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• **Original Paper** •

Influence of Tropical Cyclones on Hong Kong Air Quality

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ABSTRACT

Tropical cyclones (TCs) constitute one of the major atmospheric activities affecting the air quality of the Pearl River Delta region. In this study, the impact of TCs on air quality in Hong Kong during the TC active season (July–October) from 2000 to 2015 is investigated. It is found that 57.5% of days with concentration of particulate matter with an aerodynamic diameter $\leqslant$ 10 μm (PM_{10}) above the 90th percentile are related to TC activity. TCs in three regions, located to the east, southeast, and southwest of Hong Kong, have obvious impacts on pollutant concentration. When TCs are located east of Hong Kong near Taiwan, 65.5%/38.7% of the days have high or extremely high PM_{10}/ozone (O_3) levels, which are associated with northerly wind, sinking motion, and relatively low precipitation. When TCs are located southeast of Hong Kong, 48.1%/58.2% of the days have high pollution levels, associated mainly with continental air mass transport. When TCs are south or west of Hong Kong, only 20.8%/16.9% of the days have high PM_{10}/O_3 levels, and the air quality in Hong Kong is generally good or normal due to TC-associated precipitation, oceanic air mass transport, and an enhanced rising motion. The higher chance of high O_3 days when TCs are present between Hong Kong and Taiwan, possibly due to lower-than-normal precipitation along the east coast of China under TC circulation. The results in this study highlight the important influence of TC position and associated atmospheric circulations on the air quality in Hong Kong.

Key words: PM_{10}, O_3, air quality, HK, TC

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1. Introduction

Tropical cyclones (TCs) are a frequent atmospheric activity in late summer and early autumn in the western North Pacific (WNP) that can cause economic losses and other problems such as flooding, the collapse of buildings, landslides, and sometimes even deaths. To date, many studies have focused not only on the physical damage that TCs can do, but also on their potential to cause episodes of serious air pollution (Wu et al., 2005; Lee and Savtchenko, 2006; Feng et al., 2007; Wei et al., 2007; Yang et al., 2012), which is especially important for highly developed and urbanized cities.

Air quality has received increasing attention in recent decades, associated with the rapid increase in anthropogenic emissions, especially in rapidly developing regions. In Asia, large amounts of anthropogenic emissions of sulfur, nitrogen, and particulates from biomass burning and energy consumption have been reported by many studies (Husar et al., 1997). This is one of the major reasons for haze and the rapid increase in the concentration of particulate matter (PM) in recent decades. High concentrations of PM can cause serious harm to human health, especially in the respiratory and cardiopulmonary systems. This hazard strongly affects the public, increasing hospital admissions and mortality, and causing even greater harm to both children and the elderly. More than two million premature deaths each year are the result of diseases related to air pollution throughout the world (World Health Organization, 2006). In addition, PM can have an obvious effect on visibility and climate (Davidson et al., 2005) and has been found to be a major cause of low visibility and haze in Hong Kong (Wang, 2003). On the other hand, an increasing number of serious surface ozone (O_3) episodes have been reported recently. Surface O_3 formation is related mainly to anthropogenic activity, but it is not a directly emitted pollutant. O_3 is a secondary pollutant associated with atmospheric chemical reactions with carbon monoxide, nitrogen oxides (NO_x), volatile organic compounds (VOCs), and so on. Certain atmospheric conditions favor O_3 formation, such as light winds and high solar radiation, as has been reported elsewhere (e.g., Colbeck and MacKenzie, 1994; Wang et al., 2001a, 2001b; Lee et al., 2002). However, locally emitted NO_x will sometimes reduce the O_3 concentration. Due to its complex formation, it is not easy to control its occurrence.

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In some cities, O_3 can become one of the dominant pollutants during pollution episodes.

The Pearl River Delta (PRD) is on the southeastern coast of China. This region is recognized as one of the four major regions in China that experience significant haze (Lee and Savtchenko, 2006). With rapid development over the last several decades, the PRD has been transformed into a dense, highly urbanized and highly populated area, causing rapid deterioration of air quality and frequent occurrences of low visibility, with abundant emissions of sulfur dioxide, NO_x, and VOCs (Wang et al., 1998, 2001b; Lai and Sequeira, 2001; Deng et al., 2008). In the past, one of the major pollutants that contributed to poor air quality was PM_{10} (PM with an aerodynamic diameter $\leqslant$ 10 μm). The annual concentration of PM_{10} in Hong Kong at most monitoring stations can reach 55 μg m^{-3}, and the maximum 24-h concentration can exceed 150 μg m^{-3}. Numerical studies have focused on the composition, temporal and spatial variation, and possible sources of the pollutants in this area. Qin et al. (1997) analyzed PM_{10} from 11 air monitoring stations in Hong Kong and reported that about half the PM_{10} by mass is carbonaceous aerosols. A quarter of the mass of PM_{10} consists of sulfate (SO_4^{2-}), ammonium (NH_4^+), and nitrate (NO_3^-), which show an even spatial distribution over Hong Kong because they are mainly from long-distance transport, and 5.7% of the PM_{10} mass is marine aerosols. Ho et al. (2003) analyzed carbonaceous species at industrial, roadside, and rural stations in Hong Kong during winter. Non-sea-salt sulfates accounted for the majority of sulfates measured at all stations, illustrating their anthropogenic source. The ratio of organic carbon (OC) to elemental carbon at rural stations was larger than 3, and the correlation coefficient was high, which was comparable to the correlation between OC and SO_4^{2-}, indicating atmospheric transport of OC with prevailing northeasterly wind during winter. Yuan et al. (2006) studied the composition of PM_{10} from July 1998 to December 2002 using receptor models and positive matrix factorization, and found that about 60% of the PM_{10} mass was from regional sources. Similar results were also observed during pollution episodes in 2003 and 2004 (Lee and Savtchenko, 2006). On the other hand, the increasing trend in O_3 concentration and pollution episodes in the PRD in recent decades has prompted many studies. Wang et al. (2009) pointed out that there was an increasing trend in O_3 concentration in the coastal area around Hong Kong from 1994 to 2007. This increasing concentration was probably contributed by northern coastal regions of China, with increasing atmospheric NO_2 observed by Global Ozone Monitoring Experiment (GOME) and Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY). Except for background transport to the PRD, some studies of O_3 episodes have suggested that the emission of local O_3 precursors could play an important role (Jiang et al., 2010; Shen et al., 2015).

Air quality deterioration is not only associated with abundant emissions; meteorological conditions are another important factor associated with air quality. For example, the monsoon, a well-known circulation system with seasonally changing wind, moisture, precipitation, and cloud formation, can have an important influence on pollutant formation, dispersion, and transport (Chan and Chan, 2000; Lam et al., 2001; Zhao et al., 2010; Hien et al., 2011; Kim et al., 2013). In Hong Kong, seasonal variations of PM_{10} and O_3 have been observed in previous studies (Qin et al., 1997; Chan et al., 1998; Cheng et al., 2000; Wang et al., 2001a, 2001b; Yu et al., 2004; Louie et al., 2005; Wang and Lu, 2006). Stable atmospheric conditions and a continual flow of anthropogenic emissions generally occur in winter, leading to worse air quality than unstable and oceanic air masses in summer. Except for the seasonal variation of meteorological conditions, dust transport and TCs can cause rapid deterioration of air quality at synoptic or intraseasonal scales. Dust can be transported from the Gobi, Arabian, and Sahara deserts (Lee et al., 2010), and although it rarely influences air quality in Hong Kong because of the long distance it must travel, it will sometimes influence severe pollution episodes. Serious dust transport that occurred in March 2010 caused the PM_{10} concentration to reach 500 μg m^{-3}. TCs occur frequently in the WNP in summer and autumn every year. Visibility impairment and rapid increases in aerosols and O_3 associated with TC activity have been observed in numerical studies in recent years. TC-associated pollution episodes can sometimes be on a regional scale, simultaneously causing severe pollution in several cities on the PRD (Wu et al., 2005; Feng et al., 2007; Yang et al., 2012). A locally stable atmosphere with a low boundary layer is usually reported in these studies, along with the advection of regional pollutant transport. Although the impacts of TCs on Hong Kong or the PRD have been extensively studied, the relationship between TC position and the mechanisms that contribute to the occurrence of pollution episodes is still unclear. Therefore, a comprehensive analysis to assess the variability of pollution levels during TC activity is needed. In this study, we attempt to analyze PM_{10} and O_3 concentration during TC events in 2000–2015 and discuss the potential probability of TC-induced pollution episodes in Hong Kong. This can give us a deeper understanding of the variability of air quality and potential changes in the future.

2. Data and methodology

The influence of TCs on daily air quality from July to October in 2000–2015 is the focus of this study. We use the Joint Typhoon Warning Center Best Track Data to obtain TC tracks and locations. This is a six-hourly instantaneous data product, giving updated TC data at 0000, 0600, 1200, and 1800 UTC. Since daily concentrations are used throughout the study, we pick TC positions at 1200 UTC, the middle of the day, to represent daily TC positions. During the study period, when a TC is found within the oceanic region of East Asia (5°–30°N, 100°E-130°E), the day is defined as a TC-involved day (TC-day); otherwise, it is a no-TC-involved day (NTC-day).

Hourly PM_{10} and O_3 concentrations (in μg m^{-3}) at monitoring stations located at Tap Mun and Sham Shui Po, and the

Table 1. Annual mean PM_{10} concentration during 2000–2015 over Hong Kong.

Station	Latitude (°N)	Longitude (°E)	Area type	Mean PM_{10} concentration ($\mu g\ m^{-3}$)
Central/western	22.28	114.14	Urban	49.7
Eastern	22.28	114.22	Urban	44.5
Kwai Chung	22.36	114.13	Urban	50.5
Kwun Tong	22.31	114.23	Urban	51.6
Sham Shui Po	22.33	114.16	Urban	50.5
Sha Tin	22.38	114.18	New Town	47.2
Tai Po	22.45	114.16	New Town	47.3
Tap Mun	22.47	114.36	Rural	45.2
Tsuen Wan	22.37	114.11	Urban	50.9
Tung Chung	22.29	113.94	New Town	48.5
Yuen Long	22.44	114.02	New Town	56.1
Causeway Bay	22.28	114.19	Urban Roadside	76.1
Central	22.28	114.16	Urban Roadside	62.4
Mong Kok	22.32	114.17	Urban Roadside	60.5

PM_{10} concentration data at Mong Kok during July–October are available and collected from the Hong Kong Environmental Protection Department (HKEPD). An annual mean PM_{10} concentration measured over all the air monitoring station is illustrated as Table 1, which showing spatial variations of PM_{10} concentration. Tap Mun is in a rural area northeast of Hong Kong and is generally used as a background monitoring station for remote pollutant transport. The height of the measurement is 11 m above the ground. The other measurements, from Sham Shui Po and Mong Kok, are used to monitor the air quality in urban and roadside areas, respectively. The daily pollutant concentration is defined by the daily average of hourly data. To improve the data quality, daily data converted from two or more missing hourly data are excluded.

In order to understand the impacts of TCs on the large-scale circulation in the WNP and on the air quality in Hong Kong, several meteorological fields are used to explore the changes. Daily mean wind, vertical motion, and geopotential height are collected from NCAR–NCEP Reanalysis-1 with a $2.5° \times 2.5°$ horizontal resolution. Precipitation data are collected from the Global Precipitation Climatology Project, version 1.2. This dataset provides daily precipitation data with a $1° \times 1°$ horizontal resolution. For local observations, sounding data from the Hong Kong observatory at King Park, taken two times per day, at 0000 UTC (0800 LST) and 1200 UTC (2000 LST), are used to provide vertical meteorological profiles.

In addition to an immediate relationship between atmospheric circulation and air quality, pollutants can also be transported remotely. Backward air mass trajectories can help demonstrate the remote location of pollutant sources along the air mass movement. Backward air mass trajectories of 36 h are calculated using the NOAA HYSPLIT model driven by the NCEP Reanalysis-1 (Draxler and Hess, 1997). The HYSPLIT model has been extensively used for pollutant and aerosol studies, as well as moisture-related analysis (Lee et al., 2004; Strong et al., 2007; Ding et al., 2013; Stein et al., 2015). Since the highest elevation in Hong Kong is above 957 m, the end points of the trajectories are set at 1000 m altitude to avoid simulation errors. The simulations provide trajectories four times per day, which are averaged to represent the daily mean air mass trajectories used in this study.

3. Results

3.1. *Characteristics of PM_{10} and O_3 during the TC season*

In the time series of PM_{10} and O_3 concentration at Tap Mun station during 2000–2015 from July to October (JASO), variation can be separated into seasonal variation and high-frequency variation by daily climatology and linear regression, as shown in Fig. 1. From the subtracted time series, the mean PM_{10} concentration increases from July, with about 20 $\mu g\ m^{-3}$, to October, with about 70 $\mu g\ m^{-3}$, illustrating an obvious seasonal variation of PM_{10}. Some of the chemical components in PM_{10}, such as SO_4^{2-}, NH_4^+, and NO_3^-, have shown similar variation patterns, with a high in winter and a low in summer, in previous studies (Qin et al., 1997). This seasonal variation pattern of PM_{10} is also observed at Sham Shui Po and Mong Kok stations (data not shown). In long-term variation, after filtering the seasonal variation, weak decreasing trends are observed. The decreasing trend in urban areas is larger than that in rural areas, which may be the result of efforts to reduce emissions in Hong Kong and nearby regions. In Hong Kong, HKEPD introduced several measures to reduce pollutant emissions, such as phasing out Pre-Euro IV Diesel commercial vehicles, installing emission reduction devices in power plants, and using natural gas for power generation. The rest of the PM_{10} variations from the seasonal and long-term linear trend shown in Fig. 1b range mainly from −25 $\mu g\ m^{-3}$ to 40 $\mu g\ m^{-3}$, covering 90% of the data, and the maximum and minimum reach 102 $\mu g\ m^{-3}$ and −50 $\mu g\ m^{-3}$. These variations could be related to some kind of high-frequency variation compared to the seasonal scale.

In addition to the PM_{10} variation, an obvious seasonal variation is also found in the subtracted time series of the O_3 concentration. The O_3 concentration increases from 40 $\mu g\ m^{-3}$ in July to 100 $\mu g\ m^{-3}$ in October. Such variation has also been observed in a previous study (Wang et al., 2001b). On the other hand, a difference in the long-term trend between PM_{10} and O_3 is observed. Generally, a high concentration of PM_{10} is observed during 2004 to 2008 and decreases in later years, while high O_3 concentrations seem to occur in the later years of the time series. Linear regression shows that the O_3 concentration increases by 0.418 $\mu g\ m^{-3}\ yr^{-1}$, which agrees with the increasing O_3 concentration found in a previous study (Wang et al., 2009). In the high-frequency variation, the range of O_3 with 90% of the data is between −40 $\mu g\ m^{-3}$ and 50 $\mu g\ m^{-3}$, and the minimum and maximum are −88 $\mu g\ m^{-3}$ and 122 $\mu g\ m^{-3}$, respectively.

TCs may be one of the major factors contributing to such high-frequency variation. A case study showing the time series of anomalous PM_{10} and O_3 concentration in Hong Kong

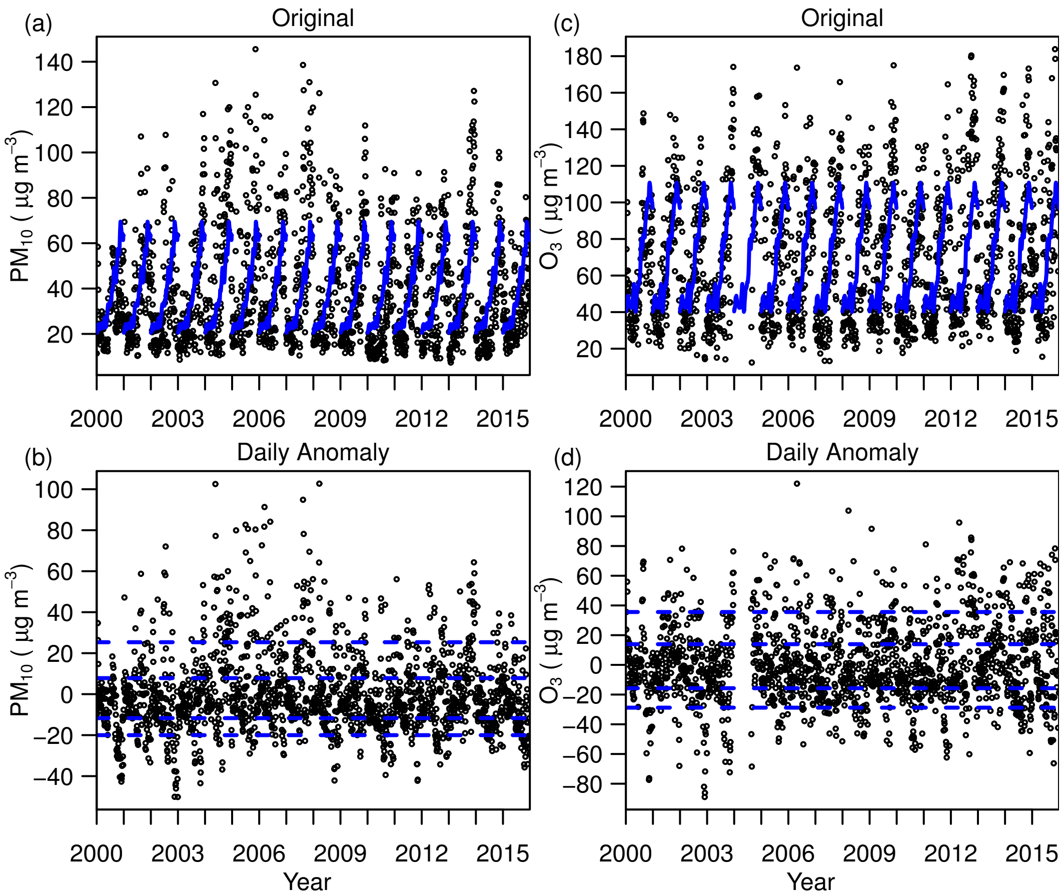

Fig. 1. Time series of the daily PM_{10} concentration (units: µg m^{-3}) at Tap Mun based on the (a) original data and (b) detrended daily anomaly, from July to October 2000–15. (c, d) As in (a, b) but showing the daily O_3 concentration. The blue solid lines in (a, c) represent the daily climatology. The four blue horizontal dashed lines from low concentration to high concentration in (b, d) represent the 10th, 25th, 75th and 90th percentile, respectively.

with TC activity from 10 September 2008 to 15 September 2008 is illustrated in Fig. 2. The time series is separated into two periods: phase 1 without TC activity, and phase 2 with TC activity. Although Mong Kok is a roadside station where concentrations are highly affected by traffic emissions, it is still found that the daily concentrations at Tap Mun, Sham Shui Po, and Mong Kok along the time series show similar levels and variation after a data separation method is applied. During phase 1, the pollutant concentration is steady within a normal level, and no TC is observed during these days. On 8 September 2008, a TC is generated in the WNP. The concentration in the following days shows a rapid increase from normal to extremely high, with about a 40 µg m^{-3} increase, in which the TC moves toward the northern WNP. The concentrations remain high for several days until the TC moves northeast and leaves Hong Kong. A similar variation is also observed in the O_3 concentration at Sham Shui Po. Many case studies have reported variation in pollutant concentrations and aerosols during the approach of TCs. Feng et al. (2007) showed that when Typhoon Melor arrived, the PM_{10} concentration (visibility) become higher (lower) due to the horizontal transport of upstream inland emissions to the coastal PRD region. Similar conditions were also found in observations of visibility and MODIS satellite measurements in Guangzhou (Wu et al., 2005).

TC influence is also apparent outside of individual cases. During the study period, 191 TCs entered coastal and nearby oceanic regions of East Asia (5°–30°N), giving 765 TC-days out of 1968 days in this period. A probability density function (PDF) is used to show the difference between the residual PM_{10} and O_3 concentration in TC-days and that in NTC-days, as shown in Fig. 3. It is obvious that the difference in concentration distribution in TC-days is shifted to the right compared to that in NTC-days, showing that TC-days generally have a higher PM_{10} concentration than NTC-days. The difference in the two groups of daily concentration reaches the 0.01 significance level in the Student's *t*-test and Wilcoxon rank-sum test, showing distinguishable concentration distribution characteristics. Similar to the results of the case study, comparable results of the distribution of PM_{10} concentration with the two other stations are observed, which means that TC influence is not only apparent at the

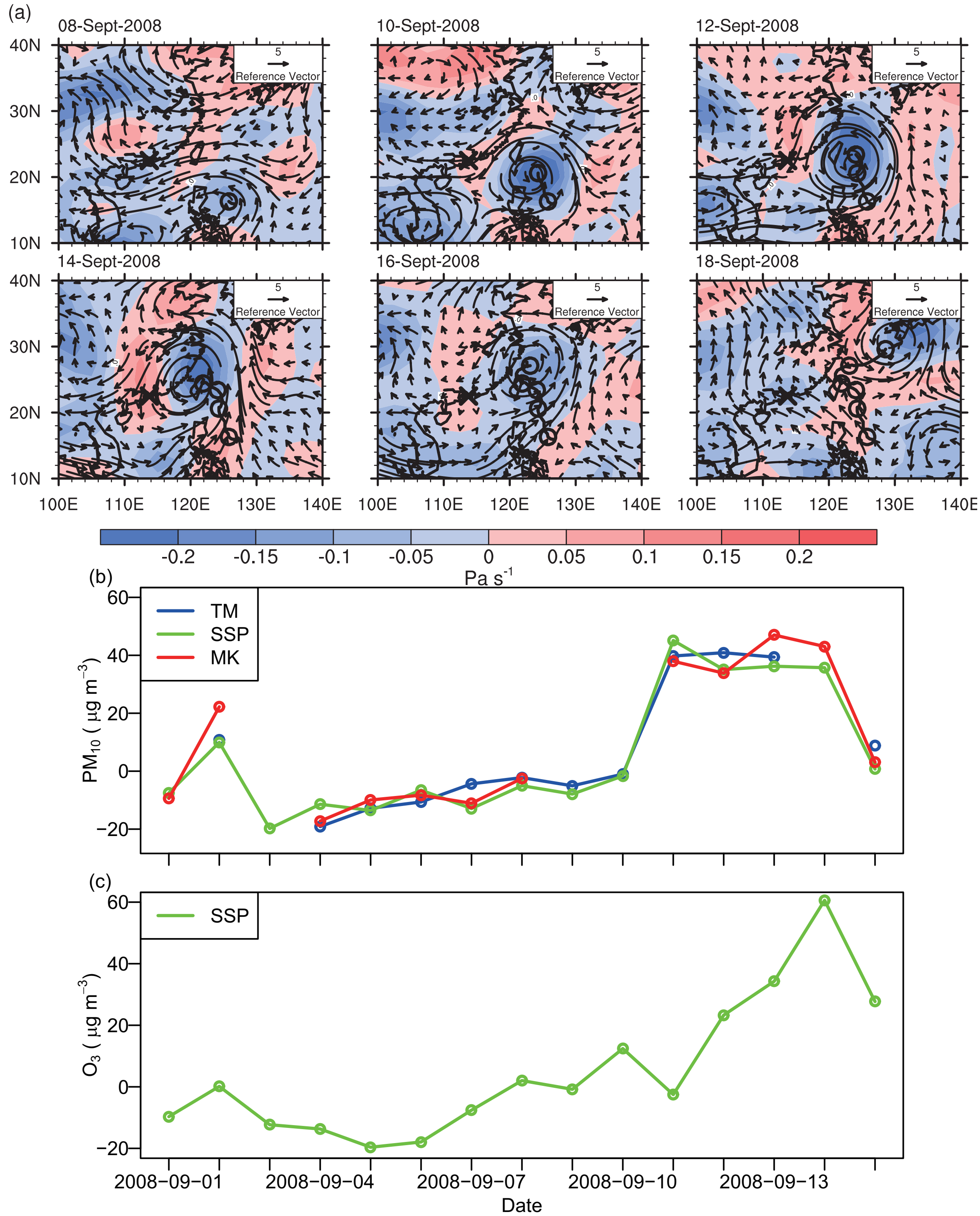

Fig. 2. The (a) atmospheric conditions during Typhoon Sinlaku during 8–18 September 2008, and the (b, c) time series of the (b) anomalous PM_{10} concentration (units: $\mu g\ m^{-3}$) and (c) anomalous O_3 concentration (units: $\mu g\ m^{-3}$) during 1–15 September 2008. The shading and vectors in (a) denote vertical velocity (units: Pa s^{-1}) and horizontal wind velocity (m s^{-1}), respectively. TM, SSP, and MK in (b, c) represent observations from Tap Mun, Sham Shui Po, and Mong Kok stations, respectively.

rural station, but also has an overall impact on Hong Kong.

To deepen our understanding of the influence of TCs on Hong Kong air quality, the involvement of TCs at different pollution levels of PM_{10} and O_3 are shown in Table 2 and 3 respectively. Pollutant concentration is separated into five groups according to percentiles. The levels are extremely low, low, medium, high, and extremely high, with percentile ranges of 1st–10th, 10th–25th, 25th–75th, 75th–90th, and

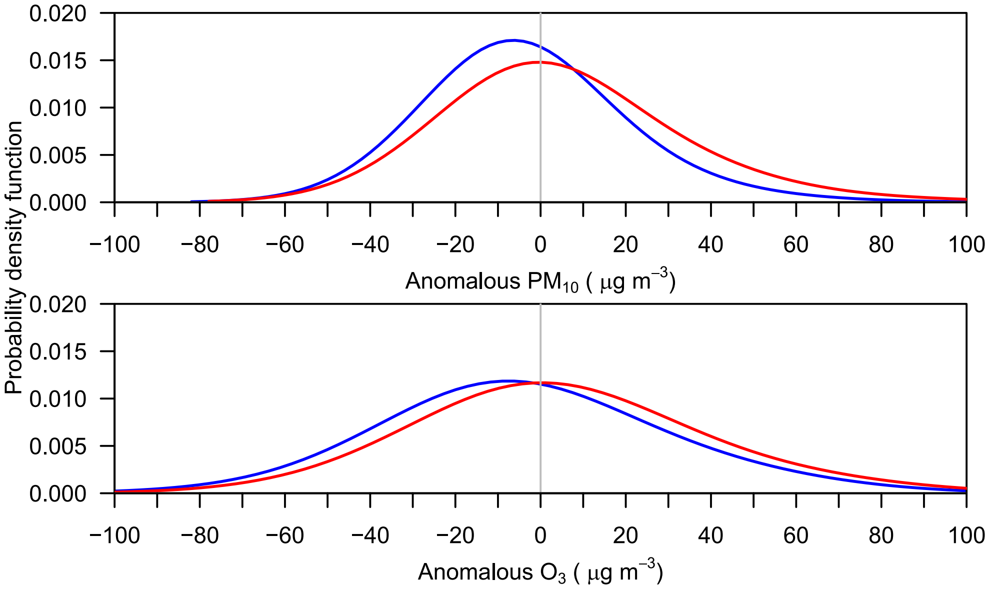

Fig. 3. PDF of the PM_{10} and O_3 concentration (units: μg m^{-3}) on TC-days (red) and non-TC days (blue) during JASO from 2000 to 2015.

Table 2. Occurrence frequency of TC days with different PM_{10} levels.

Pollution level	Percentile range	Number of days	Number of days with TC activity	
Extremely low	1st–10th	178	44	(24.7%)
Low	10th–25th	267	72	(27.0%)
Medium	25th–75th	877	319	(36.4%)
High	75th–90th	262	113	(43.1%)
Extremely high	90th–100th	174	100	(57.5%)

Table 3. As in Table 2 but showing O_3 levels.

Pollution level	Percentile range	Number of days	Number of days with TC activity	
Extremely low	1st–10th	164	49	(29.9%)
Low	10th–25th	248	63	(25.4%)
Medium	25th–75th	802	304	(37.9%)
High	75th–90th	239	113	(47.3%)
Extremely high	90th–100th	164	73	(44.5%)

90th–100th, respectively. PM_{10}/O_3 increases obviously with TC occurrence, from 24.7%/29.9% at the extremely low pollution level to 57.5%/44.5% at the extremely high pollution level, illustrating a close relationship between TCs and pollution levels during this period. The location of TC distribution and different pollution levels is demonstrated in Fig. 4. Obvious TC distributions associated with pollution levels are found. At the extremely high PM_{10} and O_3 levels, a condensed TC distribution pattern is observed, located in Taiwan and the nearby region, and the rest of the TCs at this level are irregularly distributed in the South China Sea. A similar pattern is found at the high PM_{10} level, but the pattern is shifted southwestward compared to the extremely high pollution level. At the high O_3 level, the pattern is located mainly in the ocean south of Taiwan. At a medium pollution level, within the range of the 25th–75th percentile, TCs are distributed mainly within 15°–20°N. While some are at the eastern boundary of the study domain, these are too far away from Hong Kong and would have no significant impact on Hong Kong air pollution. For lower pollution levels, the TC distribution is still mainly within 15°–20°N, but the distribution is shifted west, mainly to the south and southwest of Hong Kong, as shown in the probability density by the contour lines. This distribution is more concentrated in the lowest pollution levels. Based on such a TC distribution at different pollution levels and the distance to Hong Kong, three regions are chosen: Taiwan and nearby areas (region 1), southwest of Taiwan (region 2), and southwest of Hong Kong (region 3), and the associated impact of TCs in each region on air quality in Hong Kong is studied in depth.

3.2. *Distinct pollution levels with three TC regions and associated atmospheric conditions*

The frequency of occurrence and the PM_{10} levels associated with TCs located in the defined regions are shown in Table 4. Considering the impacts of all TCs on air quality, it is found that the extremely high pollution level is dominant with TCs in region 1; up to 37.2% of the TC-days are in the extremely high pollution level, and fewer than 6% of the TC-days are at the low and extremely low pollution levels. The occurrence of pollution levels with TCs in region 2 is dominant at higher pollution levels over the 75th percentile and at the medium pollution level, but the percentage of TC-days at the extreme pollution level is less than in region 1. The pollution level with TCs in region 3 is dominant at the medium level, with 50% of the TC-days. The number of extremely

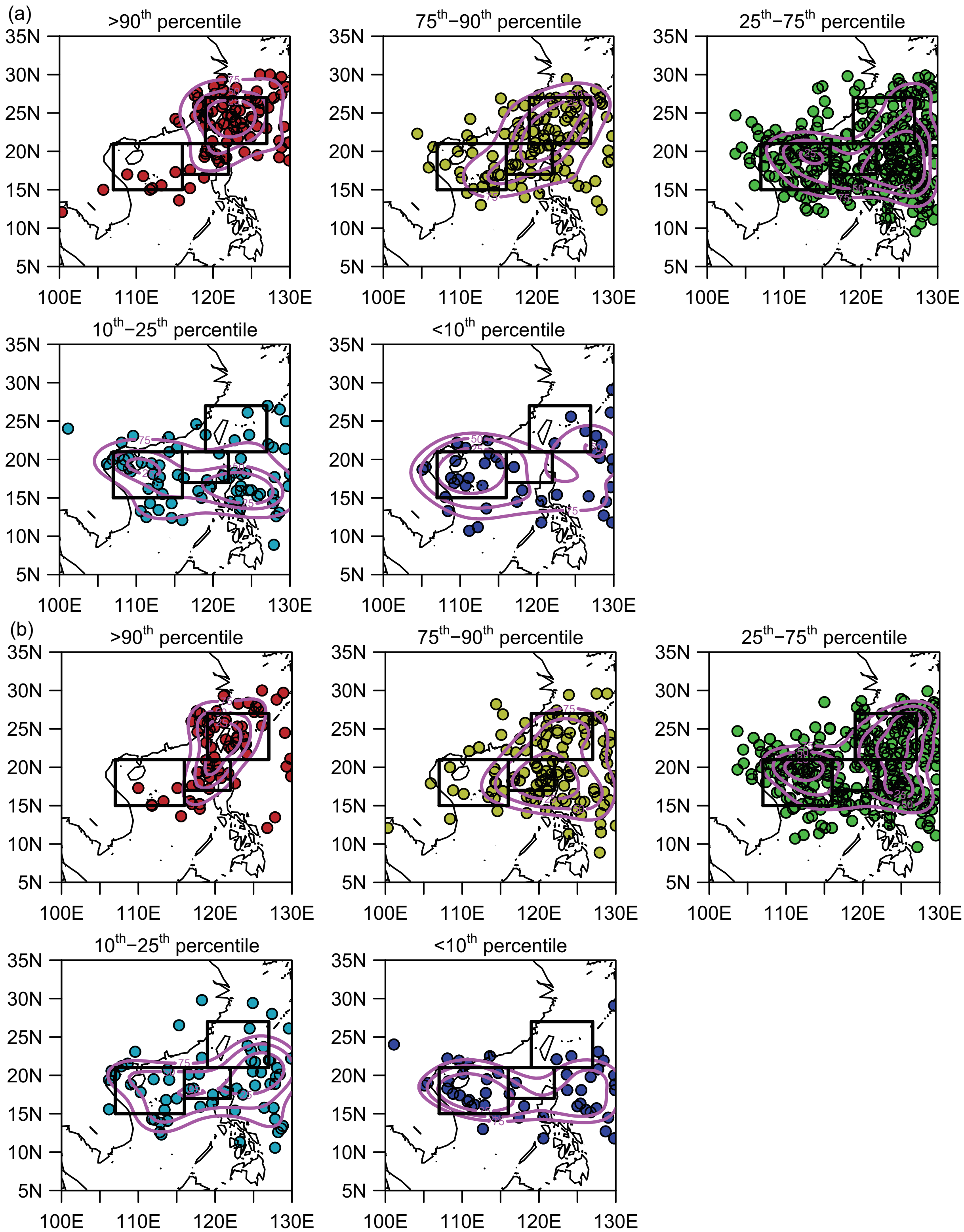

Fig. 4. Location of TCs associated with (a) anomalous PM_{10} levels and (b) anomalous O_3 levels, at Tap Mun. The pink lines represent the probability density of TC occurrence with intervals of 0.25, 0.5, and 0.75 from inner to outer, respectively. Black boxes from east to west denotes obvious TC distributed regions during extreme high, high and low pollution levels accordingly.

low pollution days is greater than that of the extremely high pollution days, generally giving low to medium pollution levels. While the relationship between TC position and O_3 level is shown in Table 5, the distribution is slightly different compared to that with PM_{10} levels. It is found that the frequency of extremely high O_3 levels is associated mainly with TCs in region 2, with 27.3%, compared to that in region 1, with 20.8%, and the second highest rank of O_3 levels in region

Table 4. Occurrence frequency and PM_{10} levels during days when TCs were located in Taiwan and nearby areas (21°–27°N, 119°–127°E), southwest of Taiwan (17°–21°N, 116°–122°E), and southwest of Hong Kong (15°–21°N, 107°–116°E), named region 1, region 2, and region 3, respectively.

	Region 1		Region 2		Region 3	
Extremely high	42	(37.2%)	12	(22.2%)	5	(5.2%)
High	32	(28.3%)	14	(25.9%)	15	(15.6%)
Medium	33	(29.2%)	23	(42.6%)	48	(50.0%)
Low	3	(2.7%)	4	(7.4%)	16	(16.7%)
Extremely low	3	(2.7%)	1	(1.9%)	12	(12.5%)
Total	113		54		96	

Table 5. As in Table 4 but showing O_3 levels.

	Region 1		Region 2		Region 3	
Extremely high	22	(20.8%)	15	(27.3%)	4	(4.5%)
High	19	(17.9%)	17	(30.9%)	11	(12.4%)
Medium	56	(52.8%)	15	(27.3%)	53	(59.6%)
Low	7	(6.6%)	6	(11.0%)	8	(9.0%)
Extremely low	2	(1.9%)	2	(3.6%)	13	(14.6%)
Total	106		55		89	

2/region 1 is 30.9%/17.9%. The total ratio of frequency days with O_3 concentration in the upper quantile is 58.2%/38.7%, with TCs located in region 2/region 1.

A composite of anomalous atmospheric circulations with TCs in the different regions is shown in Fig. 5. The impacts of the TCs here are illustrated by vertical and horizontal motion. With the presence of TCs in region 1, TC-associated anomalous cyclonic flows over the WNP are observed. The circulation can bring anomalous northerly wind to its western area, in which Hong Kong will suffer continual outflow from China, as shown in Fig. 6, which increases continental and regional pollutant transport. On the other hand, anomalous sinking motion in southern China is observed, which leads to calm atmospheric conditions. The precipitation shown in Fig. 7 illustrates consistent results; with anomalous sinking motion, significantly less precipitation than normal is observed when TCs are located in region 1. Therefore, there is less possibility of precipitation and wet deposition that can affect the air quality in Hong Kong. Figure 8 shows a general vertical profile at King Park with TCs in the three defined regions. The mean wind flow with TCs in region 1 in the low-level atmosphere has a direction comparable to that in the wind fields in Fig. 6. On the other hand, stability, derived by the vertical temperature profile, is higher near the surface, which provides evidence that vertical pollutant dispersion is weaker in this condition, which favors increasing pollutant concentrations.

When TCs are located in region 2, the center of the anomalous cyclonic flow is located southwest of Taiwan. Due to the position of the TCs, the wind direction in Hong Kong becomes northeasterly. The mean trajectories show that it comes mainly from the southeastern coastal regions of the Chinese mainland to Hong Kong. In addition, precipitation in Hong Kong and nearby regions becomes insignificant compared with that when TCs are in region 1. Except for local precipitation, it is also found that the anomalous precipitation north of Hong Kong is significantly less than normal. This is one of the important conditions contributing to higher O_3 concentrations with TCs in region 2. Following Wang et al. (2009), the coastal region of eastern China is generally a region of high NO_2 density. The lower-than-normal precipitation that accompanies the northeasterly coastal wind flow with TCs in region 2 would enhance more super-regional transport.

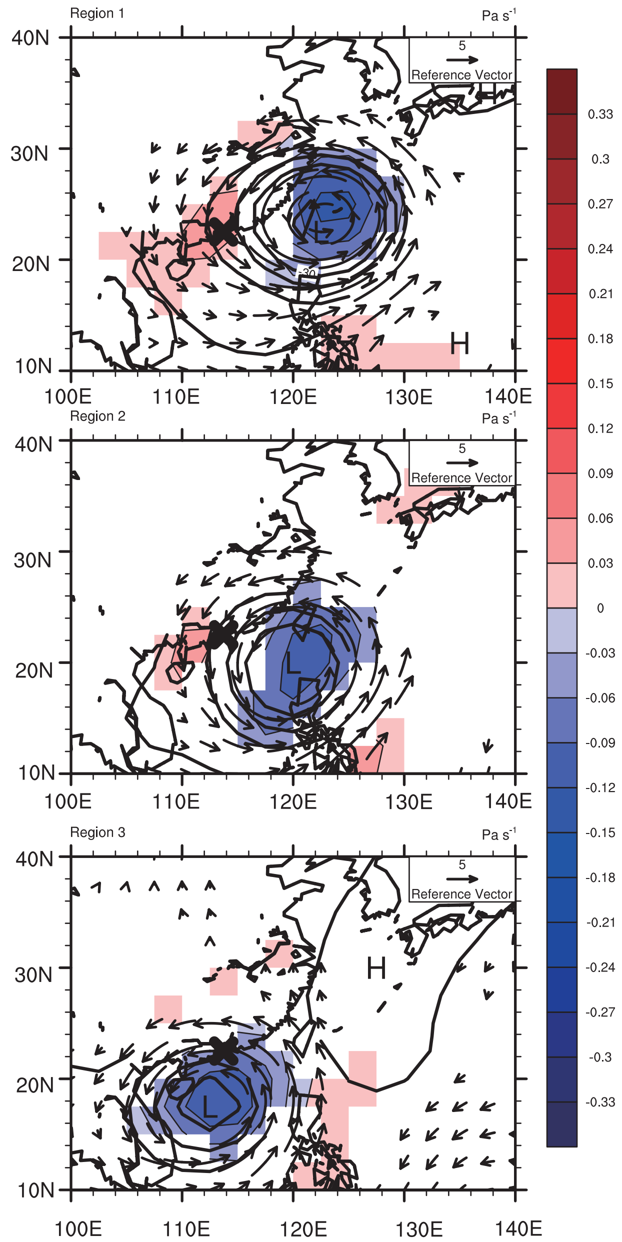

Fig. 5. Anomalous atmospheric conditions at 850 hPa showing the wind flow (units: m s^{-1}) and vertical motion (Pa s^{-1}) with TCs in three regions as defined by vectors and colored shading, respectively. Only signals exceeding the 0.1 significance level are presented.

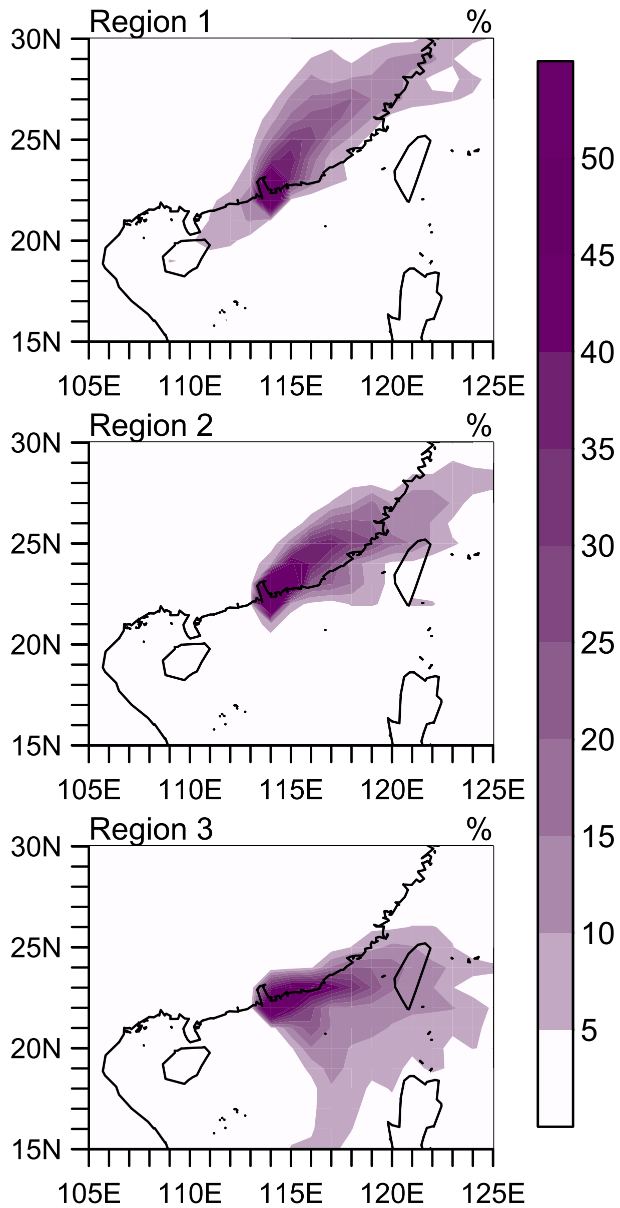

Fig. 6. Similar to Fig. 5 but showing mean air mass trajectories at 1000 m. Shading represents the trajectory frequency (%) of air masses approaching Hong Kong with TCs in three regions.

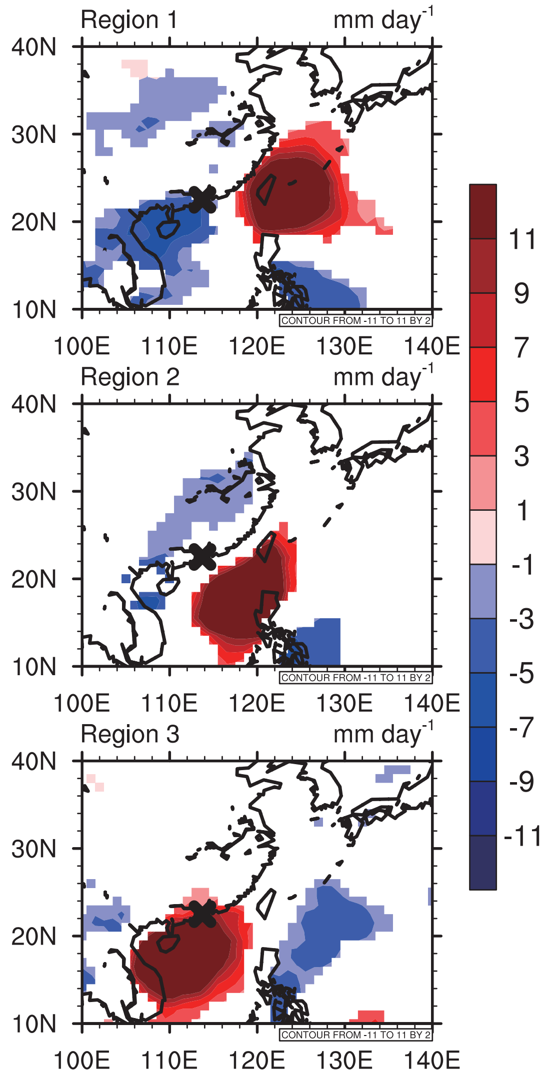

Fig. 7. Similar to Fig. 5 but showing anomalous precipitation. Only signals exceeding the 0.1 significance level are presented.

When TCs are located in region 3, with cyclonic flow southwest of Hong Kong, an easterly anomalous wind flow is observed. The oceanic air mass generally brings fewer pollutants compared with the continental air mass and the mixed air mass with TCs in regions 1 and 2, respectively, which leads to lower pollution levels in Hong Kong. On the other hand, wind speed is also larger than when TCs are in regions 1 or 2 because of the flat sea surface compared to the roughness of the land, which provides less frictional force to the flow, and it is relatively easy to blow out the local or continental pollutants. In addition, due to TCs being close to Hong Kong, TC-associated circulation will bring more precipitation, representing a greater ability to remove ambient pollutants. In addition to local weather conditions, a composite high-pressure system is observed northeast of Taiwan, which may not be related to local meteorological conditions in Hong Kong but can control the position of TCs.

4. Summary

TCs have a significant impact on air quality in Hong Kong. Although TCs can also enhance the occurrence of high PM_{10} and O_3 days, the mechanism due to TC activity shows a slight difference. Based on pollution levels at Tap Mun, it is suggested that the impact of TCs on air quality can be separated based on TC location. Three defined regions, located east, southeast, and southwest of Hong Kong in the WNP, are chosen to analyze the different impacts and mechanisms of TCs on air quality in Hong Kong. When TCs are located in Taiwan and nearby regions, 65.5% of the days have high or extremely high PM_{10} levels. The atmospheric influence of TCs within this region favors vertical sinking motion, continental wind flow, and less precipitation, which cause high

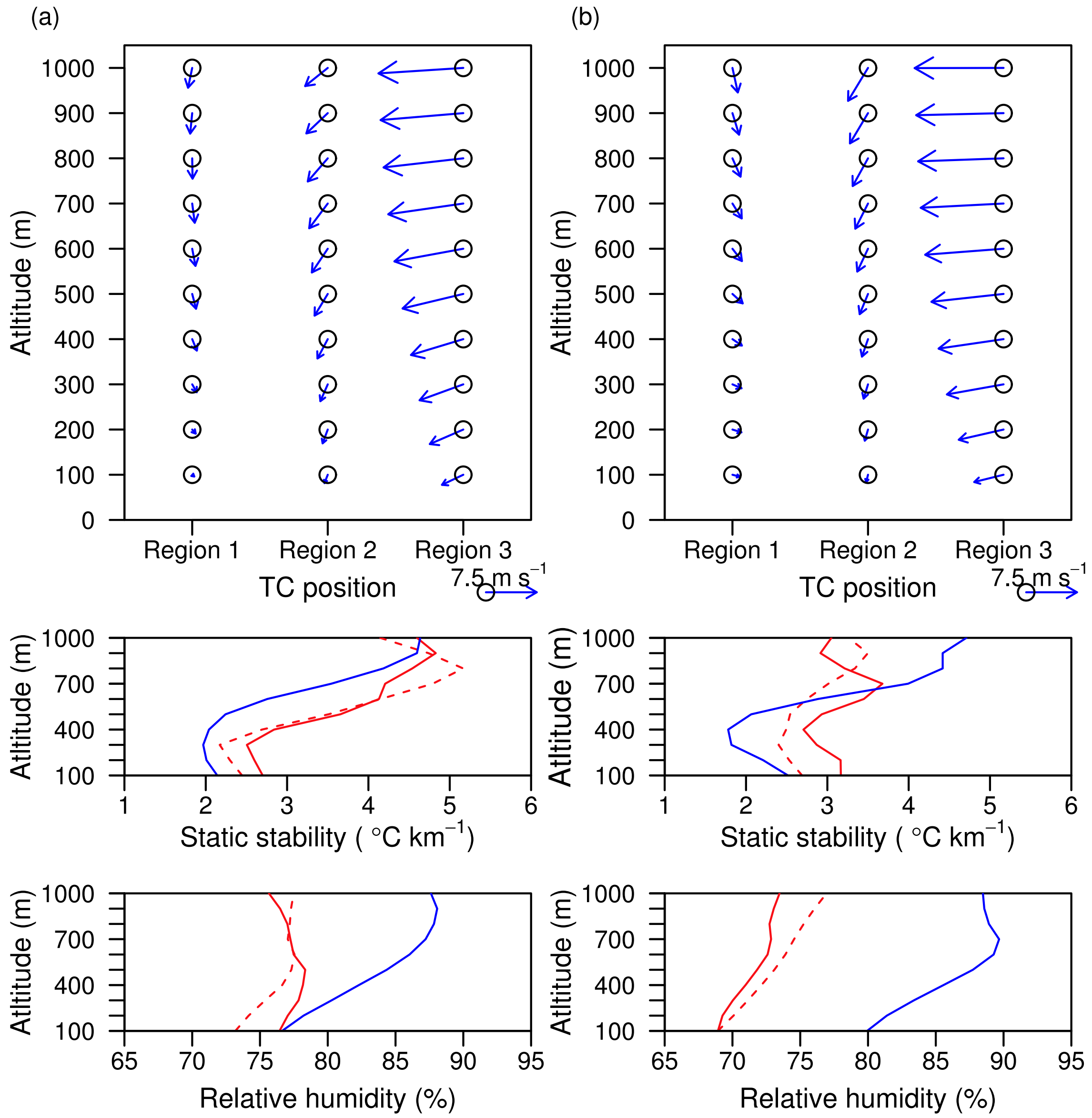

Fig. 8. Mean vertical wind profiles (units: m s^{-1}), static stability (units: °C km^{-1}), and relative humidity (%) with TCs in different regions at (a) 0000 UTC (0800 LST) and (b) 1200 UTC (2000 LST). The red solid lines, red dashed lines, and blue solid lines represent TCs in region 1, region 2, and region 3, respectively.

pollution levels during the study period. On the other hand, high stability near the surface is dominant, which will trap the local pollutants at the surface and favor pollution accumulation. With the addition of these effects, TCs located in Taiwan and nearby regions will always lead to high pollution levels in Hong Kong. When TCs are located between Hong Kong and Taiwan, the sinking motion and precipitation do not lead to significant results, which may be associated with the variability of TC intensity and the distance to Hong Kong. In this condition, the northerly coastal flow is dominant, which leads to medium to high PM_{10} concentrations in Hong Kong. On the other hand, the relationship between O_3 and TC region is different from that with PM_{10} pollution. A lower-than-normal precipitation pattern is observed when TCs are in region 2. Accompanied by northeasterly coastal flow, 58.2% of days have extremely high or high O_3 levels, compared to 38.7% with TCs in region 1. When TCs are south or west of Hong Kong, the air quality in Hong Kong is generally good or normal, because when TCs are close to Hong Kong, the associated precipitation, oceanic air mass transport, and vertical rising motion favor pollutant dispersion. This study not only explores the influence of TC position on the major air pollutants PM_{10} and O_3 in Hong Kong, but also shows the difference with respect to TC position.

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