Comparison of Atmospheric CO$_2$, CH$_4$, and CO at Two Stations in the Tibetan Plateau of China

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Abstract The research of greenhouse gases on the Tibetan Plateau is of great importance since its unique topography as the third pole of our planet and profound response on the climate change. In this study, we compared the concurrent observations of atmospheric carbon dioxide (CO$_2$), methane (CH$_4$), and carbon monoxide (CO) during 2010–2016 from two stations located on the Tibetan Plateau, which are Mt. Waliguan station (WLG), the only World Meteorological Organization/Global Atmosphere Watch global station in the inland of Eurasia, and Shangri-La station, a Chinese national station (XGLL).

Although both stations are located at remote area, the atmospheric CO$_2$, CH$_4$, and CO concentrations are frequently influenced by regional sources, especially for XGLL throughout the year and WLG in summer. Due to the unique topography and regional conditions, the atmospheric CH$_4$ and CO at both stations display different trends with other sites in China, with higher values in summer. The atmospheric CO$_2$, CH$_4$, and CO at the XGLL mainly represent the conditions in regional scale. As the only World Meteorological Organization/Global Atmosphere Watch global station in the inland of Eurasia, the observation results at WLG can be used to represent the conditions on the Tibetan Plateau, but some of them are frequently influenced by the emissions from the cities located on the east or north east, and some even can be affect by emissions from the Ganges basin in autumn and winter, which should be treated with caution. By subtracting the influences of the cities, we updated the growth rate of 2.45 ± 0.02 ppm yr$^{-1}$ for CO$_2$, 8.2 ± 0.1 ppb yr$^{-1}$ for CH$_4$, and −0.4 ± 0.1 ppb yr$^{-1}$ for CO, compared to the prior estimation of 2.31 ± 0.02 ppm yr$^{-1}$ for CO$_2$, 8.1 ± 0.1 ppb yr$^{-1}$ for CH$_4$, and −0.6 ± 0.1 ppb yr$^{-1}$ for CO on the Tibetan Plateau.

1. Introduction

The concentration of greenhouse gases (GHGs) in atmosphere has reached an unprecedented level since 1750. Carbon dioxide (CO$_2$) is the most important anthropogenic GHG in the atmosphere (WMO WDCGG data summary, 2018). Methane (CH$_4$) is the second most important GHGs and contributes ~17% of the radiative forcing (Cambaliza et al., 2014). Carbon monoxide (CO) is not a direct GHG, but it can react with hydroxyl radicals (OH) in the atmosphere, indirectly affecting the lifetime of atmospheric CH$_4$ and consequently influencing the global climate (Rajab et al., 2009; Silva, 2010).

The Qinghai-Tibetan Plateau is “the Asian water tower” and “the third pole of the Earth” (Guang-you, 2013; Madsen, 2016; Wilson & Smith, 2015). Surrounded by the highest mountains on Earth, such as the Himalayas and Pamir, the Tibetan Plateau has a profound thermodynamic and dynamic impact on the atmospheric climate and local weather as well as the atmospheric circulation in the Northern Hemisphere (Bollasina & Benedict, 2004; Chen et al., 2003). Recent research shows that surface pollutants in Asia can be transported from the Tibetan Plateau to the global stratosphere (Bian et al., 2020). And Li and Fang (1999) point out that the Tibetan Plateau has become a sensitive indicator of regional and global climate change because of earlier and intense warming. As a result, the impact of increased GHG emissions on climate change in the Tibetan Plateau may be more pronounced than the other parts of the world (Duan 2016; Wilson & Smith, 2015).
et al., 2006). Many scientists have devoted to study the climate change in Tibetan Plateau by using the atmospheric GHGs observations (Chen et al., 2014; Olivier et al., 2005). Some studies also estimate the GHGs fluxes from Asia area based on the expanding network in this region (e.g., Lin et al., 2018; Thompson et al., 2015; Tohjima et al., 2014). However, the surface observations on the Tibetan Plateau are sparse, especially for the long-term observations.

The China Meteorological Administration (CMA) is responsible for the operation and maintenance of GHGs observations over China under the framework of World Meteorological Organization/Global Atmosphere Watch (WMO/GAW). To understand the characteristics of CO₂, CH₄, and CO and the response to increasing atmospheric GHGs concentrations in the Tibetan Plateau region, CMA has started GHGs observation in northeast of the Tibetan Plateau (Mt. Waliguan, Qinghai, China) since 1994. The observed data at this site are routinely submitted to World Data Center of Greenhouse Gases (WDCGG) and used for many scientific products (e.g., Global View database, WMO/GAW GHGs bulletin) (Zhang et al., 2010, 2014). Previous studies mainly focused on analyzing the characteristics of GHGs at WLG station (Cheng et al., 2003; Liu et al., 2014; Zhang & Zhou, 2013; Zhang, Zhou & Xu, 2013; Zhang et al., 2015; Zhou et al., 2007). In 2006, another background station in the Qinghai-Tibetan Plateau named as Shangri-La (XGLL) was built to monitor the GHGs over the Tibetan Plateau. This station is the only regional background station in southwest China (Li et al., 2015). Although both stations are located on the Tibetan Plateau, our previous study noted that the levels and variations of atmospheric CO₂, CH₄, and CO showed different features, which reflected that the observations at these stations had different representative (Fang et al., 2016). To better define the characteristics of GHGs on the Tibetan Plateau, in this study, the observed CO₂, CH₄, and CO from the two stations are compared based on the concurrent data set from 2010 to 2016. Moreover, we try to understand the contribution of regional sources/sinks by investigating the influence of surface wind and air mass transport.

2. Experiment

2.1. Sampling Sites

The locations of Mt. Waliguan (WLG) and Shangri-La station (XGLL) are illustrated in Figure 1. The Waliguan Baseline Observatory (36.29°N, 100.9°E, 3,816 m above sea level [a.s.l.]) is the only WMO/GAW global atmospheric background station in the interior of Eurasia. The observatory is built on the top of Mt. Waliguan in the northeast of the Tibetan Plateau. The GHGs observation has been conducted since 1994. Xining (2.35 million inhabitants) and Lanzhou (3.26 million inhabitants) are the nearest cities, 90 km to the northeast and 260 km to the east, respectively. The area around the site is covered by arid, semi-arid grassland and desert, growing sparse vegetation. There are small agricultural regions located in the lower valley of the mountain. Yak and sheep grazing are the main activities during summer (Zhou et al., 2004). The Shangri-La station (28.01°N, 99.73°E, 3,580 m a.s.l.) is located at the southeast of the Tibetan Plateau. It is ~30 km to the north of the Shangri-La, a tourist town (174,000 residents). There are no villages, agricultural fields, or factories within 5 km radius of the station. The major vegetation types are coniferous and mountain meadows. Atmospheric CO₂, CH₄, and CO mole fractions have been acquired since 2010.

At WLG, the sampling tower, with a height of 89 m above ground level, is 15 m from the laboratory, and the sampling inlet is fixed at 80 m height of the tower. At XGLL, the sampling inlet is fixed at 50 m height on a 55 m sampling tower that is close to the observatory. Meteorological sensors are installed next to the sampling port to automatically measure the wind direction, wind speed and other meteorological factors at both stations.

2.2. Measurement System

Two Cavity Ring-Down Spectroscopy systems (G1301, G1302, Picarro Inc.) were used to continuously measure CO₂, CH₄, and CO at both the stations. In 2015, the instruments were updated to the G2401 model. The air sample is delivered to the instrument by a vacuum pump (UN022, KNF Neuberger, Freiburg-Munzingen, Germany) through a 10 mm O. D. sampling line (Synflex 1300 tubing, Eaton, OH, USA). Then, the ambient air is filtered and induced through a glass trap submerged into a −70 °C methanol bath (MC480D1, SP Industries, PA, USA) to reduce the interference of water vapor. An automated sampling module equipped
with a VICI 8 port multiposition valve is designed to select separate gas streams (stand gases and ambient air) to the instrument. The sample air from inlet at the tower to the analyzer takes less than 5 min. More details about schematic of the system can be found in Fang et al. (2013).

2.3. Calibration, Quality Control, and Data Processing

The dry CO₂, CH₄, and CO mole fractions are referenced to a working high and a working low standard. In addition, a calibrated cylinder containing compressed air is used as the target gas (T) to be regularly fed into the instrument to check the accuracy and stability of the system. All standard gases are pressurized in 29.5 L treated aluminum alloy cylinders (150A, Scott-Marrin, CA, USA) fitted with high-purity, two-stage gas regulators (CGA-590, Scott Specialty Gases, PA, USA). The scale for CO₂ in this study complies with the WMO X2007 scale (Zhao & Tans, 2006). The standard gas of CH₄ is linked to the National Oceanic and Atmospheric Administration (NOAA)/WMO 2004 scale (Dlugokencky et al., 2005; Novelli et al., 1991). The scale for CO is NOAA/WMO 2004 scale, and the measured values are further updated to WMO X2014A scale. The two standards and target gas are analyzed for 5 min every 4 hr. The data used in this research are hourly averages based on each 5 min segments. Detail description of the data processing routine could be referred to Fang et al. (2013). Except for special notes, 95% confidence intervals were used in this study.

3. Results and Discussions

3.1. Diurnal Variations

Figure 2 shows the average diurnal variations of CO₂, CH₄, and CO during 2010–2016, with months of MAM for spring, June–August for summer, September–November for autumn, and December–February for
winter. As located on the high barren mountains, concentrations of CO$_2$ at the WLG are relatively constant in all seasons, except for summer, with distinct diurnal cycles and average peak to valley amplitude of 2.0 ± 0.7 ppm. Contrarily, the atmospheric CO$_2$ at XGLL display distinct diurnal cycles in warmer seasons, with the maximum at 7:00 LT and the minimum at 16:00 LT, which are similar to the results observed at stations located in the eastern China (Fang et al., 2011; Tian et al., 2014), and reflect the influence of the regional terrestrial ecosystem. The XGLL is located at southwestern corner of the cross between the Himalayas with a west-east direction and Hengduan mountain with a north-south direction. With the mountain blocking the humid stream from the Indian ocean, the relatively abundant rainfall (average yearly precipitation 650 mm) induces forest coverage up to 76% in Shangri-La region (Lin, 2016) and consequently, introduces apparent diurnal CO$_2$ cycles in warm seasons. These results also indicate that the CO$_2$ at the XGLL may be mainly subjected to regional conditions, although it is located on the Tibetan Plateau.

Figure 2. Mean diurnal variations of CO$_2$, CH$_4$, and CO mole fractions in four seasons. Spr: MAM; Sum: JJA; Aut: SON; Win: DJF. Error bars are calculated from 95% confidence interval.
However, we find that the CH$_4$ observed at the WLG may be partly influenced by local anthropogenic emissions such as herding and grazing. CH$_4$ concentrations at this site gradually rise after 08:00, reaching its maximum (1,880 ± 2.5 ppb in spring, 1,891 ± 2.8 ppb in summer, 1,884.6 ± 2.3 ppb in autumn, and 1,882.2 ± 2.9 ppb in winter) between 10:00 and 12:00. These increasing values could be ascribed to the transport of emissions from lower valley of the mountain by upslope wind in early daytime. For this reason, unlike to the commonly applied sampling time (14:00 LT) around the world, we collect samples at 8:00 LT in the discrete flask program at WLG to avoid the local influence (Zhou et al., 2004). Similar to characteristics of CO$_2$, the diurnal cycles of CH$_4$ at XGLL are also quite normal and similar to other regional stations in the eastern China, with the lowest value at 14:00–16:00 in the all seasons, when the tropospheric diffusion and photochemical sink by OH radicals are the strongest (Vaghjiani & Ravishankara, 1991).

Like the observation at the high-altitude mountains such as Mt. Tai (1,534 m a.s.l.) in the central east of China (Gao et al., 2005), the CO at both WLG and XGLL present similar patterns with high values during daytime. As there are no distinct CO sources around the stations, these high values probably reflect the transport of boundary layer pollution to the high-altitude mountain due to the daytime upwind slope and the growth of convective planetary boundary layer. By looking at the amplitudes, the values at the WLG are generally higher than those at the XGLL in the respective season, which may reflect the stronger contributions of regional anthropogenic emissions from the cities in WLG region and will be discussed below.
3.2. Influence of Surface Winds

The wind-rose distribution patterns of CO$_2$, CH$_4$, and CO can help to understand the transport of local and regional sources on the concentration (Subramanian et al., 2015). Figure 3 illustrates the distributions of these three gases on the 16 sectors at both stations. The distributions at the WLG clearly reflect the influence of regional transport on the atmospheric concentrations. The average GHGs mole fractions from NNE-NE-ENE-E-ESE sectors are generally high, typically for CO. That is related to the two big cities located at the northeast (Zhou et al., 2004). Contrarily, on the southwest sectors, the GHGs mole fractions are the lowest throughout the year due to the transport from the mainland of Tibetan Plateau with weak anthropogenic emissions. The horizontal wind speed at the WLG also display an inverse variation with other sites with lower speed during daytime and higher in night and the lowest at 10:00–12:00 LT. These variations were negatively correlated to the diurnal variations of CH$_4$ and CO and further reflect the diffusion effects for the local or regional sources (Walters & Fogg, 2015; Zhang et al., 2016), as discussed in the above section.

The transport of local emission may also partly influence the atmospheric GHGs at the XGLL. As the Shangri-La region is famous on the tourism with town of Shangri-La, Lijiang, and Dali to the south or southeast, hordes of tourists visit this place all year around. The intense anthropogenic emissions would enhance the GHGs mole fractions on the south or southeast sectors, especially in summer and autumn when the nicest season comes and southeast wind dominants, with CO$_2$, CH$_4$, and CO mole fractions on southeast sectors about 3.42 ± 0.5 ppm, 8.2 ± 2.3 ppb, and 1.8 ± 2.5 ppb higher than the respective seasonal averages in autumn. However, it should be pointed out these potential sources are located at least 10 km away. This influence may represent regional conditions.

3.3. Impact of Regional Source

To extract the background CO$_2$, CH$_4$, and CO mole fractions, which are minimally affected by nearby sources and sinks (local crops, vegetation, and motor vehicles, etc.), we applied similar methods in previous studies (Cheng et al., 2016; Zhou et al., 2004) to flag the raw data into “background” and “nonbackground” events. For CO$_2$ and CH$_4$, we filtered the data by considering the identical meteorological conditions at WLG similar to the previous studies (Zhou et al., 2003). First, hourly CH$_4$ and CO$_2$ values at 6:00–7:00 LT (local time) were excluded, then the spiking hourly CH$_4$ and CO$_2$ values were flagged by looking at
concentration versus surface wind direction distribution patterns. Generally, hourly CH4 and CO2 values were excluded when the surface wind was originated from the NNE-NE sectors. Finally, hourly records with wind speed less than 1.5 m s\(^{-1}\) were excluded to reduce the possible local pollutions. The data selecting approach at XGLL was different to WLG due to the strong influence of regional vegetation canopy. In terms of the diurnal cycles of atmospheric CO2 and CH4, we first chose the data from 12:00–18:00 LT in the daytime (slightly different in four seasons) and then eliminated those with wind speed less than 1.5 m s\(^{-1}\). For CO, we used the Robust Extraction of Baseline Signal to filter the records, which is widely used in the Global Atmospherics Gases Experiment/Advanced Global Atmospherics Gases Experiment network (Novelli et al., 2003). This method is widely proved to be suitable for identify the background CO at remote sites (Ruckstuhl et al., 2012).

To extract the seasonal cycles and long-term trends at both stations, we applied a curve fitting method, which is commonly used in the community (Thoning et al., 1989). First, three polynomial terms and four harmonic terms were used to fit the data. Then two different low-pass filters were used to filter the residual of the function in time domain (a Butterworth filter that calculates the weighted average over 1.07 years at full width at half maximum [FWHM] of the weighting function and the second filter [1.5 months] at FWHM). The smooth residual was then added to the function to obtain a smooth time series that removes the seasonal cycle (1.07 years FWHM), or represented the approximate monthly value of the second filter.

Figures 4a and 4b show the filtered and fitted CO2, CH4, and CO mole fractions at the two stations. The data gaps are due to the malfunction of instruments, unexpected power failure or maintenance of the gas sampling system. For comparison, we illustrate the discrete CO2 and CH4 weekly measures at WLG collected

Figure 5. Cluster analysis of 72 hr back trajectories for hours when CO2, CH4, and CO mole fractions were all background representative in four seasons. C1, C2, and C3 represent Cluster 1, Cluster 2, and Cluster 3, respectively. The percentages present the relative occurrences.
by NOAA/Earth System Research Laboratory flask program. The sampling time for flask is 8:00 LT in the morning every Wednesday. The mean difference between the flask and in situ measurements is 1.13 ± 0.12 ppm for CO₂ and 4.5 ± 0.5 ppb for CH₄, indicating the consistent of the two measurements.

Totally, at the WLG, 69.2% of hourly CO₂ and 66% of hourly CH₄ are flagged as "background" events. At the XGLL, 34.9% of hourly CO₂ and 25.9% of hourly CH₄ are classified into "background" values. For CO, 66.3% at WLG and 87.5% data at XGLL are considered as background events. The proportion of background events for CO₂ and CH₄ at WLG are apparently larger than those at XGLL, indicating that the CO₂ and CH₄ observed at WLG may be less influenced by local or regional sources. The CO₂ and CH₄ at XGLL are severely influenced by local or regional sources and sinks, especially in summer and autumn; the proportion of background events are only 21.7% and 20.5% for CO₂ and 21.7% and 18.1% for CH₄, respectively. There are few anthropogenic sources in vicinity of the station (within 10 km radius). The observations of GHGs at the XGLL may be dominated by regional events instead of the background information on the Tibetan Plateau. For CO, both stations have high percentage of background events with higher values at XGLL. The lower percentage of background CO at the WLG is also probably due to the sources from surrounding cities (Xining, 90 km to the northeast, and Lanzhou, 260 km to the east).

### 3.3.1. Air Mass Transport

We used the Hybrid Single-Particle Lagrangian Integrated Trajectory model based on National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data to constrain the source/sink-receptor relationships (Cheng & Kabela, 2016; Stein et al., 2015; Stohl, 1996; Zhang, Wang, et al., 2013). The arrival height of the trajectory is set at 500 m above ground level (Zhang et al., 2011). We calculated the 3-day back trajectories at hours corresponding to the background events for CO₂, CH₄, and CO simultaneously. The trajectories in January, April, July, and October were used to represent events in winter, spring, summer, and autumn, respectively. The back trajectories were further clustered by using TrajStat software by Angle distance algorithm (Wang et al., 2009).
Figure 5 and Table 1 illustrate the results of cluster analysis at WLG and XGLL. Although the air mass arrived at the WLG are mostly from the Tibetan Plateau with back trajectories percentage higher than 76.4% in spring, autumn, and winter, there are also 23.6% of trajectories in spring and 11.6% in autumn from the east or northeast, which would transport the emissions from the big cities such as Xining or Lanzhou to the site and enhance the observed values. For example, the average CO mole fraction is 140.2 ± 2.0 ppb for Cluster 1 in spring and 106.6 ± 4.5 ppb for Cluster 2 in autumn, which across the cities area shown in Figure 5. Besides the trajectories from east or northeast, in summer, the Cluster 2 crossing the western Xinjiang, where is rich in grass land resources and Yak and sheep husbandry (Liu & Lv, 2009), obtained significant higher average CH4 mole fraction with value of 1,888.3 ± 2.7 ppb than the other directions (Table 1). More than half of air masses arriving at the XGLL are strongly influenced by regional sources such as northern Myanmar and large cities of the Ganges valley including Kathmandu and Thimbu. As a result, the CH4 and CO mole fractions on the clusters from these directions are apparently higher. A previous study indicated that the CO2 and CH4 mole fractions in the Kathmandu Valley in Nepal, although it is located at the central Himalayas, were much higher than that observed values at XGLL during the same period (Mahata et al., 2017). The transport of air masses may bring the polluted air to the site and consequently elevate CO and CH4 mole fractions (Table 1). Particularly, in summer, large amount of air masses from the cities located at the south (Lijiang, Dali, and Kunming) and northeast (Chengdu) of the station, the average CO mole fractions on Cluster 1 and Cluster 3 are apparently higher than Cluster 2. Besides the emissions from anthropogenic sources, the emissions from wetlands may also contribute to the higher CH4 mole fractions for Clusters 1 and 2. In the southeast of Yunnan, there are many wetlands, such as Lashihai wetland and Bitahai wetland. It has been reported that this area is also an important source of atmospheric CH4 (Chen et al., 2013; Jin et al., 1999). It should be noted that, as the land biosphere may have strong influence on the atmospheric CO2, especially for XGLL in summer and autumn, the load of CO2 mole fractions on each cluster do not display apparent difference at both stations.

3.3.2. Potential Source Contribution

The potential source contribution function (PSCF) method uses the residence time of the back trajectory in space to analyze spatial distribution of probable geographical source locations. To calculate the PSCF, the
The geographic region covered by the trajectories was divided into an array of 0.5 × 0.5° grid cells. Take the average background concentration per season for each site as the background concentration for each grid cell. The number of endpoints that fall in the \(ij\)th cell is denoted by \(n_{ij}\), while the number of trajectories resulting in values that exceed the background value is designated as \(m_{ij}\) (Polissar et al., 1999). The PSCF value for the \(ij\)th cell is then defined as

\[
PSCF_{ij} = \frac{m_{ij}}{n_{ij}}
\]

(1)

The uncertainty of PSCF calculation is large when \(n_{ij}\) is small. Thus, weight function \(W_{ij}\) is introduced to reduce the uncertainty of calculation when the total trajectory numbers in a particular cell are small. \(W_{ij}\) was defined as follows:

\[
W_{ij} = \begin{cases} 
1.00 & 80 < n_{ij} \\
0.70 & 20 < n_{ij} \leq 80 \\
0.42 & 10 < n_{ij} \leq 20 \\
0.05 & n_{ij} < 10 
\end{cases}
\]

(2)

Figures 6 and 7 show the potential source regions of \(\text{CO}_2\), \(\text{CH}_4\), and \(\text{CO}\) at both stations. At the WLG, the potential sources of atmospheric \(\text{CO}_2\), and \(\text{CH}_4\) and \(\text{CO}\) are mainly from the Qinghai-Tibetan Plateau. The atmospheric \(\text{CO}_2\), \(\text{CH}_4\), and \(\text{CO}\) at this station can roughly represent the characteristics on the Qinghai-Tibetan Plateau region. Although the data are filtered when the surface wind was originated from the NNE-NE sectors, the potential sources also partly include from the Lanzhou, Xining and other large cities located in the east and northeast of the site, especially for \(\text{CO}\).

As shown in Figure 7, the atmospheric \(\text{CO}_2\), \(\text{CH}_4\), and \(\text{CO}\) at XGLL station probably influenced by the air mass from South Asia, such as Myitkyina in Myanmar and its surrounding areas, where emissions from biomass burning are relatively active (Nara et al., 2011; Pochanart et al., 2003; Zheng et al., 2004). The phenomenon is more pronounced in the spring. Similar to the previous study (Fang et al., 2016), in spring and...
winter, the GHGs mainly come from some Asian countries and regions in the Ganges basin, such as northern India, Nepal, and Bhutan. The XGLL is in the downwind of India, there are no mountains to block the air mass. The high concentrations of gases emitted from these densely populated areas can easily be carried to the station. In summer, tourism cities like Chengdu and Chongqing in the northeast are acting strong potential sources for high GHGs. Considering the potential sources of CO₂, CH₄, and CO, it can be further indicated that observations at XGLL dominantly represent the characteristics in regional scale instead of conditions on the Tibetan Plateau.

3.3.3. Seasonal Variations of Background Values

Figure 8 shows the detrended seasonal cycle of background CO₂, CH₄, and CO at WLG and XGLL. The surface values during the same period (2009–2016) from the marine boundary layer (MBL) computed by NOAA/Earth System Research Laboratory/Global Monitoring Division at similar latitudes (XGLL compares to sin value of 0.45, MBL 1, WLG compares to sin value of 0.6, MBL 2). CO is compared to the Mauna Loa (MLO, 19.54°N, 155.58°E, 3,397 m a.s.l) in the United States. (b) Difference between from MBL or MLO.

Figure 8. (a) The seasonal variations of CO₂, CH₄, and CO mole fractions at WLG and XGLL. Also compared with the surface values computed at the marine boundary layer (XGLL compares to sin value of 0.45, MBL 1, WLG compares to sin value of 0.6, MBL 2). CO is compared to the Mauna Loa (MLO, 19.54°N, 155.58°E, 3,397 m a.s.l) in the United States. (b) Difference between from MBL or MLO.
trends with MBL, similar to some other stations like the Longfengshan in China (Fang et al., 2017). The largest difference is observed in summer with the bias of $42 \pm 1.5$ ppb at WLG and $48 \pm 1.6$ ppb at XGLL. The CH$_4$ peak in summer should be caused by anthropogenic emissions including yak and sheep grazing (Ma et al., 2002), biomass burning, and as discussed above, the weak photochemical sink by OH radicals at high altitude mountain area (Renhe, 2001).

Similar to CH$_4$, the seasonal CO also display unique variations compared to the Northern Hemisphere and MLO station (WDCGG data summary, 2018) with high value in summer, which is caused by the transport from the southern Asia and regional cities. In the previous study, measurements performed by the CARIBIC aircraft between Germany and India showed that CH$_4$ and CO increased throughout summer, which is similar to the trend in this study (Schuck et al., 2010). These results also indicate that the CH$_4$ and CO observed at the XGLL station can only be used to denote regional events.

### 3.4. Characteristics of Background GHGs at WLG

As the only WMO/GAW global station in the inland of Eurasia, the data at this site are used to represent the background conditions over the Eurasia. We filtered the observations by combining the surface wind.

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**Figure 9.** The growth rates of CO$_2$, CH$_4$, and CO at the WLG station. Blue solid lines represent the background mole fractions, and the dark dashed lines represent further filtered mole fractions (Tibetan Plateau events) by combing the back trajectory.
direction, wind speed, and local topography, as described in section 3.3. This method is also used in our previous studies. However, from the study of air mass transport, the regional anthropogenic emissions from the east or northeast unavoidably influence the atmosphere mole fractions. To precisely understand the background events at the WLG and exclude the information from regional sources, we further filtered the CO₂, CH₄, and CO mole fractions when the trajectories at the corresponding hours are from the east or northeast (Xining and Lanzhou). Table 2 shows further filtered results at the WLG station, with “background” denotes originally filtered values and “Tibetan Plateau” denotes post filtered values exclude the transport of regional sources. As most of the air mass arriving at WLG in spring and winter are from the west, the post filtered mole fractions are almost identical with the previous results. The main differences occurred in summer with the average CH₄ in the post filtered events (Tibetan Plateau events) at 1,892.3 ± 0.6 ppb, ~12.9 ppb higher than the background value. This is opposing to the supposed situations as the potential transport of emissions from the cities are excluded. Actually, in the summer, as discussed in section 3.3, the yak and sheep grazing may play a more important role on the atmospheric CH₄ emissions on the Tibetan Plateau than transport from the cities, which induce much higher CH₄ mole fractions on Cluster 2 (Figure 5 and Table 1). The concentration of CO₂ from the post filtered events is also ~2.57 ppm higher than the background value. Unlike to the CH₄, this higher value is probably due to the absorption from the large area of agricultural regions located between the Xining and Lanzhou (Figure 1).

3.5. Trends of Atmospheric CO₂, CH₄, and CO on the Tibetan Plateau

The growth rates of CO₂, CH₄, and CO are calculated by the first derivative of curve fitting results discussed above. The results were shown in Figure 9. As the GHGs at the XGLL are dominated by regional influence, the results at WLG are considered as the conditions on the Tibetan Plateau. CO₂ in both the background and Tibetan Plateau events display increasing trends, with the value of 2.31 ± 0.03 ppm yr⁻¹ (1σ) for background events, and (2.45 ± 0.02 ppm yr⁻¹) for Tibetan Plateau events. Due to the exclusion of events when air masses are from the east and northeast, the growth rate of 2.45 ± 0.02 ppm yr⁻¹, ~0.14 ppm higher than the prior estimation, should be more appropriate to represent the trend on the Tibetan Plateau. Similarly, we obtained an updated CH₄ growth rate of 8.2 ± 0.1 ppb yr⁻¹ from 2010 to 2016, compared to the prior evaluation of 8.1 ± 0.1 ppb yr⁻¹. The CO mole fractions at WLG display a descending trends in the past years, with the value of −0.4 ± 0.1 ppb yr⁻¹ for Tibetan Plateau events and − 0.6 ± 0.1 ppb yr⁻¹ for background events.

4. Conclusion

In this study, we reported the ground-based observations of atmospheric CO₂, CH₄, and CO from two stations located on the Qinghai-Tibetan Plateau. The influence of local and regional sources on the diurnal cycles, seasonal variations, and trends are discussed by combining the meteorology factors such as wind speed, wind direction, and air mass transport. The trends of CO₂, CH₄, and CO on the Tibetan Plateau are also studied. It is found that both the Mt. Waliguan and Shangri-La station are frequently influenced by local and regional sources. Although both of the two stations are located on the Tibetan Plateau, the atmospheric CO₂, CH₄, and CO at the XGLL can only represent the conditions in regional scale. Due to the unique topography and regional conditions, the atmospheric CH₄ and CO at these two stations

| Season | Tibetan Plateau | Background | Tibetan Plateau | Background | Tibetan Plateau | Background |
|--------|----------------|------------|----------------|------------|----------------|------------|
| Spring | 400.15 ± 0.09  | 399.9 ± 0.12| 1,873.7 ± 0.4  | 1,872.4 ± 0.5| 129.6 ± 0.3    | 129.7 ± 0.3|
| Summer | 393.86 ± 0.15 | 391.29 ± 0.17| 1,892.3 ± 0.6  | 1,879.5 ± 0.7| 125.7 ± 0.5    | 125.8 ± 0.4|
| Autumn | 394.95 ± 0.1  | 394.25 ± 0.12| 1,872.5 ± 0.5  | 1,875.4 ± 0.6| 102.4 ± 0.3    | 104.4 ± 0.3|
| Winter | 396.96 ± 0.07 | 396.96 ± 0.07| 1,868.7 ± 0.3  | 1,868.7 ± 0.3| 112.8 ± 0.2    | 112.8 ± 0.2|

Note. The error bar represents 95% confidence interval.
display different trends with other sites. As the only WMO/GAW global station in the inland of Eurasia, the observation results at WLG can be used to represent the conditions on the Tibetan Plateau. But some results are frequently influenced by the emissions from the cities located on the east or northeast, and they even can be affected by emissions from the Ganges basin in autumn and winter, which should be treated with caution.

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