Combined Impact of Tropical Cyclones and Surrounding Circulations on Regional Haze-Fog in Northern China

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ABSTRACT

Some haze-fog events in Asia have been attributed to tropical cyclone activity; however, uncertainty exists regarding the relationship between the influence of tropical cyclones and the occurrence of haze-fog events. In this study, the statistical relationship between tropical cyclones in the Northwest Pacific and the haze-fog events in northern China during summers from 2001 to 2012 were analyzed. It was found that 30.5% of regional haze-fog events were related to tropical cyclones. The influence of tropical cyclones on haze-fog events was analyzed and compared based on classification of tropical cyclones by position and path. The results showed that tropical cyclones can form advantageous conditions for regional haze-fog events through dynamic and thermal processes, such as strengthening the downdraft, and increasing relative humidity and stability. The dynamic influence was dominant when the distance between a tropical cyclone and northern China was larger than the range of tropical cyclone airflow, and the contribution of thermal influence increased as the distance decreased. Furthermore, the surrounding circulations, such as the Northwest Pacific subtropical high and the westerly trough, also contributed to the regional haze-fog events. Their position, intensity and collocation with tropical cyclones could be the determining factors for haze-fog occurrence. This study illuminates the primary mechanisms of the combined effect of tropical cyclones and the surrounding circulations on regional air quality, which could improve forecasts of summer regional haze-fog events in northern China.

Keywords: Haze-fog; Tropical cyclone; Circulation; Northwest Pacific subtropical high; Westerly trough.

INTRODUCTION

Haze and fog are two weather phenomena that can lead to low visibility, and they are deeply concerning for both the public and researchers due to their threat to human health and negative impact on transportation (Cools et al., 2010; Xu et al., 2013). The main difference between haze and fog is their composition: fog is a suspension of water droplets whereas haze is a suspension of dry particles (World Meteorological Organization, 2014). However, it is hard to distinguish them from each other because haze and fog often coexist and could be in a state of transition (Wu et al., 2009; Ding and Liu, 2014). Furthermore, the favourable meteorological conditions for haze and fog are basically the same, namely under calm weathers (Fu et al., 2014), so haze and fog are often studied together as haze-fog (or fog-haze) when analyzing the influence of meteorological factors on them (Han et al., 2014; Li et al., 2016; Yang et al., 2016).

Although haze-fog events are less likely to occur during summer in China, studies have shown that summer haze-fog events have increased steadily in recent years (Ding and Liu, 2014; Fu et al., 2014; Chen and Wang, 2015), and midsummer has gradually become a haze-fog-prone season in the North China Plain (Cao et al., 2015). Haze-fog events usually occur under the influence of certain weather systems that are favorable to the accumulation of air pollutants, such as weak highs, uniform pressure fields and col pressure fields (Tie et al., 2015; Zheng et al., 2015; Zhang et al., 2016; Miao et al., 2017). In summer, China is often under the influence of tropical cyclones (Xiao and Xiao, 2010). Although tropical cyclones are normally associated with pollutant removal processes by intense rainfall and fierce wind, they may increase the occurrence of air pollution episodes in certain areas.

Some studies have explained how tropical cyclones affect regional aerosol concentration through peripheral circulation by diagnostic analysis (Wu et al., 2005; Yang et al., 2012) and numerical simulation (Feng et al., 2007; Wei et al., 2016). These studies have analyzed tropical-cyclone-related air pollution episodes on the southern
Tropical cyclones can block circulation systems, leading to channel, resulting in regional air pollution episodes. (2) Wind field in the affected areas and form an aerosol transfer affected area (Wang and Kwok, 2003; Wei stagnant weather and continuous calm or weak wind in the cyclonic circulation of tropical cyclones could alter the transport by tropical cyclone airflow (Fang et al., 2009; Huang et al., 2009; Yang et al., 2012) and suggest that the cycloic circulation of tropical cyclones could alter the wind field in the affected areas and form an aerosol transfer channel, resulting in regional air pollution episodes. (2) Tropical cyclones can block circulation systems, leading to stagnant weather and continuous calm or weak wind in the affected area (Wang and Kwok, 2003; Wei et al., 2007; Wei et al., 2012). This is not advantageous to the dilution and diffusion of aerosols, and results in increased aerosol concentrations. Special topography can make the situation worse under such circumstances (Cheng et al., 2014; Hung and Lo, 2015). (3) Peripheral subsidence of tropical cyclones generates adiabatic heating, which can dry the mid-low atmosphere and increase local static stability (Wu et al., 2005; Feng et al., 2007). At the same time, the downward motion lowers the boundary layer height (Zhang et al., 2010; Fan et al., 2011) or forms a low-level temperature inversion (Chan and Chan, 2000; Lee and Savtchenko, 2006). These effects eventually lead to accumulation of pollutants and air pollution episodes.

Previous studies have proposed reliable mechanisms of how tropical cyclones influence air quality, but these studies have mainly focused on a few coastal cities. There are few analyses concerning inland areas or wide-range regions, even though the atmospheric circulation status in most regions of China can easily be influenced by tropical cyclones in summer. Wang et al. (2009) indicated that tropical cyclone tracks in the Northwest Pacific could be related to the calm and stagnant weather in Beijing. Therefore, tropical cyclones could be involved in air pollution episodes occurring in other areas in China, and tropical cyclone track differences should be considered when analyzing air pollution formation mechanisms (Yang et al., 2012). Furthermore, all previous studies have been based on pollution cases that have already happened. The conditions and prerequisites of tropical cyclones for an air pollution episode to emerge have not been analyzed or discussed. Namely, uncertainty still exists regarding the relationship between the influence of tropical cyclones and the occurrence of haze-fog events, knowledge of which is important for air pollution forecasts.

In this study, summer regional haze-fog occurrence in northern China under the influence of tropical cyclones was analyzed, and the conditions and detailed physical processes of how tropical cyclones lead to an increase in haze-fog events were explored. Furthermore, the study analyzed not only the characteristics of tropical cyclones and their possible influence on regional haze-fog events, but also the surrounding circulations and their contribution to haze-fog formation. Through statistical analysis of a large number of cases, the uncertainty regarding whether a regional haze-fog event will occur in northern China under the influence of a tropical cyclone is preliminarily solved. Conclusions on the primary mechanisms of the combined effect of tropical cyclones and the surrounding circulations on regional air quality are drawn, which could improve forecasts of summer regional haze-fog events in northern China.

**DATA AND METHODS**

About 80% of total tropical cyclone landfall in China occurs between July and September (Xiao and Xiao, 2010), and summer haze-fog events mainly occur in July and August (Cao et al., 2015). Summer haze changed steadily during 1981–2000 and began to increase rapidly after 2001 (Ding and Liu, 2014; Wang and Chen, 2016). Therefore, the study period was chosen as July and August from 2001 to 2012.

Fig. 1 shows the frequency of haze-fog occurrence in East China, where is the climatological large-scale susceptible region to haze in China (Xu et al., 2016). Summer haze-fog events mainly occur in northern China, including North China and the Yangtze-Huaihe region (111°–121°E, 31–40°N), and the spatial distribution is uniform over this region. Therefore, northern China was chosen as the study area. Northern China is bounded by the Yangtze River in the south, the Yanshan Mountains in the north, the Taihang Mountains in the west and the coastline in the east (Fig. 1). There are 70 meteorological stations with consistent weather records in this region.

![Fig. 1. Frequency of haze-fog occurrence at each station (colored dots, unit: %) over East China in July and August during 2001–2012. The rectangle represents northern China.](image-url)
**Determination of Haze-Fog Days and Meteorological Data**

Based on the criterion established by the China Meteorological Administration (CMA), haze-fog events were determined by the daily mean visibility and a haze-fog phenomenon was assumed to have occurred when the visibility was less than 10 km without other weather phenomena that could limit or block vision (CMA, 2007). The station observation data were provided by the CMA, which includes four-times daily (0:00, 6:00, 12:00 and 18:00 UTC) visibility and weather phenomena data from 2001 to 2012.

The data are available from the China Meteorological Data Service Center (http://data.cma.cn/en) and the National Centers for Environmental Information, NOAA (https://www.ncdc.noaa.gov/isd).

Atmospheric circulation data were derived from the ERA-Interim reanalysis dataset (http://apps.ecmwf.int/data sets/data/interim-full-daily/) provided by the European Centre for Medium-Range Weather Forecasts (ECWMF), which includes daily geopotential height, wind field, temperature and relative humidity data for each pressure level.

**Tropical Cyclone Data and Criterion for those Affecting China**

Tropical cyclone data were derived from the Regional Specialized Meteorological Centre (RSMC) Best Track Data (http://www.jma.go.jp/jma-ang/jma-center/rsme-hp-pub-eg/besttrack.html) provided by the RSMC Tokyo-Typhoon Center of the Japan Meteorological Agency (JMA). These data provide detailed information on tropical cyclones in the Northwest Pacific, such as international number ID, name, time series of intensity, center position, maximum sustained wind speed, and so on. Tropical cyclones are tracked every 6 h (0:00, 6:00, 12:00 and 18:00 UTC) after reaching tropical depression intensity.

Tropical cyclones are ranked by five degrees by the JMA, mainly according to their maximum sustained wind (Table 1). In general, tropical cyclones are referred to as cyclones of tropical storm intensity or higher. The analysis in this study started from the tropical depression phase and included the extra-tropical cyclone phase. A tropical cyclone was assumed to affect China on the day its center was located in the region of 110–125° E and 20–40° N more than once in the four-times daily positioning. This simple method was adopted to find tropical cyclones close to the coastline of China, which would have a greater influence than the others, and to select typical cases.

**RESULTS**

**Statistics of Haze-Fog Events and Tropical Cyclones**

In the summers (July and August) of 2001–2012, there were only 3 days when none of the stations in northern China experienced haze-fog, which confirmed this is a haze-fog-prone area. On average, 12.0 stations (17.1% of the total number of stations) experienced a haze-fog event every day. Based on the probability distribution of the number of haze-fog stations per day (Fig. 2), it was found that 4–16 stations experienced haze-fog events on most summer days, and such days accounted for 68.7% of the total days.

According to the JMA records, 101 tropical cyclones generated in the Northwest Pacific in July and August during 2001–2012. According to the methods introduced in section 2.2, a total of 48 tropical cyclones affected China for 172 d, accounting for 47.5% of the total Northwest Pacific tropical cyclones. The probability distribution of the number of haze-fog stations per day during these 172 d is shown in Fig. 2, and it is similar to the distribution of all summer days, indicating that uncertainty exists regarding the relationship between the occurrence of haze-fog events and the influence of tropical cyclones, as not all tropical cyclones led to haze-fog events. Therefore, the impact of tropical cyclones was analyzed by categorizing the haze-fog cases.

Here we define a regional haze-fog day as the day 21 (30% of the total stations) or more stations encountered a haze-fog event, and an individual haze-fog day as the day 5 (7% of the total stations) or fewer stations encountered a haze-fog event. The statistics showed that there were 29 regional haze-fog days and 26 individual haze-fog days.

Regional haze-fog days corresponded to 16 tropical cyclones, accounting for 33.3% of the total number of the tropical cyclones affecting China; individual haze-fog days corresponded to 15 tropical cyclones, accounting for 31.3% of the total cyclones. The fact that both regional and individual haze-fog cases corresponded to about one-third of the total tropical cyclones indicated that the existence of a tropical cyclone was not bound to an increase or a decrease in the number of haze-fog stations, and that other factors might play a part in the relationship between tropical cyclones and haze-fog episodes in northern China. To determine whether regional haze-fog cases were indeed induced by tropical cyclones, the number of haze-fog stations on the regional haze-fog days and three days before were calculated. The average number of stations experiencing a haze-fog event on the regional haze-fog days was 23.3, almost twice the daily average number of haze-fog stations in summer. Meanwhile, on each day of the three days before the regional haze-fog days, the average numbers of haze-fog stations were 16.8, 14.7 and 15.5, respectively, which were close to the daily average number of haze-fog stations. Thus, the selected regional haze-fog cases were possibly under the influence of tropical cyclones. As binary tropical cyclones are complicated and different...

<table>
<thead>
<tr>
<th>Degrees of tropical cyclones in the RSMC Best Track Data.</th>
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<tbody>
<tr>
<td>Tropical Depression</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>10-minute sustained winds (kt)</td>
</tr>
</tbody>
</table>

1 kt = 0.514 m s⁻¹.
Fig. 2. Frequency of the number of daily haze-fog stations (unit: %) in northern China.

from single tropical cyclones, and the impacts of inland tropical cyclones are very different from those that do not or only just make landfall, the binary tropical cyclones and inland tropical cyclones were removed from the analysis. This resulted in 20 regional haze-fog days and 18 individual haze-fog days for analysis, and they were classified into three types based on the central position and path of the tropical cyclone on each day (Fig. 3).

Type 1: A tropical cyclone located in coastal South China or the northern South China Sea, with a westward path. There were 3 regional haze-fog days and 6 individual haze-fog days that met these conditions, indicating that individual haze-fog events were more likely to happen under the influence of Type 1 tropical cyclones.

Type 2: A tropical cyclone located near Taiwan Island, with a northwestward path. There were 14 regional haze-fog days and 11 individual haze-fog days that met these conditions, indicating that both regional and individual haze-fog events were more likely to happen under the influence of Type 2 tropical cyclones.

Type 3: A tropical cyclone located in the Yellow Sea, with a northward or northeastward path. There were 3 regional haze-fog days and only 1 individual haze-fog day that met these conditions, indicating that regional haze-fog events were more likely to happen under the influence of Type 3 tropical cyclones.

The average statuses of the three types of tropical cyclones on the influencing day are listed in Table 2. As the table shows, the average centers for each type of tropical cyclone were different for the regional and individual haze-fog cases, but the differences were small compared with the distance between the tropical cyclones and northern China. The differences between the regional and individual haze-fog cases for each type of tropical cyclone are embodied in various aspects. In Type 1, tropical cyclones in regional haze-fog cases had a greater intensity than in individual cases in terms of central pressure and maximum wind speed, but the radius of 30 kt winds or greater was slightly smaller. In Type 2, there was no significant difference in the central pressure or the maximum wind speed, but the radius of 30 kt winds or greater in the regional cases was larger than that in the individual cases. In Type 3, the intensity in each of the cases was similar according to central pressure.

This study considers haze and fog as a single analysis object, but essentially haze and fog are different weather phenomena, so the proportion of haze and fog in all haze-fog events was calculated (Table 3). Relative humidity was used to distinguish between haze and fog. Among all the haze-fog events (visibility less than 10 km), haze was identified if the relative humidity was less than 80% and fog was identified if the relative humidity was higher than 95% (China Meteorological Administration, 2010; Quan et al., 2011; Zhao et al., 2016). If the relative humidity is between 80% and 95%, fog and haze can coexist or be in a transition process (Ding and Liu, 2014). It was found that about half of the haze-fog events were haze and less than 3% were fog, which means 45% of the haze-fog events in summer northern China were probably a combination of haze and fog. Table 3 also shows that the proportion of haze and fog under the influence of the three types of tropical cyclones were roughly the same. Therefore, it is appropriate to study haze and fog together.

Changes in Regional Atmospheric Environment under the Influence of Tropical Cyclones

To determine the main factors leading to regional and
Fig. 3. Tracks of selected tropical cyclones (a) and their paths on the influencing day in regional (b) and individual (c) haze-fog cases. The rectangle in (a) represents the boundary for determining whether a tropical cyclone affects China.

Table 2. Average status of tropical cyclones on the influencing day* (R: regional haze-fog days; I: individual haze-fog days).

<table>
<thead>
<tr>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>I</td>
</tr>
<tr>
<td>Longitude of the center (°)</td>
<td>113.1</td>
<td>114.7</td>
</tr>
<tr>
<td>Latitude of the center (°)</td>
<td>20.8</td>
<td>21.4</td>
</tr>
<tr>
<td>Distance** (°)</td>
<td>15.0</td>
<td>14.2</td>
</tr>
<tr>
<td>Central pressure (hPa)</td>
<td>973</td>
<td>984</td>
</tr>
<tr>
<td>Maximum sustained wind speed (kt***)</td>
<td>57.8</td>
<td>47.7</td>
</tr>
<tr>
<td>The longest radius of 30kt winds or greater (nm***)</td>
<td>202.2</td>
<td>211.3</td>
</tr>
<tr>
<td>The shortest radius of 30kt winds or greater (nm)</td>
<td>136.7</td>
<td>157.0</td>
</tr>
</tbody>
</table>

* Maximum sustained wind speed, and the longest and shortest radius of 30 kt winds or greater are only measured or estimated when the tropical cyclone is of tropical storm intensity or higher. Relevant values in Type 3 are left blank because there was only one individual haze-fog day and the corresponding tropical cyclone had turned into an extra-tropical cyclone.

** The distance between the average central position of tropical cyclones and the center of northern China (116°E, 35.5°N).

*** 1 kt ≈ 0.514 m s⁻¹, 1 nm ≈ 1.852 km.

Table 3. Proportion of haze and fog in all haze-fog events during summers of 2001–2012 and under the influence of the three types of tropical cyclones.

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haze</td>
<td>51.5%</td>
<td>50.7%</td>
<td>50.7%</td>
<td>44.1%</td>
</tr>
<tr>
<td>Fog</td>
<td>3.0%</td>
<td>2.8%</td>
<td>3.1%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Coexist</td>
<td>45.4%</td>
<td>46.5%</td>
<td>46.2%</td>
<td>54.4%</td>
</tr>
</tbody>
</table>

individual haze-fog episodes, regional atmospheric environment changes during the influencing period of the tropical cyclones were investigated. It is known that high relative humidity, positive vertical difference of the equivalent potential temperature (stable stratification), downdraft, negative vorticity, and weak or calm near-surface wind are preferable conditions for haze-fog events (Qu et al., 2013; Mu and Zhang, 2014; Zhang et al., 2014; Zhang et al., 2015; Liu et al., 2017). In this study, meteorological parameters and the diagnostic values for both regional and individual haze-fog cases in northern China were analyzed, including relative humidity, vertical difference of the pseudo-equivalent potential temperature between 1000 and 850 hPa (representing the stratification stability), vertical velocity and relative vorticity at different pressure levels, and surface wind speed (Table 4). Here surface wind speed comes from surface observation data and the other variables come from reanalysis data.
During the influencing period of Type 1 tropical cyclones, the stratification stability was not in favor of haze-fog formation in both regional and individual haze-fog cases; relative humidity in the regional and individual cases showed only a small difference compared with the long-term summer average value. An evident negative anomaly of relative vorticity and a positive anomaly of average vertical velocity were found in the regional haze-fog cases, which indicated the strengthening of downward motion in the regional cases. During the influencing period of Type 2 tropical cyclones, compared with individual cases, the regional haze-fog cases had higher relative humidity and a relatively more stable atmosphere. Furthermore, there was a negative vorticity anomaly and a strengthened downdraft. These changes were all conducive to the accumulation of air pollutants. During the influencing period of Type 3 tropical cyclones, relative humidity was much higher in the regional haze-fog cases than in the individual cases, and the stratification stability in the regional cases was relatively more stable, but the downdraft was weakened. In addition, the surface wind speed in 3 regional cases and Type 2 individual cases were close to the average wind speed, and in Type 1 and Type 3 individual cases surface wind speed increased a little but was still weak. Therefore, it is speculated that in summer, horizontal wind in northern China is usually weak and thus its influence on haze-fog is relatively insignificant compared with other meteorological factors.

From the above analysis, it can be concluded that tropical cyclones influence the regional atmospheric environment in two ways: through influencing thermal conditions, including moisture and stability; and through affecting the dynamic conditions, including vorticity field and vertical motion. For Type 1 tropical cyclones, the main difference between the regional and individual haze-fog cases was the dynamic conditions. For Type 2 tropical cyclones, differences in both the thermal and dynamic conditions were apparent. For Type 3 tropical cyclones, the main difference was the thermal conditions. These differences were assumed to affect the number of haze-fog stations in northern China, and the spatial distribution of some of the main factors was examined subsequently to describe the influence of the dynamic and thermal processes in detail.

For Type 1 tropical cyclones, there was a wide-range negative vorticity anomaly in the mid-low troposphere in the regional haze-fog cases (figure omitted), and the descending motion was strengthened in most central and southern areas (Figs. 4(a)–4(c)). For Type 2 tropical cyclones, the distribution of vertical velocity showed that descending motion existed in most areas except for the Shandong Peninsula in the regional cases, while ascending motion existed in the individual cases (Figs. 4(d)–4(f)). At the same time, the relative humidity increased in the regional cases compared with the individual cases (Figs. 4(g)–4(i)). The difference in the stratification stability between the regional and individual cases was similar to the difference in relative humidity at 850 hPa (figure omitted), so the increase of stratification stability in the regional haze-fog cases was possibly due to rapid moistening at 850 hPa, and vertical uneven moistening could be the reason for the stability change. For Type 3 tropical cyclones, the relative humidity in the regional cases was higher in almost the whole region than in the individual cases (Figs. 4(j)–4(l)). Moreover, as in Type 2, the stratification was more stable in the regional cases due to higher relative humidity at 850 hPa (figure omitted).

Mechanisms by Which Tropical Cyclones and Surrounding Circulations Contribute to Haze-Fog Events

According to above analysis, the main meteorological factors influencing regional haze-fog events in northern China during the influencing period of different tropical cyclones were determined. This section investigates how tropical cyclones change the dynamic and thermal environment in northern China.

**Type 1 Tropical Cyclones**

For Type 1 tropical cyclones, the increase in haze-fog events in the affected area was mainly due to the dynamic influence (section 3.2). To determine the role of tropical cyclones in the strengthened downdraft, a comparison
Fig. 4. Average vertical velocity between 850 and 500 hPa (shading, unit: Pa s$^{-1}$) and wind field at 850 hPa (vectors) in regional (a, d) and individual (b, e) haze-fog cases, and the difference (c, f). Average relative humidity (shading, unit: %) and wind field (vectors, unit: m s$^{-1}$) at 850 hPa in regional (g, j) and individual (h, k) haze-fog cases, and the difference (i, l). Dots (c, f, i, l) represent the haze-fog frequency at each station.

Analysis was conducted. Fig. 5 shows the average circulation pattern in regional and individual haze-fog cases affected by Type 1 tropical cyclones. The locations of tropical cyclones in the regional and individual haze-fog cases showed little difference, and although tropical cyclones in the regional cases had a stronger intensity, the peripheral airflow could not reach northern China in both cases. The difference in circulation lies in the position and intensity of the Northwest Pacific subtropical high. The subtropical high extended westward and northward in the regional haze-fog cases, compared with its average position in summer (depicted by the 5760 gpm geopotential height isoline in Fig. 5), and the intensity was stronger. The ridge of the subtropical high in the regional haze-fog cases was located at the southern boundary of northern China (around 30°N), so northern China was located in front of the ridge. An
obvious deformation of the subtropical high was found in the regional cases, and it was very likely caused by the squeeze of tropical cyclones. In contrast, the position and intensity of the subtropical high in the individual cases were relatively close to the average status.

As known, sinking airflow exits in the peripheral areas of a tropical cyclone. Furthermore, the negative vorticity advection area, which corresponds to the area in front of the ridge of the subtropical high in the upper air, could also result in airflow sinking in the mid-low troposphere. To identify the cause of the downdraft strengthening in the regional haze-fog days under the influence of Type 1 tropical cyclones, profiles of wind field were analyzed (Fig. 6). Here, latitude–height wind profiles along 116°E (central longitude of northern China, also close to the longitude of the average tropical cyclone center), as well as longitude–height wind profiles along 31°N (the southern boundary of northern China, also the latitude of the ridge of the subtropical high), in the regional haze-fog cases were analyzed.

The wind field profile along 116°E (Fig. 6(a)) shows that the strong updraft area of the Type 1 tropical cyclones was located south of 24°N. There were two strong downdraft airflows: one located around 25°N at the north of the strong updraft area, which was assumed to be the peripheral subsidence of the tropical cyclones; and the other located around 32°N, in the south of northern China. The wind field profile along 31°N (Fig. 6(b)) shows that there was a wide-range deep downdraft zone along the ridge of the subtropical high. Therefore, the wide-range downdraft zone was assumed to be caused by the subtropical high.

By comparing the wind field profile with the average position and intensity of the subtropical high in summer, it is speculated that the strengthening and westward extension of the Northwest Pacific subtropical high was the cause of the wide-range downdraft zone. The presence of Type 1 tropical cyclones in coastal South China or the northern South China Sea forced the ridge of the subtropical high to move northward to the south of northern China, situating this region in the strong downdraft zone in front of the ridge. Thus, the aerosol diffusion conditions were worsened by the joint effects of the subtropical high and tropical cyclones, which were conducive to regional haze-fog episodes.

Type 2 Tropical Cyclones

The increase in haze-fog events under the influence of Type 2 tropical cyclones was due to both dynamic and thermal reasons (section 3.2). The tropical cyclones in the regional haze-fog cases had a wider range of strong wind than those in the individual cases (Table 2, Fig. 7). However, it was found that the peripheral subsidence of the tropical cyclones could not lead to the downdraft strengthening in the west of northern China (Fig. 4(d)), because the distance between the tropical cyclones and northern China was quite far in both the regional and individual haze-fog cases (figure omitted). Furthermore, it was inferred that the subtropical high was not the cause of the downdraft strengthening, because the position of the subtropical high in both the regional and individual haze-fog cases was relatively shifted eastward (Fig. 7). Meanwhile, the downdraft area in the west in the regional haze-fog cases (Fig. 4(d))
corresponded to areas behind a shallow trough in the upper air — a shallow westerly trough existed over northern China with its trough line located around 115°E (Fig. 7(a)). Then the western area of this region was located behind the trough, where it corresponded to a negative vorticity advection zone in the lower atmosphere, which could possibly be the reason for the strengthened downdraft. However, in the individual haze-fog cases, the trough was located to the west of northern China (Fig. 7(b)), which was similar to its average position (depicted by the 5720 gpm geopotential height isoline in Fig. 7), and placed the area in front of the trough. Therefore, the position of the shallow trough was presumed to be the influencing factor for the strengthened downdraft.

Enhancement of the moisture conditions in the whole region was also analyzed as well as the strengthening of the downward motion in the western area. It was concluded that as the tropical cyclones in the regional haze-fog cases had a wider range of strong wind than in the individual cases, the strong southeasterly flow brought more water
vapor directly from the sea (Fig. 7(a)), causing the relative humidity to rise in almost all of northern China (Fig. 4(g)). However, the easterly flow in the individual cases failed to do so due to the weaker intensity and smaller influencing range of tropical cyclones (Fig. 7(b)). Therefore, the vapor transportation of tropical cyclones was the reason for the whole-region enhancement of the moisture conditions.

Type 3 Tropical Cyclones

Thermal changes were the main reason for the increased haze-fog occurrence under the influence of Type 3 tropical cyclones (section 3.2). When the North China and the Yangtze-Huaihe region was affected by Type 3 tropical cyclones, it was located at the peripheral subsidence area, so the downdraft was strong in both haze-fog cases (Table 4). The main difference in meteorological fields between the two cases was the relative humidity in the lower atmosphere (represented by 850 hPa, Figs. 4(j)–4(l)), which was mainly determined by the wind field (represented by 850 hPa, Fig. 8). In the regional cases, northerly winds prevailed in northern China under the influence of tropical cyclones, which brought abundant moisture from the sea (Fig. 8(a)); in the individual case, continental westerly winds prevailed in northern China (Fig. 8(b)), which resulted in lower relative humidity. A deep westerly trough, with its trough line located around 115°E, existed on the northwest side of the tropical cyclones at 500 hPa (Fig. 8(b)) in the individual case. This corresponded to a cyclone in the lower atmosphere (center location at 850 hPa: 117°E, 45°N, Fig. 8(b)) near the tropical cyclone, which led to strong westerly winds in northern China. This was the reason for the existence of the westerly winds and lower relative humidity in the individual case.

Here, it should be noted that there was only one individual haze-fog event that qualified as a Type 3 tropical cyclone case. This may because when these tropical cyclones move northward to the Yellow Sea, they usually bring plenty of moisture to northern China by altering the prevailing wind direction, so the common influence of Type 3 tropical cyclones is conducive to regional haze-fog episodes. Namely, it would be normal to have regional haze-fog episodes while it would be uncommon to have individual haze-fog episodes in this situation. This speculation is in accordance with the conclusion of a study by Wang et al. (2009). They analyzed the possible relationship between paths of tropical cyclones and PM$_{10}$ pollution episodes around Beijing during 2004, and found that when tropical cyclones moved northward and landed in the Korean Peninsula or Japan, Beijing and its nearby areas were controlled by a weak high or weak low, which usually led to air pollution.

**CONCLUSIONS AND DISCUSSION**

Regional haze-fog events can occur on some of the tropical cyclone influencing days; however, uncertainties exist regarding the relationship between haze-fog formation in northern China and the influence of tropical cyclones. When China was affected by tropical cyclones, the occurrence of regional haze-fog episodes was determined not only by the tropical cyclones, but also by the surrounding circulations.

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![Fig. 8. Geopotential height at 500 hPa (shading, unit: gpm) and wind field at 850 hPa (vectors, unit: m s$^{-1}$) in the regional (a) and individual (b) haze-fog cases affected by Type 3 tropical cyclones. Line denotes the 5720 gpm isoline of the summer average. Rectangle represents northern China.](image-url)
The position and intensity of the tropical cyclones, the location and intensity of the Northwest Pacific subtropical high and the westerly trough as well as their collocation with tropical cyclones were all factors impacting the local meteorological elements that determined haze-fog formation in northern China.

When tropical cyclones were located in coastal Southern China or the northern South China Sea, they did not influence the moisture and stability conditions in northern China. Instead they affected the local vertical velocity, a critical criterion in regional haze-fog formation, by altering the circulation. Tropical cyclones squeezed the strengthened and westward-extended subtropical high, leading to a northward-placed ridge, and placed northern China in the wide-range downdraft area in front of the ridge, which was favorable to the occurrence of regional haze-fog episodes. When tropical cyclones were located near Taiwan Island, the southeasterly wind at the north of the tropical cyclones changed the moisture conditions over northern China. The stronger the intensity and the larger the wind range of the tropical cyclones, the more water vapor was transported to the region by the southeasterly wind, and the increased relative humidity was conducive to the occurrence of regional haze-fog episodes. At the same time, the westward shifting of the shallow trough in the upper air strengthened the downward motion, which was also an important advantageous condition for haze-fog formation. When tropical cyclones were located in the Yellow Sea, the wind field over northern China was changed by the cyclonic circulation of the tropical cyclones, resulting in more water vapor being brought to this region from the sea, which was beneficial to regional haze-fog episodes.

The influence of tropical cyclones on regional haze-fog episodes can be divided into two aspects, thermal factors and dynamic factors. Thermal factors, including moisture and stability, were directly influenced by tropical cyclones, and dynamic factors, including vorticity field and vertical movement, were directly and indirectly influenced. By comparing the impact processes of different tropical cyclones, it was concluded that when the distance between tropical cyclones and northern China was larger than the radius of the tropical cyclone, tropical cyclones mainly affected the haze-fog events indirectly by influencing the surrounding circulation systems; meanwhile, the closer the distance, the stronger the direct influence was.

The mechanism of how tropical cyclones and the surrounding circulations contribute to haze-fog events can also explain the regional haze-fog occurrence frequency (ratio of regional haze-fog cases number to all cases, Table 4) under the influence of different tropical cyclones. When tropical cyclones were located in the northern South China Sea, the occurrence of regional haze-fog events depended on the westward extension of the subtropical high, which resulted in a relatively low occurrence frequency (33.3%) of regional haze-fog events. When tropical cyclones were located near Taiwan Island, the direct influence of tropical cyclones could affect northern China as well as the indirect influence, so the occurrence frequency increased to 56%. When tropical cyclones were located in the Yellow Sea, appropriate conditions for regional haze-fog formation were usually formed, so the occurrence frequency (75%) was the highest. Moreover, there were 29 tropical cyclones related to regional haze-fog days in northern China during summers from 2001 to 2012, accounting for 30.5% of the total summer regional haze-fog days in this region. Variations in the number or the characteristics of tropical cyclones in the Northwest Pacific may affect the variation of summer regional haze-fog events in this region. Forecast and prediction information for tropical cyclones could be used to improve forecasts of regional haze-fog events in northern China.

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