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Lapse Rate Peculiarities in the Arctic from Reanalysis Data and Model Simulations

M. G. Akperov[a*], **I. I. Mokhov**[a, b], **M. A. Dembitskaya**[a],
M. R. Parfenova[a], **and A. Rinke**[c]

[a]*Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Pyzhevskii per. 3, Moscow, 119017 Russia*

[b]*Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow, 119991 Russia*

[c]*Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Telegrafenberg, A45, Potsdam, 14473 Germany*

**e-mail: aseid@ifaran.ru*

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Abstract—Monthly mean data of the ERA-Interim reanalysis (1979–2014) are used to estimate the lapse rate in the Northern Hemisphere high-latitude troposphere. The relationship between the lapse rate and surface air temperature T_s is analyzed in terms of interannual variability for different seasons. The study analyzes the ability of the HIRHAM5 regional climate model to simulate the features of lapse rate distribution in the Arctic troposphere and the parameter of its sensitivity to the variation in surface air temperature $d\ /dT_s$ that were derived from reanalysis data. The regional features of the link between the vertical stratification of tropospheric temperature and the Arctic Oscillation are revealed. The estimates obtained from reanalysis data and model simulations are especially significant as the Arctic climate has higher variability and sensitivity under global changes that is characterized by so called Arctic amplification.

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INTRODUCTION

The most rapid and significant climate changes are registered in the Arctic [6, 9]. Surface air temperature in the Arctic has risen since the end of the 19th century by more than two times quicker than in the whole Northern Hemisphere. In the recent three decades, it has increased by ~2 K in the Arctic and by ~0.8 K in the Northern Hemisphere [9].

The Arctic amplification characterizes a degree of more substantial climate changes in the high latitudes as compared with the lower latitudes and is associated with the impact of a number of climatic feedbacks [2, 25]. The Arctic amplification is favored by the dependence of heat radiation and albedo of the system on temperature, change in the vertical temperature stratification of the atmosphere, meridional heat transfer, water vapor (being the main greenhouse gas in the terrestrial atmosphere) content in the atmosphere, and cloudiness. The reduction of the extent and thickness of sea ice in the Arctic basin leads to increasing heat fluxes from the ocean to the atmosphere and to the change in the atmospheric stability and cyclone activity in the Arctic region [22].

The vertical temperature stratification of the troposphere is defined by a number of processes and factors including radiation and convective transport, general atmospheric circulation and its regional features, water vapor content. The tropospheric profile of temperature is rather well characterized by the mean lapse rate . The altitude-averaged tropospheric lapse rate varies both in time (its seasonal and interannual variability is registered) and in space (along the latitude and longitude) [4–8, 10, 23].

The changes in the vertical temperature stratification of the atmosphere (in particular, in the vertical gradient) and the changes in its static stability are associated, in particular, with the changes in convective atmospheric processes, in the regimes of cloudiness and of eddy and wave activity [11–16]. The generation of extratropical cyclones including the polar latitudes is associated with the manifestation of baroclinic instability and depends both on the meridional temperature gradient and on atmospheric stratification. The climate sensitivity to various impacts depends much on the climatic feedback through the tropospheric lapse rate [1, 2, 4, 5, 7, 10, 12–14, 17, 21, 23–26].

The major climatic characteristic is surface air temperature T_s. Therefore, the sensitivity of climate to various natural and anthropogenic impacts can be described by surface temperature variations. The relationship between and T_s, in particular, the sensitivity of to the variations in T_s allows assessing the climatic feedback through the tropospheric lapse rate .

One of the key problems of the analysis of the temperature regime in the polar latitudes is the low density of the weather station network which affects the quality of analyzed data. The research capabilities are considerably enhanced by satellite observations, but they do not allow obtaining all data required to analyze cyclone activity characteristics and their variability. The most complete dataset with a sufficient spatial and temporal resolution can be obtained using climate models, in particular, regional models for the Arctic. Reanalysis data are formed based on the modern models with the assimilation of available observational data. At present, there are different global and regional reanalysis systems used to study climate variability in the polar latitudes. The objective of the present paper is to analyze the features of the lapse rate in the Arctic troposphere and its sensitivity to surface air temperature variations based on reanalysis data and to assess the possibility of simulation of the revealed features and trends using the regional climate model.

DATA AND METHODS

Monthly mean data of the ERA-Interim reanalysis (1979–2014) for the Northern Hemisphere high latitudes (60 –90 N) [19] including those for winter (December–February) and summer (June–August) were used to calculate the tropospheric lapse rate . The results of corresponding calculations with the HIRHAM5 regional climate model (RCM) [20] were taken to assess the ability of modern climate models to simulate the features of temperature stratification in the Arctic troposphere.

The mean values of for the troposphere were determined similarly to [10]: based on the linear regression using the monthly mean and average annual values of temperature at standard atmospheric levels from the underlying surface to the tropopause level. The tropopause was determined as the lowest level above 450 hPa, where the lapse rate decreases to 2 C/km provided that the mean lapse rate in the overlying 2-km layer does not exceed 2 C/km [27].

Reanalysis data for 28 levels were analyzed: 1000, 975, 950, 925, 900, 875, 850, 825, 800, 775, 750, 700, 650, 600, 550, 500, 450, 400, 350, 300, 250, 225, 200, 175, 150, 125, 100, and 70 hPa. The results of model simulations were performed at 15 levels: 1000, 975, 950, 925, 900, 875, 850, 800, 700, 600, 500, 300, 250, 200, and 70 hPa. Data on surface air temperature T_s were also used for the analysis. The spatial resolution of reanalysis data was 0.75 , the model resolution was 0.25 . The model results were extrapolated to the coarser grid (0.75) during the comparative analysis.

Monthly mean data on the Arctic Oscillation index were also used [29].

The statistical significance of the results (at the significance level $p < 0.01$) was assessed using the *t*-test.

RESULTS

Figure 1 presents the mean distributions of for winter and summer in 1979–2014 based on the ERA-Interim reanalysis data and model simulations (RCM HIRHAM5) for the Northern Hemisphere high latitudes. According to the ERA-Interim data, the mean lapse rate varies from 4.7 to 5.3 K/km in winter and from 5.3 to 6.1 K/km in summer (Figs. 1a and 1b). According to the model simulations, the lapse rate values are slightly smaller than analogous values from reanalysis data. The difference between them is about 0.2 K/km in winter and varies from 0.03 (in the subpolar latitudes) to 0.18 K/km (in the polar latitudes) in July. One of the reasons for the decrease in and for the increase in its standard deviation with the latitude increase is temperature inversions in the higher latitudes. According to [18], surface inversions favor the intensification of the Arctic amplification, in particular, in winter and the formation of the positive climatic feedback.

Figure 2 presents the spatial distributions of the tropospheric lapse rate and respective standard deviations for winter and summer derived from the ERA-Interim reanalysis data and HIRHAM5 simula-

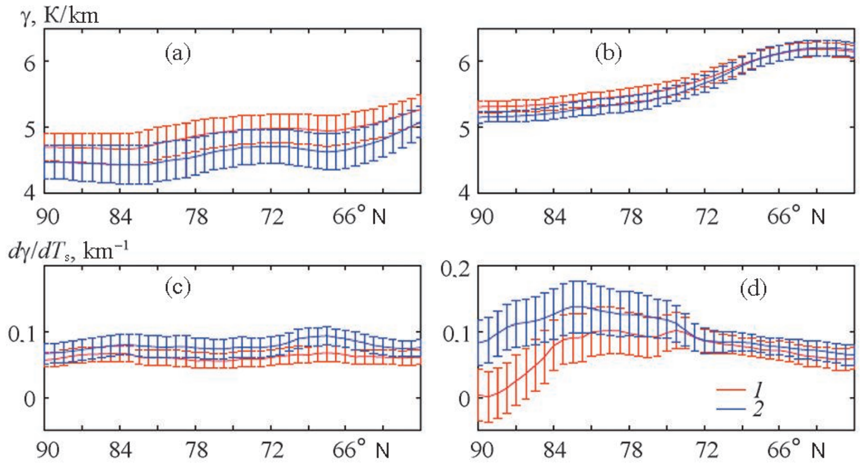

Fig. 1. The latitudinal dependence of (a, b) the lapse rate γ and (c, d) the parameter of its sensitivity $d\gamma/dT_s$ to variations in surface air temperature T_s for (a, c) winter and (b, d) summer derived from (*1*) reanalysis data and (*2*) model simulations for the period of 1979–2014. The vertical segments characterize interannual standard deviations for different latitudes.

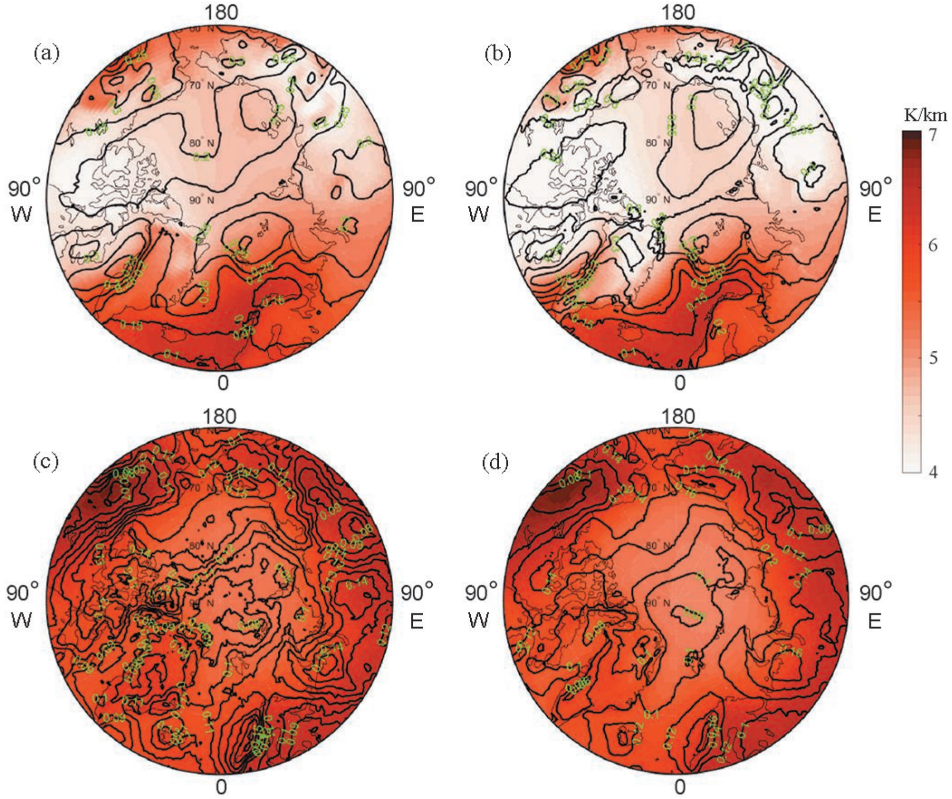

Fig. 2. The spatial distribution of the lapse rate γ (the color scale) for (a, b) winter and (c, d) summer from (a, c) the ERA-Interim reanalysis data and (b, d) RCM HIRHAM5 simulations for the period of 1979–2014. The numerals near the black curves characterize interannual standard deviations (K/km).

tions for the Northern Hemisphere high latitudes for the period of 1979–2014. The coefficients of spatial correlation R for the lapse rate calculated using reanalysis data and model simulations are statistically significant ($R = 0.98$ for winter and $R = 0.99$ for summer). In general, the model rather accurately simulates the spatial features of the standard deviation of the tropospheric lapse rate in the interannual variability as compared to ERA-Interim data for both seasons ($R = 0.95$ for winter and $R = 0.93$ for summer).

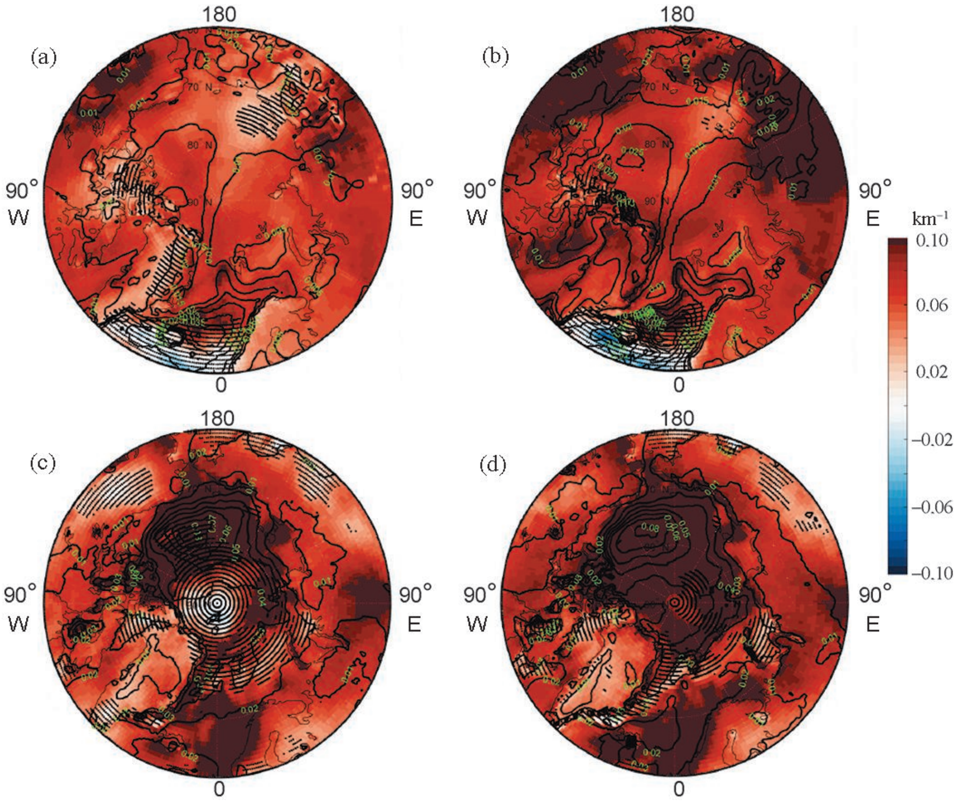

Fig. 3. The spatial distribution for the parameter of the sensitivity (the color scale) of values to variations in surface air temperature T_s for (a, b) winter and (c, d) summer derived from (a, c) the ERA-Interim reanalysis data and (b, d) RCM HIRHAM5 simulations in the interannual variability for the period of 1979–2014. The numerals near the black curves characterize interannual standard deviations. The zones of statistically insignificant changes are marked with the dots.

The maximum values of (~6.5 K/km) are registered in winter over the Atlantic sector of the Arctic, where the highest values of surface air temperature are observed (Fig. 2a), and the minimum values are registered over the continents, in particular, over North America and Eurasia both from reanalysis and model data (Fig. 2b). In general, in summer the values of are higher than in winter. In summer, over the land they are higher (~7 K/km) than over the Arctic basin (Figs. 2c and 2d); in winter, the “tongue” linked to the North Atlantic effects is manifested in the Arctic latitudes (Figs. 2a and 2b).

The coefficients of spatial correlation for the values of $d\ /dT_s$ derived from reanalysis data and model simulations (Fig. 3) are statistically significant ($R = 0.74$ for winter and $R = 0.66$ for summer). In general, the model also rather well simulates the standard deviation for $d\ /dT_s$ in the interannual variability as compared to the ERA-Interim data for both seasons ($R = 0.93$ for winter and $R = 0.94$ for summer). According to Fig. 3, the correlation between the interannual variation in and T_s is positive over most of the Arctic based on both types of data. The negative correlation between and T_s in winter is typical of the Atlantic sector of the Arctic, but it is statistically insignificant. In summer, this correlation is positive everywhere in summer. The statistically insignificant correlation between and T_s was revealed over the Arctic center based on reanalysis data, and it is not manifested for model data simulations. The values of $d\ /dT_s$ derived from reanalysis data are much smaller than those based on model simulations (Figs. 3c and 3d), and the maximum difference between them is 0.015 km^{-1} in winter. In summer, the differences increase with the latitude growth and reach about 0.1 km^{-1} (near the pole). It should be noted that the negative values of $d\ /dT_s$ detected over the ocean are typical of the dependence of the moist-adiabatic lapse rate on temperature.

The connection between the vertical temperature stratification in the Arctic troposphere and the Arctic Oscillation was also revealed. In winter, the highest positive correlation ($R > 0.6$) was revealed over the high latitudes in Eurasia. In summer, the negative correlation over the Arctic basin (with the correlation coefficient of ~0.7) and the positive correlation over the Arctic and subarctic regions of the Northern Hemisphere were registered.

The positive values of $d\ /dT_s$ characterize the positive climatic feedback through the lapse rate. Such feedback increases the sensitivity of surface temperature regime and indicates the decrease in the static stability of the troposphere under the global warming near the surface and in the troposphere [10]. This facilitates the increase in the cyclone activity, in particular, in the Arctic region, whereas the decrease in the meridional temperature gradient between the high and middle latitudes favors the cyclone activity decline [3, 13, 14, 28]. The competing role of these factors may lead to various changes in the cyclone activity in the Northern Hemisphere high latitudes.

CONCLUSIONS

The regional features of lapse rate in the Northern Hemisphere high-latitude troposphere were revealed for different seasons (including winter and summer) based on the ERA-Interim reanalysis data for 1979–2014. The sensitivity of lapse rate to the surface air temperature variations $d\ /dT_s$ was assessed. The values of derived from the ERA-Interim data are minimum in the polar latitudes (~4.7 K/km in winter and ~5.3 K/km in summer) and generally increase with the latitude decrease under the corresponding rise of surface air temperature (reaches 5.3 K/km in the subpolar latitudes in winter and 6.1 K/km in summer). The estimates of $d\ /dT_s$ derived from the reanalysis data in the interannual variability are positive over most of the Arctic. The negative correlation between and T_s was obtained in winter for the European sector of the Arctic and in summer for the Arctic center.

We analyzed the ability of the HIRHAM5 regional climate model to simulate the regional features of the lapse rate in the Arctic troposphere and its sensitivity to the surface air temperature variations (these features were derived from reanalysis data). It was found that the regional model rather accurately simulates the spatial features of the distribution of lapse rate and its changes derived from the ERA-Interim reanalysis data. The lapse rate values simulated with the model are slightly smaller than those based on the reanalysis data. The estimates of $d\ /dT_s$ based both on model and reanalysis data in the interannual variability are positive over most of the Arctic. No regional features with the negative estimates of $d\ /dT_s$ derived from reanalysis data were revealed for the model simulations. The estimates of $d\ /dT_s$ based on model simulations are generally slightly higher than those from reanalysis data.

The new results of the comparison of model simulations and reanalysis data are useful to determine the interrelation between the climate change in the Arctic latitudes and on the whole globe and to assess the degree of adequacy of model simulations of climate changes.

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