Formation of water aerosols in the upper stratosphere in periods of anomalous winter absorption of radio waves in the ionosphere

V.V. Bychkov[1] and V.N. Marichev[2]

[1] *Institute of Cosmophysical Researches and Radio Waves Propagation, Far Eastern Branch of the Russian Academy of Sciences, Paratunka, Kamchatka Region*
[2] *Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, Tomsk*

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The results of lidar observations obtained at the Institute of Atmospheric Optics SB RAS, Tomsk, in January–March, 1996–2000 are presented. The data on the presence of water in mesosphere and upper stratosphere are discussed. The influence of geophysical processes on aerosol layer formation is considered. The correlation between aerosol layer formation in the upper stratosphere and anomalous winter absorption of radio waves in the lower ionosphere is considered. It is shown that the conditions for water condensation and water aerosol formation appear in periods of anomalous winter absorption of radio waves in ionosphere above the stratopause, which can descend in these periods to altitudes of about 40 km.

Introduction

Analysis of data on lidar observations for March, 1988 and 1989 over Tomsk have been presented in Ref. 1. The data of 1988 have revealed a correlation between stratospheric aerosol density at 45 km altitude and the daily mean index of geomagnetic activity K_p. In March, 1989, no correlation was detected. A wider range of data have been analyzed for January – March periods (1996–2000).[2] In other seasons the aerosols at these altitudes were not detected. High correlation coefficients of the stratospheric aerosol density at altitudes of 40–45 km with index K_p averaged over night time were obtained for January, 1998. The correlations for other months are lacking. Altitude profiles of the aerosol dispersion ratio R (the ratio of the sum of the aerosol and molecular backscattering coefficients to the molecular backscattering coefficient), obtained for January–March, 1988 are given in Fig. 1.

As it was mentioned in Ref. 3, the increase in water content immediately leads to an increase in ionization and condensation centre levels due to photochemical reactions and can result in formation of water aerosols. However, the main question about the reason of water content change at the stratopause and whether it is connected with an increase of geomagnetic activity or not, still remains to be answered.

An increase of the specific water content in stratopause is proved by experimental data. Data on spectral measurements of water content in stratosphere and mesosphere over California, Hawaiian islands, and New Zealand are given in Ref. 4. The measurements were conducted with WVMS (Water Vapor Millimeter-wave Spectrometer) at 22 GHz frequency. The device allowed obtaining high-altitude water profiles in the range 40–80 km (Fig. 2).

In all profiles shown in Fig. 2 the specific water content at 40 and 80 km altitudes makes up 6 and 2–3 ppm, respectively, and at altitudes of 50–55 km it is 6–8 ppm. Seasonal trend of water content in stratopause was observed at all stations. According to data of mid-latitude station in New Zealand (45° S), an increase of specific water content up to 7–8.5 ppm was observed every January. A winter increase of water content is also observed, however, not every year and at a less concentration; the increase is not as pronounced as the summer one and has a short time interval (probably about one month). On the whole, seasonal variations of water content at 55 km altitude are not high and make up less than 20%. As compared to 55 km level, the water content at a height of 40 km increases no more than two-fold. At equatorial stations of California and Hawaiian islands, situated in the northern hemisphere, the situation is not so contrasting. The water content is lower, but no qualitative differences are observable.

Measurements of vertical electric field in the atmosphere at 50° N have shown[5] an anomalous change in the sign alternation and value increase of the field up to 4–6 V/m. Such field behaviour can be induced by a local change of conductivity within 50–60 km altitude range, which can be explained by aerosol formation in this area, which separates the ionization[6] similarly to separation of charges in clouds.

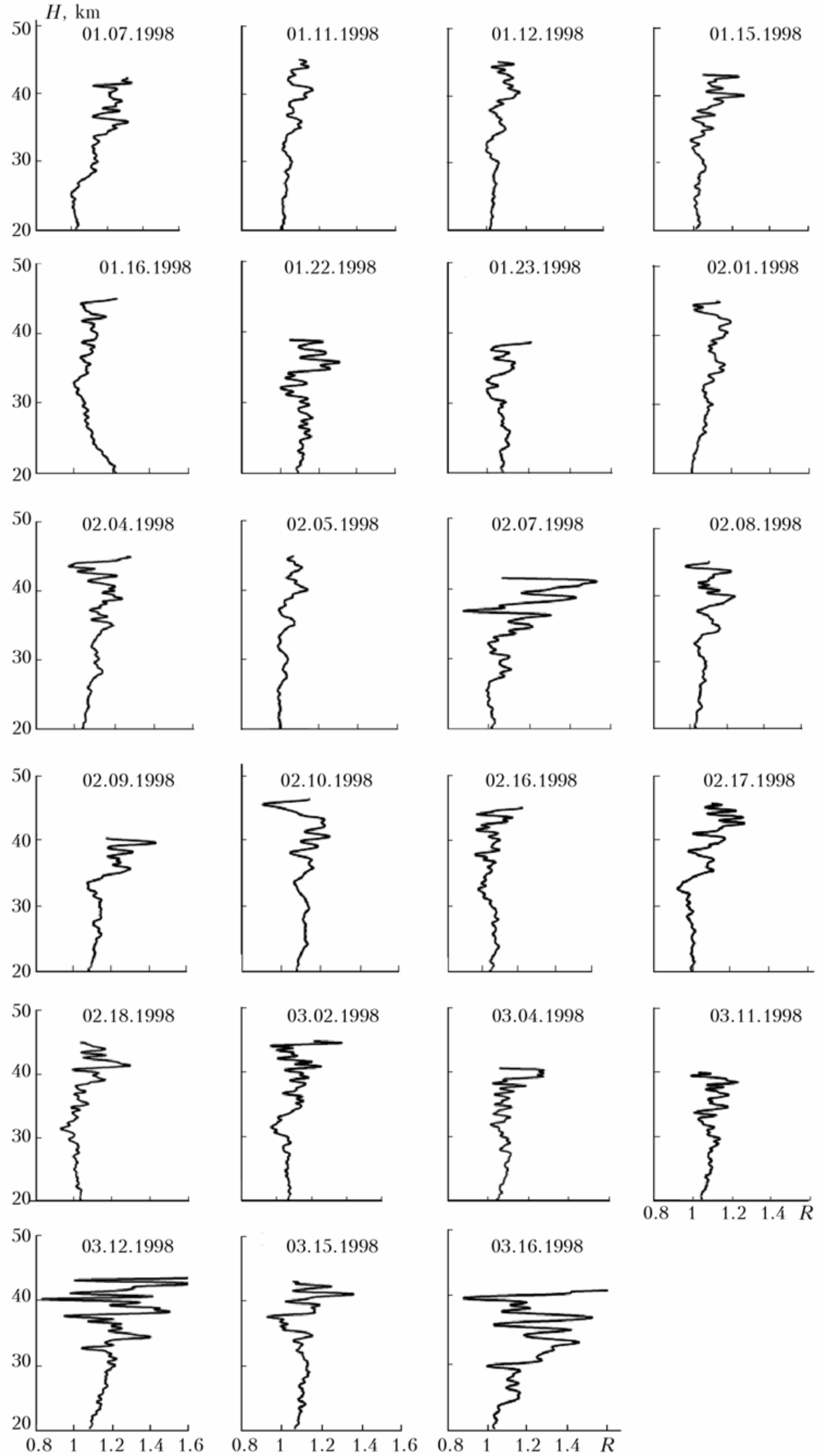

Fig. 1. Profiles of aerosol scattering ratio R, obtained at the Tomsk lidar station for January–March, 1998 [Ref. 2].

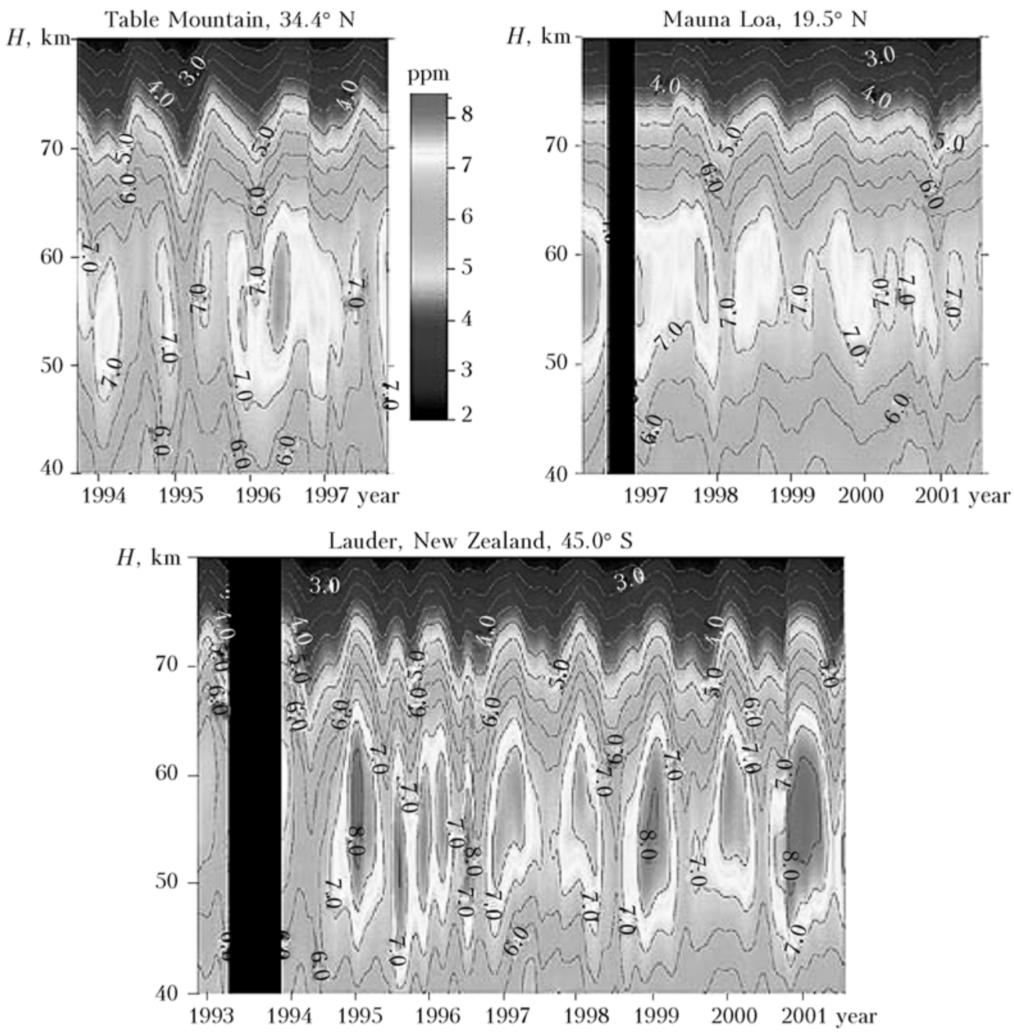

Fig. 2. Water vapour content in stratosphere from spectrometric measurements [Ref. 4].

These observations, as well as aerosol profiles show that the increased values of aerosol scattering coefficient can be observed at mid-latitude stratopause. This work is aimed at the study of possible causes of their formation.

Role of water in the upper stratosphere and lower mesosphere

Remind peculiarities of the lower part of the ionosphere layer D, described in Ref. 3. Cluster ions, $H^+(H_2O)_3$ and $H^+(H_2O)_4$ proton–hydrate complexes with an approximately equal content of about 10^3 cm^{-3} are the main positively charged components at altitudes of 50–70 km. The model calculations have shown that moderate temperature changes in mesosphere weakly affect the ion concentration, whereas the water content lowering can significantly (by several times) decrease the content of $H^+(H_2O)_3$ complex and decrease by the order of magnitude the content of $H^+(H_2O)_4$. As well, in photochemical reactions at altitudes higher than 50 km the total rate of water molecule loss is higher than the rate of their formation in other reactions. All the reactions proceed with water shortage and the value of ion concentration at all altitudes is defined mainly by the processes of water vapor transport from lower levels.

Let us estimate the water content in the stratopause (see Table).

Data on atmospheric temperature and pressure were calculated using the MSIS-2000 model. Water vapor content (column 4) for altitudes of 40–80 km was obtained by approximation of data in Fig. 2 (New Zealand) for the period from January to February, 2001. The water content for altitudes of 20–35 km was taken as 4.2 ppm, according to Mastenbruk data,[7] obtained as a result of a series of observations from 1964 to 1973 for the ratio of water vapor mixture $2.6\cdot10^{-6}$ g/g at altitudes from 16 to 28 km [Ref. 8]. The saturated water vapor pressure E above ice was calculated by the Magnus formula

$$E = E_0 \cdot 10^{9.5t/(265+t)},$$

where t is the temperature, °C; E_0 = 6.1078 Mbar [Ref. 9].

Table. The values of temperature *T*, pressure *P*, the number of water molecules, and water vapor content log*e* in altitude range from 20 to 80 km for winter period

N, km	*T*, K	*P*, mbar	*q*, ppm	log*e*, mbar	*E*, mbar	*P*/*E*	*e*/*E*
1	2	3	4	5	6	7	8
20	221.48	5.32E+01	4.2	2.23E–04	2.88E–02	1848.67	7.76E–03
25	225.23	2.49E+01	4.2	1.05E–04	4.62E–02	538.57	2.26E–03
30	229.55	1.18E+01	4.2	4.97E–05	7.83E–02	151.11	6.35E–04
35	234.68	5.70E+00	4.2	2.39E–05	1.43E–01	39.98	1.68E–04
40	248.43	2.83E+00	5.5	1.56E–05	6.27E–01	4.51	2.48E–05
45	259.25	1.46E+00	6.8	9.94E–06	1.79E+00	0.81	5.54E–06
50	254.00	7.61E–01	8	6.09E–06	1.09E+00	0.70	5.59E–06
55	241.90	3.87E–01	8.5	3.29E–06	3.17E–01	1.22	1.04E–05
60	233.56	1.91E–01	8	1.53E–06	1.25E–01	1.52	1.22E–05
65	228.50	9.22E–02	6.8	6.27E–07	6.90E–02	1.34	9.09E–06
70	224.47	4.40E–02	5.5	2.42E–07	4.20E–02	1.05	5.75E–06
75	219.31	2.06E–02	4.2	8.66E–08	2.17E–02	0.95	3.99E–06
80	211.23	9.49E–03	3	2.85E–08	7.19E–03	1.32	3.96E–06
85	202.30	4.23E–03	3	1.27E–08	1.91E–03	2.21	6.64E–06

A very low value of relative atmosphere humidity equal to 0.7% has been obtained for an altitude of 20 km, which correlates well with Hrgian's estimation: 0.6–0.3% for altitude between 16 and 20 km.

A similar calculations were performed for summer and winter periods (Fig. 3: *a* – for summer, *b* – for winter; *c* – McClatchey model[10] (for comparison)).

It is seen from Fig. 3 that despite the increased specific humidity in the stratopause (Fig. 2) the water vapor pressure at an altitude between 20 and 80 km is lower than a ppt for mbar. In summer, within altitude range 40–60 km the water condensation in conditions defined by the standard atmospheric models, seems to be impossible, because the necessary water vapor pressure exceeds the overall atmospheric pressure. A usual water shortage is equal to 2–5 orders of magnitude of the actual water content relative to the saturated vapor pressure. However, the observation of nacreous clouds in upper stratosphere and noctilucent clouds in mesosphere evidence that the specific humidity in that region is significantly higher.

The connection between the aerosol layer formation in the upper stratosphere and phenomena in the ionosphere

By data of the Tomsk lidar station, the aerosol layers at altitudes of 40–45 km can be observed from January to March. To reveal possible causes of the water aerosol formation at these altitudes we estimated the ionosphere layer **D** state by the available ionospheric data. The minimal frequency f_{min} is the only parameter available for analysis, in which the trail of **E** and **F** layers can manifest itself.

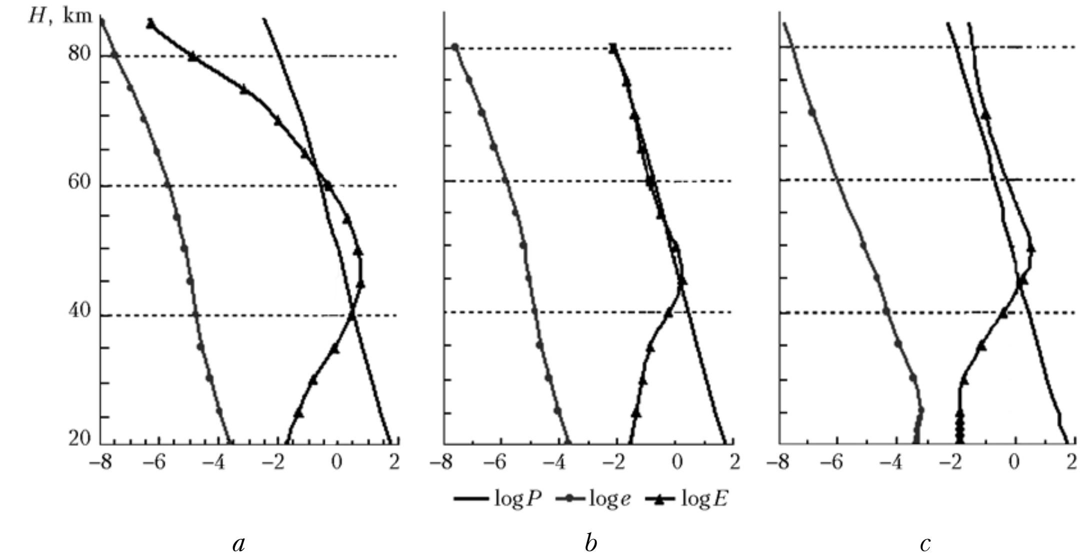

Fig. 3. Water content *e* (mbar), the pressure of saturated water vapor above ice *E*, and atmospheric pressure *P* at an altitude of 20–80 km.

To analyze f_{min} we used the fullest data, obtained at the Klyuchi station (Novosibirsk) situated about 250 km from Tomsk. The diurnal variation of f_{min} for January, February, and March, 1998, averaged throughout the whole period, are presented in Fig. 4. It is seen that its standard nighttime value for winter of 1998 was 1 MHz. The daytime values are slightly higher: 1.2–1.4 MHz for a usual winter day. A maximal mean value of 1.5 MHz between 7 and 9 h UT can be explained by a statistical contribution of days with an anomalous behavior of this parameter. In Fig. 4, the diurnal variation of f_{min} for the period from 21 to 23 January is also seen, with an anomalous excess more than 0.5 MHz above the mean.

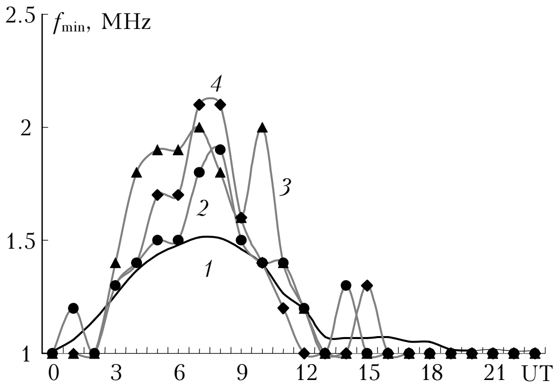

Fig. 4. The daily trend of f_{min} (curve *1*) averaged over January, February, and March, 1998, as compared to daily average trend during the days of the f_{min} anomalous behavior: for January, 21 (*2*); for January, 22 (*3*); for January, 23 (*4*).

The variation of f_{min}, averaged for night hours, coinciding with the time of lidar observations (21.00–02:00 LT) for the period from January to the end of March is shown in Fig. 5. Figure 6 presents the same data, although f_{min} is averaged over 24-hour period. The bold line indicates the time of observation of aerosol layers presented in Fig. 1.

A choice of this nighttime interval is caused by the difference in duration of daylight hours in January and March, as well as by the practice of lidar observations. The time of data accumulation for each profile makes up several hours. The straight line in Fig. 5 indicates the value averaged for a season and additionally averaged for the same LT hours. As is seen, the appearance of aerosol layers in most cases is accompanied by an increased mean nighttime f_{min} value and, consequently, by an increase of plasma concentration in the layer **D**. During the days with an insignificant nighttime value excesses over the mean, for example, January 21 and 23, large daytime excesses are observed (Figs. 4 and 6).

The correlation coefficient from observations conducted from January to March, 1998 in Tomsk and Klyuchi at altitudes from 35 to 45 km, between mean aerosol density values (scattering ratio R) and f_{min} mean values was 0.83 for nighttime values and 0.61 for daily-average ones.

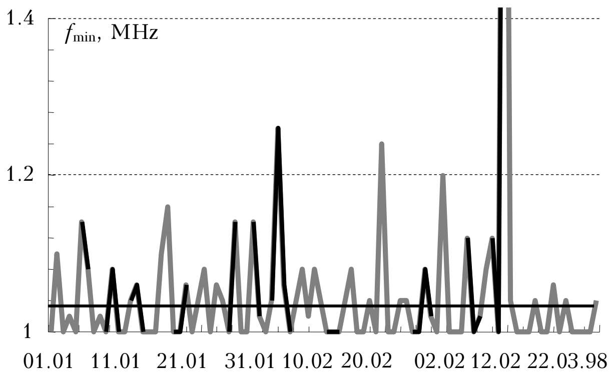

Fig. 5. Night-mean trend of f_{min} for March and January, 1998.

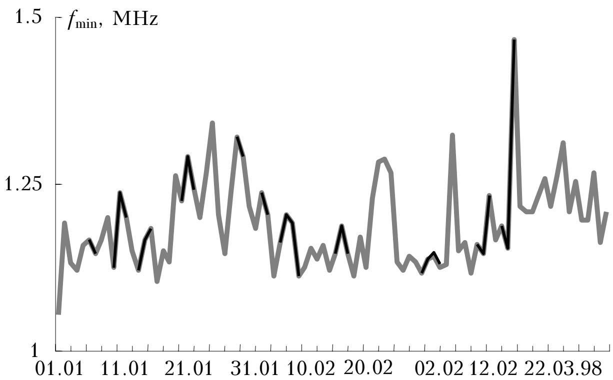

Fig. 6. Daily-mean trend of f_{min} for January–March, 1998 from data of the Klyuchi station.

The analysis of observation results, obtained from January to March, 1996–2000 in Tomsk and Klyuchi stations, allows an assumption that the appearance of aerosol layers almost always is accompanied by an anomalous daytime and nighttime behavior of f_{min}, which characterizes the absorption in the layer **D**.

Winter anomalous absorption in the ionosphere

Winter anomaly in **D** region of the ionosphere was studied in the framework of International complex program of 1975–1976, as well as by independent researchers. This phenomenon has the following peculiarities:

– the winter anomaly is a phenomenon leading to an increased absorption of radio waves. It is usually observed in the period from November to March in an altitude range from 30 to 60° both in Southern and Northern hemispheres. The duration of this phenomenon ranges from 2 to 6 days;

– the winter anomaly takes place at a spatial scale of about 1000–2000 km and is often accompanied by stratospheric warming;

– the region responsible for the anomalous absorption of radio waves is located at altitudes from 80 to 100 km. This was proved by direct rocket measurements. Its appearance was caused by an increased concentration of NO^+ and electrons. The increase of plasma concentration can make up an order of magnitude;

– significant turbulence in individual regions of the mesosphere and upper thermosphere is observed for days with winter anomaly. Significant wind shifts in mesopause region are observed during the period of high absorption.

Studies of the connection between the electron concentration and temperature have shown that the temperature profile significantly differs from the standard profile for days with the anomalous absorption. At altitudes from 70 to 85 km, the temperature inversion and formation of the second "warm layer" similar to stratopause layer are observed. At altitudes of 55–70 km the temperature can be lower by 50 °C, whereas at altitudes of 80–100 km it is significantly (by 80–100°) higher[11] than usually. Figure 7 presents the model profile (curve *3*) and the profiles for the days of anomalous absorption for January 4 (curve *1*) and January 21, 1976 (curve *2*).[3]

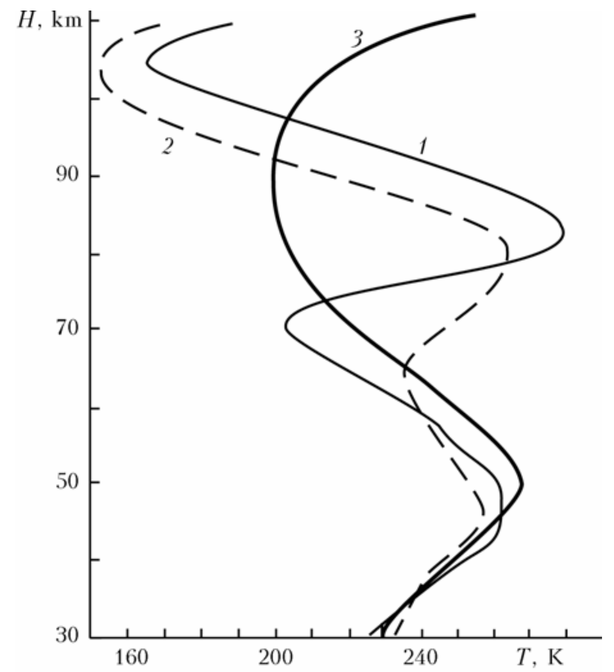

Fig. 7. Mean temperature profile for days of anomalous absorption (*1*, *2*) and the model profile (*3*).

The analysis of data on temperature during anomalous days has shown that a significant change of profiles takes place not only from day to day, but also during a twenty-four-hour period. As it was shown in Ref. 14, a significant change of conductivity profiles at altitudes lower than 60 km and a significant change (with an increase by the order of magnitude or more) of the ion concentration in stratopause was revealed from the analysis of measurements.

The ionosphere layer **D**, responsible for anomalous absorption was modeled in Ref. 3. It was shown that even a temperature change can cause a significant increase of the ion concentration in the upper part of **D** region and in a narrow altitude range. Model study of the effect of the turbulent diffusion coefficient on the concentration distribution in the layer **D** is presented in Ref. 13. The main conclusion of this work is the following: the main factors determining the anomaly in the layer D are changes of transfer conditions and the increase of turbulence. The factor favoring this circumstance is the temperature increase. The registration of such factors allowed the authors of Ref. 3 to model unambiguously all peculiarities of the anomalous absorption phenomenon, known from numerous experiments.

These very factors – the turbulence increase and the temperature profile change – contribute to the aerosol formation in stratopause. The turbulence increase causes the augmentation of water vapor inflow from lower layers to stratopause. A significant temperature decrease in this region results in the water condensation and the formation of aerosol vapors.

Model studies of the possibility of formation of the conditions, necessary for water condensation in the region of aerosol observation, were conducted using the atmospheric pressure and humidity profiles given in the Table. Model temperature profile was changed in accordance with experimental data for the days with anomalous absorption. In the range between 55 and 60 km the temperature was underestimated as compared to the model data by 50°, at an altitude of 40 km the temperature equal to −40° C was chosen. At a height of 85 km the chosen value was equal to 0 °C. All other points have been constructed so that the curve remains smooth.

To estimate augmentation of the water vapor content, the data[15] on the increase of positive ions concentration in the stratopause during the anomalous days by two orders of magnitude were used (Fig. 8).

It follows from model calculations for "wet" and "dry" mesosphere[3] that in order to increase plasma concentration in mesosphere by an order of magnitude, the water content should be twenty times lower. According to Fig. 8*a*, during the days of anomalous absorption the increase of ion concentration n in the stratopause makes up two orders of magnitude and, consequently, the water content increases approximately 400-fold.

Figure 8*b* illustrates the results of the model experiment. Following to Fig. 8*a* [Ref. 15], the specific water content between 40 and 60 km is increased 400-fold, i.e., by 2.5 orders of magnitude. At altitudes lower than 40 and higher than 80 km the specific water content is unchanged. The pressure of saturated water vapor $\log E$ for days with anomalous absorption is calculated from the temperature profile.

It is seen in Fig. 8 that during the days of winter anomalous absorption of radio waves, the condition for water condensation and formation of water aerosols can appear above the stratopause. In this case, the stratopause can shift to an altitude of about 40 km.

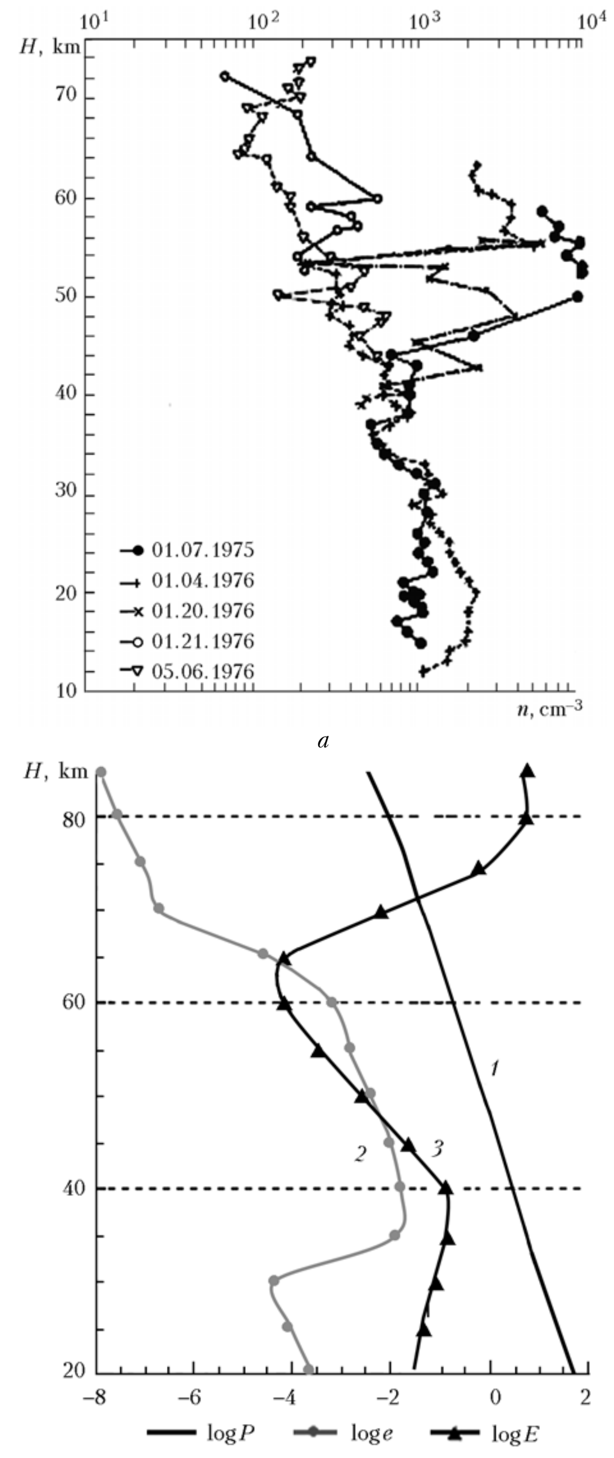

Fig. 8. Content of positive ions (*a*) and water (*b*) in stratopause for the days of anomalous absorption in ionosphere: $\log P$ (*1*); $\log e$ (*2*); $\log E$ (*3*).

The connection between the aerosol layer formation in upper stratosphere and the geomagnetic activity

It was noted in Ref. 13 that the phenomenon of radio wave anomalous absorption develops stronger during the years of high solar and magnetic activity, i.e., there is a correlation between 11-years solar cycle scales. However, it was also underlined that according to numerous tests, there are no short-period correlations between the magnitude of radio wave absorption L and the indices of geomagnetic and solar activity. A somewhat different result was obtained in Ref. 1, where a lowering of aerosol layers at the speed of 5 km per 24 hours was revealed based on the correlation between the aerosol density and the index of geomagnetic activity K_p. Based on the same methods, our own correlation analysis of data for the period from 1996 to 2000, as well as data in Fig. 8 do not confirm this result. The curve of saturated vapor pressure E shows that during days with anomalous absorption warm, the stratopause is located at altitudes of 40 km, under the aerosol layer. The lowering aerosol evaporates. Thus, the only fact can be treated as reliably established, which is concerned with a significant correlation between the aerosol density at an altitude of 40–50 km and the daily-mean index of geomagnetic activity K_p for two of six sets of month data under analysis. However, it is difficult to say whether this fact is accidental or not, because of a relatively small sample size, which is defined by the number of days in a month with favorable weather conditions.

The mechanism of such interaction is still unclear. For example, our estimates of the water entry from above, necessary for initiation of the condensation due to increasing atmospheric currents (their carriers are $H^+(H_2O)_3$ and $H^+(H_2O)_4$ proton-hydrate complexes at an altitude of 50 km) in the period of magnetosphere perturbation, have shown that the necessary increase of the current should make up 7–8 orders of magnitude relative to the standard value ($2 \cdot 10^{-12}$ A/m^2), that seems to be impossible.

The transport of water, NO, and other products of aurora polaris to the equator in periods of geomagnetic perturbation is observed in higher layers in the lower thermosphere. The mechanisms of their effect on the stratosphere state should be well argued, taking into account the exponential rise of the atmosphere density downward. In any case, the arguing of the connection with geomagnetic activity, expressed only in the appearance of additional ionization and condensation centers, should be supported by a definite mechanism of aerosol formation. Under conditions of water shortage the only consequence of the additional ionization appearance could be its further recombination.

The water entry from below at the expense of the increasing turbulence, that accompanies the anomalous absorption in ionosphere, requires a quantitative estimation as well. Due to a very lower water content in stratosphere, we should search for the cause of water aerosol formation, especially at the initial stage, not in the direct humidity increase (up to the dew point) but in photochemistry and enlarging of ion bonds in the $H^+(H_2O)_n + H_2O + M \rightarrow M + H^+(H_2O)_{n+1}$ reaction or similar reactions.

Conclusion

It has been shown that the considered cases of aerosol layers observed in stratopause are accompanied by an increase of the standard ionosphere parameter $f_{\min}$, the minimal frequency of the probing radio pulse reflection from **E** and **F** layers, and, consequently, by an increase of radio wave absorption in the ionospheric layer **D**. The presented estimations and the experimental data allow a conclusion that the temperature decrease and an the water content increase in the stratopause, occurring due to transfer processes typical for winter anomalous absorption of radio waves in stratopause region, can result in formation of aerosol layers at altitudes of 40–65 km. The most favorable weather conditions for the water aerosol formation appear above the stratopause, which can descend to an altitude of 40 km during the days of radio wave anomalous absorption in the ionosphere.

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