

Characteristics And Source Analysis of Greenhouse Gas Concentration Changes at Akedala Station in Central Asia

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Akedala Atmosphere Background Station

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Abstract

Mole fractions of atmospheric carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and sulphur hexafluoride (SF₆) have been continuously measured since September 2009 at the Akdala station (47°06'N, 87°58'E, 563.3 masl) in China. The station is located in the Central Asia and northwest of China, and it is the only station in that region with background conditions for long-term greenhouse gas observations. Characteristics of the mole fractions, growth rates as well as influence of long-distance transport were studied considering data from September 2009 to December 2019. The greenhouse gases concentrations at Akedala Station show a trend of year-on-year growth, with CO₂ concentrations ranging from 389.80×10^{-6} to 408.79×10^{-6} (molar fraction of substances, same below), CH₄ concentrations ranging from 1890.07×10^{-9} to 1976.32×10^{-9} , N₂O concentrations ranging from 321.26×10^{-9} to 332.03×10^{-9} , and SF₆ concentrations ranging from 7.04×10^{-12} to 10.07×10^{-12} , the growth rate of which is similar to the decadal average growth rate in the northern hemisphere. There exist obvious seasonal variations, with CO₂ concentrations showing high in winter and low in summer and CH₄ showing a distinct "W"-shaped trend while N₂O and SF₆ showing little difference between the four seasons. A relatively strong correlation and homology exist among the four greenhouse gases except in summer, and the analysis based on backward trajectories model shows that the Akedala Station is influenced by the airflow from northwest or southwest throughout the year. The Akedala station is an important atmospheric background station in Central Asia, and its greenhouse gas concentration levels and variation characteristics are significantly different from those of the background stations in the monsoon region. Its degree changes are closely related to local source emissions, monsoon transport, and atmospheric photochemical processes.

Introduction

In recent times, the technology of human society has developed very rapidly. With the accelerating global industrialization following the industrial revolution, the concentrations of greenhouse gases in the atmosphere have shown a significant trend of increase (IPCC, 2021; WMO, 2020). Carbon dioxide (CO₂), Methane (CH₄), Nitrous oxide (N₂O) and Sulfur hexafluoride (SF₆) are the gases in the atmosphere with long life and potential to heat up (WMO, 2020). Greenhouse gas emissions from human production activities have become an important driver of climate change. The increase in global temperature is caused by the increase in greenhouse gas concentration, which brings about a series of extreme weather events such as droughts, floods, cold waves, and sea level rise, leading to a negative impact on people's production and life and bringing great damage to the natural environment (An X, 2012; Ou-Yang C F, 2014; He J H, 2020). To achieve the 2°C warming target of the Paris Agreement, the study of the characteristics and sources of long-term changes of greenhouse gases in typical regions is essential for formulating energy conservation and emission reduction policies and actively responding to climate change such as global warming.

At present, domestic and foreign atmospheric background stations have carried out continuous observations of greenhouse gas concentrations for many years (Lioubimtseva E, 2009), and long-term atmospheric composition observations are necessary to assess the impact of human activities on climate and the environment, and to provide basic data for regional climate change research work. The study of CO₂ and CH₄ concentration levels and variation characteristics from 2009 to 2013 at Shangdianzi atmospheric background station in North China background region and Longfeng Mountain atmospheric background station in Northeast China background region shows that there are obvious differences in CO₂ and CH₄ variations between North China and Northeast China (Dong, 2016; Fang, 2017). Hyeon-Kook Kim (2020) analyzed the characteristics and sources of CO₂ and CH₄ concentrations in the southern highlands of Korea, and found that CH₄ concentrations showed a significant upward trend and seasonal variation, and contributed to the development of environmental protection measures by using a backward trajectory model to identify its winter sources as Mongolia, northeastern China, and industrial cities in northwestern Korea. The Valiguan Global Atmospheric Background Station represents the atmospheric background characteristics of the Asian and European continents, and the changes in greenhouse gas concentrations are an important data support for global climate change (Xu, 2018). While the atmospheric background stations in Asia and Europe show an uneven distribution, the number of atmospheric background stations in Europe and the eastern monsoon region of Asia is high and concentrated in the research work (Cheng, 2015). Studies on the concentration characteristics and sources of greenhouse gases in Central Asia and the arid zone of Northwest China are limited, and the time scales of the studies are relatively short, and there are insufficient studies on the correlation of atmospheric CO₂, CH₄, N₂O, and SF₆ concentration changes and their sources.

Central Asia is one of the most important arid regions in the world, and its climate characteristics are significantly different from those of East Asia and Europe, with interspersed mountain basins, deserts and oases (Zhang, 2020; Li, 2017). At the same time, the Central Asian region is the upper reaches of China's weather and the core area of the "Belt and Road" construction. Although important progress has been made in climate and environmental research on precipitation and temperature in the Central Asian region (Sorg A, 2012), there is insufficient research on the characteristics of long series changes of greenhouse gases such as CO₂. The Akedala National Atmospheric Background Station is one of the six regional atmospheric background stations established by the China Meteorological Administration, located in the Gobi of the Altai region of Xinjiang, China, and the background parameters have been scientifically demonstrated to be representative of the background conditions in Central Asia and the northern border of Xinjiang(Xu, 2004).

This paper presents the long-term trends and seasonal variations in akedala atmospheric CO₂, CH₄, N₂O and SF₆ concentrations and discusses the possible influencing mechanisms during 2009 to 2019. The linear trend analysis method, the contrastive and statistical analysis method and Mann-Kendall method are applied to explore characteristics of the time series and seasonal trends of greenhouse gases at this station and tested whether abrupt change exists. In addition, Pearson Correlation Coefficient is used to determine the correlation and homology among the four greenhouse gases and backward trajectories model is applied to explore the source of greenhouse gases at Akedala Station in different seasons. Our study is expected to provide valuable information for the study of the long-term atmospheric composition evolution and the impact of atmospheric composition on the climate, ecology and environment of Central Asia and Northwest China.

Material And Methods

2.1 Overview of the Station and Data Sources

Central Asia is a globally important arid zone, which has formed a unique climate system due to its unique topography, substratum type, and water cycle variability characteristics. During the global warming process, Central Asia has shown a jump in temperature increase in the last 20 years, which has attracted the attention of many scholars (Chen, 2016; Hu, 2014). Akedala Background Atmosphere Station (AKDL, 47°06'N, 87°58'E, 563.3m above sea level) is located in the Gobi wetland in the eastern part of Fuhai County, Altay Prefecture, Xinjiang, also the northern margin of Junggar Basin. Within 50km around the station are alluvial flat land and Gobi. The nearest village is 5 km away from the site, with few people around and no trails of complex human activities (Feng, 2021). Akedala Station is located in an area of temperate continental arid climate, which is a typical arid and semi-arid region. The climate in this region is characterized by hot summer with little rain, large temperature difference between day and night, relatively cold winter, short spring and autumn and frequent windy days. The vegetation type of its underlying surface is desert steppe, which is representative in North Xinjiang and in the hinterland of Asia. Westerly and northwesterly winds prevail throughout the year, with more easterly winds in winter. Akedala station is located in the hinterland of Asia and Europe, far from the ocean, and belongs to the westerly wind belt control area, which is also the upstream area of Chinese weather (Wang, 2012). The geographical location of Akedala Station is shown in Fig. 1.

2.2 Data Sources and Quality Control

The sampling point is located at Akedala Regional Background Atmosphere Station, which is one of the field test bases of the China Meteorological Administration. The samples of greenhouse gases were collected and analyzed according to the method recommended by WMO/GAW, using a portable sampler and Flask rigid glass bottles, with a sampling frequency of 1 time per week. The time for sampling was chosen to be around 14:00 Beijing time with wind speed faster than 2m/s, avoiding rain, fog, sand and dust during this period. The samples were sent to the greenhouse gas laboratory of the China Meteorological Administration for the analysis of trace components of greenhouse gases. The data used in this study were obtained from the China Meteorological Administration after quality control and the study period was from September 2009 to December 2019.

The data for the same period of the Waliguan Global Background Atmosphere Station, Hohenpeissenberg Global Background Atmosphere Station in Germany, and Tae-ahn Peninsula Regional Background Atmosphere Station in Korea were obtained from the WMO World Data Centre for Greenhouse Gases (<https://gaw.kishou.go.jp/>) for the comparative analysis of time series changes. The data sources and location of each station are shown in Table 1.

2.3 Research Methods

The trend analysis method, contrastive and statistical analysis method were used for analysis of time series characteristics of greenhouse gases, and Mann-Kendall method was used to study abrupt change (Mann, 1945; Kendall, 1975; Wei, 2007, Xing et al., 2015, Yang et al., 2018). Pearson Correlation Coefficient was used to research the correlation of between greenhouse gases, and HYSPLIT backward trajectory analysis was adopted to study of potential source regions.

Results And Discussion

3.1 Time Series Analysis of Greenhouse Gases Concentrations

The location and time series variation of greenhouse gases concentrations from 2009 to 2019 at Akedala Station, Waliguan Station, Hohenpeissenberg Station, and Tae-ahn Peninsula Station are shown in Fig. 2 and 3. Fig. 3 shows that CO₂, CH₄, N₂O, and SF₆ concentrations at these four stations have all experienced an increasing trend and had a pronounced seasonal periodic variation.

The CO₂ concentration ranged from 387.38×10⁻⁶ to 411.06×10⁻⁶ at Waliguan Station, from 389.80×10⁻⁶ to 408.79×10⁻⁶ at Akedala Station, from 387.88×10⁻⁶ to 413.21×10⁻⁶ at Hohenpeissenberg Station and from 390.24×10⁻⁶ to 418.67×10⁻⁶ at Tae-ahn Peninsula Station. The CO₂ concentration at TAP station was significantly higher than the other three stations, with the concentration in these stations ranked from high to low as TAP>HPB>AKDL>WLG. And the growth rates were 2.37×10⁻⁶ yr⁻¹ at WLG, 1.90 ×10⁻⁶ yr⁻¹ at AKDL, 2.53×10⁻⁶ yr⁻¹ at HPB and 2.85 ×10⁻⁶ yr⁻¹ at TAP (Fig. 4, a). The growth rate of CO₂ in the Northern Hemisphere was 2.27×10⁻⁶ yr⁻¹ in the last decade with the growth rate of Akedala Station slightly lower than the average level, which may be related to the location of the background station and the source and sink. The WLG Station is located on the Qinghai-Tibet Plateau, which is sparsely populated and is less affected by the source region of emission (Liu, 2014). the HPB Station is located in the mountainous region of southern Germany, and it is an important crop production area. And the Altay Prefecture of Xinjiang, where the AKDL Station is located, has a long heating period, which may be a factor influencing the concentration of CO₂, while the TAP Station is located in the coastal area of South Korea, with a relatively developed economy and more human activities (Chung, 2013; KJ Lee et al., 1993; Jeeyoung Ham et al., 2019).

The CH₄ concentration variation range was from 1899.92×10⁻⁹ to 1991.08×10⁻⁹ at WLG, from 1890.07×10⁻⁹ to 1976.32×10⁻⁹ at AKDL, from 1912.42×10⁻⁹ to 1984.67×10⁻⁹ at HPB and from 1912.35×10⁻⁹ to 1991.07×10⁻⁹ at TAP. Overall, the CH₄ concentration at HPB Station and TAP Station were slightly higher than those at WLG Station and AKDL Station. The growth rates were 9.12 ×10⁻⁹ yr⁻¹ at WLG, 8.62 ×10⁻⁹ yr⁻¹ at AKDL, 7.22 ×10⁻⁹ yr⁻¹ at HPB, and 7.87 ×10⁻⁹ yr⁻¹ at TAP (Fig. 4,b) with a decadal average growth rate of 7.3 ×10⁻⁹ yr⁻¹ for the Northern Hemisphere (WMO, 2020), and the growth rates of WLG Station and AKDL Station were significantly higher than those of HPB Station and TAP Station. The variation and growth of CH₄ concentration were affected by source region, biological factors and photochemical factors (Zhang, 2018). HPB Station and TAP Station are located in wet areas, which are major crop production areas and urban zones (Kim,2020, Dlugokencky,2013), while WLG Station and AKDL Station are relatively less influenced by source regions, so differences in concentrations arose. The location of HPB Station and TAP Station might have strong photochemical action, resulting in relatively low growth rates of CH₄ concentration, and the relatively high growth rates of CO₂ were due to the formation of CO₂ from CH₄ under photochemical action (Zhang, 2021).

The variation range of N₂O concentration was from 322.88×10⁻⁹ to 332.43×10⁻⁹ at WLG, from 321.26×10⁻⁹ to 332.03×10⁻⁹ at AKDL, from 323.46×10⁻⁹ to 333.16×10⁻⁹ at HPB and from 323.35×10⁻⁹ to 333.42×10⁻⁹ at TAP, with the growth rate of 0.95 ×10⁻⁹ yr⁻¹ at WLG, 1.08 ×10⁻⁹ yr⁻¹ at AKDL, 0.96 ×10⁻⁹ yr⁻¹ at HPB and 1.01 ×10⁻⁹ yr⁻¹ at TAP (Fig. 4,c), not significantly different from the decadal average growth rate of 0.96 ×10⁻⁹ yr⁻¹ in the Northern Hemisphere. The SF₆ concentration ranged from 6.97×10⁻¹² to 10.19×10⁻¹² at WLG, from 7.04×10⁻¹² to 10.07×10⁻¹² at AKDL, from 7.01×10⁻¹² to 10.21×10⁻¹² at HPB and from 7.14×10⁻¹² to 10.36×10⁻¹² at TAP (Fig. 4,d). Although the content of N₂O and SF₆ are relatively low in the atmosphere, it is quite evident that they had a clear rising trend in the last decade, and the results from four stations had a strong consistency on this point. More attention is needed for the variation of N₂O and SF₆ concentrations in the atmosphere.

3.2 Seasonal Variation of Greenhouse gases Concentrations

Affected by biological and non-biological sources, the emissions of greenhouse gases showed a pronounced seasonal variation. Fig. 5. represents the variation of the average values in every months of greenhouse gases concentrations at Akedala Station over the years. At this Station, CO₂ and CH₄ concentrations showed more obvious seasonal variation while N₂O and SF₆ concentrations showed less. The CO₂ concentration rose to the highest level in March and April, with a highest value of 406.0×10^{-6} in April, and then fell to the lowest level in August, with the lowest value of 389.0×10^{-6} . The change of CH₄ concentration presented an approximate "W"-shaped trend, with a downward trend from January to June, and a rising to a peak in July and August, followed by a gradual decrease till to the bottom in September, and an increase afterwards. The "W"-shaped trend was roughly similar to the trend of CH₄ concentrations at Stations like Shangdianzi Station and Longfenshan Station (K. Mueller, 2018; Dai, 2018). The CH₄ concentration showed two peaks in July and January of the following year (Zhang, 2011). The CH₄ concentration at Akedala Station reached 1924.6×10^{-9} in August and 1975.6×10^{-9} in January. The monthly average concentration of N₂O and SF₆ showed fluctuations, with insignificant seasonal variations and small fluctuating range.

In China, winter is from December to February, spring is from March to May, summer is from June to August, and winter is from September to November. Based on the average values in every months of greenhouse gases concentrations at Akedala Station, the analysis of the data of different seasons was carried out. Figure 6 shows the seasonal variation of greenhouse gases at Akedala Station. It can be seen that there were obvious seasonal differences in CO₂ and CH₄ concentrations, while N₂O and SF₆ concentrations didn't vary significantly from season to season. The CO₂ concentration at Akedala Station in the four seasons was in the order of winter, spring, autumn and summer from high to low, which were roughly consistent with the variation of CO₂ concentration at Shangdianzi Station (Zhang, 2020). Similar to Shangdianzi Station, Akedala Station is located in the northern part of Xinjiang where winter is cold and residents need to heat their homes by means like burning coal. The burning of fossil fuels increased the CO₂ content in the atmosphere in winter, while in summer, ground living plants consumed CO₂ in the atmosphere through comparatively strong photosynthesis, so CO₂ concentration showed obvious seasonal variation (Ou-Yang et al., 2014). CH₄ concentration showed an overall trend of high in winter and autumn and low in spring and summer, and this trend was opposite to the seasonal variation at Waliguan Station and Shangdianzi Station (Zhang, 2013; Fang, 2017). The air masses in winter and autumn were mostly influenced by the northwest airflow, and in winter the airflow from the northern economic zone increased significantly. In summer, both rainfall and UV light were more intense, contributing to the photochemical action of CH₄ (Xu, 2011).

N₂O concentrations in summer were slightly lower than those in the other three seasons, while SF₆ concentrations remained essentially unchanged in all seasons, which were mainly influenced by various factors such as photochemical action and long-range air mass movement.

The seasonal variation of greenhouse gases at Akedala Station reflected the influence and effect of the periodic variations in the terrestrial biosphere in typical regions of Northwest China and Central Asia on the atmosphere.

3.3 Mann-Kendall Test on Greenhouse Gases Concentrations

Mann-Kendall method is frequently used to analyze the internal characteristics of hydrological time series. The results of M-K test for greenhouse gases concentrations at Akedala Station are shown in Fig. 7. The U_F and U_B of CO₂ concentrations at the Akedala Station were higher than 0 from 2009 to 2017 and lower than 0 from 2017 to 2019, with a clear rising trend of the annual average concentration over the 11 years, reaching a maximum in 2018 and then a decrease in 2019. The change trend of CH₄, N₂O and SF₆ concentrations were roughly the same, and U_F and U_B were higher than 0 during the observation period, indicating that their concentrations showed a rising trend. The results of the M-K test for CO₂, N₂O and SF₆ exceeded the 0.05 trend line since 2012 and exceeded the 0.001 significance level since about 2014 ($U_{0.001}=2.56$), proving that the growth of CO₂, N₂O, and SF₆ concentrations showed a non-significant growth from 2009 to 2012, while showed a very obvious increasing trend from 2012 to 2019. And the result for CH₄ exceeded the 0.05 trend line in 2014 and showed an evident increase since that year. Since 2000, with the gradual advancement of The Great Western Development Strategy, Xinjiang's economic and social development has been promoted significantly. According to the Xinjiang Statistical Yearbook, the GDP of the region increased rapidly from 427.705 billion yuan in 2009 to 1219.9 billion yuan in 2018, which had a clear synchronous change with the rising trend of greenhouse gas concentration.

Both GDP and population growth became important anthropogenic sources of greenhouse gases emissions. In 2012, the opening year of the 12th Five-Year Plan, Xinjiang's GDP reached 750.531 billion yuan, achieving a 12% growth, of which the above-scale industrial added value reached 285.006 billion RMB, an increase of 12.7%. The rapid economic growth might become one of the important reasons for the increasing emission of greenhouse gases such as CO₂. According to the Xinjiang Statistical Yearbook, Xinjiang's GDP grew to 727.346 billion yuan in 2014 compared with the previous year, with a growth rate of 10%, and above-scale industrial added value reached 315.129 billion yuan. It is worth nothing that CO₂ concentration might have shown a decreasing trend since 2019, which might be related to the strong control policies in the source regions. Since 2018, the Altay Prefecture has realized electric heating in the whole region for environmental protection and ecological construction. In addition, some progress has been made in mine management, and work related to the disposal of abandoned mines has been started in order to realize the goal of building a beautiful China.

3.4 Correlation Analysis of Greenhouse Gases Concentrations

To better explore the potential source regions of greenhouse gases at Akedala Station, it is necessary to make further investigation of the correlation between various greenhouse gases concentrations. Correlation analysis was performed on the monthly averages of greenhouse gases concentrations at the Akedala Station from 2009 to 2019, and the numbers of data involved in the analysis totaled 32 of spring, 34 of summer, 34 of autumn and 32 of winter. Pearson correlation coefficients were calculated between the greenhouse gases concentrations throughout the year and in each season, and the results are presented in Tab 2. Pearson correlation between greenhouse gases was more significant in spring, autumn and winter than in summer at the Akedala Station, which was particularly evident between CO₂ and CH₄. Pearson correlation coefficients between CO₂ and CH₄ were 0.746 (p<0.01), 0.880 (p<0.01), 0.328 (p<0.05), 0.870 (p<0.01), and 0.860 (p<0.01) for a year-round, spring, summer, autumn, and winter respectively. From the data, it is obvious that CO₂ and CH₄ were significantly correlated except in summer. The reason for the exception in summer was mainly because the CO₂ concentration in the atmosphere in summer was more influenced by source-sink effect of terrestrial ecosystems, while the photochemical action of CH₄ was stronger in summer, and the OH free radical concentrations was higher in this season, leading to the conversion of part of CH₄ into CO₂ through photochemical action. Pearson correlations between CO₂ and N₂O, CO₂ and SF₆, CH₄ and N₂O, and CH₄ and SF₆ were significant throughout the year as well as in all seasons respectively.

In summary, the Akedala background station is located at the margin of Junggar Basin, the south of which is the core economic region of northern Xinjiang. Greenhouse gases concentrations were affected by anthropogenic greenhouse gas emissions and terrestrial ecosystem. The homology of greenhouse gases was more obvious in spring, autumn and winter, while the influence of terrestrial ecosystems and photochemical action in summer made the homology of greenhouse gases less obvious in this season. Therefore, the subsequent analysis of air mass pathways and potential source regions needs to be researched according to different seasons.

3.5 Analysis of Potential Source Regions in Different Reasons

The variation of greenhouse gases concentrations at background atmosphere station is also closely related to the external air masses. In order to study the effects of long-range transport and atmospheric boundary layer conditions on the variation of greenhouse gases concentrations at Akedala Station in different seasons, a backward trajectory model was used to trace the trajectories of air masses in different seasons. Based on the result of the backward trajectory, six main trajectories were identified for each season (Fig. 8), and their pressure distribution was shown in Fig. 9. From Fig. 8, differences in the trajectories of air masses in four seasons at Akedala station with significant seasonal transport characteristics. The Akedala Station was mainly influenced by the air mass from the northwest, accounting for 46.22%, 61.90%, 52.90% and 72.82% of all trajectories in winter, spring, summer and autumn respectively (Tab 3), and air pressures of most of air masses were above 800hPa (Fig. 9). Therefore, the northwest path originating from Central Asia and parallel to the valley of the Irtysh River is the main channel for the movement of air masses.

In winter, air masses 1, 2 and 3 played a dominant role, accounting for 75.80% of all trajectories (Tab.3). Air mass 1 came from the northern Xinjiang, arriving at Akedala station from the southeast., which was in line with the direction of Urumqi, the provincial capital of Xinjiang. In winter, under the influence of Mongolian high pressure, part of the airflow from Urumqi and other places crosses the Guerbantonggute Desert, and greenhouse gases are transported to Akedala Station via the air mass over a short

distance (Li, 2020). The air mass 1 might have high greenhouse gases concentrations due to the need to burn biomass fuel for heating in northern Xinjiang. Air mass 2 arrived here after a long distance. It came from the industrial zone of eastern Kazakhstan, where heavy industries such as mining and non-ferrous metal smelting were concentrated. Under the combined effect of westerly winds, it was transported eastward to arrive the Akedala Station, potentially bringing more greenhouse gases. Air mass 3 came from Mongolia. Air masses 4 and 6 came from the northern Xinjiang, passing through cities with developed industries such as Karamay, and air mass 5 came from the southern part of Russia after a long-distance transport. Except for air mass 5, the air pressures of the rest air masses were all above 750 hPa (Fig. 9).

In the spring, air masses 4, 5, and 6 played a dominant role, and they accounted for 72.07% of all trajectories (Tab.3). Air masses 4 and 5 came from the eastern part of Kazakhstan, while air mass 6 came from the northern part of Xinjiang, located to the southeast of Akedala Station. Therefore, the greenhouse gas concentrations in the spring were mainly affected by industrial emissions transported from eastern Kazakhstan for a long distance and from northern Xinjiang for a short distance, which might carry some of the greenhouse gases to Akedala Station (Zhao,2021). Air mass 1 crossed the industrially developed cities of Karamay, while air masses 2 and 3 came from the south of Russia, passed the border of Mongolia and reached Akedala Station from the northeast. The air pressures of these two air masses were below 750 hpa, which were relatively low, and the air pressures of other air masses were above 750hpa (Fig. 9).

In summer, air masses 1, 2 and 4 became the dominant, accounting for 82.37% of all trajectories. Air masses 1 and 2 both came from the eastern part of Kazakhstan, accounting for about 67.23% of all trajectories (Tab.3), and air mass 4 came from southern Russia and reached here after a long distance. Because the Akedala station is located in the arid zone of Central Asia, far from the ocean, it is significantly affected by the westerly wind belt in summer, and almost all air masses come from Central Asia or further away from Russia. There existed noticeable difference in terms of pressure distribution. Air masses 2 and 4 were dominant and air pressures of them were mainly above 860hpa, while those of others were basically below 860hpa. (Fig. 9).

In autumn, the predominant air masses were number 2, 4 and 6, accounting for about 68.47% of all trajectories (Tab 3), mainly from the eastern part of Kazakhstan. Air masses 2 and 4 were formed when airflow from distant Kazakhstan reached the Akedala Station under the influence of the westerly wind, so their air pressures were relatively close to each other. In addition, air masses 1 and 3, which came from the northern Xinjiang, accounted for 27.19% of the total trajectory (Tab 3). Air mass 5 reached the Akedala Station over the long distance of Altai Mountains. Since southern Russia was sparsely populated, the amount of greenhouse gases carried in the airflow might be relatively low, and the air mass pressure was significantly lower (Fig. 9).

Conclusion

CO₂, CH₄, N₂O and SF₆, as common greenhouse gases, are among the key contributors to global climate change and extreme weather events. In this study, greenhouse gases concentrations at Akedala Station from 2009 to 2019 were analyzed, and conclusions were drawn as follows.

(1) After a comparative analysis of the annual average concentrations and growth rates of CO₂, CH₄, N₂O and SF₆ in four regions at the same latitude as the northern hemisphere and located in the monsoon and westerly wind control regions, respectively, and in different locations in Asia and Europe, the greenhouse gas concentrations at the four stations showed a clear upward trend from 2009 to 2019. The growth rates of CO₂ concentration in the four regions were $2.37 \times 10^{-6} \text{ yr}^{-1}$ (WLG), $1.90 \times 10^{-6} \text{ yr}^{-1}$ (AKDL), $2.53 \times 10^{-6} \text{ yr}^{-1}$ (HPB) and $2.85 \times 10^{-6} \text{ yr}^{-1}$ (TAP). The growth rates of CH₄ concentration were $9.12 \times 10^{-9} \text{ yr}^{-1}$ (WLG), $8.62 \times 10^{-9} \text{ yr}^{-1}$ (AKDL), $7.22 \times 10^{-9} \text{ yr}^{-1}$ (HPB) and $7.87 \times 10^{-9} \text{ yr}^{-1}$ (TAP). N₂O concentration growth rates were $0.95 \times 10^{-9} \text{ yr}^{-1}$ (WLG), $1.08 \times 10^{-9} \text{ yr}^{-1}$ (AKDL), $0.96 \times 10^{-9} \text{ yr}^{-1}$ (HPB) and $1.01 \times 10^{-9} \text{ yr}^{-1}$ (TAP).

(2) Changes in greenhouse gas concentrations were closely related to factors including biological and non-biological sources, atmospheric boundary layer conditions and sources regions. The results of the M-K test for greenhouse gases concentrations at Akedala Station showed a significant rising trend during the observation period. The results indicated that CO₂ concentration showed a distinct increase since 2014, while CH₄, N₂O, and SF₆ showed a clear increase since 2012. The greenhouse gases concentrations at Akedala Station showed obvious seasonal variations, with CO₂ concentration being high in winter and low in summer, CH₄ concentration showing a clear "W"-shaped trend, and N₂O and SF₆ concentrations showing little difference between

the four seasons. A strong correlation and homology were observed between the different greenhouse gases concentrations at the Akedala Station in spring, autumn and winter, while a poor homology was observed in summer. The Akedala station is critically located in the core area of Central Asia and can reflect the trend of background atmospheric background concentration in Central Asia, which is of great significance for climate change research work in Central Asia.

(3) The results of the backward trajectory analysis showed that the Akedala Station was influenced by strong northwesterly airflow in all seasons, with eastern Kazakhstan being one of the main sources of the airflow. And the station was also affected by airflow from the northern Xinjiang. The airflow from the south of Russia was noticeably stronger in summer, which might have an impact on the greenhouse gases concentrations at Akedala Station.

Declarations

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Conflict of 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.

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Author's Contribution

All authors contributed to the study conception and design.

Conceptualization: Zhujun Zhao; Methodology: Zhujun Zhao and Zhongqi Lu; Formal analysis and investigation: Zhujun Zhao and Quanwei Zhao; Writing - original draft preparation: Zhujun Zhao and Zhongqi Lu; Writing - review and editing: Zhujun Zhao and Qing He; Funding acquisition: Qing He; Resources: Jianlin Wang; Supervision: Qing He.

All authors have read and agreed to the published version of the manuscript.

Data availability

Results from this research can be shared. However, the original greenhouse gas data were collected with the agreement regarding its distribution to which we have to be complying with. The Akdala data used in this study were obtained from the China Meteorological Administration after quality control. The data for the same period of the Waliguan Global Background Atmosphere Station, Hohenpeissenberg Global Background Atmosphere Station in Germany, and Tae-ahn Peninsula Regional Background Atmosphere Station in Korea were obtained from the WMO World Data Centre for Greenhouse Gases (<https://gaw.kishou.go.jp/>) for the comparative analysis of time series changes.

Code availability

The software that has been used is free software and can be accessed freely.

Ethics approval

The authors declare that there is no human or animal participant in the study. Not applicable.

Consent to participate

The authors declare that there is no human or animal participant in the study. Not applicable.

Consent for publication

The authors give their consent to the publication of all details of the manuscript including texts, figures, and tables.

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Tables

Table 1
The data sources and location of four stations

GAW ID	Station	Contributor	Country/territory	Latitude(north: +; south: -)	Longitude(east: +; west: -)	Elevation(m)
AKDL	Akedala	CMA	China	47.10	87.93	563
WLG	Mr.waliguan	NOAA	China	36.17	100.54	3816
HPB	Hohenpeissenberg	NOAA	Germany	47.80	11.01	985
TAP	Tae-ahn Peninsula	NOAA	Republic of Korea	36.73	126.13	20

Table 2

Pearson correlation coefficients were calculated between the greenhouse gases concentrations throughout the year and in each season.

Pearson correlation coefficient	All year	Spring	Summer	Autumn	Winter
CO ₂ - CH ₄	0.746**	0.880**	0.328*	0.870**	0.860**
CO ₂ - N ₂ O	0.690**	0.815**	0.668**	0.794**	0.886**
CO ₂ - SF ₆	0.598**	0.816**	0.523**	0.791**	0.877**
CH ₄ - N ₂ O	0.670**	0.829**	0.834**	0.828**	0.615**
CH ₄ - SF ₆	0.633**	0.858**	0.868**	0.830**	0.631**
N ₂ O- SF ₆	0.935**	0.964**	0.931**	0.936**	0.932**

Note: * Represents Significant Correlation at 0.05 level, ** Represents significant correlation at 0.01 level.

Table 3

Trajectory numbers and percentage based on all trajectories (bold values represent the polluted clusters).

Season	Clusters	The Percentage of All Trajectories (%)	The Source Area of Air Masses
	1	34.48	northeast Xinjiang, China
	2	26.60	eastern Kazakhstan
Winter	3	14.72	Mongol Uls
	4	6.59	northeast Xinjiang, China
	5	10.28	southern Russia
	6	9.34	northeast Xinjiang, China
	1	13.78	northeast Xinjiang, China
	2	6.05	southern Russia
Spring	3	8.20	southern Russia
	4	25.81	eastern Kazakhstan
	5	27.89	eastern Kazakhstan
	6	18.28	northeast Xinjiang, China
	1	25.44	eastern Kazakhstan
	2	41.79	eastern Kazakhstan
Summer	3	2.36	eastern Kazakhstan
	4	15.14	southern Russia
	5	8.75	eastern Kazakhstan
	6	6.53	northeast Xinjiang, China
	1	19.22	northeast Xinjiang, China
	2	25.45	eastern Kazakhstan
Autumn	3	7.97	northeast Xinjiang, China
	4	22.72	eastern Kazakhstan
	5	4.35	southern Russia
	6	20.30	eastern Kazakhstan

Figures

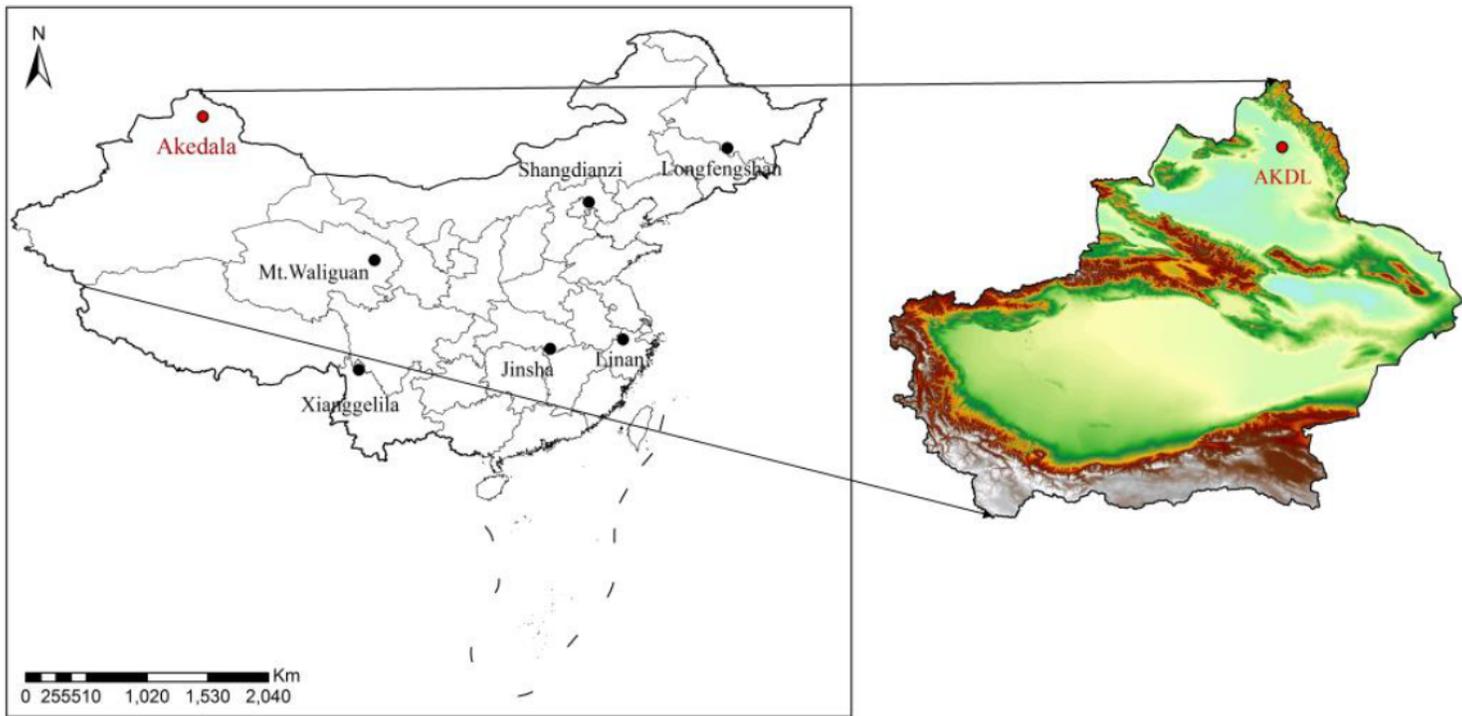


Figure 1

Location of Akedala Background Atmosphere Station

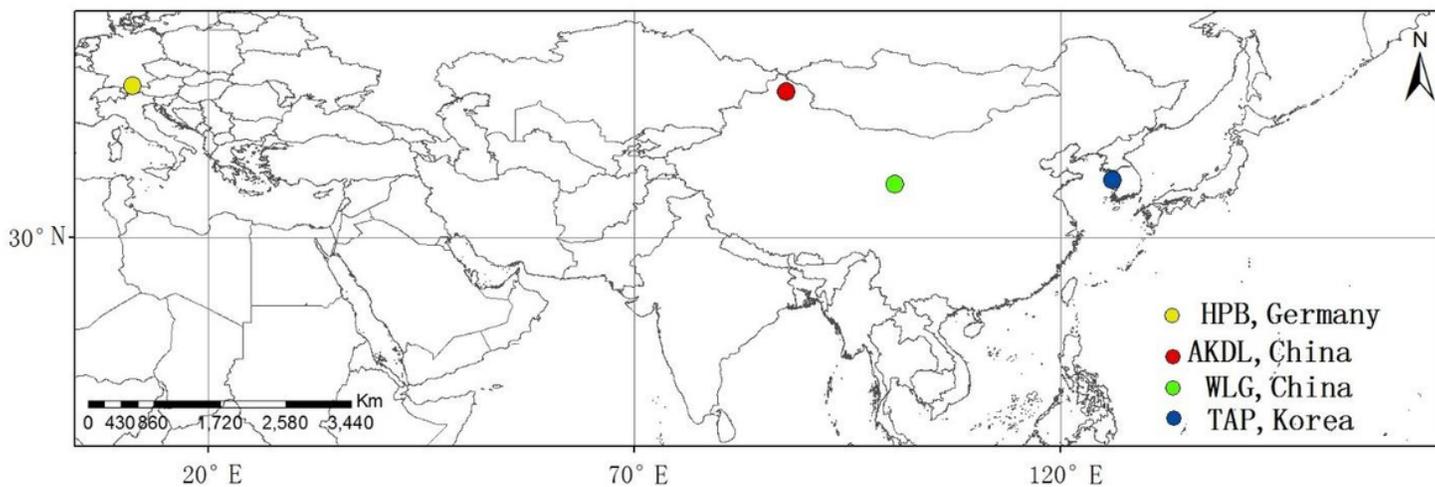


Figure 2

The location of four stations

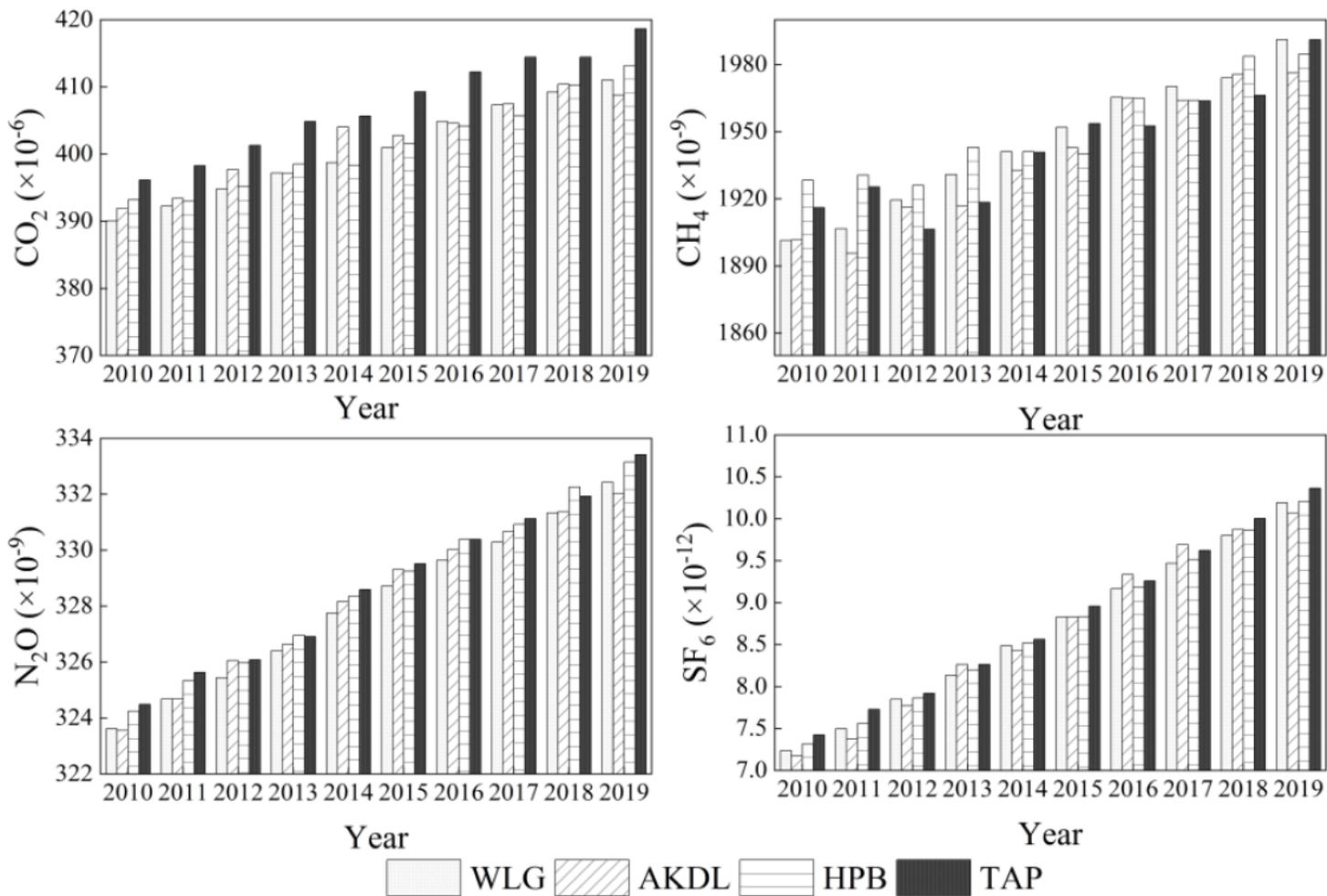


Figure 3

The year variation of greenhouse gases concentrations at four stations

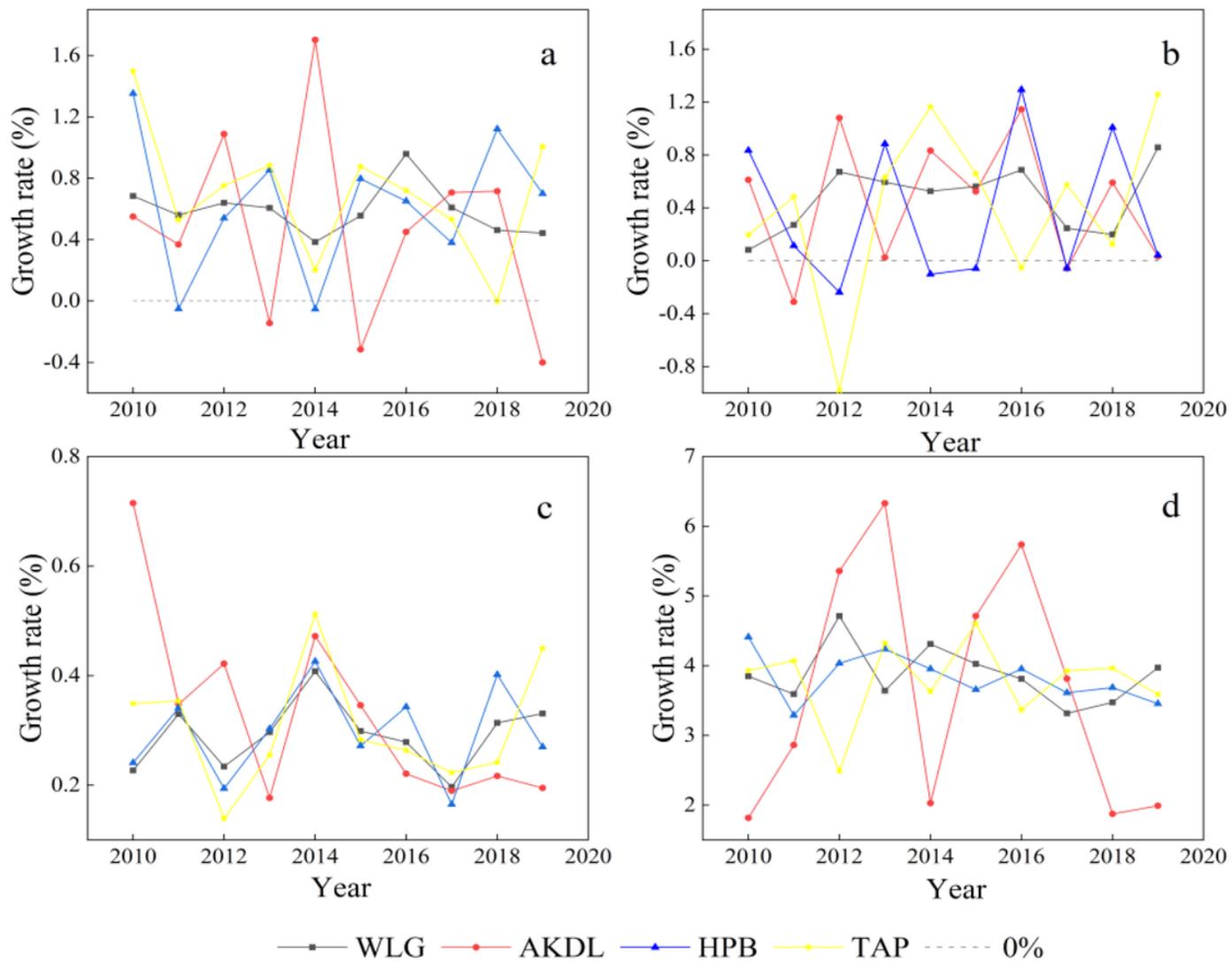


Figure 4

WLG▲AKDL▲HPB▲TAP station annual growth rate(a, CO₂ each station annual growth rate; b, CH₄ each station annual growth rate; c, N₂O each station annual growth rate; d, SF₆ each station annual growth rate)

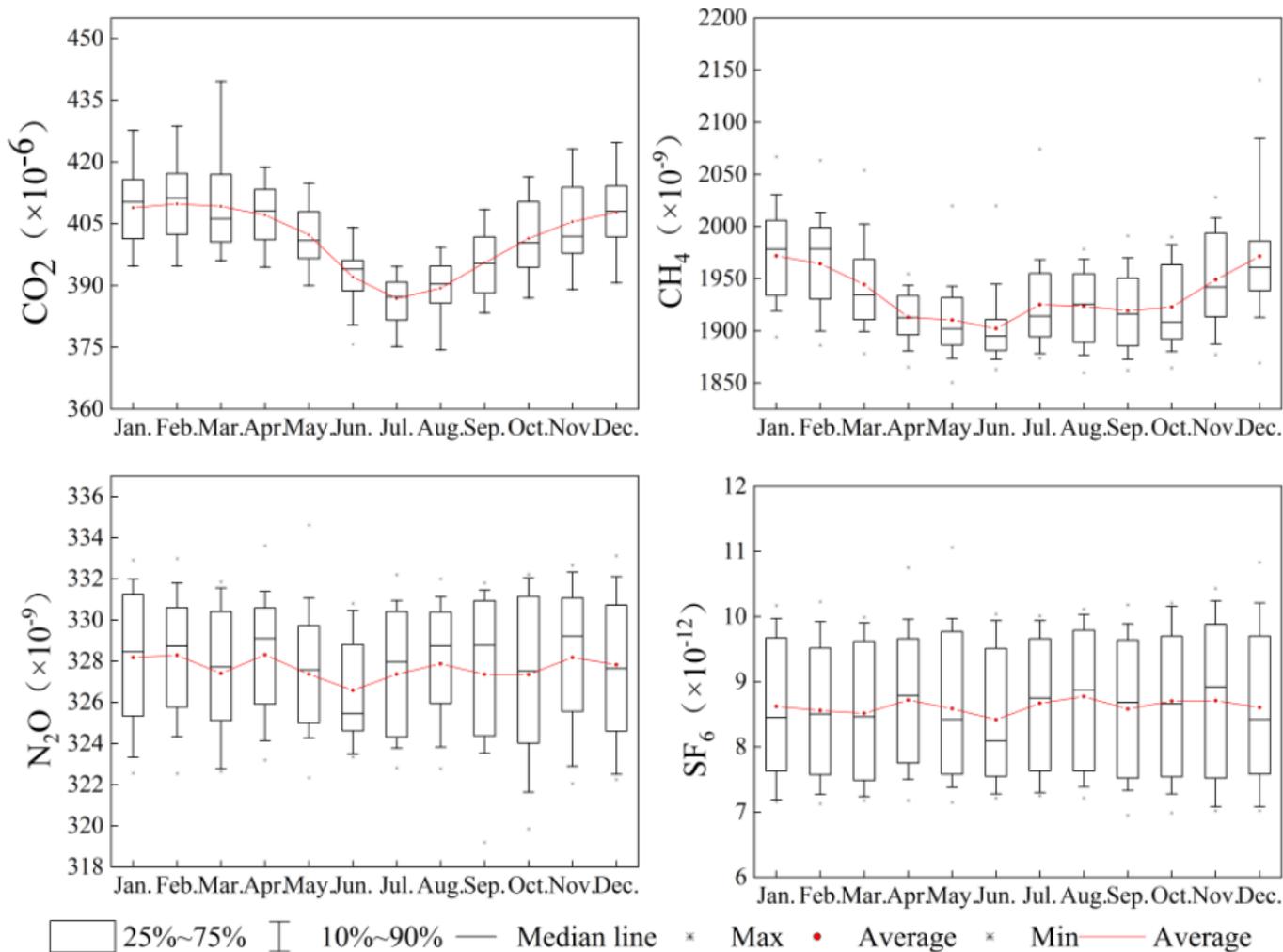


Figure 5

The variation of the average values in every months of greenhouse gases concentrations at Akedala Station over the years.

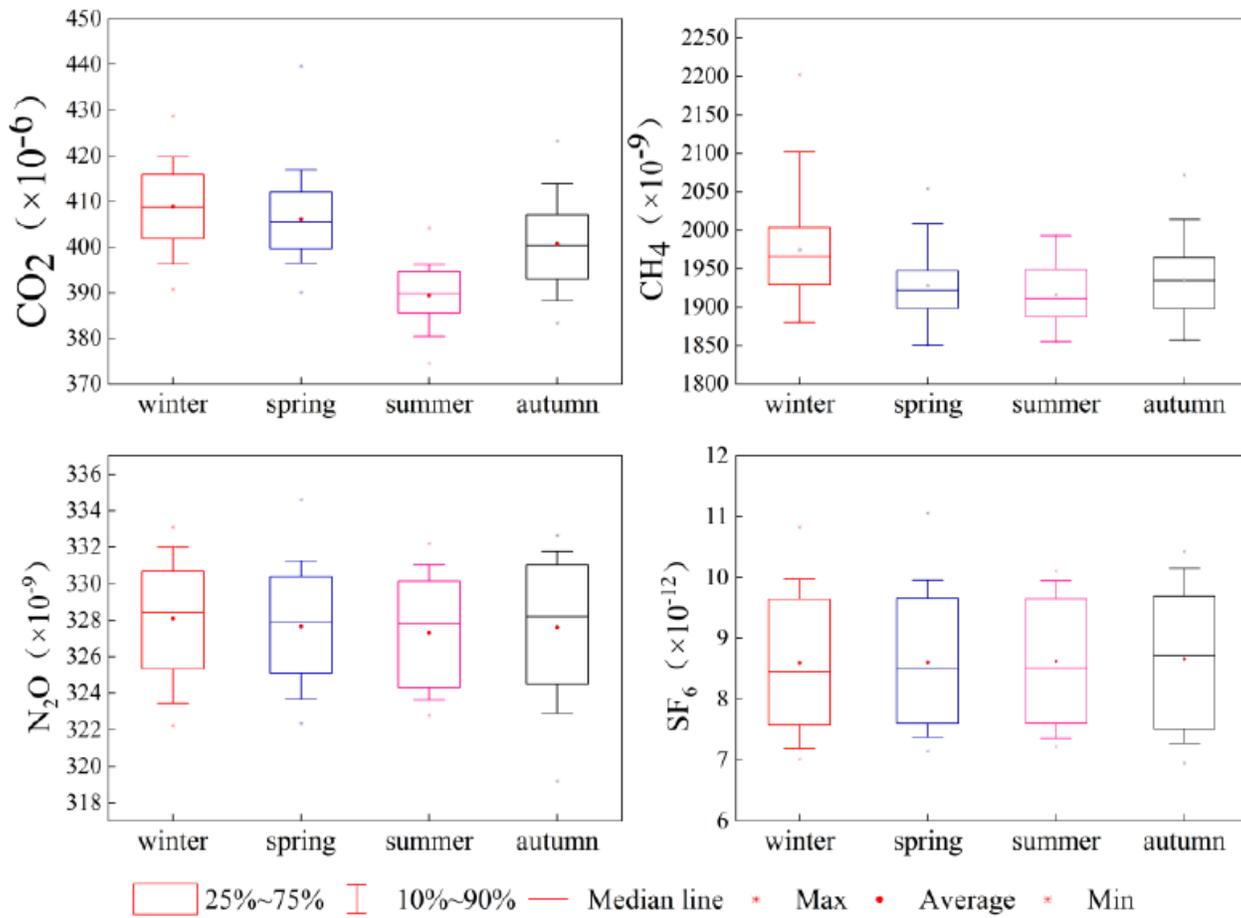


Figure 6

The seasonal variation of greenhouse gases at Akedala Station.

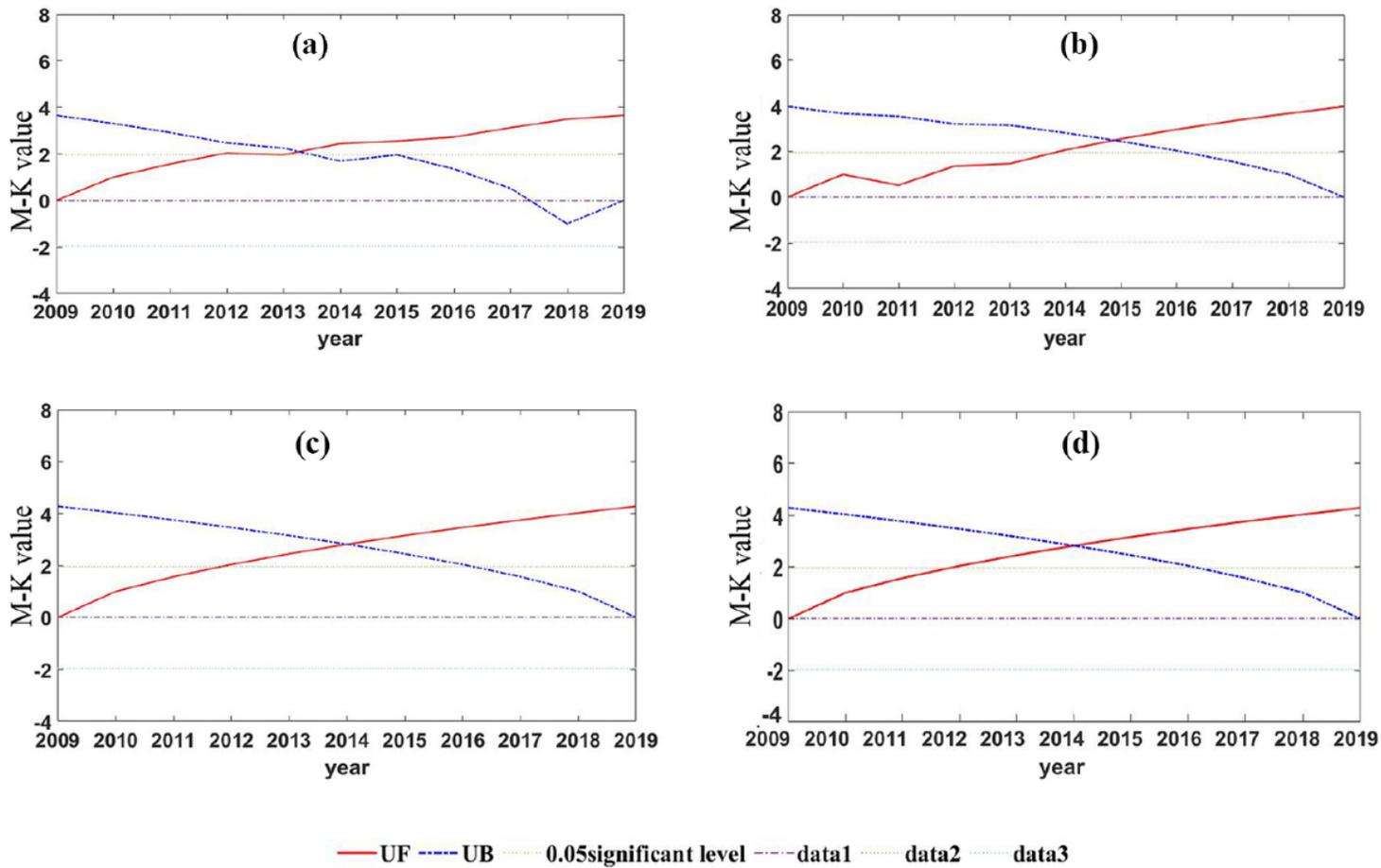


Figure 7

The results of M-K test for greenhouse gases concentrations at Akedala Station (a, CO₂ ; b, CH₄; c, N₂O; d, SF₆)

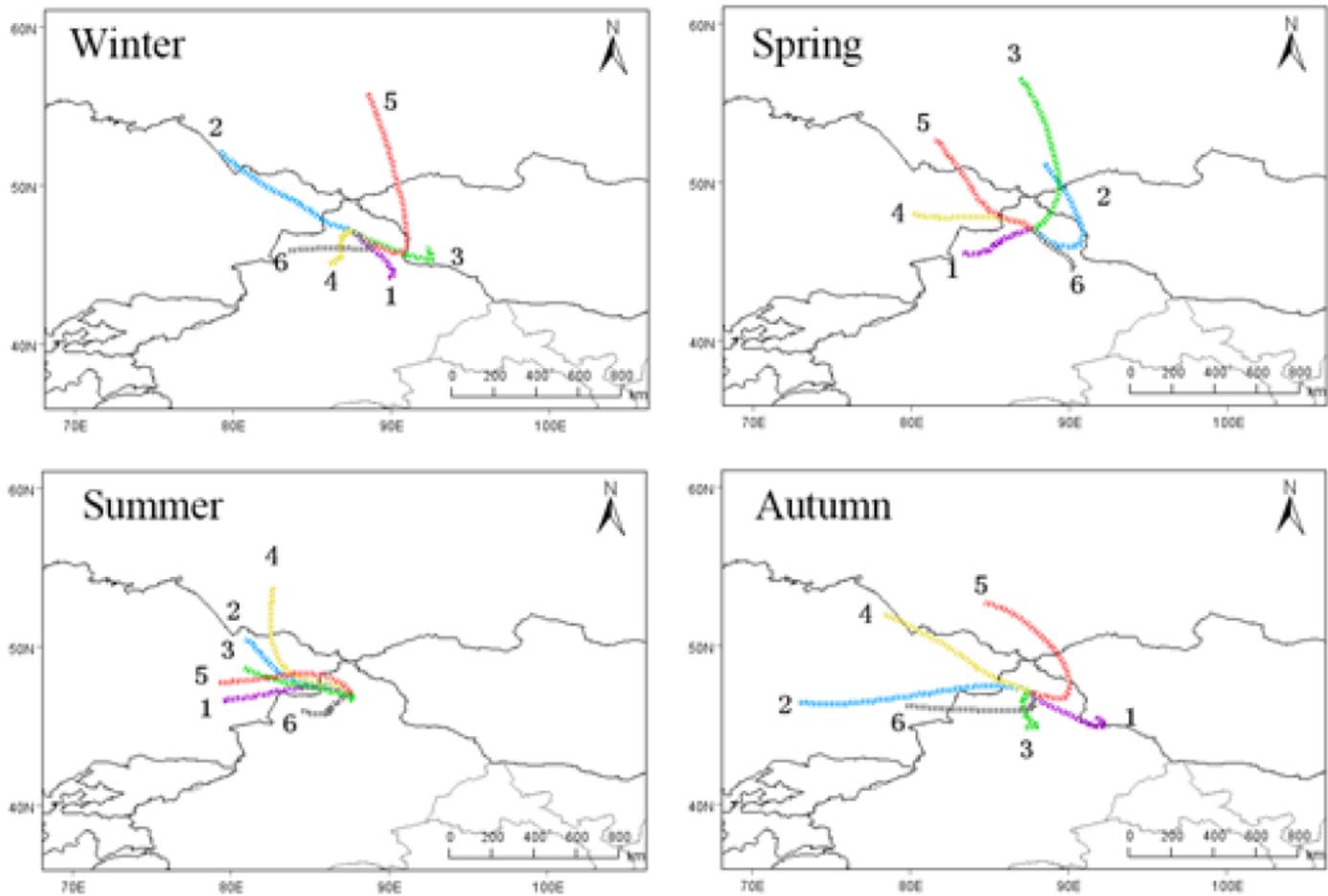


Figure 8

Cluster-mean back-trajectories by using the hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model in Akedala Station from January 2010 to December 2019.

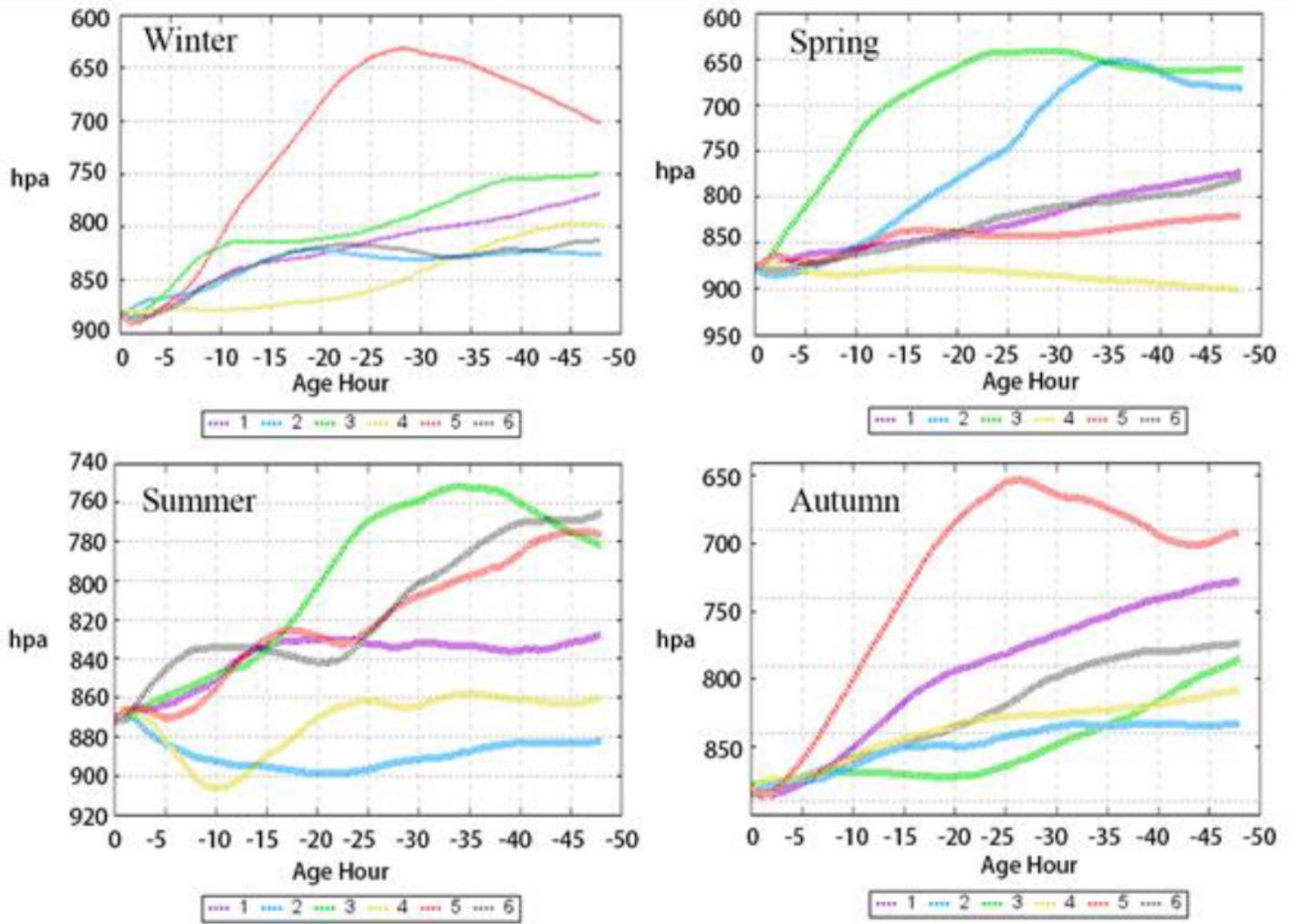


Figure 9

Air pressure profiles of the backward trajectories from January 2010 to December 2019