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Modeling air temperature changes in Northern Asia

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ABSTRACT

Based on time series (1950–2005) of monthly temperatures from 73 weather stations in Northern Asia (limited by 70–180° EL and 48–75° NL), it is shown that there are statistically significant spatial differences in character and intensity of the monthly and yearly temperature trends. These differences are defined by geomorphological and geographical parameters of the area including exposure of the territory to Arctic and Pacific air mass, geographic coordinates, elevation, and distances to Arctic and Pacific oceans. Study area has been divided into six domains with unique groupings of the temperature trends based on cluster analysis. An original methodology for mapping of temperature trends has been developed and applied to the region. The assessment of spatial patterns of temperature trends at the regional level requires consideration of specific regional features in the complex of factors operating in the atmosphere–hydrosphere–lithosphere–biosphere system.

1. Introduction

Accelerating climatic change and growing recognition of its importance for the Earth system and humanity have resulted in intensification of debates concerning driving forces, future scenarios, and mitigation of undesirable effects of climate change (IPCC, 2007). In spite of evident achievements on these topics, climate science still did not develop complete climatic models, which would comprehensively explain the causes of temporal and spatial climate dynamics, separating the role of anthropogenic and natural drivers with high reliability. It is believed that the uncertainty of future climate assessments based on hydroclimatic models is quite large (Gruza et al, 2006; Jin et al., 2010; Anisimov and Zhiltsova, 2012; Dong et al, 2012).

Contributions of natural and anthropogenic factors to global climate change are a research issue of heated debate (Kondratyev, 1992, 2004; Wang and Fu, 2000; Izrael, 2004, 2008; Meleshko et al., 2004; Rahmstorf et al., 2007; Bonan, 2008; Gulev et al., 2008; Zykin and Zykina, 2008; Hansen et al., 2010; Roger et al., 2011).

Discussions on variability of estimates of climatic parameters in response to a known or suspected exposure related to such indicators as greenhouse gas concentrations in the atmosphere, volcanic and anthropogenic aerosols, dynamics of the solar radiation, specifics of land use, etc. It has been found that in different geographical conditions the reaction of precipitation in response to atmospheric pollution can be various (Rosenfeld, 2000; Givati and Rosenfeld, 2004; Woodley Weather Consultants, 2007; Onuchin and Musokhranova, 2013).

It has been suggested that there is uncertainty in the assessment of current climate change, which is caused by, inadequate spatial coverage of stations and imperfect methods of obtaining spatially distributed climatic characteristics (Karl et al., 1994; Jones and Wigley, 2010). One of the factors influencing the spatial distribution of climatic trends is local warming from urban areas (Hansen et al., 2007). In the context of studying spatial patterns of climate change an important issue is the delimitation of homogeneous climatic regions. Zoning that is based on an arbitrary choice of regions does not allow taking into account the details and factors which would explain the cause-and-effect relationships in the climate system (Anisimov and Zhiltsova, 2012).

Understanding causes of climatic changes, forecasting, and taking appropriate decisions on mitigation of climate change effects could be improved by the analyses of physical and geographical factors controlling these changes at different scales and by differentiating local and mesoscale climate trends. Insight of the regional features of climate change may contribute to clarifying the causes of global climate change and avoid unnecessary investments in adaptation to ongoing climate changes (Roger et al., 2011). Researchers investigating changes of meteorological field structure and dynamics under global warming emphasize that further research efforts need to be taken to identify mechanisms of variations of mesoscale meteorological field (Ippolitov et al., 2008; Dong et al., 2012). Therefore, generalization of mesoscale data and comparative analyses of results obtained by different methods could generate a useful approach in regional climate change modeling. Without a full understanding of current climatic events, any solid discussion of their underlying mechanisms and effects is difficult.

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Northern Asia is recognized as the region of the current greatest contrasts of spatial and temporal dynamics of near-surface air temperature (SAT). However, the reasons for these contrasts have not been sufficiently considered. In this study we show that spatial temperature trends can be adequately described by regression models using appropriate physical and geographical parameters as variables. Regularities of SAT spatial and temporal variability using GIS technologies can be applied for detailed mapping and analysis of spatial and temporal dynamics of climatic characteristics. While knowledge of seasonal air temperature trends could provide certain insights into climate system functioning, studies dealing with this area are practically absent for Northern Asia (Onuchin, 2009).

Up-to-date science of global change supposes that the global warming above 2 °C generates substantial risks for global forests (IPCC, 2007). The most dramatic climatic change over the planet is expected in Northern Asia, and might reach +7–10 °C in its continental regions. About 95% of the forest cover of Russia (and above 20% of the world forests) is represented by boreal forest ecosystems which evolutionarily formed under stable cold climate. Adaptive thresholds and buffer capacity of boreal forests are not known. It is supposed that under a certain level of warming (about +7 °C of the annual average air temperature) boreal forests may become a "tipping element", i.e., enter in a unstable phase when relatively small changes of environment lead to a non-linear response in ecosystem's functioning and death of its elements with the least adaptive capacity (Lenton et al., 2008). Additional problems for surviving the boreal forests are caused by thawing of permafrost. These specifics of the region point out a particular importance of the detailed knowledge of regional distribution of the current temperature trends for application in regional ecological models and understanding of adaptation strategies.

2. Regional setting

The region of study covers a vast area of northern Asia, stretching from the Ural Mountains to the Pacific Ocean and limited by location of the Hailar weather stations in North China. It includes the northern part of Western Siberia, Central and North-Eastern Siberia, Chukotka, Kamchatka and the Amur region, Mongolia and Inner Mongolia (North China). According to the climate classification of Alisov (1956) the area belongs to the arctic, subarctic, and temperate climatic zones. The region is characterized by significant differences in climatic conditions, because it spreads about 4000 km from north to south (48°–75° NL) and above 6000 km from west to east (70°–180° EL). About two-third of the region is covered by high mountains (mostly in the southern part) and large plateaus (to the east from the Yenisey River). Almost half of the area (47%) is covered by boreal forests (Siberian *taiga*). The largest wetland territory over the globe is situated in West Siberia. Major part of the region is underlaid by permafrost of different type. In 1975–2010, the average warming trend across the region was almost three times higher than the global one.

3. Materials and methods

Although climatologists have progressed considerably in investigating global climate change (Smirnov and Vorobyev, 2002; Beniston et. al., 2007; IPCC, 2007; Derevyanko, 2008; Giorgi and Lionello, 2008; Ippolitov et al., 2008; Rapp, 2008; Singer et al., 2008; Gudkovich et al., 2009; Li et al., 2011), a number of climatic system functioning aspects have not been addressed. One of them is the influence of regional and local geographical characteristics on climate change. Knowledge of the mechanisms of such an impact can provide insights into global change causes and effects.

The spatial variability of climatic trends is often estimated by interpolation of point (i.e. weather stations) data. Despite the fact that there are diverse methods for mapping of temperature trends (polynomials, splines and kriging), these methods are not always adequate in regions where weather stations are spaced out and non-uniformly distributed.

Spatial distribution of climate characteristics is best analyzed if we use regional mathematic climate models which incorporate geomorphologic and geographical characteristics (Onuchin et al., 2003).

Based on statistical analysis, we identified the major factors controlling monthly average air temperature trends in northern Asia. These factors include a specified area geographical location, elevation above sea level, distance to the ocean, and exposure to air currents which determine energy-mass exchange in the land–ocean–atmosphere system.

Placement of location relative to oceans was quantified as a Euclidian distance between a specified point on land (a pixel) and the shoreline of the Pacific or Arctic oceans. The levels of exposure sites to Arctic and Pacific air masses were determined using a method of virtual ray relief echolocation. The exposure was calculated as a cumulative proportion of direct and relief isoline-reflected rays radiated from a specified point (pixel) over eight directions in horizontal planes at different elevations, which reached an ocean shoreline (Onuchin et al., 2004). An algorithm was used to calculate by-pixel exposure assumed to account for elevation rays which reached an ocean coastline after it had been reflected from relief isolines up to three times. The intensity of reflected rays decreased proportionally to the number of reflections.

These characteristics control energy-mass exchange in the system "ocean–atmosphere–underlying surface" (Onuchin et al., 2004; Shafer et al., 2005). Such models enable development of high-resolution maps of regional climatic trends and analysis of region-specific climatic changes. Since each of these models "works" only in a certain geographical region, a set of models needs to be joined in order to obtain climate change maps for large territories. For constructing mathematical models of climate trends, we used series of average SAT values provided by 73 meteorological stations for the area limited by the longitude 80–180° east and the latitude 48–80° north for a 56-year period (1950 through 2005). The gaps in data records have not exceeded three years. For each of the stations the values of trends are recalculated at the centenary period scale.

The study area was divided in 6 areas (domains) similar by monthly temperature trends assessed by measurements at the weather stations (see Section 4.1). The grouping of the trends was provided using cluster analysis (Fig. 2). Boundaries between the domains were identified using Thiessen polygons (de Berg et al., 2000), which were built for a network of points (weather stations). To smooth spatial distribution of temperature trends, linear-weighted extrapolation of trend values was carried out along adjacent polygon boundaries.

An air trend spatial interpolation method was based on regression models, which enabled spatial differentiation of air temperature trends accounting relief parameters of different areas and their levels of exposure to air masses coming from either ocean. Models of spatial variability of temperature trends were based on multiple regression analysis

$$\Delta T = \alpha_0 + b_1 * En + b_2 * Ee + b_3 * S + b_4 * L + b_5 * H + b_6 * Ln + b_7 * Le \quad (1)$$

where ΔT is air temperature change, °C/100 years; b_0–b_7 are the equation parameters; En and Ee denote levels of exposure sites to Arctic and Pacific air masses, respectively; S is the latitude, degrees N; L is the longitude, degrees E; H is the elevation above sea level, m; Ln and Le are the distances from a pixel to Arctic and Pacific oceans, respectively, km.

Significance of the coefficients of the arguments in the regression equations by the types of trends was assessed by t-test. Only those factors were included in the final models, coefficients of which were significant at the 95% confidence level. Typical values of the multiple coefficients of determination were in the range from 0.6 to 0.8. As an example, Table 1 shows the significance of coefficients in the February trend models obtained for different domains.

The mapping algorithm used the GTOPO-30 digital elevation model, which provided topographical characteristics, such as elevation above sea level, geographical location, distances from the oceans, and

Table 1
Significance of coefficients in models of February trends and values of the coefficients of multiple determination in different domains.

Arguments of model	Domains			
	Chukotka $R^2 = 0.76$	Arctic-Putoran $R^2 = 0.66$	Continental $R^2 = 0.76$	Far East-mountain $R^2 = 0.81$
Residual	0.5	1.8	−1.51	4.97
En	–	–	2.32	–
Ee	2.51	–	–	−2.12
S	–	−5.94	1.91	−5.47
L	–	3.6	–	6.22
H	–	–	−3.91	−4.2
Ln	−3.26	–	3.13	−4.2
Le	–	4.35	–	–

exposure to air masses. The spatial climatic information distribution was generated using the regression models. Unlike the method of point data interpolation and generalization, the proposed approach allows us to represent spatial information on air temperature trends in connection with physical and geographical characteristics of the territory.

4. Results and discussion

4.1. Zoning of Northern Asia by climate trend type

Our analysis of the 1950–2005 climatic changes in northern Asia revealed both considerable differences between monthly air temperatures trends obtained at weather stations located relatively close to each other and in some cases good similarity on stations located in different regions. For example, the trend of monthly average air temperatures measured at Olenek weather station (68°30′ NL, 112°30′ EL) differed markedly from the trend obtained at Zhilinda weather station (70°06′ NL, 113°64′ EL). Both stations are in northeastern Yakutia and less than 200 km apart. The temperature trends at Zhilinda weather station varied from −3 to +6 °C/100, with a minimum in January and a maximum in March, whereas at Olenyok weather station such a range was −0.1 to +11.5 °C/100, with the minimum and maximum in June and December, respectively (Fig. 1a). Conversely, weather station Kalakan (55°06′ NL, 116°48′ EL), located in Trans-Baikal region, and Kolpashevo (58°30′ NL, 83°00′ EL), which is located in western Siberia, over 2000 km away from Kalakan, appeared to have similar tendencies of inter annual variation of temperature trends (Fig. 1b).

Evidently, while there is a definite spatial differentiation of climate trends, we could also observe their similarity over vast territories. This allowed us to group weather stations in spatial clusters which would be homogeneous by within-year variability of trends of monthly air temperature (Fig. 2a,b,c,d)..

Each of the separated six temperature trend types is specific for a certain geographic area (domain). The *Arctic–Okhotsk Sea trend type* covers Arctic Ocean islands and the coastal zone between Yamal Peninsula and Chukotka, wide valleys of big rivers penetrable by Arctic air masses, the northwestern part of Okhotsk Sea coast, and an isthmus of a long Kolyma river connecting these two coasts. The *Putoran trend type* is specific for Putoran Plateau and a part of West Siberian Lowland adjacent to Putoran in the west. The *Chukotka trend type* is attributable to Chukotka peninsula. The *Continental type* covers the areas that are found in Lena river middle waters, Yenisei river middle and headwaters, and Angara river headwaters. *The Far East-mountain trend type* is characteristic for vast mountainous areas of southern Siberia, Mongolia, and the Trans-Baikal area stretching eastward right to the Pacific. The monthly air temperature trends constituting *the Bagdarin trend type* are unique, as they are limited to single Bagdarin weather station, which is located in a deep intermountain hollow in northeastern Buryatia (Fig. 3a).

These domains differ in the types of temperate change. Arctic–Okhotsk trends appeared to be the most uniform on a monthly basis, with a maximum temperature increase (up to 2.5 °C for 100 years) observed from March to May, and not exceeding 1 °C/100 from June to January. While Arctic–Okhotsk Sea and Putoran trend types were fairly similar, monthly temperature trends are more pronounced in the latter case (Fig. 3b). Continental monthly temperature trend type indicates the maximum temperature increase of 10.3 °C/100 in February, while the increase from June to October does not exceed 2 °C/100. The variation of monthly temperature within the Far East-mountain trend type was analogous to that characteristic for the Continental trend type. In the Far East and mountain areas of North Asia, the most pronounced warming was found to occur in late winter and early spring, but the temperature increase did not exceed 7.5 °C/100.

The identified well-pronounced warming in wintertime in the Continental domain might be a result of the specific geographic conditions. First, sea water has better heat capacity and heat conductance than land, thus it slows down climatic changes more effectively compared to land. Probably it is the main reason for underestimating the temperature trends over the continents and especially in areas that are far from the coasts that is typical in assessments by climatic models at the global level (Dong et al, 2012). Second, atmospheric circulation is

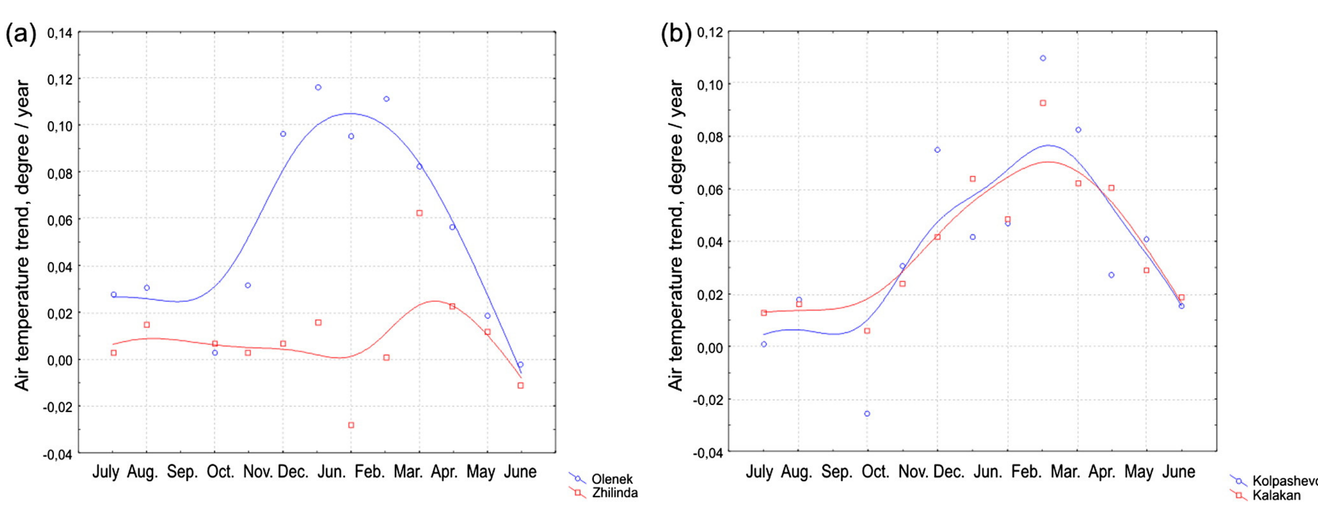

Fig. 1. Monthly air temperature trends can be markedly different (a) between weather stations located close to each other and (b) similar at weather stations located far apart.

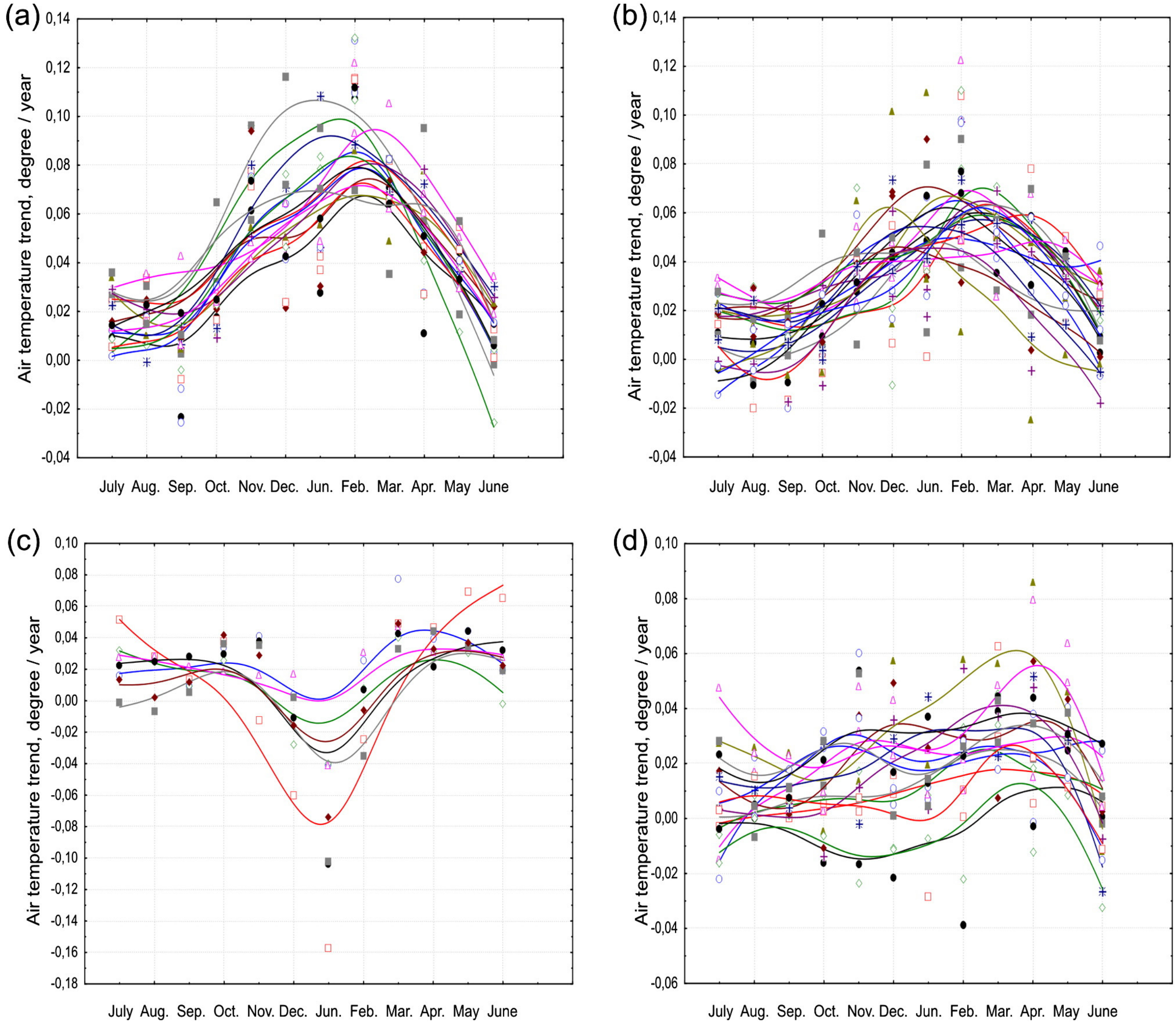

Fig. 2. Examples of geographical distribution of monthly air temperature trends: (a) Continental, (b) Far East-mountain, (c) Chukotka, and (d) Arctic–Okhotsk Sea.

more intensive in mountains than in closed hollows and this might be a cause of air temperature trend smoothing with increasing elevation above sea level. A shift of maximum temperature increase from February in continental conditions to March and April in the Arctic zone can also be attributable to specific geographical conditions.

Chukotka type of trends in monthly temperatures appeared to be opposite to the Continental one. Winter temperatures generally fell down in a number of Chukotka areas, with January temperatures having decreased by as low as 10 °C/100.

However, the monthly air temperature trends obtained for other seasons indicated warming in this region and varied from 1.5 to 5.0 °C/100 (Fig. 3b). It is obvious that the downward trends in January air temperature in Chukotka cannot be a direct effect of global warming, which is expected to be manifested by increasing air temperature. This decrease in January temperatures is presumably attributed to changes in cyclonic activity and blocking of warm currents, which reached Chukotka before, during wintertime. This is also supported by the conclusion of Ippolitov et al. (2008) that January cooling on Chukotka is a result of increasing atmospheric pressure in January.

These changes of atmospheric and sea currents were likely induced by warming in other regions. Sea current dynamics are highly complicated near Chukotka (Khrapchenkov, 2007) and unidirectional structural changes of interactions are observed within the climatic system of northwestern Pacific (Plotnikov, 2007). This might be attributable to the characteristics of atmospheric circulation in the north Pacific region. Smirnov and Vorobyev (2002) reported that the circulation of the oceanic water and the atmosphere is more closed here compared with the north Atlantic and Indo-Pacific regions, because the Pacific and the Arctic Oceans do not merge here and the north Pacific region is bounded by mountains along almost the entire perimeter, especially in its eastern and northern parts.

The trends in monthly air temperature found at Bagdarin weather station appeared to differ considerably from the trends obtained at all other stations included in the analysis. This uniqueness might be caused by the location of this station in a hollow surrounded by high mountains in northeastern Buryatia. Monthly air temperatures at Bagdarin exhibited the highest variability, with the maximum temperature increase (up to 14 °C/100) in April, while January temperatures remained stable (Fig. 3b).

4.2. Climatic change modeling and mapping

Prior to using any approach to modeling of current climatic changes, it should be recognized that, disregarding their driving forces, an overall

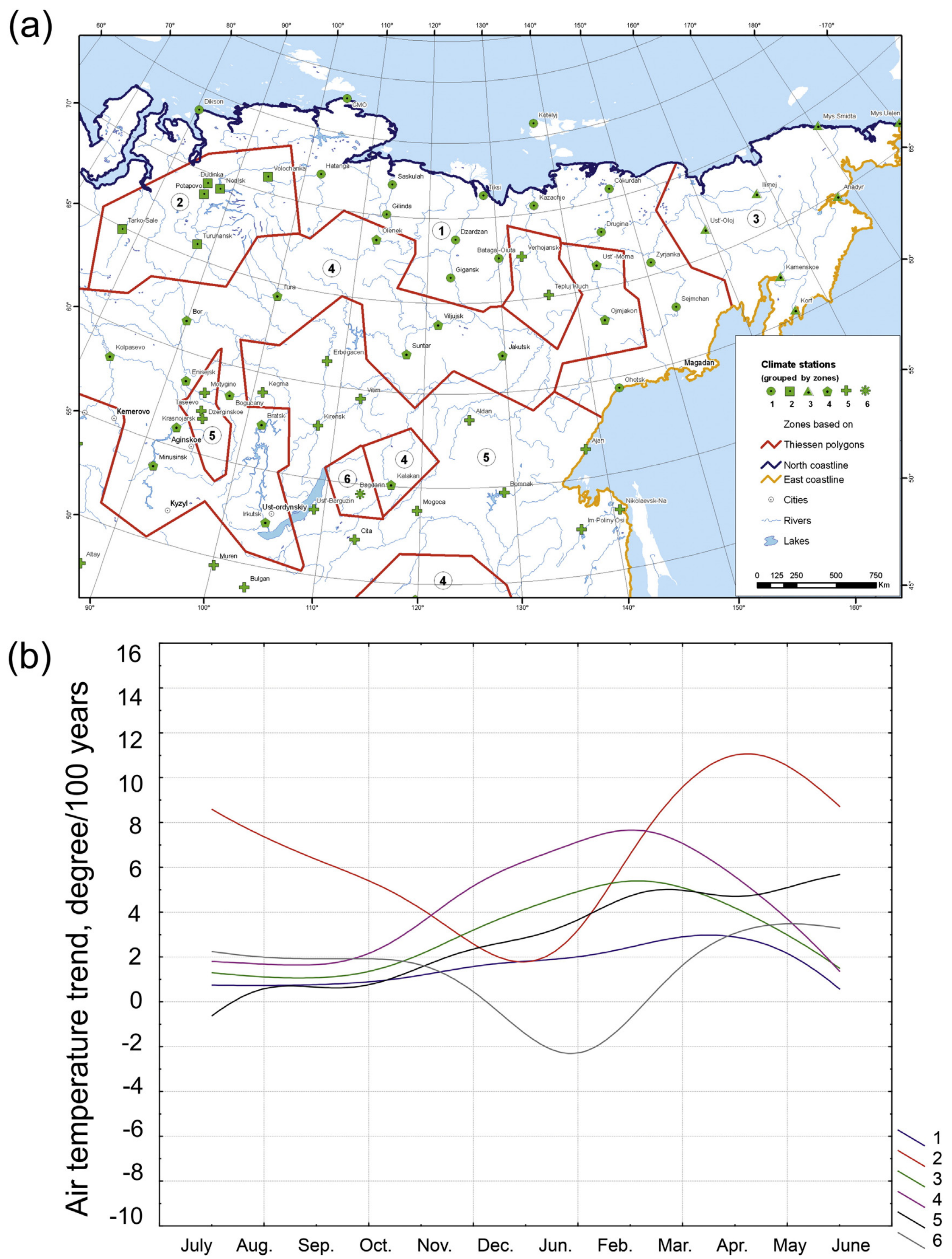

Fig. 3. Northern Asia air temperature trend types (a) spatial zoning; (b) trend curves: 1) Arctic–Okhotsk Sea; 2) Putoran; 3) Chukotka; 4) Continental; 5) Far East-mountain; and 6) Bagdarin domains.

air temperature increase is observed over the entire northern hemisphere. The above-mentioned non-uniformity of these changes caused by physical and geographical specifics of the domains is also obvious. Consistency of these models depends on geographic data completeness, representativeness and validity.

The temperature trends in Arctic and Okhotsk Sea coasts and Putoran Plateau (domains 1 and 2) showed the greatest increase in May air temperatures with decreasing exposure of area to air masses coming from the Arctic Ocean (En). At the same time, the trends increase with increasing longitude (L) and exposure to Pacific air masses (Ee). Increasing air temperature trends with decreasing the exposure to Arctic air masses (En) is also characteristic for other months.

In the major part of northern Asia including Central Siberia, Russian Far East and mountain areas (domains 4 and 5), winter air temperature trends are represented most clearly but decrease markedly with increasing elevation. Our analysis of changes of winter temperature in continental conditions (domains 4) revealed that, on the one hand, the warming tended to decrease southward (i.e., the lower the latitude, the greater the decrease), and, on the other hand, to increase with increasing distance from the Arctic Ocean. This ambiguity of winter temperature trends resulted in their shift upward, proceeding from the south to the north (up to a certain conditional geographical boundary) and then downward with decreasing distance from the Arctic Ocean. The location of this conditional geographical boundary might depend on Arctic Ocean coastline configuration.

Climatic changes in Chukotka appeared to be highly specific. While winter air temperature trends had a tendency to decrease, they indicated warming in other seasons, of 2–3 °C/100 in summer and fall and up to 5 °C/100 in spring (Fig. 3b). Interestingly, winter cooling and the-rest-of-the-year warming grew more pronounced with increasing elevation. We cannot explain this phenomenon that contradicts to the general regularities of decreasing temperature trends with increasing elevation.

As an experience of modeling climate trends, the models of global level, in spite of the fact that they take into account a range of factors, do not always have a good function at the regional level (Phipps et al., 2011; Dong et al., 2012). Our results suggest that even simple regression models that take into account local conditions can significantly improve the accuracy of simulations of current climate change (Table 2.). At the same time, for regional models, the smaller the region, the higher the accuracy of the model estimates, but for the global scale this is conversely, the larger the region, the higher the accuracy of the model estimates. Analysis of Table 2 shows that the average annual air temperature in different regions of northern Eurasia over the last 50 years have increased by 2–3 °C, which is significantly higher than in the inland areas of China, where their growth during the same period amounted to 0.6–12 °C (Dong et al., 2012).

The above mentioned regularities were used to develop maps of air temperature changes (Figs. 4, 5). The air temperature trend maps provide an overview of seasonal climatic changes in northern Asia between 1950 and 2005. The trends indicated a general increase in winter and spring temperatures by 5–8 °C/100. However, climatic changes were substantially non-uniform spatially.

The highest spatial variability of air temperature trends was found for winter, whereas summer and early spring temperatures exhibited the lowest variations. Therefore, summer-early fall warming, which was least manifested among seasonal temperature changes, occurred most uniformly across northern Asia. January air temperatures were found to decrease considerably in Chukotka and increase simultaneously in Amur region. This asynchrony was presumably a result of seasonal sea current restructuring associated with global circulation (Khrapchenkov, 2007).

Warming was less evident from Taymir Peninsula to Chukotka compared to interior regions. This inertia of climatic changes was probably caused environmentally, as this part of the Arctic Ocean is relatively isolated from the world's major ocean currents.

Table 2
The simulated and observed linear trends of the surface air temperature over the different regions of Northern Asia (units: °C/100) and over the globe, global continents and China (units: °C/100).

Region	Observation	Simulation	CC[a]
Regional regression models (1)			
Arctic–Okhotsk Sea and Putoran	0.40	0.44	0.70
Continent (Northern Asia)	0.66	0.60	0.67
Far East-mountain	0.60	0.62	0.52
Chukotka	0.29	0.28	0.97
Atmospheric general circulation model IAP AGCM4.0 (Dong et al, 2012)			
Globe	0.55	0.57	0.89
Continents	0.65	0.57	0.81
China	0.68	0.55	0.28

[a] Correlation coefficient between the simulation and observation.

5. Conclusion

This study identified vast homogeneous geographic regions of northern Asia that are specified by highly similar monthly air temperature trends, while the temperature trend types of the different regions differ markedly. The trend distinctness and directions were found to depend on region-specific combinations of geographic and geomorphological parameters, such as the rate of an area's exposure to oceanic air masses, disposition and distance from the oceans, locations' coordinates, and elevation above sea level.

The study's results allowed us to assume that the trends of regional climate dynamics reveal, to a certain extent, the causes of the variation of spatial non-uniformity and seasonal specificity. Distinct boundaries were found between domains with different specific climate changes that are defined by specified sets of geographical and physical parameters. This confirms inherent non-uniformity of such changes in the "atmosphere–hydrosphere–lithosphere–cryosphere–biosphere" system (Gorshkov, 1990; Kondratyev, 1990, 2004). The system approach used in this study allowed us to understand the causes of extreme wintertime warming in closed hollows found in the continental regions, as well as the much weaker warming in territories along the Arctic coast and in high-mountain areas. Based on the system analysis of climate anomalies on Chukotka, we hypothesized that the northwestern Pacific currents are subject to both seasonal restructuring and the regional atmospheric circulation change that seems to be responsible for wintertime cooling in northeastern Russia.

Results of this study could be used for different goals. First, they could serve as a source of detailed climate-specific historic information for regional climatic and ecological modeling. Second, they seem useful for clarification of climatic predictions for the Northern Eurasian Arctic. As implied by the ACIA (2005) and IPCC (2007), current understanding of the polar climate system continues to be incomplete and very uncertain. Many scientists and scientific teams assert that the recent climate change in Polar Regions had mostly natural drivers (e.g. Kondratyev, 2004; Frolov, 2006; Karklin and Yulin, 2011). While there is no doubt that current climatic models accumulated the best and most advanced scientific knowledge, they do not explain a number of important historical phenomena like cycling of climate dynamics (see a discussion, e.g., in Shvidenko et al., 2011).

It should be noted that the conclusions of this study are based on only 73 weather station data sets which are available across the huge area. Thus, the above results should be taken with a precaution. However, they present important empirical information for understanding recent climatic change in Northern Asia and could be used for analyzing differences with results of other studies (e.g., Roshydromet, 2008; Karklin and Yulin, 2011).

To better understand the climate change magnitude, its variability and spatial distribution, it is necessary to include in consideration geographical specifics of areas which control energy and mass exchange in the "atmosphere–hydrosphere–lithosphere–cryosphere–biosphere" system. This requirement highlights the key importance of using appropriate methodologies, enabling to select relevant qualitative and quantitative characteristics of natural processes that would provide an adequate description of the phenomenon of interest.

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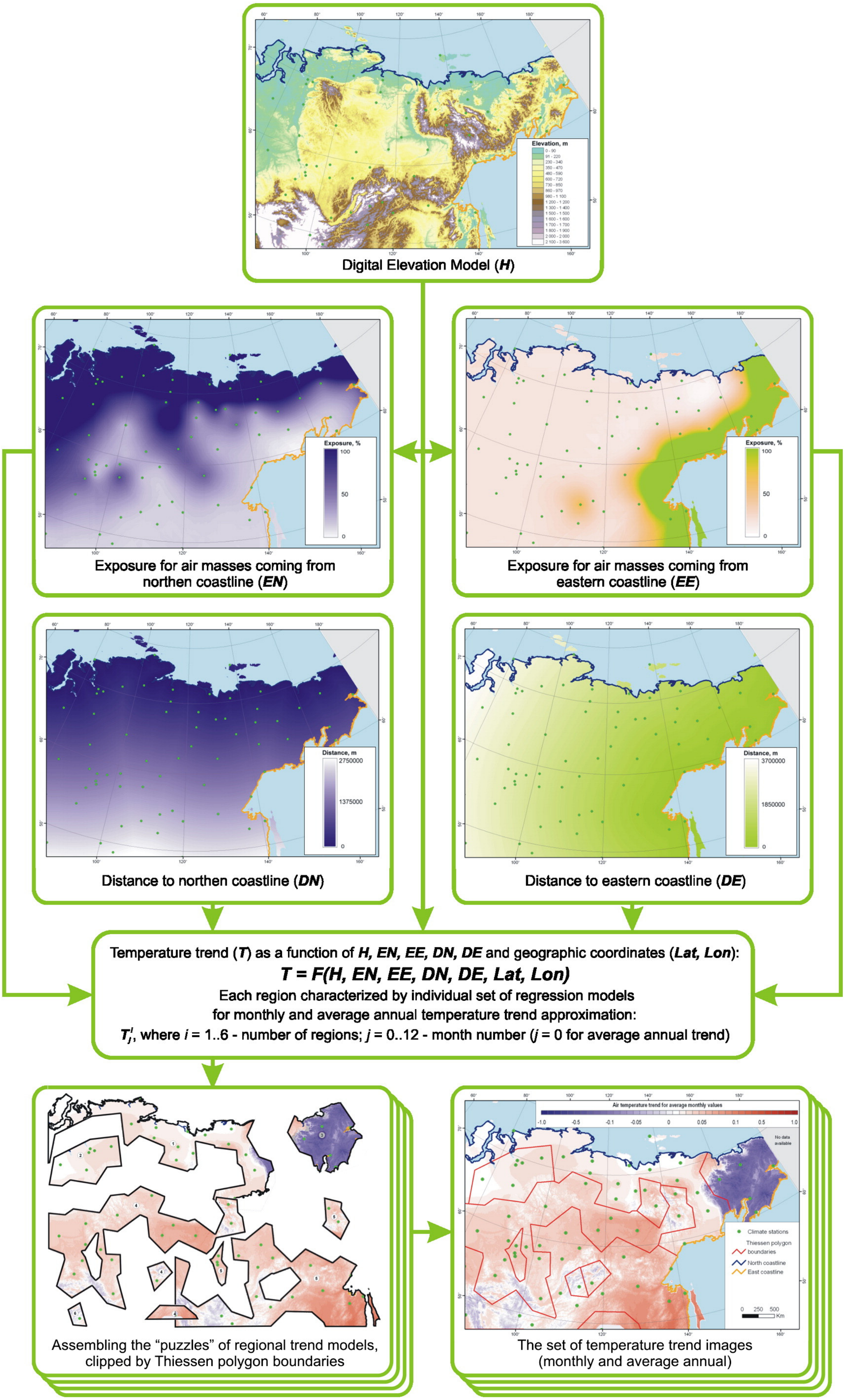

Fig. 4. Air temperature trend mapping algorithm.

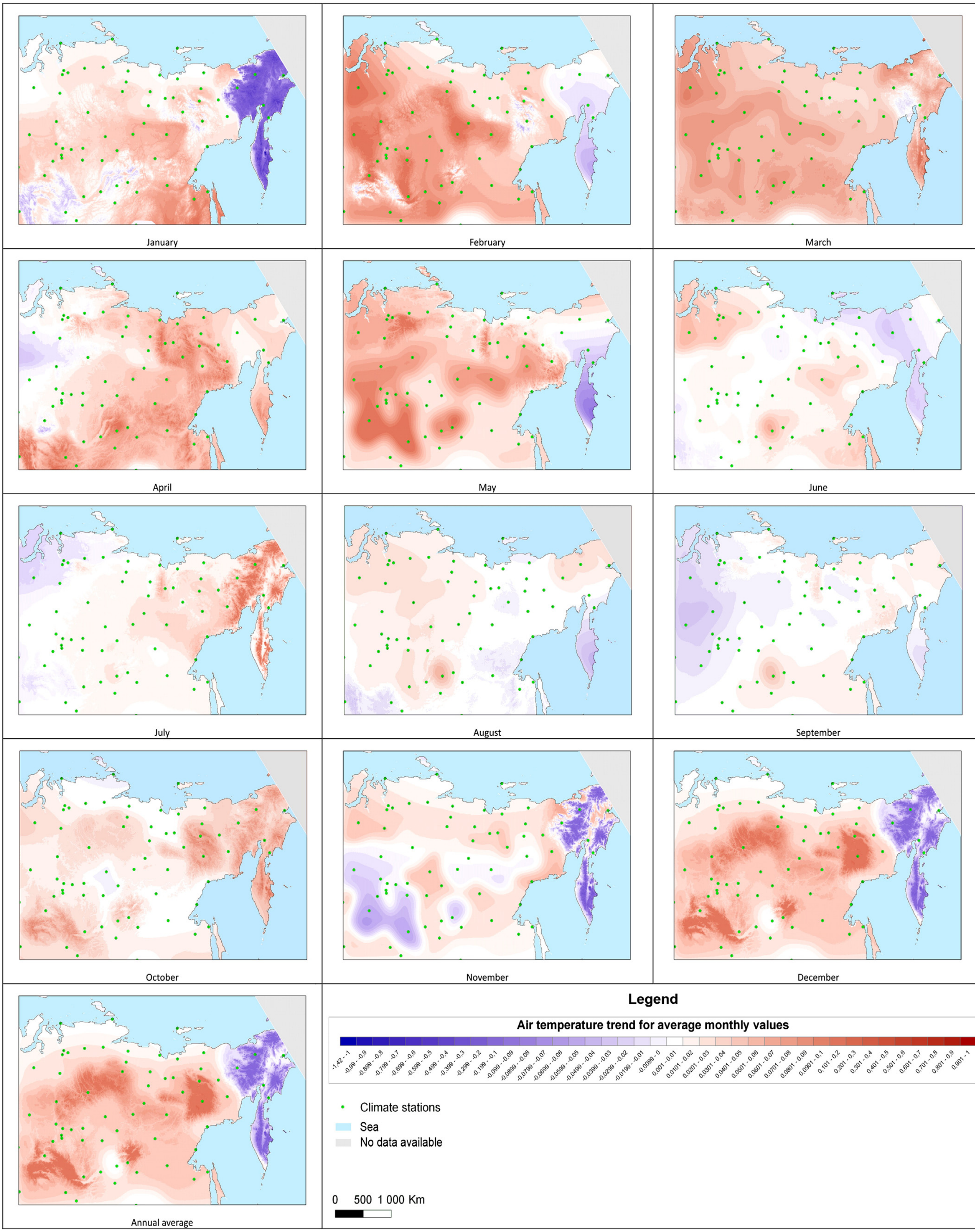

Fig. 5. Air temperature trends.

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