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THE SPATIO-TEMPORAL DISTRIBUTION OF MESOSCALE CONVECTIVE COMPLEXES OVER SOUTHEASTERN WESTERN SIBERIA

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The temporal variability of mesoscale convective complexes (MCCs) formed over southern Western Siberia for the period 2010–2019 has been assessed. During the period of study a total of 279 cases of MCCs were recorded, and two centers having the highest occurrence of MCC were identified. The first repeatability maximum is observed over the northwestern slopes of the Altai Mountains, the Salair Range and the Baraba Lowland, and the second is located over the southern Omsk Region. It was found that higher MCC repeatability over the northwestern Altai Mountains is represented by the air mass genetic type, whereas the MCCs, occurring over the Salair ridge and the Baraba lowland, are related to the frontal type. When evaluating the characteristics of the MCC, it was revealed that the areas of the air mass MCCs are smaller than for the frontal ones, but their cloud top height and the cloud effective radius is higher than for the frontal ones.

Keywords: *mesoscale convective system (MCS), mesoscale convective complex (MCC), MODIS spectroradiometer*

Introduction

In the second half of the 20th century and the beginning of the 21st century, in the regions of Northern Eurasia, an increase in the proportion of convective clouds was noted [Chernokulsky et al., 2011]. The continuation of present trends could lead to an increase in frequency of associated hazardous phenomena such as hail, intense showers, squalls, etc. Mesoscale convective systems (MCS), and especially the subtype termed "mesoscale convective complexes" (MCCs) [Vel'tishchev, Stepanenko, 2006] are a severe manifestation of convective cloudiness. The MCC is a complex of cumulonimbus clouds united by a common quasi-oval anvil [Maddox, 1980; Houze, 2004, 2014].

Infrared images of MCCs have the following characteristics: the area of more or less continuous cloud cover with the upper boundary temperature below –32 °C is not less than 10^5 km^2, and the area of the inner region with upper boundary temperature below –52 °C is not less than 5×10^4 km^2. The specified dimensions are retained for 6 hours or more. The lifetime of the MCC is about 16 hours, but in some cases can last more than a day. Most MCCs exhibit a nocturnal life cycle that begins in mid to late midday, reaches its peak after midnight, and ends shortly after dawn [Laing, Fritsch, 1997]. Known for its production of severe weather and copious rainfall [Maddox, 1980; Fritsch et al., 1986; McAnelly, Cotton, 1989], a MCC typically forms in association with a weak mid-tropospheric short-wave trough and a weak surface front or outflow boundary. Its environment often exhibits pronounced low-level temperature and moisture advection in association with a well-defined low-level jet [Cotton, 1989; Augustine, Howard, 1991].

MCCs can be found in different geographic regions [Maddox, 1980; Velasco, Fritch, 1987; Augustine, Howard, 1991; Laing, Fritsch, 1997; Houze, 2004, 2014], including in Western Siberia [Kuzhevskaya et al., 2018; Zhukova et al., 2019]. However, in temperate latitudes, their sizes may be significantly smaller than those described for tropical regions. MCCs are known for generating hazardous weather conditions and heavy rainfall [Maddox, 1980; Fritsch et al., 1986; McAnelly, 1989]. It is widely known that MCCs significantly change the environment in which they develop [Fritsch, Maddox, 1981; Wetzel et al., 1983; Augustine, Zipser, 1987; Johnson, Bartels, 1992], and that they play an important role in initiating subsequent convective weather events [Fritsch et al., 1994]. MCC studies over the temperate latitudes of the United States [Maddox, 1980; Augustine, Howard, 1991; Houze, 2004] revealed a tendency for their formation from the anticyclonic side of a wide and relatively weak frontal zone. It is also known that the presence of synoptic heterogeneity is necessary to ensure the convergence of air flows and the inflow of a large amount of moisture into the lower atmosphere. For North America, such conditions are easily achievable due to the proximity of the Atlantic Ocean.

The territory of the south of Western Siberia is characterized by a complex terrain, which influences the development and evolution of convective clouds, as well as the nature of the associated hazardous phenomena. However, this complexity makes it difficult to predict atmospheric convection. Earlier studies analyzed the temporal and spa-

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tial dynamics of atmospheric instability characteristics over the territory of Western Siberia in the presence of registered hazardous convective phenomena such as thunderstorms and hail [Gorbatenko et al., 2020; Gorbatenko, Konstantinova, 2011], and also for thunderstorms in the cold season [Zhokhova et al., 2018]. Studies of the height of cumulonimbus clouds were carried out in the presence of extensive thunderstorms, hail, and squalls [Gorbatenko et al., 2020; Ananova et al., 2007].

It has been noticed that over the last decade, the boundary of active convection, assessed by the temperature and humidity characteristics of the atmosphere, has shifted to the north. There has also been an increase in the duration of the thunderstorm season and the number of days with thunderstorms per year, as well as the number of days with prolonged hail and large diameter hail [Gorbatenko et al., 2020; Kuzhevskaia et al., 2019]. Using information from meteorological satellites, the cloudiness was measured diagnosed during the periods of heavy precipitation [Kuzhevskaya et al., 2018] and approaches to the numerical modeling of the spatial localization of convective cells were developed [Nechepurenko et al., 2016].

The synoptic situations favorable to MCC formation and the production of hazardous phenomena were determined; the state of the atmosphere was assessed using the instability indices KIND and LIFT. It was noted that the MCC is formed during periods of both average and low degree of atmospheric instability [Zhukova et al., 2019]. In addition, estimates were obtained of the influence of powerful convective clouds, including MCC, as well as associated adverse and hazardous phenomena on the electrical state of the atmospheric surface layer in southern Western Siberia [Nagorskiy et al., 2014; Pustovalov, Nagorskiy, 2016, 2018a, 2018b; Nagorskiy et al., 2019].

The present study is aimed at assessing the spatio-temporal distribution and typical characteristics of the MCCs in southeastern Western Siberia. The assessment of the repeatability and characteristics of the MCCs was carried out for all recognized cases and also separately for the MCCs of frontal and air mass origin. This separate analysis is important because of significant differences in the conditions of formation, structure and form of MCCs of these two genetic types [Maddox, 1983; Houze, 2004; Zhukova et al., 2019].

Description of the study area

The study was carried out for an area in southern Western Siberia, located in the central part of Eurasia, far from any oceanic coastline. The study area is mainly represented by flat terrain – the Vasyugan, Ket-Tymkaya, Ishim and Kulundinskaya plains and the Barabinskaya lowland (Fig. 1). The exception is the south-eastern part of the territory, which is characterized by the mountainous Salair Ridge, Kuznetsk Alatau, as well as the northern part of the Altai Mountains and the western part of the Western Sayan. The northern part of the study area is heavily swampy and includes the largest swamp system in the northern hemisphere – the Vasyugan Swamp [Gorbatenko, Tunaev et al., 2020]. According to the authors [Tunaev, Gorbatenko, 2018], the Vasyugan Swamp plays a significant role in the formation and development of young cyclones, and the maximum contribution of swamps is noticeable in the summer. Above the Vasyugan Swamps, there is a so-called energy “recharge” and a significant increase in the moisture content and convective potential of the atmosphere.

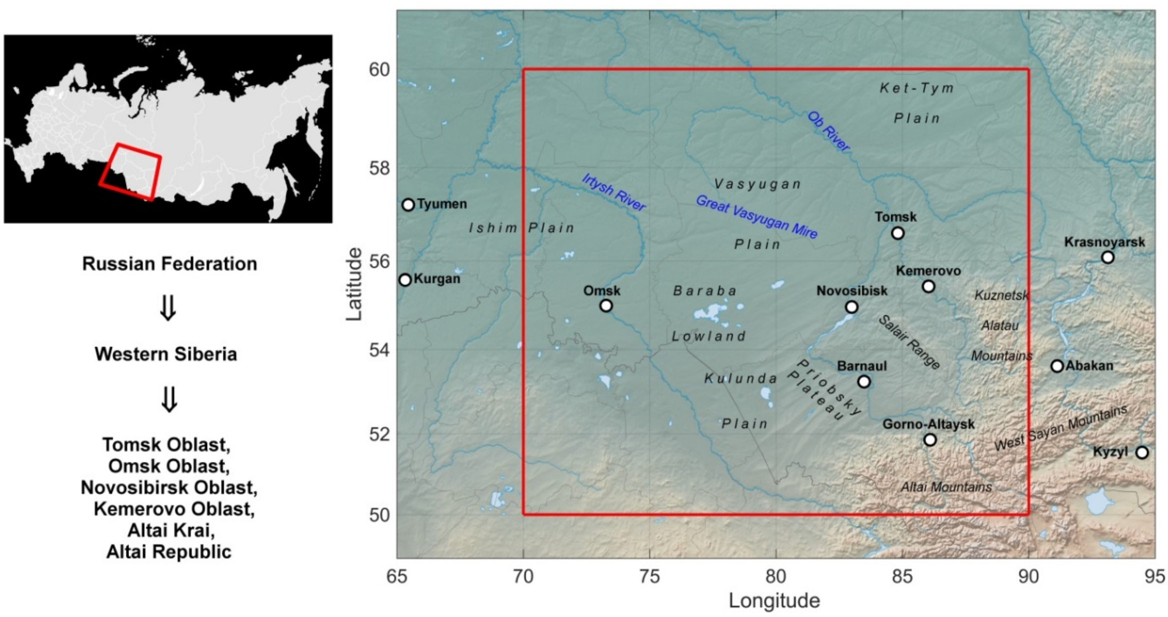


Fig. 1. Location of the study area

Рис. 1. Расположение территории исследования

The main part of the study area is occupied by a unique landscape zone – the forest-bog zone of Western Siberia, with swamp systems covering about 40 %, and in some areas, up to 90 % of the area. To the south of the forest-bog zone, there is a forest-steppe zone, which is also characterized by high (up to 25 %) boggy terrain and a large number of lakes. The influx of a large amount of moisture into the atmosphere in this region occurs with the arrival of transformed air masses of southern Mediterranean cyclones, but could also be due to evaporation directly from the underlying boggy (water-rich) surface.

Based on the classical ideas about the climate pattern in Southern Siberia in summer, cyclonic circulation should dominate here. Observations of the last two decades have revealed features in the summer circulation over the regions of Siberia. An increase in the frequency of occurrence of meridional southerly flows in summer over Western Siberia is noted [Kononova, 2015; Podnebesnykh, Ippolitov, 2019]. Such synoptic situations contribute to the formation of abnormally warm air over vast areas, which, given the existing synoptic heterogeneity, contribute to the development of powerful cumulonimbus clouds and even MCCs.

Data used and research methodology

RGB images of clouds [https://worldview. earthdata.nasa.gov/] and second-level processing products MODATML2 and MYDATML2 (resolution 5×5 km) [http://ladsweb.nascom.nasa.gov/], obtained from the MODIS spectroradiometer data, were selected. The MODIS spectroradiometer (Moderate Resolution Imaging Spectroradiometer) is one of the key instruments on the Terra and Aqua spacecraft [Qu et al., 2006]. Additionally, the synoptic charts with frontal analysis [https://meteoinfo.ru/mapsynop] were used.

The first stage of the study was based on satellite images, and a visual interpretation of MCSs of an asymmetric type was carried out [Vel'tishchev, Stepanenko, 2006; Houze, 2014], these have a quasi-oval shape and a cross section of at least 50 km. Over the period from 2010 to 2019, more than 460 such cases were recorded. Based on synoptic maps [https://meteoinfo.ru/ mapsynop], the noted MCS cases were divided into air mass and frontal genetic types. A distinguishing characteristic of the frontal MCS is the entry into the cloudy band of a warm or cold front, which is detected near the occlusion point from the side of the warm air mass. Air mass MCSs are interpreted as single cloud structures, occurring in clusters of *Cumulonimbus* clouds, in the frontal zones of the cold front and zones of fully occluded cloud systems. The timing of selected MCSs was identified and the coordinates of their centers were determined.

Comparison of selected cases of asymmetric MCS passage in the southeast of Western Siberia (Fig. 2, *a*) with MCC over different regions of the globe (Fig. 2, *b*, *c*) showed that despite the fact that the selected convective systems, as a rule, do not reach the threshold size established for the MCC [Vel'tishchev, Stepanenko, 2006; Houze, 2014], in terms of their other characteristics and characteristics of the accompanying atmospheric phenomena [Zhukova et al., 2019], they generally correspond to MCCs. Thus, the authors made the assumption that the selected MCS of an asymmetric type in the southeast of Western Siberia, in general, can be considered MCCs, however, due to regional features, their sizes are somewhat inferior to the MCCs in the tropical belt and the threshold sizes described in [Vel'tishchev, Stepanenko, 2006; Houze, 2014], are not fully applicable to the study area. Thus, it is necessary to develop new criteria for identifying MCC in the southeast of Western Siberia.

The second stage of the study involved formalization of the recognized MCS cases and the calculation of their morphological and microphysical characteristics based on the data of MODIS cloud products and according to the methodology developed by the authors (see below). The MODATML2 / MYDATML2 [http://ladsweb. nascom.nasa.gov/] files were selected for the transit date and coordinates of the selected MCS of the asymmetric type, containing two-dimensional data arrays (cells of which are 5 × 5 km in size) with cloud products, the following of which were used in this work: Cloud Optical Thickness (COT); Cloud Effective Radius (CER); Cloud Top Height (CTH); Cloud Water Path (CWP); Cloud Top Pressure (CTP); Cloud Top Temperature (CTT).

Based on MODIS cloud products, a mask was constructed consisting of pixels of 5×5 km, with the following recognized conditions: $CTT \leq 200$ K (–32 °C) [Maddox, 1980], $COT \geq 30$. For each case, the mask area was computed as the sum of all pixels within the mask multiplied by the area of one pixel (25 km^2). The lengths of the mask chords along latitude ($l_{lat(i)}$) and longitude ($l_{lon(i)}$) were also calculated as the product of the sum of pixels along the meridian and parallel, respectively, multiplied by the pixel size (5 km). The values l_{lat} and l_{lon} corresponding to the 95th percentile were taken as the lengths of the entire convective complex along latitude and longitude – L_{lat} and L_{lon}. In addition, based on the values of the products *CTH, CWP, CER, CTT, CTP* in pixels falling inside the mask, the average values of the upper boundary height, integral moisture content, effective particle radius, temperature and pressure at the upper boundary of the MCC were calculated. The scheme for performing these calculations is shown in Figure 3.

To exclude small convective complexes from further consideration, additional filtering of cases was carried out. We eliminated those convective complexes with a mask area less than a certain threshold area ($S_п$). Two variants of $S_п$ were used:

1) 5,000 km^2 (1/20 of the threshold area determined for tropical regions [Maddox, 1980]);

2) 10,000 km^2 (1/10 of the threshold area determined for tropical regions [Maddox, 1980]).

a

b

c

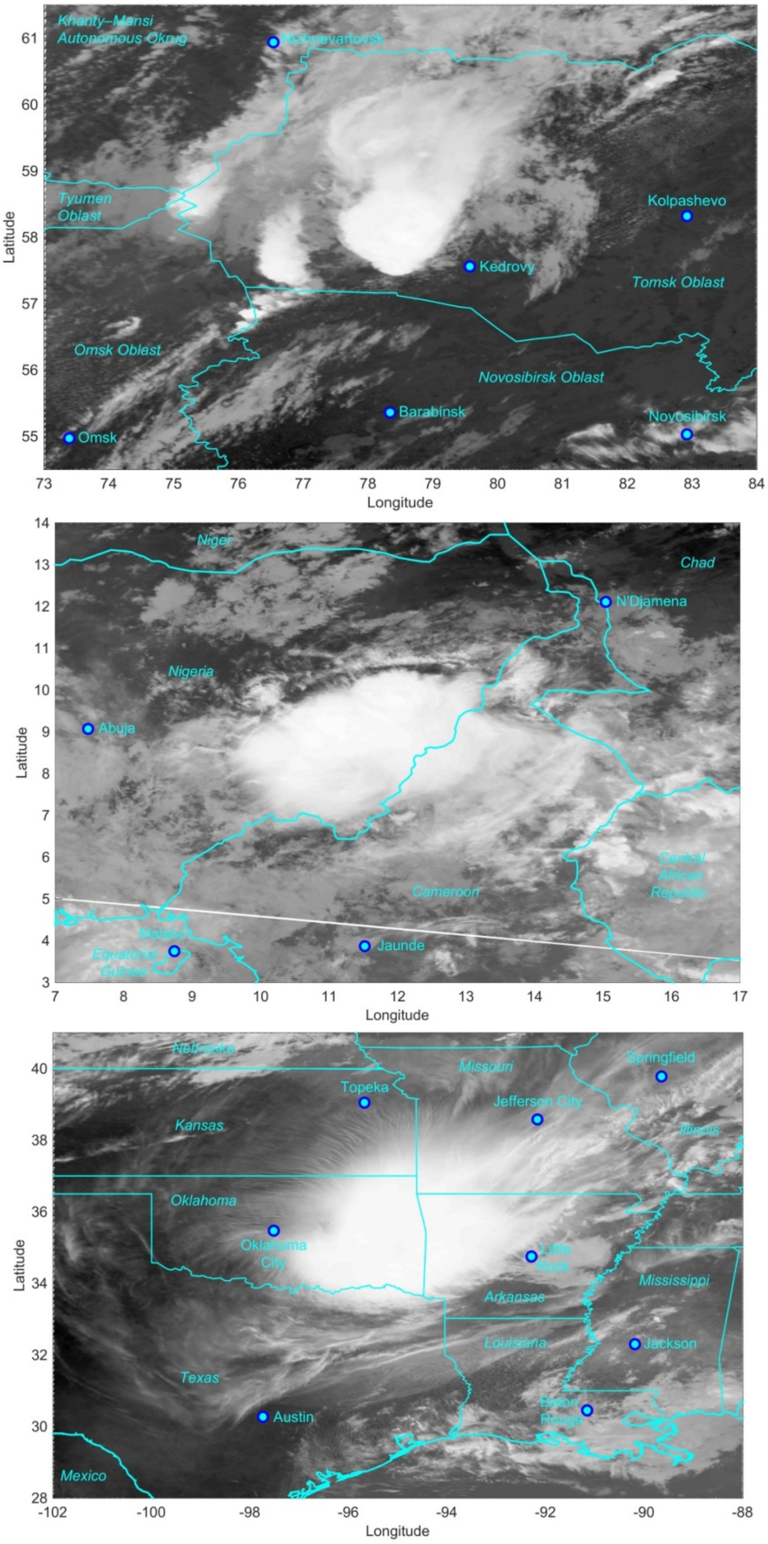


Fig. 2. Examples of asymmetric MCC (mesoscale convective complexes) images in the southeast of Western Siberia (06/29/2017; a), in central Africa (09/19/2019; b) and over the Great Plains of the USA (06/17/2017; c) according to data from 31 channels (10.8–11.3 μm) of the MODIS spectroradiometer (Terra satellite)

Рис. 2. Примеры изображений МКС асимметричного типа (мезомасштабных конвективных комплексов) на юго-востоке Западной Сибири (29.06.2017; a), в центральной Африке (19.09.2019; b) и над Великими Равнинами США (17.06.2017; c) по данным 31 канала (10,8–11,3 мкм) спектрорадиометра MODIS (спутник Terra)

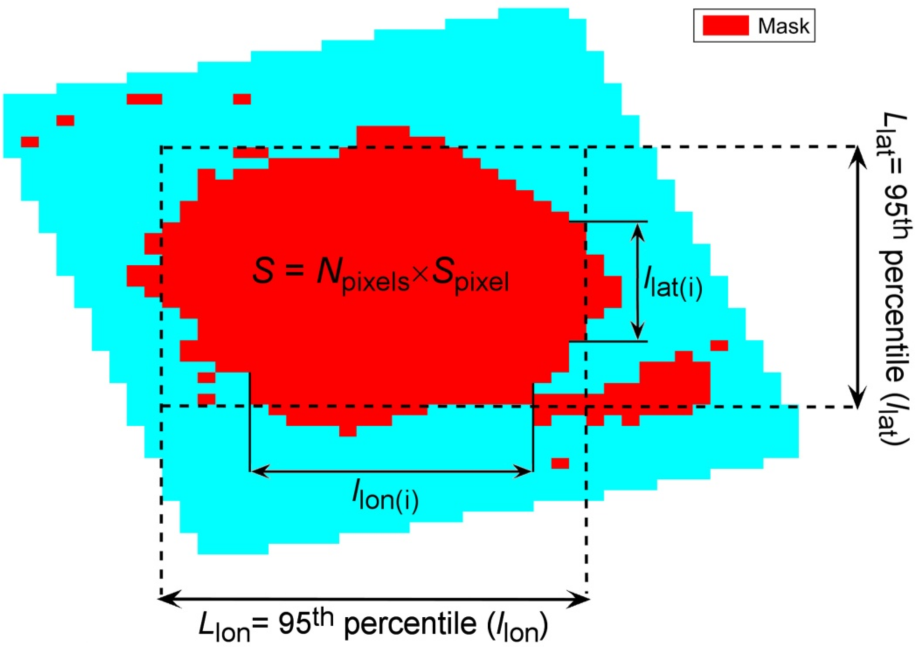


Fig. 3. Scheme for calculating the linear characteristics of the MCC

Рис. 3. Схема расчета линейных характеристик МКК

Each of the categories of the selected MCC cases was subdivided into frontal and air mass. Since the use of $S_п$ = 10,000 km^2 leads to a strong decrease (by a factor of five) in the number of cases under study, then in the further study, we considered the cases of MCC selected at $S_п$ = 5,000 km^2.

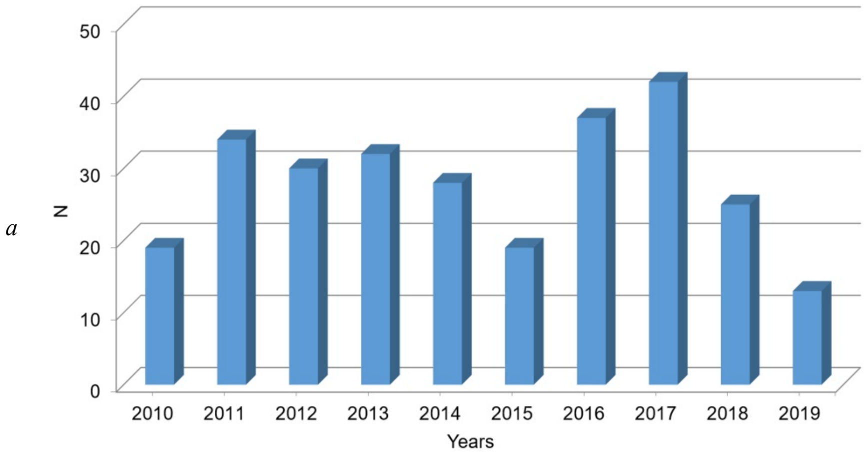
The third stage of the study assessed the spacio-temporal variability of the MCC over the study area, as well as the typical values and variability of the morphological and microphysical characteristics of the MCC cloudiness. To assess the MCC occurrence frequency over the study area, the number of cases per cells 2 × 2° in latitude and longitude was calculated, both for all cases and separately for frontal and air mass cases. Based on the calculations performed, smoothed frequency distributions (in % of the total) were constructed over the study area of MCCs (Fig. 4).

Results obtained and their analysis

Based on the methodology described above, 279 cases of the MCC were identified in southern Western Siberia for the period from 2010 to 2019. The frequency of MCC recurrence is shown in Figure 4; an average of 27 cases of MCC were noted per year. The maximum frequency of occurrence was recorded in 2017 (42 cases), the minimum in 2019 (13 cases). This minimum can, presumably, be explained by the fact that in 2019 there were strong forest fires in Siberia, smoke plumes from which spread over the study area, creating zones of stable stratification. There is cyclicity of MCC occurrence with a period of ~ 5 years. So, in 2010, 2015 and 2019, a minimum of recurrence is noted, and in 2011 and 2017, the maximum. This cyclicality is due to the variability of the MCC occurrence frequency of air mass origin. At the same time, in the occurrence frequency of frontal MCCs, it is also possible to trace the cyclicality with a period of 10 years or more. In addition, it can be noted that in 2010–2011 and from 2016 to 2019, air mass MCCs prevailed over frontal ones, and from 2012 to 2015 they were inferior to them.

The highest frequency of MCC is observed in southwestern Western Siberia (Fig. 5), in particular, over the northwestern slopes of the Altai Mountains, the Salair Ridge and the Barabinsk Lowland. A weaker maximum is noted over the southern Omsk Oblast. In addition, it can be noted that above the floodplain of the Ob River and the Ob reservoir, there is a decrease in the frequency of MCCs, and an increase over the southwest of the Tomsk Oblast (the Vasyugan Swamp). The analysis of the occurrence frequency of frontal and air mass types of MCCs separately (Fig. 5, *b, c*) showed that the source of the MCC recurrence over the northwest of the Altai Mountains is represented mainly by the air mass type, and the sources over the Salair Ridge and the Baraba Lowland are of the frontal type.

Next, we consider the characteristics of the MCC over southwestern Western Siberia. Table 1 shows the values corresponding to the 5th, 50th and 95th percentiles of some MCC parameters, both for all cases, and separately for those MCC of frontal and air mass origin.



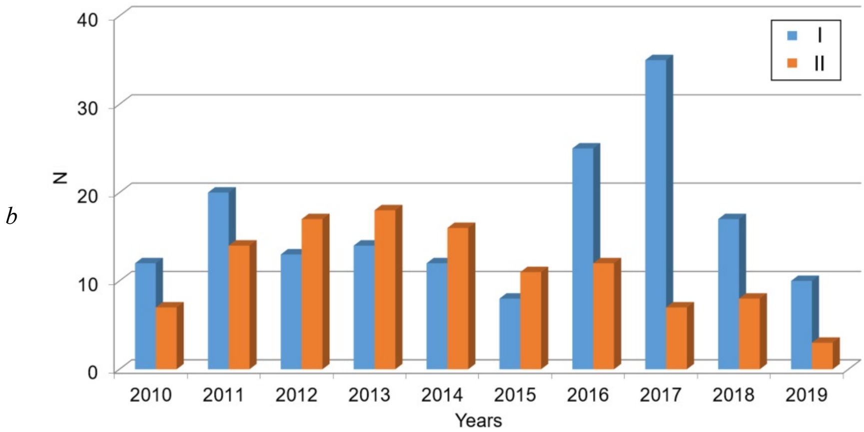


Fig. 4. The frequency of occurrence of MCCs formation in different years (a), of air mass (I) and frontal (II) origin separately (b) for the period 2010–2019

Рис. 4. Временной ход повторяемости МКК различного генезиса (a), а также отдельно внутримассового фронтального происхождения (b) за период 2010–2019 гг.

Table 1

Values corresponding to the 5th, 50th, and 95th percentiles of some parameters of the MCC various genesis

Таблица 1

Значения, соответствующие 5-, 50- и 95-процентилям, некоторых параметров МКК различного генезиса

Parametr / Параметр	S, ×10^3 km^2	*CTH*, km	*CWP*, kg/m^2	*CER*, μm
All cases with MCC	5,2/8,3/17,1	9,2/10,6/12,1	1,0/1,3/1,5	23/26/29
Frontal MCC	5,3/9,2/18,4	9,3/10,6/12,0	1,0/1,3/1,5	22/26/29
Air mass MCC	5,2/7,9/15,9	9,0/10,7/12,1	1,0/1,3/1,5	23/27/29

In general, for all studied cases, the median value of the MCC area is 8.3×10^3 km^2, and its minimum and maximum values (at a confidence level of 95 %) are 5.2×10^3 and 17.1×10^3 km^2, respectively (Table 1). The height of the MCC, as a rule, varies from 9.2 to 12.1 km, and its median value is 10.6 km. The cloud water path for MCC in the south of Western Siberia averages 1.3 kg/m^2 and varies from 1 to 1.5 kg/m^2. The median, minimum, and maximum (with a confidence level of 95 %) of the cloud effective radius in the MCC are 23, 26, and 29 μm, respectively. Comparison of the characteristics of MCCs of frontal and air mass genesis shows that air mass MCCs are much smaller in area than frontal ones, but their cloud top height and cloud effective radius are, in general, larger than those of frontal ones.

Conclusion

Assessment of temporal variability of the MCC for the period 2010–2019 was carried out. On average, there were 27 cases of MCC per year in the southern part of Western Siberia. The maximum frequency of MCC was observed in 2017 – 42 cases and the minimum was observed in 2019 – 13 cases.

A total of 279 cases of MCC were recorded during the study period. During the study period, a cyclic recurrence of the MCC (period ~ 5 years) was observed in the southwestern Siberia. In 2010–2011 and 2016–2019, air mass MCCs prevailed over frontal ones, and was less in 2012–2015.

a

b

c

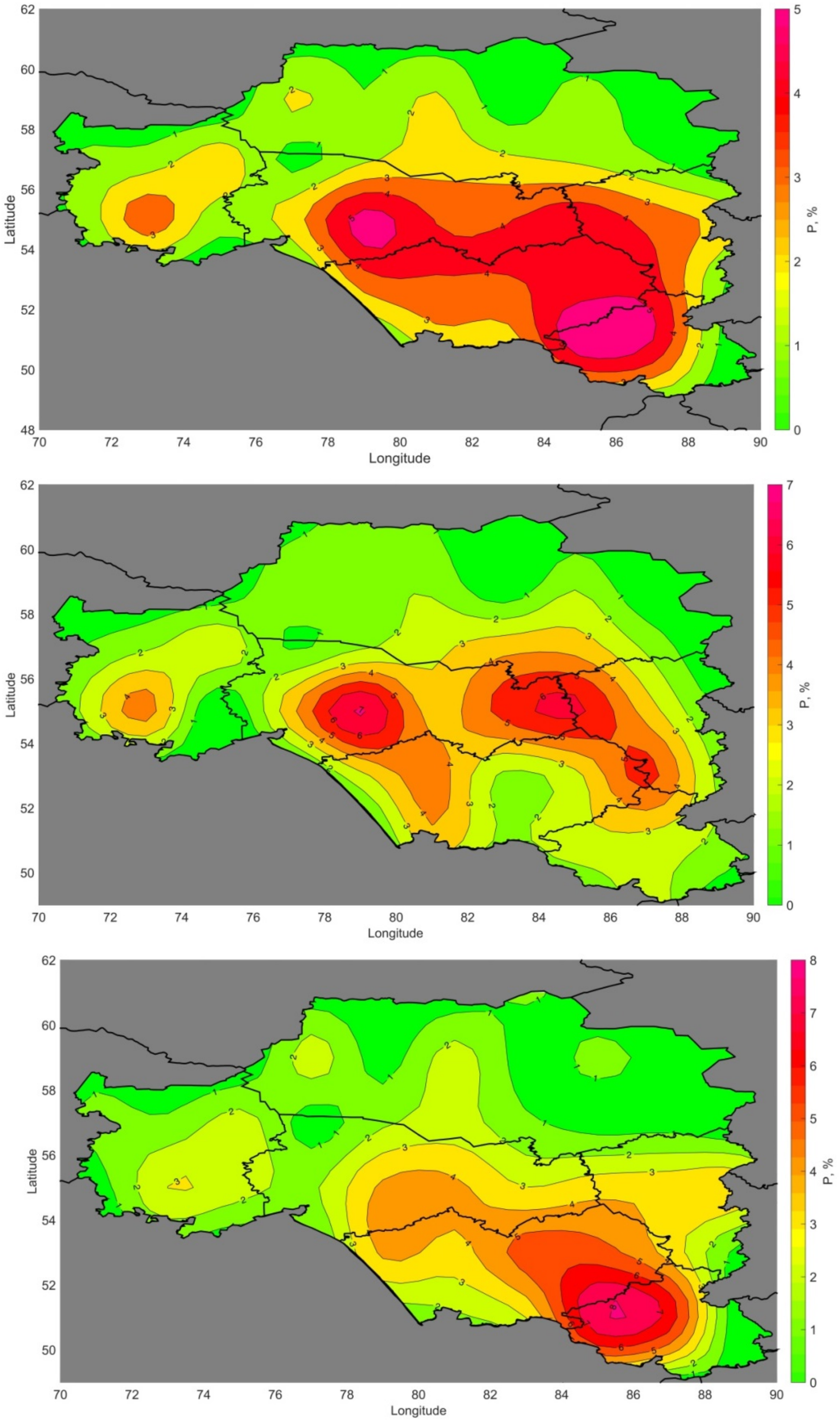


Fig. 5. Smoothed distribution of the occurrence frequency for all selected cases of MCC (a), distribution of the occurrence frequency separately for MCC of frontal (b) and air mass (c) origin in southeastern Western Siberia

Рис. 5. Сглаженное распределение повторяемости всех отобранных случаев МКК (a), а также распределение повторяемости отдельно МКК фронтального (b) и внутримассового (c) происхождения на юго-востоке Западной Сибири

When assessing the spatial heterogeneity of the MCC, it was found that the highest frequency of the MCC was observed over the northwest slopes of the Altai Mountains, Salair Ridge and Baraba Lowland.

A lower maximum is observed over southern Omsk Oblast. The location of the centers of high MCC frequency over the peripheral parts of Altai and the Salair Ridge can be explained by the intensification of convective processes when the air flow enters the windward slopes of these mountain massifs. The centers of high frequency of MCC over the Barabinskaya lowland and the southern part of the Omsk region are associated with intense daytime heating of large volumes of air over the plain territory, mainly covered with meadow-steppe and bog vegetation with low albedo. In addition, the source of moisture for the formation of MCCs is reservoirs and lakes located in the Baraba lowland. A decrease in the frequency of MCC is observed above the Ob river floodplain and the Ob reservoir, while an increase is noted over the Vasyugan Swamp. Analysis of the occurrence frequency of MCCs of frontal and air mass origin separately, showed that the MCCs over the north-western Altai Mountains are mainly belong to the air mass genetic type, and the centers over the Salair Ridge and the Baraba Lowland belong to the frontal type.

In general, the following parameter values are characteristic for all investigated cases of MCC: area is from 5.2 to 17.1×10^3 km^2; the cloud top height is between 9.2 to 12.1 km; cloud water path ranges 1 to 1.5 kg/m^2; the cloud effective radius is 26–29 µm. When comparing the obtained characteristics with the characteristics given by the authors [Maddox, 1980; Vel'tishchev, Stepanenko, 2006], for other regions of the study, it can be concluded that MCCs over southeastern Western Siberia are much less frequent, but at the same time, they are no less dangerous for human activities. An assessment of the MCCs characteristics of frontal and air mass origin showed that the areas of air mass MCCs are much smaller than the frontal ones, but they characterized by larger values of the cloud top height and cloud effective radius.

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МЕЗОМАСШТАБНЫЕ КОНВЕКТИВНЫЕ КОМПЛЕКСЫ НА ЮГО-ВОСТОКЕ ЗАПАДНОЙ СИБИРИ И ИХ ПРОСТРАНСТВЕННО-ВРЕМЕННОЕ РАСПРЕДЕЛЕНИЕ

Проведена оценка характеристик мезомасштабных конвективных комплексов (МКК) с помощью данных, полученных с искусственных спутников Земли. Отмечено, что прослеживается двухлетняя цикличность изменчивости характеристик МКК на юге Западной Сибири за период 2010–2019 гг. Установлены тренды повышения влагосодержания и размера облачных частиц, что может являться индикатором роста энергетики процессов, следствием чего является увеличение повторяемости опасных явлений погоды.

Ключевые слова: мезомасштабная конвективная система, мезомасштабный конвективный комплекс, спектрорадиометр MODIS

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