ISSN 1028-334X, Doklady Earth Sciences, 2007, Vol. 413, No. 2, pp. 324–326. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © G.S. Golitsyn, I.I. Mokhov, M.G. Akperov, M.Yu. Bardin, 2007, published in Doklady Akademii Nauk, 2007, Vol. 413, No. 2, pp. 254–256.

GEOPHYSICS

Distribution Functions of Probabilities of Cyclones and Anticyclones from 1952 to 2000: An Instrument for the Determination of Global Climate Variations

Academician of the RAS G. S. Golitsyn[a], Corresponding Member of the RAS I. I. Mokhov[a], M. G. Akperov[a], and M. Yu. Bardin[b]

Received November 17, 2006

DOI: 10.1134/S1028334X07020432

Global climate changes are not desirable and are even dangerous for two reasons. Slow variations in mean values, such as air temperature at the surface, lead to prolongation of the period without frost, decreasing of the time favorable for winter sports, and other changes. On the other hand, a shift in the mean characteristics leads to variations in the distribution functions for hazardous and even catastrophic events such that they can become more frequent and intense. Moreover, they can appear in atypical regions, where the population is not accustomed to such events. The standard procedure is currently as follows: the percentage of probability of draughts, floods, frosts, hot weather periods, or other extreme phenomena are calculated on the basis of observation data or climate models. Then variations for other climatic periods are analyzed relative to their intensity, duration, recurrence frequency, and so on. Analysis of their distribution functions related to the target parameter is a more detailed and representative method to understand the variations in the statistics mentioned above. We have calculated such distribution functions related to the intensity and area of cyclones and anticyclones based on the data of reanalysis weather charts [1] for the second half of the 20th century. They have an exponential character. The variations in such distribution functions are most informative for determining climate changes.

This approach has already been in use in geophysics for many decades. The most detailed example is provided by seismology, in which the number of earthquakes $N(m)$ is calculated as function of their magnitude m on a global or regional scale [2] for a fixed time interval. The dynamic variation range of the parameter that is used to plot the distribution, for example, m in seismology, is divided into equal subintervals Δm (usually in the logarithmic scale), and the number of events $N(\Delta m)$ is calculated in each subinterval. Bar charts based on this method have become the estimate of empirical (not normalized) density of the probability distribution. Cumulative bar charts $N(\Delta m)$ usually plotted in practice are related to the number of events with a magnitude greater or equal to m.

This value is statistically more stable than its derivative with respect to m, which is equal to $N(m)$. Feller [3] proved a theorem that the inversed value to cumulative frequency is the mean expectation time $\tau(\geq m)$ of an event with intensity $\geq m$. Many natural events (earthquakes, tsunamis, landslides, and so on) are characterized by power distributions $N(\geq m) \sim m^{-n}$, where usually $n \sim 1$. Golitsyn [4] was first to explain this fact. Such distributions are important for determining risk in the construction of various objects in a certain region.

In this paper, we suggest a method for the determination of distribution functions for cyclones and anticyclones (the main weather-forming elements) as a function of their kinetic energy and areas. This method has the following important advantage: the parameter used to find the distribution is proportional to the square of the pressure deviation from its mean value (for the energy) and to the deviation of the pressure (for areas) [5]. This fact was first tested in [5] for Arctic mesoscale cyclones.

It is desirable that the parameter used to find the distribution would be dimensionless. For example, in the Maxwell distribution of molecules with respect to velocities, the kinetic energy of a molecule $\frac{mv^2}{2}$ is normalized by kT, where $k = 1.38 \cdot 10^{-23}$ J/K is the Boltzmann constant. Here, we shall determine the pressure scale used to obtain a dimensionless variable by means of normalizing by unity the probability of existence of

[a] *Oboukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Pyzhevskii per. 3, Moscow, 119017 Russia*

[b] *Institute of Global Climate and Ecology, Russian Academy of Sciences, Glebovskaya ul. 20b, Moscow, 107258 Russia; e-mail: aseid@mail.ru*

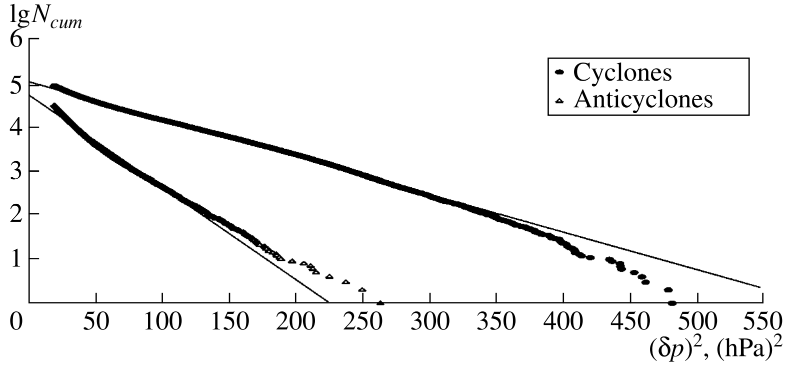

Fig. 1. Cumulative distributions of the number of cyclones and anticyclones as a function of $(\delta p)^2$. The coefficient of determination for the exponential approximation is $r^2 = 0.9965$, $\log N(\geq \delta p^2) = 5.0656 - 0.0086\delta p$ for cyclones and $r^2 = 0.9840$, $\log N(\geq \delta p^2) = 4.7756 - 0.0210\delta p$ for anticyclones during the period from 1952 to 2000.

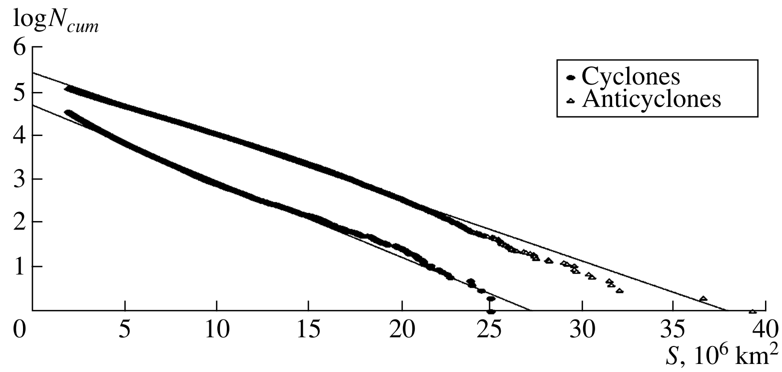

Fig. 2. Cumulative distributions of the number of cyclones and anticyclones as a function of their areas. The coefficient of determination for exponential approximation is $r^2 = 0.9917$, $\log N(\geq S) = 4.7312 - 0.1726S$ for cyclones and $r^2 = 0.9945$, $\log N(\geq S) = 5.4678 - 0.1434S$ for anticyclones during the period from 1952 to 2000.

an eddy with energy $K \sim (\delta p)^2$ in the entire interval of the fixed limits of pressure variations.

We used the NCEP reanalysis data of the geopotential of the 1000 hPa isobaric surface in the 20°–80° N band over a grid of 2.5° × 2.5° for each 12-h period from 1952 to 2000; i.e., we do not trace time evolution of eddies here.

Cyclones and anticyclones were characterized as low- or high-pressure regions limited by closed contour lines (isohypses for the geopotential data). The coordinates of the grid node with minimal/maximal pressure were considered the center of the eddy. The depth of the synoptic eddy was determined as the difference between the geopotential in its center and at the last closed contour line. We analyzed contour lines with a step of 1 geopotential meter (gp.m) [6].

Transformation of geopotential meters to more customary hectopascals in the case of static approximation $\delta p = -\rho g \delta z$ requires knowledge of the density, i.e., the temperature at a level of 1000 hPa. This is a problem that requires special efforts. For simplification of the calculations and interpretation, we used everywhere the relation δp (hPa) = $0.12\Delta z$ (gp.m) at the last isohypse. At 1000 hPa, this relation corresponds to $T = 280.6\ K = 7.3$°C.

The total number of cyclones (in the sense defined above) in the data archive analyzed in this research exceeds half a million, and the number of anticyclones exceeds four hundred thousand. Figures 1 and 2 present their cumulative distributions with respect to the parameter. In both cases, we cut-off small formations with $\delta p = (20)^{1/2} = 4.5$ hPa and considered only the eddies with a high value of pressure dispersion. Figure 1 shows cumulative bar charts for the number of eddies recorded over 49 years of our analysis with dispersion greater than 20 (hPa)^2. Such a bar chart is convenient because one can immediately count the number of eddies $N(\geq \delta p^2)$, while the inverse value to this number according to the Feller theorem [3] gives the mean expectation time of an event with dispersion $\geq \delta p^2$. The following two circumstances draw one's attention: (i) linear dependences $\log N(\geq \delta p^2)$ over pressure dispersion variations by approximately more than one order of magnitude; (ii) different patterns of the bar chart tails, i.e., empirical functions of the distribution of strong events. This is recurrence, which decays faster than the exponent for cyclones and decays slower than the exponent for anticyclones. The first circumstance can be considered favorable for society because strong cyclones are usually associated with anomalous phenomena such as strong winds and anomalous precipitation. Our analysis shows that their probability decays faster than the exponent. The second circumstance is unfavorable and means a high probability of anticyclones (according to the reanalysis data, the doubled number of anticyclone days means a greater probability of draughts, periods of hot weather, and so on). Figure 2 shows similar exponential dependences for the distribution of both types of eddies as a function of only the eddy area.

We also note that larger cyclones and anticyclones are represented by the Iceland minimum, Azores maximum, and other quasi-permanent atmospheric centers of action.

DISCUSSION

The distribution of the number of atmospheric eddies with respect to their intensity (energy) is close to the exponential one. This fact indicates the independent character of the appearance of eddies. In this case, the probability of the sum of events $f(x_1 + x_2) = f(x_1)f(x_2)$ is equal to the product of their probabilities. The solution of such a functional equation is the function $f(x) = e^{-x}$ with normalization depending on specific conditions. The eddies at the tails of these distributions cease to be independent, and they influence each other due to the finite size of the Earth's surface. The exponential character of the distribution of the number of eddies with respect to energy can be interpreted by the Boltzmann or Gibbs distribution. One can consider that the atmosphere and the underlying surface, 70% of which is the ocean, form a canonical ensemble [7]. The ocean plays the role of a thermostat, while the atmosphere is a subsystem with fluctuations exponentially distributed with respect to energy.

The exponential distribution of the number of different atmospheric eddies was already published, for example, for tropical cyclones (TC). Such distributions were plotted on the basis of the pressure deficit at their centers δp. According to [8], it is sufficient to know the estimate of the squared wind velocity calculated from the pressure deficit. In our case, however, the quadratic dependence appears due to the account of the eddy area on the basis of the squared Rossby deformation radius. However, substitution of variable δp by $(\delta p)^2$ does not change the exponential character of the distribution functions. It was found that the distribution of TCs with respect to their lifetime is also exponential. The authors of [9] also found that the TC distribution in the southwestern Pacific (with respect to the pressure deficit) is close to exponential. They present the probabilities of the appearance of TC-related typhoons in Hong Kong, Taipei, Tokyo, and Vladivostok. Similar regularities were also found for polar hurricanes. Exponential distributions also approximated the distribution of tornados [5, 10–12] and convective thermic cycles with respect to their size.

It seems that plotting of such distribution functions for atmospheric eddies should be an important field of activity in estimation of the risk of global climate changes in different regions.

ACKNOWLEDGMENTS

This work was supported by the by the Presidium of the Russian Academy of Sciences (Program no. 16), the Earth Sciences Division of the Russian Academy of Sciences (Program no. 11), the Ministry of Education and Science (Federal Agency on Science and Innovations, State Contract no. 02.434.11.4003), and the Russian Foundation for Basic Research (project no. 05-05-64907).

REFERENCES

1. R. Kistler, E. Kalnay, K. Cillins, et al., Bull. Am. Meteor. Soc. **82**, 247 (2001).
2. B. Gutenberg and R. Richter, Ann. Geophys. **9**, 1015 (1954).
3. W. Feller, *Introduction into Probability Theory and Its Applications* (Wiley, New York, 1971), Vol. 1, Chap. 13.
4. G. S. Golitsyn, Dokl. Physics **49**, 501 (2004) [Dokl. Akad. Nauk **398**, 177 (2004)].
5. G. S. Golitsyn, Dokl. Earth Sci. **401**, 277 (2005) [Dokl. Akad. Nauk **401**, 72 (2005)].
6. M. Yu. Bardin and A. B. Polonskii, Izv., Atmos. Ocean. Phys. **41**, 127 (2005) [Izv. Akad. Nauk, Fiz. Atmos. Okeana **41**, 147 (2005).
7. C. Kittel, *Introduction into Statistical Physics* (Wiley, New York, 1958).
8. G. S. Golitsyn, P. F. Demchenko, I. I. Mokhov, and S. G. Priputnev, Dokl. Earth Sci. **366**, 537 (1999) [Dokl. Akad. Nauk **366**, 116 (1999)]
9. G. S. Golitsyn, V. F. Pisarenko, M. V. Rodkin, and M. I. Yaroshevich, Izv., Atmos. Ocean. Phys. **35**, 663 (1999) [Izv. Akad. Nauk, Fiz. Atmos. Okeana **35**, 334 (1999).
10. I. I. Mokhov, *Research Activities in Atmospheric and Oceanic Modeling*, WMO TD-no. 987, 2.18 (2000).
11. I. I. Mokhov and S. G. Priputnev, *Research Activities in Atmospheric and Oceanic Modeling*, WMO TD-no. 1064, 2.22 (2001).
12. M. V. Kurganskii, Dokl. Earth Sci. **371**, 408 (2000) [Dokl. Akad. Nauk **371**, 240 (2000)].
13. A. N. Vul'fson, Izv., Atmos. Ocean. Phys. **33**, 715 (1997) [Izv. Akad. Nauk, Fiz. Atmos. Okeana **33**, 771 (1997)].