SCIENTIFIC JOURNAL
EARTH'S CRYOSPHERE

*Earth`s Cryosphere*, 2014, vol. XVIII, No. 4, pp. 69–74 http://earthcryosphere.ru/

*ATMOSPHERIC PHENOMENA AND CLIMATE*

# SEASONAL FEATURES OF THE ARCTIC FRONT OVER THE TERRITORY OF RUSSIA IN THE 20th AND 21st CENTURIES

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The location of the arctic front and its possible changes over the territory of Russia were investigated using various meteorological parameters during the winter and summer seasons at the end of 20th – beginning of 21st century and using the climate projection from the regional climate model developed by the researchers of the Main Geophysical Observatory. Climate warming was observed in the north of Russia at the end of 20th – beginning of 21st century. The location of the branches of the arctic front was quasi-steady in the same period. According to the regional model scenario, the situation is not expected to change until 2060. The trend for the increase in the winter and summer temperatures will continue. It is possible to expect multidirectional changes of the largest surface air temperature gradients as the characteristic of the arctic front. The values of gradients can be reduced in the territory during the winter season in the first half of 21st century. Increase of the temperature gradient will be observed at the area of the main branch of the arctic front in summer. This can affect the structure of the vegetation cover in the subarctic zone in the north of Russia.

*Arctic front, territory of Russia, regional climate model, climate change*

## INTRODUCTION

Climatic changes are being currently observed in all the regions of the Russian Federation; however, under conditions of the continuous warming of Arctic, the study of changes in the north of Russia continues to remain quite topical. Indicated as causes of the climatic warming in the Arctic are the increased supply of heat and moisture into the region, accompanied by the inflow of long-wave radiation, accumulation of heat by the waters of the Arctic Ocean losing ice cover, the decline of a large amount of ice, and the prevalence of the first-year ice (according to the presentation by G.B. Alexeyev (Arctic and Antarctic Research Institute), delivered at a workshop in the Global Climate and Ecology Institute of Roshydromet, RAS, in October 2013).

The interest for the climatic aspect of the arctic front (AF) is caused by the sustainability of its geographical location under conditions of a climate change and of the most intense warming in high latitudes, as its displacement is primarily associated with changes in the permafrost zone, as well as in the subarctic sea and land ecosystems.

Studying the geographical location of climatic fronts started in the middle of the 20th century by *S.P. Khromov* [*1950*]. The term "climatic front" means the average position of fronts of a certain geographic type in a certain area. In [*Zolotokrylin et al., 2014*] it is noted that the arctic front has a double-branch structure and is divided into primary and secondary fronts. The primary branch of the arctic front is located over the North Atlantic and separates the arctic air masses from the marine air masses in the western part and from the continental (subarctic) air masses in the eastern part. The secondary branch of the AF is located in the northern part of Eurasia and separates the subarctic air masses from the moderate continental masses.

The objective of the study was the following: based on the data from the weather stations and the Regional Climate Model project data set of the Main Geophysical Observatory (MGO) named after Alexander Voyeykov, to investigate the characteristics of the arctic front and its geographic location over the territory of Russia in winter and in summer in various periods of the 20th and 21st centuries.

## THE TERRITORY, ITS NUMERICAL CHARACTERISTICS AND THE INVESTIGATION METHODS USED

The territory of investigation was limited by latitudes 50° N and 80° N and longitudes 27° E and 90° E (The European sector is located to the west of 60° E, the Asian sector – between 60° E and 90° E).

The climatic front passes in the area of a pressure trough, where frequent synoptic fronts are formed. That means, an area with increased frequency of cyclone centers, with maximum values of the module of the horizontal temperature gradient may indicate a climatic front [*Mikhailov et al., 2012; Zolotokrylin et al., 2014*].

The location of the arctic front in the 20th and 21st centuries was revealed by using the minimum values of the geopotential height at 1000 hPa (H1000), the area of maximum occurrence of cyclone centers on the same geopotenial height, and maximum values of horizontal temperature gradients on the same surface (AT1000). The average seasonal heat advection module was also considered, characterizing the horizontal exchange rate and the area of maximum front formation. A two-dimensional array of values of different meteorological components from reanalysis obtained at the University of East Anglia (UEA CRU) [*Data Centre..., 2011*] with spatial resolution 2.5° × 2.5° hourly data for H1000 (hPa) and daily temperature) in the period from 1981 to 2012 were utilized. The details of the method of calculating the characteristics of the arctic front can be found in [*Zolotokrylin et al., 2014*].

Due to the limited data of the Regional Climate Model, the only available method to reveal the location of an AF in the 21st century on the basis of areas with increased gradients of surface air temperature was used. Surface monthly air temperature was obtained from reanalysis CRU 3.21 with spatial resolution 0.25° × 0.25° for comparison of the location of observed and model AF over land at the end of the 20th century.

The absolute value of the temperature gradient $Gt$ (°C/1° latitude) was calculated by the formula

$$Gt = \sqrt{Gx^2 + Gy^2}\,, \tag{1}$$

where $Gx = (t_{i+1,j} + t_{i+1,j+1} - t_{i,j} - t_{i,j+1})/(2\cos\varphi)$ – the horizontal temperature gradient; $Gy = (t_{i,j+1} + t_{i+1,j+1} - t_{i,j} - t_{i+1,j})/2$ – the vertical temperature gradient; $t$ – surface air temperature; $i$ – the model grid cell increasing from west to east longitude; $j$ – the model grid cell increasing from south to north latitude; $\varphi$ – the geographic latitude of the given grid cell.

The location of the arctic front and changes in its characteristics in the periods 1981–2000, 2011–2030, and 2041–2060 were analyzed based on the results of a numeric simulation experiment using the regional climate model (RCM) the Main Geophysical Observatory (MGO) named after Alexander Voyeykov of the Federal Service for Hydrometeorology and Environmental Monitoring (MGO of Roshydromet).

Built-in into the global model T42L25 of general atmosphere circulation of MGO, the regional model with limiting conditions for the ocean surface, borrowed from the calculation results of the combined models of the CMIP3 project, includes description of the major physical processes in the atmosphere and on the surface: convection and condensation, radiation heat transfer in the clouds considering the diurnal variations, horizontal and vertical turbulent exchange of heat, moisture, and momentum [*Shkolnik et al., 2010; Shkolnik et al., 2012a*]. In reproducing the spatial-temporal climate variability, the model, characterized by a high spatial resolution (horizontal distribution 25 km and 25 vertical layers), considers the geographic features of the territory of Russia: large natural/man-made water reservoirs and rivers, playing a significant role in the local moisture cycle, as well as mesoscale orography, which affects the movement of air masses over the plains of Russia. According to the Intergovernmental Panel on Climate Change (IPCC), scenario of the increase in the concentration of greenhouse gases and aerosols in the earth atmosphere SRES A2 is applied in the RCM data. The scenario is in agreement with one of the most convincing descriptions of climate warming. Ensemble evaluations were considered, including three model computations with differing original conditions. Using the data of an earlier model version, an effort was taken to study the polar front variations in the territory of Russia in the summer months in various climatic periods of the 21st century [*Cherenkova and Shkolnik, 2012*]. Using the RGM data, processes in the permafrost zone were investigated; in particular, possible changes permafrost and seasonally frozen grounds in the 21st century under the climate warming in the territory of Eurasia were evaluated [*Nadyozhina et al., 2008*], the future projections of seasonal thawing layer depth in the permafrost regions of Siberia were analyzed [*Shkolnik et al., 2012b*].

Changes in the RGM/MGO data were compared in relation to the base period of 1981–2000. Statistical significance of the results was determined with the Student criterion (t-test at the 0.95 probability level) for independent samples by groups.

## RESULTS AND DISCUSSION

Firstly, we analyzed the winter and summer surface air temperatures changed in the late 20th and early 21st centuries, and its trend. The increase of the winter temperature was observed in the northern part of Russia (on average by 0.64 °C in the European sector and by 1 °C in the Asian sector) in the period of 2001–2012 in comparison with the previous twenty years. The maximum rise of the winter temperatures was detected in the north of the European part of Russia (1 °C) and in the north of Western Siberia (1.5 °C). Weak cooling was observed in the southern part of the territory: on average by 0.25 °C in the European sector and by 1.2 °C in the Asian sector. Warming increasing from east to west (from 0.4 °C to 0.8 °C) was observed in the European part of Russia in summer, in the same period. The heterogeneous changes of temperature with insignificant cooling in the small area in the south and warming increasing towards the north to the maximum value of 1 °C were revealed in Western Siberia.

According to the scenario of the RGM/MGO, the patterns of the air temperature can be preserved in the nearest future and in the middle of the 21st century. It is expected that winter air temperature will increase in the south-north direction in both periods of the 21st century. However, warming may affect the entire territory: winter temperature can rise in the period of 2011–2030 (in average from 0.8–1.5 °C in the south of the territory to 1.5–2.0 °C in the north) and also in the middle of the 21st century (from 2.5–3.0 °C in the south of the territory to 3.5–4.0 °C in the north of the European sector and 4.5–5.0 °C in the north of Western Siberia). For the summers of 2011–2030, the model predicts air temperature changes, similar for their structure to the changes of the observations. According to the model projection, the summer warming may occur in the European part of Russia and in the Asian sector (0.5–1.0 °C) with the exception of a small part in the south. Differences in the summer temperature can reach 1.5–2.0 °C in the period of 2041–2060 compared to the last twenty-year period of the 20th century.

Under conditions of the observed continuing and predicted non-uniform warming and of the most essential warming in the north of Russia, monitoring of ecosystems and engineering systems in the region (especially of those located in the permafrost zone) continues to remain quite topical. To understand the dynamics of the future processes, it is important to know how the characteristics of the arctic front and its location are changing and may change.

Consider the position of AF by the climatic data and the model projections in the winter and summer periods. As previously mentioned in [*Zolotokrylin et al., 2014*], in winter the division of the AF into the primary and secondary branches was observed over Scandinavia.

Fig. 1, *A* demonstrates the position of AF in the winter, based on evaluation of the maximum recurrence of cyclone centers, the maximum values of the altitudinal horizontal temperature gradients and of the average seasonal heat advection module according to the observations for the period of 1981–2012 and the RCM data for the period of 1981–2000.

In the winter season, the primary AF branch, passing over the Barents Sea and crossing Novaya Zemlya, is in a deep baric depression. The primary AF branch (Fig. 1, *A*) is located in the area of the maximum air temperature gradients and the maximum values of the average seasonal module of the heat advection. The area with the maximum number of the cyclone centers was detected to the south. The area of the primary AF branch (Fig. 1, *A*) is accompanied by increased surface air temperature gradients. According to the RCM data, the area of increased surface air temperature gradients is also located here. The drawback of the simulation of the AF front by the model is lower intensity of this area over the water surface compared to the observation data, which makes identification of the primary AF branch more difficult.

The secondary AF branch (Fig. 1, *A*) over the northern part of European Russia is quite well expressed by increased recurrence of cyclone centers and by the average seasonal module of heat advection and by maximum altitudinal and surface air temperature gradients. The area of increased air temperature gradients, detected using the RGM data is also located here. This area is associated with the secondary AF branch. In Western Siberia, the evidence of AF can be found only in the fact of maximum recurrence of the cyclone centers. According to the model projections, in this region there are certain centers of increased temperature gradients between the Irtysh and Ob rivers, approaching the area of high recurrence of cyclone centers.

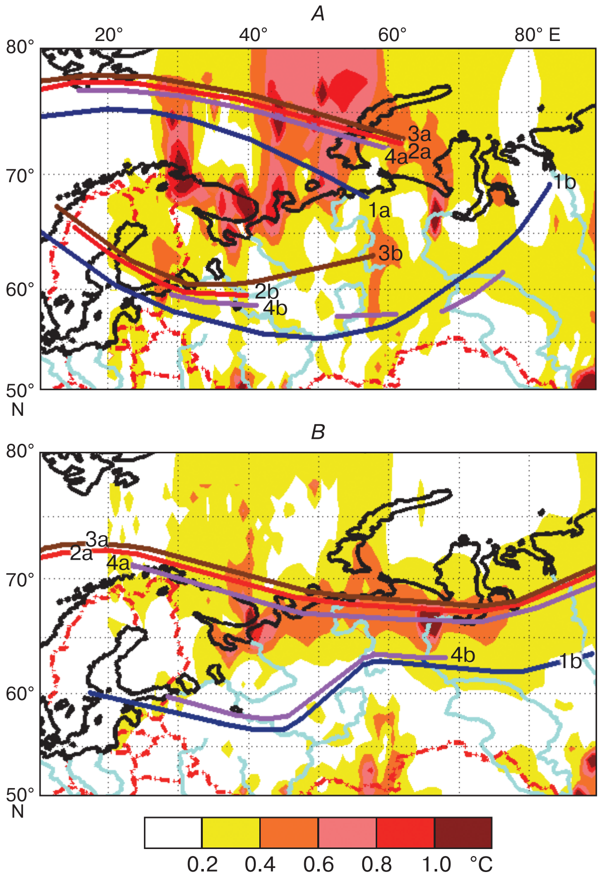


**Fig. 1. The location of the arctic front (the main (a) and secondary (b) branches and the gradients of surface air temperature in winter (*A*) and in summer (*B*) in the period of 1981–2012:**

1 – the curve of maximum recurrence of cyclone centres at H1000 (hPa); 2 – the curve of the maximum values of the horizontal air temperature gradients at AT1000 (hPa); 3 – the curve of maximum values of the average seasonal module of heat advection; 4 – the curve of the maximum air temperature gradients according to RCM/MGO in 1981–2000.

The differences arising during transition to different underlying surfaces (ocean–land) in the area of Scandinavia and the northern coastline of Russia and manifesting themselves in increased surface air temperature gradients and precipitation are reproduced in the regional model more clearly than in the observation data. This characteristic of the RGM/MGO makes identification of the arctic front branches somewhat more difficult, masking the increased gradient values attributed to it.

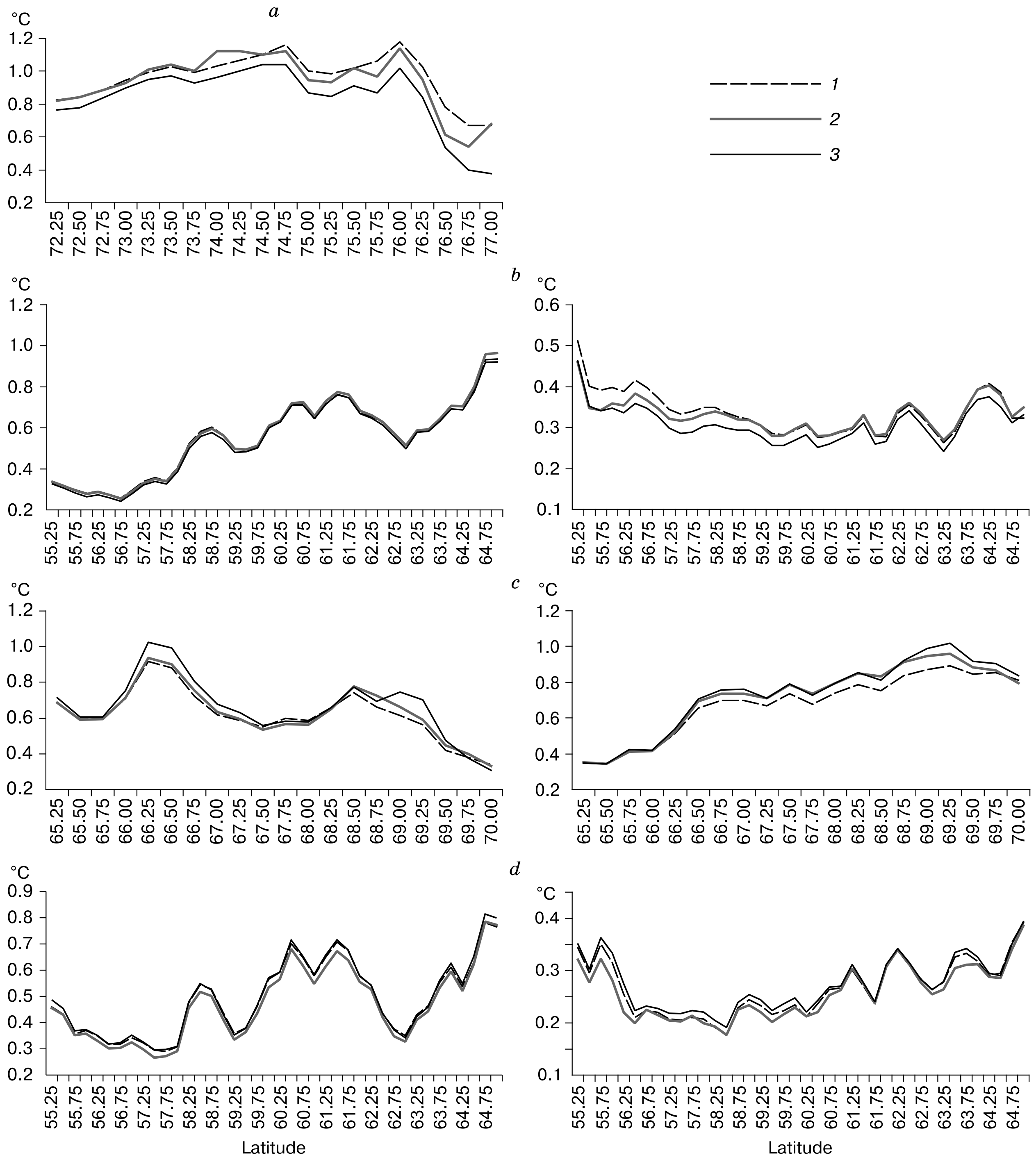


**Fig. 2. The latitudinal changes in surface air temperature gradients (°C) according to RCM/MGO in the periods of 1981–2000 (*1*), 2011–2030 (*2*) and 2041–2060 (*3*) in the area of the main AF branch (*a*, *c*) in the European (*left*) and Asian (*right*) sectors of Russia in the winter season and of the secondary AF branch (*b*, *d*) in the European (*left*) and Asian (*right*) sectors of Russia in the summer season.**

Thus, the primary AF branch (over the Barents Sea) and the secondary AF branch (over the land part of northern Russia) in the winter period are quite satisfactorily reproduced by the regional climate model (Fig. 1, *A*).

In the summer period, cyclonic processes over the territory of northern Russia are less intense than in the winter period: the area of low pressure is unstable. Using several analyzable characteristics, AF branches may be identified, just as in the winter period. The primary arctic front branch (Fig. 1, *B*) is expressed in the surface layer by increased temperature gradients, as well as by the maximum values of the average seasonal module of heat advection and is not revealed by increased recurrence of the cyclone centers. The branch passes along the Scandinavian coast and the Kola Peninsula, comes over the land in the area of the 45$^{th}$ meridian, then it crosses the Gulf of Ob to reach the north of Western Siberia (Fig. 1, *B*). The area of the main maxima of surface temperature is located here, according to the observations and the model computations. This is an area of abrupt south-north transition of thin tundra forest and tundra (southern tundra) to tundra-suffruticose and suffruticose-moss vegetation (northern tundra).

In the summer period, the secondary AF branch (Fig. 1, *B*) is observed only as an area of increased recurrence of cyclone centers over the northern part of European Russia and Western Siberia on the geopotential height at 1000 hPa. According to the simulation estimates, it is accompanied in the European part of Russia by increased surface air temperature gradients. This AF branch passes over the zone of transition of the southern taiga forest to the middle taiga forests in the European part of Russia and it passes over the area of transition of the middle taiga forests to the pine forests of the northern taiga in Western Siberia.

Thus, in the summer period the regional climate model adequately describes the main AF branch (Fig. 1, *B*) on the basis of the surface air temperature gradient. Simulation of the secondary AF branch is mainly to be seen in the European part of Russia and up to 70° eastern longitude in the east, excluding the greater part of Western Siberia (Fig. 1, *B*).

It can be supposed that, just as in the winters of the 20$^{th}$ century, in the winters of the 21$^{st}$ century the main arctic front branch will be located in the sector limited by the 72–77° N and 27–60° E, and in summer – 65–70° N and 27–90° E. The secondary branch both in winter and in summer will be revealed in a rectangular area with borderlines of 55–65° N and 27–90° E. Note that the characteristics were averaged within the limits of these rectangular areas, separately for the European and Asian sectors of Russia.

Consider the differences of the winter and summer temperature gradients in the territory of Russia in the periods of 2011–2030 and 2041–2060 versus the basic period according to the RGM data. It can be seen in Fig. 2 that the position of the arctic front over the territory of Russia is rather stable in both seasons.

Despite the changes in the averaged gradient values, the areas of the maximum values in the 21$^{st}$ century will not be essentially shifted. The smallest difference can be revealed in the area of the secondary AF branch in the European sector (Fig. 2, *b*, *d*).

Therefore, it can be stated that, according to the RGM/MGO data, the position of the arctic front will remain quasi-stationary in the winter and summer periods until the 60s of the current century.

Changes in the intensity of frontal processes were observed and are expected to occur in the future along with the quasi-stationary of the AF branches observed over the recent 30 years and predicted till

Table 1. **Differences in the air temperature gradients at AT1000 (hPa) averaged in the area of AF location in 1981–2012, compared to 1951–1980, in the surface air temperature in 2001–2012 (according to CRU) and in the 21$^{st}$ century (according to RCM/MGO), compared to 1981–2000**

| Season, AF branch | Air temperature gradients, °C | | | | Surface air temperature gradients, °C | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | At AT1000 (hPa) | | Surface air temperature | | 2011–2030 | | 2041–2060 | | 2011–2030 | | 2041–2060 | |
| | 1981–2012 | | 2001–2012 | | ETR | | | | WS | | | |
| | ETR | WS | ETR | WS | All territory | Land | All territory | Land | All territory | Land | All territory | Land |
| | According to CRU | | | | According to RCM/MGO | | | | | | | |
| *Winter* | | | | | | | | | | | | |
| Main branch | –1.0 | – | –0.03 | – | *–0.02* | *0.3* | *–0.1* | *0.2* | – | – | – | – |
| Secondary branch | –0.2 | –0.2 | –0.02 | –0.02 | 0 | 0 | *–0.01* | *–0.01* | –0.01 | –0.01 | *–0.03* | *–0.03* |
| *Summer* | | | | | | | | | | | | |
| Main branch | 0.08 | 0.1 | –0.02 | –0.02 | 0.01 | –0.01 | *0.04* | *0.03* | 0.03 | *0.02* | *0.05* | *0.04* |
| Secondary branch | 0.04 | 0 | 0.01 | –0.02 | –0.02 | –0.02 | 0.01 | 0.01 | *–0.01* | *–0.01* | 0.01 | 0.01 |

Note. Significant differences according to RCM data are italicized. ETR – European territory of Russia. WS – Western Siberia.

2060. According to reanalysis data and the RGM/MGO data, the changes of surface air temperature gradients are similar (Table 1). The differences in the altitudinal temperature gradients are somewhat greater, which is explained by the difference in the measurement altitudes. Note also the differences of gradient changes averaged for the land according to reanalysis data, related to the image contrast of the thermal gradient fields in the RGM/MGO during transition from one underlying surface to another one.

In accordance with the scenario prediction of the RGM/MGO, opposing trends of changes in the increased surface air temperature gradients in the area of each AF branch can be expected in both periods of the 21st century (Table 1). In the winter period, the temperature gradients in the 21st century will decrease actually all over the territory, increasing only in the area of the main AF branch in Novaya Zemlya, and will not change in the nearest 20 years in the area of the secondary AF branch. In the summer seasons of the 21st century the intensity of the frontal processes will be increased in the area of the main AF branch all over the territory. In the European sector, this increase is caused by the growth of the air temperature gradients over the water surface. In the area of the secondary AF branch, the gradient changes will be not similar: while the intensity of the frontal processes will decrease in the summer season of 2011–2030, it will grow again by the middle of the 21st century versus the present time. Later significant changes are not predicted, which is likely not to make essential changes in the characteristics of the vegetative cover.

## CONCLUSIONS

Analysis of the observation data and of the regional climate model data allows the following conclusions to be drawn.

It was revealed that the most essential warming in 2001–2012, compared to the previous two decades, was observed in the north of Russia: in winter up to 1.0–1.5 °C, and in summer up to 0.6–1.0 °C.

According to the RGM/MGO projections, the trends of the air temperature changes may be extrapolated to the nearest future and to the middle of the 21st century. Warming will affect the entire territory: the winter air temperature may rise on average by 3 °C in the period of 2041–2060. The increase of summer temperature may reach on average up to 1.7 °C in the European sector and up to 1.6 °C in the Asian sector in 2041–2060.

Two branches of the arctic front were identified over the north of Russia (up to 90° eastern longitude). The main branch in winter was located over the Barents Sea. The secondary branch was located over the north of Russia in the area of 55–60° northern latitude in the European part of Russia and to the north of 70° northern latitude in Western Siberia. In summer, the main AF branch was shifted towards the south and partly passed over the continent in its eastern part. The secondary branch in the west of the European part of Russia was located in the summer season at approximately the same latitudes as in winter, while in Western Siberia it was observed at 62–64° northern latitude.

Location of the arctic front was quasi-stationary for the recent thirty years, according to the observation data, and will remain the same in the period till 2060, according to the regional climate model. At the same time, the seasonal patterns of the arctic front over the territory of Russia will be also preserved.

It is expected that the changes of the intensity of the frontal processes will be multidirectional in winter and in summer in the 21st century, compared to the last two decades of the 20th century. The increase of the intensity of the frontal processes can be observed in summer in the area of the main branch of the arctic front. It may affect the structure of the vegetation in the subarctic belt of northern Russia.

The authors present their acknowledgements to I.M. Shkolnik for the provided data from the regional climate model of the MGO.

This work was supported by the RFBR under grant 13-05-00031.

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*Received March 5, 2014*