Dynamics of lidar returns in Kamchatka mesosphere in period of anomalous wintertime radiowave absorption in ionosphere

V.V. Bychkov,[1] V.N. Marichev,[2] A.S. Perezhogin,[1] B.M. Shevtsov,[1] and A.V. Shumeiko[1]

[1] *Institute of Cosmophysical Researches and Radio Wave Propagation, Far Easten Branch of the Russian Academy of Sciences (IKIR), Paratunka, Kamchatka Region*
[2] *V.E. Zuev Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, Tomsk*

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We describe the Rayleigh lidar, brought into use in Kamchatka in 2007. The relation between lidar measurements and simultaneous ionospheric observations is analyzed. We present the data, which confirm the observations, performed at IAO, Tomsk, in period from 1988 to 2000; they reveal the formation of aerosol layers in the region of stratopause at wintertime. We study the relation between formation of aerosol layers, observed above the stratopause in Kamchatka, and the anomalous radiowave absorption in ionosphere, observed at the same time. Regular growth of the scattering ratio is revealed, starting from altitudes of about 60 km. The dynamics of lidar signals in this region and its relation with the state of the lower ionosphere are studied.

Introduction

It is generally accepted that the stratosphere is very dry, and water vapor condensation there is absent. Nonetheless, the elevated ratio of scattering coefficients in a height range 40–45 km at wintertime was observed over Tomsk in period from 1988 to 2000.[1] Estimates[1] show that the water content in the stratopause region is five orders of magnitude lower in winter and six orders of magnitude lower in summer than the dewpoint. Moreover, it is revealed that the aerosol layers at altitudes of 40–45 km have been observed, as a rule, in periods of the elevated radiowave absorption in ionosphere. It was also shown that the experimentally observed characteristic changes in the temperature profile in mesosphere and the content of positive ions in the stratopause region, accompanying the phenomenon of the anomalous wintertime radiowave absorption, may lead to creation of conditions for the water vapor condensation and formation of water aerosols at heights of 45–65 km.

Most favorable conditions for the condensation appear at a height of about 60 km. Simultaneously, the stratopause descends down to heights of 40 km, giving rise to the phenomenon of the stratospheric warming. The lidar and ionospheric observations, conducted synchronously in Kamchatka in January–March, 2008 have made it possible to reveal in period from 18 to 23 January the appearance of aerosol layers in the region between 50 and 65 km. The anomalously high radiowave absorption at the same time was recorded from data of the IKIR ionospheric station.

Observation facilities

The Rayleigh lidar station, put into operation in Kamchatka, consists of the Brilliant B solid-state laser and a telescope, assembled according to the Newtonian scheme; it has the following characteristics: a wavelength of 532 nm of the second harmonic of Ni:YAG, a beam diameter after exit from the collimator of 6 cm, a pulse energy of 0.4 J, a pulse duration of 5 ns, a frequency of laser pulses of 10 Hz, a diameter of the receiving mirror of 60 cm, a focal distance of 210 cm, beam divergence after exit from the collimator of 10^{-5} rad, the receiver's field of a view angle of $5 \cdot 10^{-4}$ rad. Possible distances between the emitter and the receiver axes are 0, 130, and 510 cm. The 1.5 km vertical resolution is stipulated by the 10 μs time resolution of the Hamamatsu-H8784 photon counter. The photodedector unit uses the H8259-01 photomultiplier and the light filter at a wavelength of 532 nm with the following parameters: the maximal transmission is larger than 60%, the width at the half-height is 3 nm, and the suppression in the blocking region 180–850 nm is less than 0.1%.

All results, presented in this paper, are obtained on the basis of the 510 cm lidar. To eliminate the illumination from signals of the near zone, the electronic gating of the photomultiplier up to a height of 21 km was applied. To observe the ionosphere state, a standard automated ionospheric station (AIS) with a digital receiving unit was used. The computers, controlling the operation of AIS and lidar station, were synchronized using the GPS time.

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The program for lidar control, as well as the programs for the signal processing, have been developed at IKIR,[2] using the method of calculation of the ratio total scattering coefficient/aerosol scattering coefficient R [Ref. 3]. The coefficient of the molecular scattering was calculated in accordance with Ref. 4, and the atmospheric temperature and pressure were calculated from CIRA [Ref. 5] or MSIS-2000 [Ref. 6] models. There is also the option of calculating altitude profiles of the scattering, using the experimental data arrays of the temperature and pressure. The altitude range of received signals in 2007 was 20–150 km with a step of 1.5 km. Since February 18, 2008 the altitude of recorded signals was increased up to 300 km and since March 28, 2008 – up to 600 km.

Experimental data

The radiowave absorption in ionosphere was estimated from the value of the regularly measured standard ionospheric parameter $f_{\min}$, i.e., minimal frequency, at which the trace of the layer E or F appears in ionograms. The radiowave absorption in the atmosphere is determined primarily by the product of electron density and the density of the neutral component. In the Earth's atmosphere, the conditions for the absorption of radiowaves with a frequency of 1–2 MHz are realized in a height interval of 80–100 km; therefore, this parameter is used in ionospheric studies for estimation of the important plasma characteristic, namely, the electron density in the D region. In December and March, no pronounced phenomena of the anomalous absorption were observed. Figure 1*a* presents diurnally average behavior of the $f_{\min}$ for January and February, 2008 according to data of the IKIR ionospheric station. Thin line shows monthly mean value for unperturbed days.

It is seen from Fig. 1*a* that in period from January 18 to February 5, there was a series of three distinct successive events of the anomalous absorption with maxima on January 22 and 28, as well as on February 3. The intensity and duration of each succeeding event decreased. Weather conditions were favorable for lidar observations on January 18, 20, 23, 24, and 29. All profiles of the scattering ratio, presented below, were obtained through accumulation over 4 hours and contain about 140 thousands of initial signals. The background signal level was measured for 2 ms, between 20th and 22th ms in each inter-pulse interval. Thus, for every single signal profile, the average over 200 values of the background signal, measured in the inter-pulse interval, was taken as the background one. The final value of the background signal over 15 min was obtained by summation and averaging of 1800000 measured values.

Figure 1*b*, *c* presents the background signal N_f with 15 min accumulation and signal-to-background ratio, obtained on January 18 and 29 for signals summed over 4 hours. The difference in the behavior of the curves is explained by the change of the lunar phase, close to the full moon on January 18 and close to new moon on January 29. Values of the background and signal-to-background ratio on January 20, 23, and 24 fall between curves for January 18 and 29 in correspondence with the lunar phase decrease.

The anomalous absorption was accompanied by the stratospheric warming. Figure 2 presents the temperature behavior in the altitude region between 10 and 85 km by the Aura satellite data.

The lower raw of plots shows the profiles of the scattering ratio, obtained those days. The stratospheric warming has begun on January 18, with approximately the 7–8 K temperature increase at a height of 10 km and with the 15° cooling in region 50 km. On January 20, the region of warming propagates to altitudes from 10 to 40 km, and more than the 30° cooling is observed simultaneously near the 63 km altitude. On January 23, the stratopause shifts to a height of about 30 km, and the region of maximal cooling shifts from the 63 km height to 70 km.

The temperature profile begins to recover on January 24, though the warming below the stratopause and marked cooling in the 70 km region still remain. Anomalous absorption in the ionosphere on January 24 is not already observed. In the second wave of the anomalous absorption (on January 29),

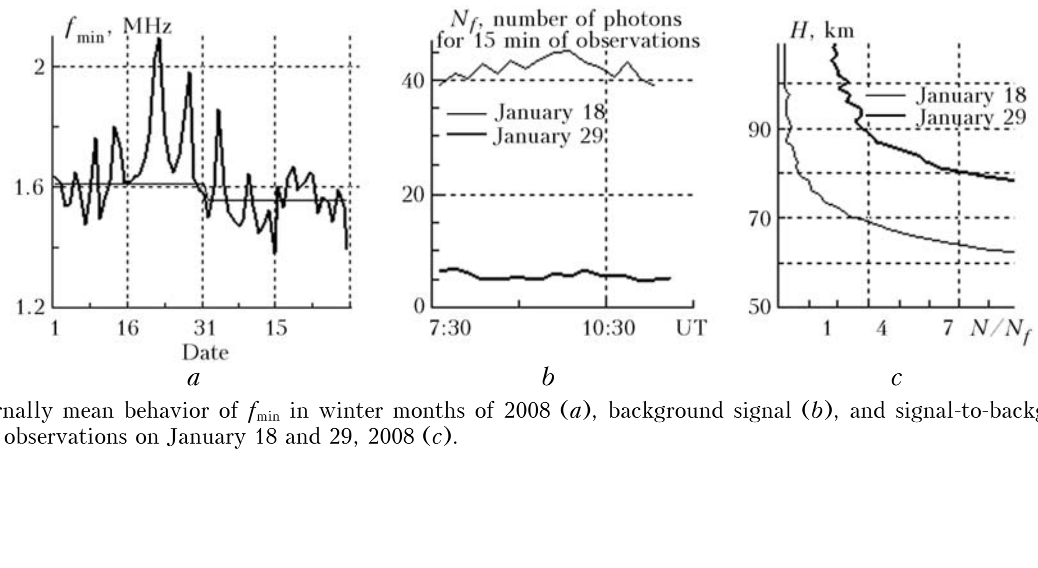

Fig. 1. Diurnally mean behavior of $f_{\min}$ in winter months of 2008 (*a*), background signal (*b*), and signal-to-background ratio during lidar observations on January 18 and 29, 2008 (*c*).

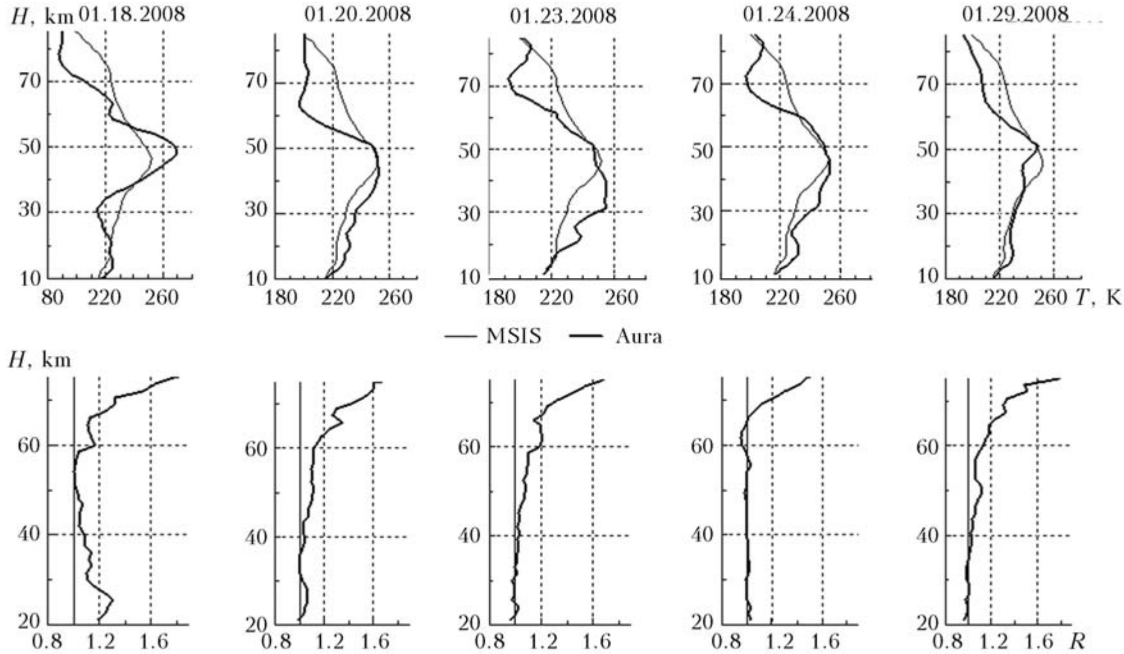

Fig. 2. Temperature profile from the Aura satellite data (upper raw) in comparison with the MSIS-2000 model and scattering ratio on those days from the lidar observation data (lower raw).

temperature changes above 50 km have the same character; however, in the region from 40 to 50 km there is a cooling down to 14°.

The lower raw in Fig. 2 shows the profiles of aerosol scattering ratio $R = 1 + R_a/R_m$ for January 18, 20, 23, 24, and 29, where R_m and R_a are the coefficients of molecular and aerosol scattering, respectively. The accumulation of signals is large, and the profiles of the confidence interval are not presented, because at this scale they practically coincide with the signal profile. The onset of the anomalous radiowave absorption in the ionosphere starts on January 18. The well pronounced maximum with $R = 1.2$ in the 60 km region and the elevated scattering ratio in the region 20–40 km are characteristic. In the profiles for all other days, no elevated scattering in region 20–40 km is observed, with exception of the insignificant increase on January 20 at the 25 km height. On January 20, the maximum of the scattering ratio migrates from the 60 km region to the 65 km; on January 23, R values in the profile start to decrease; and the profile peak totally disappears on January 24, the final day of the first wave of the anomalous absorption in ionosphere.

January 29 is the final day of the second wave of the anomalous absorption in ionosphere. A small increase in the behavior of R takes place at altitudes of about 50 km; but in view of the lack of the data for preceding days, nothing can be added to the aforesaid. It can be only noted that there was a temperature decrease this day in that region.

Based on the results of the first year of lidar observations in Kamchatka, scattering profiles from the late March to November have the same shape as the profile for January 24. As a rule, the R value is practically equal to unit up to a height of 60 km. Starting approximately from the 60 km height, all profiles without exception show the growth of the scattering ratio. In wintertime profiles of usual days, episodically small increases of the scattering ratio in the region 40–60 km are noted. The study of these phenomena using actual temperature data was not performed. The comparison of the presented profiles with profiles, obtained using temperature and pressure data from the MSIS model shows that for days of the anomalous absorption and stratospheric warmings, the use of the model results may lead to serious distortions.

Dynamics of lidar signals

We calculated by the moving average method the correlation coefficients K between series of 15-min f_{min} values and scattering ratios R in 1.5-km layer, smoothed over the 3 km interval. For series of 16 values, the correlation coefficient, higher than 0.25, was considered to be significant. The curve of the correlation coefficient height behavior for January 18 is presented in Fig. 3*a*.

For clarity, figure 3*b* presents the distribution of the scattering ratio in height-time coordinates for 4 hours of observations. The distribution is plotted using 15-min altitude profiles of R, and R values are plotted using two-point smoothing by the moving average method.

From Fig. 3*a* it is seen that beginning from a height of about 50 km the correlation coefficient starts to vary in wave-like manner from zero to values, markedly exceeding the significance level. In the region of heights of 60 and 70 km, we obtained maximal correlation coefficients, equal to 0.82 and 0.88. The positions of maxima in behavior of the final profile of $R(H)$ for January 18 at altitudes of 60 and 70 km (see Fig. 2) well correspond to positions of maximal correlation coefficients (see Fig. 3*a*). Nearly identical distance between peak values of the correlation coefficient, equal to 6–7 km, may point to the presence of wave processes in the atmosphere, accompanying the phenomenon of the anomalous wintertime radiowave absorption in ionosphere.

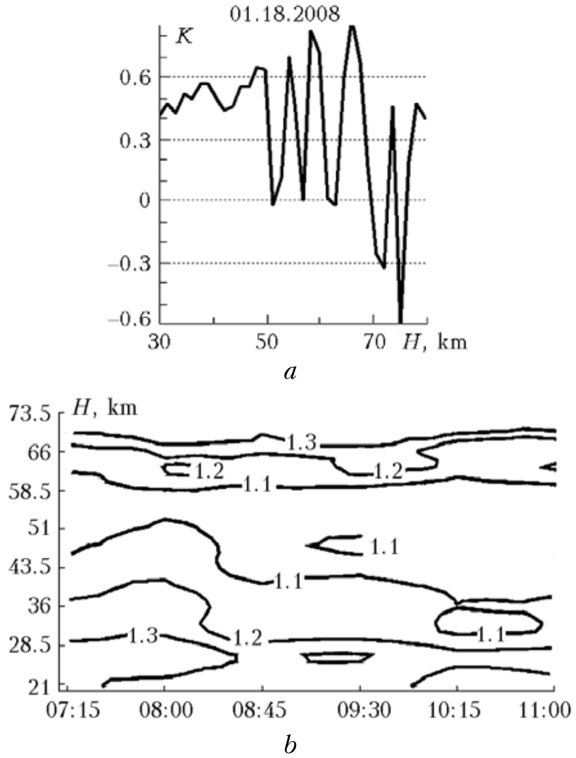

Fig. 3. Altitude behavior of the correlation coefficient between $R(H)$ and $f_{\min}$ for January 18 (*a*) and distribution of $R(H)$ over 4 hours of observations (*b*).

On January 20, the behavior of the correlation coefficient between R in 1.5-km layers and $f_{\min}$ exhibits already no such periodicity. The correlation coefficients, considerably exceeding the significance level, were observed in the regions 50–60 and 67–73 km. We calculated the correlation coefficients between $f_{\min}$ and mean R value in these regions. The region of the positive correlation in interval of 67–73 km, with the 0.55 correlation coefficient, coincides with a dip in this height interval at the growing, on the whole, R behavior. No marked correlations were found on January 23 and 24, and the correlation coefficients practically do not fall beyond the significance interval. Because of very small number of days, available for the study, the results presented in Fig. 3 can be considered only as preliminary.

The phenomenon of the anomalous wintertime absorption of radio waves with a frequency of 1–2 MHz in the lower ionosphere was studied during International Geophysical Year (IGY) in 1975–1976. Based on the model calculations, the works of 1980s, such as Ref. 7, show that this phenomenon can be explained by the turbulence intensification in the atmosphere and the water vapor transport to the upper mesosphere. Thus, the physical causes for relation between the scattering ratio and $f_{\min}$ may be determined by the fact that the growth of the electron concentration in the region 80–100 km at nighttime is ensured by the water content increase. In the underlying layers, the water content growth may trigger the growth of the scattering ratio.

All presented profiles show the increase of the scattering ratio, starting from a height of about 60 km. This increase is characteristic of all profiles without exception, obtained at IKIR in 2007–2008. At a height of 100 km, the characteristic R value lies in the range 20–40. In the region 80–100 km, the growth of the ratio of the scattering coefficients can be determined by the presence of meteorite dust and the exponentially decreasing molecular scattering coefficient. This growth continues with the increase of the altitude and is not discussed below.

Due to strong growth of the scattering ratio coefficients in the region 80–100 km, the temperature data are insufficiently reliable at altitudes near 100 km, and the signal-to-background ratio is pour; therefore, in this altitude range we studied the dynamics of lidar signals themselves, but not the dynamics of the scattering ratio coefficients. We calculated the correlation coefficients between series of 15-min values of the signal, normalized by the square of the distance to receiver, and $f_{\min}$ values. In the correlation calculations, we used average $f_{\min}$, determined using two values at the boundaries of every 15-min interval.

To calculate the correlation, we have chosen in the lidar data the normalized values of signals, summed over 15 min and determined as $N_n = (N - N_f) \cdot H^2$, where N is the summed signal, N_f is the summed background signal, and H is the height. Preliminarily, the calculations were made for 1.5-km layers; then, we selected the thickest layer with the positive correlations, calculated the layer-summed normalized signal, and finally we repeated for the summarized signal the calculation of the correlation coefficient with $f_{\min}$. Because of pour signal-to-background ratio at these altitudes the series of 15-min lidar data were smoothed once by two points by the moving average method. The calculations were made for all observation days from January to early March of 2008 without exception. The results are presented in Table.

Analysis of the table shows that at least in a half of the studied winter days there were marked correlations between lidar signals in large altitude ranges and $f_{\min}$ values. Significant correlations are observed for all days of the anomalous absorption in ionosphere. Marked correlations are also observed on February 11 and 18, when no pronounced anomalous absorption in ionosphere was noted according to diurnally mean values. To determine possible causes for the presence or the absence of the correlation between lidar data and $f_{\min}$, we have analyzed the behavior of $f_{\min}$ for those days. Analysis of the behavior of $f_{\min}$ according to 15-min values has shown

Table. Correlation coefficients between signal, averaged over altitude intervals, N_n, and ionospheric parameter f_{min}

Date	01.18	01.20	01.23	01.24	01.29	02.11	02.18	02.19	03.03	03.04
K	0.48	0.63	0.4	0.37	0.5	0.62	0.74	0.46	0.407	0.274
dH, km	78.5–81.5	82–100	85.5–91.5	78.5–91.5	78–102	90–97.5	77–100	94.5–96.5	94.5–96.5	94.5–96.5

that for all days with the correlation, there is a strong variation of f_{min} values during observations, usually accompanied by a marked trend toward their increase or decrease.

Figure 4 presents typical plots of the behavior of f_{min} for the days with the presence (January 20 and 29) and the absence (February 19) of the correlation. Thin line shows the trend. On January 20 and 29, there are strong variations of f_{min}, reaching values in excess of 1.8 MHz at nighttime. Such f_{min} behavior is characteristic for days of the anomalous wintertime radiowave absorption in ionosphere. On February 19, there are small f_{min} variations around the horizontal line of the trend near 1.4 MHz, typical for Kamchatka AIS. Similar f_{min} plots are also obtained for March 3 and 4. The f_{min} values are stable in these plots, and are practically within the accuracy of the measurement of these parameters. Thus, the correlation between lidar signals and f_{min} can be revealed only in the presence of marked trend toward the increase or decrease of f_{min} during the observation period, which is generally observed in days of the anomalous wintertime absorption in ionosphere, and is not observed in other seasons.

Physical causes for the correlation between lidar signals in the 80–100 km region and f_{min} can be explained by the same factors. There are evidences about the aerosol particles as large as 70 nm in D region of ionosphere.[8] All photochemical reactions in the mesosphere proceed with insufficient water content. Some increase of the water content causes the growth of the rate of all photochemical reactions, determining the electron density in D region. Thus, the water content growth leads to increase of the electron density in the 80–100 km region and, consequently, to the f_{min} growth. Simultaneously, the size of aerosol particles may also increase due to condensation of water molecules on them, because the temperature is very low in the mesopause region.

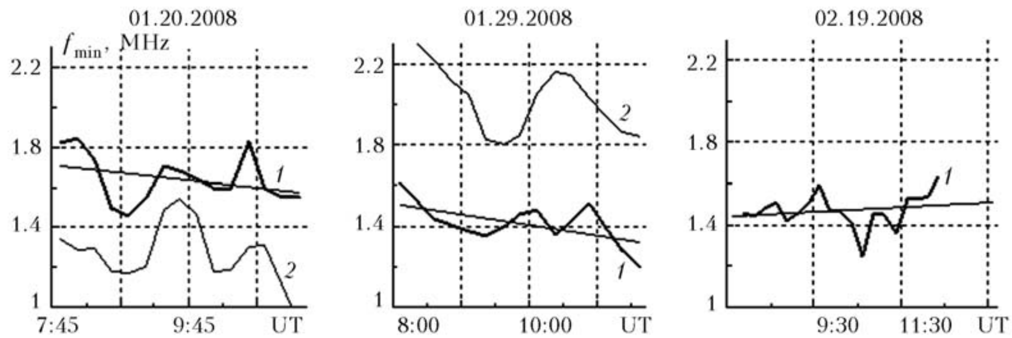

Fig. 4. Behavior of f_{min} (*1*) and summed (over correlation region) signal (*2*), normalized by the squared height.

Conclusion

Conclusions drawn in Ref. 1 about the possibility of formation of aerosol layers above the stratopause in periods of the anomalous wintertime radiowave absorption in ionosphere are confirmed by lidar observations in Kamchatka. The conclusions of works of 1970s–1980s that the anomalous wintertime radiowave absorption may be caused by the turbulence intensification in the atmosphere and the carrying of water vapor beyond the stratopause are also qualitatively confirmed (for example, of Ref. 7). The analysis of this phenomenon in more detail requires somewhat larger datasets. Our weather-restricted dataset for one year was insufficient to make more generalized conclusions.

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