Thermodynamic Parameter Variations in the Troposphere and Stratosphere in 1979-2016

Y P Perevedentsev, K M Shantalinskii, V V Guryanov, and A V Eliseev

Kazan (Volga Region) Federal University, Russia

Abstract. Changes in the air temperature, ozone mass mixing ratio, and characteristics of wave activity on 26 levels in the tropo-stratosphere during 1979-2016 are discussed. Reanalysis data ERA-Interim and indices of atmospheric circulation are used as initial data. Vertical profiles of the coefficient of slope in a linear temperature trend are built. The vertical correlations between the levels are estimated. The differences in the thermal regime and ozone mass mixing ratio in three sectors of the Northern Hemisphere: Atlantic-European, Asia-Pacific, and American are shown. A credible correlation between the wave activity in the stratosphere and the atmospheric circulation indices (AO, QBO-50) has been obtained.

1. Introduction

Papers [6-8] provide a description of spatiotemporal variability of atmospheric pressure, air temperature, and wind speed fields between 1900 and 2014, which permitted identifying long-term trends of meteorological parameters on different isobaric surfaces in the troposphere. It was demonstrated that atmospheric pressure variations in the North Atlantic and the North Pacific Oceans are antiphase. In the recent years the development of measuring and information technologies has made it possible to more thoroughly study the processes taking place in higher atmospheric layers. Study of the dynamic interaction between the troposphere and stratosphere, as well as sudden stratospheric warmings, wave action, temperature trends observed in the stratosphere, etc. [1] should be considered the most pressing challenges.

Using ERA-Interim reanalysis data for 1979-2016, a number of thermodynamic characteristics were calculated in this article for the temperate zone (65-30° N) of the Northern Hemisphere (NH) and its 3 sectors: the Euro-Atlantic (I), Asia-Pacific (II), and American (III) ones.

2. Results

Table 1 presents the vertical distribution of long-term air temperature means AV (°C) and linear trend slopes А (°С/year) on 26 isobaric surfaces for the entire temperate zone. The data averaged for the temperate zone for both January and July revealed a temperature fall with altitude in the troposphere, its rise in the stratosphere, and a new fall in the mesosphere. A marked annual cycle of temperature was registered, including the upper atmosphere. Linear trend slopes (LTSs) testified to the heterogeneous nature of temperature variation in time at different levels. In the troposphere LTSs were positive, which was an evidence of its warming between 1979 and 2016. In summer in the stratosphere and lower mesosphere the temperature was falling more intensively than in winter. Consequently, the atmosphere stratification by its response to the global warming of the climate was observed (Figure 1).

Analysis of height-time sections of the first-order differences of low-frequency components (LFCs) with a period exceeding 10 years performed for the temperature (°С/year) in January and July revealed the following. In January the processes were more active in the layer of 40-64 km, which was manifested in subsequent alternation of negative and positive centres of the LFC at different levels. In the troposphere LFCs were positive, which was an evidence of its warming between 1979 and 2016. In summer in the stratosphere and lower mesosphere the temperature was falling more intensively than in winter. Thus, at the level of 2 hPa in July LTS=-0.9°С/10 years. Consequently, the atmosphere stratification by its response to the global warming of the climate was observed (Figure 1).

In the lower mesosphere the signs of the centres changed to the opposite. In July no large temperature differences were actually registered. Interannual variations were unnoticeable. Periods with insignificant temperature rises alternated with the opposite periods.
A rather active dynamics was observed for ozone LFC in January and especially in July in the layer of 15-45 km, where the sign of LFC centres with negative and positive tendency was consequentially changing throughout the 38 years of study.

Table 1. Characteristics of low-frequency variability of temperature means in the temperate zone of the Northern Hemisphere on 26 isobaric surfaces.

| Level, hPa | January | | | July | | |
| --- | --- | --- | --- | --- | --- |
| | Av. °C | σ °C | A. °C/year | Av. °C | σ °C | A. °C/year |
| 1000 | -0.60 | 0.64 | 0.026 | 19.54 | 0.40 | 0.028 |
| 925 | -3.77 | 0.56 | 0.026 | 16.38 | 0.45 | 0.031 |
| 850 | -5.87 | 0.51 | 0.024 | 12.97 | 0.44 | 0.028 |
| 700 | -12.33 | 0.45 | 0.021 | 4.19 | 0.39 | 0.022 |
| 600 | -18.98 | 0.42 | 0.018 | -2.97 | 0.40 | 0.023 |
| 500 | -27.59 | 0.39 | 0.017 | -11.63 | 0.42 | 0.023 |
| 400 | -38.53 | 0.36 | 0.016 | -23.00 | 0.44 | 0.022 |
| 300 | -50.60 | 0.37 | 0.018 | -37.97 | 0.50 | 0.027 |
| 250 | -54.98 | 0.46 | 0.018 | -45.90 | 0.49 | 0.024 |
| 200 | -56.16 | 0.55 | 0.014 | -51.28 | 0.49 | 0.013 |
| 150 | -56.34 | 0.50 | 0.013 | -55.05 | 0.45 | 0.005 |
| 100 | -59.22 | 0.50 | 0.005 | -58.29 | 0.53 | -0.013 |
| 70 | -60.19 | 0.71 | -0.005 | -56.86 | 0.62 | -0.026 |
| 50 | -59.88 | 1.01 | -0.009 | -53.95 | 0.59 | -0.032 |
| 30 | -58.49 | 1.38 | -0.009 | -49.62 | 0.55 | -0.030 |
| 20 | -56.51 | 1.46 | -0.002 | -45.31 | 0.48 | -0.025 |
| 10 | -50.89 | 1.68 | 0.016 | -37.14 | 0.44 | -0.021 |
| 5 | -45.01 | 1.78 | -0.030 | -32.02 | 0.45 | 0.016 |
| 3 | -38.69 | 1.96 | -0.073 | -26.24 | 0.59 | 0.029 |
| 2 | -31.21 | 2.16 | -0.054 | -14.51 | 1.02 | -0.063 |
| 1 | -27.35 | 2.88 | -0.046 | -7.38 | 1.37 | -0.090 |
| 0.8 | -22.50 | 3.04 | -0.023 | -3.98 | 1.65 | 0.046 |
| 0.51 | -19.47 | 3.36 | 0.023 | -10.39 | 2.13 | 0.113 |
| 0.29 | -22.82 | 3.27 | 0.041 | -24.30 | 1.89 | 0.078 |
| 0.1 | -34.44 | 2.52 | -0.001 | -51.25 | 1.66 | -0.032 |
Figure 1. Vertical profile of the linear trend slopes of the air temperature (°C/year), averaged for the temperate zone of the Northern Hemisphere (black curve), land area of the temperate zone (red curve) and oceanic area of the temperate zone (blue curve).

Analysis of the obtained height-time sections showed that in sector I in the troposphere the temperature was 3°C as high as in the entire temperate zone. In the layer of 10-35 km in winter, oppositely, it considerably decreased (by 4.5°C), in the higher atmosphere the temperature rose (~ by 3.5°C) in comparison with the zone. In sector II the opposite picture was observed: in the winter troposphere the air temperature was 4°C as low as in the zone. In the layer of 10-40 km an intensive temperature anomaly was registered (+6.5°C), at altitudes higher than 40 km in the upper stratosphere and lower mesosphere the temperature decreased again. In sector III the temperature anomalies were less intensive: in winter in the layer between the Earth and 20 km it was warmer than in the zone; in the layer of 25-55 km the temperature was significantly lower (by 4°C), and in the lower mesosphere, as in the troposphere, it rose again in comparison with the entire temperate zone. In summer the processes were not as intensive. In such a way, alternation of positive and negative vertical air temperature deviations, especially expressed in the Asia-Pacific sector, was detected (Figure 2).

In the temperate zone maximum values of the ozone mass mixing ratio (OMMR) were registered in the layer of 31-34 km in July – August, where this value reached 13·10^6, making about 12·10^6 in winter (December – February). Analysis showed that in sector II in the layer of 15-35 km in the cold season maximum positive deviations of 0.4·10^6 were detected in the ozone content in comparison with the entire zone. Contrasts were the largest in November – January; in July – August the OMMR anomaly was negative. In sector I, on the contrary, a negative anomaly of the ozone mass mixing ratio was observed at these altitudes. There possibly exists a physical mechanism provoking warming and ozone concentration increase in the Asian sector.
Figure 2. Differences of the air temperature and ozone mass mixing ratio averaged for Asia-Pacific sector of the temperate zone of the Northern Hemisphere and the entire temperate zone.

Comparison of the winter temperature means for the entire NH, land \( t_l \), and ocean \( t_o \) demonstrated that it was much warmer in the troposphere above the ocean (especially in the lower troposphere) than above the land; from the level of 150 hPa to the level of 30 hPa (lower stratosphere) \( t_o < t_l \), from the level above 20 and up to 0.29 hPa (in the main mass of the stratosphere and lower mesosphere) \( t_o > t_l \), which meant alternation of layers with different temperatures.

Moreover, LTS \( > 0 \) above the land and ocean up to the level of 100 hPa, i.e. throughout the troposphere, then up to the level of 2 hPa the stratosphere cooled (LTS \( < 0 \)), and from 1 hPa LTS \( > 0 \), i.e. in the lower mesosphere, the temperature rose in winter. Thus, parallel air temperature (AT) change was observed over the land and ocean: the trend was either positive or negative (Figure 1).

In summer the picture was noticeably different. From the level of 1000 hPa to AT850 the land was warmer than the ocean, then up to the level of 250 hPa \( t_o < t_l \), then up to 0.29 hPa \( t_o < t_l \), and only at the level of 0.1 hPa \( t_o > t_l \). Consequently, the underlying surface spread its influence on the thermal regime up to high altitudes.

The LTS behaviour in summer was as follows: in the layer of 1013-200 hPa the LTSs above the land and ocean were positive, at the same time the air temperature (AT) rise above the land significantly exceeded the rise above the ocean. Thus, at the ground (1013 hPa) \( A_t = 0.035 \degree \text{C/year} \), and \( A_o = 0.011 \degree \text{C/year} \). In the stratosphere from the level of 100 hPa to 2 hPa \( A < 0 \), while above \( A > 0 \), here the processes were homogenous irrespective of the type of underlying surface.

Comparison of the annual air temperature means (AATMs) above the land and ocean in the temperate zone of the NH testified that in the troposphere (1013 – 200 hPa) the air above the ocean
was warmer than above the land. The difference (Δ) was especially large in the lower troposphere. Thus, at the level of 1013 hPa the AATM above the ocean was 11.3°C, while above the land it was 3.7°C only (the difference was 7.6°C); at the level of 850 hPa \( t_0 = 3.5°C \), and \( t_c = 2.1°C \) (the difference was 1.4°C); in the upper troposphere at the level of 200 hPa the temperature differences levelled out \( (t_0 = -54.3°C, \ t_c = -54.6°C, \ \Delta = 0.3°C) \). In the stratosphere the temperature above the land, except for the layer of 50-20 hPa, was higher than above the ocean by tenths of degree, and no large differences were practically registered.

In the layer of 1013-200 hPa above the land, especially in the lower troposphere (1013-850 hPa), the LTS (°C/year) significantly exceeded the LTSs above the ocean. At the same time, the temperature rose in the entire troposphere mass, over both the land and ocean. At the level of 1013 hPa \( A_s = 0.037°C/\text{year} \), \( A_o = 0.017°C/\text{year} \). In the stratosphere the differences levelled out, and the trends had negative values. In the lower mesosphere the LTS became positive again in both cases (in the layer of 1-0.29 hPa). Thus, at the level of 0.51 hPa \( A_s = 0.109°C/\text{year} \), \( A_o = 0.123°C/\text{year} \).

The authors also studied the difference in the AATM distributions above the Atlantic and Pacific Oceans (AO and PO) in the temperate zone of the NH. In the lower troposphere the AT above the Atlantic was higher than above the Pacific Ocean. Thus, at the level of 1000 hPa the AT above the AO was 11.2°C, while above the PO it was 9.4°C, the difference was 1.8°C. The same picture was observed up to the level of 400 hPa, where the air temperatures equalized, making -30°C; then up to the level of 5 hPa (upper stratosphere) the AT above the AO was lower than above the PO, which was explained by the circulation factors only. Particularly, a high Aleutian anticyclone was located in the northern part of the PO. When shifting to the North Pole it caused sudden winter stratospheric warmings. In the stratopause area and lower mesosphere the AATMs above the Atlantic were again slightly higher than the air temperature above the Pacific Ocean. Vertical alternation of the layers with different temperature indexes took place. As for tendencies of the AT variations with time, in the troposphere warming was observed above the waters of the both oceans, LTS>0, at the same time at the level of 1000 hPa \( A_{AO} = 0.026°C/\text{year} \), \( A_{TO} = 0.014°C/\text{year} \). In the stratosphere LTS<0 (the cooling process), and only near the stratopause and lower mesosphere warming was registered again, as in the troposphere. At the level of 0.51 hPa the AT increase rate above the AO was 0.136°C/year, while above the PO it was 0.112°C/year.

The seasonal AT cycle was rather well marked above the oceans. Thus, at the level of 1013 hPa the AT above the AO was 7.7°C in winter and 17.3°C in summer, above the PA the AT was 6.2°C in winter and 15.4°C in summer. In this way, in close proximity to the water the air above the Atlantic was warmer than above the Pacific Ocean. At the same time, in winter up to the level of 400 hPa the AT above the AO was higher than above the PO; in the upper troposphere and stratosphere up to the level of 5 hPa the AT above the PO was higher than above the AO. In the upper stratosphere and lower mesosphere, on the contrary, the atmosphere above the PO was colder than above the AO. The lowest temperatures were registered in the lower stratosphere (70 hPa), where AT=-62.8°C above the AO, and AT=-56.9°C above the PO.

In summer in the lowest tropospheric layer (1013-850 hPa) the air in the Northern Atlantic was warmer than above the PO. Thus, at the level of 1000 hPa the AT above the AO was 16.1°C, while above the PO it was 14.1°C (the difference was 2°C). In the higher atmospheric layers, from the level of 700 hPa to 200 hPa, the AT above the AO was lower than above the PO.
In the whole stratospheric mass and lower mesosphere the atmosphere above the AO was warmer than above the PO. The LTSs above the both oceans were positive in the troposphere (up to AT₁₅₀), negative at higher levels, and >0 again in the lower mesosphere.

To estimate the degree of correlation between the neighbouring isobaric surfaces in the temperate zone, the authors calculated the coefficients of correlation between the air temperatures for the whole year, January and July. In the troposphere the correlations between the levels were close. They significantly weakened when passing through the tropopause, especially in summer (in July between the layers of 200 and 150 hPa r=0.615). In January in the stratosphere and mesosphere the inter-level correlations were also strong, while a number of cases were registered in July in the upper stratosphere and lower mesosphere when the correlation coefficients were small. Thus, the temperature correlation between the levels of 7 and 5 hPa was 0.097, i.e. it was non-significant. Due to an active dynamic interaction in winter the atmosphere was more homogeneous than in summer when radiation and photochemical factors started playing an important part.

The vertical autocorrelation coefficients calculated for the temperature in January and July demonstrated the following: (Figure 3): in January the correlation coefficient values (r) rapidly decreased in the troposphere. When passing through the tropopause, the r sign changed, but, as a whole, the correlations between the tropospheric and stratospheric levels were rather weak; the r value changed from -0.2 to 0.2. The situation drastically changed in summer. In the troposphere the correlations between the levels were strong. When reaching the tropopause, the r coefficient decreased from 1 to 0.8, then, when passing through the tropopause, this value dramatically decreased and changed the sign with altitude. The correlation between the troposphere and stratosphere was wavelike, depending on the altitude. Remarkable were the levels of: 20 km, where r=-0.6, 33 km, where r=0.4, 37 km (r=-0.5), and 50 km (r=0.6). As for the correlations in the (lower and upper) stratosphere, here in January the correlation coefficients smoothly decreased and changed the sign to negative at the level of 40 km. In July the correlations weakened with altitude, but mostly r>0. According to the data in Figure 1, the warm and cold atmospheric layers alternated. The correlation coefficients calculated for January confirmed this statement. Thus, the r sign change at the level of 40 km evidenced that the processes contributing to stratosphere warming could lead to cooling of the mesosphere.

The wavelike behaviour of the parameter r was connected with wavelike properties of certain processes of fluctuation transfer from the lower to upper layers. Thus, [3] reported the wave nature of vertical temperature deviations from the mean state. Papers [2, 9, 10] studied the wave activity in the troposphere-stratosphere of the Northern Hemisphere in winters throughout 1979 – 2016. Here the authors present findings for the identified statistical correlations between the climate variability indexes and the Hayashi spectrum components [5] of selected waves propagating eastwards (E) and westwards (W), and stationary waves (S).
Figure 3. Coefficients of correlation between the air temperature at a certain level and the air temperature at all overlying levels within the period (1979-2016) in the troposphere and stratosphere of the temperate zone of the Northern Hemisphere in January and July.
The correlation distributions of calculations that were made, as well as processing of 1979-2016 data, permitted making a conclusion that the authors managed to build a half-empiric model of height-latitude distribution of stationary and (eastwards and westwards) propagating waves. The closest positive correlations were discovered between E waves and the AO index in the troposphere of the temperate latitudes and the major part of the stratosphere of the extra-tropical latitudes, with the maximum value (0.7-0.8) registered at 55-60° N in the lower stratosphere. The correlation distributions of W waves were of the opposite nature to a certain degree: negative correlations (-0.7-0.8) in the troposphere to the north of 60° N and positive (0.7-0.8) in the troposphere of the low latitudes.

The use of the spatiotemporal Hayashi spectrum for the study of meteorological fields in the troposphere and stratosphere demonstrated their efficiency and ability to identify correlations with the physical mechanisms of processes taking place in the atmosphere. The latter fact proves that the Hayashi method can be successfully used for diagnostic studies of the general atmospheric circulation. The calculations that were made, as well as processing of voluminous calculation and graphic material, its analysis and summarization permitted making a conclusion that the authors managed to build a half-empiric model of height-latitude distribution of stationary and (eastwards and westwards) propagating waves. The closest positive correlations were discovered between E waves and the AO index in the troposphere of the temperate latitudes and the major part of the stratosphere of the extra-tropical latitudes, with the maximum value (0.7-0.8) registered at 55-60° N in the lower stratosphere. The correlation distributions of W waves were of the opposite nature to a certain degree: negative correlations (-0.7-0.8) in the troposphere to the north of 60° N and positive (0.7-0.8) in the troposphere of the low latitudes.

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propagating components of the spectrum of climatic thermodynamic fields in the troposphere and stratosphere of the Northern Hemisphere.

Conclusions
1. The vertical LTS profiles plotted for the whole temperate zone, land and ocean show a vertical atmosphere stratification of air temperature variations. A trend of temperature rising in the troposphere, decreasing in the lower and middle stratosphere, and again rising in the area of stratosphere has been found.

2. The influence of the oceanic surface on the air temperature is noticeable up to the level of 200 hPa. No influence of the underlying surface has been observed on the higher levels.

3. The vertical correlations in the temperature field evidence a sign change in passing through the tropopause and a wave nature of the meteorological parameter fluctuations, especially in winter, when the wave processes intensify.

4. A correlation between the wave activity in the stratosphere and the atmospheric circulation indexes (Arctic Oscillation, zonal wind index at the level of 50 hPa) has been revealed.

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