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*Graphical Abstract

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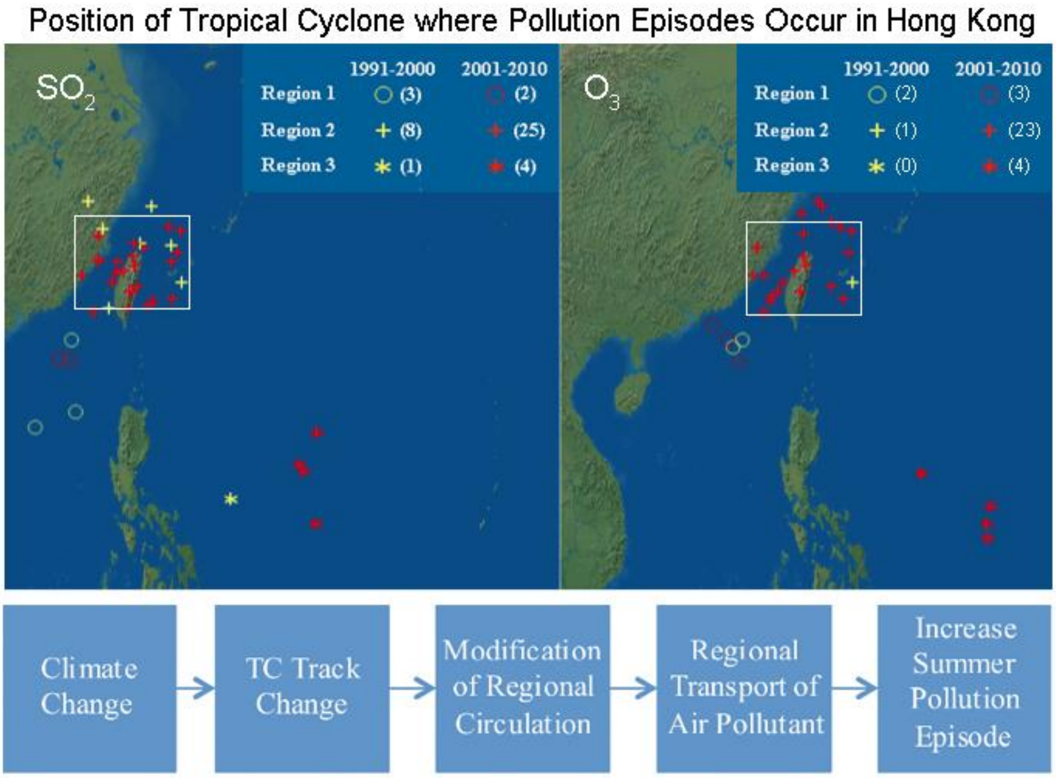

Highlights

1) Under the influence of climate change, tropical cyclone (TC) track changes in the western North Pacific (WNP) have potential impact on the regional air quality in South China.

2) TCs in the vicinity of Taiwan have the highest impact on Hong Kong air quality due to regional transport of air pollutants from the Pearl River Delta (PRD) region, leading to significantly higher chances of episode occurrences.

3) While the impact on primary pollutants such as SO_2 is diminishing due to reduced emissions in the PRD, the impact on the secondary pollutant O_3 is intensifying due to the effects of global climate change, and precursor's enhancement.

4) If the prevailing track change towards the Taiwan region persists, the occurrence of TC-related O_3 episodes in Hong Kong will increase.

Impact of Tropical Cyclone Track Change on Regional Air Quality

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Keywords: Ozone, Tropical cyclone track, air quality, climate change, South China and SO_2

Abstract

There has been an increase in tropical cyclones (TCs) in the western North Pacific (WNP) that traverse with a northward recurving track towards East Asia and a decrease in TC tracks entering the South China Sea (SCS) in the past few decades. To investigate the potential impact of the prevailing TC track change, an analysis has been carried out based on historical data (1991 to 2010) of TC tracks and air quality. Compared to TCs in other regions, TCs in the vicinity of Taiwan have the greatest impact on Hong Kong air quality due to regional transport of air pollutants from the highly industrialized Pearl River Delta (PRD). In fact, the number of days with TCs in this region increased from 41 in the period 1991-2000 to 62 in 2001-2010 (51% increase) because of the TC track change. The mean RSP, SO_2 and O_3 concentrations of these days are higher than the summer averages by approximately 82%, 153% and 68% in a remote area, and by 58%, 50% and 65% in an urban area respectively, and the chance of episode occurrence is significantly higher. Additionally, while the effects on SO_2 concentrations are diminishing because of reduced emissions in the PRD, the impact of the TCs on O_3 concentrations is intensifying. The O_3 concentrations on the TC-affected days are increasing at the estimated rates of 0.5 µg/m^3 and 2.6 µg/m^3 per year respectively in the urban and remote areas, which are significantly higher than the increase of 0.3 µg/m^3 and 0.4 µg/m^3 per year in the average summer concentrations.

1. Introduction

Hong Kong air quality has deteriorated in recent years due to the regional transport of air pollutants from the rapid industrialization of the Pearl River Delta (PRD); as Hong Kong (HK) is situated at the mouth of the Pearl River estuary. According to the Hong Kong Environmental Protection Department (HKEPD), late autumn and winter account for more than 67% of air pollution episodes, while summer accounts for 26% of episodes (HKEPD, 2016). Previous studies showed that tropical cyclones (TCs) approaching HK have significant effects on local air quality in summer as TCs produce a reversal of wind direction (from the southwesterly prevail into northerly, westerly or northwesterly wind), which results in the transport of air pollutants from PRD to HK. This is similar to the effect of northeasterly monsoon that occurs in late autumn and winter (Lee & Savtchenko, 2006; Feng et al., 2007; Huang et al., 2009; Yang et al., 2012; Lam et al., 2017). When TCs are hovering in the Western North Pacific (WNP) near the Luzon Strait or in the vicinity of Taiwan, the subsidence of airflow on their periphery creates temperature inversion and stagnation (low wind condition) which inhibit the dispersion of air pollutants in South China (Lam & Lau, 2005; Huang et al., 2009; Yang et al., 2012), resulting in accumulation of pollutants that increase the severity of TC-related air quality episodes. Similar influence from TCs has also been found in the Malaysia peninsula (Oozeer et al., 2016).

In the last two decades, many high particulate matter (PM) and ozone (O_3) episodes have been reported under the influence of TCs in the summer for HK. These episodes have been noted to have higher O_3 concentration compared to the autumn and winter episodes, as the intense sunlight under the large-scale subsidence with high temperature encourages the formation of O_3 (Lee et al., 2002; So & Wang, 2003; Lam et al., 2005; Wei et al., 2016); Huang et al. (2009) and Zhang et al. (2013) reported that the top 33% percentile of O_3 episodes in HK is associated with TC events. Moreover, there is an observed increase of summer episodes in recent years (HKEPD, 2016). Wu et al. (2005) and Tu et la. (2009) found that more TCs were entering the western North Pacific (WNP) near the Luzon Strait or Taiwan in the last decade. This is linked to the observed increase of northward recurving TC tracks towards East Asia with a decrease in the westward track towards the South China Sea (SCS) (Tu et al., 2009). The shift of TC track is found to be associated with the change of global sea-surface temperature (SST) anomalies and the associated changes in the WNP subtropical ridge of high pressure and large-scale steering flows (Ho et al., 2004; Wu & Wang, 2004; Wu et al., 2005; Goh & Chan, 2009). In addition, it may also be related to global warming or climate change, as Wang et al. (2011) reported that the prevailing TC track change to Luzon Strait may continue until year 2040 under the A1B scenario of the Intergovernmental Panel on Climate Change (IPCC). This suggests the possibility that climate change may have an impact on the regional air quality through its influence on TC tracks in the future.

As meteorological conditions resulting from different TC positions are significant to the occurrence of summer pollution episodes in HK, understanding the TC track change in recent decades is important. In this study, a systematic analysis on the effect of changes in TC positions on HK air quality was performed using historical data (i.e., 1991 to 2010) to establish the relationship between the TC position and pollutant concentration. The characteristics and magnitudes of the impacts in different regions were analyzed with reference to the changes of pollutant concentrations (i.e., SO_2, PM_{10} and O_3) for a better understanding of the influence of TC track change on summer pollution episodes in South China.

2. Material and Methods

In order to investigate the change of TC track in recent years using historical data, we have selected year 2000 as our dividing point. The selection of year 2000 was made based on considerations of data availability (the study was first developed in 2012) and the corresponding historical period of the IPCC AR4 scenario. As a result, the study period is divided into two epochs: (1) May to August of 1991 to 2000 and (2) May to August of 2001 to 2010. All TC track and air quality data were collected from the Hong Kong Observatory (HKO) and the Hong Kong Environmental Protection Department (HKEPD).

2.1. *Tropical Cyclone data from the Hong Kong Observatory*

The track information (e.g., latitude/longitude position), maximum sustained wind speed and pressure of the storm center for all TCs formed in the WNP and SCS are available in the annual tropical cyclone publication (HKO, 2012). The publication covers various types of TC systems including tropical depression, tropical storm, severe tropical storm, typhoon, severe typhoon and super typhoon that happened in a particular year. It recorded the entire TC track from its formation to its landfall/dissipated. In this study, we collected 6-hourly TC track data with latitude and longitude information from 1991 to 2010. Fig. 1 shows the difference in TC track density between those two epochs (second minus first). It is clear that there is a decrease in the number of TCs entering the SCS and the Philippines Sea (blue color) and an increase in track density in the vicinity of Taiwan (red color). These results are consistent with the northward shift of TC tracks reported in literature (Wu et al., 2005; Tu et al., 2009; Wang et al., 2011). To further understand the impacts of TC track change on local air quality from 1st epoch to 2nd epoch, we subdivided the position of TC tracks into three separate regions: SCS region (Region 1, R1), Taiwan region (Region 2, R2), and the Philippines Sea (Region 3, R3), as shown in Fig. 1.

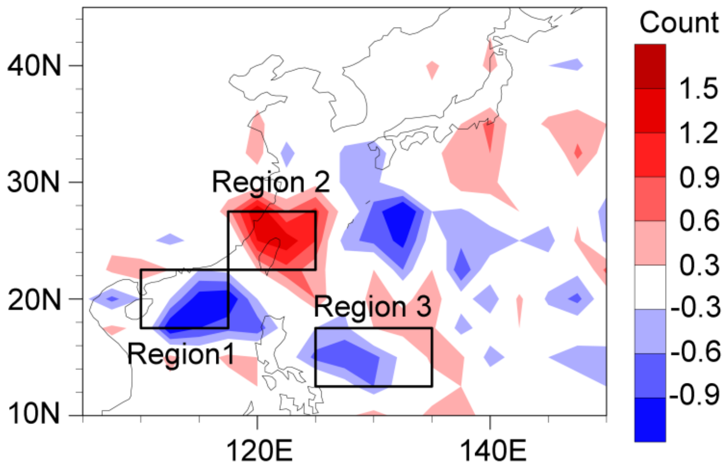

Fig. 1. TC track density difference between 2001-2010 and 1991-2000 (May – August)

2.2. European Reanalysis-Interim (ERA-Interim) Data

The ERA-Interim dataset from 1991 to 2010 was used to analyze the meteorological condition when TCs were entering those three regions. Parameters such as wind direction and vertical velocity were adopted to understand the spatial and horizontal circulations induced by TCs in the regions. The ERA-Interim data is a global climate reanalysis dataset that uses European Center for Medium-Range Weather Forecasts (ECMWF) model with 4-dimensional variation analysis (4D-Var) to generate 6-hourly atmospheric and 3-hourly surface fields. It contains the spectral resolution of T255 (80 km horizontal resolution) with 60 vertical levels from the surface up to 0.1 hPa (Dee et al, 2011).

2.3. Air Pollution Data from Hong Kong Environmental Protection Department

The Hong Kong air quality observation network was first established in early 1990, as an effort to protect public health and to understand the ambient air quality in HK. The network was first established with 7 stations including Central Western, Kwai Chung, Kwun Tong, Sham Shui Po, Shatin, Tai Po and Mong Kok measuring hourly SO_2, NO_2, NOx, CO, Total Suspended Particulate (TSP) and O_3. Not until 1995 and 2011, PM_{10} (also called Respirable Suspended Particulates (RSP)) and $PM_{2.5}$ (also called Fine Suspended Particulates

(FSP)) were included in the sampling protocol, respectively. Currently, more than 16 stations (i.e., 13 ambient stations and 3 roadside stations) are in operation (HKEPD, 2012). In this study, we selected two distinct monitoring stations: Kwai Chung (KC) and Tap Mun (TM); KC station is located in the highly polluted/urbanized area near the Kwai Chung Container Terminal with the longest monitoring records. It covers the period 1991 to 2010 for SO_2 and O_3 and a shorter period 1995 to 2010 for RSP. The selection of this station is used for understanding local pollution trends in the past two decades under the influence of TCs; Tap Mun station is a regional background station located at the far eastern side of HK (away from all major emission sources) on a remote island. It covers the data from 1998 to 2010 for RSP, SO_2 and O_3 and is intended to be used for understanding the effect of regional transport of air pollutants into HK in recent years, as shown in Fig. 2 a.

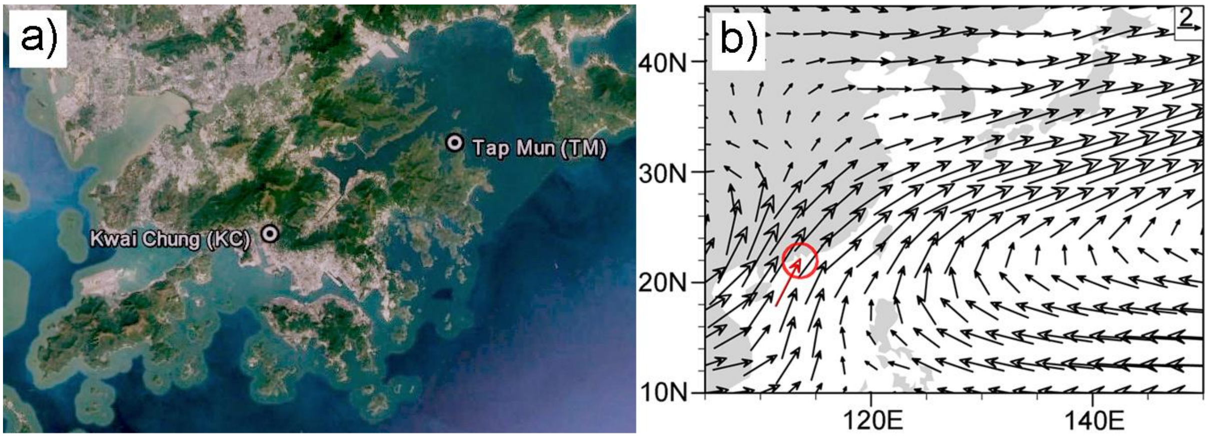

Fig. 2. a) Locations of selected HKEPD monitoring stations: Kwai Chung (KC) and Tap Mun (TM); b) Composite wind at 1000 hPa for non-TC condition from ERA-Interim data (red circle indicates the position of HK, and red arrow signifies the prevailing wind direction).

3. Results and discussion

3.1. Comparisons on local meteorological influence from TCs

Based on the ERA-Interim data, the composite horizontal and vertical wind at 1000 hPa during the period 1991 to 2010 are plotted in Fig. 2b and Fig. 3a-c. Comparing with the prevailing circulation of southwesterly monsoon in summer (Fig. 2b), TCs are clearly influencing the regional circulation (see the red arrows in Fig. 3a-c), and depending on the TC position, the effect on the wind direction in HK could be quite different. For example, when TCs are in R1 and R3, HK is mainly downwind of the oceanic southeasterly wind, with a lower wind speed for TCs in R3 due to weaker TC influence. On the other hand, when TCs are in R2, the wind direction changes to northerly/northwesterly and putting HK at the downwind direction of PRD with weak wind. In terms of vertical velocity, a sinking airflow (shown in red) on HK has been observed under the influence of TCs in R2, in contrast with the upward direction (shown in blue) over HK for TCs in R1 and R3. As the composite vertical velocity is found by averaging all TC days from 1991 to 2010 for each region, this can only be interpreted as having less subsidence of airflow for TCs in R1 and R3 than TCs in R2 in general; the result does not reflect the actual vertical motion of individual TCs.

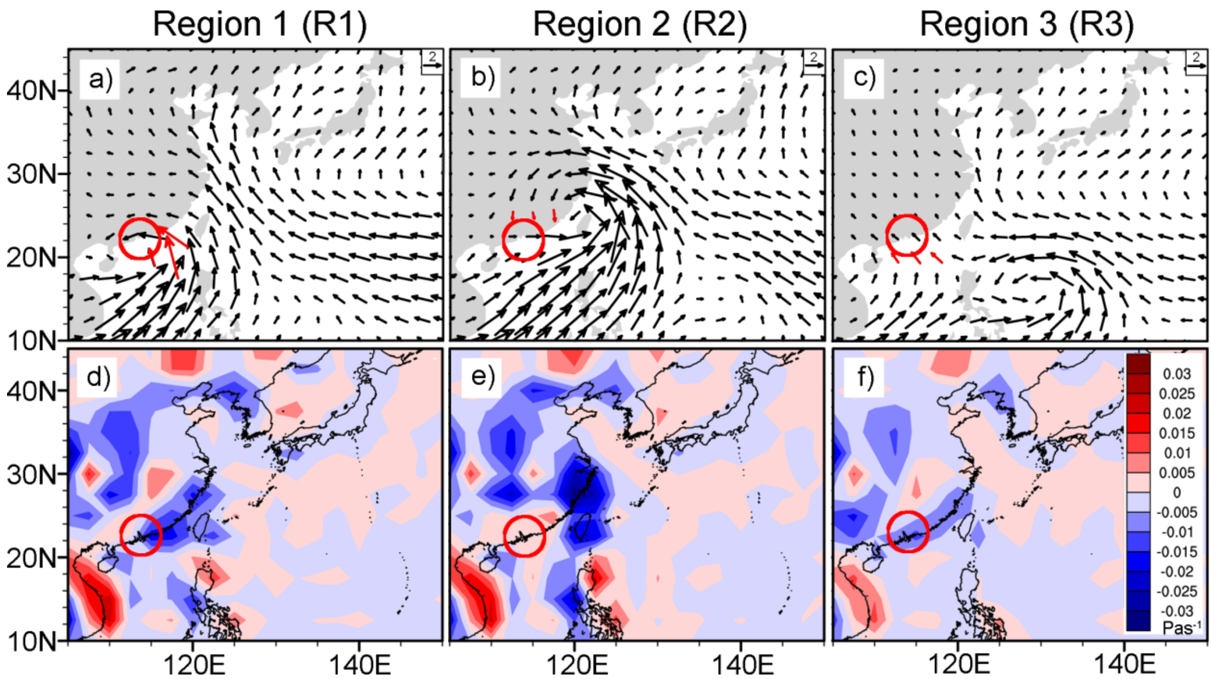

Fig. 3. a) Composite wind at 1000 hPa for TC conditions (red circle indicates the position of HK, and red arrow (s) signifies the prevailing wind direction induced by the influence of TCs; b) vertical velocity at 1000 hPa when TCs are in R1, R2 and R3. (Red circle indicates the position of HK).

3.2. *Comparisons of local air quality for TCs at different regions*

To understand the local air quality on the TC-affected days in the summer, the cumulative distribution function (CDF) of daily average RSP, daily average SO_2 and maximum daily average 8-hr (MDA8) O_3 concentrations in TM and KC stations are shown in Fig. 4. The "all summer days" curve (black color) represents the overall distribution of the concentrations in the summer (May to August) regardless of TC occurrence. The values on the right hand corner represent the mean concentration for "all summer days" (black), R1 (green), R2 (red) and R3 (blue)), and the percentage differences of the R1, R2 and R3 mean concentrations from the "all summer days" mean concentration are stated inside the parentheses. In TM station (Fig. 4a-c), the CDF curves of RSP, SO_2 and MDA8 O_3 for days with TCs in R1 and R3 are approximately the same as the "all summer days" curves, with +1% to +7% change in the average mean concentrations. The similar/overlapping CDF pattern reveals that TM station receives very limited pollution impact from the PRD emissions under the southerly wind. The average mean concentrations of RSP, SO_2 and MDA8 O_3 (average of R1 and R3) is reported as ~28.7 μg/m^3, ~9.4 μg/m^3 and ~78.0 μg/m^3, respectively, which is much lower than the World Health Organization (WHO) air quality guidelines (AQG) of daily average RSP of 50 μg/m^3, daily average SO_2 of 50 μg/m^3 (Interim target-2), and MDA8 O_3 of 100 μg/m^3. On the other hand, in KC station (Fig. 4d-f), the CDF curves for TCs in R1 and R3 are both shifted to the lower side (to the left) for RSP and SO_2 with average mean differences of -5% to -49%, while slightly to the higher side (to the right) for MDA8 O_3 with average mean difference of +8% to +42% compared with "all summer days". The higher CDF of RSP and SO_2 in "all summer days" is mainly caused by the channel effect induced by the hilly terrains on the southwesterly wind passing through the Victoria Harbor, which drives emissions from the coastal PRD (e.g., local marine vessel in western HK, Macao, and Zhuhai) to the western part of HK (i.e., non-TC condition, see Fig. 2b)), resulting in higher marine background concentrations in "all summer days" than in R1 and R3. It is observed that the impact on air quality with TCs in R3 is less pronounced than TCs in R1, which is probably due to the fact that the centers of TCs in R3 are usually over 1,000 km away so they have limited influence on HK/South China. Compared with TM station, KC station is located in the container port area which is affected by local port emissions, so the average mean RSP and SO_2 concentrations are much higher than those in TM, reported as ~35 μg/m^3 and ~20.6 μg/m^3, respectively, against ~28.7 μg/m^3 and ~9.5 μg/m^3 in TM. For the MDA8 O_3, some increases are found for TCs in R1 and R3 (Fig 4f), which reflects the influence of the stagnating high-pressure systems at the peripherals on HK, depending on the size and intensity of the TCs (See Table A1 in Appendix for some notable examples). Since this study focuses on the effect of the TC position/TC track change on air quality, the effect of TC size and intensity will not be covered.

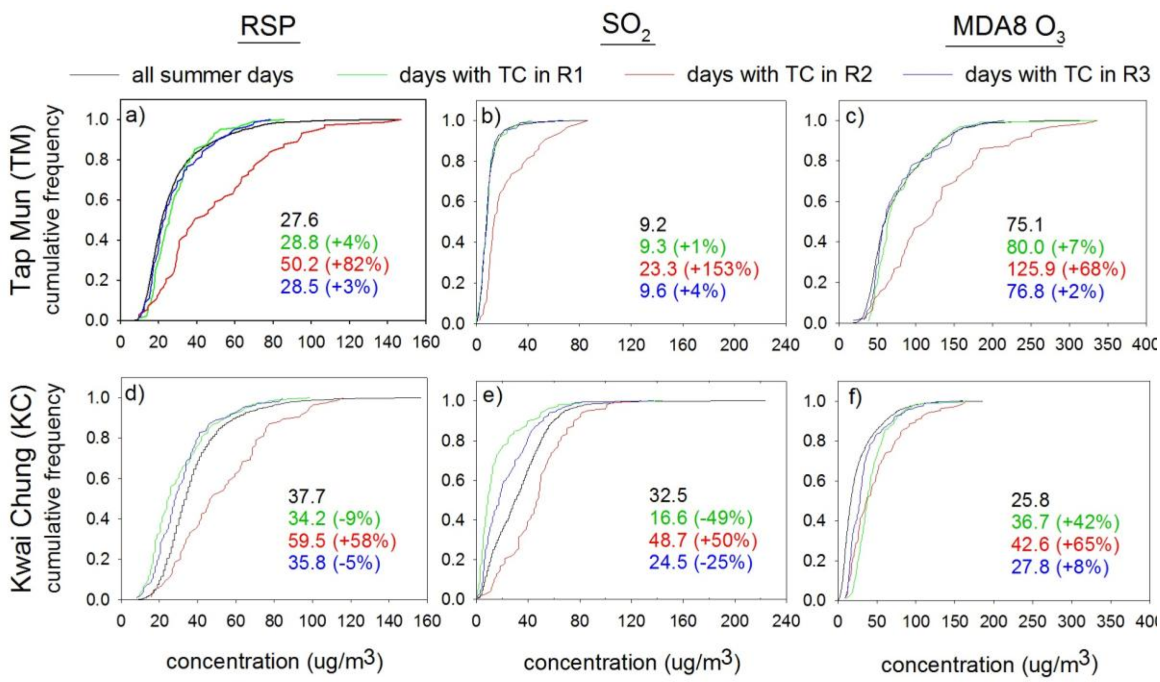

Fig. 4. Cumulative distribution function of daily average RSP, daily average SO_2 and MDA8 O_3 concentrations for all summer days and days with TC in R1, R2 and R3. The values on right hand corner report the mean concentrations of "all summer days" (black), R1 (green), R2 (red) and R3 (blue)) with the percentage differences between "all summer days" and the regions (i.e., R1, R2 or R3) in the parentheses.

Compared with the average summer day, for days with TCs in R2, the CDF are clearly shifted to the higher side (to the right) regardless of stations or pollutants, which indicates that poor air quality has been stimulated under TCs in R2. The adverse air quality effect is mainly caused by the regional transport of air pollutants from PRD induced by the change of wind circulation from southwesterly to northwesterly, which has been discussed earlier. The combined effects of the subsidence of air flows, high temperature, and the light northwesterly wind induced by TCs discourage the dispersion of pollutants and encourage the formation of secondary pollutants such as O_3 and $PM_{2.5}$. The average mean concentrations of RSP, SO_2 and MDA8 O_3 (average of TM and KC) are reported as ~55.5 $\mu g/m^3$, ~36.0 $\mu g/m^3$ and ~86.0 $\mu g/m^3$, respectively, with the range of +50% to +153% change in the average mean concentrations. It is observed that the percentage increase for RSP and SO_2 in TM station are much higher than that of KC station, as the seasonal means of TM station are relative low at the background station. However, it should be noted that their absolute changes, in fact, are similar, which echoes the fact that the pollution enhancement is caused by the regional air mass, and not from local emissions. In terms of MDA8 O_3, TM station exhibits much greater enhancement than KC station, as less O_3 scavenging/NOx titration effect is observed in the background station than in the urban station (Chan et al., 1998; Sillman, 1999). Furthermore, as the rural station TM is generally a NOx limited area, when rich precursor emissions (e.g., NOx and reactive VOCs) from PRD reach HK, the non-linear chemistry of O_3 production significantly enhanced the formation of O_3, and as a result, the mean MDA8 O_3 drastically increased from 75.1 $\mu g/m^3$ to 125.9 $\mu g/m^3$ (Jiang et al., 2008; Lee et al., 2014).

In terms of policy implication, Fig. 5 shows the frequencies of exceedance of World Health Organization (WHO) air quality guidelines (AQG) for the difference between "all summer days" and days with TCs in each region. Compared with "all summer days", the exceedance frequencies for those days with TCs in R2 are strongly increased for all three pollutants on both stations, while the exceedance frequencies for days with TCs in R1 and R3 are mostly unchanged or slightly decreased. The increase (average of TM and KC) for RSP, SO_2 and MDA8 O_3 with TCs in R2 are reported as 35% (26 extra days), 16% (18 extra days) and 18.5% (11 extra days), respectively. The increase of exceedance in TM station is usually lower than KC station for RSP and SO_2, while it is higher for MDA8 O_3. This agrees with the early findings on the relationship of concentration difference for those two stations.

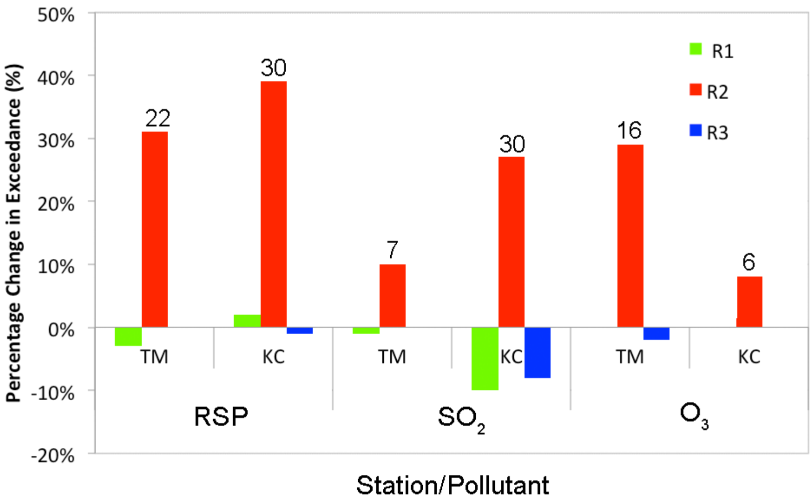

Fig 5. Percentage change of exceedance frequencies of WHO AQG limits (daily avg RSP > 50 $\mu g/m^3$, daily avg SO_2 > 50 $\mu g/m^3$ (Interim target-2), and MDA8 O_3 > 100 $\mu g/m^3$); the numbers on top of the red bar report the extra exceedance when TCs in R2.

3.3. Interdecadal Comparisons of Pollution Trends under the Influence of TCs

Based on the TC data from HKO, the total number of TCs found in the WNP and the adjacent seas bounded by the Equator, 45°N, 100°E and 180°E, and those found in R1, R2 and R3 in the first and second epochs are summarized in Table 1. Comparing epoch 2 with epoch 1, there had been an overall decrease of approximately 9% in the total number of TCs (from 144 to 131). It is observed that the number of TCs found in R1 and R3 also dropped by about 15% (from 39 to 33), and 8% (from 38 to 35), while the number of days in R1 and R3 dropped by 10% (from 87 to 78 days) and 32% (95 to 65 days), respectively. Conversely, both the number of TCs and number of days in R2 has a noticeable increase of about 29% (from 24 to 31), and 51% (from 41 to 62 days), respectively. The increase of TCs occurrence in R2 in the second epoch certainly produces a negative impact on HK air quality, as demonstrated in the early section. Moreover, the increase of average TC residence time (from 1.7 to 2.0 days/event) in R2 may also lengthen the time of air pollution episode. Therefore, it is expected the summer air pollution episode will intensify due to this observed TC track change if the phenomenon continues.

Table 1. Effect of track change from first epoch (1991-2000) to second epoch (2001-2010): Change in number of TCs and change in number of days with TCs in each region

Ep-och	Period	All TCs	R1		R2		R3	
			Number of TC/ Number of days	Avg. days	Number of TC/ Number of days	Avg. days	Number of TC/ Number of days	Avg. days
1	Summer 1991 - 2000	144	39 / 87	2.2	24 / 41	1.7	38 / 95	2.5
2	Summer 2001 - 2010	131	33 / 78	2.3	31 / 62	2.0	35 / 65	1.8
-	% change	-9%	-15% / -10%	+6%	+29% / +51%	+18%	-8% / -32%	-28%

To further understand the impacts of air quality due to the increase of TCs in R2, we have selected SO_2 and O_3 as a probing species to better evaluate their air quality impacts. Fig. 6 shows the trend of mean SO_2 concentration for "all summer days" and R2. Both KC and TM stations with TCs in R2 show a clear increase trend from 1990 to 2005 while a downward trend after 2005. The reduction of SO_2 in 2005 was attributed to the massive installation of flue-gas desulfurization (FGD) system in power generation sector over PRD under the China's 11th Five-Year Plan (2005 to 2010) (Lu et al., 2010). As mentioned before, air quality impact with TCs in R2 is mainly caused by long-range transport from PRD, therefore, SO_2 concentration reduction is more pronounced with TCs in R2 than the "all summer days". In terms of decadal change, the first epoch (38.4 – 30.0 = 8.4 μg/m^3) shows a lower SO_2 incremental enhancement from TCs than in the second epoch (51.1 - 34.8 = 16.3 μg/m^3). This was attributed by the difference in magnitude of the overall SO_2 emissions in PRD on those two periods (emission in first epoch is greater than in second epoch). As China SO_2 emission is highly correlated with HK SO_2 concentrations with TCs in R2 (see Appendix Fig. A1), it is expected that the impact of TCs on SO_2 pollution in HK will eventually be mitigated if SO_2 emissions in China continue to decrease.

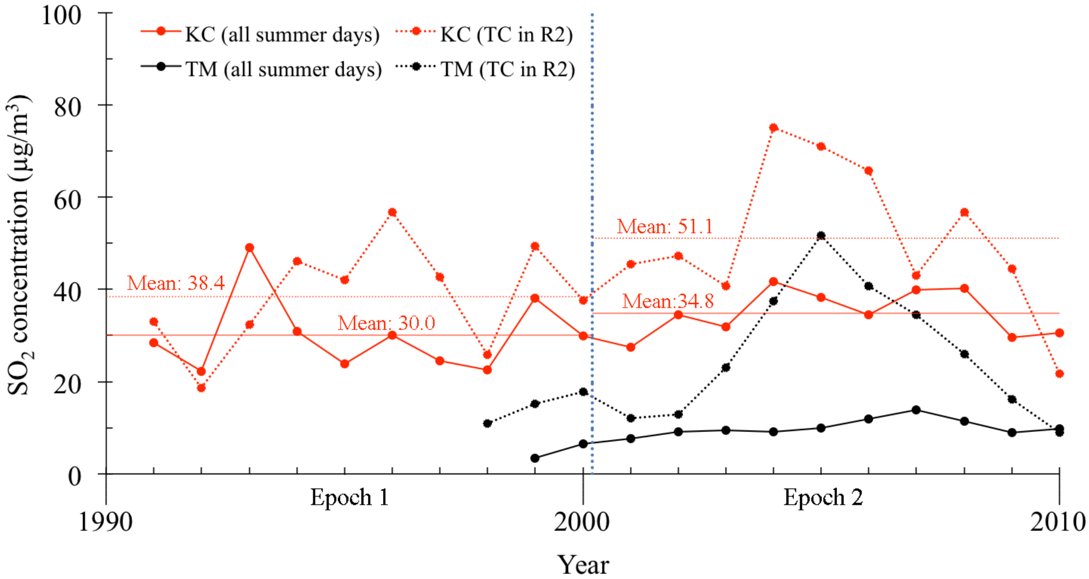

Fig. 6. Mean SO_2 concentrations for all summer days and days with TCs in R2

In terms of ozone, Fig. 7 shows the mean O_3 concentrations for "all summer day" and days with TCs in R2. The mean O_3 concentration in KC station in the second epoch (23.3 μg/m^3) is slightly higher than the mean of 19.8 μg/m^3 in the first. Although there are fluctuations reflecting the variation of the impact of TCs in R2 in different years, no downward trend can be found at the end of the second epoch as in the case for SO_2. Furthermore, linear regression of the mean O_3 concentrations for the TC days show an increasing trend at the rate of approximately 0.5 μg/m^3 per year in KC station and 2.6 μg/m^3 per year in TM station, which are higher than the rate of increase in the mean summer concentrations at 0.3 μg/m^3 and 0.4 μg/m^3 per year in KC and TM stations for the "all summer days" respectively. It is also higher than 0.54 to 0.76 μg/m^3 per year reported by Lee et al. (2014). These results indicate that the impact with TCs in R2 on O_3 concentrations has been increasing from 1991 to 2010 and will become more intense if the trend continues. One of the possible causes of the escalating impact is related to urban heat island effect and global warming, as summer air temperature in HK reaches even higher levels under stagnating high pressure and intense sunlight when TCs are in R2. Another factor that potentially intensifies the TC impact is the change in the concentration levels of O_3 precursors such as NO_x and volatile organic compounds (VOCs), as Lee et al. (2014) reported that the level of VOC emissions (e.g., formaldehyde) in PRD has increased drastically since 2004 (Lee et al., 2014). In urban areas (i.e., KC station) with high NO_x concentrations, the increasing VOC concentrations would amplify the impact of the light northwesterly wind as photochemical formation of O_3 is typically VOC-limited. In remote areas like TM where the reaction is NO_x-limited, increase of the TC impact may similarly result from higher NO_x concentrations when TCs are in R2 (Ling and Guo, 2014).

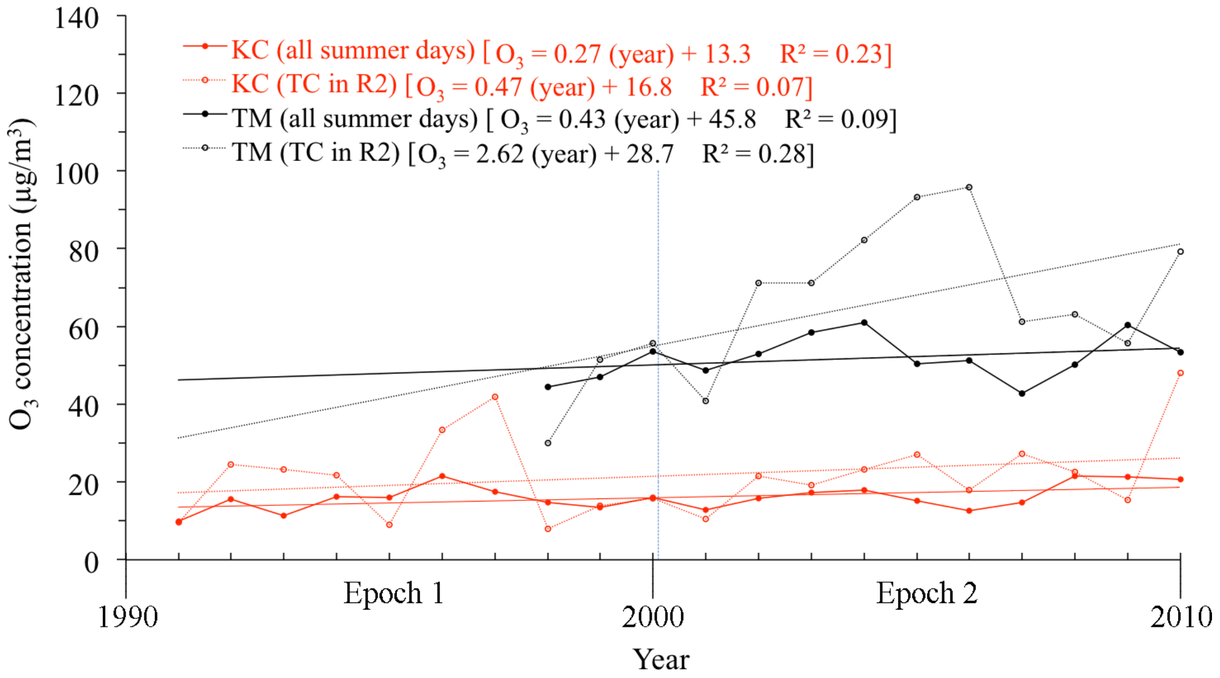

Fig. 7. Annual mean O_3 concentrations for all summer days and days with TCs in R2; the straight lines correspond to the linear regression fit for each case.

4. Conclusions

Based on the changes in TC track density in May to August from epoch 1 (1991-2000) to epoch 2 (2001-2010), an analysis has been performed focusing on the impact of TCs in three regions of interest (R1 in the South China Sea, R2 in the vicinity of Taiwan and R3 in the Philippines Sea) on the air quality of Hong Kong in the summer season. It is found that, from epoch 1 to epoch 2, the number of TCs in R2 was increased by 29% (from 24 to 31), while the numbers of TCs in R1 and R3 were decreased by 15% (from 39 to 33) and 8% (from 38 to 35) respectively. The observation agrees with the prevailing shift of TC activities towards the vicinity of Taiwan in association with the WNP-East Asian climate change (Wu et al., 2005; Tu et al., 2009), and it has been suggested this track change may continue to prevail for a few decades due to global SST anomalies under the influence of global warming or climate change (Wu & Wang, 2004; Wang et al., 2011).

The impact of TCs in the three regions are studied by comparing the RSP, SO_2 and O_3 concentrations based on the HKEPD air quality data from two monitoring stations (TM and KC) to respectively represent the remote and urban areas in Hong Kong. It is found that, on days with TCs in R2 (near Taiwan), obvious increase of pollutant concentrations is observed in both the remote and urban areas (82% and 58% for RSP, 153% and 50% for SO_2 and 68% and 65% for O_3, in TM and KC respectively). The frequencies of exceedance of WHO AQG limits are also increased for days with TCs in R2, indicating that the probability of episode occurrence is most increased when TCs are in this region. These observations show that the impact of TCs on local air quality is highly related to the TC position and the adverse effects are highest when they are in the vicinity of Taiwan. The increased number of TCs in this region resulted in higher impact on Hong Kong's summer air quality in the decade after 2000, and it can be projected that, the impact of TCs will be intensified if the prevailing track change towards Taiwan persists due to global warming or climate change. A summary of conceptual model for the relationship between TC track change and summer pollution episode is shown in Fig. 8.

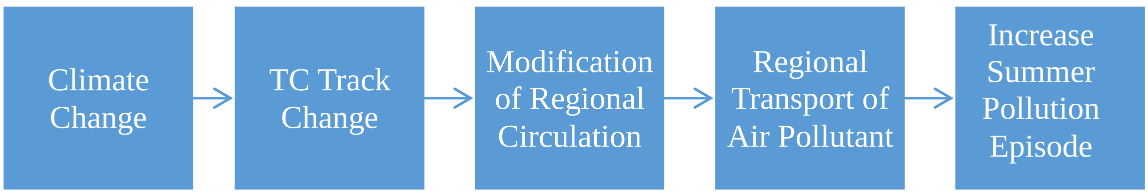

Fig. 8. Summary of conceptual relationship

From the intra-annual variations, it has been found that the elevated concentrations of primary pollutants such as SO_2 on TC-affected days are highly correlated with the emissions in China and PRD due to regional transport of air pollutants by the northwesterly wind. The impact of TCs on SO_2 concentrations escalated after 2000 during the economic boom in PRD and started to decline around 2005. It can be expected the impact on SO_2 concentrations will continue to diminish with reduced SO_2 emission in PRD. For the secondary pollutant O_3, the impact of TCs is related to the meteorological conditions for active photochemical reactions as well as regional transport of O_3 and its precursors. When TCs are in the vicinity of Taiwan, formation and accumulation of O_3 are accelerated by conditions of stagnation, high temperature and intense sunlight under the high pressure systems at the TC peripherals, and at the same time supplemented by the light northwesterly wind that brings in O_3 and O_3

precursors from PRD. As a result, the increase in O_3 concentrations is particularly pronounced and most severe summer O_3 episodes are associated with TCs in this region. Furthermore, the yearly changes show that the mean O_3 concentrations of the days affected by TCs near Taiwan are increasing at a higher rate than the average summer concentrations in both the remote site (i.e., TM) and the urban area (i.e., KC), indicating an increasing TC impact on top of the overall increasing trend of O_3 concentrations. If the circumstances remain unchanged, it can be expected the prevailing TC track change towards the Taiwan region will have an intensifying impact leading to more severe summer O_3 episodes in Hong Kong.

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7. Appendices

Table A1. Top ten MDA8 O_3 concentrations at Tap Mun (TM) from 1998 – 2010.

Rank	MDA8 O_3 ($\mu g/m^3$)	Year	Month	Day	TC Name	TC Position	TC Intensity*
1	337	2006	8	8,9	Bopha	R2, R1	TS/TD
					Saomai	R2	T
2	320	2008	7	28	Fung-wong	R2	T
3	277	2005	7	18, 19	Haitang	R2	T
4	260	2009	7	10	Soudelor	R1	TD/TS
5	257	2005	8	31	Talim	R2	T
6	251	2006	7	24, 25	Kaemi	R2	T/STS/TS
7	248	1999	8	19,20	Sam	R3, R1	TD/STS/T
8	243	2007	5	17	Yutu	R3	STS/T
9	231	2003	6	18	Soudelor	R2	T
10	225	2004	6	9	Conson	R2	T

* T.D. - Tropical Depression has maximum sustained winds of less than 63 km/h; T.S. - Tropical Storm has maximum sustained winds in the range 63-87 km/h; S.T.S. - Severe Tropical Storm has maximum sustained winds in the range 88-117 km/h, and T - Typhoon has maximum sustained winds of 118 km/h or more.

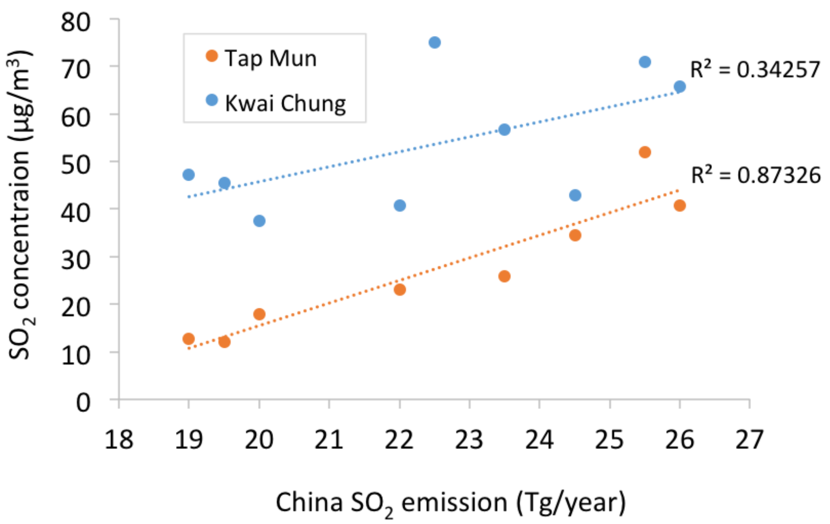

Fig. A1. Mean SO_2 concentrations for days with TCs in R2 vs. yearly China SO_2 emissions (2000 – 2008).