Aerosol vertical distribution characteristics over the Tibetan Plateau

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Abstract. The Stratospheric Aerosol and Gas Experiment II (SAGE II) aerosol products are widely used in climatic characteristic studies and stratospheric aerosol pattern research. Some SAGE II products, e.g., temperature, aerosol surface area density, 1020 nm aerosol extinction coefficient and dust storm frequency, from ground-based observations were analysed from 1984 to 2005. This analysis explored the time and spatial variations of tropospheric and stratospheric aerosols on the Tibet Plateau. The stratospheric aerosol extinction coefficient increased more than two orders of magnitude because of a large volcanic eruption. However, the tropospheric aerosol extinction coefficient decreased over the same period. Removing the volcanic eruption effect, the correlation coefficient for stratospheric AOD (Aerosol Optical Depth) and tropospheric AOD was 0.197. Moreover, the correlation coefficient for stratospheric AOD and dust storm frequency was 0.315. The maximum stratospheric AOD was attained in January, the same month as the tropospheric AOD, when the Qaidam Basin was the centre of low tropospheric AOD and the large mountains coincided with high stratospheric AOD. The vertical structure generated by westerly jet adjustment and the high altitude of the underlying surface of the Tibetan Plateau were important factors affecting winter stratospheric aerosols.

1. Introduction

Aerosols in the upper troposphere and stratosphere play an important role in global climate change [1]. Aerosols are very important trace constituents in the stratospheric atmosphere, playing an important role in atmospheric radiation and photochemical processes. Moreover, stratospheric aerosols can strongly scatter and reflect solar radiation and reduce incoming short-wave solar radiation, which reduces the surface temperature. Simultaneously, stratospheric aerosols absorb solar radiation and terrestrial long-wave radiation, which increases the stratospheric temperature, i.e., the parasol effect. Moreover, when the temperature and water vapour (cirrus) are just right, a series of non-homogeneous reactions occur on the surface of some stratospheric aerosols, generating active chlorine, which destroys ozone in the stratosphere [2-4], reduces the absorption of UV radiation, and reduces radiant...
heat in the lower stratosphere. Considine D B, Rosenfield J E and Fleming E L [5] showed that aerosols also affect stratospheric methane and water vapour. These two typical stratospheric greenhouse gases can further affect the radiative balance of the earth-atmosphere system. Therefore, understanding the distribution and variation of stratospheric aerosols is very important for examining stratospheric radiative processes [6].

Globally, stratospheric aerosols primarily originate from volcanic eruptions. Approximately 1/4 to 3/5 of the upper tropospheric and stratospheric air in tropical regions is from the mid-latitude lower atmosphere because of the Brewer-Dobson Circulation [7]. Therefore, low-level air pollution affects the aerosol distribution in the upper troposphere and stratosphere. The Qinghai-Tibet Plateau (referred to as Plateau in this paper), known as the "Roof of the World" and "Earth's third pole", promotes and regulates the Northern Hemisphere climate change [8-9]. Climate change on the Plateau not only directly drives climate change in eastern and south-western China but is also sensitive to global climate change and may feedback on the global scale. The stratosphere-troposphere exchange (STE) over the Plateau has a significant effect on the surrounding area and the global atmosphere [10]. The change in stratospheric aerosol content over the Plateau inevitably affects the radiation balance and the heat budget. Ultimately, these effects alter the climate in China and the entire world. Therefore, examining the distribution and variation of the stratospheric aerosol content on the Plateau is very important [6].

2. Study area and data set

2.1. Study area

The study area is the Qinghai-Tibet Plateau, which includes all of Tibet and Qinghai, western Sichuan, southern Xinjiang, and parts of Gansu and Yunnan, with an approximate area of 2.4 million square kilometres (figure 1) (figure 1 does not show all of China).

![Figure 1. Study area and surface observation stations.](image)

2.2. Dataset and Analytical method

This paper uses the SAGE II (The Stratospheric Aerosol and Gas Experiment II) satellite dataset. The SAGE II observation period was from November 1984 to August 2005. The dataset contains, e.g., ozone, aerosol, nitrogen dioxide, water vapour, and temperature data. Moreover, SAGE II measurements were obtained using a 7-band radiometer, namely, 385 nm, 448 nm, 453 nm, 525 nm, 600 nm, 940 nm and 1020 nm, equipped on the ERBS (Earth Radiation Budget Satellite). The ERBS has a 610-km circular orbit at an inclination of 57° [11-13]. The data vertical resolution is 0.5 km [14], and the aerosol extinction coefficients are in good agreement with other observations [15-19]. The 1020 nm aerosol extinction coefficient provides the most accurate information considering the four aerosol channels [20]. SAGE II aerosol extinction coefficient data are widely used in the field of global stratospheric aerosol climate characteristic monitoring, analysis and pattern studies [21-25].

Temperature, aerosol surface area density and aerosol extinction coefficient from the 1020 nm channel are used in this study from the SAGE II dataset. Because the SAGE II horizontal resolution is
not uniform, only 199 months are available, i.e., 724 files for the entire observation period. In this study, the monthly mean values for the study area correspond to the same arithmetic average of the monthly data. The optical thickness is the integral of the 1020 nm extinction coefficient to the corresponding height [1]. This study also uses dust storm frequency data from ground-based observations provided by the National Meteorological Centre of the China Meteorological Administration for November 1984 to August 2005; data from 103 stations are used.

3. Results and analysis

Figure 2 shows the vertical distribution of temperature over the Plateau from 0.5 km to 70 km.

![Figure 2](image)

**Figure 2.** Multi-year monthly average of the vertical temperature distribution over the study area.

The tropopause height over the Plateau is approximately 18 km to 19 km, and the stratopause height is approximately 48 km to 49 km. The aerosol extinction coefficient and surface density distribution height of the SAGE II data are from 0.5 km to 40 km. Therefore, in this paper, we analyse troposphere aerosol data from 0.5 km to 18 km and the stratosphere aerosol data from 19 km to 40 km.

![Figure 3](image)

**Figure 3.** Temporal changes in aerosol surface density over the Plateau (from 0.5 km to 40 km) on a logarithmic scale (base 10).

The Mount Pinatubo eruption in June 1991 released 2 million tons of sulphur dioxide gas into the lower stratosphere. These gases were converted to sulphate particles, which caused the formation of a high aerosol concentration layer in the stratosphere from 1992 to 1993 [26]. The changes in the Plateau stratospheric aerosol surface density reflect the effect of the Mount Pinatubo volcanic eruption on aerosols in the stratosphere because the aerosol surface area density reached its maximum during the first half of 1992 (figure 3). Thereafter, the surface area density gradually decreased. Moreover, the 1020 nm aerosol extinction coefficient reached its maximum value between the end of 1992 and early 1993. Because of the Mount Pinatubo volcanic eruption, the aerosol concentrations at 20 km
increased rapidly from October 1991, reaching their highest values in December 1991; relatively high concentrations were maintained until September 1993. Four months after the Mount Pinatubo eruption, volcanic ejecta reached the Plateau stratosphere, resulting in an aerosol extinction coefficient increase of nearly two orders of magnitude compared with typical values; this high extinction coefficient was maintained in the stratosphere for nearly 2 years.

The plateau aerosol extinction coefficient has well-pronounced seasonal variations (figure 4). In the troposphere, the high extinction coefficients appear in summer (June to August) above 10 km. However, in the lower stratosphere, low values appear in August to September. Therefore, aerosols in the troposphere and stratosphere may have different sources.

![Figure 4](image_url)

*Figure 4. The monthly variation in the 1020 nm extinction coefficient over the Plateau (from 0.5 km to 40 km) on a logarithmic scale (base 10).*

By integrating the 1020 nm aerosol extinction coefficient from 0.5 km to 18 km and 19 km to 40 km, tropospheric and stratospheric optical thicknesses are determined, respectively (figure 5).

![Figure 5](image_url)

*Figure 5. Temporal changes in the tropospheric and stratospheric optical thicknesses over the Plateau.*

The tropospheric and stratospheric optical thicknesses are inversely correlated with a correlation coefficient of -0.4243 (figure 5) (significant at the 0.01 significance level). The Plateau stratospheric aerosol concentration increases because of the volcanic ejecta erupted from Mount Pinatubo. However, the tropospheric aerosol concentration simultaneously decreases. We exclude the data from June 1991 to December 1993, which are affected by the volcanic eruption. As a result, the correlation coefficient of the optical thicknesses in the troposphere and stratosphere increases to 0.193 (significant at the 0.01 significance level), indicating that the stratosphere aerosols also affect the tropospheric aerosols.

We divide the dust weather phenomenon into three categories, i.e., sandstorm, blowing sand and floating dust, to further study the relationship between dust storm frequency on the Plateau and the optical thickness. We find that the correlation coefficients for the stratospheric and tropospheric optical thicknesses with the sandstorm frequency are 0.315 (significant at the 0.01 significance level)
and 0.187 (significant at the 0.02 significance level), respectively. Therefore, stratospheric aerosol is more sensitive to sandstorms on the Plateau.

![Figure 6](https://example.com/fig6.jpg)

**Figure 6.** Multi-year monthly average of the tropospheric and stratospheric optical thicknesses and the dust storm occurrence frequency over the study area.

The maximum optical thicknesses in the troposphere and stratosphere appear in January (figure 6). The Plateau stratosphere atmospheric aerosol optical thicknesses also have obvious seasonal variations. Specifically, the highest and lowest values appear in winter and summer, respectively, which is consistent with the 1020 nm aerosol extinction coefficient. The high stratospheric optical thickness in January is distributed along the large mountains, e.g., Mount Kailash, the Kunlun Mountains and Qilian Mount, indicating that the troposphere and stratosphere are more easily mixed over the higher terrain on the Plateau.

4. Conclusions

The stratospheric aerosol extinction coefficient increased by more than two orders of magnitude because of a large volcanic eruption. After removing the volcanic eruption effects, the correlation coefficient between stratospheric AOD and tropospheric AOD was 0.197; the correlation coefficient of stratospheric AOD and dust storm frequency was 0.315. The maximum stratospheric AOD was attained in January.

Acknowledgments

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