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On the Relation of the Number of Extratropical Cyclones to Their Sizes

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Abstract—Extratropical cyclones were identified on the basis of sea level pressure NCEP/NCAR reanalysis data for the Northern Hemisphere from 1948 to 2004. Cyclone positions were determined with a time interval of 6 h. Cyclone sizes were obtained with the use of a numerical scheme based on a rotation of the spherical coordinate system such that the pole of the new coordinate system coincide with the cyclone center. Cyclone sizes were determined at each step of the trajectory. The last closed isobar was assumed to be the outer boundary of the cyclone. The pressure deficit in the cyclone center was regarded as a characteristic of the intensity of a synoptic formation. The interrelation between the number of cyclones and their sizes was estimated for all extratropical cyclones of the Northern Hemisphere regardless of the stage of their development. The number of cases being analyzed is 1.5×10^6. Cyclone areas vary from 0.13×10^6 to 6.4×10^6 km^2, and 80% of extratropical cyclones have an intensity of 1–15 hPa. The distribution of the number of cyclones depending on their intensities is shown to be of an exponential character. The distributions of the number of cyclones were approximated with a very high accuracy, so that the regularities obtained are very stable during several past decades.

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INTRODUCTION

Characteristics of extratropical cyclones are effec-
tive indicators of changes in the atmospheric circula-
2 tion at midlatitudes. The construction of reliable
3 cyclone climatologies has become possible only in
recent decades with the appearance of new databases
and the development of adequate technologies for
their processing. Automatic identification or tracking
of cyclone trajectories is the most effective method for
the study of cyclone activity. To date, several numeri-
cal schemes of cyclone classification have been devel-
3 oped in the world [1–8]. However, although the climatologies of cyclone activity obtained in different studies are, on the whole, similar to one another, cyclone characteristics such as intensity, lifetime, velocity of motion, etc., depend heavily on both the data used and on the methods of cyclone identification. Recently, the investigation of cyclone activity has also been used for the validation of numerical models of the atmosphere, because such investigations make it possible to estimate the possibilities of the models for reproducing the most important dynamic processes.

In the context of the study of climate changes, investigation of the long-period variability of cyclone activity is one of the important problems. Many investigations show that extratropical cyclones intensify in a warmer climate [9–11]. Recent study [12] investigated changes in the number and intensity of cyclones within the framework of the ECHAM5/OM model for the IPCC A1B scenario. This investigation showed that variations in the carbon dioxide amount affect the number of cyclones only slightly, whereas the main climatic distinctions manifest themselves in displacements of the main storm tracks. Similar results were obtained in [13], where a wider set of experiments with the ECHAM4 and ECHAM5 models were analyzed.

During investigations of the climatology of extratropical cyclones, particular attention is given to the recurrence frequencies of cyclones. Nevertheless, for estimating the role of cyclones in a climatic system and its variability, it is also necessary to quantitatively estimate parameters of the life cycle of cyclones, such as characteristics of the sizes and shape of cyclonic formations. While the knowledge of cyclone trajectories and pressure characteristics in cyclone centers is sufficient for the estimation of such parameters as depth, lifetime, travel velocity, rate of deepening, etc., the determination of cyclone sizes is associated with the complication of the identification system. First and foremost, it is difficult to analyze the fields of characteristics at each moment of tracking, a situation that produces great technological problems and uncertainties in the interpretation of results. Determination of the "boundary" of a cyclonic formation is one of the main problems. The cyclone boundary is traditionally determined in synoptic meteorology by the so-called "last" closed isobar; however, if such an approach is used, the cyclone size depends on the step chosen for the construction of isobars in the synoptic map. If an

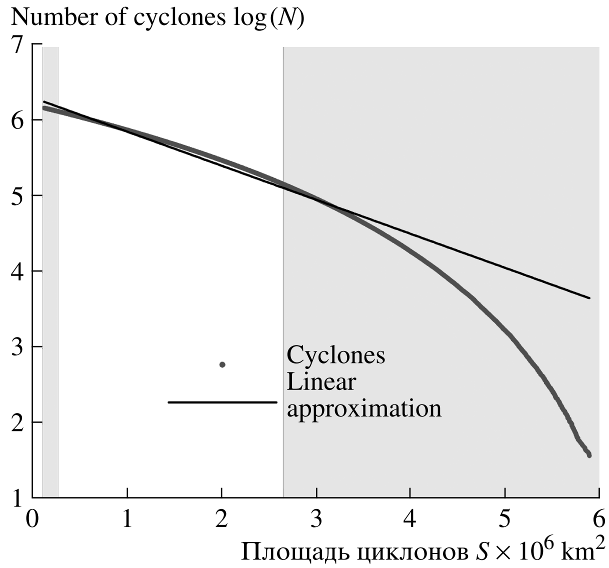

Fig. 1. Cumulative distribution function of the number of cyclones $\log(N)$ depending on their sizes over the period 1948–2004. The solid line is the linear approximation. The determination coefficient is $r^2 = 0.9667$. The quantiles of levels 0.1 and 0.9 are indicated by gray color.

automated numerical approach to determination of the cyclone size is used, the distance between isobars can be smaller, which will substantially increase the determination accuracy of the desired quantity. However, there is a methodological difficulty associated with a quantitative estimation of linear sizes on the sphere in

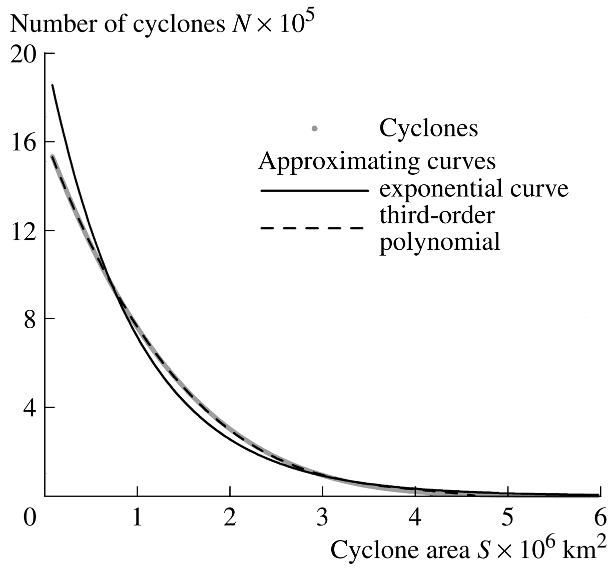

Fig. 2. Cumulative distribution function of the number of cyclones N depending on their sizes over the period 1948–2004. The solid line is the approximating exponential curve ($r^2 = 0.9667$), the dashed line is the linear approximation ($r = 0.9999$).

different latitude regions. Presently, only several studies on this subject have been published [6, 14–17].

In study [18], we developed our own methodology for the determination of geometric characteristics of extratropical cyclones and constructed the climatology of cyclone sizes for the midlatitudes of the North- 2
ern Hemisphere over the period 1948–2004. We have shown that the mean radius of cyclones varies from 300–400 km over continents to 900 km over oceans. The largest sizes are characteristic of long-lived and intense cyclonic formations. The relation of the sizes and number of cyclones on the sphere is interesting from the dynamic standpoint. The investigations performed in [18] show that an increase in the number of cyclones on the sphere leads to a linear decrease in their mean sizes (see [18], Fig. 15). It is also important to note that, according to [18], the relation of the sizes and number of cyclones on the sphere remains relatively constant in the period under consideration.

Using the method of determination of cyclone sizes [1], Golitsyn et al. [19] have shown that the cumulative distribution functions of cyclone areas and intensities during the second half of the 20th century have an exponential form. Construction of the cumulative distribution functions is traditionally used in geophysics. In practice, these functions are important for estimating the risks of such natural phenomena as earthquakes, landslides, and tsunamis. In their study [19], the authors propose to use such distribution functions for atmospheric vortices in problems estimating the risks of global climate changes. In this study, we will analyze the size distribution of cyclonic formations by using the results of determination of extratropical cyclone sizes in the period from 1948 to 2004 [18].

DATA AND METHODOLOGY OF CYCLONE IDENTIFICATION

The sea-level pressure NCEP/NCAR reanalysis data over 1948–2004 [20, 21] were used for the identification of cyclones. The data are presented on the grid 2.5° × 2.5° with a time resolution of 6 h. The cyclones were identifies and their trajectories were determined with the use of the Tsiklon numerical scheme developed at the Shirshov Institute of Oceanology, Russian Academy of Sciences (patent no. 2006612244). The numerical tracking of cyclones was performed in the polar stereographic projection on the 4
grid 181 x 181 with the center at the North Pole. This interpolation was accomplished by the method of local procedures [22]. The method used allows us to smoothly interpolate spatial fields specified at arbitrary points without producing additional intermediate extrema and retaining the smoothness of interpolation.

The preprocessing of data involves the dynamic interpolation of the surface-pressure field to a step of 1 h. This interpolation satisfies the equation $\partial(P)/\partial t = \mathbf{u}\nabla(P)$, where P is the surface pressure and $\mathbf{u}$ is the velocity vector. The interpolation to shorter time steps allows us to decrease cyclone displacements and distinguish them from characteristic distances between cyclone centers. The tracking procedure begins with the finding of local pressure minima. For this purpose, 13 neighboring points are considered. All of these minima are divided into three categories depending on the sizes of the region belonging to the minimum under consideration. Further, according to the algorithm, the preliminary determination of cyclone trajectories is accomplished. To do this, we applied the so-called algorithm of "nearest neighbors," which was also used in the schemes presented in [23–27]. The selected cyclone trajectories are considered in pairs, and, if the cyclone trajectories from the pair under consideration intersect at a fixed time moment or have points coinciding in time, these points are eliminated from the cyclone with a shorter lifetime, which, therefore, either decreases its lifetime or becomes divided into two cyclones. After that, cyclones with short lifetimes (shorter than 18 h) are excluded from analysis. In study [18], this scheme was substantially improved through the use of data of the ECMWF atmospheric general circulation models with a resolution of 1 h. The described numerical scheme was used for the identification of cyclones from reanalysis data [29], climatic models [13], and high-resolution ECMWF atmospheric general circulation models [28].

To determine cyclone sizes, we used our numerical scheme developed in [18]. At the first stage, the spherical coordinate system is rotated so that the pole of a new coordinate system coincide with the cyclone center. Such an approach is traditionally used in oceanology to avoid the incorporation of the convergence of meridians during the integration of numerical circulation models at high latitudes. In our case, this approach is used because it simplifies computational procedures performed for determining horizontal sizes of cyclones. At each step, the sea-level pressure field is interpolated in the new coordinate system [22]. Further, we analyze the pressure field along 36 radii and find the "last" closed isobar, which is regarded as the cyclone boundary. Such a determination of the cyclone size corresponds to the synoptic approach, according to which the term "cyclone" means an atmospheric disturbance with an air pressure decrease (minimum pressure is in the center) [30], and the last closed isobar multiple of 5 hPa is taken to be the cyclone boundary. According to our methodology, any isobar (and not only that multiple of 5 hPa) can serve as a cyclone boundary, a circumstance that allows us to more accurately determine the size of a cyclonic formation. Having determined the point at which the isobar taken to be the cyclone boundary intersects each of 36 radii, we calculate the area S occupied by the cyclone as the sum of the areas of 36 sectors S_i:

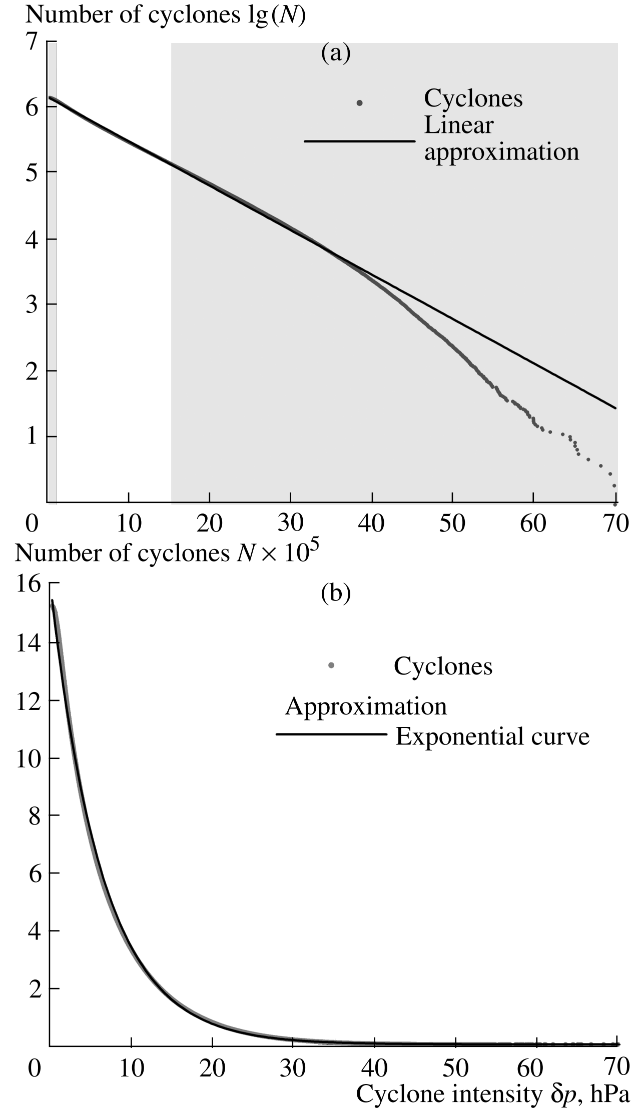

Fig. 3. Cumulative distribution function of the number of cyclones (a) $1\log(N)$ and (b) N depending on their sizes over the period 1948–2004. The solid line is the linear approximation. The determination coefficient is r^2 = 0.9983. The quantiles of levels 0.1 and 0.9 are indicated by gray color.

$$S_M = \sum_{i=1}^{36} S_i. \quad (1)$$

The described procedure of determination of cyclone sizes allows us to find the geometric characteristics of cyclones (occupied area, minimum and maximum radii) and the circulation intensity at each moment of the cyclone lifetime. Additionally, we can determine the pressure deficit in the cyclone center δp:

$$\delta p = P_l - P_c, \quad (2)$$

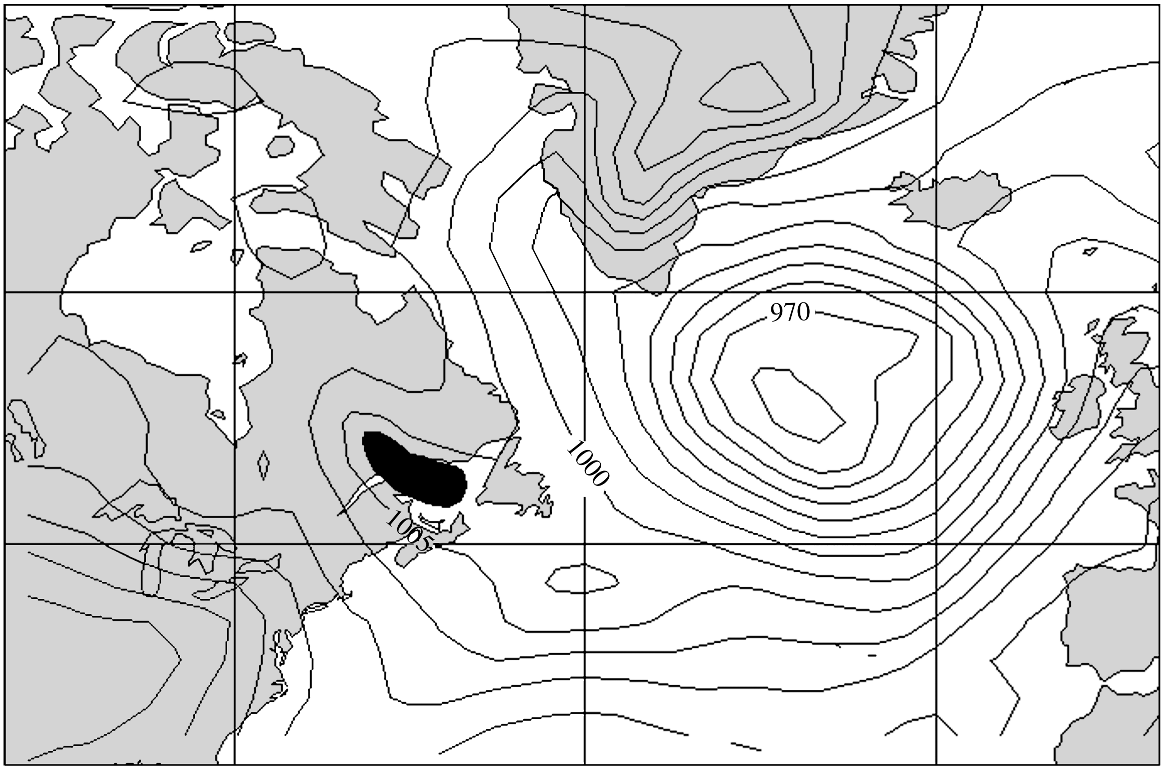

Fig. 4. Surface-pressure field on January 7, 2004, at 00:00 (UTC) from the NCEP/NCAR reanalysis data. The solid line shows a cyclone with a pressure at its center of 1001 hPa and δp = 1.3 hPa. The cyclone center coordinates are 49°N and 65°W. The interval between contours is 5 hPa.

where P_c is the pressure (hPa) in the cyclone center and P_l is the pressure (hPa) corresponding to the last closed isobar. In this study, we will use the δp value as a characteristic of the synoptic formation intensity.

CUMULATIVE DISTRIBUTION FUNCTIONS OF THE NUMBER OF CYCLONES

As in s [19], for constructing the distribution functions, we take into account cyclones at all moments of their lifetime, except for the stage of their development. In other words, we take into account the number of local minima over the period from 1948 to 2004 that were the centers of the cyclones identified with the use of the Tsiklon numerical scheme. Thus, the number of analyzed cases N used for constructing the distribution functions can be obtained from the following formula:

$$N = \sum_{yr = 1948}^{yr = 2004} \sum_{i = 1}^{i = n_{yr}} num_{i\ yr}, \quad (3)$$

where n_{yr} is the number of cycles per year and yr, $num_{i\ yr}$ is the lifetime of a cyclone determined with a discreteness of 6 h. The number of cyclones observed in the Northern Hemisphere during one year is, on average, 2497. The standard deviation of this quantity is 56, which points to a low variability of the number of cyclones during the second half of the 20th century. Thus, the total number of extratropical cyclones over the period from 1948 to 2004 is about 140 000. Since the mean cyclone lifetime is 3–5 days, the approximate number of cases is 1.5×10^6. Note that the number of cyclones analyzed in [19] is 4×10^4, which is 40 times smaller than the number of cyclones N analyzed in this study.

The cumulative size distribution of cyclones is shown in Fig. 1. The areas of extratropical cyclones vary from 0.13×10^6 to 6.4×10^6 km^2. The mean cyclone size is 1.1×10^6 km^2. However, according to [19], the cyclone size varies from $\sim 1.6 \times 10^6$ to 25×10^6 km^2 (Fig. 2 of the cited study). Thus, about 44% of the extratropical cyclones considered in this study are smaller in size than the smallest cyclone considered in [19]. If we imagine that the cyclone with an area of 1.6×10^6 km^2 (minimum size of a synoptic formation in [19]) has the shape of a circle in the horizontal plane, the radius of such a circle will be 713 km. However, studies [17, 18] show that the mean radius of a cyclone at the moment of its nucleation is significantly smaller (300–500 km).

Golitsyn et al. [19] have shown that $\log(N)$ linearly decreases with increasing area occupied by a cyclone. In our case (Fig. 1), the linear approximation of the distribution $\log(N)$, depending on the cyclone size, is characterized by the determination coefficient $r^2 = 0.9667$. The closeness of the determination coefficient to unity supports the validity of the linear approximation and suggests that the size distribution of cyclones is exponential, a result that confirms the conclusions made in [19].

However, for a more comprehensive analysis of the distribution obtained, one should note that the distribution of points in Fig. 1 is very irregular. The quantiles of levels 0.1 and 0.9 are indicated in the plot by gray color. In Fig. 1, the largest amount of points are concentrated in the left-hand part of the plot, which generally imposes limitations on the use of the apparatus of linear regression. To obtain more correct estimates for the size distribution of cyclones, we constructed the plot of this distribution in linear coordinates (Fig. 2). In spite of a high value of the determination coefficient, the determination error of the number of cyclones with the use of the approximation by an exponential function attains 10–20%. In this case, the number of small cyclones ($< 1 \times 10^6$ km^2) is overestimated by up to 20%, whereas the number of medium-size cyclones ($1 \times 10^6 - 3 \times 10^6$ km^2) is underestimated by up to 10%. On the other hand, the distribution obtained can be much more accurately described with the use of the third-order polynomial:

$$N = 16.64 - 11.20 \times S + 2.64 \times S^2 - 0.21 \times S^3. \quad (4)$$

This approximation is characterized by a very high determination coefficient $r^2 = 0.9999$. Thus, knowing the size of a synoptic formation, one can use Eq. (4) to estimate the occurrence frequency of corresponding cyclones in the Northern Hemisphere with a high accuracy.

Apart from analyzing the number of cyclones depending on their sizes, we constructed the distribution of the number of cyclones depending on their intensities (Fig. 3). The intensities of extratropical cyclones vary within the range from 1 to 70 hPa, and 90% of the cyclones under consideration are characterized by intensities no higher than 15 hPa. Figure 3a shows the cumulative distribution $\log(N)$, which is well approximated by a straight line ($r^2 = 0.9983$):

$$\log(N) = -0.068 \times \delta p + 6.189. \quad (5)$$

If $\delta p > 40$ hPa, the exponential function somewhat overestimates the number of cyclones; however, the fraction of such cyclones is smaller than 0.2 N. Figure 3b shows that the approximating curve corresponding to an exponential function very well reproduces the intensity distribution of cyclones in the entire range of δp values.

CONCLUSIONS

We analyzed the distribution of the number of extratropical cyclones of the Northern Hemisphere, depending on their horizontal sizes and intensities. The intensity distribution of cyclones has an exponential character. The exponential distribution of the number of extratropical cyclones depending on δp^2 was obtained in [19]. The δp quantity is proportional to the kinetic energies of extratropical cyclones. However, according to our data, no exponential dependence of the number of cyclones on the square of the pressure deficit was revealed.

The distribution of the number of cyclones depending on their horizontal sizes is well described by a third-order polynomial. However, the results obtained in [19] show that, as in the case with the intensity, the size distribution of the number of cyclones has an exponential character. Additionally, the sizes of cyclones considered in [19] are significantly larger than the values appearing in our study. However, if the distribution of the number of large cyclones is analyzed, the approximation by a third-order polynomial will also yield better results than the approximation by an exponential curve.

As distinct from [19], we did not investigate extratropical anticyclones, because our scheme of cyclone identification was not adapted to the tracking of anticyclones. On the other hand, the fact that we took into account cyclones of all intensities substantially develops study [19], where only the formations with intensities exceeding 4.5 hPa were considered. Such a limitation was possibly chosen because isobars are drawn with an interval of 5 hPa in synoptic maps; consequently, cyclones with a pressure deficit smaller than 5 hPa are not reflected in such maps. At the same time, the majority of extratropical cyclones at the initial stage of their development or at the stage of filling represent shallow synoptic formations. As Fig. 3b shows, about 50% of N are characterized by values $\delta p < 4.5$ hPa. A cyclone with $\delta p = 1.3$ hPa nucleating in the rear part of a more intense formation in the North Atlantic is shown in Fig. 4 as an example. Additionally, it should be noted that cyclones with low δp values often develop in the Mediterranean region; nevertheless, such cyclones bring very intense precipitation in Europe.

We approximated the distributions of the number of cyclones with a very high accuracy, so that the regularities obtained have been very stable during several recent decades. These results can be used for the validation of prognostic models on the one hand and for estimating the risk of the appearance of very intense synoptic formations on the other.

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SPELL: 1. Пло, 2. midlatitudes, 3. climatologies, 4. stereographic