Convective potential of the atmosphere of Western Siberia amid global climate change

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Abstract. In the process of warming, the atmosphere of Western Siberia gets warmer and wetter due to local sources of moisture. This is accompanied with amplification of convection processes in the warm seasons and increasing frequency of extreme weather phenomena. Trends in atmospheric instability and their causes on a territory located in the Ob-Irtysh interfluve and limited by 50–64 °N, 60–95 °E, including the Vasyugan Swamp, are analyzed. The swamp boundaries distinctly marked on temperature maps in the last decade indicate changes in the thermal radiation of the swamp surface. These changes in heterogeneity of heating and heat exchange are reflected in changes in atmospheric instability as well. The greatest changes in the atmospheric temperature mode have been observed in the Great Vasyugan Swamp.

1. Introduction

According to the results of studies of hazardous convective phenomena and their recurrence for the West Siberia territory, it was found that the hail cases including large hail [1], the thunderstorm season duration [2], the convective cloud height [3, 4] have increased in the recent decade. This indicates that the convective potential of the atmosphere of Western Siberia has changed. Amid global climate change, the convective processes have become more powerful and began to develop much more often.

The physical processes caused by the stratification of temperature and humidity determine the potential power of convective processes in the Earth’s atmosphere. To maintain convection the vertical temperature gradient must be greater than the dry-adiabatic gradient to the condensation level and greater than the moisture-adiabatic gradient above this level, i.e., the atmosphere must have an unstable stratification. Such conditions are created in summer in the air above the heated land and are intensified in the presence of sources of moisture entering the atmosphere as it warms up. The more the atmosphere is heated, the more it can potentially raise the water vapor to the upper boundary of the troposphere and form powerful cumulonimbus clouds [5].

The purpose of this research is to analyze trends in the atmosphere instability and its causes in the summer period for a territory located in the Ob-Irtysh interfluve limited by 50–64 °N, 60–95 °E.

The climate change in Russia in general (on average per year and across the territory) is characterized as continuing warming against the background of a slowdown in global warming that has been outlined in the last decade. On the territory of Western Siberia, the warming of the atmosphere continues in all seasons, except for winter, when warming has slowed down [6]. Macrocirculation processes and local factors can be reasons for the warming. If there are extensive sources of moisture in the form of swamps on the underlying surface of the study area, an increase in the atmosphere instability is natural and, consequently, an increase in the frequency of hazardous convective phenomena in the form of heavy rain, thunderstorm, hail, and even the appearance of tornadoes. In this regard, it is important to reveal the presence of changes in the degree of convective
atmosphere instability of Western Siberia, especially in the last decade noted by increased cyclogenesis for the researched territory [7].

2. Methods of research and initial data
In accordance with this goal, we estimated the variability of the degree of convective instability for the Western Siberian territory by using the KIND index. The KIND is a measure of thunderstorm potential based on the vertical temperature lapse rate, and the amount and vertical extent of low-level moisture in the atmosphere. The values of KIND depend on the temperature and humidity of the atmosphere in the layer up to the level of 500 hPa (5.5 km):

\[
\text{KIND} = (T_{850} - T_{500}) + TD_{850} - (T_{700} - TD_{700}),
\]

where \( T_{850}, T_{700}, \) and \( T_{500} \) is the temperature at levels 850, 700, and 500 hPa, °C, respectively; \( TD_{850}, TD_{700} \) is the dew point temperature of 850 and 700 hPa, respectively, °C.

KIND is one of the best indexes for analyzing the atmosphere instability degree of Western Siberia [8, 9] at which the development of hazardous convective phenomena is probable. For example, with KIND > 30 the probability of a thunderstorm over the analyzed area is at least 70%, and with KIND > 33 it is at least 90%.

The temperature and KIND values for the summer months at the 0.25 ° × 0.25 ° grid points from 1990 to 2019 were determined from data of the ERA5 reanalysis, which represents the fifth generation of the reanalysis of global atmospheric observations developed by the European Centre for Medium-Range Weather Forecasts. The use of ERA5 data is due to their advantages: continuous data series over a period of more than 40 years (from 1979 to the present), high spatial (0.25 ° × 0.25 °) and temporal (1 hour) resolution [10], and high accuracy of description of the temperature mode. ERA5, like the previous version of ERA-Interim, has a mean error of temperature values of 0.8 °C and a mean square deviation of 2–2.5 °C. The time series of temperature in ERA5 are homogeneous for the territory of Siberia and, therefore, can be used to identify spatial heterogeneity due to local factors.

3. Results and discussion

3.1. Analysis of the spatial distribution of temperature in summer
The mean values of temperature for the summer months at 09:00 and 18:00 Coordinated Universal Time (UTC) and median values for the same periods were analyzed to identify features of the spatial distribution of temperature. The geographic distribution of the mean temperature values for 1990–1999 constructed according to the ERA5 reanalysis data can be called typical for the period up to 2000. The temperature zoning is disturbed by a trough in the northeastern direction, which can be traced on all early maps and diagrams representing the climatic features of Western Siberia. Such a distribution of temperature over Western Siberia is possibly due to the presence of the Great Vasyugan Swamp. At present, it is believed that the area of the Great Vasyugan Swamp is from 53 to 55 thousand square kilometers, 1.7 times exceeds the area of Baikal Lake. Excluding the irregularities of the boundaries, its length is 570 km and its width is 320 km, the coordinates are from 55.40 to 58.60 °N and from 75.30° to 83.30° E. An object of this size undoubtedly affects the temperature and humidity of the region's atmosphere. At the same time, monitoring the temperature and humidity state of the atmosphere over the territory of the swamp system is a very difficult task. First of all, this is due to the inaccessibility of the territory for equipping it with direct measurement sensors and an extremely sparse network in the vicinity of the swamp. Remote measurements of the temperature characteristics of the underlying surface also remained a difficult task until recently. The reasons for this were insufficient accuracy of the parameters measured from meteorological satellites and low spatial resolution. The mean values of temperature over the studied region for three decades: 1990-1999, 2000-2009, and 2010-2019 are shown in Figure 1. Moreover, the values are given typically for the period when the maximum development of convection is observed in the atmosphere (09:00 UTC). This temperature characterizes a combination of the influence of advective and local factors on the thermal mode of the atmosphere. By the end of the study period, the isolines of equal temperature values began to demonstrate a more latitudinal temperature variability in the Ob-Irtysh interfluve,
although for many decades before the warming period they showed a trough. Isotherm 21 °C has begun to be located to the north.

Figure 1. Inter-decadal changes of mean temperature: a case study of isotherm 21 °C.

The position of the isotherm 14 °C for the summer months at 18 UTC for three periods: 1990–1999, 2000–2009, and 2010–2019 is demonstrated in Figure 2. The measurement time 18 UTC is more representative of the temperature, since the atmosphere heats up during the day because of various heat transfer processes between the atmosphere and the underlying surface. In our opinion, the analysis of long-term variability of this temperature most fully characterizes the influence of local factors on climate change in the region.

Note that the 14 ºС isotherm, since 2019, began to practically outline the Great Vasyugan Swamp from its southern and western sides. Moreover, the spatial position of the isotherm has changed significantly in the last decade. Heat centers that are one degree or more higher than the mean background temperature values for this territory appeared in the Ob-Irtysh interfluve and above the swamp complex southwest of Khanty-Mansiysk. A tornado was recorded in Khanty-Mansiysk region in 2012 [11]. The presence of temperature inhomogeneities of the underlying surface in conditions of high atmospheric moisture content could be the cause of the origin of the tornado. Such temperature inhomogeneities located both within the Great Vasyugan Swamp territory and along the contours have appeared in the last decade. One of the explanations for this process is an increased methane content.

A clear seasonal variation with significant methane fluxes in summer is noted over the swamp systems. An increase in the temperature values can be expected given the high heat capacity of methane. These increases occur unevenly over the territory, but in separate centers due to the diversity of the structures of the swamp complex. This process makes a regional contribution to the existing climate warming trends in Siberia. An increase in the content of water vapor in the atmosphere and a manifestation of its instability in general is expected amid an increase in the mean annual temperature.

The distribution map of the median values of daytime temperatures (09:00 UTC) over the Ob-Irtysh interfluve in the last decade also demonstrates the presence of temperature inhomogeneity in the form of centers with a warmer atmosphere near the underlying surface. Note that the geographical location of such heat centers coincides in studies for different periods. However, the median values of mean summer temperatures show higher values over the entire area covered by the interfluve swamp systems. Differences in the distribution of the daytime temperatures can be caused, first, by the changed conditions of heating of the underlying surface. Differences in heating will undoubtedly intensify convection in the study region and, as a result, non-uniform thunderstorm activity distribution [12, 13].
A significant increase in the values of night temperatures can be explained by several reasons: an increase in the water vapor condensation with the release of latent heat and an increase in the cloudiness at night against the background of a stronger heating of the underlying surface during the day.

If the tendencies of temperature rise in the summer months and sources of additional atmospheric humidification persist, its instability may increase significantly and, as a result, the frequency of hazardous convective phenomena will also increase.

3.2. Spatial features of convective instability fields in different decades

To identify the zones of territorial heterogeneity of the convective atmosphere instability, an analysis of the change in the KIND values for the summer months (June-August) at 09:00 UTC of the periods 1990–1999, 2000–2009, and 2010–2019 was carried out. The KIND values directly proportionally reflect the atmosphere instability degree due to the temperature and moisture content of the layers up to 5000 m. If the atmosphere is stable, its values are close to 0, the more unstable is it, the greater is the KIND value. The threshold values of the index in case of thunderstorm formation with a probability of 70% and 90% for most aerological stations in Western Siberia are KIND values > 30 and > 33, respectively [8].

Analysis of the spatial location of the KIND values isolines demonstrates an increase in the degree of convective atmosphere instability of Western Siberia assessed by the temperature and humidity characteristics in a layer up to 500 hPa.

The variability of the 30 °C isoline position correlates with the variability of the temperature fields shown in Figure 3. The greatest changes in the atmosphere instability capable of increasing the recurrence of hazardous convective phenomena were in the range of 60-62 °N.

Figure 4 is of greatest interest for demonstrating the results of our research, since it illustrates the emergence of centers with a high level of atmospheric instability in the Ob-Irtysh interfluve. This heterogeneity cannot be explained by the presence of orographic features. The only logical explanation may be the increased temperature heterogeneity of the underlying surface, which forms a strong instability with an increase in the moisture capacity of the atmosphere, which allows powerful convective clouds to generate heavy rain, hail, and thunderstorm.

These findings are consistent with an increase in the thunderstorm activity and cases of hail, including large-diameter hail [2]. In addition, there is an increase in the mean values of the upper limit of cumulonimbus clouds and, accordingly, the convectively unstable layer, which indicates more powerful convective processes in general. Before global warming, the mean long-term number of days with a thunderstorm in the north of Tomsk Oblast was 16-19 days, in the southern part it reached 25-
28 days [12]. In the recent years, thunderstorms above 60° latitude of Western Siberia are being recorded more frequently. Moreover, a comparison of the characteristics of hail under the conditions of modern climate change (compared with the period 1936–1965) demonstrated a tendency to double the number of days with a prolonged hail (30-60 minutes), as well as a hail with a diameter greater than 10 mm [1].

Figure 3. Isolines of mean values of KIND 30 °C.

Figure 4. Isolines of mean values of KIND 31 °C.

4. Conclusions
As a result of the above analysis of spatial distributions of temperature and features of convective instability fields, the following conclusions can be made: Over the past thirty years, the boundary of active convection has gradually moved northward and by 2019 has reached a parallel of 62 °N. A particularly noticeable increase in atmospheric instability is observed in a region limited by 75–85 °E and 60–62 °N.

The greatest changes in the atmospheric temperature mode have been observed in the Great Vasyugan Swamp and swamp systems in a confluence area of the Ob and Irtysh rivers. In the last decade, the Great Vasyugan Swamp boundaries clearly marked on night temperature maps indicate
changes in the thermal radiation of the underlying surface over the swamp territory. The inhomogeneity of heating and heat transfer are reflected in the change in atmospheric instability amid increasing moisture capacity of the atmosphere.

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