Impacts of Two East Asian Atmospheric Circulation Modes on Black Carbon Aerosol Over the Tibetan Plateau in Winter

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Abstract Light-absorbing particles over the Tibetan Plateau (TP) can accelerate glacial retreat, thus causing a series of serious environmental and social problems. Previous studies mainly focus on seasonal transport of aerosols over the TP, while the potential factors influencing the subseasonal variation in airborne black carbon (BC) are almost ignored. In this study, the Weather Research and Forecasting coupled with chemistry (WRF-Chem) model and multiple observations are used to investigate the impacts of East Asian atmospheric circulation on BC aerosol over the TP in winter. Results show that the weakness of westerly wind over northern TP, acceleration of westerly wind over southern TP, and eastward shift of East Asia major trough are responsible for the high BC concentration over east slope of the TP. In this circumstance, more BC from northern India can be transported to eastern TP and the south slopes of the TP by the enhanced westerly wind. The intensified southwestward wind over eastern TP brings more BC from the Sichuan Basin to northeastern TP. The BC can also penetrate to eastern TP in planetary boundary layer. Subsequently, the weakened westerly wind over northern TP and positive anomalous updrafts over east slope of the TP support the accumulation and uplift of BC. Another circulation mode is opposite to the pattern above and results in low BC concentration over the TP. These two circulation modes are possibly associated with the low-level meridional temperature anomaly over East Asia, which modulates the upper level atmospheric circulation through the transient eddy feedback.

1. Introduction

The Tibetan Plateau (TP), which is also known as the “Third Pole” and “water tower,” possesses the largest glacier in the midlatitude region (Xu et al., 2008, Xu et al., 2014; Yao et al., 2012). Because of its high elevation and therefore unique thermal and dynamic effects, it influences atmospheric circulation and the hydrologic cycle over East Asia, even for the entire Northern Hemisphere (Wu et al., 2017; Wu & Liu, 2016). A warming effect of 0.44°C decade⁻¹ from 1980 to 2013 was observed over the TP, which is faster than warming rate of 0.23°C decade⁻¹ over the Northern Hemisphere at the same latitude (Duan & Xiao, 2015) and leads to considerable problems, such as glacial retreat and precipitation changes over East Asia (Wang et al., 2008; Xiang et al., 2018; Xu et al., 2009; Yao et al., 2004). Greenhouse gases are not the only factor influencing temperature variability (Bolch et al., 2012; Kang et al., 2010; Qin et al., 2006; Wang et al., 2008); the positive radiative forcing of light-absorbing aerosols also plays important roles (Flanner et al., 2009; Qu et al., 2014; Zhang et al., 2017).

Light-absorbing aerosols are mainly composed of black carbon (BC) and dust aerosols, which can strongly absorb solar radiation and further heat the atmosphere (Chen et al., 2017, 2018; Gao et al., 2014; Huang et al., 2015; Qian et al., 2011). Moreover, light-absorbing aerosols deposited on snow/ice can accelerate snow melting and increase solar radiation at the surface by reducing snow albedo (Dang et al., 2017; Ji et al., 2016; Lau & Kim, 2018; Ming et al., 2013; Qian et al., 2009). Notably, the mass absorption efficiency of BC is stronger than that of dust on snow (Qian et al., 2015). Bond et al. (2013) assessed the climatic effects of BC aerosol and revealed that BC was the second most important type of human forcing after carbon dioxide, with a total
climate forcing of $+1.1 \text{ W m}^{-2}$. Moreover, it has been suggested that the impact of BC on snow and ice is approximately twice as high as that of carbon dioxide and other types of anthropogenic forcing (Flanner et al., 2007; Hansen et al., 2005; Hansen & Nazarenko, 2004; Qian et al., 2011). Himalayan ice core records showed that BC deposited on the TP increased significantly since 1990 (Xu et al., 2009). Thus, the increase of atmospheric pollutants in the TP may have potential impacts on the local ecological environment and even influence Asian weather and climate (Dang et al., 2015; Kang et al., 2019; Lau et al., 2006; Huang et al., 2013, 2016).

Tracking the origin of BC over the TP based on different methods, researchers concluded that South Asia is a major contributor, followed by East Asia, and the local sources only accounted for $\sim$10% of the total BC (e.g., Ming et al., 2010; Zhang et al., 2015; Zhao et al., 2013). Ming et al. (2008) and Zhao et al. (2013) found that BC emitted from northern India could be transported to the southern and southeastern TP using HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. With the same method, Lu et al. (2012) revealed that South Asia and East Asia contributes to 50% (40%) and 9% (30%) of BC transported to the TP in winter (summer), respectively. Due to the wet removal of precipitation in summer, BC emitted from South Asia mainly influences the southern and central TP through the South Asia summer monsoon (Ming et al., 2008, 2009; Wang et al., 2015; Xia et al., 2011; Zhao et al., 2017). Based on the Community Atmosphere Model version 5 (CAM5) with a source-tagging technique, Zhang et al. (2015) found that BC from northern India mainly extended to eastern TP all year around along with the strong westerly winds under the dry winter monsoon climate, while East Asia sources were responsible for BC over the northeastern TP in all seasons. Moreover, Han et al. (2014) indicated that the easterly winds on the south and southwest sides of the surface anticyclonic cold high could also bring BC from southeastern China to the southeastern part of the TP in winter in the planetary boundary layer (PBL). Subsequently, Li et al. (2016) suggested that the contribution of fossil fuel and biomass to the BC in the Himalayas was consistent with the Indo-Gangetic Plain source, whereas it originated from Chinese sources in northeastern TP using the source-diagnostic $\Delta^{14}\text{C}/\Delta^{13}\text{C}$ compositions.

As an important weather system in winter, the East Asian winter monsoon (EAWM), which is characterized by an intense Siberian High, a warm Aleutian low over the eastern North Pacific Ocean, East Asian (EA) major trough in the middle troposphere extending from the east coast of China to Japan, and a subtropical westerly jet in the upper troposphere, is vital to the weather and climate of East Asia (Chang et al., 2006; Ding, 1990; Mai et al., 2019; Zhang et al., 1997). Wang et al. (2010) identified two distinct modes in the variability of EAWM: the northern mode with a westward movement of EA major trough and southern mode with a deepening EA major trough. It has been found that the atmospheric circulation and other meteorological conditions in winter are associated with frequent haze days and variations of BC in China (Ding & Liu, 2014; Mao et al., 2016; Wang et al., 2018; Yang et al., 2019). For example, Chen and Wang (2015) found that severe haze in northern China is related to the northward shift of the westerly jet and weakened EA major trough and northerly winds. Zhang et al. (2016) concluded that the shallow EA major trough and weakened Siberian High are responsible for haze in Beijing-Tianjing-Hebei in winter.

However, less attention has been paid to the relationship between EA atmospheric circulation and absorbing aerosols over the TP in winter. Jiang et al. (2017) firstly found that the BC deposited on snow could induce TP warming and accelerate the westerly jet around 40° through the transient eddy feedback. Since BC is mainly delivered to the TP by atmospheric circulation from nearby source regions (such as South Asia and East Asia), it is worthy of investigating that what kind of EA atmospheric circulation modes is responsible for the change of BC concentration. Because continuous situ surface observations at multiple sites over the TP are unavailable, the Weather Research and Forecasting coupled with chemistry (WRF-Chem) model is used in this study to simulate the BC concentration over East Asia to address this question. This paper is organized as follows: model descriptions and observation data sets are listed in section 2. The model evaluation and results are shown in section 3. The conclusions and discussion are illustrated in section 4.

2. Data and Methodology

2.1. WRF-Chem Model Description and Configuration

The WRF-Chem model is a mesoscale atmospheric chemistry model that achieves fully online coupling of chemistry and meteorological fields. Photolysis schemes and various gas-phase and aerosol chemical
mechanisms are also included. Moreover, this model considers a variety of coupled physical and chemical processes, such as aerosol emission and transport (i.e., advection, diffusion and convection), chemical reactions, dry/wet deposition, aerosol interactions, and radiation effects (Grell et al., 2005). In particular, it computes the feedback between meteorological and aerosol fields, such as direct and indirect effects of aerosols (Fast et al., 2006). It has also been widely used to investigate aerosol transport (e.g., Chen et al., 2013; Jin et al., 2016; Zhao et al., 2010). For example, Hu et al. (2016) indicated that the WRF-Chem model captures the seasonal and spatial distribution of aerosol optical depth (AOD) and vertical profile of aerosol extinction well over Pacific compared with satellite observations. It can also simulate the transport of aerosols such as the southward transport of dust aerosol to the TP (Chen et al., 2013) and the Trans-Pacific transport of aerosols (Hu et al., 2019).

The Regional Acid Deposition Model version 2 (RADM2) photochemical mechanisms and Model Aerosol Dynamics Model for Europe (MADE) with the Secondary Organic Aerosol Model (SORGAM) (MADE/SORGAM) were implemented into the WRF-Chem model by Grell et al. (2005). This aerosol model divides aerosols into three modes: Aitken, accumulation, and coarse modes. Aerosol species, including nitrate, sulfate, ammonium, organic matter (OM), BC, sea salt, and mineral dust, are considered. Aerosol optical properties (e.g., AOD, single-scattering albedo, and extinction) are calculated as a function of wavelength. Anthropogenic emissions of BC, OC, PM2.5, PM10, nitrogen oxides (NOx), SO2, and volatile organic compounds (VOCs) are derived from the 2006 emission inventory developed by David Streets (Zhang et al., 2009). Biomass burning emissions are obtained from the Global Fire Emissions Database version 3 (GFEDv3) (van der Werf et al., 2010). The mineral dust emission is online calculated by the Goddard Chemistry Aerosol Radiation and Transport (GOCART) dust emission scheme (Ginoux et al., 2001). The Morrison two-moment microphysics scheme (Morrison et al., 2005), the Kain–Fritsch cumulus convection scheme (Kain, 2004; Kain & Fritsch, 1990), and the Noah land surface model (Chen et al., 1996; Chen & Dudhia, 2001) are used in this experiment. In addition, the Rapid Radiative Transfer Model (RRTMG) for both longwave and shortwave radiation (Iacono et al., 2000; Mlawer et al., 1997) is also used.

The meteorological field is initialized by the National Centers for Environmental Prediction Final Operational Global analysis (NCEP/FNL) data set with a 6-hr temporal resolution and a 1° × 1° spatial resolution, and the aerosol field is initialized by the default profiles. The model domain covers East Asia (10.7–59.8°N, 51.6–154.4°E) with a resolution of 36 km × 36 km. Considering that the 2006 emission inventory was used, it was more accurate to conduct this experiment from 1 June 2006 to 31 December 2011, and 2006 was used as the spin-up year. Thus, five boreal winters (December–January–February) from 2007 to 2011 were finally used to analyze.

### 2.2. HYSPLIT Model

The HYSPLIT model is one of the widely used atmospheric transport and dispersion models and is frequently used to determine the track of air mass (https://ready.arl.noaa.gov/HYSPLIT.php). In this study, the HYSPLIT-4 model provided by the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory is used to explore the potential transport paths of BC aerosols based on the three-dimensional meteorological data generated by National Centers for Environmental Prediction Global Data Assimilation System. These data have a horizontal resolution of 0.5° and 6-hr interval. Two locations (30°N, 100°E; 35°N, 100°E) lying in the TP are selected as the source regions, and the start time for backward trajectory simulation is 12 February 2008.

### 2.3. Observations

The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard the Aqua satellite is designed for retrieving reliable and extensive information about clouds, aerosols, land, and atmosphere with 36 spectral bands ranging from 0.4 to 15 mm. Compared with collection 5.1, Hsu et al. (2013) developed an enhanced Deep Blue aerosol retrieval algorithm and noted that the collection 6 aerosol products improved substantially over the entire land region, especially in deserts and urban regions. To address the ability of the model to simulate aerosols, the monthly and daily MODIS Deep Blue AOD on Aqua (collection 6, level 3) from 2007 to 2011 is used in this study. The ozone monitoring instrument (OMI) near-ultraviolet (UV) aerosol algorithm (OMAERUV) product from OMI onboard the Aura satellite retrieves the optical properties of absorbing aerosols using the near-UV spectral range, which can derive the absorbing AOD (AAOD) at...
Therefore, the daily AAOD product at 500 nm during 2007–2011 is used, with a resolution of 1° × 1°. The Aerosol Robotic Network (AERONET), which was established by the U.S. National Aeronautics and Space Administration (NASA) (Holben et al., 1998), is used to retrieve aerosol properties via sun photometers (Dubovik & King, 2000). Additionally, the AOD product (level 2) is used, with quality-assured and cloud-screened data and fewer missing values at the Semi-Arid Climate Observatory and Laboratory (SACOL) and NAM_CO sites, as well as in Kanpur, Taihu, and Beijing (locations are shown in Figure 2a). The geopotential height and wind components at 700 and 500 hPa, derived from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-interim) during 2007–2011 with a horizontal resolution of 0.75° × 0.75°, are used in this study to verify the simulated atmospheric circulations.

3. Results

3.1. Model Evaluation

Due to the complex terrain and meteorology of the TP and the coarse resolution of the model, model evaluation is very important for further studies. The simulated surface BC concentration over the TP is compared with a few available sample sites (Table 1). There is a spatial gradient in BC concentration, with the concentration decreasing from the margins of the TP to the inner TP (Figure 1a). The BC concentration is the highest in eastern TP, where the value is more than 1.2 μg m⁻³. At the southern TP, the BC concentration is approximately 0.3 μg m⁻³. The BC concentration reaches a minimum of 0.03 μg m⁻³ in the central TP, which is mainly caused by local anthropogenic emissions (Zhang et al., 2015). As mentioned in Yang et al. (2018) and Han et al. (2014), the higher BC concentrations in the southern and eastern TP are highly associated with strong emissions from India and China. Our model has a similar performance with the CAM5 model used by Zhang et al. (2015). The simulated surface BC concentration is close to the observation at Muztagh, Hanle, NCO-P, and QSSGEE (Figure 1b). The BC concentration at Zhuzhang is underestimated by approximately 0.25 μg m⁻³. In NCO which is located in central TP, the sampled mean BC concentration is 0.057 μg m⁻³ from December 2006 to January 2007, which is about 6 times higher than the simulated concentration. Notably, Ming et al. (2010) indicated that NCOS might be mainly influenced by BC from Indo-Gangetic basin through the westerly wind in winter rather than from Lhasa. Therefore, the underestimation of BC at NCOS may be attributed to the underestimation of anthropogenic aerosols in northern India (Figure 2). Besides, simulated BC represents the average concentration in a grid box, while the observed value is measured at a sample site, which will lead to large deviations over complex terrains (Zhang et al., 2015). Moreover, part of the deviation between the model results and observations can also be attributed to the uncertainties in the parameterization of precipitation and wet removal of aerosols during transport in the complex terrain of the TP. Many studies have indicated that fewer BC over the TP are transported from Central Asia, the Middle East and Europe by westerlies in the nonmonsoon season (January to April and October to December) (e.g., Han et al., 2014; Yang et al., 2018; Zhang et al., 2015). Therefore, ignoring these sources may also account for this underestimation. In addition, the observation also has large uncertainties (Table 1) which are related to the different sample methods, locations, and time periods (Bond et al., 2013; Petzold et al., 2013).

To verify the ability of the model to simulate the spatial distribution and daily variation of aerosols over the domain, the AOD from MODIS onboard Aqua (Figure 2) and daily average AOD from AERONET at five sites (Figure 3) are compared with the model results. As shown in Figure 2b, high AOD centers mainly

| Site        | Location         | Altitude (m) | Time period          | BC concentration (μg m⁻³) | Reference       |
|-------------|------------------|--------------|----------------------|--------------------------|-----------------|
| Muztagh     | 75.01°E, 38.3°N  | 4,500        | 2003–2006            | 0.052 ± 0.041            | Cao et al. (2009) |
| Hanle       | 79°E, 32.8°N     | 4,250        | 2009–2010            | 0.066 ± 0.062            | Babu et al. (2011) |
| NCO-P       | 86.8°E, 28°N     | 5,079        | 2006–2008            | 0.125 ± 0.147            | Marinoni et al. (2010) |
| Zhuzhang    | 99.72°E, 28°N    | 3,583        | January–February 2005| 0.36 ± 0.17              | Qu et al. (2008) |
| NCOS        | 91°E, 30.8°N     | 4,730        | 03 December 2006–28 January 2007 | 0.057 ± 0.048 | Ming et al. (2010) |
| QSSGEE      | 96.5°E, 39.5°N   | 4,214        | 2009–2011            | 0.047                    | Zhao et al. (2012) |
exist in eastern China, the Sichuan Basin, and northern India, where the AOD is >0.7, indicating that these regions are major aerosol sources. The spatial distribution of the AOD from the WRF-Chem model is consistent with that of the MODIS AOD, particularly in the Sichuan Basin and eastern China. However, the AOD from the model in northern India and Bangladesh is approximately 0.45, which is lower than that from MODIS (Figure 2a).

Further, available data from five AERONET sites across the TP and near aerosol source regions are also selected (locations are plotted in Figure 2a) during 2007–2011 (Figure 3). The SACOL and NAM_CO sites are located in the northeastern and central TP, respectively. In central TP, the AERONET AOD ranges from 0.01 to 0.08, which is approximately one order of magnitude lower than that in SACOL (0.1–1.3). This is because SACOL lies in the downwind region of the Taklimakan Desert and is often influenced by dust storms (Huang et al., 2008; Yuan et al., 2019), while NAM_CO is remote to the anthropogenic source regions

![Figure 1. Comparison of surface BC concentration (μg m⁻³) from samples and WRF-Chem model.](image)

![Figure 2. Spatial distribution of the average AOD at 550 nm in winter from the (a) WRF-Chem model and (b) MODIS (stars represent the locations of the AERONET sites in Figure 3) during 2007–2011.](image)
and has a high altitude (~ 4,730 m). Nevertheless, the AERONET AOD is as large as 3.0 in large anthropogenic aerosol emission regions, such as Kanpur in northern India, Beijing in northern China and Taihu in eastern China, respectively. Compared with the AERONET AOD, the model generally captures the day-to-day variation in AOD over the TP, especially in the SACOL, Beijing and Taihu sites with the linear correlation coefficients ($r$) of 0.52–0.74. Simultaneously, the WRF-Chem model slightly underestimates the AERONET AOD with regression coefficients of 0.37–0.44, except for those at the Kanpur site in northern India, where aerosols are strongly underestimated (Figure 3). The underestimation of anthropogenic aerosols over northern India and Bangladesh compared with AERONET and MODIS can be possibly attributed to the large uncertainty of the anthropogenic emission inventory in India (Bong et al., 2013; Granier et al., 2011; Lu et al., 2011) and the neglect of year-to-year emission change in our experiment, since BC emission in South Asia rose about 35% from 2000 to 2010 in South Asia (Lu et al., 2011). Moreover, part of the bias may also be associated with the uncertainties in the parameterization of aerosol transport and wet deposition. Generally, the WRF-Chem model reasonably reproduces the spatial and temporal variations of aerosol fields through comparison with AERONET and MODIS (Figures 2 and 3), which lays the foundation for investigating the impacts of atmospheric circulation on BC over the TP.

3.2. Selected BC Extreme Cases and their Anomalous Distribution Over the TP

The spatial distribution of BC mass loading over the domain in winter is shown in Figure 4. In general, the TP is always surrounded by high BC emission regions, including southern India, northwestern China, eastern China, and the Sichuan Basin (Figure S1 in the supporting information), where the BC mass loading can be up to 400 μg m$^{-2}$. The main body of the TP has the smallest BC emission, but the emission in northeastern India, China, and Bangladesh is relatively high. The high BC mass loading in these regions is partly due to the strong emissions from anthropogenic activities such as biomass burning and industrial processes. Moreover, the high BC mass loading in the Sichuan Basin is attributed to the high population density and industrial production in this region.
TP is higher than that in west part of the TP. The BC mass loading is the lowest in the inner TP (<10 μgm−2), while it is the highest on the east and southeast sides, with values of 90–700 μgm−2 (Figure 4). Moreover, the results indicate that BC loading has a sharp gradient from the inner TP to its source regions (northern India, Sichuan Basin, and eastern China) due to its high altitude, especially along the south side of the TP (where the Himalayas exist).

To identify the major weather pattern supporting high BC over the TP in winter, the regional average of BC mass loading each day from 2007 to 2011 during wintertime in the blue box region in Figure 4 where the elevation >2 km is calculated. Daily variability of regional BC mass loading, with a removed mean value, over the TP in winter from 2007 to 2011 is shown in Figure 5a. The average BC mass loading is 96.92 μgm−2 with a standard deviation of 30.91 μgm−2. The winter season in East Asia is characterized by frequent cold air outbreaks which last several days and are often related to the reconstruction process of EA major trough. Therefore, 74 high BC days (red dots in Figure 5a) and 69 low BC days (blue dots in Figure 5a) with BC mass loading anomalies over the TP larger than one standard deviation are chosen as extreme cases in this study. As shown in Figure 5b, on high BC days, positive anomalies of BC mass loading mainly occur over the region south of the TP (i.e., north of the Bay of Bengal), eastern TP, and central China, where the anomalies are more than 400 μgm−2. The slightly high positive anomalies over the northeastern and southeastern TP are approximately 100 μgm−2. Negative anomalies mainly occur over eastern and northeastern China. On low BC days, the anomalies of BC mass loading are similar to those on high BC days, but the sign is opposite (Figure 5c). Overall, in terms of the TP, the eastern TP is the key area where the BC concentration has large variability.

As one of the major light-absorbing aerosols, BC can significantly absorb solar radiation, which can be represented by AAOD from OMI instruments (Figures 5d and 5e). Following the method above, it is evident that the positive AAOD anomaly is high over the TP on high BC days while it shifts to northeast China on low BC days, which has been also captured by WRF-Chem model (Figures 5b and 5c). However, the high positive BC loading anomaly in northeastern India and Bangladesh from model is not obvious in OMI AAOD. Thus, the MODIS AOD is further used to demonstrate the aerosol anomaly (Figure S2). The positive AOD anomaly appears over the northeastern India, Bangladesh, and central China on high BC days, which is similar to the distribution of BC mass loading anomaly from model, although MODIS AOD includes scattering aerosols. Notably, the inversion algorithm of the satellite also has some uncertainties, which can result in some discrepancies between two satellite products (Koch et al., 2009). Overall, compared with MODIS AOD and OMI AAOD, the WRF-Chem model also well captured the aerosol anomaly over the TP and its surrounding regions.
To highlight the transport paths of BC over the TP at different layers, the spatial distributions of the wind field and BC concentration on high and low BC days are shown in Figure 6. In the winter, the westerly wind is remarkable over the whole domain at 500 hPa, which results in the highest BC concentration belt (~0.06 μg m$^{-3}$) extending from eastern TP to eastern China on high BC days (Figure 6a). Influenced by the westerly wind, BC originated from South Asia can be easily transported to eastern TP along the south slope of the TP, and a small part of BC from Middle East, Central Asia, and northwest China can be...
transported to western and northeastern TP, which is consistent with previous studies (Lu et al., 2012; Zhang et al., 2015). The anomalous westerly wind on high BC days is in favor of the BC transport from South Asia, leading to high BC anomaly (>0.03 μg m\(^{-3}\)) over central China, southeastern and eastern TP (Figure 6c). In the lower atmosphere (Figure 6d), the westerly winds are divided into two branches due to the high elevation of the TP (Wu et al., 2007), which then converges over east side of the TP, leading to a weak wind area. This area is beneficial to the accumulation of BC both from local emission other remote transport. Thus, a high BC concentration center occurs along the east slope of the TP regardless of on high or low BC days in the lower atmosphere (Figures 6b and 6e). Simultaneously, the southern branch of the westerly wind can bring BC from northern India to the region south of the TP, where the BC concentration is approximately 1.5 μg m\(^{-3}\) larger than that on low BC days (Figures 6d and 6f). The enhanced southwesterly wind at southwest China can also bring BC from Sichuan Basin to northeastern TP where the BC concentration anomaly

Figure 6. Spatial distribution of BC aerosol concentration (color; units: μg m\(^{-3}\)) and wind field (vectors; units: m s\(^{-1}\)) on (first column) high BC days, (second column) low BC days, and (third column) the difference between high and low BC days at (top panel) 500 hPa and (middle panel) 700 hPa, respectively; bottom figures show the BC transport flux (units: μg m\(^{-2}\) s\(^{-1}\); vectors represent transport direction, and color represents the magnitude) at the planetary boundary layer (above ground at 899 m) on high (first column) BC days, (second column) low BC days and (third column) the differences between high and low BC days, respectively.
is the highest (Figure 6f). In the PBL, the strong BC transport flux from central China promotes the increase in BC over east slope of the TP on high BC days, which is in agreement with the results of Han et al. (2014), whereas the eastward transport flux on low BC days is not conductive to the transport of BC to eastern TP (Figures 6g and 6h). These transport paths are further confirmed by using HYSPLIT model (Figure 7).

During a period when the BC concentration over eastern TP is high, it is clear that BC in southern TP and northern TP originates from South Asia and is transported to these regions with westerly wind. Near surface the northeasterly wind from central China facilitate the transport of BC to northeastern TP (Figure 7b).

Figure 8 presents the cross section of difference of meridional circulation and BC concentration between high and low BC days along 30°N and 35°N, respectively. These two figures cross the southern and northern TP, respectively, and are used to demonstrate the vertical transport of BC. A strong westerly anomaly appears in the region west of the TP (northern India), indicating the westerly wind is intensified on high BC days and can deliver more BC from India to eastern TP (Figure 8a). In the Sichuan Basin (the region east of the TP), the positive vertical motion is strong and transports more BC to the east slope of the TP, leading to positive BC concentration anomaly (~0.4 μg m⁻³) at the altitude of 1–5 km. Moving to northern TP (Figure 8b), the BC concentration anomaly is more than 0.5 μg m⁻³ and extends from surface to 5 km over the east slope of the TP. The anomalous updrafts and easterly wind can bring BC from central China to this region and then climb to the top of the TP along this slope. The anomalous easterly wind indicates the westerly wind over northern TP (or northeastern TP) is weakened, which is also shown in Figures 6c and 6f. Therefore, once the BC is transported here and emitted from local source, the weak westerly wind and strong vertical motion benefit the uplift and accumulation of BC over the east slope of the TP on high BC days, finally resulting in higher BC concentration from eastern TP to central China (Figure 5b). Besides, we also examine the possible effect of wet deposition on the difference of BC concentration between high and low BC days and found that positive precipitation anomaly is obvious over the eastern TP, northern India and central China (Figure S3). Although the positive precipitation anomaly is strong, the large positive BC deposition...
concentration indicates the wet deposition may be less important to the BC concentration anomaly (Figures 6c and 6f). This small effect of wet deposition is common, because the winter monsoon climate is normally dry, thus causing small positive precipitation anomaly (around 2 mm day$^{-1}$). Therefore, the transport is important to the BC difference over the eastern TP and its surrounding regions. These results can be attributed to the differences in EA weather patterns, which will be discussed in the next section.

3.3. Two EA Atmospheric Circulation Modes and their Possible Relationship With Temperature Change

First of all, the air temperature and atmospheric circulation anomalies on high and low BC days are depicted. It is obvious that the surface temperature increases over Russia and decreases over central China and the TP, where the anomalies can reach up to 4°C on high BC days (Figure 9b). These dipole
temperature anomalies weaken the meridional thermal gradient over northern China and indicate that the lower level atmospheric baroclinicity may decrease in northern region of East Asia mainland (around 40–50°N). Associated with the surface cooling over the China mainland, the sea-level pressure increases in China, implying a colder winter (Figure 10a). The climatological northeasterly is intensified by positive sea-level anomalies, especially of the region east of the TP (Figures 9a and 9b), and can carry BC from central China to southeastern TP in the PBL (Figure 6g). During low BC days, the temperature decreases over Russia and increases over the most of China, indicating a warm winter in China. There is no doubt that these opposite temperature anomalies enhance the meridional thermal gradient over the northern region of East Asia mainland. Moreover, the sea-level pressure also decreases in China mainland (Figure 10b) and causes the southwesterly anomalies which is not in favor of the BC transport from central China to east slope of the TP on low BC days in the PBL (Figure 6h).

Figure 10. Composites of anomalies for sea-level pressure (contour lines; only those that pass the 0.05 significance level are plotted) from the WRF-Chem model over the domain on (a) high BC days and (b) low BC days. Colors indicate the winter mean sea-level pressure (units: hPa) (solid lines indicate positive values, and dashed lines indicate negative values; the same applies to all figures).

Figure 11. Cross section of air temperature anomaly (units: °C) and westerly wind anomaly (contours, units: m s$^{-1}$) averaged on (a) high BC days and (b) low BC days along 85°E, respectively (dotted areas indicate values pass the 0.05 significance level; black areas indicate topography).
Figure 12. Composites of maximum eddy growth rate anomalies (units: day$^{-1}$) averaged between 850 and 600 hPa from the WRF-Chem model over the domain on (a) high BC days and (b) low BC days (dotted areas indicate values pass the 0.05 significance level).

Figure 13. Composites of BC concentration anomalies (color; units: $\mu g m^{-3}$), geopotential height anomalies (blue contour lines; units: gpm; only those that pass the 0.1 significance level are plotted) and wind field anomalies (units: m s$^{-1}$; only vectors passing the 0.1 significance level are shown) from the WRF-Chem model at (a and b) 500 hPa and (c and d) 700 hPa on (left panel) high BC days and (right panel) low BC days (blue solid lines indicate positive values, and blue dashed lines indicate negative values; red solid contour lines indicate the winter mean geopotential height from 2007 to 2011).
Figure 11 shows the vertical structures of anomalous temperature and westerly wind on high and low BC days. On high BC days, significant temperature cooling over the TP extends to an altitude of 9 km with a maximum cooling of 3°C. The temperature warming anomalies are also prominent below 4 km in Russia. The lower level baroclinicity could enhance the latitudinal shift of the eddy-driven jet by modifying the meridional wave propagation and breaking and thermal wind distribution (Nie et al., 2016). Therefore, the weakness of the low-level atmosphere thermal gradients on high BC days may lead to the weakness of westerly in northern China. This phenomenon is further confirmed by the maximum eddy growth rate (Fang & Yang, 2016), which represents low-level baroclinicity. The maximum eddy growth rate is calculated following Equation 1:

$$\sigma = 0.31 f \frac{du}{dz} / N,$$  (1)

where $f$ is the Coriolis parameter, $N$ is the Brunt-Väisälä frequency, $u$ is the zonal wind, and $z$ is the vertical height. As shown in Figure 11a, due to the weakness of the meridional thermal gradient in northern region of East Asia mainland, the maximum eddy growth rate decreases significantly over the northern China, Mongolia and parts of Russia. Hence, the westerly decreases by 0–7.5 m s$^{-1}$ over the region north of the TP due to the weak eddy activity (Figure 11a). Moreover, the increase of the meridional thermal gradient at the region south of the TP leads to large eddy generation and further increases the westerly over this region, implying a southward shift in the westerly jet through the thermal wind principle and eddy feedback (Figures 11a and 12a).

On low BC days, the positive temperature anomaly increases from the surface to 9 km over China but decreases in the lower troposphere over Russia (Figure 11b). In this case, the maximum eddy growth rate increases substantially because of the increase in low-level baroclinicity in northern region of East Asia.

Figure 14. Composites of geopotential height anomalies (blue contour lines; units: gpm; only those that pass the 0.1 significance level are shown) and wind field anomalies from ERA-interim data (units: m s$^{-1}$; only vectors passing the 0.1 significance level are shown) at (a and b) 500 hPa and (c and d) 700 hPa on (left panel) high BC days and (right panel) low BC days.
mainland and further intensifies the westerlies over the region north of the TP (Figure 12b). However, the westerly wind over the region south of the TP decreases associated with the weakness of maximum eddy growth rate (Figure 11b). These results indicate that two distinct modes of the EA atmospheric circulation are related to BC variation over the TP. One of the modes is linked to a colder winter over China, where the tropospheric westerly wind decreases over northern China but increases over the southern TP (Figure 11). Another mode is opposite to the mode mentioned above.

Furthermore, the two EA atmospheric circulation modes are critical to BC transport from source regions to the TP. Fang and Yang (2016) found that transient eddy vorticity forcing can result in an equivalent barotropic atmosphere in north of the westerly anomalies which is also found in Figure 13. On high BC days, a dipole of the geopotential height anomalies is found over the domain with a strong positive anomaly center over the Lake Baikal and negative anomalies over the entire TP, where the anomalies reach up to 40 gpm at 500 hPa (Figure 13a). The positive geopotential height anomalies over the Lake Baikal tend to shift the EA trough eastward and deepen it, leading to a strong cold air break over China (Figure 10a). The weak westerly winds over the northern TP and northern China benefit the suspension and uplift of BC aerosols over the east slope of the TP (Figure 8). The intensified westerly winds over the southern TP enhance the transport of BC from India to the eastern TP at 500 hPa (Figure 6). A similar pattern also appears at 700 hPa, except for the positive anomaly regions extending southeastward toward northern China (Figure 13c). The negative geopotential height anomalies over India result in westward shift of the south trough over the Indochina Peninsula. Thus, the southern branch of the westerly is also intensified and responsible for the high BC mass loading anomalies over the region south of the TP (Figure 5b). This southwesterly can also bring more BC from the Sichuan Basin to eastern TP and central China.

The geopotential height anomalies on low BC days are generally consistent with those on high BC days, but the anomaly sign is opposite due to the opposite eddy vorticity forcing (Figures 13b, 13d, and 12b). Therefore, the EA major trough tends to shift westward, and the southern trough shifts eastward. The anticyclone anomaly over the TP blocks the transport of BC from India. Simultaneously, the intensified northwesterly can also decrease the BC concentration over the eastern TP and central China. These circulation anomalies

Figure 15. Schematic diagram of the EA atmospheric circulation supporting the transport of BC to the east slope of the TP and its surrounding areas on high BC days.
on high and low BC days are also confirmed using the ERA-interim reanalysis data sets (Figure 14). Regardless of the geopotential height and wind field anomaly center or intensity, the WRF-Chem model accurately captures these features. Overall, these results indicate that EA circulation pattern on high BC days is beneficial for the formation of a high BC concentration layer over the eastern TP, while the EA circulation pattern on low BC days reduces the TP BC.

4. Conclusion and Discussion

In this study, the impacts of two EA atmospheric circulation modes on BC transport to the TP and its surrounding areas are investigated based on the WRF-Chem model combined with multiple observations. The model well captures the spatial and temporal distribution of AOD and wind field over East Asia (Chen et al., 2017). In particular, the surface BC concentration and AAOD over the TP are also reasonably simulated by the model. However, the WRF-Chem model underestimates the AOD over northern India and Bangladesh, which may be possibly associated with the uncertainty of anthropogenic emission inventory in South Asia (Bond et al., 2013) and the neglect of year-to-year growth in BC emission (Lu et al., 2011). The TP is always surrounded by large BC source regions, including northern India, the Sichuan Basin and eastern China. In winter, influenced by the strong westerly and southwesterly wind, a large amount of BC from northern India is transported to eastern TP and the region south of the TP, respectively. BC from Sichuan Basin and central China can be transported to eastern TP along the low-level south wind and northeasterly wind in the PBL, respectively, which is in agreement with previous studies (Lu et al., 2012; Han et al., 2014; Zhang et al., 2015; Li et al., 2016).

In order to identify the typical weather patterns that influence the BC loading over the TP, we use composite analysis method to select high and low TP BC loading days relative to the winter mean BC loading. The strong positive BC anomaly centers near the TP mainly occur over the region south of the TP, eastern TP and central China on composited days (Figures 5b and 5c), indicating that BC aerosol over these regions are sensitive to the EA circulation change. As shown in Figure 15, the EA atmospheric circulation related to high BC days (referred to strong EA circulation mode) is associated with the weakness of westerly wind over northern TP, acceleration of westerly wind over the southern TP, eastward shift of East Asia major trough, strong sea-level pressure, and colder air in China. This circulation mode is possibly associated with the low-level meridional temperature anomaly over East Asia, because the colder air in China weakens the meridional thermal gradient and low-level atmospheric baroclinicity over northern region of East Asia mainland (around 40–50°N), which is prone to decrease the transient eddy activity and then weaken westerly wind over northern China at the entire troposphere. In contrast, the westerly winds over the region south of the TP (around 20–30°N) are intensified due to the enhanced low-level atmospheric baroclinicity and increasing eddy activity. In this case, more BC particles from northern India can be transported to the eastern TP by the enhanced westerly wind in the middle troposphere. In the low troposphere, the transport of BC from India to the south slopes of the TP (i.e., northeastern India and Bangladesh) is also strengthened (Figures 6d and 6f). The enhanced southerly wind over the eastern TP brings more BC from the Sichuan Basin to the northeastern TP and central China (Figures 6a and 6c). In addition, due to the negative transient eddy vorticity forcing over Mongolia and Russia (positive geopotential height anomaly), the EA major trough shifted eastward. As a result, both the sea-level pressure and northeasterly wind increase, and BC from the central China is transported to the east slope of the TP in the PBL (Figures 6g and 6i). The weakened westerly wind over the northern TP and positive anomalous updrafts over east slope of the TP promote the accumulation and uplift of BC that is emitted from local emission and transported from remote sources (Figure 8b), leading to higher BC anomaly over the eastern TP to central China (Figure 5b). In terms of the EA atmospheric circulation on low BC days (referred to weak EA circulation mode), it is opposite to the strong EA circulation on high BC days, and the relationship with thermal anomaly can also be explained using the transient eddy feedback theory. This circulation mode strongly weakens the transport of BC from other source regions to the TP and is not beneficial to the accumulation of BC aerosol, thereby resulting in low BC anomaly over the TP and its surrounding regions (Figure 5c).

The two EA circulation modes in winter mentioned above were first identified by Wang et al. (2010) on the basis of long-term surface temperature variability in winter. Here, the EAWM northern (southern) mode
proposed by Wang et al. (2010) is the same as the EA circulation pattern on low (high) BC days. From our study, we find that the EAWM southern mode supports the transport of BC to the TP while the northern mode weakens this transport. The relationship between BC and EAWM circulation was also investigated by Jiang et al. (2017) based on CAM5 model. Although our study and Jiang et al. (2017) used the same theory (transient eddy feedback) to connect the atmospheric circulation change with low-level meridional thermal gradient, they mainly focused on the effect of TP warming induced by BC on snow on EAWM circulation rather than the effect of atmospheric circulation change on the transport of BC aerosol to the TP. Based on two different BC emission scenarios, they found that BC deposited on snow could spur snow-albedo feedback and increase TP surface air temperature (~1.5 K). The increase in meridional thermal gradient and low-level baroclinicity subsequently intensify the EAWM northern mode through transient eddy feedback. However, this snow-darkening effect of BC on snow is not included in our experiment, which means that the BC deposited on snow has no effect on the TP surface temperature in this study. It is interesting that when EAWM southern mode increases, the BC transport to the TP and the growth in BC deposition on snow may further reverse EAWM southern mode via snow-darkening effect. This topic is worth discussing in future research.

Surface temperature anomaly can be modulated by several potential factors and influence the EA atmospheric circulation significantly. We follow Jiang et al. (2017) and Fang and Yang (2016) to link the BC-related atmospheric circulation change to surface temperature anomaly with the transient eddy feedback mentioned by Nie et al. (2016). Wang et al. (2010) revealed that the development of La Nina episodes and reduction in snow cover over northeast Siberia could promote the formation of EAWM southern mode, a cold winter in China. Li et al. (2018) suggested that when the TP snow cover was higher, the temperature over the TP decreased, and the geopotential height at upper troposphere was lower, thereby enhancing the EAWM southern mode. Jiang et al. (2017) indicated that BC on snow could intensify the EAWM northern mode. In our study, the sea surface temperature is fixed, and the snow-darkening effect of BC is not included, so snow cover change may be an important factor leading to temperature anomaly. As shown in Figure S4, the positive snow water equivalent anomalies appear in the TP, and negative anomalies occur in part of northeast Siberia (the northeast region of domain) on high BC days, which corresponds to the negative surface temperature anomaly in the TP and positive temperature anomaly in northeast Siberia (Figure 9b). Therefore, in this study, the snow cover may be responsible for the surface temperature anomaly, which deserves to be systematically investigated in the future through sensitivity experiments.

Data Availability Statement

The WRF-Chem code is available from https://www2.mmm.ucar.edu/wrf/users/download/get_sources.html#WRFDA. The MODIS aerosol products are available from https://ladsweb.modaps.eosdis.nasa.gov/. The OMI aerosol products are available from https://disc.gsfc.nasa.gov/datasets/OMAERUVd_003/summary?keywords=OMI. The data for the five sites (SACOL, NAM_CO, Kanpur, Taihu and Beijing) are available from the AERONET website (https://aeronet.gsfc.nasa.gov/). The Era-Interim reanalysis data can be derived from https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/. The NCEP/FNL reanalysis data can be derived from https://rda.ucar.edu/datasets/ds083.2/index.html#sfol-wl-/data/ds083.2?g=2.

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