

Table 1. Relationship between solar radiation and air-temperature and characterization of the ozone hourly average concentration. (Source: Yin et al. 2004)

Ozone concentration is closely related to solar radiation and temperature. (Table 1) Due to higher temperatures in June and stronger solar radiation, resulting in higher ozone concentrations than other months. While the temperature in October is low and the solar radiation is weaker, so the ozone concentration does not exceed the national standard.[17]

1.5 Comparison with other location around the world

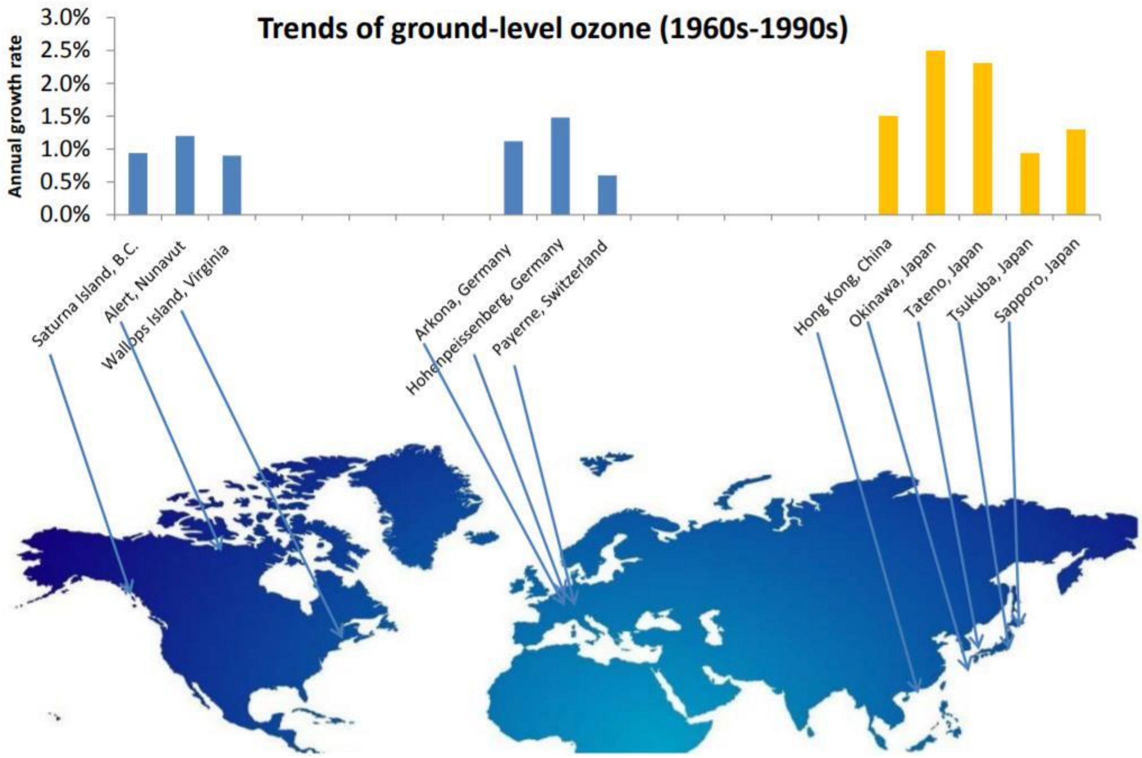

Figure 4. Trends of ground-level ozone(1960s-1990s) (Source: Vingarzan 2004, Wang et al. 2009)

From the 1960s to 1990s, the ground-level ozone concentrations of different places in North America, Europe, and Asia are generally increasing with various growth rates. The annual growth rate of ground-level ozone in Hong Kong is slightly higher than those in North America. However, the rate in Hong Kong is significantly lower than two cities in Japan. The annual growth rate in Payerne, Switzerland is the lowest among these cities. (Figure 3)[19][20]

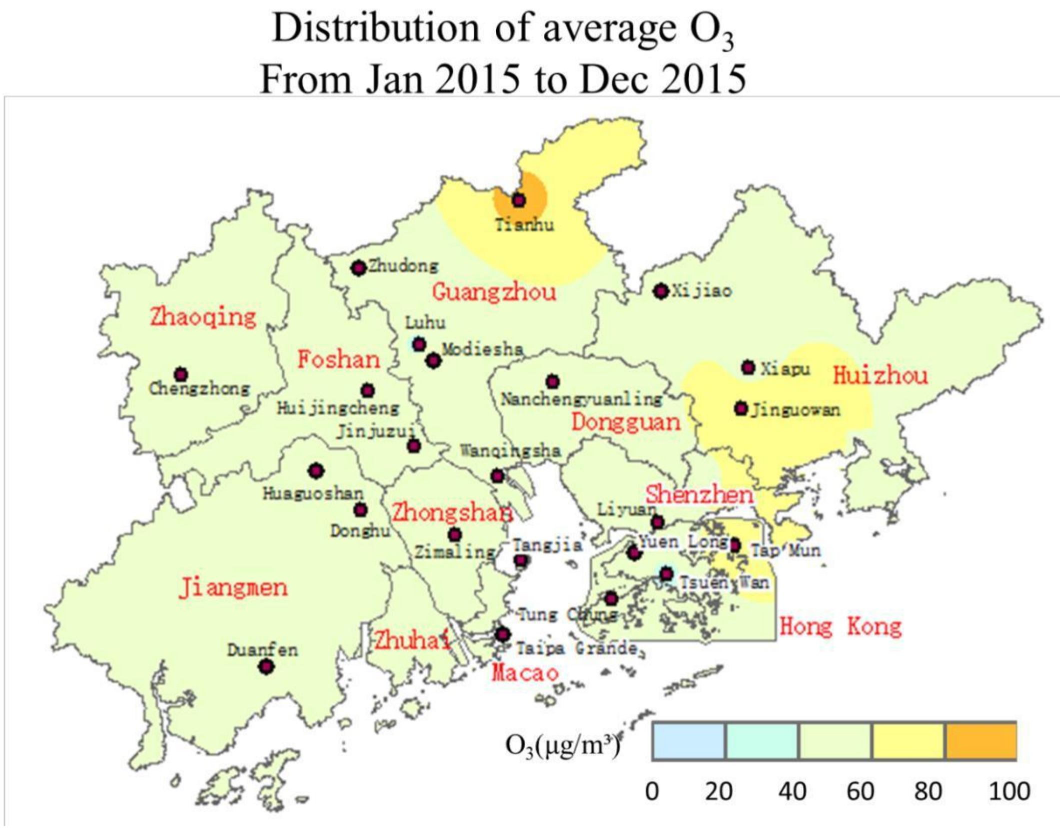

Figure 5. Spatial distribution of annual average concentrations of Ozone. (Source: Pearl River Delta Regional Air Quality Monitoring Report for Year 2015)

In 2015, the annual averages of ozone among Pearl River Delta of South China ranged from 37µg/m^3 to 85µg/m^3 with higher average values being recorded in rural areas such as Tianhu of Guangzhou, Tap Mun of Hong Kong and Jinguowan of Huizhou. During the year, one monitoring station was in compliance with the national daily maximum 8-hour average concentration limit (160µg/m^3) while the corresponding compliance rates ranged from 83.1% to 100%. Except for Tap Mun of Hong Kong, the ozone concentrations in the most areas of Hong Kong are generally lower than other places among Pearl River Delta. (Figure 4, Table 2)

Monitoring Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Luhu (Guangzhou)	33	36	20	47	29	36	46	52	57	51	24	19	38
Modiesha (Guangzhou)	46	52	26	56	34	44	55	68	72	65	36	29	48

Wanqingsha (Guangzhou)	58	61	38	73	46	44	74	73	84	88	53	33	60
Tianhu (Guangzhou)	102	93	67	98	71*	91	83	98	106	107	53	50	85
Zhudong (Guangzhou)	51	52	31	59	47	56	66	53	65	60	33	27	50
Liyuan (Shenzhen)	50	52	46	49	43	32	50	46	69	79	65	41	52
Jinjuzui (Foshan)	41	47	25	60	40	42	66	67	78	69	39	23	50
Huijingcheng (Foshan)	35	46	20	66	28	43	59	66	69*	69	32	19	46
Tangjia (Zhuhai)	65	71	42	57	40	36	36	31	32	43	40	34	43
Donghu (Jiangmen)	46	47	26	51	27	26	33	57	68	55	28	20	40
Duanfen (Jiangmen)	72	72	51	68	56	43	65	66	26	56	55	35	55
Huaguoshan (Jiangmen)	51	48	25	69*	46*	36	58	50	46	56	33	20	44
Chengzhong (Zhaoqing)	48	51	30	59	56	59	64	70	70	69	43	26	54
Xiapu (Huizhou)	62	67	43	69	47	49	55	61	75	74	51	41	58
Xijiao (Huizhou)	63	62	45	61	55	60	61	59	63	55	39	38	55
Jinguowan (Huizhou)	94	89	64	88	63	51	58	62	78	77	55	45	69
Zimaling (Zhongshan)	33	40	27	56	37	37	58	56	74	77	43*	25	47
Nanchengyuanling (Dongguan)	49	65	40	71	51	52	68	75	86	74	50	34	59
Tap Mun (Hong Kong)	98	90	77	75	63	45	65	62	94	108	93	-	79
Tsuen Wan (Hong Kong)	47	46	35	35	19	16	33	33	51	58	47	31	37
Yuen Long (Hong Kong)	40	43	36	43	29	24	44	38	57	58	42	23	40
Tung Chung (Hong Kong)	49	53	46	46	40	34	51	42	65	67	55	29	48
Taipa Grande (Macao)	54	68	51	57	49	41	59	59	75	87	54	26	56

Remark: All concentration units are in micrograms per cubic meter ($\mu g/m^3$).

*The average hourly monitoring data capture rate of certain pollutant is below 85%.

Table 2. The monthly and annual averages of Ozone among Pearl River Delta in 2015. (Source: Pearl River Delta Regional Air Quality Monitoring Report for Year 2015)

2. Determining Air Quality

2.1 Different standard of AQI

The establishment of ambient air quality standards can play an active role in the management of environmental air quality, the protection of human health, the maintenance of ecological environment and the promotion of human and social, natural and harmonious sustainable development.[21] In the 1970s, the United States first publish a pollution standards index (PSI), the integration of multiple pollutants in an indicator system, to guide people's daily life behavior by the release of pollution standards index.[22] Subsequently, countries around the world have established air quality index publishing systems based on their respective air quality conditions, such as China's API (air pollution index) and AQI (air quality index), PSI and AQI of US, the UK's daily air quality index (DAQI), Australia's regional pollution index (RPI), and regional air quality index (RAQI) in New South Wales, Australia.[23]

Country	Name of Index	Year	Number of Indexes	Pollutants		
				24 h mean	1 h mean	8 h mean
China	API	1997-1999	3	SO_2,NOx,TSP		
	API	2000-2011	5	SO_2,NO_2,PM_{10}	CO,O_3	
	AQI	2012-now	10	SO_2,NO_2,CO,PM_{10},$PM_{2.5}$	SO_2,NO_2,CO,O_3	O_3
United States	PSI	1971-1993	5	SO_2,TSP	O_3,NO_2	CO
	PSI	1994-1998	5	SO_2,PM_{10}	O_3,NO_2	CO
	AQI	1999-2010	7	SO_2,PM_{10},$PM_{2.5}$	O_3,NO_2	CO,O_3
	AQI	2011-now	8	SO_2,PM_{10},$PM_{2.5}$	O_3,SO_2,NO_2	CO,O_3

Table 3. Development of air quality index in China and America (Source: Gao et al. 2015) [24]

Over the past decade, the United States has continuously updated its air quality index. Its AQI pollutant project and the release period has undergone great changes.[23] China and the United States air quality index indicators are showing a growing trend. China's ambient air quality standards are relatively late, but the development is swift. From the United States AQI pollutant development process, it can be seen that the United States determine the NO_2, CO and O_3 and other gaseous pollutant concentration limits and time at the very beginning. In comparison, China began to pay attention to NO_2, CO, O_3 later than the US. After 2012, the AQI index in China has been fully expanded on the basis of the original. CO and PM2.5 were added to 24h average concentration limit, and SO_2 and NO_2 were added to 1-hour average concentration limit. Ozone was added to 8-hour average concentration limit. Then, the total amount of indicators reached ten, which is higher than the United States, ranking first in the world, which also fully reflects the characteristics of China's current composite pollution. (Table 3)

2.2 Ozone is one of the important factors

In the autumn and winter, meteorological conditions are not conducive to the dispersion of pollutants, leading to frequent haze in the eastern region of China. With the onset of summer and rising temperatures, in many cities, ozone replaces PM2.5 (fine particles) as the primary air pollutant. In accordance with the implementation of the 2013 "ambient air quality standards," PM2.5 (fine particulate matter), PM10 (inhalable particles), sulfur dioxide and other six pollutants were included in the routine monitoring. Over the past few years, among the six pollutants, only the ozone concentration has risen. In 2015, the number of days when ozone over standard in 2015 represented 16.9% of the total number of over-standard days.[25] Compared with the haze, ozone pollution is very inconspicuous, often hidden in the blue sky and white clouds.

In 2015, all 338 APL cities level[1] across the country conducted environmental monitoring based on the newly amended Ambient Air Quality Standard. The monitoring results show that 73 cities met national air quality standard[2](21.6%) while 265 cities failed to meet national air quality standard (78.4%). In the non-attainment days, those with PM2.5, O_3, and PM10 as the primary pollutants[3] were in dominance, accounting for 66.8%, 16.9% and 15.0% of total non-attainment days respectively. The Ministry of Environmental Protection announced in May 2016 air quality data also shows that for both the Beijing-Tianjin-Hebei region or the Pearl River Delta and the Yangtze River Delta region, ozone has become the primary air pollutant.[26]

[1] Cities at or above prefecture level (APL cities): including municipality, cities or regions at prefecture level, autonomous prefectures and league.

[2] Air quality meeting the standard: the ambient air quality meets the standard when the concentrations of all pollutants under assessment meet the standard.

[3] Primary pollutant: When AQI >50, the pollutant with the biggest individual AQI is the primary pollutant.

Percent of 338 cities at or above prefecture level with different concentrations of major pollutants in 2015

Figure 6. Percent of 338 cities at or above prefecture-level with different concentrations of major pollutants in 2015. (Source: Report on the State of the Environment in China 2015)

2.3 Other pollutants

In 2015, the annual average PM2.5 concentration was 22-107μg/m^3 with an average of 55μg/m^3; 16.2% of the cities met National Ambient Air Quality Standard. The range of annual average PM10 concentration was 40-174μg/m^3 with an average of 93μg/m^3; 28.4% of the cities met the national air quality standard. The range of the annual average SO_2 concentration was 5-71μg/m^3 with an average of 25μg/m^3; 95.9% of the cities met the national air quality standard. The range of annual average NO_2 concentration was 14-61μg/m^3 with an average of 39μg/m^3; 51.4% of the cities met national air quality standard. The 90th percentile concentration of O_3 daily maximum 8-hour average was 95-203μg/m^3 with an average value of 150μg/m^3; 62.2% of the cities met the national air quality standard. The 95th percentile concentration of daily average

CO was 0.9-5.8 mg/m^3 with an average value of 2.1 mg/m^3; 94.6% of the cities met the national air quality standard. (Figure 5)[27]

3. Ozone and its variation in Hong Kong, South China

3.1 Research object and expectation

In the high-altitude atmosphere, the ozone layer is beneficial. The reduction or disappearance of ozone is a problem that people need to solve. However, in the near-surface atmosphere, too much ozone is harmful. People need to address the problem of rising ozone concentrations. In recent years, China's rapid economic development has led to the emergence of more and more densely populated cities. The development of industry has made the problem of ozone pollution in urban areas be paid more and more attention. It is necessary to study the change of local ozone concentration in a particular area due to the different geographical environment and pollutant discharge conditions because the variation of ozone concentration and pollution in the various regions are different.

Hong Kong is one of China's two special administrative regions and has a population of 7.39 million. Hong Kong's economy proliferated in the late twentieth century and gradually developed into a modern international metropolis with an important position in the Asia-Pacific region. As a highly populated and economically developed city, Hong Kong has a high practical significance in studying ozone pollution and applying it to protect the lives and safety of citizens.

In order to analyze the variation of ozone concentration in Hong Kong, this present thesis uses data from four observation sites from the Hong Kong Environmental Protection Agency (http://www.epd.gov.hk/epd/sc_chi/top.html). The four sites are located in Hong Kong's northeast corner (Tap Mun), the northwest corner (Yuen Long), the southwest corner (Tung Chung) and the south corner (Causeway Bay). (Figure 6) Among them, the south of Causeway Bay is located in the city center, while the other three sites are located in the suburbs. The hourly, daily, and monthly ozone concentration data for each site were downloaded from the EPD and then analyzed.

In order to better analyze the relationship between ozone concentration and radiation, cloud cover and precipitation, this present thesis also downloaded the relevant meteorological data at the same time from the Hong Kong Observatory (located near Mong Kok) website, including the data table of radiation, cloud cover and rainfall for some time in 2015.

Figure 7. Hong Kong Air quality monitoring map. (Source: http://epic.epd.gov.hk/EPICDI/air/download/images/air_station_map.jpg)

3.2 Ozone daily variation

In order to better analyze the changes and reduce the impact of accidental circumstances, taking the daily concentration graphs of four consecutive days (in January, April, July, and October) of each four seasons.

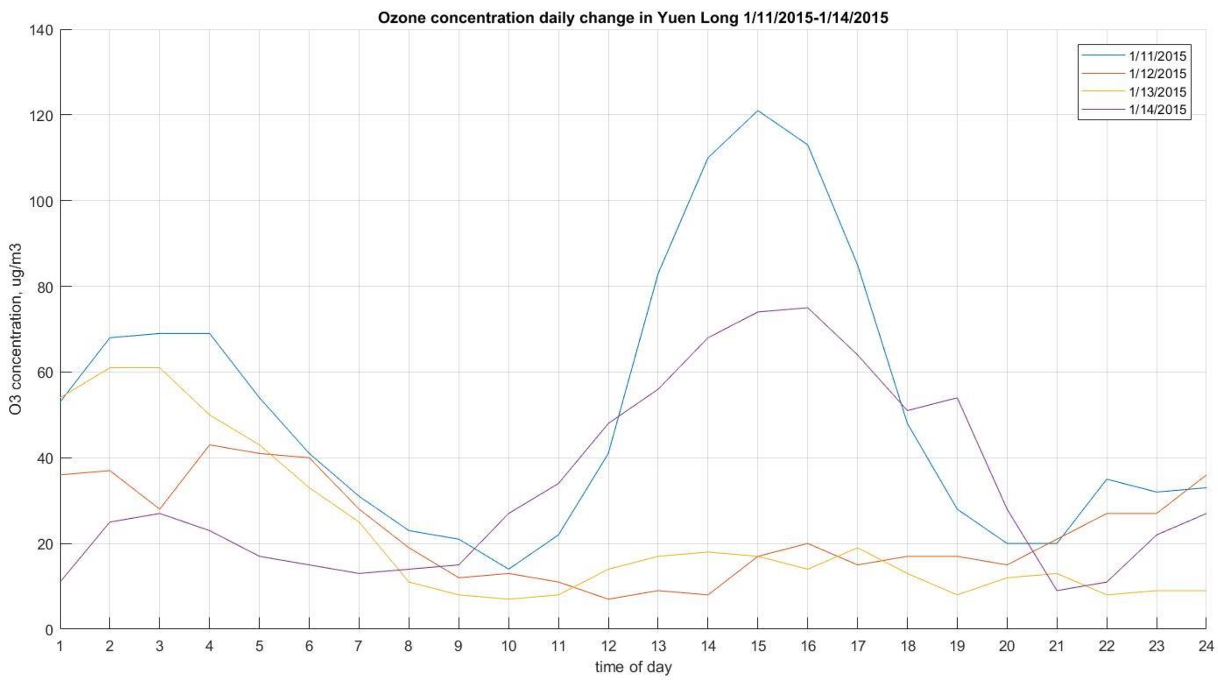

Figure 8. Ozone concentration daily change in Yuen Long 1/11/2015-1/14/2015

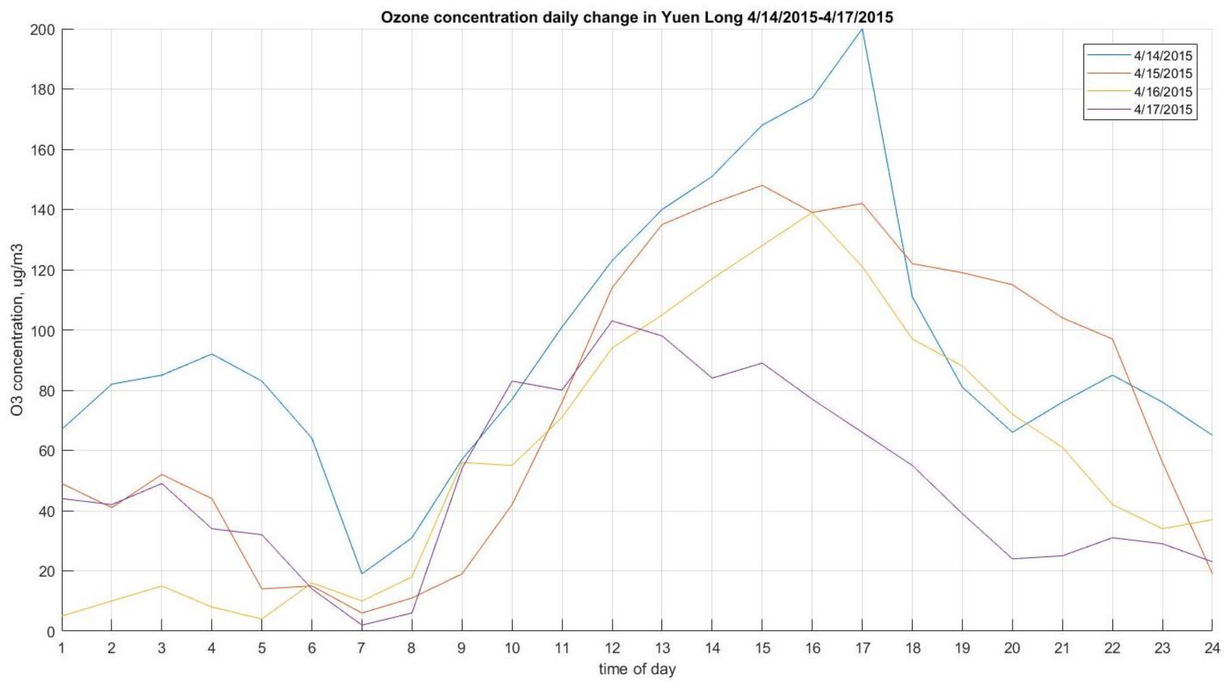

Figure 9. Ozone concentration daily change in Yuen Long 4/14/2015-4/17/2015

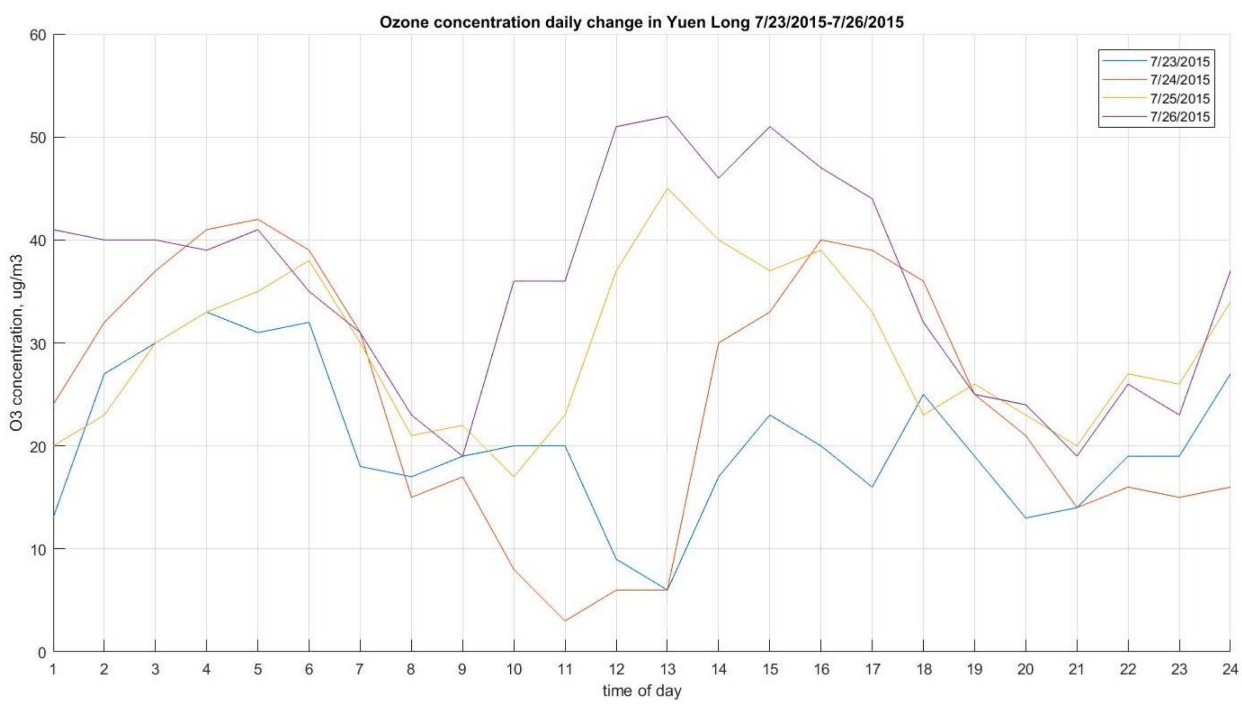

Figure 10. Ozone concentration daily change in Yuen Long 7/23/2015-7/26/2015

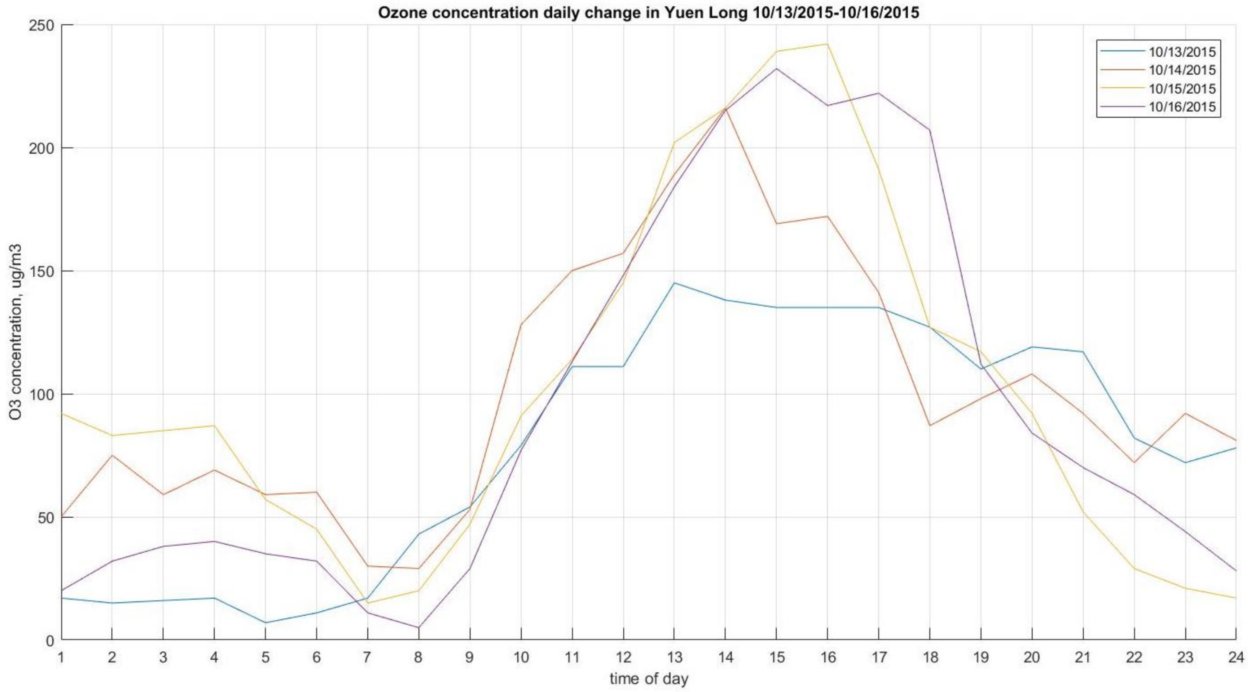

Figure 11. Ozone concentration daily change in Yuen Long 10/13/2015-10/16/2015

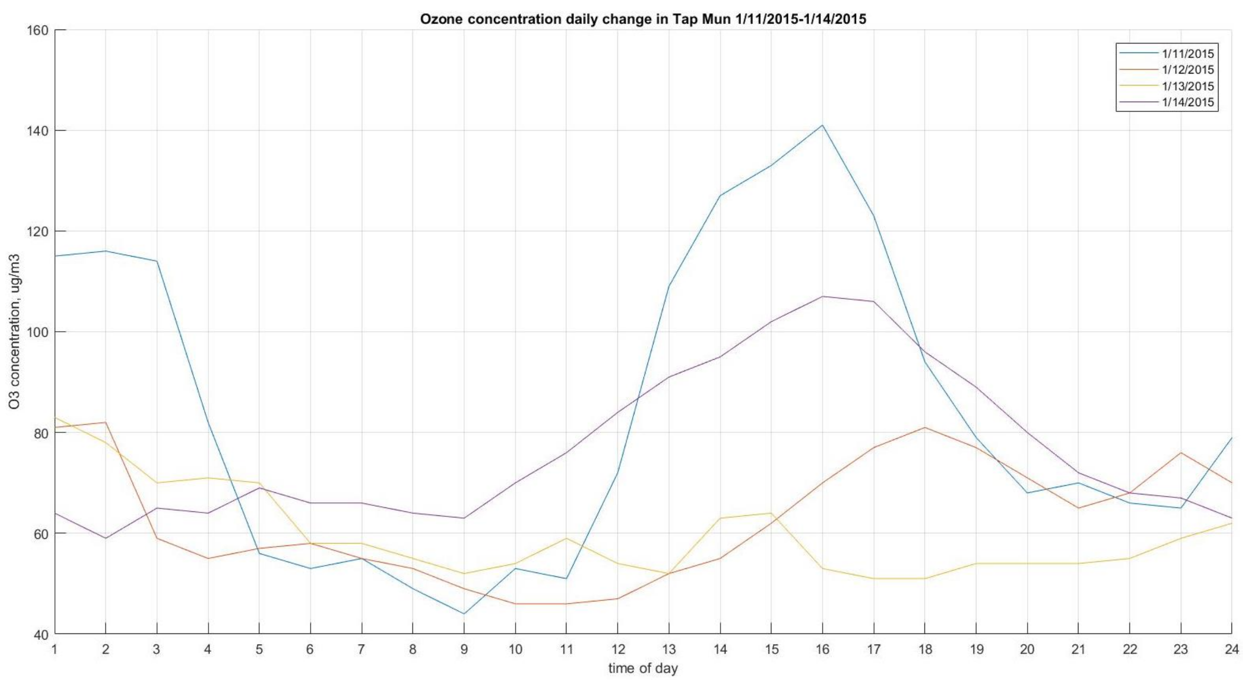

Figure 12. Ozone concentration daily change in Tap Mun 1/11/2015-1/14/2015

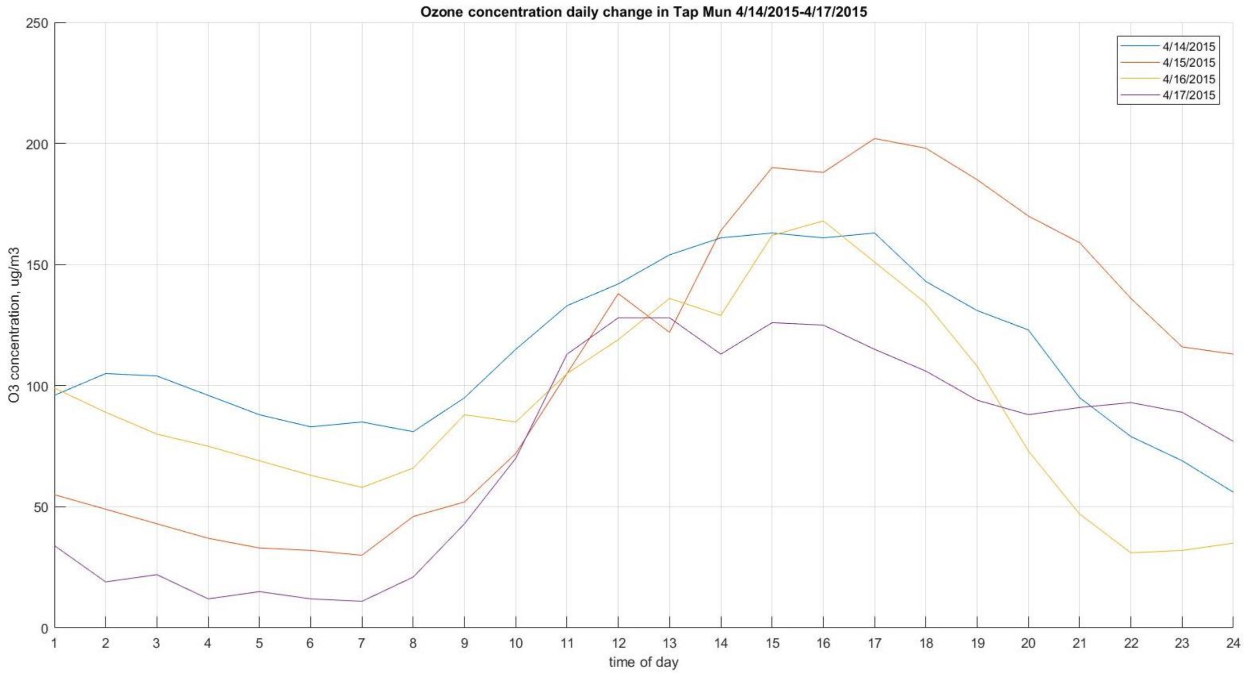

Figure 13. Ozone concentration daily change in Tap Mun 4/14/2015-4/17/2015

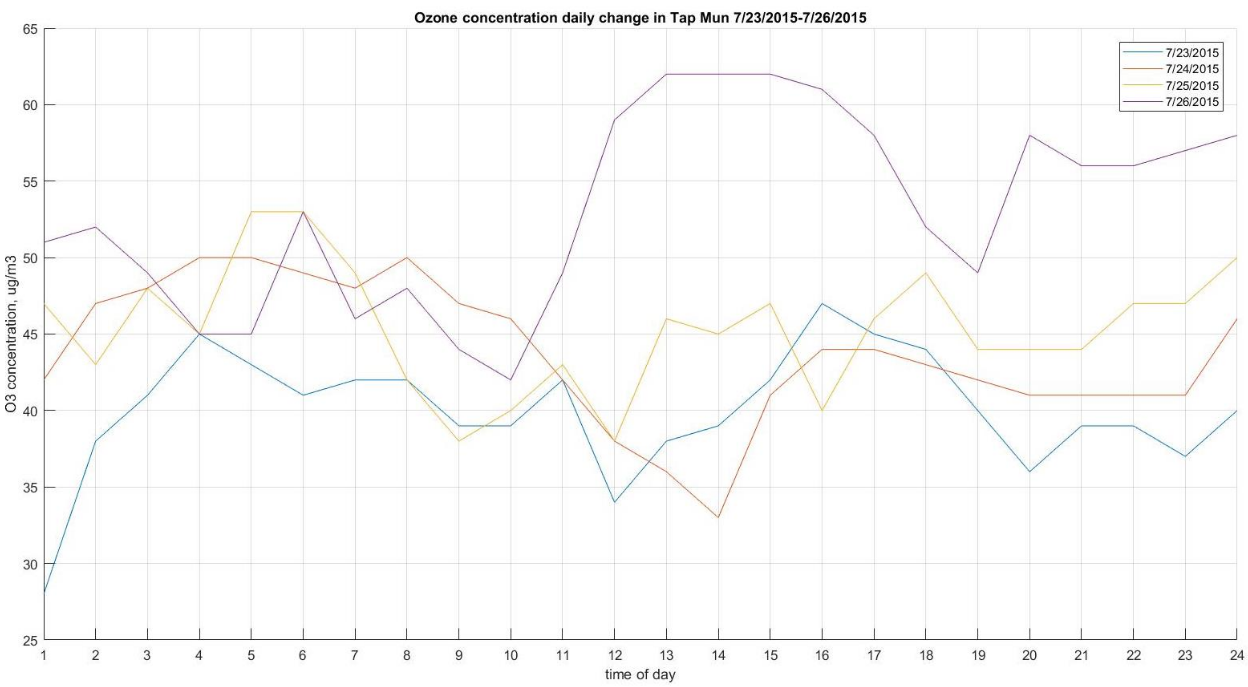

Figure 14. Ozone concentration daily change in Tap Mun 7/23/2015-7/26/2015

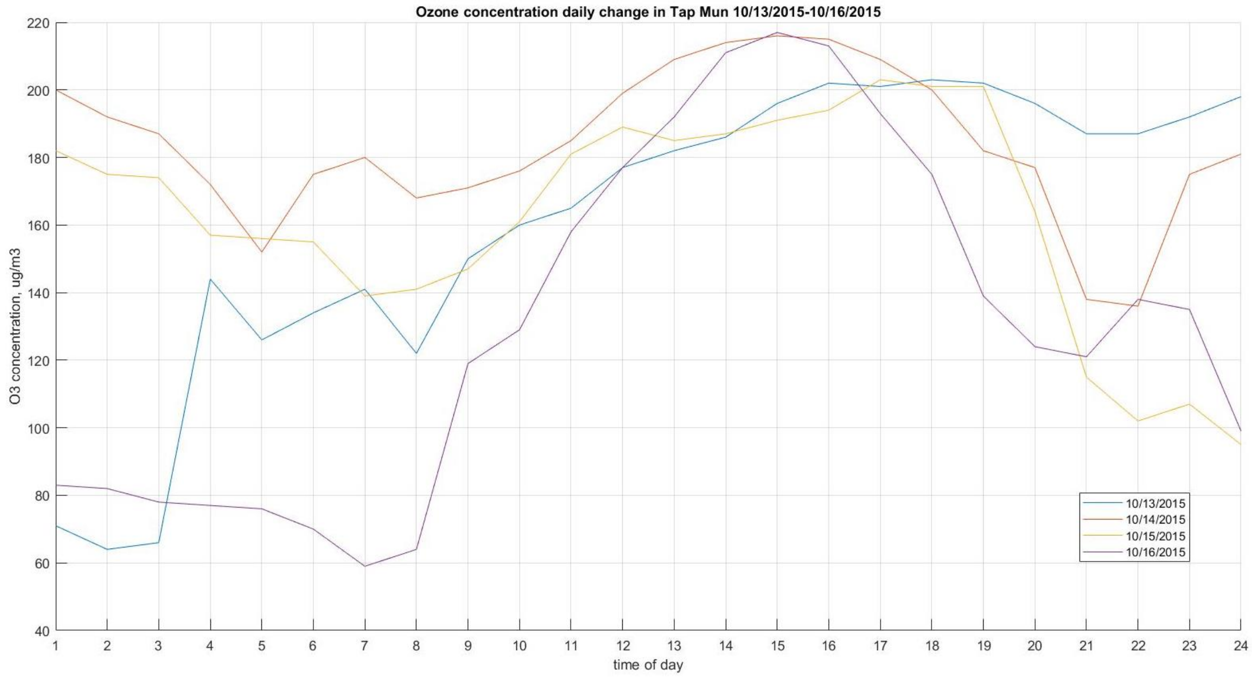

Figure 15. Ozone concentration daily change in Tap Mun 10/13/2015-10/16/2015

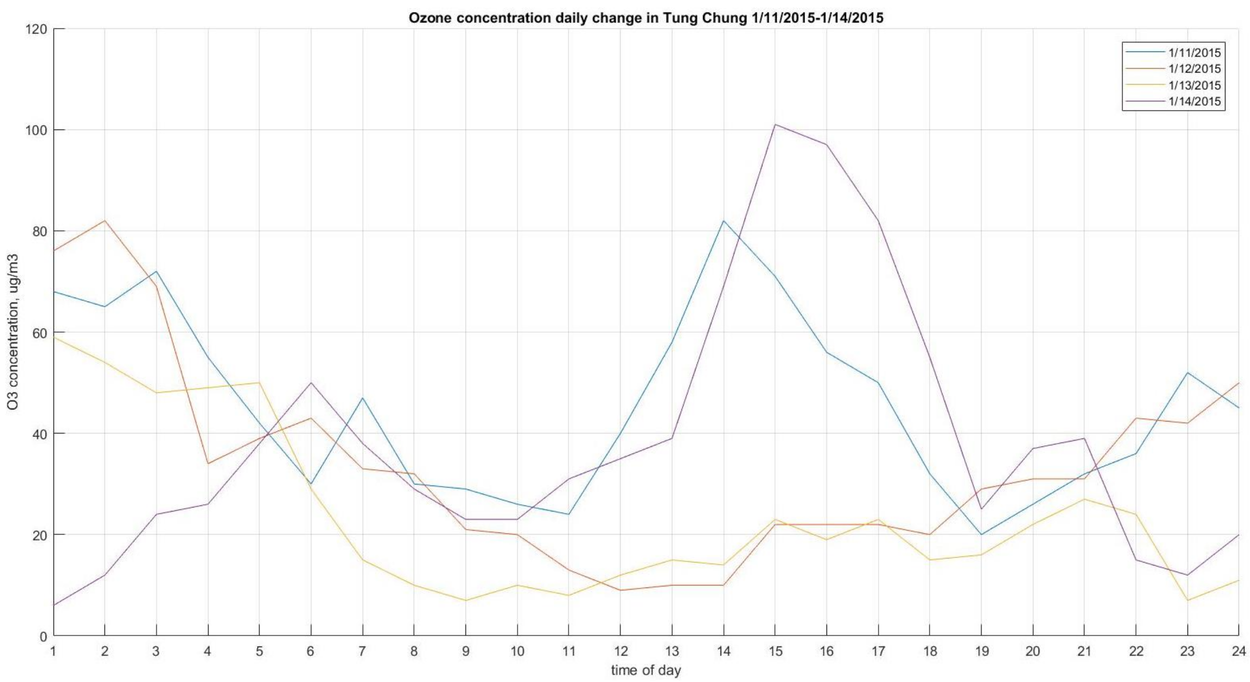

Figure 16. Ozone concentration daily change in Tung Chung 1/11/2015-1/14/2015

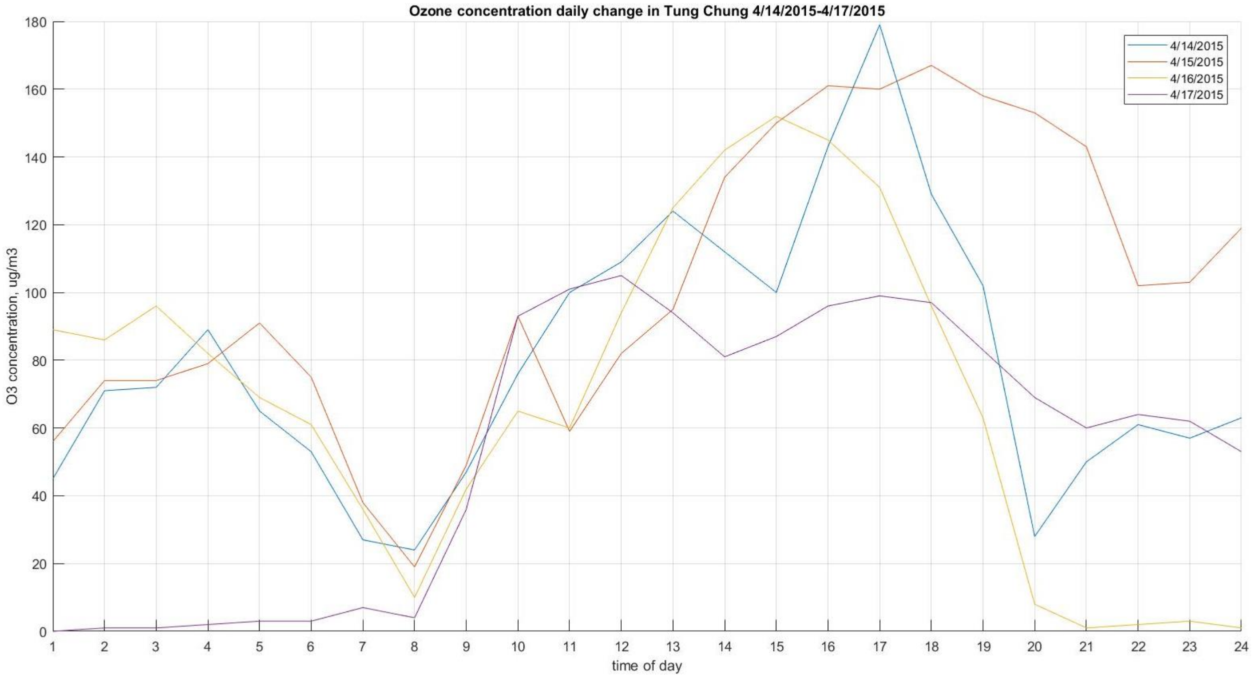

Figure 17. Ozone concentration daily change in Tung Chung 4/14/2015-4/17/2015

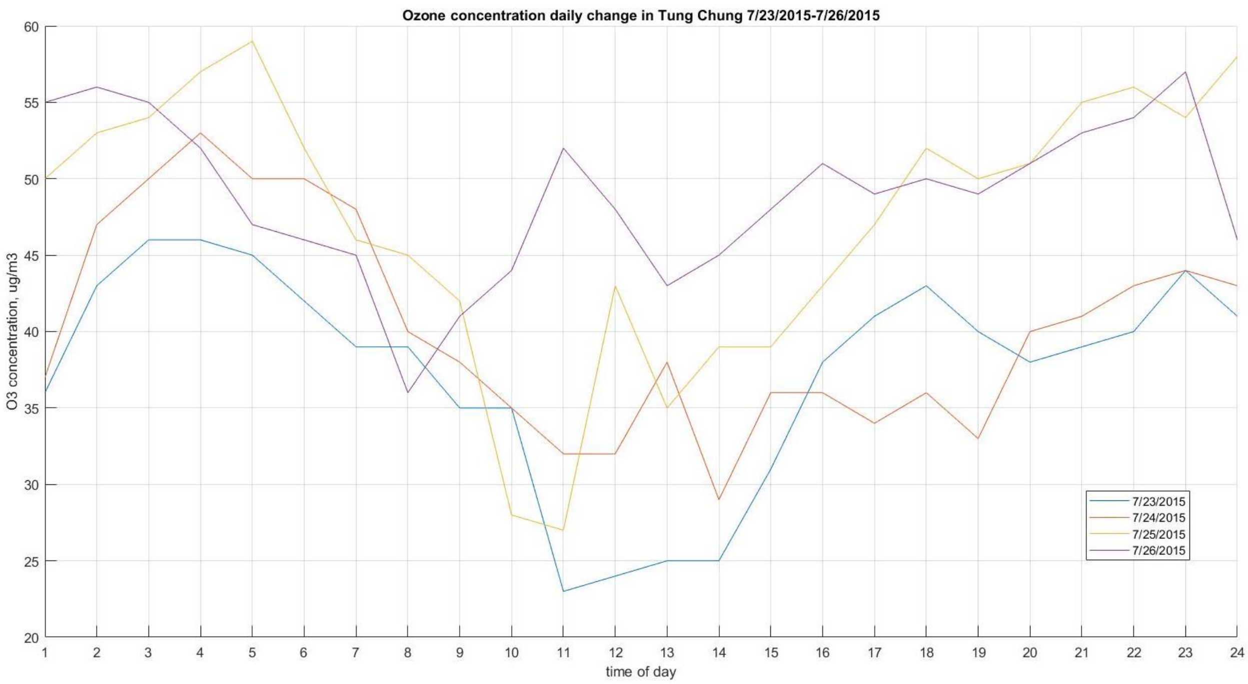

Figure 18. Ozone concentration daily change in Tung Chung 7/23/2015-7/26/2015

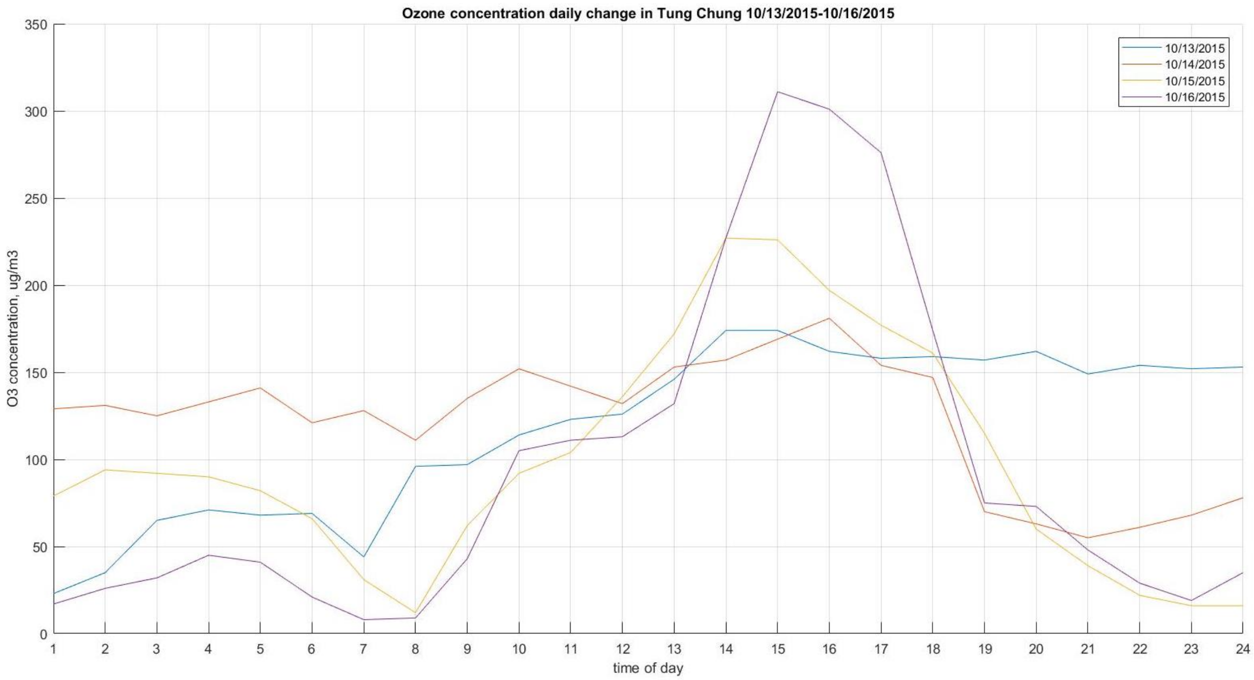

Figure 19. Ozone concentration daily change in Tung Chung 10/13/2015-10/16/2015

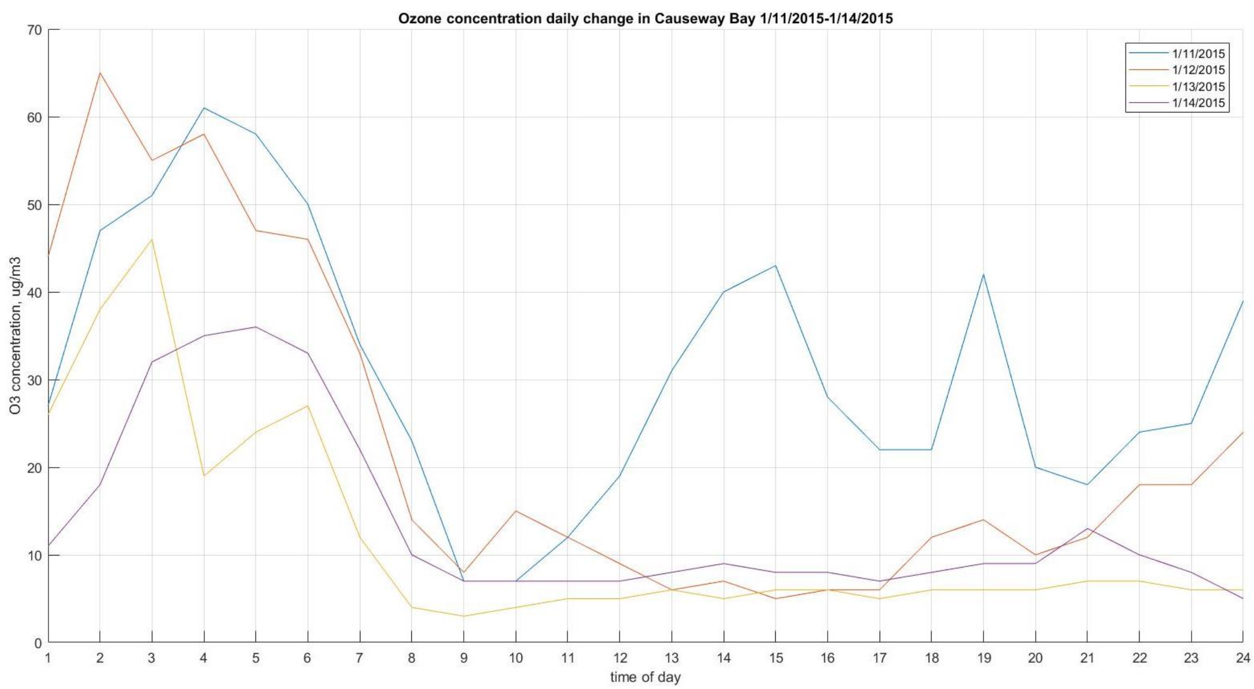

Figure 20. Ozone concentration daily change in Causeway Bay 1/11/2015-1/14/2015

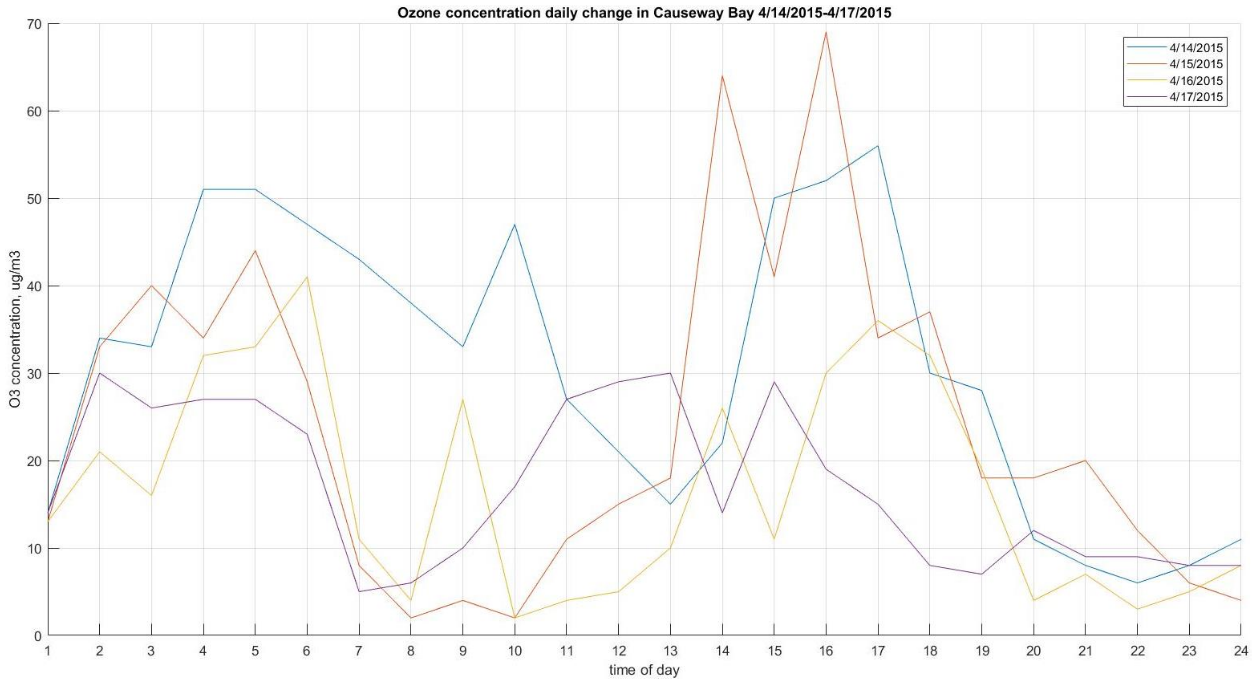

Figure 21. Ozone concentration daily change in Causeway Bay 4/14/2015-4/17/2015

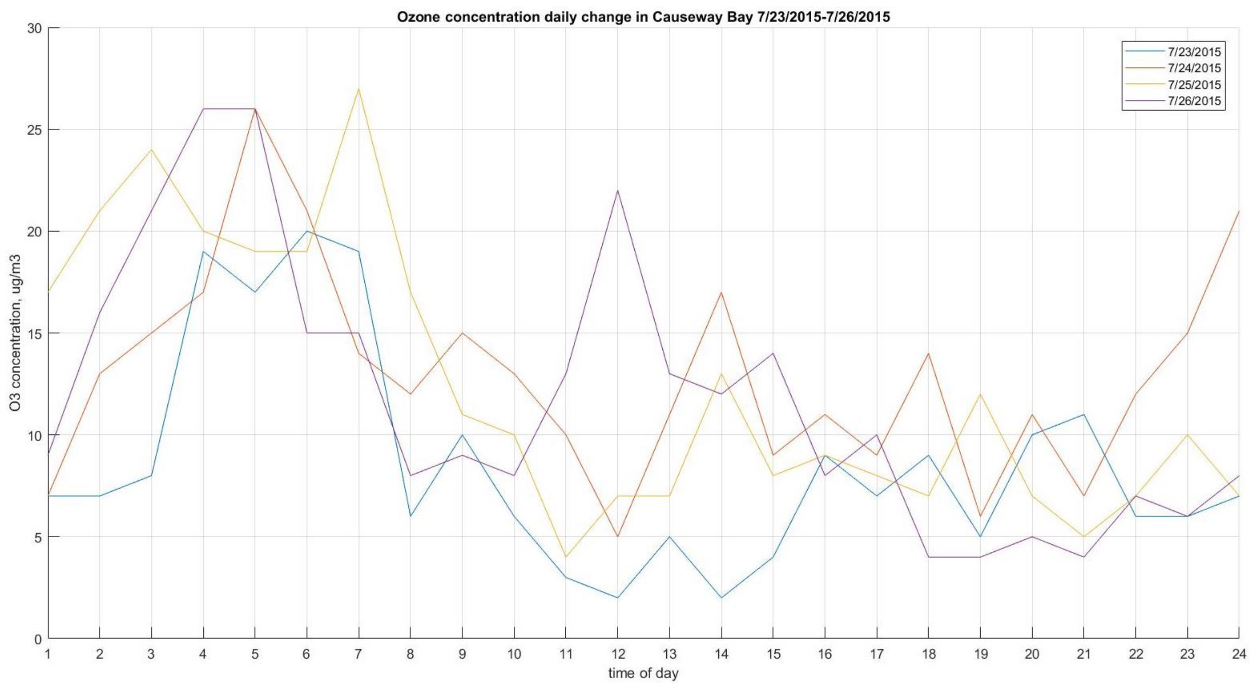

Figure 22. Ozone concentration daily change in Causeway Bay 7/23/2015-7/26/2015

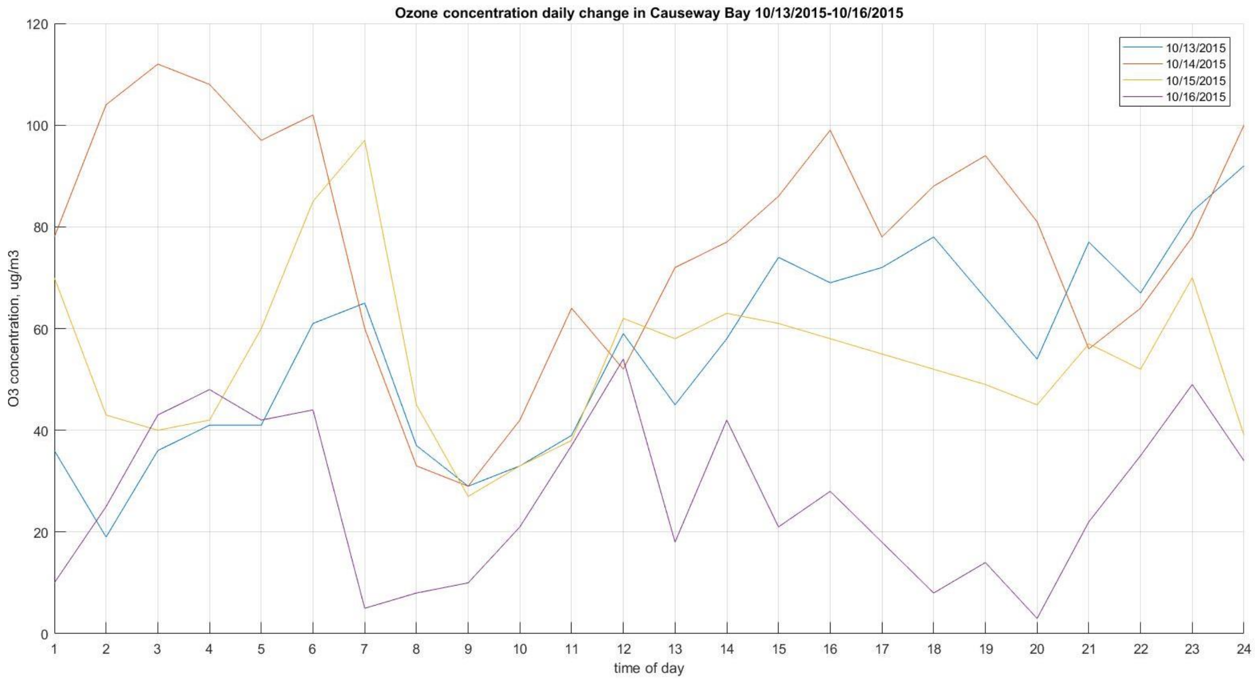

Figure 23. Ozone concentration daily change in Causeway Bay 10/13/2015-10/16/2015

The ozone concentration in the four areas (Yuen Long, Tap Mun, Tung Chung, and Causeway Bay) of Hong Kong follows the similar pattern. (Figure 7-22) There are two significant concentration changes (two peaks and two valleys) each day, respectively, from night to midnight and from morning to afternoon. Ozone concentration began to rise after 8 pm every night, reaching a peak at about 2 am to 4 am followed by a slow decline, until approximately 8 am when it arrived at the lowest daily value. After the early morning nadir, ozone concentration rose again until it reached the second peak shortly after noon, then began to decline to the second lowest value slowly. The causes of these two concentration changes are different, and the process of change during the day is a natural change. It is because of the increasing solar radiation from the sunrise to the noon, as well as emissions of a vast number of ozone precursors due to human activities, such as truck waste gas, coal-fired power generation emissions and so on. There are many photochemical reactions in the air. Ozone is generated by the reaction of volatile organic carbon (VOC) and nitrogen oxides (NOx), causing the ozone concentration to grow rapidly from

8 am. In the afternoon, the solar radiation intensity reached its maximum, and the ozone concentration ceased to grow. From the beginning of the afternoon, the radiation intensity gradually decreased until the sun sets, the ozone concentration gradually decreased to the lowest value during the day. Moreover, the reason for the increase in ozone concentration at night is not clear, pending further study. It can also be seen that the difference between the peak and valley values in the most polluted autumn is the largest and the diurnal variation is significant, while the difference between the peak and valley values in the least polluted summer is the smallest. Those two peaks do not look prominent.

date	cloud cover (%)	rainfall(mm)
1/11	79	little
1/12	89	14.9
1/13	82	25.8
1/14	13	0.0

Table 4. Cloud cover and rainfall in Hong Kong (1/11/2015-1/14/2015) (Source: Hong Kong Observatory, located at Mong Kok)

date	cloud cover (%)	rainfall(mm)
4/14	9	0.0
4/15	15	0.0
4/16	25	0.0
4/17	52	0.0

Table 5. Cloud cover and rainfall in Hong Kong (4/14/2015-4/17/2015) (Source: Hong Kong Observatory, located at Mong Kok)

date	cloud cover (%)	rainfall(mm)
7/23	90	45.0
7/24	88	5.7
7/25	88	9.6
7/26	85	24.9

Table 6. Cloud cover and rainfall in Hong Kong (7/23/2015-7/26/2015) (Source: Hong Kong Observatory, located at Mong Kok)

date	cloud cover (%)	rainfall(mm)
10/13	68	little
10/14	51	0.0
10/15	19	0.0
10/16	20	0.0

Table 7. Cloud cover and rainfall in Hong Kong (10/13/2015-10/16/2015) (Source: Hong Kong Observatory, located at Mong Kok)

Ozone concentration is affected not only by solar radiation but also by cloud cover and precipitation. There was significant cloud cover (79% and 89%) on January 12 and 13, accompanied by light to moderate rain. It can be seen that the trend of changes in ozone concentration is different on cloudy and sunny days. In the cloudy days, the ozone concentration did not rise at noon but remained at a low level. On 13 January, when there was no precipitation, the temperature was reduced, and the cloudiness was very low (only 13%), so the solar radiation led to an increase in ozone concentration. From April 14 to 17, cloud cover is increasing day by day, and no precipitation is generated, which means that the amount of radiation decreases day by day and the average concentration decreases day by day. (Table 4-7)

3.3 Ozone seasonal variation

This present paper uses the traditional season division, spring runs from March to May, summer from June to August, autumn from September to November, and winter from December to February. The ozone concentration in Hong Kong is lower in summer and spring than in fall and winter. (Table 8) Whether it is an average seasonal concentration or hour maximum concentration, in the urban and suburbs of the four seasons, the summer is the lowest, while the fall is the highest. In contrast, in a study of the variation of ozone concentration in Guangzhou area of Xuemei Wang et al., concluded that winter had the highest concentrations and spring the lowest.[28] So, there are differences between the two places. The trend of daily concentration change in autumn and winter is larger than that in summer and spring. Moreover, the distribution of daily ozone concentration variation in summer is more uniform, while that of in winter is more dispersed. (Figure 7-22) Hong Kong is located on the south coastline of China (22°N), belonging to the subtropical maritime climate. So, the summer and autumn are hot, and the wind blows in from the south. Occasionally, typhoons form over the Pacific Ocean, so the pollutants are not easy to accumulate, but easy to spread. In the summer, the late flood season, there are higher winds and frequent thunderstorms. This is conducive to the proliferation of pollutants. In the fall, there are also individual typhoon systems that affect Hong Kong. In the winter, the weather is sunny and dry. With the monsoon weaker, the cloud cover gradually increased, but there is little chance of heavy rain. So, the winter climate is not conducive to the dispersion of pollutants.

season	Causeway Bay(urban)			Yuen Long(suburbs)		
	average	maximum	variance	average	maximum	variance
spring	16.3	52.0	12.44	33	95	21.08
summer	8.6	31.0	5.15	34	125	23.78
autumn	23.3	77.0	14.12	48.7	110	29.88
winter	22.7	55.0	12.90	33.3	97	19.03

Table 8. Average and maximum ozone concentration in urban and suburbs ($\mu g/m^3$)

season	average in Tung Chung	average in Tap Mun
spring	41.00	66.00
summer	39.67	53.33
autumn	57.30	94.33
winter	40.33	84.00

Table 9. average ozone concentration of two suburb areas in different seasons ($\mu g/m^3$)

I calculated the variance of the daily concentration values for each season, resulting in the degree of dispersion of ozone pollution in each quarter. It is clear that, regardless of Causeway Bay or Yuen Long, the largest variance is in the fall, the most polluted season. In this season, the magnitude of the change in ozone concentration is relatively large, while the high peak pollution process appears. In the summer of the city center (Causeway Bay), the variance of the concentration is the smallest, and the daily difference is the lowest. (Table 8)

3.4 Ozone spatial variation

The average level of ozone concentration in Yuen Long station is significantly higher than the mean measured at the Causeway Bay monitoring station. (Table 8) Regardless of the average monthly concentration, or the maximum concentration of hours, suburban concentrations are greater than those found in the urban area. The average annual ozone concentration in the Yuen Long area is 37μg/m^3, and the monthly average maximum is 54μg/m^3. The average annual value of the Causeway Bay region is 17.8μg/m^3, and the monthly average maximum is 27μg/m^3. The mean concentration of each month in Yuen Long is also generally higher than the Central region. Similarly, in the suburbs of the northeastern corner of Hong Kong, the average ozone concentration in the Tap Mun area is also higher than the Causeway Bay area with an annual average of 73μg/m^3 and a monthly average maximum of 99μg/m^3. Tung Chung area, in the southwest corner of Hong Kong, is the coastal suburbs, where the average concentration of ozone is also higher than the Causeway Bay area. The average annual concentration in Tung Chung area is 45μg/m^3, and the monthly average maximum is 62μg/m^3. (Table 9, Figure 23)

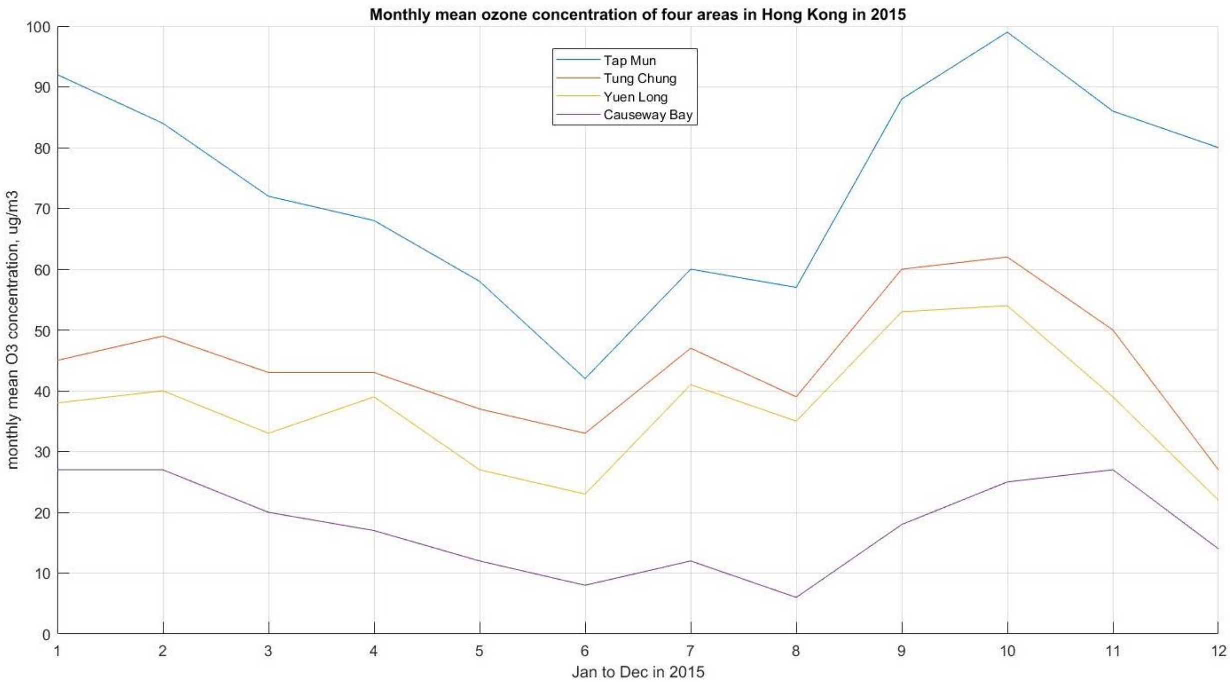

Figure 24. Monthly mean ozone concentration of four areas in HK in 2015

In the summer, the southerly and southwest winds prevailed in Hong Kong. (Table 10) A large number of ozone-contaminating precursors produced in the southern part of Hong Kong Island and urban areas undergo photochemical reactions during horizontal transport and eventually reach Tap Mun in the northeastern region of Hong Kong, resulting in increased ozone concentrations in the Tap Mun area, which is the most polluted area.

Day of month	Jan	Feb	March	April	May	June	July	August	Sep	Oct	Nov	Dec
1	80	60	20	150	120	190	220	20	50	30	20	70
2	70	60	70	180	200	190	220	100	110	10	20	70
3	70	50	40	170	210	220	210	20	60	60	70	20
4	50	70	60	170	210	230	170	10	80	120	80	50
5	40	20	70	50	200	230	40	220	220	100	70	70
6	40	50	50	30	170	210	20	220	240	100	80	10
7	20	70	50	70	180	200	10	290	250	140	80	10
8	20	20	40	20	180	200	10	290	60	300	70	30

9	60	70	30	30	210	220	360	220	70	20	50	60
10	60	70	80	20	30	210	90	230	60	20	80	20
11	50	50	60	30	110	220	220	220	100	20	80	60
12	20	50	30	20	100	210	220	220	90	50	80	70
13	10	50	50	10	100	210	210	230	50	70	80	70
14	20	50	40	20	170	200	180	210	60	70	30	50
15	30	30	40	180	200	200	150	220	70	90	80	10
16	50	40	40	230	220	220	220	230	70	30	80	10
17	80	40	50	140	230	230	230	230	70	70	80	20
18	70	50	40	180	210	230	60	220	70	60	80	40
19	20	70	50	200	210	230	40	230	180	20	70	30
20	70	50	40	210	220	130	60	270	200	10	80	40
21	30	30	40	20	70	110	230	350	190	10	70	50
22	40	40	70	80	60	130	220	10	110	120	80	60
23	50	40	80	70	210	160	200	220	110	80	90	40
24	50	40	80	70	30	170	200	10	230	80	70	40
25	40	30	70	70	210	200	200	10	230	80	20	10
26	40	40	70	80	200	220	200	40	90	80	20	30
27	60	90	30	50	200	200	200	200	90	60	60	30
28	70	50	50	230	210	220	200	210	10	110	70	20
29	50		50	220	210	220	190	230	230	90	60	70
30	40		50	190	230	220	190	220	140	100	100	20
31	50		40		220		70	40		80		20

Table 10. Wind direction of Hong Kong in 2015 (unit: degree) (Source: Hong Kong Observatory)

3.5 Ozone level assessment

In the summer, there are often many high-temperature low-pressure centers in Hong Kong. Southerly winds prevail, so typhoons and thunderstorms are more frequent in Hong Kong. Moreover, convection is strong, so it is not conducive to the accumulation of pollutants but is conducive to the proliferation of contaminants. Therefore, although Hong Kong is a highly developed modern city, the ozone pollution is not particularly severe, especially in the city center, the ozone concentration remained at a low level for a long time.

The national GB 3095-2012 secondary requirement is that the average ozone concentration for one hour must be less than 200μg/m^3, and the maximum daily average of 8 consecutive hours is less than 160μg/m^3. (Table 11) In the Causeway Bay area of Hong Kong, the maximum daily average of 8 hours per day for each day of the year is below the pollution threshold of 160μg/m^3. However, the difference between urban and suburban areas in Hong Kong is still very evident. In less polluted Causeway Bay and other downtown areas, the ozone concentration is lower than 25μg/m^3. In the outskirts of the coastal areas of Hong Kong Island, the ozone concentration is above 40μg/m^3. Among them, the Tap Mun region, the most remote and has the least population; the pollution situation is the most severe. The highest average hourly concentration in the Tap Mun region was 310μg/m^3. Among the 8016 hours in a year, only 46 hours exceeded the standard of 200μg/m^3. However, by EU standards, US standards and WHO standards (Table 12), that is, in the developed areas and the United Nations Environment Program standards, there is no 1-hour concentration limit but provides an 8-hour maximum concentration value. In 1997, the WHO developed a large number of studies that defined the 8-hour maximum concentration limit for ozone that could protect against acute exposure within 1 hour. China has added a maximum limit of 8 hours (160μg/m^3) in the new standard promulgated in 2012, but it is much higher than the norm for developed regions such as the European Union (120μg/m^3) and the UK (100μg/m^3). As a result, ozone pollution in Hong Kong still needs to be further managed and improved.

In addition to urban development and population density impacts, wind direction also affects changes in ozone concentrations. From the above analysis can be concluded that the ozone pollution in Hong Kong is good. With the increasing emissions of NOx and VOC, human-made activities have become the main cause of ozone pollution.[29] Although both affect the ozone concentration, VOCs have a greater impact and are more likely to cause ozone pollution when other conditions remain unchanged. Therefore, the control of VOC emission reduction prevails over the control of NOx emissions.[30]

Ozone concentration	Daily maximum average within 8 hours	160μg/m^3
	Hourly average	200μg/m^3

Table 11. China national standard GB 3095-2012 (Source: www.mep.gov.cn)

Ozone(μg/m^3)	EU 2005	EU 2010	US	WHO	China (residential area)	China (commercial area)	China (industrial area)
1-hour average	180/240		240		120	160	200
8-hour average		120	160	120			160

*Table 12. Air quality standards of ozone. *For EU 2005, there is an information threshold of 180 μg/m^3, and a warning threshold of 240 μg/m^3. For a warning to be issued, the value must be exceeded during three consecutive hours. (Source: http://www2.dmu.dk/AtmosphericEnvironment/Expost/database/docs/AQ_limit_values.pdf)*

4. Summary

The daily change in ozone concentration has two pollution processes, one that occurs in the morning and the second happens in the afternoon. The peak of the afternoon is due to the increasing human activities and enhancing solar radiation; the cause of the morning is unknown, still need more in-depth study.

On sunny days, when solar radiation is the strongest, ozone concentration is also the highest, which shows in sunny days strong solar radiation is conducive to the generation of ozone. In the cloudy or rainy days, the solar radiation is relatively weak, which is not conducive to the generation of ozone, so the ozone concentration is relatively low.

Ozone concentration Seasonal changes in the process of pollution: the summer is the lowest, the autumn is the highest, and the difference between spring and winter is not big. Because of the low level of overall pollution in Hong Kong, the degree of discretization is low in summer. While in the heavy contamination of the fall, the level of dispersion is higher. The peak of the summer pollution process is not as obvious as the autumn.

The ozone concentration is significantly various in different regions. The ozone concentration in the suburbs (Tung Chung, Yuen Long and Tap Mun) is higher than that of the city center (Causeway Bay), which is often located in the downwind direction, is the most severe. The city discharges a large number of ozone precursors to produce ozone pollution by horizontal transport and photochemical reactions.

The overall situation of ozone pollution in Hong Kong is not particularly severe, and the air quality is mostly good. In accordance with the China national standard GB 3095-2012(Table 3.8), there is never a day that the daily average concentrations of more than 200 ($\mu g/m^3$) in Hong Kong and there are five times that the mean concentration of more than 200 ($\mu g/m^3$) per hour. Even the number of days of the maximum daily average of more than 160 ($\mu g/m^3$) for eight consecutive hours is also minimal, and the air quality is good. However, there is still a gap between the pollution situation in Hong Kong and the standards of developed areas. The Hong Kong Government still needs to continue its work on pollution prevention and control.

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