Characteristics of atmosphere on days with thunderstorms in the Southeast of Western Siberia

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Abstract. Due to the higher rate of change of air temperature over the territory of Siberia in comparison with other regions, it is important to clarify the parameters of convection in general and the characteristics of clouds with which thunderstorms are associated. The paper presents the features of thunderstorm activity and the study results of the following atmospheric characteristics: the cloud top and base height and the convective cloud thickness; air temperature at level of condensation; the amount of total water vapor in the surface layer of the atmosphere and the strength of upward flows.

Introduction
Convective cloudiness plays an important role in shaping the weather, but the task of its modeling, namely quantity, top and base height, depth of cloud layers and microphysical properties, still requires serious research. Cloudiness is largely a setting factor for the hydrodynamic models of weather forecasting, as well as climate, which are designed and used in different countries. Moreover, the algorithms tooled in one model do not provide satisfactory outcomes in other models due to differences in the methods for describing physical processes that occur in clouds of different types and with varied spatial model resolution. The difficulty of describing clouds and precipitation in climate models and large-scale numerical weather prediction (NWP) models is that cloudiness and precipitation are a sub-grid process that differs in regions \([1, 2]\). Under contemporary climate change in temperate latitudes, an increase in convective clouds producing hazardous convective phenomena such as hail, squall, heavy downpours has been observed \([3, 4]\). Since Siberia has a higher warming rate than other regions, and not only during winter \([5]\), it is important to clarify the parameters of convective clouds, which are associated with thunderstorms.

The study aimed to determine the characteristics of the layer in which the convective instability is concentrated and its temperature and humidity structure over the south-east of Western Siberia on the days with thunderstorms. Thunderstorms occur almost exclusively in the warm season of April to November in the south of Western Siberia; however, all examinations are restricted to summer period. A day is considered a thunderstorm day if a thunderstorm was detected by weather stations observer at any time during the observation hours.

The object is *Cumulonimbus* clouds, which are observed in the south-east of Western Siberia and associated with thunderstorms and the temperature and humidity characteristics of the atmosphere.
For study we selected days, when in areas located near the upper-air stations, thunderstorms were observed at no less than in three neighboring points. The task of research is to assess the energy parameters of convective clouds: their vertical extent or depth, cloud top and base height, the strength of vertical movements, air temperature and moisture content in different layers of the atmosphere.

Within summer the atmospheric state has been studied on the basis of information was taken from upper-air soundings conducted at 0000 and 1200 UTC by Aleksandrovskoye (60.43 °N, 77.86 °E), Kolpashevo (58.31 °N, 82.95 °E), Novosibirsk (54.96 °N, 82.95 °E), Barnaul (53.35°N, 83.81 °E) and Altay station, located in China (47.73 °N, 88.08 °E).

**Thunderstorm activity over Western Siberia**
The formation of thunderstorm clouds and, consequently, thunderstorm activity depends on climatic conditions and terrain. Thunderstorm activity over the study area is minor [6], although it varies across the territory [7, 8]. The thunderstorm season usually begins in April, ends – in November, but the greatest intensity of thunderstorm activity (over 90%) is related to summer months. The average long-term number of days with thunderstorms (Figure 1) varies from 12 days with thunderstorms per year (65 °N) to 36–38 days in the territory of Gorny Altay (50–52 °N). There is no doubt that the increase in thunderstorm activity from the north to south accounted by temperature differences. However, against the background of a significant dependence of the number of days with a thunderstorm on the geographical latitude, there is a clear relation on the height above sea level. The centers of increased thunderstorm activity have been marked off over the Altay Mountains (Altay station) and Kuznetskiy Alatau located to south from Mariinsk station.

![Figure 1. Distribution of mean multi-year number of days with thunderstorms](image)

The heterogeneity of thunderstorm activity along longitude is obvious (Fig. 1). The average total duration of thunderstorms varies over the territory from 15 to 50 hours per year and reveals a similarity in spatial distribution with the number of days with thunderstorms. The correlation coefficient between these characteristics has statistically strong significance (Table 1), as for latitude. The studies reveal a general increase in the frequency of Cumulonimbus clouds, which is related to the increase in convective and thunderstorm activity in Siberia particularly [6, 9, 10,]. There has been a growth in the frequency of spring thunderstorms, and the thunderstorm season has become longer (Figure 2). Considering the fact that an increase in average monthly temperature values was detected not only in the winter, but also in summer, a rising of thunderstorm activity over the territory of Western Siberia can be expected.
Figure 2. Frequency of thunderstorm days over Kolpashevo (58.31 °N, 82.95 °E) during 1966–2017

Table 1. Correlation between thunderstorm activity and geographical features

| Thunderstorm characteristic | Latitude, ° | Longitude, ° | Height asl, m | The average number of days with thunderstorms, days |
|-----------------------------|------------|--------------|---------------|---------------------------------------------------|
| The average duration of thunderstorms, hours | -0.64 | -0.18 | 0.01 | 0.95 |
| The average number of days with thunderstorms, days | -0.78 | -0.11 | 0.09 | 1.0 |

Due to the presence of heterogeneity of thunderstorm activity in different geographical areas, it is expedient to evaluate both the convection characteristics and the features of thunderstorm clouds formed over area under investigation.

Cloud top and base level of convective cloudiness producing a thunderstorm

It is known that the characteristics of convective clouds significantly differ in various geographic areas and depend on the terrain of the underlying surface, atmospheric temperature and humidity profiles and characteristics of atmospheric circulation patterns [11]. Therefore, the clarification of convective cloud parameters producing hazardous convective phenomena in different geographical areas, will contribute not only to the enhancement of regional weather-prediction procedure, but also to an understanding of the physical processes occurring in such clouds during the formation of thunderstorms and hail.

To investigate the hazardous phenomena caused by convection and elaboration of promising methods for their prediction, the following parameters are in particular interest: the top cloud height and convective potential energy of the atmosphere, which is limited by equilibrium level (EL) or level of neutral buoyancy (LNB) and level of free convection in the area under study [12]. The greater convective potential leads to high probability of Cumulonimbus formation and thunderstorm activity accordingly. To identify the features of thunderstorm clouds over the south-east of Western Siberia, we consider the following parameters.

Convection ($L_{\text{conv}}$, m) and condensation levels ($L_{\text{cond}}$, m). The level of condensation is conventionally considered the average height of the cloud base. At this altitude, the water vapor in the ascending air reaches a saturation state, and the air temperature equals to the dew point temperature [13, 14]. The level of neutral buoyancy (LNB), where convective cloud stops growing upwards, is accepted as the upper level of convection development. At this conditional level, the temperature of the ascending parcel close to the ambient temperature, and the upward movement stops [15]. The
The vertical thickness (also depth or extent), m. This parameter is understood as the difference between the top and base heights of the cloud. The accuracy of determining this parameter ranges from 100–200 m, since the boundaries of the clouds are difficult to define with high accuracy. The larger this value, the more likely it is to expect the occurrence of hazardous meteorological phenomena of convective origin. In addition, the growth of the cloud thickness indicates an increase in the intensity of the phenomenon [17]. This parameter, in combination with the water content and the glaciation of Cumulonimbus upper part, has a high correlation with the concentration of charged particles. It is known that thunderstorms develop in cases where the vertical extent of the cloud is more than 7 km. This fact is explained by the circumstance that electric charges which are placed and separated in Cumulonimbus are limited by the isotherms –5 °C and –40 °C. The vertical thickness of clouds over the northwestern part of the Russian Federation, according to cited studies, did not exceed 4–5 km [19]. In the south of the European part of Russia, the averaged depth of a convective cloud varies around 9 km [18].

In this paper, we studied the characteristics of cloud cover over the study area (Fig. 1), where northern taiga, steppe, and mountainous terrain are presented. Comparison of cloudiness characteristics formed over the territory of Western Siberia with clouds over area of the mountainous Altay station will make it possible to evaluate the role of the elevations in the generation of convective clouds. The statistical parameters of the convective characteristics determined according to the upper-air sounding over the south-east of Western Siberia in the summer on days with thunderstorms are presented in Table 2.

Features of thunderclouds over Western Siberia

By 1800 (local time) which corresponds to 1200 UTC, after the peak in the development of convection over territory under investigation (15–16 local time [20], the following characteristics are obtained:

1) The mean values of cloud top height have a maximum in July, gradually increasing from north (5.4) to south (9.5 km).

2) The cloud top in the summer months often surpasses 10 km and even in the north of the territory the convective clouds can reach 13 km.

3) The vertical extent in the north of the region in June and August does not outreach 2.5 km, in July – 3.5 km; in the south this parameter increases to 6 km by July. The maximum observed thickness is 8 km in the south, 7 km – in the north.

In the morning by 0600 local time (0000 UTC) thunderclouds have slightly different features:
1) The top limit of cloud close to, on average, 3.5–4.5 km, i.e. 2–5 km lower than at 1200 UTC; the maximum heights that clouds reach in their development in the morning do not superior to 8 km in the north and 11 km in the south.

2) The average vertical extent of thundercloud in the morning in the north of the region is 1.5 km in June and August, and 2–2.5 km in July. In the south of the territory by July it will increase to 3.5 km, with the maximum exceeding 6 km in the south and 3.5 km in the north.

3) During summer the thickness of *Cumulonimbus* reaches a surface of 270–280 hPa. In 50% of all cases with presence of vast centers of thunderclouds, the upper boundary bulk up to 9–11 km.

**Table 2.** Estimation of the mean cloud thickness and top height of thunderclouds over the south-east of Western Siberia at 1200 UTC

| Upper-air station | Cloud thickness, m | Cloud top height (mean/max), m |
|-------------------|---------------------|-------------------------------|
|                   | Jun     | Jul     | Aug     | Jun     | Jul     | Aug     |
| Aleksandrovskoe   | 2600    | 3500    | 2500    | 4700 / 10000 | 5400 / 12200 | 4200 / 10200 |
| 60.43 °N, 77.86 °E|         |         |         |         |         |         |
| Kolpashevo       | 3500    | 5500    | 4100    | 5000 / 10500 | 5700 / 11300 | 5800 / 11900 |
| 58.31 °N, 82.95 °E|         |         |         |         |         |         |
| Novosibirsk      | 3700    | 5400    | 4300    | 5300 / 10900 | 7300 / 11400 | 6200 / 11400 |
| 54.96 °N, 82.95 °E|         |         |         |         |         |         |
| Barnaul          | 4200    | 5900    | 4400    | 6600 / 11100 | 8400 / 11000 | 6800 / 11200 |
| 53.35°N, 83.81 °E|         |         |         |         |         |         |
| Altay            | 4200    | 5600    | 4400    | 8600 / 9500  | 9400 / 12800 | 8400 / 11200 |
| 47.73 °N, 88.08 °E|         |         |         |         |         |         |

**Temperature and humidity characteristics of the atmosphere**

*Cloud extent in the zone of negative temperatures.* Predominantly *Cumulus congestus* able to mature into *Cumulonimbus* when the top of convective clouds under influence of powerful updrafts reach layers with negative air temperatures. At the same time, a glaciation starting to form at *Cumulonimbus* top is observed at a height where the air temperature falls in the range -20 ÷ -25 °C (level of crystallization). Penetration of *Cumulus* top above freezing level is associated with the processes of the enlargement of cloud elements, the largest of which may fall as rain or snow. In particular, when *Cumulonimbus* grow up to the level of crystallization the formation of hail nucleus in the cloud and the start of separation of volume charges in the cloud, and, consequently, the initial stage of thunderstorm has been noted.

*Air temperature at the convection level (T<sub>conv</sub>, ° C).* It is empirically obtained that the lower this temperature, the more likely the formation of thunderstorms and rainfall.

*Air temperature at the condensation level (T<sub>cond</sub>, ° C).* For thunderclouds, the threshold values of temperature in the sub-cloud layer vary within 8–11 °C in summer with mean value equal 9.5 °C (Table 3). For European part of Russia the particular temperature of the sub-cloud layer close to 7 °C [17].

*The moisture content in the surface layer.* This is the most important characteristic in the formation of convective clouds. The moisture inflow cause by either due to advection of moist air in the region, or locally, as a result of evaporation of moisture from a local source like the Great Vasyugan Swamp in Western Siberia, which provides increased atmospheric instability in the studied region [21]. The presence of an additional source of moisture can introduce significant differences with the characteristics of clouds forming in same latitudes. In the framework of the present study of the surface layer moisture, the mixing ratio (r) was chosen as moisture characteristic. R shows ratio of the mass (weight, quantity) of water vapor to the mass (weight, amount) of dry air in the same volume, expressed in grams of water vapor per kilogram of dry air (Equation 1):
\[ r = 0.622e / p - e. \]  \hspace{1cm} (1)

where \( p \) is the air pressure and \( e \) is the vapor pressure.

As the vertical stratification of air temperature in the lower troposphere plays a decisive role in the development of convective instability, the values of air temperatures at the level of condensation are given in Table 3.

*Estimation of the strength of upward air currents.* To assess the maximum updraft strength \( U_{\text{max}} \) (ms\(^{-1}\)), the value of the convective available potential energy of the atmosphere (CAPE) was used. According to [22], the strength can be approximated by Equation 2:

\[ U_{\text{max}} = \sqrt{2\text{CAPE}} \]  \hspace{1cm} (2)

Precipitation noticeably make heavier the ascending air parcels. The vapor pressure depends both on the amount of rising moisture and on the strength of the upward flow, which initially holds back precipitation. Therefore, we analyzed the total amount of water vapor, \( W \), in the vertical atmospheric column expressed by the thickness of the water layer that would have formed during condensation and precipitation of water vapor in this column. The results of the evaluation of the above characteristics are presented in Table 3.

**Table 3. Physical characteristics of the atmosphere in the presence of thunderstorm clouds**

| Characteristic | Kolpashevo 58.31 °N, 82.95 °E | Novosibirsk 54.96 °N, 82.95 °E |
|---------------|-----------------------------|---------------------------------|
|                | Jun | Jul | Aug | Jun | Jul | Aug |                        |
| Temperature of the condensation level (\( T_{\text{cond}}, \ ^\circ\text{C} \)) | 7.0 | 11.0 | 8.0 | 8.0 | 12.5 | 7.0 |
| Cloud thickness (m) | 4100 | 5800 | 4700 | 5500 | 7200 | 5700 |
| Pressure of the condensation level (\( P_{\text{cond}}, \ hPa \)) | 870 | 870 | 870 | 850 | 850 | 850 |
| Strength of updrafts within convectively unstable atmospheric layer (\( U_{\text{max}}, \ \text{ms}^{-1} \)), mean/max | 10 / 13 | 10 / 14 | 10 / 12 | 10 / 14 | 9 / 12 | 10 / 14 |
| The mixing ratio in the surface layer (r, g/kg), mean/σ | 10.1 / 2.3 | 10.1 / 2.0 | 10.2 / 1.7 | 9.3 / 2.4 | 10.0 / 1.6 | 9.2 / 2.2 |
| Total water vapor amount in a vertical column of atmosphere (W, mm), mean/σ | 31.1 / 7.2 | 29.2 / 6.7 | 31.0 / 6.6 | 28.1 / 8.1 | 30.4 / 5.9 | 26.1 / 7.2 |

**Summary**

The mean daily values of air temperature at the Earth’s surface on days with thunderstorms were 16–23 °C, and vapor pressure changes from 11 to 14 hPa.

In the presence of thunderclouds, the temperature of the sub-cloud layer varies within 8–11 °C in different months of the summer with a mean value equal to 9.5 °C.
It was found that in summer over the territory of Western Siberia, the thickness of Cumulonimbus thundercloud reaches a surface of 270–280 hPa. In 50% of all cases of the presence of extensive centers of thunderstorm clouds, the cloud top lay on 9–11 km. The maximum thickness of the convectively unstable layer in the south exceeded 6 km.

The value of the mixing ratio in the surface layer of the atmosphere is quite stable and amounts to 10 g / kg.

The strength of updrafts is quite stable and generally reaches 10 ms^{-1}, which is consistent with the results of other studies [23, 24].

The total water vapor amount in an air column and cloud water in atmospheric column, is about 30 mm, and within the study area varies slightly.

The obtained results are important for the operational work of weather forecasters, including aviation, to design new and refining existing NWP models for thunderstorms forecast jointly with hail prediction in regional-scale models like WRF taking into consideration local features.

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