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Results of an Experiment on Joint Lidar and Balloon Sounding of the Troposphere and Stratosphere

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Abstract. The current problem of climate change requires studying changes in the composition and properties of the atmosphere, affecting its radiation balance. Obtaining knowledge in this direction is possible through regular measurements of climate-forming components and atmospheric characteristics and their subsequent analysis. There are contact and remote methods and means of sensing the atmosphere at its different altitude levels, including aerological, aircraft, satellite, lidar and rocket. This paper proposes a technology for monitoring the aerosol component based on remote (lidar) and contact (aerological) optical sounding. The results of simultaneous remote (lidar) and direct (sonde) measurements of the vertical distribution of aerosol loading in the troposphere and stratosphere, carried out on January 27-30, 2022 and March 15-16, 2023 in Tomsk, are presented. The purpose of the experiment was to conduct joint lidar-balloon measurements and validate aerosol backscatter profiles in the upper troposphere and stratosphere to create an all-weather lidar-balloon monitoring system of spatiotemporal and microphysical characteristics of aerosol. Good agreement is demonstrated in the obtained vertical profiles of the value of the backscatter ratio $R(H)$ for close wavelengths (528 and 532 nm for the aerosol backscatter sonde and lidar, respectively). To restore the microphysical parameters of an aerosol during joint lidar-balloon experiments, the possibility of expanding 2-wave (355 and 532 nm) lidar measurements with an additional set of wavelengths (470, 850, 940 nm) using an optical balloon aerosol sonde was shown.

Key words: stratospheric aerosol, atmospheric temperature, lidar, aerosol sonde, multi-wavelength sounding.

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Результаты эксперимента по совместному лидарному и шар-баллоному зондированию тропосферы и стратосферы

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Аннотация. Актуальная проблема климатических изменений требует изучения изменения состава и свойств атмосферы, влияющих на ее радиационный баланс. Получение знаний в данном направлении возможно на основе проведения регулярных измерений климатообразующих компонент и характеристик атмосферы и их последующего анализа. Существуют контактные и дистанционные методы и средства зондирования атмосферы на ее разных высотных уровнях, включая аэрологические, самолетные, спутниковые, лидарные и ракетные. В настоящей работе предложена технология мониторинга аэрозольной компоненты на основе дистанционного (лидарного) и контактного (аэрологического) оптического зондирования. Приводятся результаты одновременных дистанционных (лидарных) и прямых (зондовых) измерений вертикального распределения аэрозольного наполнения тропосферы и стратосферы, осуществленных 27-30 января 2022 и 15-16 марта 2023 в Томске. Целью эксперимента было проведения совместных лидарно-балонных измерений и валидация аэрозольных профилей обратного рассеяния в верхней тропосфере и стратосфере для создания всепогодной системы лидарно-баллонного мониторинга пространственно-временных и микрофизических характеристик аэрозоля. Продемонстрировано хорошее согласие в полученных вертикальных профилях значения отношения обратного рассеяния $R(H)$ для близких длин волн (528 и 532 нм для аэрозольного зонда обратного рассеяния и лидара, соответственно). Для восстановления микрофизических параметров аэрозоля при проведении совместных лидарно-баллонных экспериментов показана возможность расширения 2-х волновых (355 и 532 нм) лидарных измерений дополнительным набором длин волн(470, 850, 940 нм) с помощью оптического баллонного аэрозольного зонда.

Ключевые слова: стратосферный аэрозоль, температура атмосферы, лидар, аэрозольный зонд, многоволновое зондирование

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Финансирование. Модернизация инструментария исследований — лидарного комплекса была проведена при поддержке проектом госзадания ИОА СО РАН, а проведение экспериментальных исследований и получение данных за счет гранта Российского научного фонда No 23-27-00057, https://rscf.ru/project/23-27-00057.

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Introduction

In the context of global changes associated with the greenhouse effect, stratospheric aerosol, due to its ability to reflect part of solar radiation into space, reducing its influx to the surface of the planet, plays an important role. Academicians Golitsyn G.S. and Israel Y.A. [1] in 2011 even proposed the release of artificial aerosol into the stratosphere as a means of climate control. However, in the stratosphere there is a naturally occurring aerosol that already performs the functions mentioned above [1]. There are a number of monitoring programs, in particular Aeronet, AEROSIBNET, etc. [2], NDSC [3], from whose data it is possible to obtain certain information about stratospheric aerosol. But the information necessary for quantitative assessments, namely, spatiotemporal and microphysical characteristics, is still insufficient [4–7]. Gaining knowledge in this direction is possible through regular measurements of climate-forming components and atmospheric characteristics and their subsequent analysis.

Stratospheric lidars offer certain opportunities, especially for studying the altitude and temporal behavior of stratospheric aerosol [8]. However, lidars, as a rule, implement 2 - 3 emitter wavelengths, which is not enough to restore the microphysical parameters of an aerosol. An increase in the number of wavelengths in a lidar is associated with a significant complication of both the transmitting and receiving parts.

The fundamental solution to the problem is the use of additional multi-wavelength measurements of light backscattering, combined with lidar sounding. The Central Aerological Observatoty of Roshydromet has developed an aerosol light backscatter sonde (AZOR), which has 4 wavelengths to determine the optical parameters of light scattering from atmospheric aerosol [9, 10]. The measured backscattering parameters at different wavelengths make it possible to obtain information about the spectrum of aerosol particle sizes and the vertical distribution of aerosol loading in the troposphere and stratosphere, and to more effectively restore the microphysical characteristics of stratospheric aerosol.

Lidar complex IOA SB RAS

The transmitter of the lidar complex is an LS-2137U-UV3 YAG:Nd3+ laser with radiation at wavelengths of 532 and 355 nm, pulse energy of 400 and 200 mJ with a generation frequency of 10 Hz, complete with a 1:10 beam expander. Backscattered radiation is fed to a Newtonian system telescope with a receiving mirror with a diameter of 1 m and a focal length of 2 m. Light signals were received in two channels at each wavelength with a separation in the ratio of 10% and 90% in order to reduce the dynamic range (near and far reception zone). The separated optical signals are sent to photosensor modules (Hamamatsu), where they are converted into electrical signals in photon counting mode. Next, they are registered in a photon counter with further data transfer to a computer for collection and accumulation. A more detailed description of the complex, including its block diagram, can be found in [11].

Aerosol backscatter sonde (AZOR)

Like a lidar, the operating principle of an optical aerosol sonde is based on recording radiation scattered in the free atmosphere from a sequence of light probe pulses from onboard sources. A line of LEDs at wavelengths of 470, 528, 850 and 940 nm with a bandwidth of 40 - 50 nm is used as radiation sources. Simultaneously with successive probing pulses, echo signals are synchronously accumulated by a broadband photodetector for each channel for 1 second. The basic design of the probe [9] uses 2 channels from the presented line of LEDs. Unlike a lidar, the recorded signal is formed from a nearby (at a distance of 0.2-5 m) light-scattering volume (0.1 m3). In order to increase the signal-to-noise ratio (SNR), the optical axes of the photodetector and emitters are located at an angle of 5°, which allows, when using synchronous signal detection, to obtain an SNR value at an altitude of 30 km no worse than 50. The scattered radiation entering the photodetector is recorded in angular range 170° - 180°. The sonde is easily integrated with all types of standard upper-air radiosondes, equipped with its own temperature and pressure sensors (optional), navigation module and telemetry system, which allows its use in autonomous launches. A natural limitation in the use of AZOR is the condition of night measurements.

Results

Joint lidar-aerological experiments were carried out on January 27-30, 2022 and March 15-16, 2023 in Tomsk (560 N 850 E) at the Institute of Atmospheric Optics SB RAS. At the IAO SB RAS lidar complex, measurements were carried out in the altitude range from 7 to 50 km, and with a sonde - from 0 to 30 km.

For different dates of the experiment, vertical profiles of the dimensionless quantity $R(\lambda, H)$ were obtained at wavelengths of 355 and 532 nm (lidar) and 470, 528, 850, 940 nm (sonde). The physical meaning of the quantity $R(\lambda, H)$ is described by the formula:

$$R(\lambda, H) = \frac{\beta(\lambda, H)}{\beta_M(\lambda, H)} = \frac{\beta_M(\lambda, H) + \beta_A(\lambda, H)}{\beta_M(\lambda, H)} = 1 + \frac{\beta_A(\lambda, H)}{\beta_M(\lambda, H)}.$$

where $\beta_M(\lambda, H), \beta_A(\lambda,), \beta(\lambda, H)$, are the coefficients of molecular, aerosol and total backscattering of light at wavelength λ at height . Fulfillment of conditions $R(\lambda, H) = 1$ means the absence of aerosol at these altitudes, and, conversely, the value $R(\lambda, H) > 1$ indicates the presence of aerosol. Thus, the value of $R(\lambda, H)$ determines the magnitude of aerosol scattering in relation to molecular.

An important condition for conducting the experiment was the choice of the time period of the year with maximum aerosol loading of the stratosphere, against which the individual vertical profiles $R(H)$ at different wavelengths will be more pronounced. Based on many years of experience in lidar monitoring of the stratosphere over Tomsk, it was established that these are winter months. Fig. 1 shows vertical profiles of the backscattering ratio for January compared to June, demonstrating a significant difference between them in the aerosol loading of the lower stratosphere.

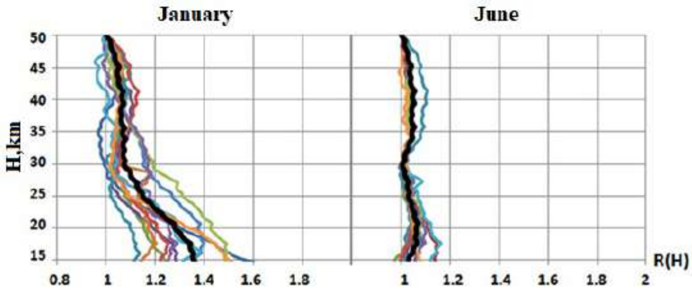

Fig. 1. Multi-colored curves - January and June backscattering ratio profiles averaged over the years at a wavelength of 532 nm for each year of the period 2010-2021 [12]. The black curve is the average January and June profile, constructed using the annual average for the entire observation period.

In Fig.2 vertical profiles $R(\lambda, H)$ obtained sequentially on the nights of January 27-30 are presented [13, 14]. The relief structure of the sonde profiles compared to the smoother lidar profile is explained by the difference in spatial resolution. For sonde measurements, signal processing was carried out with smoothing at 10 points (resolution 9-15 m depending on the balloon lifting speed). For the smoothing procedure, the formula $I_i = I_{i-1} + (T_i - I_{i-1})/K$ is used (where T is the smoothed parameter, I is the smoothing result, K is the smoothing coefficient (in our case $K = 10$). For lidar observations, the vertical resolution is ($\sim$ 500 m) was achieved by smoothing over 3 strobes. Since in the AZOR launches the height of only 21-23 km was reached, the coefficient of molecular backscattering of light $\beta_M(\lambda,)$ was used as a priori information, the same as in lidar calculations) according to the molecular model of the atmosphere [15].

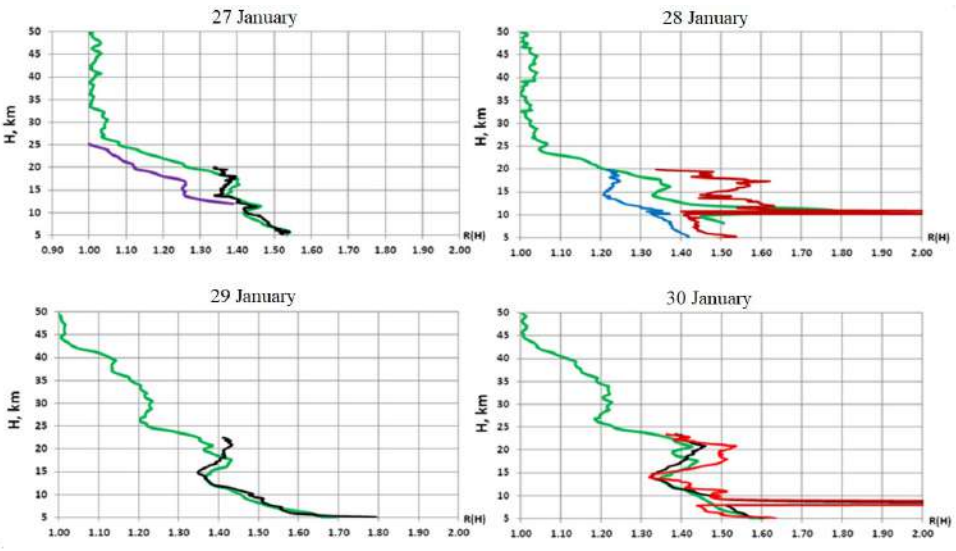

Fig. 2. Vertical backscattering ratio profiles. Green and violet curves are lidar at wavelengths of 532 and 355 nm, blue, black, red and dark red are sondes curves at wavelengths 470, 528, 850 and 940 nm.

Fig. 3 shows the values of R(λ, H) for the AZOR and lidar on March 15-16, 2023. As can be seen from the measurement results in the experiments of January 2022 and March 2023, there is agreement in the obtained R(H) profiles for close wavelengths (528 and 532 nm). Differences in data at altitudes below 12 km in the March 2023 experiment can be explained by the presence of variable cloudiness. The totality of all lidar data shown for 355 and 532 nm and balloon data for 470, 528 and 940 nm demonstrates the wide variability of R(λ, H) profiles depending on wavelength and atmospheric conditions. Such a set of measurement data at different wavelengths can be useful in analyzing the variability of atmospheric aerosol composition.

The resulting vertical profiles R(λ, H) show moderate aerosol loading, characteristic of the selected period of measurements in the absence of volcanic activity. These results are most clearly visible in Fig. 2 based on sonde data at a wavelength of 940 nm, where molecular scattering is relatively small compared to scattering at shorter wavelengths.

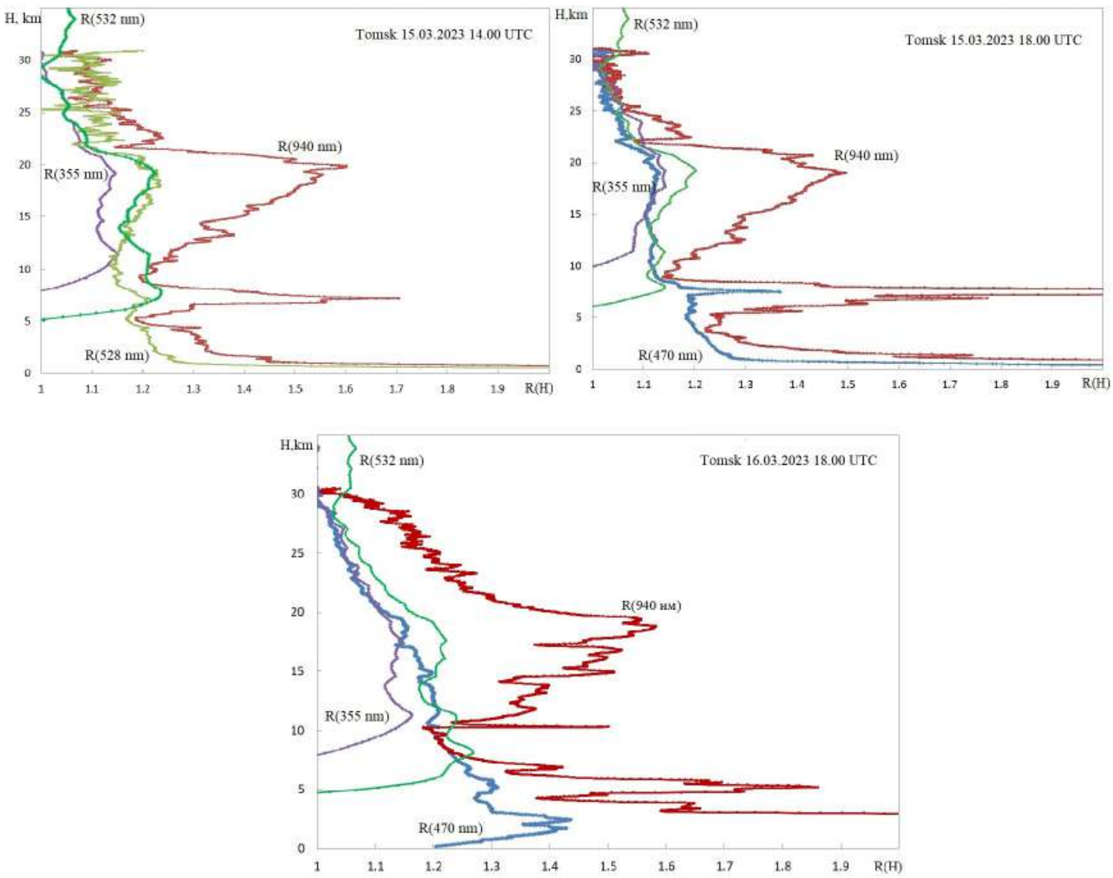

Fig. 3. Vertical profiles of the quantity R(λ, H) (see text) for the wavelengths indicated in the figure, obtained by the lidar and sonde. Lidar data in violet (355 nm) and dark green (532 nm). AZOR data are marked in blue (470 nm), light green (528 nm), red (850 nm) and dark red (940 nm).

Conclusion

Aerosol sounding of the troposphere and stratosphere using lidar and aerological technologies complement each other, ensuring all-weather observations and continuity of their series. Good agreement is shown in the vertical profiles of the value of the backscattering ratio R(H) for close wavelengths (528 and 532 nm) for AZOR and lidar, respectively, in simultaneous measurements when using the same a priori information for processing the results. To restore the microphysical parameters of an aerosol during joint lidar-balloon experiments, the possibility of expanding 2-wave (353 and 532 nm) lidar observations with an additional set of wavelengths (470, 850, 940 nm) using measurements with an optical balloon aerosol sonde was shown. The resulting consistency between lidar and balloon measurements indicates the possibility of using AZOR as a mobile tool to complement lidar observations carried out at various geographical locations. Of particular note is the cost-effectiveness of aerological technology and the possibility of its application in all regions of Russia, including the Arctic.

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