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# Long-term changes in the stratopause height and temperature derived from rocket measurements at various latitudes

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**Abstract.** Statistical analysis is performed of the weekly measurements of the temperature at altitudes of 25–75 km by meteorological rockets M-100B during 1969–1995 at the Heiss Island (81°N), Volgograd (49°N), Thumba (8°N), and Molodezhnaya (68°S) sites. A linear approximation of the temporal series of the data for every month of a year with "filtered out" long-term component made it possible to draw vertical temperature profiles and to evaluate the changes of the stratopause temperature and height for the entire observational period. A statistically significant at the $P = 0.95$ level depletion of the stratopause height by 0.4, 0.5, and 2.4 km above Heiss Island, Thumba, and Volgograd, respectively, is detected. The stratopause height above Molodezhnaya did not change. The stratopause descent at Volgograd and Thumba occurred during all seasons except for the spring months. The maximum decrease of the stratopause height by 5–7 km was observed above Volgograd in winter months. The stratopause descent above Heiss Island occurred only in January (by 2.4 km), February (by 4.5 km), and March (by 1.0 km). The stratopause temperature decreased statistically significantly above Heiss Island (by 4.9 K), Volgograd (by 2.8 K), and Thumba (by 4.0 K) and increased by 1.0 K (statistically insignificant at $P = 0.95$) above Molodezhnaya. The stratopause temperature changes obtained agree with the mean trend values in the 45–50 km layer published earlier. Estimates of the monthly mean changes of the stratopause temperature are presented. An assumption that the ozone decrease during the recent decades is the main reason of the stratopause depletion observed is discussed.

## 1. Introduction

The climatic changes of the thermal regime of the middle atmosphere which occurred at least in the second half of the 20th century are manifested not only in the global cooling, but in a considerable change of the annual temperature variations in the stratosphere and mesosphere. This change is manifested in the transformation of the phases of the annual and semi-annual temperature variations in the tropical stratosphere and mesosphere as well as the amplitudes of these variations in the nontropical zone [*Lysenko et al.*, 1997a]. Because of these processes, the negative trend of the temperature in the middle atmosphere has different values in different seasons, that is the trend has a well pronounced annual behavior [*Lysenko et al.,* 2001]. A typical feature of this behavior is that the trend in the spring-summer period is considerably less than in the fall-winter months, especially in the lower and middle mesosphere.

In some periods the temperature trend in the stratosphere has statistically significant positive sign: in the fall-winter period according to the Heiss Island, Volgograd, and Balkhash (47°N) data and in spring according to the Molodezhnaya data [*Kokin and Lysenko*, 1994; *Kokin at al.*, 1990; *Lysenko et al.,* 2001]. This fact may be principal for understanding the causes of climatic changes in the middle atmosphere, since absolutely independently of observations



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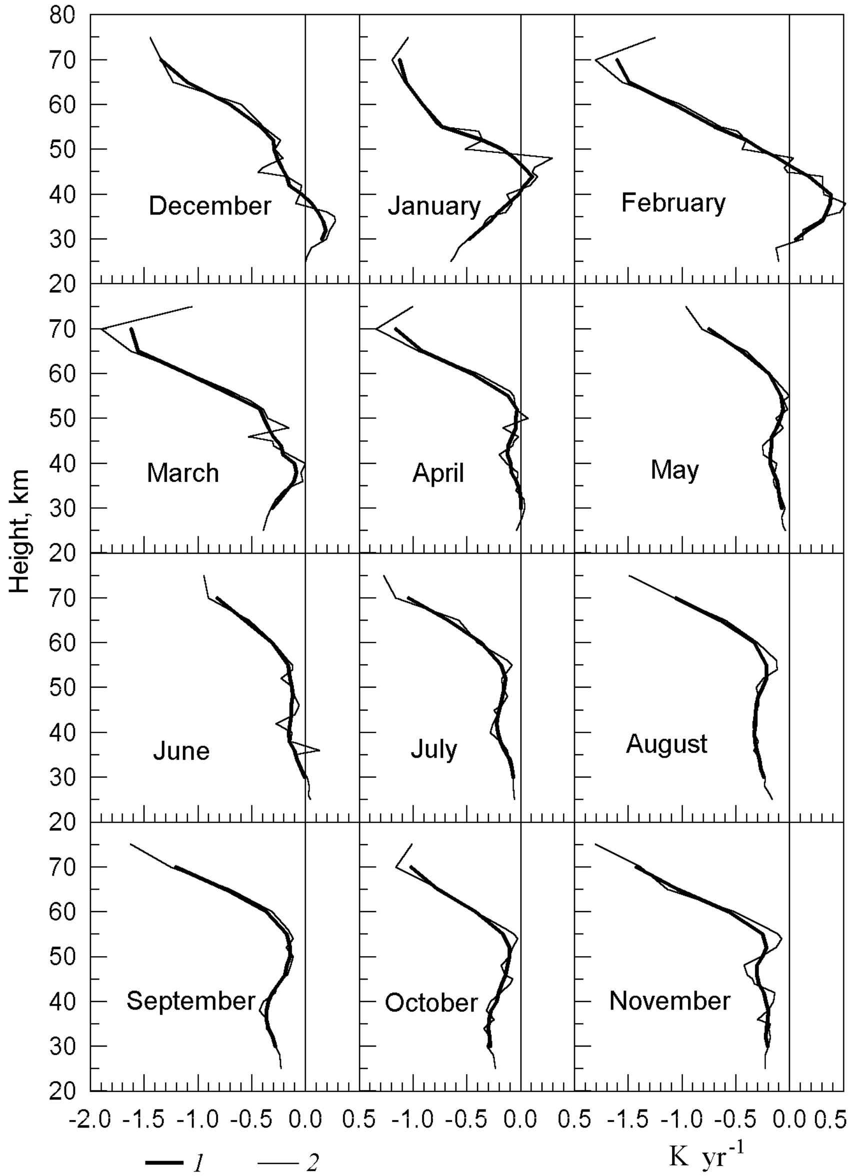


**Figure 1.** Vertical profile of the seasonal linear trends in the atmospheric temperature according to the Heiss Island data for the 1969–1994 period. 1, smoothed; 2, nonsmoothed.

[*Kokin and Lysenko*, 1994; *Kokin at al.*, 1990; *Lysenko et al.*, 2001]. Similar result has been obtained in numerical simulation of the climate with doubled content of the carbon dioxide [*Rind et al.*, 1990] and currently observed changes of the ozone concentration above Antarctic [*Mahlman et al.*, 1994]. It should, however, be noted, that the existence of a positive temperature trend in the middle and upper stratosphere has been forecasted only either at high latitudes of the northern hemisphere [*Rind et al.,* 1990], or only above Antarctic. The presence of the positive trend in both hemispheres shows that the actual change of the content of the radiative-active minor components in the terrestrial atmosphere may be a cause of the temperature climatic trends observed. The existence of the seasonal positive temperature trend in the upper stratosphere and negative trend in the lower mesosphere tends to assume that the stratopause height should decrease with time. The results of the regular atmospheric sounding by the M-100B meteorological rockets up to about 80 km during about 25-year period made it possible to obtain quantitative evaluations of the changes of the stratopause temperature and height presented below.

## 2. Database and Analysis Method

The results of weekly rocket sounding at Heiss Island (80.6°N, 58°E) for 1969–1994, Volgograd (48.7°N, 44.3°E) for 1969–1995, Thumba (8.5°N, 76.8°E) for 1971–1993, and Molodezhnaya (67.7°S, 45.8 E) for 1969–1995 have been analyzed. Since the temperature trend in the middle atmosphere is nonlinear [*Lysenko et al.*, 1997b], the data of the sounding at Heiss Island and Volgograd prior 1969 have not been used in the analysis. Thus the temperature measurement results for approximately the same observational period at various latitudes of the eastern hemisphere have been statistically treated.

The time series of the weekly values of the temperature at each height level studied were formed for each fixed month and contained about a hundred of points. Details of the formation and analysis of the time series were presented by *Lysenko et al.* [2001]. Here we note only that the mathematical model used included the initial temperature value $T_0$, linear trend and one, the best pronounced, oscillation, its period being determined from the spectral analysis results and equal to about 9–10 years.

When the values of $T_0$ and the linear trend $T'$ with their empirical standard deviations $\sigma T_0$ and $\sigma T'$ are obtained, one can easily estimate $T_k$ corresponding to the end value of the temperature for the given series and given mathematical model with the long-term component "filtered out". The procedure of $T_0$, $T'$, and $T_k$ determination was performed for each of 12 months of a year from 25 to 75 km with a step of 5 km. To form more accurate vertical profiles of $T_0$ and $T_k$ in the stratosphere, where a positive temperature trend is observed, and in the stratopause region, the calculations were also performed for each even kilometer in the 26–56 km interval.

The expert evaluation of the stratopause height and temperature was performed on the basis of the smoothed temperature profiles. It should be noted that the smoothing was done for the trend vertical profile, but not for the temperature profile itself. Then corresponding corrections in the $T_0$ and $T_k$ values were made. For example, if the absolute value of the negative trend decreased by the $\mid \Delta T' \mid$ value, the value of $T_0$ was reduced and the value of $T_k$ was enhanced by the value $\mid \Delta T \mid = \mid \Delta T' \mid (\tau/2)$, where $\tau$ is the observational period duration. The smoothing was performed by the running mean method over 5 points with 2-km step at 26–56 km and over 3 points with 5-km step with the 1–2–1 weight at 50–75 km.

## 3. Results and Discussion

### 3.1. Temperature Trends

Figures 1–4 show vertical profile of the temperature linear trends for every month for approximately 25-year period of regular observations at the rocket sounding sites indicated above. Vertical profiles of the empirical standard deviations of the trend evaluations for the spring-summer and fall-winter months are shown in Figure 5. It should be noted that the values of $\sigma T'$ for the first spring and fall months differ significantly from the averages for their group. The error in March is nearly the same as in the winter months, whereas its values in September are similar to those in August. That is why the data for these months were brought in Figure 5 to the fall-winter and spring–summer periods, respectively.

It follows from the trend vertical profiles that the cooling rate in the mesosphere of the nontropical zone is much higher that in the stratosphere and stratopause region. This fact does not agrees with numerous theoretical conclusions [see, e.g., *Brasseur et al.*, 1990; *Portmann et al.*, 1995]. According to these conclusions, the maximum of the middle atmosphere cooling due to the increasing greenhouse effect should be observed in the vicinity of the stratopause. According to the observations at the nontropical rocket sites, the negative trend increases with height from 50–55 km to 70–75 km almost in all seasons. The increase of the negative trend in the mesosphere is not so visible above the Thumba tropical station (Figure 3), especially in the September–December period, though for the majority of months the highest trend values are observed at an altitude of 75 km. On the whole, on the basis of the data of all stations, one can state that the trend increase in the mesosphere in the spring-summer period occurs at higher altitudes than in the fall-spring months.

The temperature trend varies strongly with height in the stratosphere of middle and high latitudes of the northern hemisphere. The trend vertical gradient is nearly the same as in the mesosphere, but has the opposite sign: the negative trends decrease rapidly with altitude and transfer into the region of positive values at heights of about 30–45 km. Only in January, keeping the general tendency, the trend does not become positive: the vertical profile is in some way shifted in the direction of negative values (Figures 1 and 2). A similar vertical profile of the trend is seen in March. According to the low-latitude Volgograd site, the trend in November has a profile typical for the winter months with positive values in the middle and upper stratosphere.

It should be noted that in the numerical simulation of the middle atmosphere climate with doubled amount of carbon dioxide [*Rind et al.,* 1990] a contrast in the temperature trends of the high-latitude upper stratosphere in the adjacent months of the winter season was obtained: the trend was positive in November, January, and February, but negative in December. Figures 1 and 2 show that the theoretical prediction agrees well with the observational data with only one exception: the trend is negative in January but not in December. Moreover, according to *Rind et al.* [1990], the positive anomaly of the winter trend increases from middle latitudes poleward. According to the observations, the seasonal duration of this anomaly and the magnitudes of the positive trend are significantly larger above the midlatitude Volgograd than above the high-latitude Heiss Island. For example, the maximum value of the nonsmoothed trend above Heiss Island is observed in February and is $0.52 \pm 0.21$ K yr$^{-1}$ at a height of 38 km, whereas in December the maximum is $0.28 \pm 0.14$ K yr$^{-1}$ at 34–35 km. Above the Volgograd site the maximum of $0.32 \pm 0.10$ K yr$^{-1}$ is located at 38 km, in December it is $0.75 \pm 0.16$ K yr$^{-1}$ at 40 km, and in February it is $0.32 \pm 0.13$ K yr$^{-1}$ at 44 km.

Analyzing the rocket sounding results at the Japan site Ryori (39°N, 141°E), *Keckhut and Kodera* [1999] obtained recently a very interesting result based also on about 25-year period of regular observations. The trend in the winter period at altitudes of 40–45 km is equal to zero, whereas the annual mean temperature trend at heights of 20–55 km is

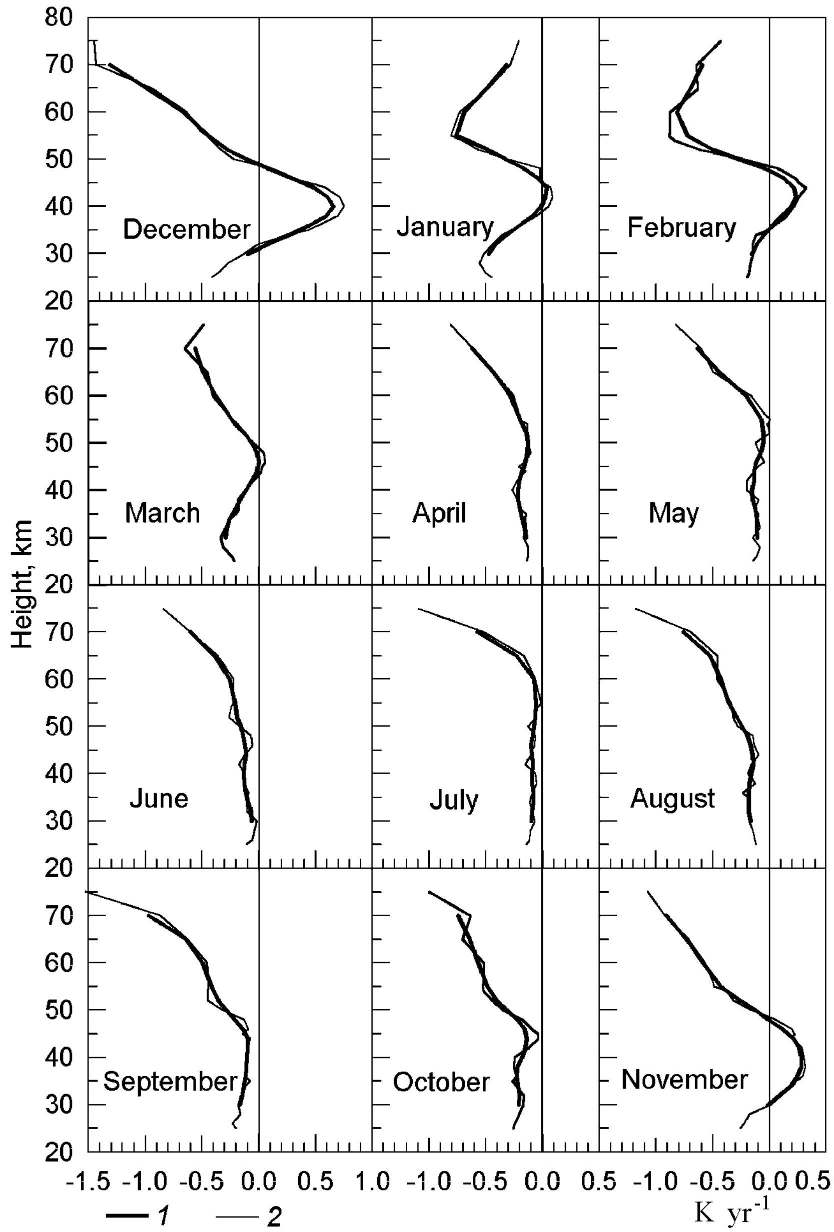


**Figure 2.** The same is in Figure 1 but for Volgograd data for the 1969–1995 period. 1, smoothed; 2, nonsmoothed.

from −0.20 to −0.25 K yr$^{-1}$. Analyzing the monthly mean trends, *Keckhut and Kodera* [1999] demonstrated that in December the trend gets positive values in the 34–47 km layer with a maximum of 0.5 K yr$^{-1}$ at a height of 41 km. Comparing these results with the Volgograd site data, one can not help being astonished by the similarity of the observation results. Slightly more narrow region with the positive trend (above Volgograd the trend has positive values in the 32–49 km layer) and smaller value of the maximum (as well as the absence of positive trend above the Ryori site in November and February) are, most probably, due to the fact that Volgograd is located 10° northward, though the longitudinal difference in 100° may also play an important role.

Seasonal evaluations of the trends since 1979 have been performed also in France (44°N, 6°E), however the results obtained [*Hauchecorne et al.*, 1991; *Keckhut et al.*, 1995] contain internal contradictions. On one hand, summarizing the measurements of 1979–1989, *Hauchecorne et al.* [1991] showed that a positive trend is observed in the winter stratosphere (October–March) at heights of 35–52 km with a maximum of about 0.25 K yr$^{-1}$ at a height of about 41 km. The confidence interval $P = 0.95$ in this case is nearly twice the maximum value. Assuming that the vertical correlation radius of the lidar measurement errors is about tens of meters, one can conclude that the positive values of the trend at 17 consequent statistically independent 1-km levels can not be

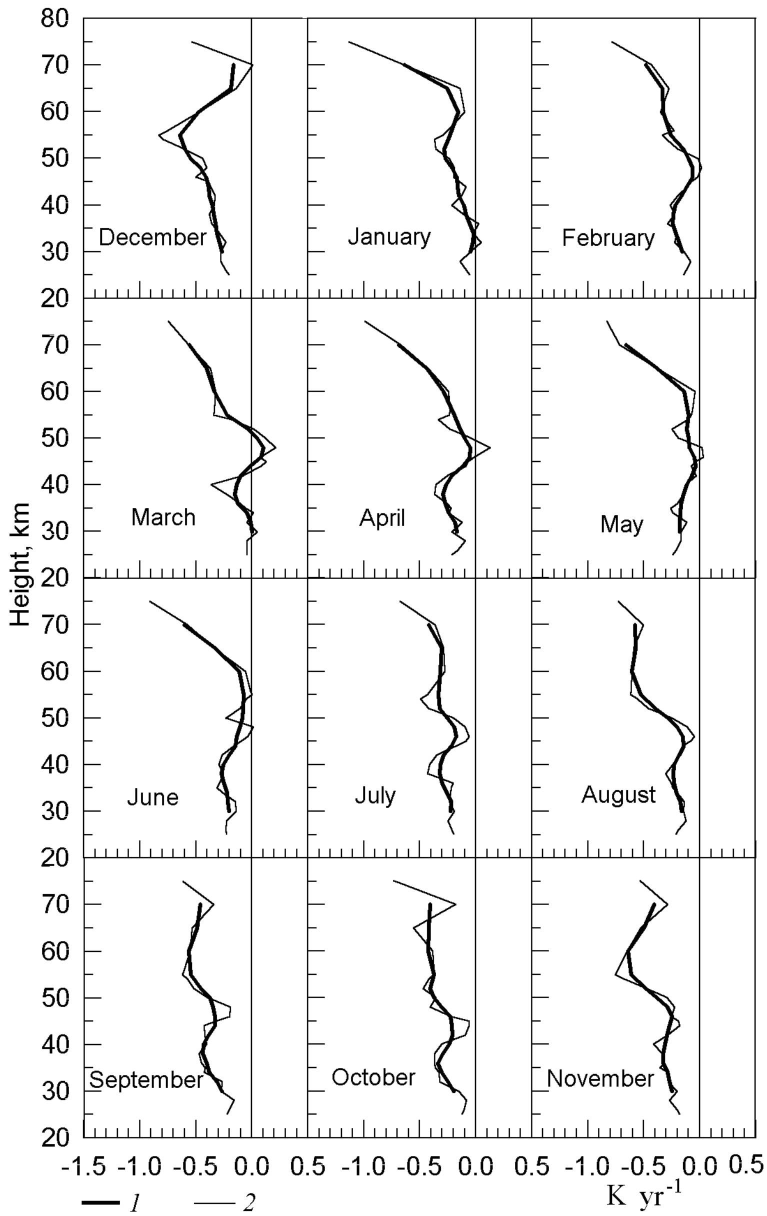


**Figure 3.** The same as in Figure 1 but for Thumba data for the 1971–1993 period. 1, smoothed; 2, nonsmoothed.

random, that is the positive sign of the trend in the winter stratosphere has a high statistical significance. On the other hand, the results of the monthly trends analysis for 1979–1991 are presented (Figure 16 of *Keckhut et al.* [1999]), according to which there is no positive trend values in the 35–52 km layer neither in summer nor in winter periods. Moreover, in October–March a negative trend with the value of $-0.2$ K yr$^{-1}$ is detected in the upper stratosphere, the trend at a height of 41 km (the altitude of the positive trend maximum of *Hauchecorne et al.* [1991]) reaching only zero values. Unfortunately, these discrepancies were left without author's comments. By the way, the trend estimates differ not only in the stratosphere, but in the mesosphere as well, where according to *Hauchecorne et al.* [1991] the annual mean trend between 60 and 70 km is about $-0.4$ K yr$^{-1}$. In the same time, *Keckhut et al.* [1995] indicate that the maximum cooling (>0.4 K yr$^{-1}$) in this layer is observed in August and in May the trend has a small positive value. In other months the monthly trend values vary from 0 to $-0.2$ K yr$^{-1}$.

Nevertheless, giving preference to the results of *Hauchecorne et al.* [1991] because the statistical significance of the monthly trends of *Keckhut et al.* [1995] is much poorer, one can assume existence of the positive temperature trend in the winter stratosphere also over 44°N, 6°E.

Thus, taking into account also the similarity of the sound-

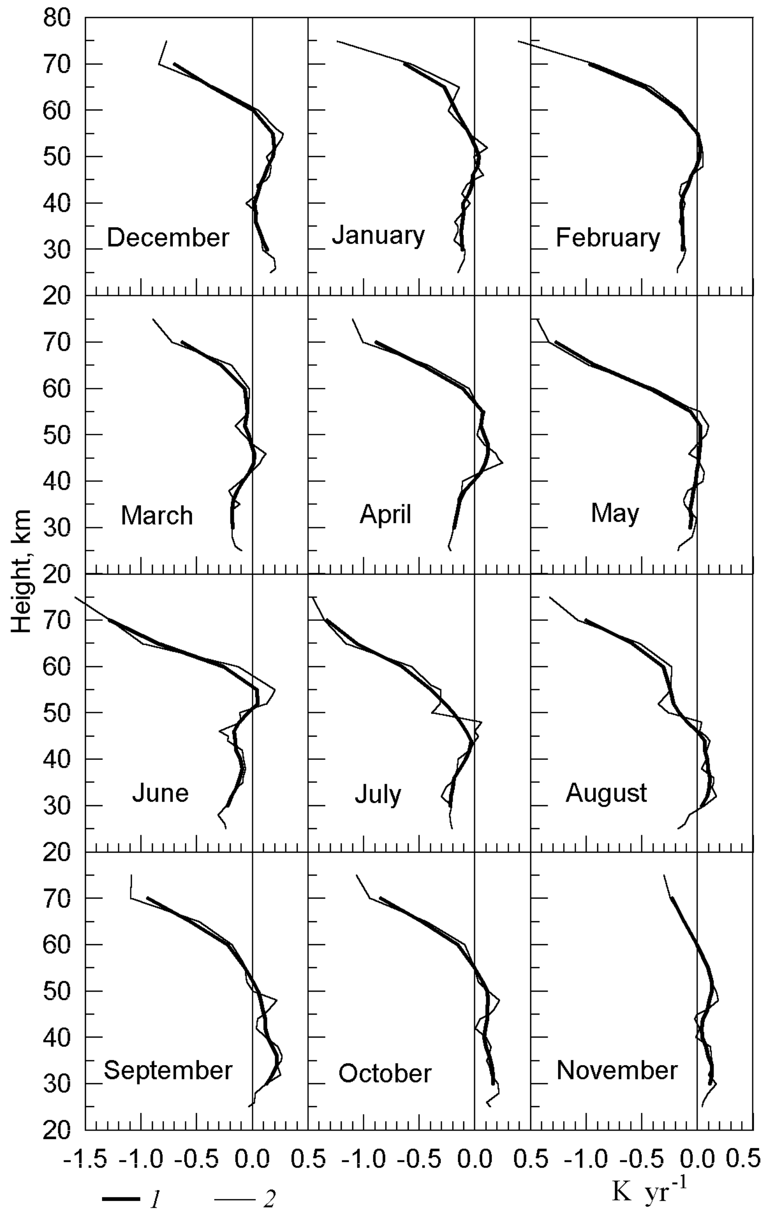


**Figure 4.** The same as in Figure 1 but for Molodezhnaya data for the 1969–1995 period. 1, smoothed; 2, nonsmoothed.

ing results at the Volgograd and Balkhash sites [*Kokin and Lysenko*, 1994], one can conclude that a positive temperature trend in the upper stratosphere is pronounced in the winter period above middle and high latitudes at least in the eastern part of the northern hemisphere. Evidently, the positive anomaly of the winter trend is the strongest (the absolute values of the trend, seasonal duration) in the 50°–60°N latitudinal belt, decreasing poleward and equatorward. It follows from the material presented above that the temperature trend in the stratosphere above the tropical site Thumba has no positive values in any month of a year.

However, the most important result of the comparison of modeling and observations is that, as it is widely known, up to now the carbon dioxide content has increases as compared with the preindustrial epoch only by 30% but not by a factor of 2. And nevertheless, the climatic trends observed in the middle atmosphere are at least not less than the trends predicted for the CO doubling. One should confess that the cause of such considerable discrepancy between the theoretical forecasts and observational results obtained by various methods [see, e.g., *Hauchecorne et al.*, 1991; *Keckhut and Kodera*, 1999; *Keckhut et al.*, 1995; *Kokin and Lysenko*, 1994; *Kokin et al.*, 1990; *Semenov*, 1996; *Taubenheim et al.*, 1997] is still obscure. It is quite possible that other factors, apart the greenhouse gases increase, do influence climatic changes. However, coming back to the phenomenon of pos-

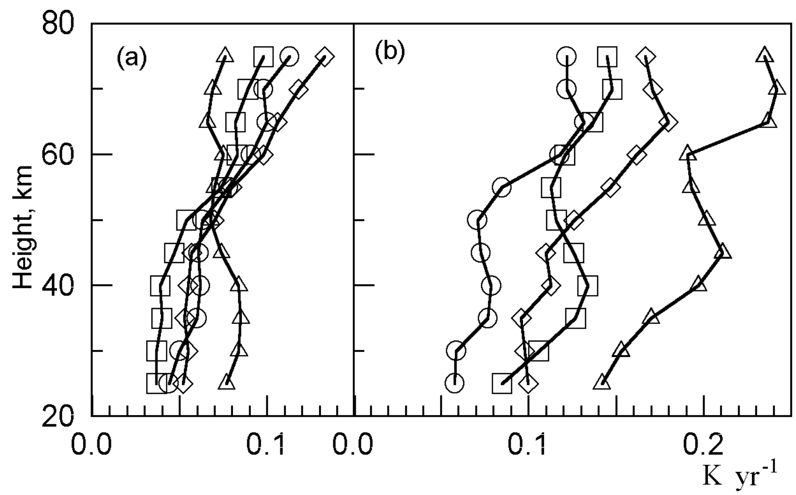


**Figure 5.** Empirical standard error (K $yr^{-1}$) of evaluation of the temperature trends in (a) spring–summer and (b) fall–winter observational periods at the Heiss Island (triangles), Volgograd (squares). Thumba (circles), and Molodezhnaya (diamonds) sites for 1969–1995.

itive trend in the winter stratosphere, one can state that there is a ground to compare the simulation results and observations because of the following. According to *Rind et al.* [1990] the positive anomaly of the winter trend is a result of the stratospheric dynamics changes induced by a depletion of the vertical static stability of the atmosphere due to the positive temperature trend in the upper troposphere and negative trend in the lower stratosphere. The trends observed during the recent decades in the stratosphere and troposphere agree well with the values obtained in the numerical simulation with doubled CO amount. Therefore one can conclude that the actual decrease of the temperature gradient in the stratosphere is responsible for the changes in the dynamics leading to the winter temperature increase in the middle and upper stratosphere which follows from the numerical simulation results by *Rind et al.* [1990].

The negative trend of the temperature only slightly changes with height in the spring–summer period beginning from April. It is about $-(0.1-0.2)$ K $yr^{-1}$ and $-(0.1-0.3)$ K $yr^{-1}$ above Volgograd and Heiss Island, respectively. Though these are comparable with the empirical standard deviation (see Figure 5), one may claim a high statistical significance of the negative trends in the stratosphere. This follows from the fact that, the correlation radius of the rocket measurements accuracy being of the order of a few hundred meters, the results of the measurements with a step of 2 km should be considered independent, whereas the temperature trend vertical profiles through the entire stratosphere have negative values slightly changing with height.

The vertical profiles of the temperature trends in the tropical stratosphere has slightly different character. Figure 3 shows that the negative trend increases with height, reaching maximum values at altitudes of 35–40 km, and then decreases down to minimum values at 45–50 km. The trend profile has no local maximum in the stratosphere only in December, January, and May.

The data obtained in the atmospheric soundings at the Molodezhnaya site look quite interesting. It follows from Figure 4 that positive anomalies of the trend are observed not only in the stratosphere, but in the lower mesosphere as well. One can doubt the results for April, May, and June, however the existence of positive trends since August till December is undoubted. Figure 4 visually shows also that the positive values of the trend in August cover the entire middle stratosphere, the region with positive sign of the trend expanding both downward and upward in the next months and the trend reaching maximum values in December at altitudes of 25 and 55 km. In the next months the "traces" of the upper maximum are seen in January–March, and the trend at 55 km has positive values in April and June.

Comparing the results obtained with the numerical simulation results by [*Mahlman et al.*, 1994], one should note a good agreement of the vertical position and values of the positive trend. However, according to *Mahlman et al.* [1994], the temperature increase in the middle and upper stratosphere should be observed at the end of spring or in the beginning of summer. The observational results at the Molodezhnaya site demonstrate that a stable positive trend of the temperature in the stratosphere appear already in the last winter month and disappears to the middle of summer. Moreover, developing since the end of winter, the positive trend region to the beginning of summer reaches lower mesosphere, where the trend values oscillate around zero during the next months until the beginning of winter.

Considering our disagreements with *Mahlman et al.* [1994], we should note that the modeled positive trend is maximum above the South Pole and disappears down to about 60°S. The Molodezhnaya site is at the edge of the forecasted zone and, moreover, at the edge of the circumpolar vortex. These two factors may explain the disagreement of the modeling and observation results. However, the balloon sounding results at the Antarctic sites show [*Randel*

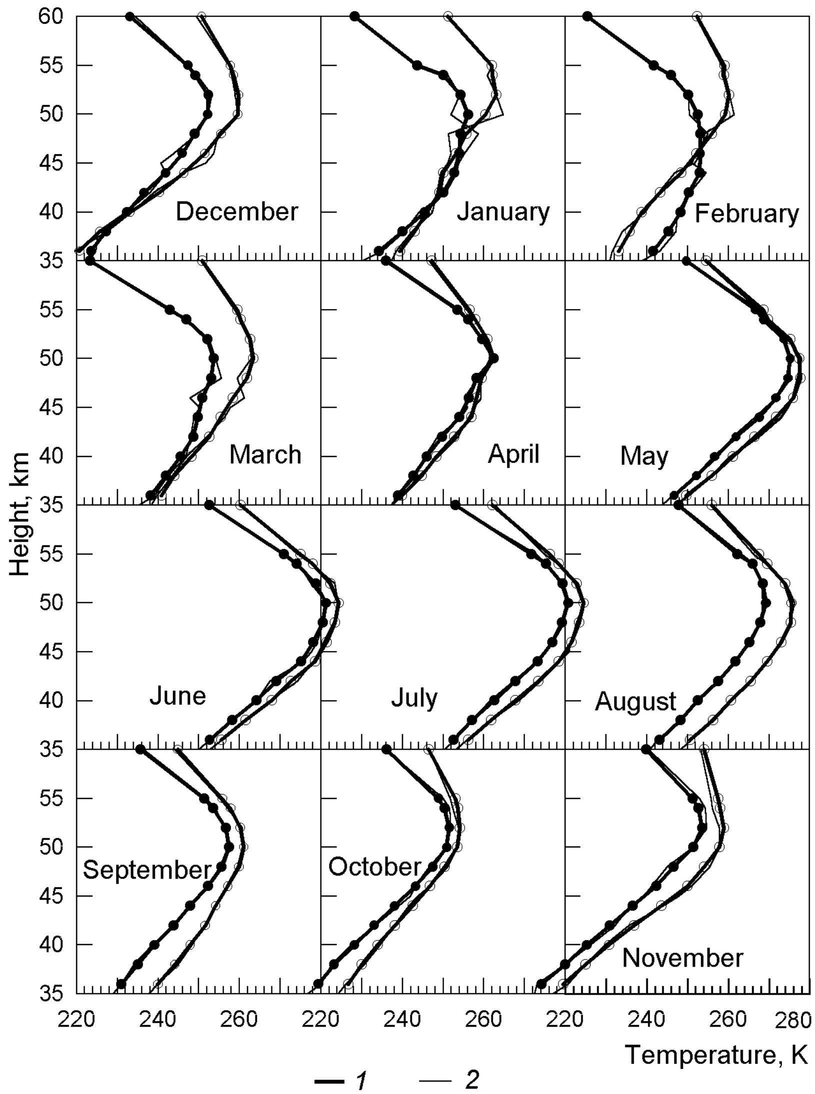


**Figure 6.** Vertical distribution of the model values of the atmospheric temperature in the vicinity of the stratopause over Heiss Island for 1969 (open circles) and 1994 (solid circles). 1, smoothed values; 2, nonsmoothed values.

*and Wu,* 1999] that there is a large negative trend in the lower stratosphere in the spring-summer period, the trend decreasing sharply with height and reaching statistically significant positive sign at the boundary with the middle stratosphere. Unfortunately, the technical limitations of the balloon sounding do not make it possible to follow this tendency above the 30 HPa level, however this result agree well with the general picture of the development of the positive temperature trend in the spring middle and upper stratosphere based on the rocket data.

### 3.2. Vertical Temperature Profiles

The model values of monthly mean temperatures $T_0$ and $T_k$ corresponding to the beginning and end of the observations were used to derive corresponding vertical profiles to determine stratopause parameters for each month of measurements during 25 years of observations. These vertical profiles of the temperature in the stratosphere and lower mesosphere according to the data of each rocket site are shown in Figures 6–9. The empirical standard error of $T$ determination in the height interval considered is less than 1 K and about 2–3 K in the summer period and winter months, respectively. Since a linear approximation of the time series has been used, it seems natural to use these errors to evaluate the $T_k$ values as well. However, the $T_k$ values were calculated using $T_0$ values and the linear trend $T'$, so formally $\sigma T_k$ should depend not only on $\sigma T_0$, but the values of $\sigma T'$ as well. To check the former assumption, the mirror conversion of particular time series (that is the last term of the series became the first, the term before the last one became

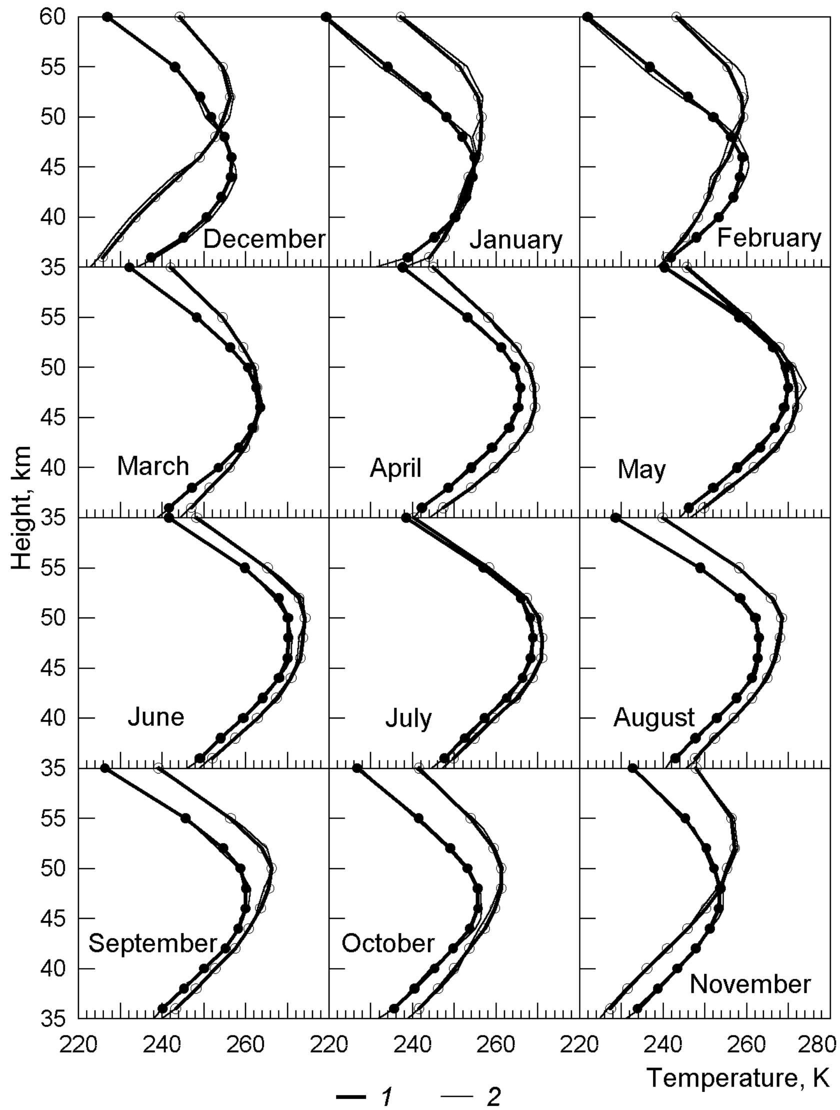


**Figure 7.** The same as in Figure 6 but for Volgograd for 1969 (open circles) and 1995 (solid circles). 1, smoothed values; 2, nonsmoothed values.

the second and so on) was treated statistically. The results show that the new initial temperature value corresponds exactly to $T_k$, the trend sign changes to the opposite, however the trend value (as well as the empirical errors of the trend and temperature) stays unchanged, i.e. $\sigma T_0 = \sigma T_k$.

Figures 6–9 show smoothed and nonsmoothed profiles of the $T_0$ and $T_k$ temperatures corresponding to the smoothed and nonsmoothed trend profiles. The evaluation of the temperature $T_s$ and height $h_s$ of the stratopause were performed using the smoothed profiles. Figures 6–9 show that the most significant changes of $h_s$ took place over Volgograd in the fall-winter period. Similar changes are seen over Heiss Island in January–February. The results of an expert evaluation of the stratopause height from the $T_0$ and $T_k$ temperature profiles, as well as the values of the stratopause temperature in the beginning and end of regular rocket observations, are shown in Figure 10. The standard error of the stratopause height expert evaluations is about 0.5 km.

Figure 10 shows that a statistically significant depletion of $h_s$ by 2.4 and 4.5 km is observed over Heiss Island in January and February, respectively. The depletion over Volgograd vary from 2.5 km in August–October to 7.5 km in December. The stratopause height over the Thumba site decreases by about 1 km in the second half of a year. No pronounced changes occurred over the Molodezhnaya site: the stratopause height decreases by about 1 km in March–April and August–September and increased by 1 km in May–June and November–December. The annual mean value of the stratopause height over the Molodezhnaya station did not change and is 48.5 km. The mean stratopause height over Heiss Island decreased by about 0.4 km from 50.7 to 50.3 km. Similar decrease over Thumba is by about 0.5 km: from 47.4 to 46.9 km. The strongest depletion of $h_s$ from 49.8 to 46.8 km occurred over the midlatitude Volgograd

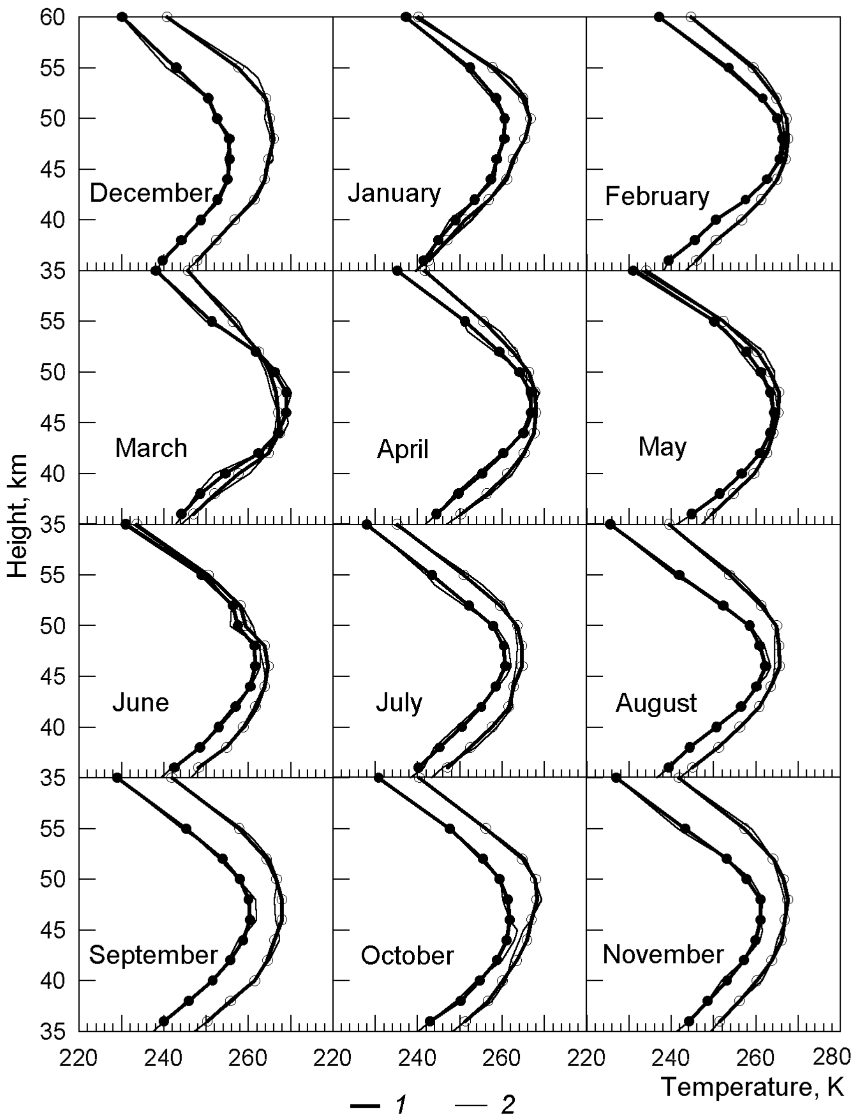


**Figure 8.** The same as in Figure 6 but for Thumba for 1971 (open circles) and 1993 (solid circles). 1, smoothed values; 2, nonsmoothed values.

site. Figure 10 visually shows that for the 27-year observational period the stratopause height almost did not change in April–June and depleted by more that 5 km in November–February. It is worth noting that according to the aerological observations at the Hohenpassenberg midlatitude station [*Steinbrecht et al.,* 1998], the annual mean value of the tropopause height increased by 450 m and the temperature at 5 km increased by about 2.1 K during 30 years of observations.

The annual mean temperature of the stratopause decreased by 4.9 K from 267.4 to 262.5 K, by 2.8 K from 264.8 to 262.0, and by 4.0 K from 266.7 to 262.7 over the Heiss Island, Volgograd, and Thumba sites, respectively. This value increased by 1.0 K from 265.0 to 266.0 over Molodezhnaya. One can see in Figure 10 that the stratopause cooling and lowering down over the Thumba tropical site is better pronounced in the second half of a year (it is 10 K in December). One should pay attention to the changes in the $T_s$ annual variations: instead of two maxima observed earlier in April and September–October, there is in the end of observations only one maximum in March. The strongest cooling of the stratopause is observed in December–March (7–9 K) and August–October (5–6 K) over Heiss Island and Volgograd, respectively. The enhancement of $T_s$ over Molodezhnaya occurs mainly in September–December (3–4 K).

Changes of the annual differences of the stratopause temperature during the recent decades are not well seen in Figure 10, so corresponding data are presented in Table 1. One can see that the difference between the maximum and minimum stratopause temperatures has decreased for the period of observations over Volgograd and increased over the other sites. This result agrees with the analysis of annual and semiannual oscillations of the stratospheric and mesospheric temperatures over the entire period of rocket measurements [*Ly-*

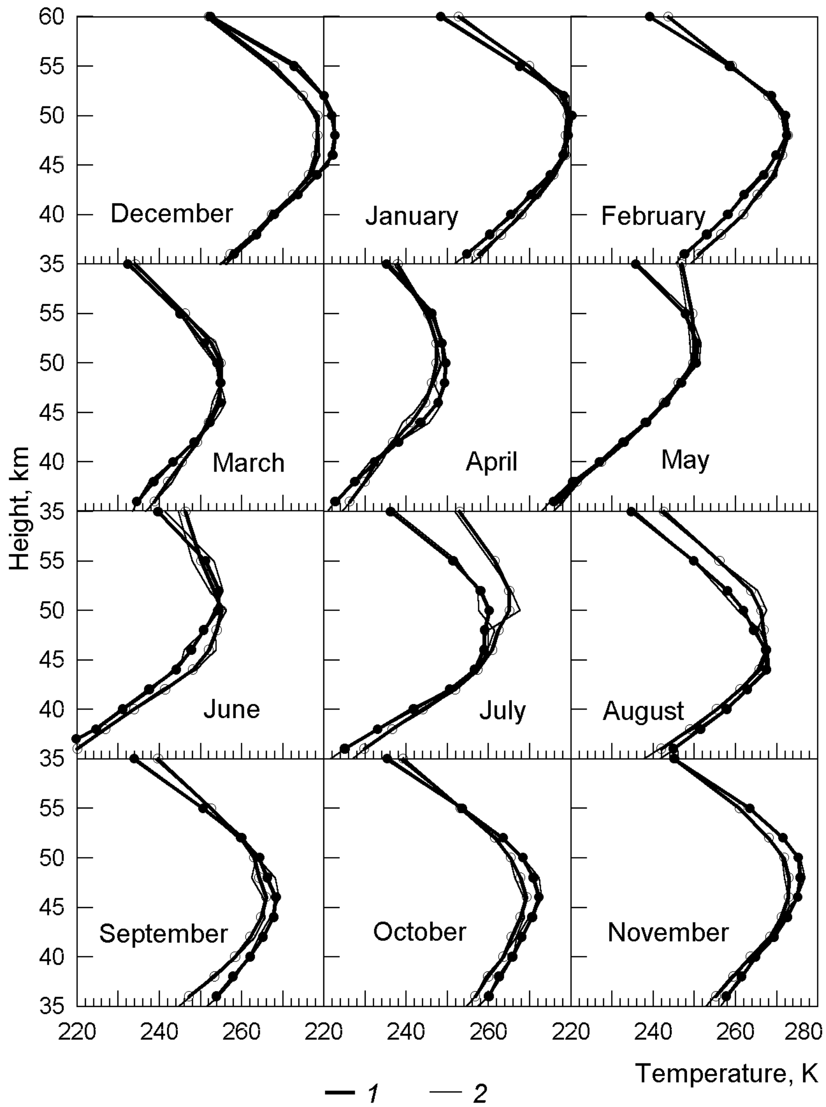


**Figure 9.** The same as in Figure 6 but for Molodezhnaya for 1969 (open circles) and 1995 (solid circles). 1, smoothed values; 2, nonsmoothed values.

*senko et al.,* 1997a]: the amplitude of these oscillations has increased according to the Heiss Island and Molodezhnaya data but decreased in the stratosphere over Volgograd. The oscillation phases stayed unchanged, except for the shift of the semi-annual harmonic phase in the stratosphere over Volgograd by about a half-period. Over the Thumba site, the oscillation amplitudes according to *Lysenko et al.* [1997a] stayed almost unchanged, but the vertical distribution of the annual oscillation phases changed significantly. As a result, a shift of the dates of the temperature extreme values over Thumba and Volgograd took place (see Table 1). It should be also noted that the increase of the stratopause temperature contrast $\Delta T_s$ over Heiss Island and Thumba is due to the prevailing role of the negative trend in the minimum temperature, whereas over Molodezhnaya a prevailing role is played by the positive trend in the maximum value of $T_s$.

It has been already noted in the section 1 that the studies of stratopause height changes were initiated by positive trends in the upper stratosphere temperature in some seasons over high-latitude and midlatitude rocket sites. However the result obtained exceeded what has been expected: the stratopause height depleted not only in the period of positive trend occurrence in the upper stratosphere. This is visually illustrated by the Volgograd site data. Thick layer with positive temperature trend in the middle and upper stratosphere is observed in November and December; however, in the adjacent months (September–October and January) the trend has no positive values (see Figure 2). Nevertheless, Figure 7 visually shows a depletion of the stratopause height both in September–October and January. Moreover, $h_s$ decreases also over the Thumba site, where a narrow layer with statistically insignificant positive trend in the upper stratosphere is observed only in March. The changes in the stratopause vertical position can hardly be

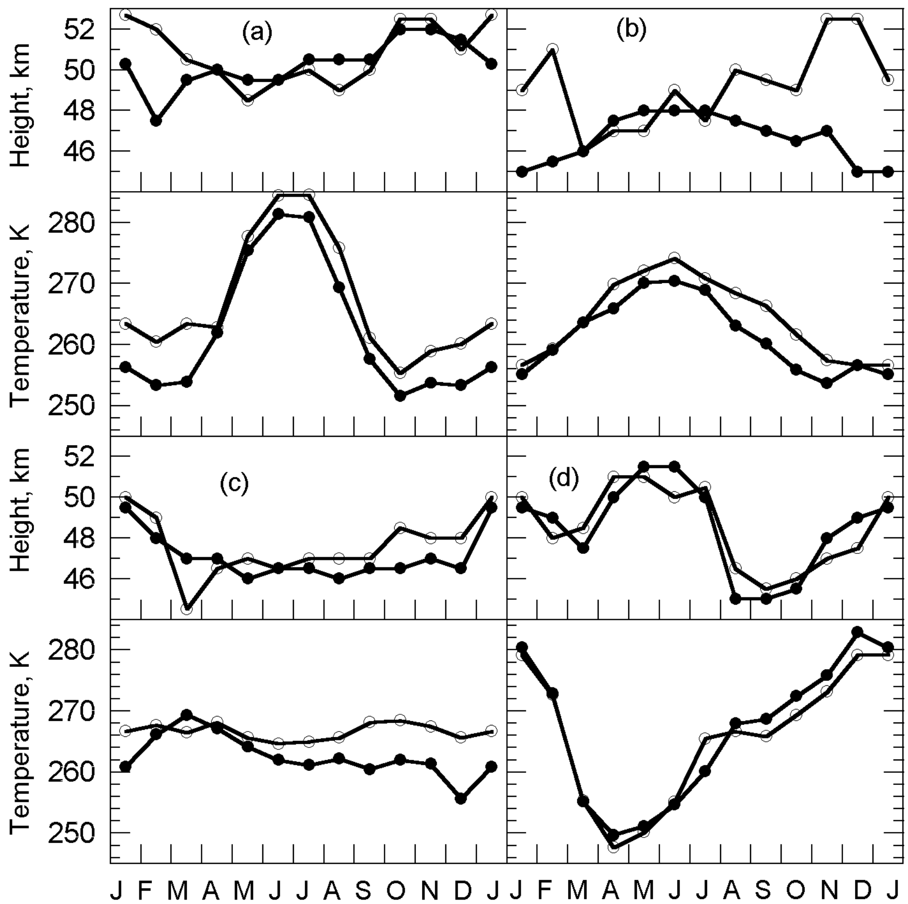


**Figure 10.** Variations in the stratopause height and temperature within a year in the beginning (open circles) and end (solid circles) of the 1969–1995 observations at (a) Heiss Island, (b) Volgograd, (c) Thumba, and (d) Molodezhnaya.

explained by impact of only dynamical factors. Most probably, the stratopause height depletion is due to the decrease of the solar radiation absorption in the mesosphere and so to a decrease of the ozone concentration below the mesopause.

We know no papers dedicated to direct evaluations of the ozone trends in the mesosphere, though corresponding measurements were conducted during half a century [*Johnson et al.,* 1951]. However, the indirect estimate of the ozone concentration in the region of its second maximum near the mesopause [*Hays and Roble*, 1973] based on the hydroxyl emission trend [*Semenov,* 1997] indicate to an ozone depletion during 1955–1995 by almost a factor of 3. This conclusion follows from the consideration of the ozone–hydrogen mechanism of hydroxyl excitation and atomic oxygen concentration increase in the vicinity of the mesopause, the latter increase being due to the increase of the methane content in the atmosphere. If the estimates of *Semenov* [1997] are close to the real depletion of ozone in the vicinity of the mesopause and the ozone content in the mesosphere also decreased by a factor of 2–3 and by 20–30% at the upper and lower mesosphere boundaries, respectively, (according to *WMO* [1999] the ozone depletion in the upper stratosphere at middle latitudes for 1979–1996 is 6–8% per decade), this depletion can explain not only the stratopause height decrease, but the observed strong cooling of the mesosphere as well. Actually, in this case, together with the increased radiation cooling in the infrared part of the spectrum due to the greenhouse gas increase, there would take place a "deficit" of the radiation heating in the UV-part of the spectrum. It should lead to an additional depletion of the temperature which, depending on the degree of the mesospheric ozone decrease, may be comparable or even exceed the effect of the enhancement of $CO_2$, $CH_4$, and other greenhouse gases. Most probably this is the cause of such a strong discrepancy between the model evaluations of the cooling rate and observational results.

In the scope of the hypothesis proposed, the absence of the stratopause height trend over the Molodezhnaya site should mean that in the mesosphere of this region the ozone concentration almost did not change during 1969–1995. Nearly the same picture should take place over the other high-latitude site Heiss Island where the stratopause height decreases only

**Table 1.** Extreme Values of the Stratopause Temperature in the Beginning and End of the Observations at Rocket Sites†

| | Site | | | |
|---|---|---|---|---|
| | Heiss Island | Volgograd | Thumba | Molodezhnaya |
| $T_{s0}^{max}$/month | 284.5/June | 274.2/June | 268.5/Oct. | 279.2/Dec.–Jan. |
| $T_{s0}^{min}$/month | 255.4/Oct. | 256.7/Dec.–Jan. | 264.7/June | 247.7/April |
| $\Delta T_{s0} = T_{s0}^{max} - T_{s0}^{min}$ | 29.1 | 17.5 | 3.8 | 31.5 |
| $T_{sk}^{max}$/month | 281.4/June | 270.5/June | 269.4/March | 282.9/Dec. |
| $T_{sk}^{min}$/month | 251.7/Oct. | 253.7/Nov. | 255.7/Dec. | 249.7/April |
| $\Delta T_{sk} = T_{sk}^{max} - T_{sk}^{min}$ | 29.7 | 16.8 | 13.7 | 33.2 |

† Temperature is in K.

in January–February and slightly in March. The negative trend of the mesosphere ozone over the low-latitude Thumba site should be well pronounced from May to February, especially in October–December. The most significant extinction of the mesosphere ozone from June to March with a maximum in November–December should occur over the midlatitude Volgograd site.

From the point of view described the difference in the vertical profiles of the annual mean trends of the mesosphere temperature according to rocket measurements at various sites located at different latitudes becomes understandable. *Kokin and Lysenko* [1994] noted that the maximum value of the temperature negative trend over the midlatitude sites Volgograd and Balkhash is observed at altitudes of 55–60 km, whereas over other sites the trend increases with height up to the upper boundary of rocket measurements. It should be noted that the negative trend profile over the low-latitude Thumba site also has a local maximum at 55 km, though pronounced not so clearly as the maximum over the midlatitude sites [see *Kokin and Lysenko*, 1994, Figure 1]. Since the radiation heating rate is maximum at the stratopause height, the depletion of the ozone concentration (the principal absorber of the solar UV radiation in the mesosphere) should be manifested, first of all, in the height layer located above the stratopause. The increase of the temperature negative trend at altitudes of 70–75 km may be due to relatively strong depletion of ozone in the region of its local minimum located at 75–80 km [*Hays and Roble*, 1973]. One can assume that the ozone concentration variations in this layer would lead to significant temperature changes at 70–80 km. It is worth noting also that the negative temperature trend over Molodezhnaya up to 65 km is by a factor of 1.5–2 less than the trend over Heiss Island.

The recent publications in which temperature trends were evaluated again from the data of the USA rocket sites for 2–3 decades in tropics and northern middle latitudes of the western hemisphere, demonstrate a similarity to the observational results at the Volgograd and Thumba sites. For example, *Keckhut et al.* [1999] presented a vertical profile of the temperature trend averaged over the data of 5 stations located in the 8°S–34°N latitudinal belt. This trend has a local maximum at 56–57 km very similar qualitatively and quantitatively to the trend profile over the Thumba site. The summary of the sounding results at 6 sites located from 9°S to 38°N in the 25–60 km altitude interval during 1962–1991 [*Dunkerton et al.,* 1998] indicates to a strong increase in the negative trend from $-0.23$ K yr$^{-1}$ at 50 km to $-0.47$ K yr$^{-1}$ at 60 km, which is qualitatively similar to the trend changes over Volgograd [*Kokin and Lysenko*, 1994].

The interpretation presented of the differences in the evaluations of the trends from rocket measurements at different latitudes does not contradict to the satellite observations at middle latitudes of the northern hemisphere at a height of 55 km [*Aikin et al.,* 1991] and in the 60–90 km altitude interval during the 1980s [*Clancy and Rush*, 1989].

## 4. Conclusion

Linear approximation of the weekly data for each month for about 25-year period of rocket measurements at altitude of 25–75 km made it possible to evaluate seasonal trends in the stratopause temperature and height over the sites located in various latitudinal zones. During this period till the mid-1990s the annual mean stratopause height decreased by 0.4, 2.4, and 0.5 km over the Heiss Island site (Arctic), midlatitude Volgograd site, and tropical Thumba site, respectively. The stratopause height over the Molodezhnaya site (Antarctic) did not change. The confidence interval of these evaluations for $P = 0.95$ is $\pm 0.4$ km. The main depletion of $h_s$ over Heiss Island took place in January and February by 2.4 and 4.5 km, respectively. The stratopause height over Volgograd decreased from August ($-2.5$ km) to February ($-5.5$ km) with a maximum in December ($-7.5$ km). The $h_s$ decrease over the Thumba site is not so strong (about 1 km), but it covers the period from May to February with the maximum value in October ($-2.0$ km). The stratopause height over the Molodezhnaya site decreased by about 1 km in March–April and August–September and increased by about 1 km in May–June and November–December. The confidence interval of the $h_s$ monthly estimates for $P = 0.95$ is $\pm 1.4$ km.

The annual mean temperature of the stratopause decreased over Heiss Island, Volgograd, and Thumba by 4.9 K, 2.8 K, and 4.0 K, respectively, and increased over Molodezhnaya by 1 K. The confidence interval of these estimates for $P = 0.95$ is $\pm 1.9$ K for Heiss Island and $\pm 1.3$ K for other stations. The $T_s$ depletion over the former three stations took place in all seasons except a statistically insignificant increase of the stratopause temperature over Thumba in March. The maximum cooling of the stratopause occurred in December–March (7–9 K) over Heiss Island, in August–October (5–6 K) over Volgograd, and in September–January (6–10 K) over Thumba. The $T_s$ increase over the Molodezhnaya site occurred in all months except June and July. In September–December the warming was especially strong (3–4 K). The confidence interval of the monthly evaluations for $P = 0.95$ does not exceed $\pm 7.6$ K and $\pm 5.1$ K for the Heiss Island data and the data of other sites, respectively.

These changes in the stratopause temperature for the 25-year period of rocket measurements agree with the values of the annual mean temperature trends in the 45–50 km published earlier [*Kokin and Lysenko*, 1994]. An acceptable agreement with the theoretical estimates of the stratopause cooling [see, e.g., *Berger and Dameris*, 1993] due to the increase of the greenhouse effect, except for the Molodezhnaya site data, should be also mentioned.

The decrease of the stratopause height occurred not only in the months when the positive temperature trend in the upper stratosphere appeared and not only over Heiss Island, but over the tropical Thumba site as well. This fact cannot be explained by the action of only dynamical factors. Most probably, the stratopause height decrease is caused by the decrease of the solar UV radiation absorption in the mesosphere and therefore by the depletion of the mesospheric ozone concentration during the recent decades.

If this hypothesis is true, then the following are correct:

1. The reason of the discrepancies in the results of numerical simulation of the middle atmosphere climate with an increase of the greenhouse gases and of observations in the mesosphere becomes understandable, since, as an addition to the infrared radiative cooling, there is a "deficit" of the radiative heating in the UV part of the solar spectrum.

2. On the basis of the obtained data on the stratopause height depletion one can assume that an extinction of the mesospheric ozone occurred over low and, especially, northern middle latitudes almost in all seasons with a maximum in October–December. The ozone depletion in the middle-latitude mesosphere of the Northern Hemisphere occurred only in the end of the polar winter and beginning of calendar spring. In other months, as well as in all seasons over middle latitudes of the Southern Hemisphere, the mesospheric ozone concentration stayed almost unchanged except the narrow layer of the ozone minimum (75–80 km) in which, according to the temperature negative trend profile at 70–75 km, the ozone content decreased significantly.

3. The difference in the vertical profiles of the temperature annual mean trend in the mesosphere according to the rocket data obtained in different latitudinal bands is explained. In particular, taking into account results 1 and 2, one can explain the presence of the maximum values of the temperature negative trends in the lower mesosphere over middle latitudes or the local maximum in this layer over tropics and subtropics. The trend increases with height up to 75 km over the high-latitude sites.

One has to confess that the statistically significant depletion of the stratopause height over Heiss Island in January (polar night) does not fit the hypothesis proposed. As any hypothesis, this one may be confirmed or rejected on the basis of corresponding measurement results. It might happen that the accumulation of the data on the mesospheric ozone currently obtained on board modern research satellites would stimulate a comparison with the data of rocket and satellite measurements in the 1950–1970s. In spite of the obvious difficulty of such comparisons due, first of all, to the statistical inhomogeneity of the data, probable depletion of the ozone concentration by several times still may be detected.

The results of numerical simulation of the middle atmosphere climate with increased content of the greenhouse gases and depleted ozone content in the mesosphere and stratosphere would have been very important. Answers to the following questions also seem very important. In what degree the ozone depletion in the mesosphere under given (and corresponding to the current one) level of the greenhouse gas concentration and depleted (current) ozone content in the stratosphere should occur to induce the stratopause height decrease observed? How the mesosphere cooling rate would increase in this case? Whether it is possible to obtain a correspondence to the observations of both, the stratopause height trend and middle atmosphere temperature trend varying only the mesospheric ozone concentration, or one needs to include into the analysis some other factors?

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