Energy of atmospheric processes in a region between the Ob and Irtysh rivers in days of cyclogenesis

E L Tunaev¹,², V P Gorbatenko¹ and I V Kuzhevskaya¹

¹ National Research Tomsk State University, 36 Lenin Avenue, Tomsk, 634050, Russia
² West-Siberian Territorial Administration for Hydrometeorology and Environmental Monitoring, 30 Sovetskaya, Novosibirsk, 630099, Russia

Abstract. It is important to study cyclone formation and its further development in various fields, and cyclone energy is of special interest. This paper presents an analysis of energy characteristics of the atmosphere in days of local cyclogenesis over Western Siberia in 2016–2017. The following types of energy important for synoptic-scale atmospheric processes are calculated: 1) kinetic energy of horizontal motion; 2) potential energy; 3) internal energy; and 4) total potential energy. The results can be used to develop software and algorithmic support for the assessment of the probabilities of local cyclogenesis and possible emergence of hazardous weather phenomena in the West-Siberian territory.

Introduction
Mid-latitude cyclones (MLC) refer to the most important elements of the general circulation of the atmosphere [1]; herewith smaller scale cyclones, so-called polar low [2] or local cyclone (LC), can form over various regions on their background. The lesser cyclones often cause forecast errors, since the location of local cyclone centers is difficult to predict.

Usually such cyclones are the result of dynamically unstable baroclinic waves on the tropospheric front [3]. Baroclinic instability is defined as dynamic instability in the main zonal flow and associated with a meridional temperature gradient, and, as a consequence, thermal wind [3]. The source of the energy of growing perturbations in such a flow is the available potential energy in the atmosphere. The role of the thermal factor, the process of heat and moisture exchange with the underlying surface during local cyclogenesis is very high [4, 5]. Moving from a cold into a warm surface, a cold and dry air mass is saturated with heat and moisture. Rapid formation of cloudiness with latent heat release leads to the development of deep convection and generation of an intense mesocyclone.

Barotropic instability of the atmosphere also evolves cyclogenesis [6, 7]. The dynamic wave instability of a non-divergent flow associated with a horizontal wind shear contributes to the formation of a so-called shear vortex of insignificant dimensions, which under appropriate additional conditions at the upper levels can be transformed into the LC. In this process, the kinetic energy of barotropic disturbances increases due to the kinetic energy of the main flow. It is well-known that kinetic energy occupies a special place among all types of energy involved in the energy transformations of MLC, as it reflects the physical essence of the processes taking place in the cyclones to the greatest degree. For this reason one of the main problems of the theory of general atmosphere circulation is the transformation of kinetic energy inside MLCs.
Methodology and data source
For the hydrodynamic description of the mesocyclone development and its convective systems, the concept of conditional instability of the second kind (CISK) is used [8, 9]. The CISK concept was originally proposed to describe the development of tropical cyclones [10, 11], but later it was also applied to other mesocycrones. The essence of the concept is focusing on the interaction and mutual enhancement of perturbations of two distinct scales: deep moist convection and a cyclonic vortex [12, 13]. It is assumed that the vortex is injected from outside and can be a consequence of the baroclinic instability (which took place in the region of occurrence of this disturbance), orographic effect, and other factors. The presence of cyclonic circulation causes the air convergence to the center, where powerful convection develops in a conditionally unstable atmosphere with the heat release leading to mutual intensification of the cyclonic circulation and convection and, as a result, an intense mesocyclone generates. The most important feature of the CISK, in contrast to the baroclinic instability, lies in the fact that the source of its energy is the release of latent heat with deep convection, and not the kinetic or potential energy of the main flow. Perhaps this mechanism can contribute to the formation of LC in the study area, but it is not the major cause.

Studies show that synoptic vortices originate as low baric formations, covering a lower layer of the troposphere 2–3 km thick at the initial stages of their development. In other words, the most frequent loss of stability occurs in the lower layers of the atmosphere [14]. The presence of planetary waves increases the possibility of appearance of synoptic vortices in the atmosphere and forms the region’s most favorable conditions for the incipience of cyclonic synoptic vortices, the so-called baroclinically active regions [15, 16]. The study territory certainly refers to such regions.

Any cyclonic vortex (low pressure area) perennially originates in an area where there is a redundant amount of energy [17]. Consequently, the role of the vortex is to dissipate energy and evenly distribute it in the atmosphere.

Thus, analyzing the characteristics of local cyclogenesis, it is important to take into account the energy reserves in the atmosphere over different territories depending on the time of the year and the diversity of macrosynoptic processes as well. It is necessary to consider the distinct types of energy that the air mass possesses and their mutual changes not only directly during the existence of the cyclone, but also a few days before its formation and after low filling. This will allow us to determine threshold values of the energy reserves in the atmosphere, when a cyclone can form above the study area in a specific synoptic situation.

To summarize, the processes of formation and development of cyclones are being studied in various fields of research, among which one of the most vital is study of their energy. With this approach, a single scale is provided for assessing the contribution of various atmospheric processes to the development of cyclones, which, in turn, makes it possible to describe the physical mechanisms of this evolution. In addition, the presence of significant reserves of any type of energy in the atmosphere can be used as a prognostic criterion of the process, provided that the threshold values of energy reserves are determined, the excess of which leads to cyclogenesis. First of all, the study of the energy of local cyclones is relevant for enhancement of weather forecasts using regional mesoscale models [18].

In [19] is shown that cyclogenesis activity of the atmosphere has commonly irregular periodicity. A long period of strong activity may be followed by a short period of weak activity, and vice versa. Atmospheric activity during cyclogenesis proceeds as follows [20, 21, 22]:
1st stage: accumulation of potential energy;
2nd stage: transition of potential energy to kinetic;
3rd stage: formation of the frontal wave as a trigger to the nascent cyclonic vorticity;
4th stage: cyclonic vortex activity leads to energy dissipation.

Eventually, the temperature contrasts decrease, and the atmosphere initiates to accumulate potential energy again.

It is worth to note that the generation of kinetic energy proceeds throughout the thickness of the troposphere, and its dissipation occurs in the boundary layer that affects its meteorological parameters.
The paper presents an analysis of the energy characteristics of the atmosphere during the days of local cyclogenesis over the territory of Western Siberia in 2016–2017. The study area is bounded by coordinates 50°–64° N and 60°–90° E. To study the energy of cyclones, the observations of upper-air sounding at 00 and 12 UTC were used. Archive of weather maps was provided by the West-Siberian Bureau of Meteorology.

The most important types of energy for synoptic atmospheric processes were calculated: kinetic energy of horizontal movements \( 10^6 \) J m\(^{-3} \), \( \pi \), potential energy \( 10^8 \) J m\(^{-3} \), and \( I \), internal energy \( 10^9 \) J m\(^{-3} \).

In the presented equations 1–3, all types of energy are referred to a unit of mass. Energy balances in the quasi-static approximation (for a unit mass) are in formula forms: [23, 24, 25, 26]:

\[
K = \frac{1}{2} g \int_0^p V^2 dV, \quad (1)
\]

\[
\pi = \frac{R}{g} \int_0^p T dp - z p, \quad (2)
\]

\[
I = \frac{C_v}{g} \int_0^p T dp, \quad (3),
\]

where \( V \) is the velocity vector of a mass element dm (m/s), \( z \) is the height (m), \( R = 287 \) J/kg·K is the universal gas constant of dry air, \( g = 9.8 \) m/s\(^2 \) is the standard acceleration due to gravity, \( C_v \) is the specific heat at constant volume (J/kg·K), \( T \) and \( P \) are the air temperature (K) and air pressure (hPa). The most substantial types of energy for synoptic-scale atmospheric processes were calculated.

All the variables of equations 1–3 were assigned to a unit area and calculated at each point (station) located in the region of the cyclone, for the atmospheric column extending up from Earth’s surface to 200 hPa. Then linear interpolation [27, 28] of meteorological fields to the center of baric formation (LC) was performed. At the same time, the maximum distance from the upper-air station to the center of the cyclone did not exceed 500–700 km. Similar calculations of the energy characteristics were previously carried out only for large-scale cyclones (2000 km in diameter) formed at temperate latitudes of the northern hemisphere [1, 29, 30].

**Discussion**

The present studies (Table 1) have shown that the cyclonic formations in question have a major energy margin; the mean value of kinetic energy in cyclones formed in the cold season is \( 1.5 \times 10^6 \) J m\(^{-3} \), which is comparable with [21] per unit air column. Nevertheless, the maximum reserves of kinetic energy are roughly twice as great as the mean, \( 2.9 \times 10^6 \) J m\(^{-3} \).

For cyclones in the warm season, mean values of kinetic energy were twice, and maximum values three times smaller \( (0.7 \times 10^6 \) and \( 1.1 \times 10^6 \) J m\(^{-3} \) respectively). Moreover, it was noted that values at nighttime are higher than at daytime (for example, the mean kinetic energy in December at 00 and 12 UTC is equal to 2.9 and \( 2.0 \times 10^6 \) J m\(^{-3} \), respectively). The reason can be the abrupt temperature contrasts precisely in winter, especially at night, since the cyclones generated in the cold season were under the influence of air masses emerging from the west and southwest to the colder underlying surface.

Comparison of the results of the energy characteristics of some local cyclones (LC) with similar indicators of larger cyclones [1] revealed (Table 1) that the cyclones had large kinetic energy reserves in winter and values had the same order \( (2.6 \) and \( 2.5 \times 10^6 \) J m\(^{-3} \), respectively). As an example, we consider the energy of the cyclone in December 2016 (Fig. 1), when there was a positive temperature anomaly (exceeding \( 1–2 \) °C above normal) and abnormal precipitation throughout the southeast of Western Siberia (up to 9 mm per 12 hours). These days an active advection of air masses from the
regions of Central Asia occurred, while the north of the Urals and Siberia were influenced by advection of the Arctic air [31]. Therefore, conditions for temperature contrasts and energy reserves have formed in the trough of the main cyclone, due to which the generation of the cyclone was more intensive.

| Table 1. Mean and maximum values of energy for polar low. |
|----------------------------------------------------------|
| Period of cyclone formation | Kinetic energy, $10^5$ J m$^{-2}$ | Potential energy, $10^8$ J m$^{-2}$ | Internal energy, $10^9$ J m$^{-2}$ |
|----------------------------|-------------------------------|---------------------------------|-------------------------------|
| Warm season                | 0.7  1.1                      | 1.1    1.3                      | 0.3   0.3                     |
| Cold season                | 1.5   2.9                      | 1.8    4.0                      | 0.4   0.6                     |

To determine the influence of local factors on the energy of cyclones, additional studies have been carried out (Table 2). It was found that most of the cyclones considered were formed on the waves of active well-developed frontal systems (76%) and had potent general energy reserves with the largest values of potential energy in comparison with other groups of cyclones (mean and maximum: 1.3 and $4.0 \times 10^8$ J m$^{-2}$, respectively).

The frequency of the wave cyclones series alternately forming and filling was much less (20%). These baric formations preserved the following kinetic energy reserves: the average values were $1.6 \times 10^5$ J m$^{-2}$, which is 2-4 times higher than other cyclones, with a maximum of $3.4 \times 10^5$ J m$^{-2}$. Apparently, this distribution of the main types of energy is caused by the fact that the front wave cyclones at the mature stage occupied a vast area (up to a diameter of 600-1000 km) and moved more slowly; thus, they accumulated more heat and emanated it into the surrounding air for a longer period of time. On the contrary, the series of cyclones was vortices of a smaller scale (600 km in diameter), as a result of which they accumulated less heat and gave it more quickly to the air; in addition, they are of a more mobile nature. Hence, the first group of cyclones had large reserves of potential energy, unlike the second group presented by kinetic energy (energy of motion). Other types of baric depressions, cyclones formed in the hollow of the main cyclone; cyclones formed on surface fronts; slow-moving, rapidly filling cyclones were extremely rare (in 4% of cases).

| Table 2. Ratio of energy forms for different types of cyclones. |
|---------------------------------------------------------------|
| Type of cyclone | Kinetic energy, $10^5$ J m$^{-2}$ | Potential energy, $10^8$ J m$^{-2}$ | Internal energy, $10^9$ J m$^{-2}$ |
|-----------------|---------------------------------|---------------------------------|-------------------------------|
| Classification by synoptic origin | mean | max | mean | max | mean | max |
| Wave cyclones   | 0.9   2.6                      | 1.3    4.0                      | 0.3   0.6                     |
| Series of wave cyclones | 1.6   3.4                      | 1.2    2.0                      | 0.3   0.5                     |
| Other cyclones  | 0.4   0.4                      | 1.0    1.0                      | 0.2   0.2                     |

| Classification by region of incipient cyclogenesis | Kinetic energy, $10^5$ J m$^{-2}$ | Potential energy, $10^8$ J m$^{-2}$ | Internal energy, $10^9$ J m$^{-2}$ |
|---------------------------------------------------|---------------------------------|---------------------------------|-------------------------------|
| Formed in the north of the territory              | 0.6   0.8                      | 1.2    1.9                      | 0.3   0.4                     |
| Formed in the center of the territory*            | 1.6   2.6                      | 1.3    4.0                      | 0.3   0.6                     |
| Formed in the south of the territory              | 1.6   3.4                      | 1.9    4.0                      | 0.4   0.6                     |

| Classification by existence | Kinetic energy, $10^5$ J m$^{-2}$ | Potential energy, $10^8$ J m$^{-2}$ | Internal energy, $10^9$ J m$^{-2}$ |
|----------------------------|---------------------------------|---------------------------------|-------------------------------|
| Existed 1 day              | 1.0   3.4                      | 1.4    4.0                      | 0.3   0.6                     |
| Existed 2–3 days            | 1.1   2.6                      | 1.2    2.4                      | 0.3   0.5                     |
| Existed 4 days and more     | 0.6   0.8                      | 1.0    1.2                      | 0.3   0.3                     |

*over the Vasyugan Swamp

During the year, more than a half of the cyclones examined by geographic features (62%) formed in the central part of the study area (54°-60° N, 60°-90° E), where the world's largest Vasyugan Swamp is located. They are the deepest and vertically developed formations (on average up to 6 km and
more). The main trajectory of their passing was mainly to the north-east, covering more than a half of the territory; the effect on weather processes, at the mean, lasted about 2 days in the cold period, and 3 days in the warm period, with the largest number of days equal to 4–7.

The predominance of other cyclone groups formed in the central regions can be explained by the fact that the terrain of this part of the study area represents a transition zone from a low swampy land including extensive spaces occupied by the water bodies to a more elevated area interspersed with forests and forest steppes. Due to this transition and supplementary moistening, as well as the heat accumulated by the swamps, cyclones can be formed having the greatest frequency and intensity. Moreover, it was revealed that about 40% of all the cyclones received an impulse to develop directly above the Vasyugan Swamp region, and these baric depressions had prevailing energy reserves, especially kinetic energy (mean = 1.6 × 10^6 J m⁻² maximum = 2.6 × 10^6 J m⁻²).

Almost every fifth cyclone generating in the south (50°–54° N, 60°–90° E) moved to the north and northeast, determining the weather conditions in most of the territory within 1 day. The baric formations had one of the largest total energy reserves and, in particular, of potential energy (with mean = 1.9 × 10^6 J m⁻² and maximum = 4 × 10^6 J m⁻²). Perhaps, this could be explained by their generation in the trough of intense main cyclones that carried away warm and moist air from the regions of the Caspian and Aral Seas and shifted to the colder underlying surface.

In 19% of the cases, cyclogenesis occurred in the north of the territory. The initial baric formations moving to the northeast and intruding into to the northern regions passed through all stages of development for 1 day; they had the lowest total energy reserves, especially the kinetic energy equal to 0.6 × 10^6 J m⁻².

In the annual cycle, the same frequency of cyclones is noted (42% of cases for each type), with an impact on the study area for 1 and 2–3 days [32]. These initial baric formations held the highest energy reserves, and the values obtained for the kinetic and potential energy were comparable (mean values are 1.0÷1.1 × 10^6 J m⁻² and 1.4÷1.2 × 10^6 J m⁻², and maximum values are 3.4÷2.6 × 10^6 J m⁻² and 4.0÷2.4 × 10^6 J m⁻², respectively).

Long-lived cyclones (4–7 days) were in 16% of the cases and mainly in the warm period of the year. Such mesovortices had significantly inferior energy reserves, especially kinetic (almost twice) to the previous two types of cyclones. This may have been explained by the fact that there are such climatic conditions during the summer when the contrasts between the air mass involved in the cyclonic vortex and the ambient air are the least. There is reason to suppose that the development of such cyclones is caused by the baroclinic instability in the summer.

As an example, the case of a local cyclone (LC) passing along the periphery of the anticyclone located above Eastern Siberia is displayed. The LC was defined in cloudiness as a mesoscale convective complex (MCS) with a group of cumulonimbus (Cb), as shown in Figure 1. The clouds are clearly discernible in the field of specific humidity, with values of 14 g/kg (Figure 2a), the surface temperature is seen to have been 24–30 °C (Figure 2b). The values of the instability index above 40 °C (Figure 2c) diagnose the development of thunderstorms with a probability of 99%. These results agree well with [2] and confirm the presence of thunderstorms over the study territory when threshold values of the convective instability index more than 32°C are exceeded.

In a more detailed analysis of the cases of formation of local cyclones (Table 2), we have noticed that kinetic energy has essential changes during their existence. There are reasons to assume that the kinetic energy of barotropic disturbances increases due to the kinetic energy of the main flow and also causes local cyclogenesis. By analyzing the distribution of different types of energy within the layers bounded by the standard isobaric surfaces it was noted that the local cyclones (LCs) had large reserves in the layer up to 12.5 km.
Figure 1. MODIS RGB composite image (bands at 864, 555 and 469 nm), 06:50 GMT on June 21, 2017.
**Summary**

The following is a brief summary of the main results:

1) There is a significant excess of reserves of all types of energy in the cold season. This can be explained by abrupt temperature contrasts over the study territory. During the cold period, cyclones are usually formed under the influence of air masses that go from the west and south-west to the colder underlying surface.

2) Higher energy parameters are observed during nighttime. However, the difference in values between day and nighttime values do not exceed 10%.

3) The potential energy of local cyclones (LC) is greater than the kinetic one and differs by 2–3 times in comparison with the mean values of other cyclone types originated in the mid-latitudes.

4) The internal energy of the local cyclones formed over the southeast of Western Siberia is about 5–6 times less than the energy of mid-latitude cyclones.

5) It was revealed that about 40% of all formed cyclones develop directly above the territory of the Vasyugan Swamp. These mesocyclones are mostly formed on waves of main cold fronts (63%) and have major general energy reserves.

6) Wave cyclones are characterized by large kinetic energy reserves in comparison with the other types. The frequency of such cyclones over the study territory is about 86%. In 84% of cases they evolve through distinctive stages of development within 1–3 days. In total, these baric formations have the largest energy reserves, especially the kinetic ones ($1.6 \times 10^6$ J m$^{-2}$) that are 2–4 times higher than the other cyclones; the maximum equals $3.4 \times 10^6$ J m$^{-2}$. The reserves of kinetic energy in days with mesocyclones can be 2–4 times higher than the average values of this energy for a single column of the troposphere in the unperturbed state.

7) The long-lived cyclones (4 days and more) form more than five times less frequently and impact the weather processes for 4–7 days. Such mesocyclones have the lowest energy reserves and their generation relates to the warm seasons. It is probably due to the fact that there are such climatic conditions during summer when the contrasts between the air mass involved in the cyclonic vortex and the ambient air are the least.

The results can be used to develop software and algorithmic support for assessment of the probability of local cyclogenesis and the possible emergence of hazardous weather phenomena in the area of responsibility of the West-Siberian Territorial Administration for Hydrometeorology and Environmental Monitoring (UGMS in Russian) and its branches and other structural subdivisions of Roshydromet.
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