Using satellite radiometric and ground based lidar measurements for detection of cirrus clouds, containing ensembles of preferred oriented ice particles

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ABSTRACT

In this paper present an example of joint analysis of the data of high-level cloud sensing with a ground based polarization lidar of Tomsk State University and satellite radiometer MODIS.
Keywords: polarization lidar, cirrus clouds, backscattering phase matrix, satellite radiometer.

INTRODUCTION

At present generally recognized fact a significant impact of high-level clouds (HLC), consisting of predominantly crystalline particles, on the radiative processes in the atmosphere and consequently the features of formation of the Earth's climate. They are formed at altitudes of 8–12 km, are sufficiently transparent in the visible wavelength range, and have large horizontal length. For several decades, conducted focused research cirrus clouds in the various national and international projects with the use of all available means and methods. But some aspects of the interaction of radiation with a non-spherical particle is still poorly understood. For example, in work [1] were summarized results of many years complex researches of radiative properties of HLC, made groups of Soviet scientists. It also notes the need to study even the most thin cirrus clouds due to insufficient knowledge of their radiative properties. Among several problems requiring refinements - features cirrus microphysics related to the manifestation of the preferred orientation of non-spherical particles, which leads to significant optical anisotropy. Aerodynamic forces created by particles that fall down and, possibly, by wind shears and electric fields can be referred to external factors causing particle orientation. Joint action of these forces engenders preferred orientation of ensembles of crystal particles. In this connection, the task of developing microphysical model HLC, adequately describes their optical properties with the preferred orientation of the crystal particles is important.

Lidar studies of crystal clouds are practically the sole tool for getting information about the state of the orientation of the crystals in the clouds. Laser polarization measurements of high-level clouds are regularly held at polarization lidar of National Research Tomsk State University (TSU) [2, 3]. A distinctive feature of the polarization lidar of TSU is the unit of polarization state transformation, which makes it possible to measure the backscattering matrices (BSM). To determine the BSM experimentally, laser radiation is sequentially sent into the atmosphere with four different polarization states, and the polarization state of backscattered radiation is measured: a lidar signal is recorded at four different positions of polarization elements of the detector. Analysis of the relations between elements of experimental BSM allows to estimate the state of orientation of crystal particles in the clouds.

CHARACTERISTICS OF HIGH-LEVEL CLOUDS FROM DATA OF SATELLITE RADIOMETER

In the last decades it is becoming increasingly important cloud monitoring from space. Information characteristics of clouds, temperature and humidity in the atmosphere at altitudes of observed clouds can be obtained by processing the satellite data.

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One of these perspective means is a radiometer MODIS (MODerate-Resolution Imaging Spectroradiometer), allows to measure rising from the surface radiation flux at 36 of the spectral ranges (including visible, NIR and IR) from 0,4 to 14,2 μm with a spatial resolution of 250 m to 1 km, depending on the wavelength. It is known that the 26th spectral channels (at the wavelength $\lambda = 1.38$ μm) of the radiometer MODIS for daytime observations allows cirrus to be detected in the upper layers of the troposphere. This spectral channel lies within the strong water vapor absorption band; therefore, solar radiation reflected from the Earth surface is almost completely absorbed in the atmosphere whose water content is $W > 1$ g/cm^2. In this channel satellite radiometer fixes the scattered radiation from the layers of cirrus clouds or aerosols in the upper atmosphere. Then using a threshold value (0.03-0.04) for the reflection coefficient $R_{1,38}$ the system "atmosphere - the earth's surface" in the channel $\lambda = 1,38$μm, possible to divide such optical situation as clear atmosphere, the presence of cirrus clouds and thick clouds with optical thickness > 0.5.

Further consider results of processing of satellite data array obtained in the afternoon nearby Tomsk (within 25 km) on May 17 – June 6, 2011. Table 1 shows the mean values of atmospheric parameters, as well as the date and time of the satellite measurements.

Table 1 – Characteristics of cloudiness retrieved from data of satellite MODIS nearby Tomsk from May 17 to June 6, 2011 (selected data)

Date	Time	τ_C	N_P, %		r_{ef}, μm		$R_{1,38}$	
			Drops	Ice	Drops	Ice	Drops	Ice
17-05-2011	11:30	5.6	100.0	0.0	11.8	0.0	0.053	0.000
22-05-2011	11:50	13.0	91.0	9.0	12.4	17.2	0.018	0.244
23-05-2011	12:30	27.1	93.3	6.7	11.5	9.8	0.027	0.076
25-05-2011	14:10	6.9	15.3	84.7	12.3	27.5	0.048	0.231
26-05-2011	14:50	38.4	43.1	56.9	10.4	19.8	0.065	0.538
27-05-2011	13:55	16.3	98.3	1.7	10.4	23.0	0.020	0.221
29-05-2011	13:35	14.5	80.4	19.6	12.1	24.3	0.036	0.128
30-05-2011	14:25	4.6	44.5	55.5	9.1	29.2	0.035	0.125
31-05-2011	11:45	1.0	22.3	77.7	0.0	20.4	0.038	0.062
01-06-2011	14:15	13.2	53.0	47.0	9.8	18.5	0.059	0.185
02-06-2011	11:30	3.0	10.8	89.2	0.0	27.5	0.153	0.228
06-06-2011	14:35	44.4	2.8	97.2	10.2	20.9	0.038	0.566

The table shows: τ_C – cloud optical thickness; N_P – numbers of drops and crystals in the cloud, in percent; r_{ef} – effective cloud particle size; $R_{1,38}$ – reflection coefficient in the channel with $\lambda = 1.38$ μm.

The data presented in Table 2 allow us to point out significant variability of optical situations from May 17 till June 6. High values of $R_{1.38}$ are indicative of the presence of scattering layers (more often cirrus) in the upper layers of the troposphere and stratosphere. During this period, there was significant variability in the optical situations. In particular, on May 21–22, on May 25–26, on May 30, on June 1–2, and on June 5–6 increased values $R_{1.38} > 0.075$ were observed, which indicated the presence of high-level clouds consisting of ice crystals. Maximum ratio $N_P > 70\%$ for ice crystals was fixed on May 25 and 31 and on June 2 and 6.

EXAMPLE OF LASER POLARIZATION SENSING OF HIGH-LEVEL CLOUDS

As one example, comparison of lidar and satellite observations of clouds, we consider the results of the laser sensing, which were obtained on May 30-31, 2011. The experiment was conducted from May 30 15:56 to 7:10 on May 31 with the accumulation of 200-500 laser pulses at a repetition rate of 10 Hz. At this time there was a cloud on 5,5-6,5km altitude (Fig. 1).

Figure 1 shows 2 altitude profiles of the backscattered radiation intensity recorded at series №2. The altitude, in km, is indicated on the *y* axis, and the number of one-electron pulses recorded from the corresponding altitude accumulated by the registration system is indicated on the *x* axis. Each profile is presented in the frame from below of the figure: S_1 is the normalized Stokes vector of sensing radiation (letter *t* denotes transposition of the matrix-row) and G_1, G_2 is the instrumental vector of the receiving lidar system characterizing the combined action of polarization devices in the receiving channel.

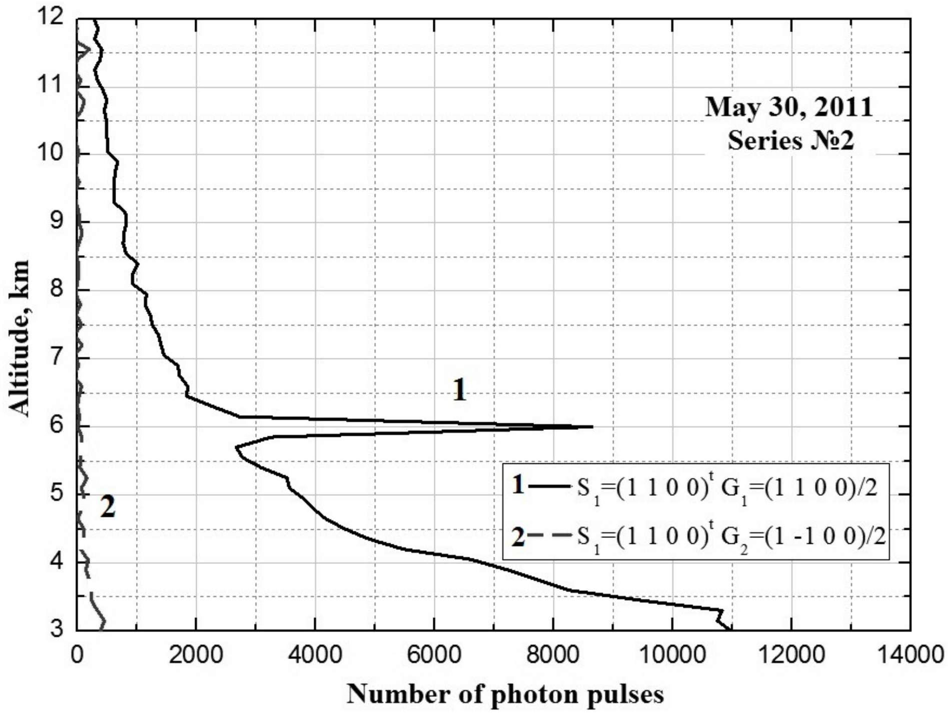

Fig. 1 Lidar signals recorded on May 30, 2011 for sensing with linearly polarized radiation (The Stokes vector S_1) and instrumental vectors G_1 and G_2 indicated in the figure. Local time of sensing session: 16:08 – 16:22

As seen from Fig. 1, the observed cloud layer had crystal nature, since the cross-polarized component of the lidar signal was nonzero at the lower cloud boundary and reached sufficiently high power compared to the parallel component. This cloud is characterized by the backscattering ratio R (6,0km) = 2.9 and the optical thickness τ = 0.26. We note that the backscattering ratio is understood as a ratio of the sum of the aerosol and molecular backscattering coefficients to the molecular backscattering coefficient:

$$R = \left(\beta_\pi^m + \beta_\pi^a\right) \Big/ \beta_\pi^m \ . \qquad (1)$$

The average BSM calculated for all cloud from the available experimental data are demonstrated below.

$$M_\pi(5.7 - 6.45km) = \begin{bmatrix} 1 & 0.03 & -0.16 & 0.13 \\ 0.03 & 0.94 & 0.06 & 0.07 \\ 0.16 & 0.30 & -0.76 & 0.23 \\ 0.13 & -0.06 & -0.13 & -0.49 \end{bmatrix}.$$

The negative element value m_{44}= – 0,49 and sensing radiation is practically undepolarized in the process of reflection from the cloud (degree of polarization 0,95-0,97) indicates that this cloud consists most likely of crystal particles whose major diameters are oriented preferably in the horizontal plane.

According to the data radiometer MODIS to the May 30 observed increased values $R_{1.38}$, which is one of the signs of the presence HLC, consisting of ice crystals. The percentage of N_P crystals in the cloud exceeds the number of drops.

CONCLUSIONS

Thus, use of satellite radiometric measurements and comparison of information about optical characteristics of the cirrus clouds (BSM), according to the synchronous lidar measurements allow classified clouds by the presence of these oriented crystals and the degree of their orientation. In other words, each type HLC is compare view BSM, which characterizes the microstructure of the cloud and the value of the reflection coefficient in the channel λ = 1,38μm.

Using data obtained from satellite observations of overcast, it will be possible to create a method for operative detecting cirrus clouds containing predominantly oriented ice particles from space. Latter is very important for improving the accuracy of calculation of radiation fluxes in the atmosphere and, therefore to increase the reliability of forecasts.

Our analysis allows us to conclude the following. The satellite radiometric measurements in visible and infrared channels allow the presence of cirrus to be detected both in the daytime and at night. Along with cirrus detection, it is possible to estimate its optical thickness, altitude, and phase composition (water drops and ice crystals). The presence of crystal particles in HLC from the data of radiometer MODIS, is confirmed by measurements of the BSM with the polarization lidar. However, the optical thickness of clouds measured with radiometer and lidar differed significantly. Here it is pertinent to note that the optical thickness of thin HLC is determined with high accuracy by the lidar method.

We suggest that cirrus with high degree of particle orientation will have higher reflection coefficient at the wavelength λ =1.38 μm. This fact can serve as a criterion for estimation of the degree of orientation of ice particles in a cloud. If we relate the $R_{1.38}$ value to the peculiarities of the BSM of such clouds, we can obtain a rule by which the degree of orientation of crystal particles in HLC can be estimated. To solve this problem successfully, a series of complex experiments with the ground-based polarization lidar capable of obtaining the total light backscattering matrix is required.

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REFERENCES

[1] Feigelson E.M. [Radiative properties of cirrus clouds], Nayka, Moscow, 224 (1989).

[2] Nasonov S.V., Samokhvalov I.V. "Analysis microstructure of the upper-level clouds by polarization characteristics of lidar returns", Proc. SPIE 9292, 20th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics, 92922L (November 25). 92922L-1–92922L-8. (2014).

[3] Kaul B.V., Volkov S.N., Samokhvalov I.V. "Study of crystal clouds through lidar measurement of backscattering matrices", Atmospheric and Oceanic Optics. V. 16. № 4. 354-361. (2003).

[4] Samokhvalov I.V., Kaul B.V., Nasonov S.V., Zyvotenuk I.V., Bryukhanov I.D. "Backscattering matrix of the mirror-reflecting upper-level cloud layers formed by horizontally oriented crystal particles", Atmospheric and Oceanic Optics. V. 25, №. 5. 403–411. (2012).