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Current Climatic Changes in the Troposphere, Stratosphere, and Mesosphere, and Inter-Layer Interactions

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Abstract. Using new data about near-surface air temperature in the Northern Hemisphere (from 1850 to 2018) and ERA5 reanalysis of temperature distributions up to a height of 80 km (from 1979 to 2018), the authors calculate and analyse mean and root-mean square deviations, linear trend slope coefficients, and low-frequency components of temperature at various levels and latitude zones. A 60-year quasi-cyclic of the temperature near the Earth’s surface has been discovered. The authors evaluate the rates of tropospheric warming and stratospheric cooling observed over the last decades. Much attention is given to the search for correlations between the atmospheric layers, thermal regime characteristics, and the Arctic Oscillation. A predictive valuation of temperature oscillations is obtained for Kazan until 2051, taking into account distant relationships revealed between the temperature status of the ocean surface and the region considered.

1. Introduction

Over recent years interest in dynamic and physico-chemical processes taking place in the thick atmospheric mass (up to an altitude of 80 km) has been growing thanks to intensive development of computers and information technologies, and the invention of “Big Data”. At the same time, the ocean surface temperature (OST) exerts certain influence on the circulation processes observed in the lower stratosphere. Thus, strong correlations have been revealed in paper [3] between the dynamics of the stratospheric vortex above the Arctic and the variability of OST anomalies in the northern part of the Atlantic and Pacific Oceans. Correspondingly, explosive winter stratospheric warmings are taken into consideration when studying the interaction between the troposphere and stratosphere. As before, the wave mechanism is used to explain the correlations between the atmospheric layers. Simulation exercises with general atmospheric circulation (GAC) models helped to identify new details in the physical mechanism of interaction between neighbouring layers and construct a general Earth system model [1,2].

The present research is a follow-up of the previous papers of the authors [6-8, 10-14], which are devoted to peculiar features of the thermodynamic processes both in the troposphere of the Northern Hemisphere in the 19th – 21st centuries, and in the higher atmospheric layers (up to 100 km). The objectives of this paper are: to study the distribution of the air temperature (AT) characteristics up to a level of 80 km; evaluate the impact on the thermal state of the troposphere and lower stratosphere by the circulation factor and the OST status; construct a predicative physical-statistical model for long-term regional forecasting of the air temperature near the Earth’s surface up to 2051.
The air temperature time series formed for 1850–2018 at regular latitude-longitude geographic grid points by the Climatic Research Unit of the University of East Anglia and Hadley Centre [5,9] (CRU data) were used as raw data. Monthly air temperature (AT) means for the Northern Hemisphere (NH) were used to characterise the processes taking place in the troposphere, stratosphere, and mesosphere (up to 80 km). They were drawn on 51 isobaric surfaces at the geographic grid points 1°x1° (latitude x longitude) for 1979-2018, as presented in ERA5 reanalysis. Correspondingly, long-term AT series for Moscow, Kazan, and Tomsk were used to establish correlations with the OST. The ocean surface temperature was taken at the grid points with the step 2x2°, which permitted identifying synchronous and asynchronous correlations between the ocean temperature and the near-surface AT, and to set up prognostic regression equations.

Near-surface temperatures kept in CRU and ERA5 data pools were compared. To make this comparison, the annual near-surface air temperature means, as well as the winter and summer AT means in the Northern Hemisphere were calculated for 1979-2018. Then the authors took their differences, built linear trends, and found the determination coefficients. High consistency was proven for all the above-listed parameters.

The mean values (norms), the mean square deviations (MSD) near the Earth’s surface and on 51 surfaces of the NH were calculated. The mean vertical profiles and distribution maps were plotted for the AT. The aforementioned manipulations permitted analyzing the processes observed in the troposphere, stratosphere, and mesosphere. In order to identify the spatial differences, the AT means were calculated for the polar (90-65° N), temperate (65-30° N), and tropical (30-0° N) zones of the Northern Hemisphere. Means in 3 sectors of the temperate zone (Atlantic-European, Asia-Pacific and American) were calculated. The monthly AT means were subjected to linear trend analysis and low-frequency filtration to pick out oscillations with a period exceeding 10 years. The linear trend slope coefficients (LTSCs) and the determination coefficients for the linear trend and low-frequency component (LFC) with a period exceeding 10 years were calculated as well. The vertical correlation coefficients were calculated to evaluate the correlations between the levels.

The Hayashi spectrum components were calculated to evaluate the wave activity and the correlations with the climatic and geophysical indices.

2. Results
Let us study key features of the climate pattern behaviour in the atmospheric mass from the Earth’s surface up to an altitude of 80 km. The multiyear curve of the annual air temperature mean (AATM) constructed according to CRU data for 1850-2018 tends to rise in the Northern Hemisphere (Figure 1). In Figure 1 the LFC depicts global long-period oscillations caused by natural forces. The positive AATM anomaly, intensively growing in the NH from 0.1 to 0.8°C from the late seventies, is explained by the greenhouse effect. Figure 1 vividly presents a quasi-60-year oscillation of the AT rise with the amplitude build-up, which is determined by taking the year-on-year first-order differences of the LFCs. Only at the very end of the period the temperature variation slightly slacks up. The global climate warming has resonance for certain Russian regions, in particular, for the Middle Volga Region.

In order to identify fundamental patterns of climatic changes in the Volga Federal Region (VFR), the authors of the paper have studied the curve of the annual near-surface air temperature mean averaged for the territory of the VFR for the period between 1955 and 2018 and two subperiods: 1955–1999 and 2000–2018 (Table 1).

One can see from Table 1 and Figure 2a that a dramatic jump in the temperature mean (by 1.2°C) was registered in the early 21st century. At the same time, interannual temperature variability halved, while the minimum value of the annual air temperature mean (AATM) sharply rose from 0.55°C to 3.58°C. All these facts evidence a significant change in the thermal regime of the region at the turn of the century. As this takes place, the contribution of the global factor to the regional temperature variation is 37% in winter and 23% in summer.
Figure 1. Multiyear curve of annual air temperature mean in the Northern Hemisphere, 1850–2018.

1 – basic series, 2 – LFC with a period exceeding 30 years, 3 – first-order LFC differences.

Table 1. Characteristics of annual air temperature mean in the Volga Federal Region.

<table>
<thead>
<tr>
<th>Period, years</th>
<th>Mean value, °C</th>
<th>MSD, °C</th>
<th>Maximum, °C</th>
<th>Minimum, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1955–2018</td>
<td>3.49</td>
<td>1.04</td>
<td>5.49</td>
<td>0.55</td>
</tr>
<tr>
<td>1955-1999</td>
<td>3.14</td>
<td>1.00</td>
<td>5.49</td>
<td>0.55</td>
</tr>
<tr>
<td>2000–2018</td>
<td>4.34</td>
<td>0.47</td>
<td>5.33</td>
<td>3.58</td>
</tr>
</tbody>
</table>

Figure 2b illustrates the transition of the thermal regime from one state to another and linear trends of the AATM in the period being studied.

Thus, for the whole period the linear trend slope coefficient (LTSC) is equal to 0.32°C/10 years (the adjusted coefficient of determination R2=31%, the trend determination reliability is over 0.99). In the earlier period, from 1955 to 1999, the LTSC=0.23°C/10 years (R2= 5%, the reliability is 0.96). In the latest period, from 2000 to 2018, the LTSC=0.08°C/10 years (R2= 0, the reliability is 0.33). It means that no sizeable rise in the annual air temperature mean has been observed over the 21st century.
Changes in the regional climate had a substantial impact on the time variation of intensive AT anomalies. Thus, in the 21st century (2000–2018) the number of negative AT anomalies decreased, while the number of positive anomalies grew in all months of the year in comparison with the period between 1955 and 1999. Winters became warmer and snowier.

Let us study the thermodynamic processes in the higher atmospheric layers. Table 2 presents a vertical distribution of long-term air temperature means \( \text{Av} \) (°C) and linear trend slopes \( \text{A} \) (°C/year) on 51 isobaric surfaces. The data averaged for the NH both for January and July show \( \text{Av} \) temperature fall with altitude in the troposphere, its rise in the stratosphere, and a new fall in the mesosphere.

<table>
<thead>
<tr>
<th>( P ) (hPa)</th>
<th>( H ) (km)</th>
<th>Year (I-XII)</th>
<th>Summer (VI-VIII)</th>
<th>Winter (XII-II)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( ^{a} \text{Av} )</td>
<td>( ^{b} \text{Rms} )</td>
<td>( ^{c} \text{A} )</td>
</tr>
<tr>
<td>1000</td>
<td>0.1</td>
<td>16.17</td>
<td>0.32</td>
<td>0.0255</td>
</tr>
<tr>
<td>975</td>
<td>0.3</td>
<td>14.65</td>
<td>0.32</td>
<td>0.0248</td>
</tr>
<tr>
<td>950</td>
<td>0.5</td>
<td>13.38</td>
<td>0.30</td>
<td>0.0232</td>
</tr>
<tr>
<td>925</td>
<td>0.7</td>
<td>12.31</td>
<td>0.29</td>
<td>0.0222</td>
</tr>
<tr>
<td>900</td>
<td>1.0</td>
<td>11.27</td>
<td>0.28</td>
<td>0.0216</td>
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<tr>
<td>875</td>
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<td>10.25</td>
<td>0.28</td>
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<tr>
<td>850</td>
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<tr>
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<td>800</td>
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<td></td>
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<td>600</td>
<td>550</td>
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<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Av</td>
<td>3.0</td>
<td>3.6</td>
<td>4.2</td>
<td>4.9</td>
</tr>
<tr>
<td>Rms</td>
<td>0.27</td>
<td>0.27</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>A</td>
<td>0.0185</td>
<td>0.0177</td>
<td>0.0167</td>
<td>0.0158</td>
</tr>
<tr>
<td>C</td>
<td>60</td>
<td>54</td>
<td>50</td>
<td>47</td>
</tr>
<tr>
<td>³C</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>³C</td>
<td>0.0172</td>
<td>0.0168</td>
<td>0.0160</td>
<td>0.0152</td>
</tr>
</tbody>
</table>

a Av = mean value, °C.
b Rms = mean square deviation, °C.
 c A = linear trend slope coefficient, °C/year.
d R'L = linear trend determination coefficient (%).
As one can see from Table 2, a marked annual cycle is registered at all levels. The largest amplitude of annual oscillations is observed in the troposphere and mesosphere. In the troposphere, on the whole, the temperature rises both in winter and summer (A>0). Thus, at the level of 500 hPa A=0.0165°C/year in winter and A=0.0157°C/year in summer. In the stratosphere, cooling is observed, as at the level of 10 hPa A= -0.0176°C/year in winter and A= -0.0145°C/year in summer. In the mesosphere, where the lowest air temperatures are registered (at the level of 0.01 hPa (80 km) the AT drops to -91.82°C in summer), the LTSCs become positive. At the level of 0.01 hPa A=0.1121°C/year in winter and A=0.2339°C/year in summer. Thus, we have obtained atmosphere stratification by behaviour of the thermal regime trend. Taken together, the LTSC distribution corresponds to the global warming theory, however, there are perceptible differences conditioned upon the radiation and dynamic factors between the year seasons and latitudinal zones.

The cooling tendency is more pronounced in the summer stratosphere than in the winter stratosphere, since during this period the vertical wave action is weak and no sudden stratospheric warmings (SSWs) typical for winters and resulting in the air warming in the polar zone occur. Furthermore, in summer at high altitudes the behaviour of the processes is more homogeneous, and owing to the ozone screen interaction with ultraviolet radiation the air masses warm up in the middle stratosphere, and the temperature trends vertically change their sign. In the mesosphere, the temperature rise is more noticeable in summer than in winter. The LTSCs in summer are larger than in winter. Seasonal heterogeneity is observed in the air temperature trend.

In the troposphere, the MSD has low values both in winter and summer (less than 0.4°C). In the stratosphere, the interannual oscillations intensify and reach their maximum in the mesosphere, where the MSD attains 5°C in summer, which is an evidence of its unstable behaviour.

To identify the geographical and seasonal peculiarities in long-term variations of the air temperature, the authors drew vertical sections for the multiyear curve of the first-order differences of LFCs with a period exceeding 10 years AT (°C/year) for the polar, temperate, and tropical zones (1979–2018). An analysis of the results demonstrates that the most sophisticated picture is observed in the January polar zone, where starting from a level of 10 hPa and higher significant interannual AT variations occur, and cooling and warming centres alternate, while in July the situation is less disturbed.

At the same time, the AT rise tendency prevails both in the winter and summer troposphere. In the temperate and tropical zones the section structures are similar: the temperature increment prevails in the troposphere in the seasons concerned, and starting from an altitude of 20 km and higher strongly pronounced quasi-cyclic AT oscillations prevail. The above-described phenomenon is especially noticeable starting from a level of 40 km, where considerable temperature drops registered between 1979 and 2000 give place to the temperature rise. In the latest period (2000–2018) in the upper atmospheric layers (at 60 km and higher) cooling is registered everywhere except for the winter polar zone.

The Asia-Pacific region stands out from the other regions of the temperate zone, since in winter in a layer of 10–40 km the air temperature there is higher by 6.5°C than in the neighbouring Atlantic-European and American sectors.

Two approaches were used to estimate the vertical correlations between the AT at different levels. In the first one, the correlation coefficients (r) were calculated between the AT of a concrete level and all upper levels. In the second approach, the calculations were made between the neighbouring surfaces, which allowed one to identify the geographical peculiarities of the correlation nature. The calculations performed have revealed that in the lower troposphere the AT correlations between the neighbouring levels throughout the Northern Hemisphere are close both in January and July (r>0.9), in the upper troposphere between levels of 300 and 250 hPa in the polar and temperate zones they considerably weaken in January (r~0.3), while in July the correlations are weak in the polar zone due to the influence of the tropopause. In the middle stratosphere (between the levels of 20 and 10 hPa), the correlations significantly weaken in January at the subtropical latitudes. However, in the polar zone, where in winter stratospheric warmings are registered and wave activity is high, the correlation
is strong: $r=0.9\div1.0$, while in July, on the contrary, $r$ has minimum values ($\sim0.3$) in the polar zone. Thus, spatial heterogeneity is manifested. At the higher stratospheric levels, the correlations between the surfaces strengthen all over the hemisphere ($r=0.9$). In such a way, the heterogeneous nature of the interlayer interaction has been established: in the troposphere the correlations are tight, in the tropopause region and in the layer of 25-45 km they weaken, and then strengthen again in the upper stratospheric layers and lower and the middle mesosphere ($r>0$) (Figure 3).

![Figure 3. Temperature correlation coefficients (1979–2018) at neighbouring levels in a layer of 0.1 – 80 km in three latitudinal zones of the NH: polar zone (left), temperate zone (centre), and tropical zone (right).](image)

It is a well-known fact that circulation processes play an important role in variations of the temperature conditions. For this reason, the correlation coefficients for 27 levels were calculated for winter, summer, and the whole year to reveal the correlation between the air temperature oscillations and the Arctic Oscillation (AO). It has been found that the correlation coefficients are nonsignificant ($r<0.32$) if we correlate the temperature averaged throughout the NH with the AO index. The strongest correlation was identified for the polar zone in winter. At an altitude of 10 km $r=-0.60$, in summer a strong correlation with the AO index ($r=0.32$) is detected at the levels of 11-12 km and 30 km. In the temperate zone $r=0.56$ in the upper troposphere in winter. It is well-known that when planetary Rossby waves propagate from the troposphere to the stratosphere, winter stratospheric warmings occur, resulting in the circumpolar cyclone breakdown. As the AO manifests itself mainly in winters, the correlation coefficients for summer turned out to be nonsignificant.

Long waves are referred to the most important components of the atmosphere dynamics [8]. There are waves propagating to the east (E), west (W), and also stationary waves (S). Using the data about the AT at the grid points $1\times1^\circ$ in a layer of 1000–1 hPa, the authors calculated the Hayashi wave spectra characteristics for the zonal waves numbered 1 through 10 for November – March, 1979–2016. Plotted thereafter were the height-latitude sections of the coefficients of correlation between the E, W, S wave intensity and the AO index. It has been revealed that height-latitude distributions of the correlations between the components and the AO index significantly differ for W and E waves. The strongest positive correlations were found between E waves and the AO index in the troposphere of the temperate latitudes and the major part of the stratosphere at the extra-tropical latitudes, with maximum values ($0.7–0.8$) reached at 55–60°N in the lower stratosphere. The correlation distributions for W waves are of the opposite nature, to a certain extent: the correlations are negative ($-0.7\sim0.8$) in the troposphere to the north of 60°N and positive ($0.7–0.8$) in the troposphere of the low latitudes.
The estimates obtained are consistent with the fact that during the positive AO phase E waves develop, the zonal circulation strengthens, and the stratosphere becomes colder. During the negative AO phase the zonal circulation weakens, and the developed W waves promote the wave energy transmission to the stratosphere and foster the stratospheric warmings.

Since the radiation and circulation factors, along with the underlying surface state, refer to the key climate forcing factors, to assess the impact of the underlying surface (land, ocean) on the thermal regime of the atmosphere the authors calculated the air temperature characteristics over the land and ocean. These calculations demonstrate that in winter warming is registered in the troposphere and over the land and ocean, while in the stratosphere cooling is observed. In the lower troposphere it is warmer over the land than over the ocean in summer. In summer the linear trend slope coefficient over the land significantly exceeds that over the ocean. Thus, in the near-surface layer over the land the LTSC is equal to 0.035°C/year, while over the ocean it is 0.011°C/year, which means that the warming is more noticeable over the land than over the ocean. In the stratosphere the nature of the underlying surface has no impact.

Taking into account the significant role played by the ocean in the climate system, as well as its impact on the weather and climate, in this paper the authors analysed asynchronous correlations of long-period oscillations of the annual air temperature mean (AATM) in Moscow (1879-2016), Kazan (1854-2016), and Tomsk (1875-2016) with oscillations of the annual ocean surface temperature mean at points of the World Ocean geographic grid 2x2° (latitude x longitude) plotted for 1854-2016.

Distant relationships were evaluated by the best (maximum) asynchronous correlation coefficients between the OST at each individual geographical grid point and the AT at the stations with an AT delay of 0 to 36 years. At each studied point of the series of asynchronous correlation coefficients, the maximum coefficient was picked out, and the OST oscillation advance was fixed at the point relative to the subsequent AT oscillations at each of the stations. The ultimate correlation shift was set considering the fact that according to [15] the propagation time for the temperature variations in the ocean within the hemisphere is 30 years.

The study has shown that long-period AT oscillations in Eurasia are, to a great extent, the consequence of global changes in the climate system, whose sources can be found in a special region of the atmosphere interaction with the Southern Ocean in the area of the Antarctic circumpolar current of westerly winds. This assumes that the long-range transport of the temperature oscillations is performed by the World Ocean’s water cycling system, known under the name of Broecker conveyor [4].

The delay in the air temperature oscillations at the stations is 30-35 years in Moscow and Kazan, and 35-45 years in Tomsk. The intensity of atmospheric interaction with the Southern ocean is strengthened by natural physico-geographical conditions of the circumpolar ocean current.

The detected delay in the fluctuation transmission has made it possible to derive asynchronous regression equations, allowing one to calculate long-period prognostic temperature oscillations at stations for the coming decades. Figure 4 presents results of a long-term AATM forecast, according to which in 2019–2025 the temperature in Kazan will be lower than the mean value (5.1°C) by 0.3–0.5°C, in 2028–2037 it will rise above this norm by 0.4–0.5°C, and by 2045 the AT will become 0.3 – 0.4°C lower than the norm again.
Figure 4. Annual temperature mean in Kazan, $T$, according to observation data for 1890-2016 (triennially smoothed) and temperature in Kazan calculated by the regression equation for the period until 2051 (Tr).

Conclusions

A trend towards a rising surface average annual air temperature in the Northern Hemisphere has been revealed. In the most active phase (from the 1970s to 2018) it increased by 0.7°C.

A quasi-60-year variation was detected in the long-term Northern Hemisphere's average annual air temperatures, whose statistical significance cannot be estimated due to the short observation range (169 years).

In the Volga Federal Region at the beginning of the 21st century, the average annual temperature increased by 1.2°C, with a minimum value rising sharply from 0.55°C to 3.58°C. The contribution of global factors to the regional temperature change in winter was 37%, and in summer 23%.

According to the above linear trends in the average annual temperature, its growth slowed greatly from 2000 to 2018 compared to the period from 1955 to 1999 (the LTSC decreased from 0.23°C/10 years to 0.08°C/10 years).

On average, in the Northern Hemisphere the linear trend slope coefficient is positive in the troposphere (1000-200 hPa) both in winter and summer; starting from a surface of 100 hPa and up to 0.5 hPa the stratosphere cools (LTSC < 0). According to the ERA5 data, in the mesosphere from a level of 0.1 hPa a warming is observed again (with a significant temperature rise from 1995 to 2015).

The strongest air cooling in the stratosphere is observed in the layer of 35 to 40 km in winter and in a layer of 35 to 45 km in summer.

The influence of the underlying surface type (land, ocean) is powerful up to a surface of 200 hPa. At the same time, in the troposphere the air temperature increase over the land significantly surpasses its increase over the ocean (in July the LTSC is equal to 0.035°C/year and 0.011 °C/year, respectively). From year on year these differences persist (0.037 and 0.017 °C/year).

According to the above analysis of the first-order differences of the LFCs with a period exceeding 10 years, in the upper stratosphere and lower mesosphere the temperature rise or drop centres are registered in winter with a cyclicality of about 10 years.

A correlation analysis revealed a heterogeneous nature of the statistical correlations in the temperature field: the correlations between the layers sharply weaken in the region of tropopause both in winter and summer. In the lower stratosphere, the vertical correlations in the temperature field
strengthen, and in the layer from 25 to 45 km the thermal processes are weakly correlated. According to the ERA5 data, a strengthening of the correlation is registered in the mesosphere.

In the summer period, negative correlations set in between the troposphere and lower stratosphere, which is an evidence of antiphase nature of the temperature variation.

According to the correlation analysis, in winter the Arctic Oscillation has the most powerful influence on the near-surface tropospheric layer (with a temperature increase) and the layer from 7 to 3 hPa in the stratosphere, where the temperature decreases.

During the positive AO phase, E waves develop, zonal circulation strengthens, and the stratosphere becomes colder.

During the negative AO phase, the zonal circulation weakens, and the developed W and S waves promote wave energy transmission to the stratosphere and foster stratospheric warmings.

A wave activity intensification has been discovered in the tropical troposphere and stratosphere (E, W, S waves), and the upper stratosphere (E, S waves) of the NH.

The distant relationships (with a delay of 30 to 45 years) identified between the regional ocean surface temperature variations in the area of Antarctic circumpolar current of westerly winds (a region near the Drake Strait) permitted running the prognostic AATM model until 2051.

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