Influences of a quasi-stationary front on particulate matter in the low-latitude plateau region in China

Wenxuan Fan¹, Jian Wu¹*, Xiaopeng Li², Fangyuan Yang² and Bing Chen¹

¹Key Laboratory of Atmospheric Environment and Processes in the Boundary Layer over the Low-Latitude Plateau Region, Department of Atmospheric Science, Yunnan University, Kunming, China

²Meteorological Observatory of Kunming, Kunming, China

Corresponding author: Wu Jian, wujian@ynu.edu.cn
Abstract

A comprehensive assessment of the main pollution characteristics of particulate matter (PM) in the low-latitude plateau (LoLaP) region in China by utilizing observation and reanalysis data and statistical methods is presented to reveal influences of the Kunming quasi-stationary front (KMQSF) on PM concentration in LoLaP in winter. It is found that the location and intensity of the KMQSF significantly influenced the distribution pattern of PM and induced high concentrations in some areas in LoLaP region in a typical pollution event in 2016. Furthermore, all the KMQSF synoptic weathers over LoLaP region from 2014-2019 were investigated and classified into 9 Patterns, which led to different air pollution patterns in LoLaP region. When the KMQSF moved westward from middle LoLaP, the PM could be transported to west part of LoLaP by the easterly wind, which led to the daily mean PM$_{10}$ and PM$_{2.5}$ concentrations increase in Kunming, a central city in the west part of LoLaP, at the same time, high concentrations of PM$_{10}$ and PM$_{2.5}$ maintained in Guiyang, a central city locating in the east part of LoLaP. When the KMQSF gradually retreated from west part of LoLaP to east part, the PM in Kunming decreased with a strengthening of the westerly, and the PM in Guiyang further increased with a decrease of the planetary boundary layer (PBL) height and boundary layer dissipation (BLD). When the KMQSF disappeared, the formation of calm inversion pollution could be caused, including a shallow PBL and weak BLD in whole LoLaP, which induced the highest daily mean PM$_{10}$ and PM$_{2.5}$ concentrations both in the two central cities in all patterns.

Keywords: Particulate matter; The Kunming quasi-stationary front; The planetary boundary layer; Atmospheric stability; The low-latitude plateau region

1 Introduction

Air pollution has been a global issue over the past several decades (Bian et al., 2017; Davis, 2017; Ding et al., 2013; Duncan et al., 2016) due to its harmful influences on human health (Lelieveld et al., 2015; Raaschou-Nielsen et al., 2017) and ecosystems as well as its severe impacts on climate (Acosta Navarro et al., 2016; Knippertz et al., 2015; Lau et al., 2017; Li et al., 2016) and synoptic systems (Fan et al., 2015; Gong et al., 2014). In addition to emissions, meteorological factors, such as wind, relative humidity (RH), precipitation, turbulent dispersion, the planetary boundary layer (PBL), vertical temperature structure and synoptic systems, have been found to play very important roles in the day-to-day variation and the long-term trend in air quality (Appelhans et al., 2013; Ding et al., 2009; Hou and Wu, 2016; Jiang et al., 2017; Li et al., 2014; Liang et al., 2017; Miao et al., 2015; Özbay, 2012; Quan et al., 2013; Thishan Dharshana et al., 2010; Tie et al., 2017; Wolf et al., 2014). Therefore, understanding the influences of meteorological factors and atmospheric circulation on air quality is very important both for improving air quality predictions and for formulating environmental protection strategies, especially in regions with large anthropogenic
emissions.

During haze events, various meteorological factors play critical roles: moist air, a shallow PBL, temperature inversions and weak/calm wind conditions. Under weak solar radiation and stagnant, moist meteorological conditions during winter, air pollutants and water vapor accumulate in a shallow PBL (Tie et al., 2017). With an increase in aerosol pollutants, less downward direct solar radiation can reach the surface, and this reduction has a cooling effect, which in turn reduces the height of the PBL; consequently, the lower PBL altitude can further strengthen haze events that have already occurred (Li et al., 2015; Li et al., 2017; Petaja et al., 2016; Yang et al., 2016). During winter, temperature inversions can enhance the probability of severe particulate matter pollution, and many air pollution events have been found to be highly dependent on the existence of ground-based inversions in previous research (Hou and Wu, 2016; Wolf et al., 2014). In addition, the effects of wind are complex and can take many different forms. For example, weak/calm wind (i.e., stagnation) can lead to the local trapping and accumulation of pollution (Lv et al., 2017), whereas high-speed wind may favor PM resuspension and thus increase coarse PM concentrations (Zhang et al., 2018a) or quickly disperse local air pollutants (Gietl and Klemm, 2009). Furthermore, wind from different directions can introduce cleaner or more polluted air masses (Wang et al., 2017).

Except for various meteorological factors, special synoptic systems also play critical roles in PM pollution events. Jiang et al. (2017) showed that a high-pressure cell over the Tasman Sea was commonly associated with elevated pollution levels. The development of brown haze in Auckland, New Zealand, was associated with a strong northeast-southwest temperature gradient that immediately preceded the brown haze event (Salmond et al., 2016). Zhang et al. (2018b) indicated that approximately 70-74% of the “Beijing blue” came from long-term trends in favorable weather conditions, such as the North China Cold Vortex, which is a stable stagnant circulation system. Southwest wind or weak southerly wind dominated the warm side of the stationary front in South China in winter. Because of the weak wind, the accumulation of pollutants resulted in a wide range of haze weather in Guangxi (Liao et al., 2018a). Stationary fronts in South China, in New York City area, and in the southern Kanto Plain of Japan were revealed to be responsible for severe air pollution in these regions (Lai, 2015; Liao et al., 2018a; Mizuno and Kondo, 1992; Nudelman and Frizzola, 1974).

The Kunming quasi-stationary front (KMQSF) is a famous synoptic system in China and often appears in the eastern part of the low-latitude plateau (LoLaP) in southwestern China during winter and spring, whose monthly average frequency is 11.8 day/month from November to April for the period of 1961-2010. Additionally, 61.5% of the KMQSF was located east of 103° E during 1961-2010. This synoptic system is usually caused by the confrontation between the southwestern warm air and the cold air from the polar region that is stopped by the Tibetan Plateau and the LoLaP (Duan
et al., 2017), and there are significant differences in the weather and climatic characteristics of the prefrontal and postfrontal sectors (Fig. 1a) (Sheng et al., 2015). Therefore, the influences of the KMQSF on air pollution in LoLaP region should be clearly investigated.

The air quality in LoLaP is usually good, and observations have revealed that the aerosol optical depth (AOD) was between 0.1 and 0.2 for the period from March 2000 to February 2010 in southwestern China (Luo et al., 2014). In addition, the hourly average concentrations of PM$_{2.5}$, PM$_{10}$ and black carbon (BC) in Tengchong City, a county in LoLaP and 750 km to the west of Kunming, were 30 μg m$^{-3}$, 32 μg m$^{-3}$, and 420 ng m$^{-3}$, respectively (Engling et al., 2011). These measurements of the particulate mass concentrations were conducted from April 7 to May 24, 2004, and coincided with the annual intensive biomass burning season in South and Southeast Asia, which can be regarded as the severest air pollution in this area (Engling et al., 2011). According to the daily air pollution measure in all cities in China between 1980 and 2005, a significant increasing trend in haziness has been revealed in LoLaP in recent years (Che et al., 2009). The observed increase in pollution should be investigated from the perspective of the geographic position and weather events, especially the influence of the KMQSF. This work analyzes the relationship between PM pollution and KMQSF. The stationary fronts frequently occur in the world, so this work is expected to be of some reference value to the study of air pollution in stationary front regions. The data and methods used in this research are presented in section 2, and analysis of a typical pollution event is presented in section 3, the relationship between fine particles and KMQSF in section 4, and the conclusions are summarized in section 5.

2 Data and methods

2.1 PM concentration data

Observation was conducted at two stations of the Key Laboratory of Atmospheric Environment and Processes in the Boundary Layer (AEPBL) in LoLaP region from November 2016 to May 2017. The two stations were established on two campuses, Donglu (102.70° E and 25.06° N at 1914 m above sea level) and Chenggong (102.85° E and 24.83° N at 1920 m above sea level) of Yunnan University, which represent typical characteristics of downtown and suburban regions, respectively. The downtown observation at Donglu station was used in this study.

The PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ mass and number concentrations were measured at Donglu and Chenggong stations using an environmental dust monitor (Grimm EDM 180-MC, GRIMM Aerosol Technik GmbH & Co. KG) (Jung et al., 2015; Khan et al., 2016) at an interval of 5 min. The precision of the Grimm 180 instrument is ±2% for PM$_{10}$, PM$_{2.5}$ and PM$_{1}$, and the environmental dust monitor was annually calibrated.
Hourly observations of surface PM$_{10}$ and PM$_{2.5}$ concentrations on December 1-14 2016 in Guiyang (106.69° E, 26.57° E) in LoLaP region (Fig. 1b) are derived from the real time platform of urban air quality of China Environmental Monitoring Station (http://106.37.208.233:20035/), which represents an average of all sites in the city. And hourly observations of surface PM$_{10}$ and PM$_{2.5}$ concentrations on November-next February from 2014 to 2019 at 25 cities in LoLaP region were also used (Fig. 1b), which was interpolated into grid data between 97° E-110° E, 21°N-30°N at a resolution of 0.5°×0.5°.

2.2 Meteorological data

The hourly air temperature, RH, wind speed, wind direction and precipitation data that were observed in Kunming and Guiyang were used in this study. The two additional stations are managed by the Kunming Meteorological Bureau, the first site is approximately 1 km southeast of the YNU Donglu station (i.e., Yuantong station, 102.71° E, 25.06° N), and the second site is the standard meteorological station (102.65° E, 25° N), which is located approximately 6 km southwest of the YNU Donglu station.

In addition, ERA-Interim reanalysis data four times day by day on November-next February from 2014 to 2019 between 97° E-110° E, 21°N-30°N at a resolution of 0.125°×0.125° were used in this research and included the wind speed at a height of 10 m above the surface, temperature at a height of 2 m, low cloud cover, PBLH and boundary layer dissipation (BLD), wind speed, temperature and RH in the upper 37 levels above 1000 hPa (Dee et al., 2011; Tavolato and Isaksen, 2011).

2.3 Meteorological diagnostic method

The scalar frontogenesis function was introduced to display the development and change in the KMQSF (Zhu et al., 2000), and this function is presented in Equation (1):

\[ F = -\frac{1}{|\nabla \theta|} \left[ \left( \frac{\partial \theta}{\partial x} \right)^2 \frac{\partial u}{\partial x} + \left( \frac{\partial \theta}{\partial y} \right)^2 \frac{\partial v}{\partial y} + \frac{\partial \theta}{\partial x} \frac{\partial \theta}{\partial y} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \right] - \frac{1}{|\nabla \theta|} \left( \frac{\partial \omega}{\partial x} \frac{\partial \theta}{\partial x} + \frac{\partial \omega}{\partial y} \frac{\partial \theta}{\partial y} \right) + \frac{1}{|\nabla \theta|} \left( \frac{\partial \theta}{\partial x} \frac{\partial \theta}{\partial t} + \frac{\partial \theta}{\partial y} \frac{\partial \theta}{\partial t} \right) \] (1)

where \(|\nabla \theta|\) can be expanded using Equation (2):

\[ |\nabla \theta| = \sqrt{\left( \frac{\partial \theta}{\partial x} \right)^2 + \left( \frac{\partial \theta}{\partial y} \right)^2} \] (2)

Equation (2) includes the individual effects on the scalar frontogenesis function from the adiabatic heating term, vertical motion tilt term, horizontal divergence term and horizontal deformation term. In addition, F>0 indicates frontogenesis, and F<0 indicates frontolysis. The scalar frontogenesis function is used to confirm the location of the KMQSF. The usual criterion of the KMQSF can be
represented by the isotherm intensive area and the west-east wind transition zone, which is associated with the ground region $|\nabla \theta| > 5K \text{ km}^{-1}$, the scalar frontogenesis function $F > 0$ (Duan et al., 2017).

The bulk Richardson number $R_b$ is defined as the ratio of turbulence associated with buoyancy to that induced by mechanical shear (Stull, 1988), which is expressed as

$$R_b = \frac{\frac{\Delta \theta}{\theta}}{\left(\frac{\Delta u}{u \Delta z}\right)^2 + \left(\frac{\Delta v}{v \Delta z}\right)^2}$$

where $z$ denotes height above ground, $g$ the acceleration of gravity, $\theta$ potential temperature, $u$ and $v$ are the component of wind speed. In the limit of layer thickness becoming small, the bulk Richardson number approaches the gradient Richardson number, for which a critical Richardson number is roughly $R_i = 0.25$. Gradient Richardson numbers less than this critical value are dynamically unstable and likely to become or remain turbulent.

3 Influences of KMQSF on a typical air pollution event

3.1 General state of this event

The observed average PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ mass concentration at Donglu station located in southeast Kunming were 62.3, 34.4 and 28.0 $\mu$g m$^{-3}$, respectively, from November 2016 to May 2017. However, the daily mean concentration of PM$_{2.5}$ at Donglu on December 9, 2016 was 89.6 $\mu$g m$^{-3}$, which was higher than 75 $\mu$g m$^{-3}$ exceeding the Grade II standard in China and was the only pollution event in the research period. In addition, PM$_{10}$ and PM$_{2.5}$ concentrations synchronously increased during December 4-9 2016 in the whole LoLaP (Fig. 2), while the high pollution event usually appeared in eastern LoLaP. A typical pollution event was selected for deeper analysis to reveal its characteristics and causes.

The continuously accumulated of PM in the typical pollution event was between two KMQSF processes on December 2-3 and after December 11, respectively (Fig. 3). The distribution of PM concentrations showed the similar structure to the KMQSF, and the isolines of PM concentrations was northwest-southeast. A discontinuity in wind direction and a significant horizontal potential temperature gradient could be used to diagnose KMQSF, and the prefrontal and postfrontal wind speed decided the location of KMQSF, which usually caused the different weather in west and east parts of LoLaP. The KMQSF marked by a significant horizontal potential temperature gradient ($|\nabla \theta| > 5K \text{ km}^{-1}$) and wind shear. When the KMQSF appeared and the westerly was stronger, the low values of PM in western LoLaP will be push to eastern LoLaP by high wind speed. When the KMQSF disappeared and this condition maintained several days, the westerly and the easterly weakened (Fig. 3), the PM accumulated.

In general, the PM concentrations were higher in eastern LoLaP and lower in western LoLaP (Fig. 2). On December 1-3, the low values area of PM in western LoLaP gradually expanded eastward
(Fig. 2a-c), when the westerly gradually strengthened in western LoLaP and the KMQSF appeared in the middle of LoLaP (Fig. 3a-c). From December 4-9, the PM in the whole LoLaP increased (Fig. 2d-j), and the daily mean concentration of PM$_{2.5}$ reached 80 $\mu$g m$^{-3}$ near Kunming and 120 $\mu$g m$^{-3}$ to the northeastern LoLaP on December 8. The wind speed was always lower in whole LoLaP in this period and the KMQSF disappeared in the middle of LoLaP (Fig. 3d-j). After December 10, the low values area of PM in western LoLaP expanded eastward again, when the westerly strengthened. A PM area with PM$_{2.5}$ of 120 $\mu$g m$^{-3}$ appeared on December 11 and 12, which was trapped in eastern LoLaP (Fig. 3k, l).

In general, the highest PM concentration mainly occurred at night, associating with a stable nocturnal boundary layer. The lower PBLH, smaller BLD and Rb>0.25 could represent a stable boundary layer. Fig. 4 shows distribution of PBLH, BLD and Rb at 1800 UTC (0200 BJT) from December 1 to 12 2016. When the KMQSF appeared in the middle of LoLaP before December 3, the PBLH was higher, the BLD was stronger, dynamically unstable area was larger (Fig. 4a-c), and the PM concentration was lower. During night from December 4 to 9, except for December 5, the stable PBLH were lower than 50 m and the BLD were lower (Fig. 4d-i), when the PM reached the highest concentrations both in Kunming and Guiyang on December 8, the BLD were lower than $3 \times 10^4$ J m$^{-2}$ (Fig. 4h). Obviously, local pollution accumulation under the stable PBL and weak dissipation was the mainly reason inducing this pollution episode. When the KMQSF reappeared in the middle of LoLaP after December 11, the PBLH and the BLD increased both (Fig. 4k-l), the low PM area in western LpLaP was pushed to eastern LoLaP. The high PM pollution was obviously blocked to the east of the frontal line of the KMQSF. The change of KMQSF was well matched with the change of PM concentrations, and the KMQSF played an important role in this pollution episode.

3.2 Temporal evolution of PM concentration in western and eastern LoLaP

In order to analyze the causes of this pollution event in detail, the temporal changes in PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ at Donglu in Kunming and the temporal changes in PM$_{10}$ and PM$_{2.5}$ in Guiyang, as well as the meteorological parameters (Fig. 5), are selected for further analysis, and a comparison between the western LoLaP site and the eastern LoLaP site can be made. The concentrations of PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ at Donglu and Guiyang during December 1-3 were lower (Fig. 5d, h). Under the control of the KMQSF, the water vapor in the west side of the stationary front is sufficient, which caused the low cloud (Fig. 6). The atmosphere was cleaner after the frontal precipitation process during December 1-2 at Donglu and during December 2-3 in Guiyang, and this state was the pre-pollution period of this episode.

The period of December 4-9 was the pollution accumulation phase of the pollution episode. The hourly maximum concentrations of PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ on December 4 were 148.7, 86.8 and 69.5
μg m⁻³, respectively, and they increased to 228.0, 133.1 and 110.2 μg m⁻³ on December 9 at Donglu (Fig. 5d). The hourly maximum concentrations of PM_{10} and PM_{2.5} reached 273.9 and 188.9 μg m⁻³ on December 8 in Guiyang (Fig. 5h). The growth rates of hourly minimum PM_{10}, PM_{2.5} and PM_{1} at Donglu changed from 7.9 μg m⁻³ 24 hr⁻¹ on December 4 to 25.8 μg m⁻³ 24 hr⁻¹ on December 7, from 4.0 μg m⁻³ 24 hr⁻¹ to 19.0 μg m⁻³ 24 hr⁻¹, and from 3.2 μg m⁻³ 24 hr⁻¹ to 15.6 μg m⁻³ 24 hr⁻¹, respectively. The growth rates of hourly minimum PM_{10} and PM_{2.5} in Guiyang changed from 22.3 μg m⁻³ 24 hr⁻¹ on December 4 to 57.1 μg m⁻³ 24 hr⁻¹ on December 7, and from 16.3 μg m⁻³ 24 hr⁻¹ to 35.2 μg m⁻³ 24 hr⁻¹, respectively. The positive growth rates of hourly minimum PM meant that the background values of the PM was increasing and there was distinct accumulation of the PM, and the accumulation occurred at Donglu and in Guiyang both.

During the pollution accumulation phase, wind speed remained at lower levels at Donglu, with an hourly maximum speed of 1.3 m s⁻¹ before December 8, and it is southerly in daytime and northerly at night (Fig. 5a). The nocturnal wind from the north of the Donglu station might contain a lot of pollution gas from the Jindinshan industrial area (Shi et al., 2016), which caused the hourly PM maximum at night at Donglu. The mean wind speed in Guiyang was larger than that at Donglu, several changes of wind direction happened from December 4 to 10 with relative lower wind speed (Fig. 6e), the air from surrounding region could be transported to Guiyang. RH was 81.3% at night on December 6 at Donglu, and then RH continually increased during both day and night until reaching 96.0% at night on December 9 (Fig. 5b). The maximum RH at night on December 8 and 9 also reached 98% and 97% without rain in Guiyang (Fig. 5f). Under high RH (i.e., >60-80%), the volume of aerosol particles can significantly increase when water vapor is absorbed onto the surface of these particles, and the enlarged aerosol surfaces/volumes lead to more rapid multiphase reactions and secondary aerosol formation, which results in elevated aerosol concentrations (Tie et al., 2017). In addition, the ground inversion layer (TIL) always existed (Fig. 5c, h). The low wind speed, high RH, and TIL induced stagnant conditions, which corresponded to the disappearance of the KMQSF and favored the accumulation of aerosol particles and secondary aerosol formation.

The RH was still high on December 10 at Donglu (Fig. 5b), and a stable TIL maintained (Fig. 5c). These conditions caused high concentrations of fine particles until midnight, and then the particle mass pollutant was dispersed by higher wind speeds and stronger turbulence on December 11 and 12 (Fig. 5a, d). The RH abruptly decreased, which meant a weather change and a warm and dry airflow immigration in western LoLaP. The TIL disappeared in Guiyang on December 10 (Fig. 5g), wind speed and RH gradually increased on December 11 and 12 (Fig. 5e, f), the southerly changed into easterly and wind speed increased on December 12 (Fig. 5e), and the low cloud moved westward from eastern LoLaP (Fig. 6c), which meant a cold and moist airflow appeared in eastern LoPaP. The PM in Guiyang also decreased in higher wind speeds but was still higher than that at Donglu in
influence of pollution transport from surrounding region. This final period of the pollution episode was called the collapsing period, which corresponded to the appearance of the KMQSF (Fig. 6).

The wind speed remained at a relatively high level during December 13-14, with hourly maximum speeds of 1.8 and 2.7 m s\(^{-1}\) at Donglu and hourly maximum speeds of 3.9 and 5.5 m s\(^{-1}\) in Guiyang (Fig. 5a, e). This change was associated with a decrease in the maximum of nocturnal RH from 85.9% to 81.1% at Donglu (Fig. 5b), and with an increase in the maximum of nocturnal RH from 91% to 99% in Guiyang (Fig. 5f). These facts indicate that warm and dry westerly winds in western LoLaP and cold and moist easterly winds in eastern LoLaP had strengthened. The KMQSF moved westward with low clouds (Fig. 6), and rainfall occurred in Guiyang and removed PM (Fig. 5f, h).

Temperature inversion can restrain the convection and dispersion of air pollutants due to weaker turbulence, and temperature inversion can also lead to a weaker surface wind speed relative to neutral and unstable stratification according to the logarithmic velocity profile. These conditions can also further decrease the transport of air pollutants. Therefore, temperature inversion favors the accumulation of air pollutants. From December 4-12, there was a ground inversion layer in Kunming at 8:00 and 20:00, and this inversion layer was usually thinner and stronger at 20:00 than at 8:00 (Fig. 5c), which was produced at night and disappeared in daytime. The surface cooling process at night might be caused by the strong upward infrared radiation and the cold air sliding down the hillside during nocturnal hours. These results support the formation of a ground temperature inversion (Duan et al., 2014; Wolf et al., 2014). The rate of the TIL appearing in Kunming obviously higher than that in Guiyang, because Kunming is located in a small basin surrounded by mountains and along the northwestern edge of a lake with the valley wind, warm advection, and infrared radiation emission of the surface (Duan et al., 2014). The temporal characteristics of TIL indicated that there was absolute stability near the ground during this pollution episode, in particular from December 5 to 10, which supplied enough time for the accumulation of air pollutants, production of chemical reactions among pollutant species, and formation of secondary aerosols. The thickness of the inversion layer reached 1024 m at 8:00 on December 9, which matched the timing of the subsequent peak value of aerosols. The thicker inversion layer was not easy to disappear immediately, so the hourly maximum concentrations of PM appeared at 11:00 before it start to rain. The TIL appeared on December 4-9 and there was a ground inversion layer at 8:00 and 20:00 on December 8 in Guiyang (Fig. 5g), when clear sky also appeared in Guiyang (Fig. 6c). The similar calm weather supported the pollution event appeared in Kunming and Guiyang both. Otherwise, there were some different between western and eastern LoLaP, the stability in western LoLaP was obviously higher than that in eastern LoLaP, which shown lower wind speed and long-term maintain of TIL.

Fig. 7 shows a backward trajectory analysis. Using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model driven with the Global Data Assimilation System (GDAS)
output, the 48-h backward trajectories of Kunming and Guiyang from December 4-10 2016 were analyzed. The air over Kunming was mainly sourced from cleaner southwest direction during the study period, except for December 6 and 7. During the pollution accumulation period from December 4-9, the wind speed decreased gradually and slowly changed to ground-to-ground airflow, and the wind nearly stopped on December 9. Although the wind speed increased on December 10, it remained a ground-to-ground airflow. There were more complicated air source in Guiyang. Except for December 6 and 7, the air over Guiyang in 48-h was mainly from the north and south direction, and the wind also nearly stopped on December 8 and 9. On December 6, the air over Guiyang in 48-h was from Inner Mongolia and turned to northeast wind near 30º N, and it was easterly in east of Guiyang (Fig. 3f). The path on December 7 was similar to that on December 6, but the wind speed decreased and it turned to southerly before reaching Guiyang. Thus, it is reasonable to assume that the source of this pollution event in Kunming was local, and there were pollution sources from surrounding areas in Guiyang, except for local source.

This typical pollution episode was triggered by the combined effects of synoptic conditions, decreasing wind speed, increasing RH, and ground temperature inversion. During the sustained synoptic process, fine particles could continuously accumulate, and secondary aerosols could continuously form and wet-grow into larger aerosols; therefore, a light haze episode formed. When the synoptic conditions changed again, e.g., when the KMQSF immigrated, wind disrupted the static and stable weather, and the haze dissipated.

4 KMQSF patterns and influences on air pollution in recent five years

The KMQSF often appears in the eastern region of LoLaP during winter and spring, and it seems that the location and intensity of KMQSF influenced the concentrations and distribution of PM from section 3. The meteorological factors and PM data on November–next February 2014-2019, were used to analyze the relationship between them, there are 601 days in total. The self-organizing maps (SOM) was used to distinguish the patterns of KMQSF (Francis et al., 2018; Gibson et al., 2017; Mattingly et al., 2016), and the horizontal potential temperature gradient and zonal wind were used as input data of SOM. Three different SOM configurations were tested: a 6-node SOM (3 columns × 2 rows), a 9-node SOM (3 columns × 3 rows) and a 12-node SOM (3 columns × 4 rows), applied to standardized horizontal potential temperature gradient data and zonal wind speed data. From these options, the output from the 9-node SOM is easier to interpret than the 6-node and 12-node SOM, and it also includes a sufficient number of nodes to represent the KMQSF, therefore, the 9-node SOM was chosen as the best classification for further analysis (Tab. 1).

The horizontal potential temperature gradient was matched with the transformation zone of westerly and easterly. When the easterly was strong, the KMQSF would be pushed to west, and when
the westerly was strong, the KMQSF would be pushed back to east. The whole eastern LoLaP and middle LoLaP were controlled by the strong and cold northeast wind under Pattern 1 (Fig. 8a). There were 246 days in Pattern 2 to 5, in which the KMQSF located between western and eastern LoLaP, and eastern LoLaP prevailed cold northeasterly and western LoLaP was covered by warm southwest wind (Fig. 8b-e). The southwesterly was very strong under Pattern 6 and 7, southerly occupied the whole eastern LoLaP and the KMQSF was pushed to the northern LoLaP (Fig. 8f, g). Pattern 8 includes 82 days, the KMQSF located middle LoLaP, but the KMQSF was weaker, associating with southerly in eastern LoLaP (Fig. 8h).

Fig. 9 shows distribution of PBLH, BLD and Rb at 1800 UTC (0200 BJT) and Fig. 10 shows distribution of daily mean PM10 and PM2.5. In general, the PBLH was higher and BLD was stronger near the KMQSF, and the high value areas of the PBLH and the BLD shown northwest-southeast distribution. When the southwest wind strengthened, the high value areas of the BLD in eastern LoLaP would move to north; atmospheric stability was bounded by the KMQSF, and the surface layer was dynamically stable (unstable) on the west (east) side of the KMQSF; the PM gradually increased from west to east, which was lower in westerly area and higher in easterly area. When the KMQSF moved to the region west to Kunming or near Kunming represented by Pattern 1 and 2 (Fig. 9a, b), the high PM area was obviously pushed toward western LoLaP (Fig. 8a, b) with daily mean PM10 and PM2.5 of 55.8±20.9 and 35.0±13.7 μg m⁻³ in Kunming (Tab. 1). When both the southwest wind and northeast wind was the strongest, represented by Pattern 3 and 4, the BLD between western and eastern LoLaP was higher than 15×10⁴ J m⁻², associated by a PBLH higher than 300m in the region east to the frontal line of the KMQSF (Fig. 9c, d), the PM was dissipated in whole LoLaP, with low values of PM covering LoLaP from southwest to northeast (Fig. 10c, d), in which the daily mean PM10 and PM2.5 concentrations were 44.6±19.5 and 28.6±12.3 μg m⁻³ in Guiyang in Pattern 3, and 51.4±15.1 and 26.0±8.7 μg m⁻³ in Kunming in Pattern 4 (Tab. 1). When the southwesterly gradually strengthened, represented by Pattern 6 to 7, the BLD in LoLaP increased from 9×10⁴ J m⁻² to 21×10⁴ J m⁻², associated by an increase of the PBLH from 100 m to 200m (Fig. 9f, h), the daily mean PM2.5 concentrations decreased from 28.3±10.9 to 23.6±7.4 μg m⁻³ in Kunming and decreased from 46.7±25.4 to 38.4±16.0 μg m⁻³ in Guiyang. The pattern 8 was similarly with Pattern 9 with much stronger wind and lower PM.

There were 72 days in Pattern 9, in which the KMQSF disappeared between western and eastern LoLaP, associating with lower southerly in LoLaP (Fig. 8i). The horizontal wind shear still existed in eastern LoLaP, but the horizontal potential temperature gradient was very low. The PM in LoLaP reached the highest value in Pattern 9 (Fig. 10i), associating with the lowest PBLH below 100 m and the weakest BLD less than 6×10⁴ J m⁻², and almost the whole region was dynamically stable (Fig. 9i), in which the difference of the PBLH and the BLD between western and eastern LoLaP was ignorable.
The PM\(_{10}\) and PM\(_{2.5}\) significantly accumulated under such stable boundary layer to 72.3±26.6 and 39.6±15.4 μg m\(^{-3}\) in Kunming, and 96.1±34.1 and 60.7±22.1 μg m\(^{-3}\) in Guiyang, respectively (Tab. 1). Furthermore, Pattern 9 showed that it was westerly between Kunming and Guiyang on average, in fact, there were 9 days when it was weak easterly and 63 days when it was weak westerly. The daily mean PM\(_{10}\) and PM\(_{2.5}\) concentrations were 67.6±31.1 and 43.6±22.7 μg m\(^{-3}\) in Kunming with weak easterly. The daily mean PM\(_{10}\) and PM\(_{2.5}\) concentrations were 72.9±26.2 and 39.1±14.3 μg m\(^{-3}\) in Kunming with weak westerly.

In general, when the KMQSF reached Kunming, the pollution could be transported to western LoLaP from eastern LoLaP by easterly under unstable atmosphere. When the KMQSF was weaker or disappeared between western and eastern LoLaP, the wind was lower in LoLaP, associating with a low PBLH and a weak BLD, these facts resulted in stable atmosphere near the surface, which restrained pollutant dispersion and led to high PM values. When PM in eastern LoLaP was higher than in western LoLaP indicated by Pattern 8 and 9, the pollutant could not be transported by the southwest wind from eastern LoLaP to western LoLaP, therefore, the local accumulation should be the important reason inducing high PM concentration in Kunming. In general, the pollution in the Pattern 8 and 9 was induced mainly by local sources in the western LoLaP and there was pollution transport in the eastern LoLaP, there was long-range transport from east to west in Pattern 1 and 2, there was transport from west to east in Pattern 6 and 7, the air converged near the KMQSF in other patterns, and the KMQSF could block air flow between western and eastern LoLaP. The pollution event on December 2016 exactly occurred in meteorological condition of Pattern 9 and was ended in Pattern 6. Pattern 9 appeared 20 days on November 2016 to February 2017, and the frequent was higher than other years. Furthermore, the PBLH was always lower in the west side of the KMQSF, and this fact indicated more stable air near the surface in western LoLaP than eastern LoLaP, but the PM in eastern LoLaP was always higher than in western LoLaP, which indicated the local pollution emission and pollution transport in eastern LoLaP should be stronger than in western LoLaP. In Pattern 8, the PM\(_{10}\) and PM\(_{2.5}\) concentrations in Guiyang was 23.7 μg m\(^{-3}\) and 21.1μg m\(^{-3}\) higher than those in Kunming, and in Pattern 9, the PM\(_{10}\) and PM\(_{2.5}\) concentrations in Guiyang was 23.8 μg m\(^{-3}\) and 21.1μg m\(^{-3}\) higher than those in Kunming.

In addition, a pollution event lasting for several days might include different KMQSF patterns. We find an example from December 24 to 27 2017 with the daily mean PM\(_{2.5}\) concentrations in Kunming of 89.7, 103.4, 80.3 and 81.7 μg m\(^{-3}\), respectively experienced temporal changes of Pattern 9, Pattern 8, and Pattern 9, respectively. Though this event also went through the weaker and even disappeared KMQSF with lower PBLH and weaker BLD, but the atmospheric circulation was different from the event on December 4-10 2016. A high pressure appeared in the middle north of the LoLaP on December 26 2017, the sinking restrained the pollution dispersion and promoted this pollution event.
The pollution source and meteorological condition might be different in different pollution event, which should be particularly analyzed through the whole continuous process.

5 Conclusions

The concentrations of PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ in downtown Kunming (Donglu) were observed from November 2016 to May 2017. The causes of a pollution event in winter were identified, the relationship between the KMQSF and changes in fine particles in LoLaP during November-next February 2014-2019 were discussed, and the main conclusions can be summarized as follows:

1) The weather change triggered the pollution episode on December 8-9, 2016 in Kunming and Guiyang, and this was a regional episode that the PM$_{10}$ and PM$_{2.5}$ concentrations synchronously increased in whole LoLaP. Before this pollution event, both the Kunming and Guiyang experienced a short precipitation event, and the aerosol concentrations were very low. From December 4-9, the KMQSF weakened to the east of Kunming gradually. During that time, the wind speed was low, the PBLH was low, the BLD was weak, the RH was high, and there were ground temperature inversions in Kunming and Guiyang. Certain weather conditions favored the accumulation of primary PM and the precursors of secondary organic aerosols and the formation and growth of small secondary aerosols. As a result, a light haze episode formed. When the KMQSF strengthened again, the strong westerly interrupted the static and stable weather, and the haze dissipated.

2) During November-next February 2014-2019, when the KMQSF was very weak and disappeared in the middle of LoLaP, both western and eastern wind was weakest, the PBLH was the lowest, the BLD was the weakest, the atmosphere near surface was dynamically stable at night, and PM concentrations was the highest under unfavorable boundary layer dispersion conditions. When the KMQSF approached Kunming from eastern LoLaP, the pollution could be transported to western LoLaP by easterly under unstable atmosphere. When the KMQSF was stronger, both the easterly and westerly was stronger, inducing low PM over LoLaP. In nine patterns of the KMQSF, the pollution in Pattern 8 and 9 was mainly induced by local emission in the western LoLaP and there was pollution transport in the eastern LoLaP, there was long-range transport from east to west in Pattern 1 and 2, there was transport from west to east in Pattern 6 and 7, the air converged near the KMQSF in other patterns, and the KMQSF could block air flow between western and eastern LoLaP. Furthermore, the PBLH was always low in the west side of the KMQSF, and this fact indicated more stable air near the surface in western LoLaP than eastern LoLaP, which inferred much severer PM pollution in western LoLaP in case of more pollution emission.

The near-surface wind speed decided intensity of the front. Dunn et al. (2016) indicated that the global average (except Australia) near-surface wind speed decreased by -0.087 m s$^{-1}$ decade$^{-1}$ (1979-2015), that over East Asia decreased by -0.07 m s$^{-1}$ decade$^{-1}$ (1979-2015), and Vautard et al. (2010)
found that near-surface wind speed over South Asia decreased by -0.08 m s\(^{-1}\) decade\(^{-1}\). The averaged trends of wind speed over China (70°-135° E; 15°-54° N) was -0.16 m s\(^{-1}\) decade\(^{-1}\) during 1966-2011 (Liu, et al., 2014), and that over Southwestern China (75°-110° E; 15°-35° N) was -0.24 m s\(^{-1}\) decade\(^{-1}\) during 1969-2009 (Yang, et al., 2012). In addition, the occurrence frequencies of air stagnation days and events in the Sichuan-Chongqing region increased over the ten-year period of 2007-2016, with linear slopes of 0.61 yr\(^{-1}\) and 0.26 yr\(^{-1}\), respectively (Liao et al., 2018b), and the Sichuan-Chongqing region locates east of the KMQSF. Therefore, the strength of the KMQSF decreased, and the air pollutants had more chances to accumulate under the weak KMQSF.

In this paper, we discuss the formation and development of a light haze event in LoLaP, and we describe the role of the KMQSF in this event. During the observation period, there was only one pollution event, but we found that the terrain and weather favored the generation of this pollution event, and the concentration of PM increased in whole LoLaP (Fig. 2). If anthropogenic emissions keep increasing, associated by a continuous weakening of the KMQSF, it is very likely that there will be frequent pollution incidents in LoLaP in the future. Thus, obtaining long-term regional aerosol data to further understand the role of the KMQSF in the generation and dissipation of air pollution will be a key emphasis of future research.

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**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Acknowledgments**

The SRTM data is available at http://srtm.csi.cgiar.org/srtmdata/. The hourly meteorological data were obtained from the China meteorological data sharing service system (http://data.cma.cn/data). The hourly PM measurement in downtown Kunming were collected through the online access to ambient air monitoring data center (http://106.37.208.233:20035/), the ERA-Interim dataset is available at https://apps.ecmwf.int/datasets/data/interim-full-daily, and the 48-h backward trajectories for Kunming and Guiyang were obtained at http://ready.arl.noaa.gov/hypub-bin/trajsrcm.pl.

**Appendix A. Supplementary data**

The PM data collected in this study is available at https://doi.org/10.6084/m9.figshare.8872724.v1.
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Table captions:

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<table>
<thead>
<tr>
<th>Pattern</th>
<th>KMQSF location</th>
<th>Sample (day)</th>
<th>PM concentrations (μg m$^{-3}$)</th>
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<tr>
<td></td>
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<td>Kunming</td>
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<td>$\text{PM}_{10}$</td>
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<td>Pattern 1</td>
<td>West to Kunming</td>
<td>47</td>
<td>55.8±20.9</td>
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<td>Pattern 2</td>
<td>Between western and eastern LoLaP, near 103.4°E</td>
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<td>67.0±17.2</td>
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<tr>
<td>Pattern 3</td>
<td>Between western and eastern LoLaP, near 104.5°E</td>
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<td>57.5±16.3</td>
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<td>Pattern 4</td>
<td>Between western and eastern LoLaP, near 104.9°E</td>
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<td>51.4±15.1</td>
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<td>Pattern 5</td>
<td>Between western and eastern LoLaP, near 105.3°E</td>
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<td>50.1±16.1</td>
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<td>Pattern 6</td>
<td>North to Guiyang</td>
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<td>Pattern 7</td>
<td>North to Guiyang with strongest southwesterly</td>
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<td>41.7±12.7</td>
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<tr>
<td>Pattern 8</td>
<td>Between western and eastern LoLaP, near 104.9°E, but being weaker</td>
<td>82</td>
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<tr>
<td>Pattern 9</td>
<td>Non KMQSF</td>
<td>72</td>
<td>72.3±26.6</td>
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Figure captions:

Fig. 1. Topographic maps of LoLaP with (a) the KMQSF and (b) 25 cities. The KMQSF appeared in the eastern region of LoLaP is usually caused by the confrontation between the south-western warm air and the cold air from the polar region that is stopped by the Tibetan Plateau.

Fig. 2. The distribution of daily average PM$_{10}$ ($\mu$g m$^{-3}$, contour) and PM$_{2.5}$ ($\mu$g m$^{-3}$, shaded) in LoLaP during (a)-(l) December 1, 2016 to December 12, 2016.

Fig. 3. The distribution of horizontal potential temperature gradient (K/100km, shaded, horizontal bar), wind (m/s) and potential temperature (K, vertical bar) at surface in LoLaP during (a)-(l) December 1, 2016 to December 12, 2016.

Fig. 4. The distribution of boundary layer height (m, contour), boundary layer dissipation ($10^4$ J m$^{-2}$, shaded) and Rb (Rb< 0.25, dots) in LoLaP during (a)-(l) December 1 to 12, 2016. The red “+” represent the location of the KMQSF.

Fig. 5. Hourly variations in (a) wind speed and wind direction, (b) precipitation and RH, (c) Thickness and lapse rate of the ground inversion layer, (d) PM$_{10}$, PM$_{2.5}$ and PM$_1$ at Donglu in Kunming; (e), (f), (g) and (h) are the same as (a), (b), (c) and (d), respectively, but for Guiyang.

Fig. 6. Spatiotemporal distributions of (a) the potential temperature (K) (contour) and zonal wind (m s$^{-1}$) (shaded) at the surface (the red line represents the location of the front line), (b) the RH (%) at the surface and the scalar frontogenesis function at 850 hPa (10$^{-10}$ K m$^{-1}$ s$^{-1}$) (shaded), (c) low cloud cover and (d) PM$_{2.5}$ in the vertical cross section across Kunming (25º N, 102.625º E) and Guiyang (26.625º N, 106.625º E) during December 1-14, 2016, and the situations of two cities are indicated by two dotted lines respectively.

Fig. 7. The 48-h backward trajectories of air parcels ending at 500-m altitude over (a) Kunming and (b) Guiyang on December 4-10. Note that trajectories were colored with ending date.

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