

Climatic changes in the troposphere, stratosphere and lower mesosphere in 1979-2016

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Abstract. Changes in thermal characteristics in the atmospheric layer from 1000 to 0,1hPa are studied based on reanalysis data. It was demonstrated that during 1979-2016 temperature increased in the troposphere in January and July, while cooling was observed in the stratosphere, and air warming in lower mesosphere in summer. Most pronounced long-period cyclic changes were registered for temperature in the upper stratosphere and the lower mesosphere, and for ozone mixing ratio in the middle stratosphere.

Modern measurement and information technologies enable to carry out analysis of atmospheric processes even at high altitudes. The present paper studies thermal regime peculiarities of the troposphere, stratosphere and lower mesosphere. It is known that in atmospheric process troposphere air is warmed by the earth surface, while in stratosphere warming is caused by ultraviolet radiation absorption by ozone molecules. In the troposphere, air temperature drops with altitude, while in the stratosphere, on the contrary, it increases with altitude, and decreases again in the mesosphere. According to [1], the troposphere, stratosphere and mesosphere have fundamental differences from the standpoint of radiation conditions, vertical temperature distribution, and chemical composition. Stratosphere-troposphere exchange-related issues have been studied in [2]. It states that a continuous mass and energy exchange takes place through the tropopause, which exerts a strong influence on atmospheric chemistry, energy and the global climate. Vertical temperature gradient γ characterizing static stability of the atmosphere is an important parameter of the atmosphere and climate system as a whole. Requisite conditions for baroclinic instability and, correspondingly, cyclonic activity in the atmosphere depend on γ [3]. In the latter paper it was noted that, under the conditions of anthropogenic climate warming, the troposphere gets warmer, while the stratosphere and mesosphere are cooled, especially near the mesopause (80-90 km). Using the monthly ERA-Interim global reanalysis data [4] about air temperature distribution and ozone mixing ratio in regular grid points $2.5 \times 2.5^\circ$ on 26 isobaric surfaces (from 1000 to 0.1 hPa) for 1979-2016, the present paper estimates a number of thermodynamic properties in January and July. All calculations are averaged over the entire Northern Hemisphere (NH), polar (90-65 °N), temperate (65-30 °N) and tropical 30-0 °N) latitudes. It gives an opportunity to characterize the atmosphere on the whole as a unified dynamic system controlled by internal and external factors, individual layers of which more or less actively interact with each other, physically differing one from another by the nature of thermal stratification and energy-related processes [5]. This interaction occurs through the wave mechanism, with the help of which meteorological disturbances propagate upward from the troposphere to the stratosphere, conditioned by atmosphere baroclinity, nonuniform heating of the underlying surface, and relief. In the previous



articles the authors examined spatial-temporal variations in temperature, wind speed and atmospheric pressure fields in the troposphere [6, 7].

Table 1 presents vertical distribution of long-term means for air temperature A_v ($^{\circ}\text{C}$) and linear trend slope A ($^{\circ}\text{C}\cdot\text{year}^{-1}$) on 26 isobaric surfaces. The data averaged for the NH both for January and July demonstrate that A_v temperature drops with height in the troposphere, rises in the stratosphere and again decreases in the lower mesosphere. Temperature inversion in lower troposphere is observed in the polar zone in January. A marked annual cycle of temperature and rather notable zonal differences in temperature distribution are registered, as well. The process of temperature change with time is vertically inhomogeneous. Linear trend slope (A) supports the latter observation. As for the troposphere, especially intense heating takes place in winter in the polar zone, where A values reach $0.107\text{ }^{\circ}\text{C}\cdot\text{year}^{-1}$ near the earth surface. Cooling ($A < 0$), most pronounced in the temperate and tropical zones, is observed in the stratosphere, while in the lower mesosphere heating ($A > 0$) is observed over the whole hemisphere. Thus, at 3 hPa level in January, A for the NH reaches $0.118\text{ }^{\circ}\text{C}\cdot\text{year}^{-1}$, while in the tropical zone $A = -0.175\text{ }^{\circ}\text{C}\cdot\text{year}^{-1}$. However, in the polar zone in the lower mesosphere, the temperature significantly decreases in January, in contrast to the tropical zone. In general, LTSC distribution confirms greenhouse origin of the contemporary global warming. Nevertheless, noticeable differences conditional on radiation and dynamic factors exist between the year seasons and latitudinal zones.

Specifically, cooling is more vividly expressed in the summer stratosphere, than in the winter stratosphere (figure 1). The latter testifies the weakening of vertical links between the layers through wave action and the absence of stratospheric warmings typical for winter, which contribute to fast heating of polar regions.

The analysis shows that processes proceed more homogeneously at high altitudes in summer, being influenced by the stratospheric ozone, thanks to which a vigorous heating of air masses takes place in the middle stratosphere. As figure 1 evidences, temperature trends change their sign vertically.

Vertical correlations between atmospheric layers have been studied for the entire Northern hemisphere and its zones in January and July. Analysis of the obtained results shows that in the polar zone in January close correlation exists at all the levels in the layer of 1000-0.1 hPa, the correlation coefficient $r > 0.9$ in the layer of 1000-5 hPa, except for the layer 400-300 hPa, where $r = 0.743$. The correlation slightly decreases in the upper stratosphere – lower mesosphere. In July, the correlation coefficients are significantly lower than those of January, especially at stratosphere-mesosphere levels, which is the evidence of atmosphere stratification. Thus, temperature variations between the levels of 10 and 7 hPa ($r = 0.268$), 5 and 3 hPa ($r = 0.076$) are weakly correlated between each other in the upper stratosphere and the lower mesosphere. During this time the ozone screen is essential to thermal regime, while dynamic mixing is not as intense (weakening of vertical wave interaction). In the temperate latitudes in January, the correlation in the layers of 250-200 ($r = 0.793$), 150-100 ($r = 0.671$), 2-1 hPa ($r = 0.716$) slightly weakens; the correlation coefficients in the troposphere in July are high except for the layers of 200-150 hPa ($r = 0.615$) – tropopause; 0.29-0.1 hPa ($r = 0.474$) – stratopause. Consequently, the vertical correlations in the polar zone in July have a more complex structure, while in the temperate zone in July the correlations significantly weaken in the transition layers: in the tropopause and the stratopause. Analysis of the vertical correlation relationships in January across the Northern hemisphere indicates that correlations are strong in troposphere, their dramatic weakening is observed between 100 and 70 hPa ($r = 0.040$), which can be explained by processes taking place in the tropical zone only. Stronger correlations are observed in the upper stratosphere – lower mesosphere. In July, the correlations are strong in the troposphere, in the layer of 200-150 hPa $r = 0.773$; 150-100 hPa $r = 0.496$; 100-70 hPa $r = 0.740$, i.e. in the lower stratosphere correlation relations weaken. In the upper stratosphere, such correlations are stronger in the layers 2-1 hPa, where $r = 0.417$, and 0.29-0.1 hPa, where $r = 0.575$. In general, the correlations are rather strong, their weakening is conditioned by physical differences between layers and seasonal restructuring of meteorological fields.

Table 1. Long-term means for temperature A_v ($^{\circ}\text{C}$) and linear trend slope A ($^{\circ}\text{C}\cdot\text{year}^{-1}$) on 26 isobaric surfaces for 1979-2016.

P, hPa	January										July									
	Northern hemisphere		Polar zone of the NH		Temperate zone of the NH		Tropical zone of the NH		Northern hemisphere		Polar zone of the NH		Temperate zone of the NH		Tropical zone of the NH		Tropical zone of the NH		Tropical zone of the NH	
	A_v , $^{\circ}\text{C}$	A , $^{\circ}\text{C}\cdot\text{year}^{-1}$	A_v , $^{\circ}\text{C}$	A , $^{\circ}\text{C}\cdot\text{year}^{-1}$	A_v , $^{\circ}\text{C}$	A , $^{\circ}\text{C}\cdot\text{year}^{-1}$	A_v , $^{\circ}\text{C}$	A , $^{\circ}\text{C}\cdot\text{year}^{-1}$	A_v , $^{\circ}\text{C}$	A , $^{\circ}\text{C}\cdot\text{year}^{-1}$	A_v , $^{\circ}\text{C}$	A , $^{\circ}\text{C}\cdot\text{year}^{-1}$	A_v , $^{\circ}\text{C}$	A , $^{\circ}\text{C}\cdot\text{year}^{-1}$	A_v , $^{\circ}\text{C}$	A , $^{\circ}\text{C}\cdot\text{year}^{-1}$	A_v , $^{\circ}\text{C}$	A , $^{\circ}\text{C}\cdot\text{year}^{-1}$	A_v , $^{\circ}\text{C}$	A , $^{\circ}\text{C}\cdot\text{year}^{-1}$
1000	9.82	0.024	-20.52	0.107	-0.60	0.026	22.63	0.012	22.23	0.020	4.46	0.025	19.54	0.028	26.89	0.013				
925	6.19	0.023	-19.23	0.078	-3.77	0.026	17.95	0.012	18.63	0.023	3.86	0.047	16.38	0.031	22.53	0.012				
850	3.48	0.020	-19.65	0.059	-5.87	0.024	14.41	0.011	15.18	0.021	1.67	0.038	12.97	0.028	18.86	0.013				
700	-3.20	0.020	-24.88	0.052	-12.33	0.021	7.37	0.014	6.63	0.018	-5.73	0.028	4.19	0.022	10.35	0.013				
600	-9.93	0.016	-30.77	0.044	-18.98	0.018	0.45	0.011	-0.83	0.016	-12.22	0.021	-2.97	0.023	2.50	0.009				
500	-18.32	0.015	-38.69	0.041	-27.59	0.017	-7.83	0.010	-9.12	0.013	-20.59	0.023	-11.63	0.023	-5.46	0.004				
400	-29.28	0.019	-48.65	0.038	-38.53	0.016	-18.94	0.018	-20.05	0.020	-32.15	0.025	-23.00	0.022	-15.94	0.017				
300	-42.65	0.023	-58.70	0.045	-50.60	0.018	-33.85	0.025	-34.99	0.027	-45.55	0.029	-37.97	0.027	-31.06	0.027				
250	-49.36	0.022	-61.20	0.051	-54.98	0.018	-43.07	0.020	-43.54	0.024	-48.24	0.018	-45.90	0.024	-40.93	0.025				
200	-55.19	0.014	-61.06	0.042	-56.16	0.014	-53.57	0.010	-51.59	0.011	-44.46	-0.013	-51.28	0.013	-52.82	0.012				
150	-61.39	0.015	-61.70	0.052	-56.34	0.013	-65.54	0.011	-60.08	0.004	-44.02	-0.012	-55.05	0.005	-66.45	0.006				
100	-69.23	0.019	-64.75	0.091	-59.22	0.005	-78.17	0.021	-66.52	-0.005	-44.91	-0.009	-58.29	-0.013	-76.33	0.003				
70	-68.72	-0.016	-67.00	0.108	-60.19	-0.005	-76.06	-0.042	-62.61	-0.033	-44.35	-0.019	-56.86	-0.026	-69.89	-0.041				
50	-64.40	-0.026	-68.48	0.120	-59.88	-0.009	-67.59	-0.060	-57.88	-0.040	-43.86	-0.026	-53.95	-0.032	-63.07	-0.048				
30	-59.45	-0.018	-68.69	0.155	-58.49	-0.009	-58.98	-0.049	-52.07	-0.029	-42.95	-0.027	-49.62	-0.030	-55.36	-0.029				
20	-55.81	-0.006	-66.23	0.155	-56.51	-0.002	-53.82	-0.032	-47.41	-0.017	-40.22	-0.023	-45.31	-0.025	-50.14	-0.010				
10	-49.00	0.002	-59.14	0.147	-50.89	0.016	-46.03	-0.030	-39.62	-0.015	-31.90	-0.006	-37.14	-0.021	-42.74	-0.012				
7	-43.24	-0.047	-52.45	0.066	-45.01	-0.030	-40.51	-0.077	-34.75	-0.006	-26.87	0.065	-32.02	0.016	-38.11	-0.034				
5	-36.87	-0.103	-46.02	-0.013	-38.69	-0.073	-34.10	-0.140	-28.83	-0.029	-21.73	0.111	-26.24	0.029	-31.95	-0.096				
3	-28.36	-0.118	-38.82	-0.089	-31.21	-0.054	-24.55	-0.175	-18.03	-0.094	-7.25	-0.028	-14.51	-0.063	-22.43	-0.128				
2	-22.84	-0.077	-34.19	-0.140	-27.35	-0.046	-17.53	-0.094	-11.33	-0.071	4.38	-0.064	-7.38	-0.090	-16.77	-0.056				
1	-16.76	0.014	-26.33	-0.098	-22.50	-0.023	-10.67	0.060	-6.85	0.054	9.67	-0.008	-3.98	0.046	-11.49	0.068				
0.8	-15.54	0.037	-23.72	-0.074	-21.14	-0.010	-9.76	0.091	-7.04	0.082	8.13	0.006	-4.60	0.085	-11.15	0.090				
0.51	-15.68	0.072	-19.15	-0.040	-19.47	0.023	-12.06	0.129	-12.18	0.113	-0.34	0.047	-10.39	0.113	-15.29	0.122				
0.29	-21.93	0.087	-19.08	-0.029	-22.82	0.041	-21.59	0.142	-24.69	0.106	-17.70	0.088	-24.30	0.078	-25.97	0.131				
0.1	-36.66	0.043	-26.68	-0.090	-34.44	-0.001	-39.87	0.098	-49.00	0.030	-55.90	0.002	-51.25	-0.032	-46.18	0.086				

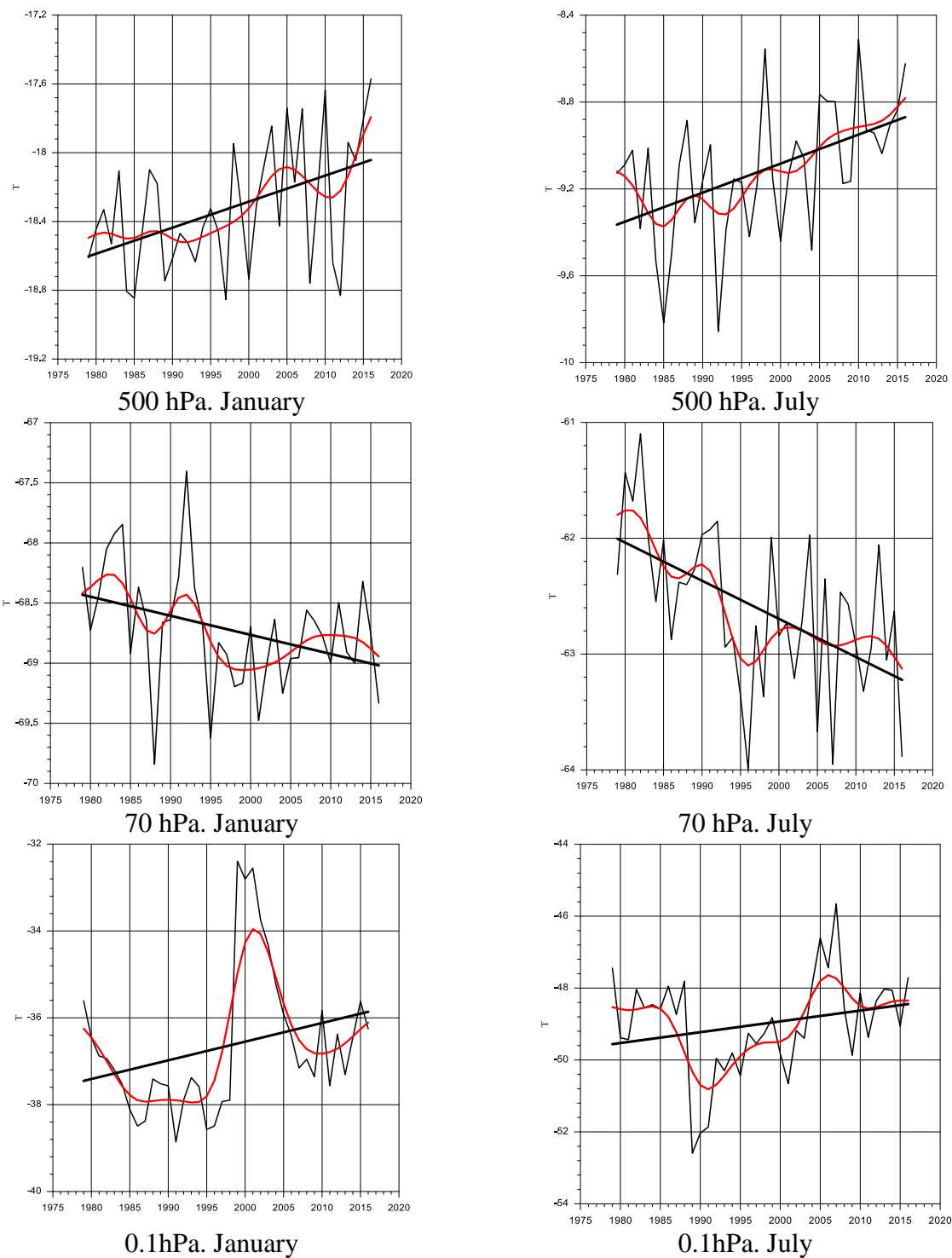


Figure 1. Air temperature, averaged over the whole Northern hemisphere at the levels of 500, 70 and 0.1 hPa. Shown are the raw data, linear trend, and low-frequency components with the period > 10 years.

Vertical correlations between atmospheric layers have been studied for the entire Northern hemisphere and its zones in January and July. Analysis of the obtained results shows that in the polar zone in January close correlation exists at all the levels in the layer of 1000-0.1 hPa, the correlation coefficient $r > 0.9$ in the layer of 1000-5 hPa, except for the layer 400-300 hPa, where $r = 0.743$. The correlation slightly decreases in the upper stratosphere – lower mesosphere. In July, the correlation coefficients are significantly lower than those of January, especially at stratosphere-mesosphere levels, which is the evidence of atmosphere stratification. Thus, temperature variations between the levels of 10 and 7 hPa ($r = 0.268$), 5 and 3 hPa ($r = 0.076$) are weakly correlated between each other in the upper stratosphere and the lower mesosphere. During this time the ozone screen is essential to thermal regime, while dynamic mixing is not as intense (weakening of vertical wave interaction). In the temperate latitudes in January, the correlation in the layers of 250-200 ($r = 0.793$), 150-100 ($r = 0.671$), 2-1 hPa ($r = 0.716$) slightly weakens; the correlation coefficients in the troposphere in July are high except for the layers of 200-150 hPa ($r = 0.615$) – tropopause; 0.29-0.1 hPa ($r = 0.474$) – stratopause. Consequently, the vertical correlations in the polar zone in July have a more complex structure, while in the temperate zone in July the correlations significantly weaken in the transition layers: in the tropopause and the stratopause. Analysis of the vertical correlation relationships in January across the Northern hemisphere indicates that correlations are strong in troposphere, their dramatic weakening is observed between 100 and 70 hPa ($r = 0.040$), which can be explained by processes taking place in the tropical zone only. Stronger correlations are observed in the upper stratosphere – lower mesosphere. In July, the correlations are strong in the troposphere, in the layer of 200-150 hPa $r = 0.773$; 150-100 hPa $r = 0.496$; 100-70 hPa $r = 0.740$, i.e. in the lower stratosphere correlation relations weaken. In the upper stratosphere, such correlations are stronger in the layers 2-1 hPa, where $r = 0.417$, and 0.29-0.1 hPa, where $r = 0.575$. In general, the correlations are rather strong, their weakening is conditioned by physical differences between layers and seasonal restructuring of meteorological fields.

It should be emphasized that interaction between the layers was also studied by the authors earlier [8], but for a shorter period (1986 – 1999), with the spectrum-based approach. A wave structure of the zonal circulation in troposphere-stratosphere and upper mesosphere-lower thermosphere was investigated for a spectral range for time scales of planetary waves (2 – 30 days). To establish interrelations between layers, we got coherent wave structures, which depended on season, interannual variability, and altitude.

Assessment of the impact of individual circulation modes (North Atlantic Oscillation (NAO), Arctic Oscillation (AO), Scandinavian Oscillation (SO) and others) on near-surface temperature in extra-tropical latitudes of the Northern hemisphere, which was done with the help of composite analysis, permitted us to identify regions with a strong response. The warming effect of the NAO was most significant in winter over Central and Eastern Europe, as well as over Central Siberia; the Arctic Oscillation had its maximum manifestation in temperature in Eastern Europe and Siberia, while Scandinavian Oscillation led to considerable air temperature changes in January in Eastern Europe, West and Middle Siberia [9].

Analysis of altitude-time sections of first-order differences, which was conducted for low-frequency components (LFC) with the period exceeding 10 years for air temperature (AT) ($^{\circ}\text{C}\cdot\text{year}^{-1}$) in January, July and for annual data was performed as well (figure 2). The most stable situation was observed in the troposphere. A sustainable (rather weak) AT growth had been observed since 1994 ($0.1\text{ }^{\circ}\text{C}\cdot\text{year}^{-1}$). Admittedly, a weak AT drop was registered in January from 2006 to 2010 ($-0.1\text{ }^{\circ}\text{C}\cdot\text{year}^{-1}$). In the stratosphere, trend coefficients changed their sign within certain time periods, and the negative trend coefficients achieved the value of $-0.2\text{ }^{\circ}\text{C}\cdot\text{year}^{-1}$ in the layer 15-30 km in January. At altitudes higher than 30 km these differences grew in January, and starting from the altitude of 45 km both negative and positive sign change centres of LFC differences were observed. An intense warming was registered in the layer of 45 km and higher within the period from 1995 to 2001, when in January the value of the first-order LFC differences exceeded $1.2\text{ }^{\circ}\text{C}\cdot\text{year}^{-1}$. At the same time, the primary maximum was located within the altitudes of 45-65 km, and in the layer between 45 and 57 km

($0.9\text{ }^{\circ}\text{C}\cdot\text{year}^{-1}$) in July. We found a ~ 8 -year cyclicity with cooling in 1980-1988 and in 2002-2008 and warming in 1994-2002. Therefore, the upper stratosphere and lower mesosphere demonstrated an unstable temperature behaviour in comparison with the troposphere [10-12].

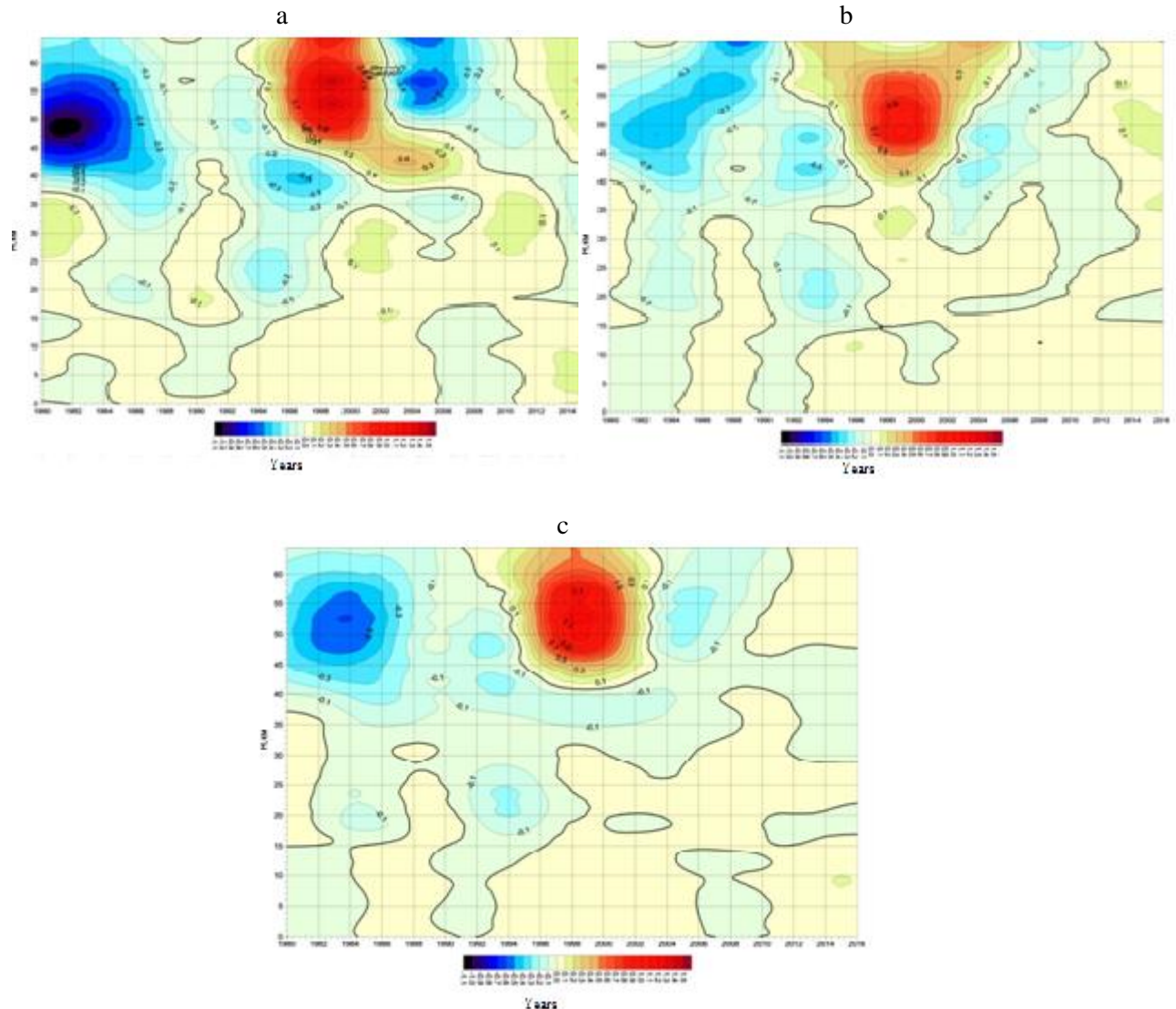


Figure 2. First-order differences of LFC with the period exceeding 10 years for air temperature in the Northern hemisphere ($^{\circ}\text{C}\cdot\text{year}^{-1}$): a – January, b – July, c – annual mean.

A similar work was done for ozone mixing. It was found that the major interannual changes of this value occurred in the layer of 20-45 km (figure 3). Besides, maximum dynamics was registered for air temperature in winter, while for ozone in summer. In the stratosphere heat is emitted when ozone absorbs ultraviolet radiation; furthermore, ozone absorbs the radiation coming from the earth surface.

Conclusions

1. ERA-Interim reanalysis data offer an unbiased reflection of fundamental patterns of dynamics in the key climatic indices in the atmospheric mass up to the altitude of 64 km.
2. The significant spatiotemporal inhomogeneity in thermal characteristic distribution, which results from differences in physical mechanisms regulating thermal regime in atmospheric layers, is discovered.

3. The sign of the vertical slope coefficient of air temperature linear trend confirms the greenhouse origin of the contemporary global warming.

4. Centres of temperature growth and decrease are observed in the upper stratosphere and lower mesosphere (45-60 km) with the cyclicity of 8 years. In the ozonosphere an analogous process occurs at smaller altitudes, in the layer of 25-40 km.

5. To get a fuller picture of changes in the thermal behaviour of the atmosphere one should also use data about circulation in its different layers.

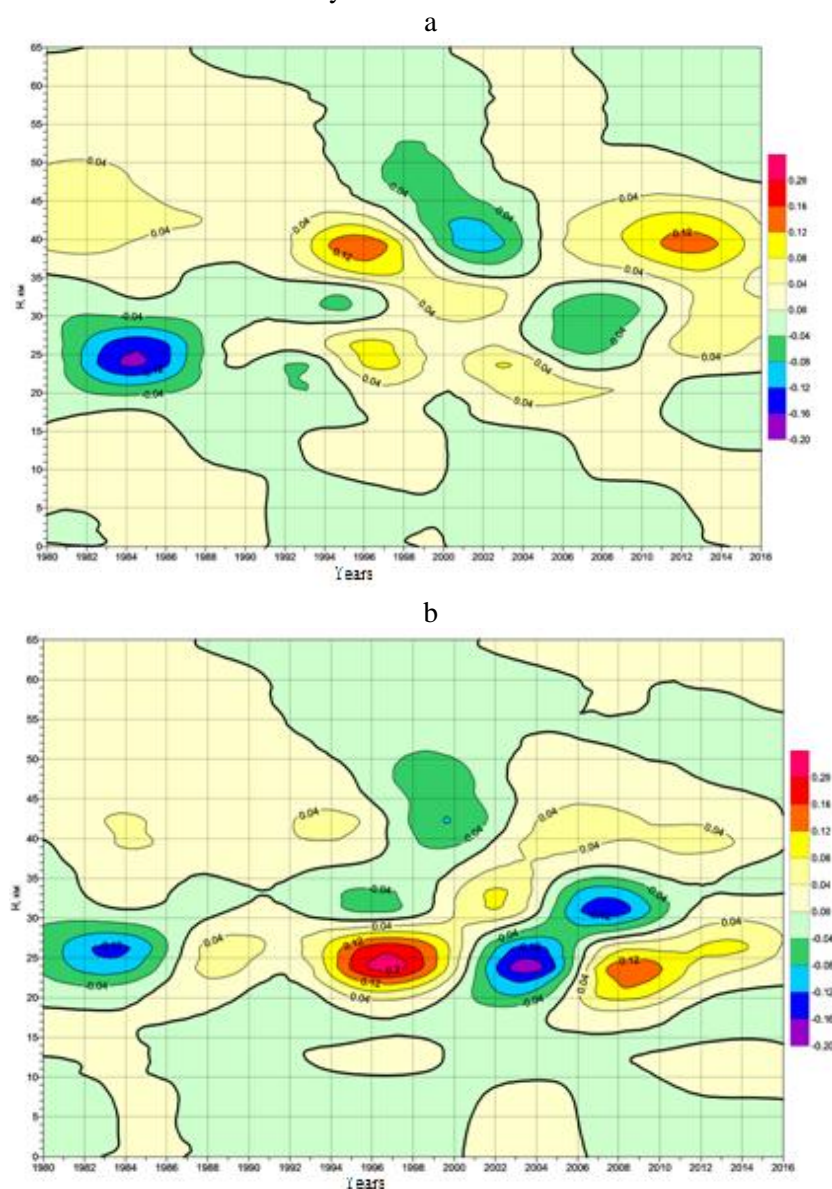


Figure 3. First-order differences of LFC with the period exceeding 10 years for ozone mixing ratio ($10^{-6} \cdot \text{year}^{-1}$) in the Northern hemisphere: a – January, b – July.

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