ISSN 1068-3739, Russian Meteorology and Hydrology, 2018, Vol. 43, No. 7, pp. 488–493. Allerton Press, Inc., 2018.
Original Russian Text D.S. Zubachev, V.A. Korshunov, N.V. Tereb, 2018, published in Meteorologiya i Gidrologiya, 2018, No. 7, pp. 113–119.

INSTRUMENTS, OBSERVATIONS, AND PROCESSING

Concentration of Stratospheric Ozone Derived from Lidar, Satellite, and Surface Observations

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Received June 21, 2016; in final form, October 26, 2016

Abstract—Data of stratospheric ozone measurements with the AK-3 lidar over Obninsk in 2012–2015 are compared with Aura/MLS and Aura/OMI satellite data and parallel surface observations of total ozone (TO) with the Brewer spectrophotometer. The maximum difference in mean ozone concentration between the lidar and Aura/MLS data in the altitude range of 13 to 32 km does not exceed 0.2 10^{12} mol./cm^3 (or the maximum of 9% at the altitude of 13 km). At the same time, Aura/OMI data have a positive bias of about 20% relative to lidar data in the range of 13 to 20 km that is associated with OMI measurement errors according to literature data. Total ozone values calculated from lidar measurements jointly with the known climatology data are compared with those measured with the Brewer spectrophotometer. It is demonstrated that the correlation between the results of measurements obtained by two methods is close to linear, and the mean relative difference in the overall measurement range does not exceed 5%.

DOI: 10.3103/S1068373918070099

Keywords: Ozone, stratosphere, lidar, Brewer spectrophotometer, satellite measurements

1. INTRODUCTION

Ozone concentration variations are associated with many processes in the atmosphere, for example, with the formation of polar stratospheric clouds which provoke ozone holes [1] or with the Brewer–Dobson circulation which favors the ozone transport to different latitudes and to its vertical stratification [13]. The importance of the ozone layer is obvious, because it protects all the Earth life from hard ultraviolet solar radiation, absorbs light radiation with the wavelength below 300 nm, and directly affects the stratospheric radiation balance. In view of this, regular measurements of ozone in different atmospheric layers as well as of total ozone (TO) in the air column are of great importance. It is desirable that the measurements are conducted by independent methods, because it allows revealing the possible sources of errors as a result of the comparative analysis of data and enhances the reliability of information. Lidar measurements of ozone profiles have been conducted in Taifun Research and Production Association (Obninsk, 55.1 N, 36.7 E) since 2012 using the AK-3 lidar developed in this organization. Besides, TO measurements with the Brewer spectrophotometer have been carried out during a long period. The present paper provides the comparison of lidar data on ozone concentration for the period of 2012 to 2015 with Aura/MLS and Aura/OMI satellite data as well as with TO data. The main objective of the paper is to control the quality of measurements with the AK-3 lidar by the comparison of their results with data obtained by the well-known and tested instruments and methods.

2. INSTRUMENTS AND METHODS

In 2011, the AK-3 net lidar was developed in Taifun Research and Production Association. It is intended for the measurement of temperature and aerosol and ozone concentration (hereinafter, the particle concentration is meant which is expressed by the number of ozone molecules per unit volume of air). The basic characteristics of the lidar are presented in the table. Ozone measurements are conducted by the method of differential absorption at two wavelengths (308 and 355 nm) in the dark time in clear weather at the altitude of 12 to 35 km. The spatial vertical resolution of obtained profiles is 1.6 km in the range of 12 to

The basic characteristics of the lidar

Transmitter		Receiver	
Parameter	Value	Parameter	Value
Mean power:		Telescope scheme	Newton scheme
Nd:YAG, 532 nm	2.8 W	Main mirror diameter	635 mm
355 nm	1.1 W	Mechanical near-zone cutoff	Available
XeCl, 308 nm	2.5 W	Field of view	1.5 –5
Pulse duration	10–20 ns	Number of optical channels	2 4
Radiation divergence:		Number of photoreceivers	4
532, 355 nm	0.2 mrad	Photoreceiver type	R7201-01
308 nm	0.2 1.0 mrad	Operation mode	Photon counting

25 km and gradually decreases to 5.8 km at the altitude of 32–35 km. The measurement duration is one hour. During the period from the beginning of 2012 till March 2015, 313 ozone measurements were conducted at Obninsk lidar station.

Let us write the well-known equation for the determination of ozone concentration C_{O_3} in the following form:

$$C_{\mathrm{O}_3}(z) \quad {}_{\mathrm{O}_3}(z) \quad \frac{1}{2}\frac{d}{dz}[\ \ln F(z)] \quad \frac{1}{2}\frac{d}{dz}[\ \ln D(z)] \quad B(z) \quad A(z)$$

where z is the distance along the sounding route; (z) is the difference in the ozone absorption cross-section at wavelengths ${}_{\mathrm{on}} = 308$ nm (in the absorption band) and ${}_{\mathrm{off}} = 355$ nm (off the absorption band); $\ln F(z)$ is the difference in the logarithms of signals at the same wavelengths; $A(z) = {}_{\mathrm{m}}(z)$ is the difference in the Rayleigh extinction coefficients. The parameters $D(z)$ and $B(z)$ were introduced to take into account the aerosol extinction (aerosol correction):

$$D(z) \quad \frac{(z)[R(\ _{\mathrm{off}},z) \quad 1]}{R(\ _{\mathrm{off}},z)}, \quad B(z) \quad {}_{\mathrm{a}}(\ _{\mathrm{off}},z)\ (z),$$

$$(z) \quad {}_{\mathrm{a}}(\ _{\mathrm{on}})/\ {}_{\mathrm{a}}(\ _{\mathrm{off}}), \qquad (\ _{\mathrm{on}}/\ _{\mathrm{off}})^4, \quad (z) \quad \frac{{}_{\mathrm{a}}(\ _{\mathrm{on}},z) \qquad {}_{\mathrm{a}}(\ _{\mathrm{off}},z)}{{}_{\mathrm{a}}(\ _{\mathrm{off}},z)}$$

where $R(\ _{\mathrm{off}}, z)$ is the backscattering coefficient at ${}_{\mathrm{off}}$; ${}_{\mathrm{a}}$ and ${}_{\mathrm{a}}$ are the coefficients of aerosol backscattering and aerosol extinction.

The parameters (z) and $v(z)$ in the expressions for $D(z)$ and $B(z)$ are computed using the optic microphysical model [2] based on the data of aerosol measurements at the wavelengths of 355 and 532 nm conducted before ozone measurements.

Ozone absorption cross-sections for the sounding wavelengths were selected from data of [4, 9, 12] taking into account the results of other measurements presented in the MPI-Mainz-UV-VIS Spectral Atlas database at the website [11].

The Brewer spectrophotometer (BREWER MKII model was used) provides high-precision automatic measurement of surface ultraviolet radiation as well as of TO and total sulfur dioxide. The direct-sun TO measurement error is ±1%. The instrument was included to the NDACC (Network for the Detection of Atmospheric Composition Change) global network and is one of several Brewer spectrophotometers on the territory of the Russian Federation. Its data are stored in the Russian database as well as in the WOUDC (World Ozone and Ultraviolet Radiation Data Centre) database.

3. COMPARISON OF LIDAR AND SATELLITE DATA

At present, operational information is available on ozone profiles measured with the Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS) instruments installed at Aura satellite [10]. OMI is the nadir instrument for monitoring TO and ozone profiles, it conducts measurements of backscattered radiation in three spectral bands (UV-1: 270 to 310 nm; UV-2: 310 to 365 nm; visible: 350 to 500 nm) with the spectral resolution from 0.42 to 0.63 nm. OMI has a wide field of view with the transversal view of

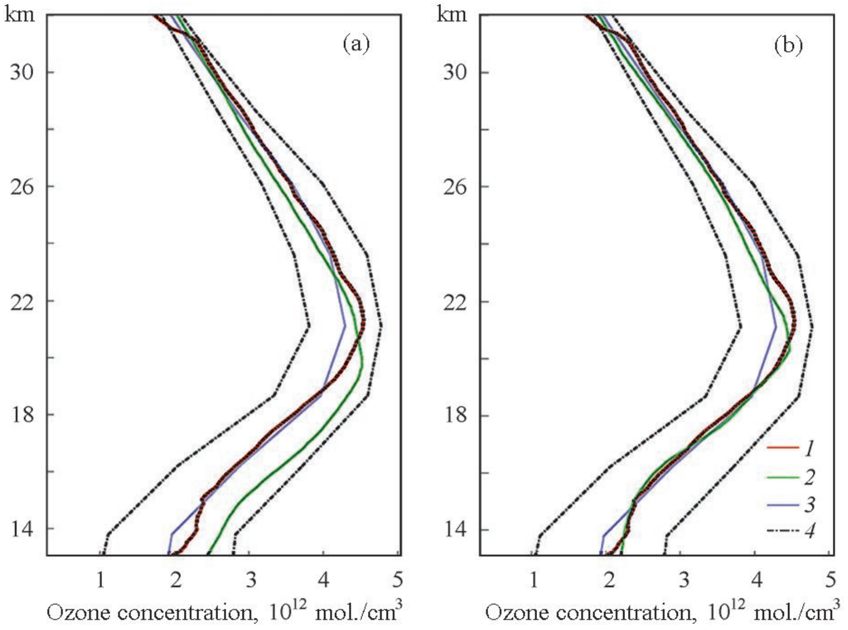

Fig. 1. The comparison of mean (2012–2015) ozone profiles derived from lidar data and satellite measurements with (a) OMI and (b) MLS instruments for the latitude of Obninsk (55.1 N, 36.7 E). (*1*) Lidar data; (*2*) satellite data; (*3*) HALOE model; the dotted line is the boundaries of the maximum permissible values of the model at the level of 1 .

2600 km and with the resolution of 30 pixels in the UV-2 band and 60 pixels in the UV-1 band. This provides the global daily view with the spatial resolution of 13   24 km (along and across the route, respectively) in the UV-2 band and 13   48 km in the UV-1 band. OMI data are presented for the altitude range of 0 to 57 km with the resolution of 3–5 km. OMI measurement errors are analyzed in detail in [6]; it is noted there that the main source of errors is scattered light in the spectrometer of the instrument. In general, measurement data agree with other measurement data for the middle stratosphere within 20%. Starting from the altitude of 22 km and at lower levels, OMI gives a positive bias reaching 20% at the altitude of 16 km and increasing further to 25–70% (depending on the measurement point coordinates) to the height of 11.5 km.

The Aura MLS instrument provides limb measurements of thermal microwave radiation in the frequency range of 118 GHz to 2.5 THz. Aura/MLS data on ozone concentration are presented at the above website for the altitude range of 10–75 km (261–0.02 hPa). The ozone measurement error is within 10% [8], the vertical resolution is about 3 km. The Aura/MLS data file is formed once a day and contains the results of 3495 measurements with the temporal resolution of 24.7 s each related to the certain latitude and longitude. The measurements which satisfied the following spatiotemporal conditions were selected from all measurements conducted by the Aura instruments: the distance is not more than 500 km from the lidar location; the time is ±17 hours from the lidar measurement time.

Figure 1 presents the comparison of ozone profiles derived from lidar and satellite data averaged over the period of 2012 to 2015. The profile based on the HALOE model [5] and the standard deviation in the framework of the model are also presented for comparison. As clear from Fig. 1a, the maximum difference is observed for the comparison of lidar and OMI data at the altitude of 13 to 20 km: the difference is 0.6 10^{12} mol./cm^3 or 20% that is consistent with data from [6]. This means that differences between lidar and Aura/OMI satellite data are largely associated with biases in satellite measurements. At the same time, the comparison with MLS data (Fig. 1b) gives the maximum difference of 0.2 10^{12} mol./cm^3 (or 5%) at the height of 22 km. The ozone profile derived from MLS data is in the better agreement with lidar data on ozone (this is especially clear for the altitude range of 13 to 20 km). The maximum relative difference of results for all altitudes does not exceed 9% that is a rather good result taking into account the differences in the spatiotemporal scales of averaging and measurement shifts in time (by 7 hours on average) and in space (by 300 km on average).

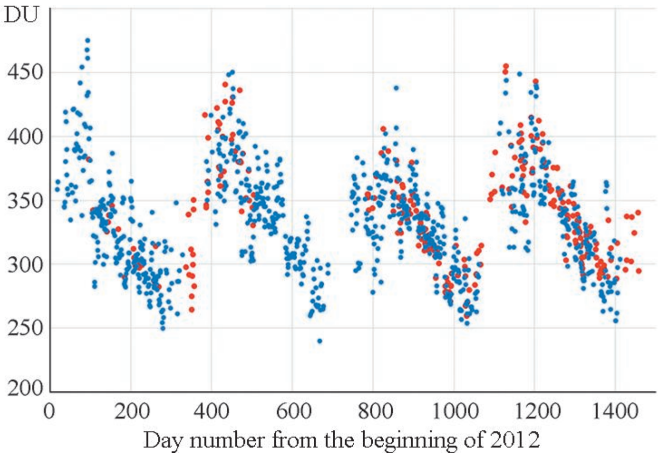

Fig. 2. Temporal variations in TO over Obninsk in 2012–2015. The red dots are the calculation based on lidar data in the altitude range of 12–35 km jointly with the known climatology [7]; the blue dots are Brewer spectrophotometer data.

4. COMPARISON OF LIDAR DATA WITH BREWER SPECTROPHOTOMETER TO DATA

To compare lidar data with Brewer spectrophotometer data, lidar data were integrated over the whole altitude range (12–35 km) and were reduced to Dobson units. However, as the spectrophotometer measures TO in the whole air column, the values of integral ozone concentration in the altitude ranges of 0–12 and 35–70 km were added to lidar data. For this purpose, monthly mean values for the latitudinal zone of 50 –60 N from [7] were utilized. In this paper, measurement data were summarized over the period of 1988 to 2002; the results of ozone sonde measurements were taken as a basis to the height of 10 km and Sage II and MLS satellite data were used for higher levels. The following correction to lidar data (DU) was obtained depending on a month and altitude range:

Month	January	February	March	April	May	June	July	August	September	October	November	December
0–12 km	43.4	50.9	55.0	59.4	56.3	53.7	50.5	44.9	40.7	38.3	38.4	40.2
>35 km	26.4	28.6	30.3	30.2	29.1	27.2	26.1	27.9	28.9	29.5	28.6	27.1

Lidar data were corrected taking into account the monthly mean values presented above. The mean correction was equal to 47.7 DU or 13.7% at the altitude of 0 to 12 km and 28.3 DU or 8.1% at the altitude of 35 km. Consequently, ozone derived from lidar data for the layer of 12–35 km makes up 80% of total ozone. The mean value of TO for all measurements is 348 DU.

Figure 2 presents temporal variations in TO values obtained by two different methods. A good qualitative and quantitative agreement is observed. Seasonal variations in ozone concentration and interseasonal differences are strongly pronounced in lidar data.

The correlation between the results of TO determination by two methods for 222 days of parallel observations is presented in Fig. 3 (as well as in the previous case, climatology data were added to lidar data for the layers below and above). The dependence between the data obtained by the two methods was close to linear; the linear regression equation is: $y = 0.861x + 51.40$, where y is TO derived from lidar data; x is TO measured with the Brewer spectrophotometer. The large bias is obviously related to the certain nonlinearity of the dependence $y(x)$. To reveal it, the squared regression equation was taken (see Fig. 3); in this case, the bias was 8 DU and was evidently associated with the measurement error and with the error of lidar data reduction to TO according to zonal mean climatology. The coefficient of determination R^2 for the analyzed nonlinear regression is 0.83, the standard deviation is 17.44 DU.

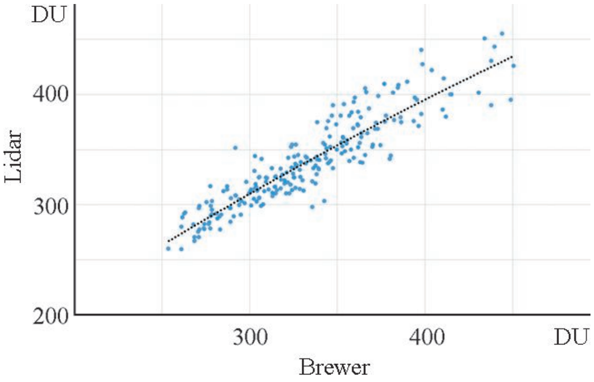

Fig. 3. The correlation between TO values derived from lidar (jointly with climatology [7]) and Brewer spectrophotometer data. The equation of the correlation dependence drawn with the black dotted line is: $y = -5.132 \times 10^{-4}x^2 + 1.214x - 8.033$.

The mean relative difference between the corrected data of the lidar and Brewer spectrophotometer for separate ranges is:

TO range, DU	250–300	300–350	350–400	400–450
	–0.046	–0.016	–0.01	0.032

i.e., its absolute value does not exceed 5%.

Thus, the total ozone value determined from lidar measurements (with addition of climatology data) is in a good agreement with Brewer spectrophotometer data. In this case, Brewer spectrophotometer data can be considered as reference ones relative to lidar data, because they are based on numerously tested and internationally accepted procedures.

5. CONCLUSIONS

The lidar measurements of ozone concentration over Obninsk in 2012–2015 were conducted using the method of differential absorption at the wavelengths of 308 and 355 nm. The comparison of mean (over the measurement time) ozone profiles derived from lidar data with Aura/MLS satellite data revealed their qualitative and quantitative coincidence in the altitude range of 12–32 km, with the maximum difference of not more than 0.2×10^{12} mol./cm^3 (or 9% in relative units at some heights). The comparison with Aura/OMI data revealed the difference of about 20% at the altitude of 13 to 20 km that may be explained by the bias of ozone measurements with OMI [6].

It was found that the dependence between TO values determined from lidar data jointly with climatology data [7] and from the data of parallel measurements of TO with the Brewer spectrophotometer is close to linear one, with the coefficient of determination equal to 0.83, and the mean relative difference does not exceed 5%.

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