Lidar observations of aerosol enhancement in the upper troposphere and lower stratosphere

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Abstract. The upper troposphere and the lower stratosphere (UTLS) are the transition areas between the troposphere and stratosphere. Water vapor, cirrus clouds and aerosols in this area have a strong modulation effect on solar short-wave radiation and earth long-wave radiation. Changes in the content and distribution of aerosols in this level will have a radiant forcing impact on the climate. This article uses the observation data of MPL lidar (micropulse lidar) at SACOL station (Semi-arid Climate and Environment Observation Station of Lanzhou University, 34.946°N, 104.93°E) and ERA-Interim reanalysis data from June to December 2011 to study the changes of stratospheric aerosol over SACOL station after Nabro volcano eruption on June 12, 2011. The result indicates that after the Nabro volcanic eruption, there is an aerosol layer with significantly enhanced scattering ratio over the SACOL station, and the depolarization ratio of particles in the aerosol layer is relatively small, mainly spherical particles; by analyzing the backward trajectory of the stronger aerosol layer, it can be determined that the special aerosol layer was caused by the Nabro volcanic eruption.

1. Introduction
The rapid development of industry and natural factors such as volcanic eruptions will increase aerosols in the atmosphere and have the following two effects on regional and global climate [1]. One is to change the radiation balance of the lower atmosphere and the ground; the other is to act as condensation nuclei or freeze nuclei, which in turn affects precipitation. UTLS is the transition area between the troposphere and stratosphere, and the region plays an important role in stratospheric-tropospheric material exchange through continuous deep convective material transport [2-3]. Aerosols in this region have a strong regulation effect on the earth's long-wave radiation and solar short-wave radiation [4], and the radiative forcing produced by them will change the energy balance of the entire earth-air system; in addition, water vapor, aerosols and other atmospheric components in this region indirectly affect the radiation balance through a series of chemical reactions [5]. Therefore, changes in aerosols in UTLS can further affect regional even global climate change through atmospheric radiation, microphysics, and chemical processes.

Previous studies have suggested that the factors which cause aerosol changes in UTLS can be divided into natural factors and human factors. A volcanic eruption will release a large amount of volcanic ash and sulfur-containing gas. During the process of atmospheric circulation, SO₂ and the volcanic aerosol transmitted to the upper troposphere will be further oxidized into sulfate aerosols, providing sufficient
condensation nodules for precipitation [6]. Due to the weak convective activity in the stratosphere, particles entering the stratosphere will stay in this layer for a longer time, and the volcanic aerosol that reaches the bottom of the stratosphere has a long-lasting effect on radiation flux, atmospheric chemical reactions, atmospheric circulation systems and climate [4,7]. Volcanic eruption will release a large amount of volcanic ash and SO$_2$ gas into the atmosphere. After the eruption of Nabro volcano (13.37°N, 41.70°E) in Southeast Africa on June 12, 2011, about 1.3 Tg of SO$_2$ gas was discharged into the atmosphere of 9-14 km, resulting in a significant increase in the amount of aerosols in the stratosphere [8]. In recent years, many scholars have studied the 2011 Nabro volcanic eruption. Zhuang et al concluded that aerosol particles were mostly concentrated in the stratosphere, non-spherical particles were mainly concentrated in the lower part of the aerosol layer [9]. Shibata et al analyzed that the Nabro volcanic aerosol particles were directly injected into the stratosphere [10]. Sakai et al found that volcanic aerosol particles can offset part of the warming effect of CO$_2$ and play an important role in global radiation balance [11]. Sawamura et al found that the 16-19 km volcanic aerosol particles gradually moved eastward along the monsoon anticyclone based on the simulated forward trajectory and the effect of deep convection on aerosol particles was small [12-14].

In this article, we use advanced MPL lidar monitoring to obtain aerosol optical characteristics data such as depolarization ratio and scattering ratio of aerosol particles at SACOL station from June to December 2011, and analyze the short-term changes in atmospheric aerosols over SACOL station after Nabro volcanic eruption. Combining with the ERA-Interim reanalysis data, this article further studies the impact of the Nabro volcanic eruption on June 12, 2011 on the aerosol particle change process over the UTLS of this station.

2. Data and Instruments

2.1. Observation site
This article mainly studies the aerosol changes at the SACOL station after the Nabro volcano erupted in June 2011 and the selected research period is from June to December 2011. SACOL station is located at the top of the Cuiying Mountain, Lanzhou University Yuzhong Campus, and is also on the way of long-distance transmission of dust aerosol in East Asia. The station has continuous observation data on atmospheric radiation, wind, atmospheric temperature and humidity, clouds and aerosols, and ground-air interaction since 2006, as well as lidar observations from 2007 to the present.

2.2. Data introduction

2.2.1. MPL lidar data
MPL was developed by NASA Goddard Space Flight Center. It is a safe, maintenance-free lidar system that can measure the aerosol and cloud vertical profiles for a long time [15]. The uncertainty of the data obtained by this system has been further studied by Welton and Campbell: over short distances, the overlapping uncertainty is dominant; above the overlapping area, the main source of uncertainty is the uncertainty in the pulse energy. However, if the laser energy is low, then at noon, high solar background levels can significantly reduce the signal-to-noise ratio (SNR) of the detector [16]. The lidar system of SACOL station has been automatically and continuously observed since May 2007, and there was only one elastic backscattering channel of 527 nm. A polarization function was added to the system upgrade to further measure the polarization characteristics of atmospheric particles since September 2009. The vertical resolution of the system is increased from 75 m to 30 m, and the time resolution is 1 minute. In this article, we use the data of Lidar from June to December.

2.2.2. ERA-Interim data
This article also uses the ERA-Interim reanalysis data provided by the European Centre for Medium-range Weather Forecasts (ECMWF). The spatial resolution is 0.125°, the temporal resolution is 6 h, the vertical space is divided into 37 layers from 1000 hpa to 1 hpa, and the physical quantities used are the
profiles of temperature, air pressure and humidity. To verify the reliability of the reanalysis data, the temperature and humidity profiles of the ERA-Interim reanalysis data are compared with the Yuzhong station 8.54 km from the SACOL station. The results show that the ERA-Interim reanalysis data is similar to the observation data at Yuzhong station. Therefore, the ERA-Interim reanalysis data can represent the atmospheric conditions near the SACOL station [17].

2.3. Calculation method

2.3.1. SNR
Considering that the lidar observations are greatly affected during the day and when the clouds are thick, so in the process of processing and analyzing data, the SNR is used to remove the noisy signal. We only analyze data with relatively large SNR.

The method of calculating the SNR [17] is shown below:

$$\text{SNR}(r) = \frac{P(r)}{\varepsilon(r)}$$

(1)

where $P(r)$ is the measured radar signal, and $\varepsilon(r)$ is the signal noise.

For MPL lidar, the SNR can be expressed as:

$$\text{SNR}(r) = \frac{NP(r)}{\sqrt{NP(r) + P_{bg}/N}}$$

(2)

where $N$ is the accumulation of average pulses over a period of time and $P_{bg}$ is the power received from the solar background.

2.3.2. Tropospheric top height
Because the stratosphere changes drastically with factors such as latitude and the troposphere top is more complicated, the definition of the thermodynamic troposphere top is used here. That is, above 500 hPa, the temperature decline rate in any 2 km gas layer is not more than 2 K/km, then the initial height of the gas layer is called the troposphere top. When calculating the temperature decrease rate, the temperature decrease rate $\Gamma$ is expressed as a function of $p^k$, as follows:

$$\Gamma(p) = \frac{\partial T}{\partial p^k} \frac{kg}{T(R)}$$

(3)

where $T$ is the temperature, $g$ is the acceleration of gravity, $p$ is the air pressure, $\kappa = R/c_p$, $R$ is the gas constant, and $c_p$ is the constant pressure heat capacity.

We analyse the scattering ratio, depolarization ratio, and tropospheric height over the SACOL station from June to December 2011. Combined with the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT), a backward airflow trajectory model provided by NOAA, the specific diffusion and changes of Nabro volcanic aerosol are studied.

3. Observation facts and analysis

3.1. Characteristics of aerosol scattering ratio and depolarization ratio
Figures 1 and 2 are the changes in the backscattering ratio and depolarization ratio of the ten-day sol in the volcanic aerosol layer observed by the SACOL station after the Nabro volcano erupted. The solid line in the figure indicates the height of the troposphere. Due to the large interference of the lidar signal, during the day (23:00-11:00 UTC), the SNR of the echo signal is low, and at night (12:00-22:00 UTC) the SNR is relatively high, and the reliability of the echo signal is high. Therefore, the focus is on the research of the night lidar signal. It can be seen from the figure that the most obvious aerosol layer was observed over SACOL station on June 19, 2011. In the height range of 15.5-16.5 km above the stratosphere, the aerosol signal began to appear at 11:00-16:00 (UTC). Due to the influence of clouds and other factors, the echo signal of the aerosol layer is not continuous. From 16:00 to 22:00 (UTC), there is a continuous lidar echo signal stronger than the previous period, and the aerosol layer scattering ratio is basically 5-7, sometimes even reaching 10. According to this, it can be seen that when the aerosol particles diffuse above the SACOL station, they cause a surge of stratospheric aerosol particles.

After the strong eruption of Nabro volcano on June 12, 2011, stratospheric aerosol layers were discovered at multiple observation sites in the northern hemisphere. He et al found that after the Nabro volcano eruption, the ground-based radar on the Tibetan Plateau observed a clear aerosol layer in the height range of 17.0-18.5 km at night [8]. Shibata et al used CALIOP observations and averaged observations between 20° north and south latitudes, and also found that there was a clear aerosol layer above 17 km after the volcano erupted [10].

Combining Figure 1 and Figure 2, it can be seen that a stratospheric aerosol layer appeared within one month after the eruption of the volcano, especially on June 19, July 17, and July 19. Although the height of the aerosol layer changes with time, it is mainly concentrated near the top of the troposphere,
which is very consistent with the conclusions of previous studies. According to the comparative analysis of the two figures, it can be concluded that the high value region of the aerosol layer scattering ratio has a good correspondence with the low value region of the depolarization ratio, especially the depolarization ratio of the aerosol layer with a significantly increased stratospheric scattering ratio on June 19 was lower. Over time, the scattering intensity of the aerosol layer gradually weakened, and the aerosol particles gradually diffused and weakened. The more obvious data of these ten weather sol layers are selected for averaging. Figure 3 shows the profile of the scattering ratio and depolarization ratio for these ten days.

![Fig. 3. Profile of 12-18 km aerosol particle scattering ratio (dash-dotted line) and depolarization ratio (solid line). In each picture, the lower horizontal axis represents the scattering ratio and the upper horizontal axis represents the depolarization ratio.](image)

In Figure 3, the dash-dotted line is the scattering ratio profile of aerosol particles, the solid line is the depolarization ratio profile of aerosol particles, and the dotted line is the height of the troposphere top. We select a profile of 12-18 km that is closer to the research altitude range. It can be seen from Figure 3 that on the seventh day after the eruption of Nabro volcano, that is, on June 19, a peak of 3.67 aerosol particle scattering ratio appeared at the height of 16 km. At this time, the height of the top of the troposphere is 14.7 km, and the concentration height of the aerosol layer is 1.3 km higher than the top of the troposphere. Based on this, it can be determined that the aerosol particles are mainly concentrated in the stratosphere, and the peak of the depolarization ratio corresponds to a height of 15.6 km, which is 0.4 km lower than the peak of the scattering ratio, that is, the non-spherical particles are mainly concentrated at the bottom of the aerosol layer. In the obvious height range of the aerosol layer, the depolarization ratio of the particles is close to 0.1, and the depolarization ratio is relatively small, that is, the spherical particles are mainly in the aerosol layer. This is consistent with the research results of Nabro volcano eruption using lidar by Zhuang et al [9] and Uchino et al [4]. According to the evolution of the aerosol particle scattering ratio profile with time, the peak of the profile lasted for a month since the obvious aerosol particle layer was observed on June 17, and its peak value continued to decrease over time and tended to be flat.

### 3.2. Analysis results of backward trajectory

In order to determine whether the aerosol layer we observed was caused by the Nabro volcanic eruption, the HYSPLIT model was used to calculate the trajectory of two air masses. During the simulation, the size of the air mass was set to 1º longitude × 1º latitude. The height of the first simulated air mass was set at 13 km above SACOL station, and the initial time was 13:00 (UTC) on June 17, 2011. The height of the second simulated air mass is set at 15.75 km above SACOL station, and the initial time is 17:00 (UTC) on June 19, 2011. Figure 4 shows the simulated backward trajectory. It is obvious from the figure: the aerosol particles left the Nabro volcano at 08:00 (UTC) on June 13 and then traveled eastward along the Asian monsoon anticyclone circulation. During the transmission process, the volcanic aerosol layer
is maintained at a high altitude, above 15 km from June 13 to June 15; from June 16, the height of the volcanic aerosol gradually decreased during its propagation, and it reached the SACOL station on June 19. This simulation result is consistent with the lidar observation result.

Figure 4. The HYSPLIT model was used to simulate the 120-hour backward trajectory of aerosol particles over SACOL station (35.946°N, 104.137°E) starting from 13:00 on June 17, 2011 (top) and the 163-hour backward trajectory of aerosol particles starting from 17:00 on June 19, 2011 (bottom). The black asterisk represents the SACOL station and the black circle represents the Nabro volcano. The variation of aerosol particle height with time during propagation is given below the trajectory diagram.

4. Summary
This article uses the observation data of aerosol particles from MPL at SACOL station and ERA-Interim reanalysis data from June to December 2011 to analyze the changes of UTLS aerosol particles over SACOL station after the Nabro volcano eruption on June 12, 2011, the result shows:
(1) A week after the volcano erupted, a aerosol layer with a significantly enhanced scattering ratio appeared in the stratosphere below the troposphere on the SACOL station. The central scattering ratio of the volcanic aerosol layer can sometimes even reach 6.0 and above, and the depolarization ratio of the aerosol particles in the layer is close to 0.1, indicating that the layer is dominated by spherical aerosol particles;

(2) According to the obvious changes in the ten-day scattering ratio and depolarization ratio of the aerosol layer thickening, it can be known that the aerosol layer is unevenly distributed and gradually diffuses over time over the SACOL station;

(3) By analyzing the backward trajectory of the aerosol layer, it was determined that the aerosol layer observed by the lidar was caused by the eruption of Nabro volcano.

In this paper, only the results of volcanic eruption aerosol particles are discussed. In the future, numerical model sensitivity experiments will be used to further explore the radiation effects and distribution characteristics of Nabro volcanic aerosols on aerosol particles in the UTLS area above SACOL.

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