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Estimating the Number of Cloud Layers through Radiosonde Data from Russian Aerological Stations for 1964–2014

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Abstract—Radiosonde data are used for the period of 1964–2014 and the method that determines the boundaries and cloud amount based on the profiles of temperature and humidity [23]; long-period statistical characteristics are computed for the cloud layer number for different altitude ranges from the ground to 10 km. The study is performed for the Russian aerological stations located at different latitudes and climate zones. To specify the spatiotemporal features of the atmosphere layering into cloud layers and cloudless layers between them, the estimates of monthly mean, seasonal mean, and annual mean values of cloud layer number as well as of their standard deviations are computed, and the amplitude of their variations is determined. The results qualitatively agree with the data of aircraft-based sounding of the atmosphere as well as with the data of radars and experiments with free balloons.

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Keywords: Russian aerological stations, radiosonde data, cloud layer number, vertical distribution

1. INTRODUCTION

The results of studying the vertical structure of the atmosphere from observational data are needed to assess the atmosphere energy and conditions for the propagation of light and radio waves as well as to provide the operation of aviation [3, 4, 6–8, 10, 15, 17–19, 23, 25–27]. In particular, great attention is paid to the investigation of the vertical structure of clouds retrieved from radiosonde data in order to determine its statistical characteristics [3, 4, 17, 18, 21, 28–30, 32]. This is explained by the fact that radiosonde data were collected over a rather long period of observations [2–4, 11, 21, 24]. The authors of [4, 18] present global estimates for the boundaries and total thickness of cloud layers for 1964–1998 as well as the estimates of the boundaries, total thickness, and number of CL for different stations over the period of 1964–2014. The statistical characteristics were obtained with account of cloud amount in the atmospheric layers of 0–2, 2–6, 6–10, and 0–10 km.

The object of the present research is the temperature-humidity layering into cloud layers (CL) and cloudless layers in the atmospheric layer of 0–10 km above the ground. The layers are determined by the CE method [3, 17, 22, 23] based on radiosonde data on temperature and humidity. The problem of spatiotemporal variability of CL number retrieved from radiosonde data for 1964–2014 from the Russian stations located at different latitudes and climate zones is considered in more detail.

2. DATA AND METHODS

To determine the boundaries and amount of cloudiness using the profiles of temperature (T) and humidity (R), the CE method was used. Its basic idea is to determine the intervals where cloud layers affect the profiles of temperature and humidity in the atmosphere. Due to inertia, the response of sensors might not almost affect the absolute values of temperature and humidity, but it is almost always manifested in relative variations (derivatives along the profile) [3, 17, 18, 23]. The identification of CL by the CE method includes two stages. At the first stage the CL boundaries are determined using the second derivatives of temperature and humidity with respect to the altitude along the profiles. The idea is that the specific features of

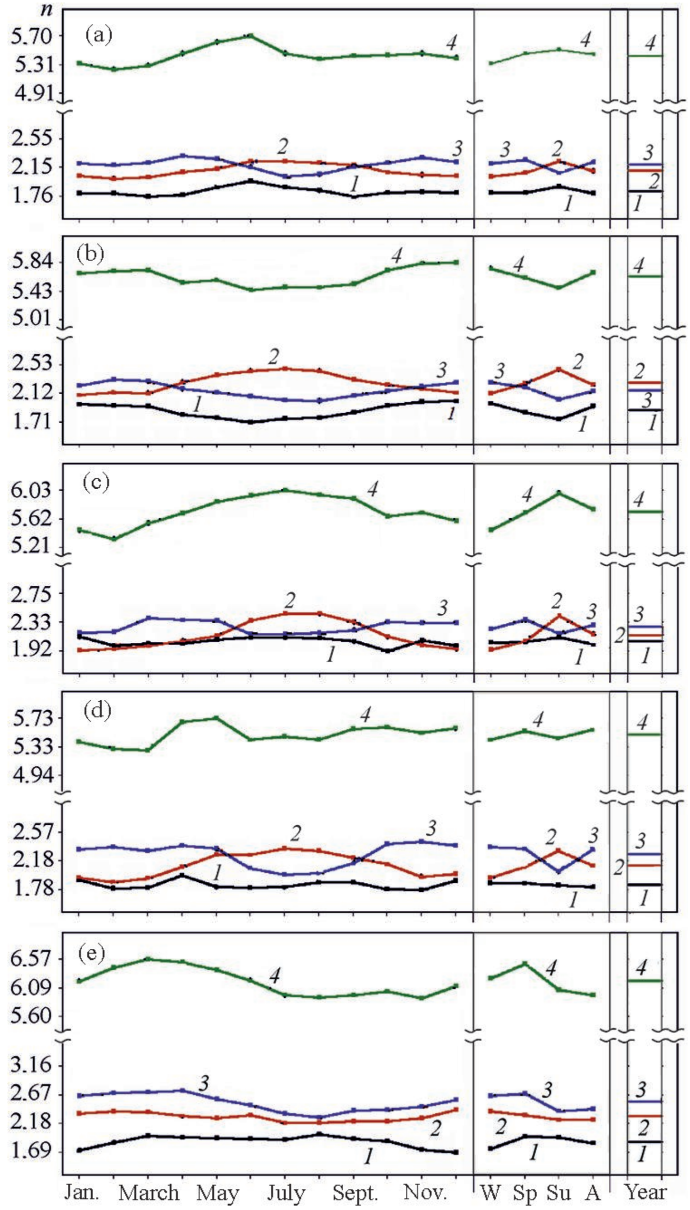

Fig. 1. Average long-term values of the number of CL (n) with the cloud amount of 0–100% for 00:00 in different air layers for every month, season, and year from radiosonde data from the Russian aerological stations located in different latitude zones and climate regions for the period of 1964–2014. (a) Murmansk; (b) Moscow; (c) Dikson Island; (d) Verkhoyansk; (e) Mirnyi. Atmospheric layers: (*1*) 0–2 km; (*2*) 2–6 km; (*3*) 6–10 km; (*4*) 0–10 km above the ground; seasons: W is winter (December, January, February); Sp is spring (March–May); Su is summer (June–August); A is autumn (September–November).

the rate of temperature and humidity variation with height may be determined by the changes in these parameters when radiosonde crosses the CL boundaries. The following conditions are assumed as a criterion of cloud layer existence:

$$T\ (h)\quad 0 \text{ and } R\ (h)\quad 0 \text{ for } h_1\quad h\quad h_2.$$

There is also a requirement of changing the sign of the corresponding second derivative to the opposite one at boundary points h_1 and h_2. This means that points h_1 and h_2 are the inflection points of the profiles of T and R as well as the points of local extremes of the first derivatives T and R (the maximum of R and minimum of T at point h_1 and, on the contrary, the minimum of R and maximum of T at point h_2). These conditions were found from the comparison of the profiles of temperature and relative humidity and their

Table 1. The ranges of intraannual variations in the monthly mean values of the number of cloud layers with the cloud amount of 0–100% in the air layer of 0–10 km above the ground for 00:00 and 12:00 and for the whole day and their average long-term values at Russian stations located in different climate zones (1964–2014)

Index	Station	Coordinates		Height, m	Observation period
		latitude	longitude		
North European area of the Arctic region of Russia					
22113	Murmansk	68.98 N	33.12 E	98	1964–2014
22217	Kandalaksha	67.15 N	32.35 E	26	1964–2014
22271	Shoina	67.88 N	44.13 E	11	1964–2014
23205	Naryan-Mar	67.63 N	53.03 E	9	1964–2014
Western Siberian area of the Arctic region of Russia					
23330	Salekhard	66.53 N	66.67 E	17	1964–2014
20674	Dikson Island	73.58 N	80.40 E	47	1965–2014
23078	Norilsk	69.32 N	88.22 E	61	1978–2014
Eastern Siberian area of the Arctic region of Russia					
24125	Olenek	68.50 N	112.43 E	204	1964–2014
21824	Tiksi	71.58 N	128.92 E	2	1964–2014
24343	Zhigansk	66.77 N	123.40 E	82	1964–2014
24266	Verkhoyansk	67.47 N	133.40 E	138	1964–2014
Mid-latitudes of the European part of Russia					
27612	Moscow	55.75 N	37.95 E	190	1964–2014
27707	Sukhinichi	54.10 N	35.35 E	240	1964–2014
Antarctica					
89050	Bellingshausen	62.2 S	58.9 W	42	1970–1999
89512	Novolazarevskaya	70.8 S	11.8 E	132	1969–2014
89592	Mirnyi	66.5 S	93.0 E	12	1969–2014

second derivatives with the data of ground-based observations of clouds [3, 17, 23]. To obtain the continuous second derivatives along the vertical profile of T and R, measurement data on meteorological parameters are approximated with cubic splines with zero boundary conditions for the second derivatives [3, 9, 13, 20].

At the second stage the degree of the sky coverage with clouds was determined for the gradations of 0–20, 20–60, 60–80, and 80–100% for each separated cloud layer using the values of temperature and dew-point deficit at the level of the maximum relative humidity within such layer based on the piecewise-linear approximation of Arabei–Moshnikov diagram [3, 23]. The cloud amount at each cloud level [5, 16, 31] is the maximum amount of cloudiness in the cloud layers situated within the respective altitude ranges (0–2, 2–6, and 6–10 km).

The authors of [3, 17, 22, 23, 27] considered different aspects of CE method testing. The results obtained with the CE method indicate the presence of separate cloud and cloudless layers [3, 17, 23] that allows the objective assessment of the CL number.

The data we used as an information base were obtained over the period of 1964–2014 from the Russian aerological stations located in different latitude zones. Data were taken from the CARDS (Comprehensive Aerological Reference Dataset) global radiosonde dataset [2, 24] supplemented with current data from the AEROSTAB [1] and AEROSTAS [11] datasets. The period selected for computations starts from 1964, because radiosonde data at the global aerological network for the Southern Hemisphere in the late 1950s–early 1960s are insufficient for long-term calculations [12]. Preliminarily the data of aerological

Table 1. (Contd.)

Variation range			Mean value				Number of observations		
00:00	12:00	24 hours	00:00	12:00	24 hours	24 hours	00:00	12:00	24 hours
North European area of the Arctic region of Russia									
5.3–5.6	5.4–5.7	5.4–5.6	5.4	5.5	5.5	1.8	15085	13837	28922
5.6–6.2	6.0–6.2	5.8–6.2	5.8	6.1	6.0	2.4	12174	12508	24682
5.6–6.0	5.7–6.1	5.7–6.1	5.8	5.9	5.8	2.5	10173	11790	21963
5.1–5.4	5.1–5.5	5.1–5.4	5.3	5.4	5.3	1.8	13971	12048	26019
Western Siberian area of the Arctic region of Russia									
5.1–5.6	5.3–5.8	5.3–5.7	5.4	5.5	5.5	1.8	14294	13618	27912
5.5–6.0	5.5–5.9	5.5–5.9	5.7	5.7	5.7	2.3	10109	10565	20674
5.2–5.3	5.3–5.4	5.3–5.4	5.3	5.4	5.3	1.6	10029	10183	20212
Eastern Siberian area of the Arctic region of Russia									
5.4–5.8	5.5–5.9	5.5–5.9	5.6	5.7	5.7	2.2	12421	12318	24739
5.8–6.0	5.8–6.0	5.8–6.0	5.9	5.9	5.9	2.0	11235	12992	24227
5.5–5.8	5.2–5.6	5.4–5.7	5.6	5.4	5.5	2.1	12546	10678	23224
5.3–5.6	5.2–5.5	5.3–5.5	5.5	5.4	5.4	2.2	12734	13528	26262
Mid-latitudes of the European part of Russia									
5.4–5.8	5.5–5.9	5.5–5.8	5.6	5.7	5.7	2.0	16790	14693	31483
5.0–5.4	5.3–5.6	5.2–5.5	5.2	5.5	5.4	2.0	12401	13200	25601
Antarctica									
5.0–5.4	–	5.0–5.4	5.2	–	5.2	1.5	5593	2	5595
5.9–6.4	–	6.0–6.4	6.3	–	6.3	2.1	9061	1315	10376
6.0–6.5	–	6.0–6.5	6.2	–	6.2	2.0	9476	2740	12216

stations which passed the procedure of the complex quality control [2] were checked for availability and completeness. Basic attention was paid to polar stations. The stations with the fullest time series located at different latitudes and climate zones were selected as a result of the analysis (see Table 1). Both continental and coastal stations are presented. Routine standard observations at the selected stations in the Northern Hemisphere were conducted at 00:00 and 12:00 UTC; at Antarctic stations, most observations were held at 00:00 UTC (hereinafter, Coordinated Universal Time is given).

The studies were carried out for the air layer of 0–10 km above the ground. It is known that cloudiness affects solar radiation coming to the Earth surface as well as terrestrial radiation [14]; therefore, the vertical structure of CL was studied both for the whole day and for the nighttime and daytime separately. To compute the CL number, only such soundings were used for which data on both temperature and humidity from the surface to the height of 10 km were available. As clouds could be absent during the sounding, only the months containing at least 10 soundings with one or more CL were included to the time series.

To investigate the CL vertical structure and its intraannual variability, average long-term values were calculated for the number of CL with the cloud amount of 0–20, 20–60, 60–80, 80–100, and 0–100% for the atmospheric layers of 0–2, 2–6, 6–10, and 0–10 km for every month, season, and year. As noted above, the first three layers correspond to the low, middle, and upper cloud levels. When considering CL with the fixed cloud amount, the existence of other CL was assumed. Cloud layers with the thickness of not less than 50 m detected by the CE method were taken into account.

Table 2. The ranges of intraannual variations in monthly mean values of the number of cloud layers, their average long-term values for the air layers of 0–2, 2–6, 6–10, and 0–10 km above the ground with account of cloud amount gradation for 00:00 and 12:00 at Moscow (Dolgoprudny) station over the period of 1964–2014

Cloud amount gradation, % of sky surface	Variation range		Mean value		Number of observations	
	00:00	12:00	00:00	12:00	00:00	12:00
			0–10 km			
0–20	2.3–3.0	2.6–3.2	2.7	3.0	11217	10536
20–60	1.47–1.51	1.5–1.6	1.5	1.6	8014	7421
60–80	1.2–1.3	1.2–1.3	1.3	1.3	6384	5666
80–100	2.5–3.7	2.3–3.6	3.1	3.0	14102	13338
0–100	5.4–5.8	5.5–5.9	5.6	5.7	16790	14693
			6–10 km			
0–20	1.5–1.6	1.5–1.7	1.5	1.6	4652	4783
20–60	1.2–1.3	1.2–1.3	1.3	1.3	3978	3888
60–80	1.1–1.2	1.1–1.07	1.1	1.1	3569	3202
80–100	1.6–2.1	1.5–2.0	1.8	1.8	10625	8336
0–100	2.1–2.3	2.0–2.3	2.2	2.1	16409	14302
			2–6 km			
0–20	1.6–1.9	1.7–1.9	1.7	1.8	9031	8372
20–60	1.1–1.2	1.1–1.2	1.2	1.2	3740	3459
60–80	1.0–1.1	1.06–1.09	1.1	1.1	3219	2698
80–100	1.6–1.7	1.5–1.6	1.6	1.6	8050	6312
0–100	2.1–2.5	2.1–2.5	2.3	2.3	16081	14109
			0–2 km			
0–20	1.3–1.5	1.5–1.6	1.5	1.6	6652	7050
20–60	1.1–1.2	1.1–1.2	1.1	1.1	3061	2817
60–80	1.0–1.03	1.03–1.05	1.0	1.0	1768	1708
80–100	1.4–1.7	1.4–1.7	1.6	1.6	8893	6820
0–100	1.8–2.0	1.8–2.0	1.9	1.9	15480	14001

Monthly mean and seasonal mean statistical characteristics of CL were smoothed using three points with the double weight for the central point.

3. RESULTS AND DISCUSSION

Table 1 presents the ranges of intraannual variations in the monthly mean values of CL number, their long-term statistical characteristics for 00:00 and 12:00 and for the whole day. Figure 1 presents the long-term smoothed mean values of the number of CL with the cloud amount of 0–100% of sky surface for 00:00 UTC in different atmospheric layers for months, seasons, and the year over the stations located in different climate zones.

The analysis of the spatiotemporal variability of the number of CL with the cloud amount of 0–100% of sky surface retrieved from radiosonde data for 1964–2014 for the considered Russian aerological stations revealed the following.

For the time scales under study (month, season, year) the mean values of CL number in the layer of 0–10 km for the whole day, for 00:00, and for 12:00 UTC vary within 5.0–6.5 for all stations; within 5.0–5.9 for the mid-latitude stations; within 5.1–6.2 and 5.0–6.5 for the Arctic and Antarctic stations, respectively (Table 1, Fig. 1). Their intraannual variability is 0.1–0.6 depending on a station.

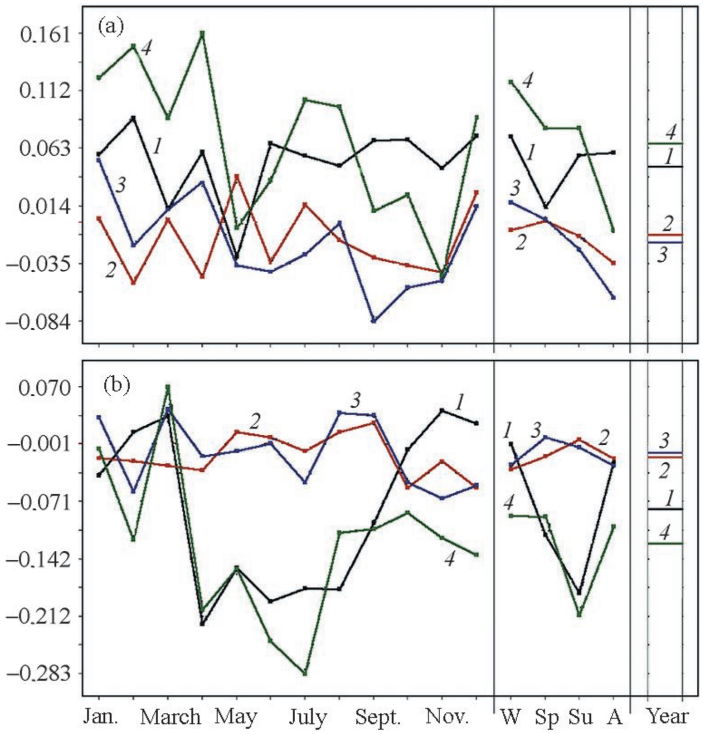

Fig. 2. The difference in average long-term values of the number of CL with the cloud amount of 0–100% for 12:00 and 00:00 in different atmospheric layers for every month, season, and year from radiosonde data from (a) Moscow and (b) Verkhoyansk stations over the period of 1964–2014. The designations are the same as in Fig. 1.

For calculations for the whole day, the ranges of intraannual variations in the mean values of CL number with account of the cloud level are as follows (see Fig. 1 and Table 2):

Level	High	Middle	Low
All stations	1.8–2.8	1.8–2.5	1.7–2.1
Mid-latitudes	2.0–2.3	2.1–2.5	1.8–2.0
Arctic	1.9–2.4	1.9–2.5	1.7–2.1
Antarctica	1.8–2.8	1.8–2.4	1.7–2.0

The amplitude of the intraannual variability of mean values of CL number is 0.2–0.6 for all levels.

Figure 2 presents the average long-term values of the difference in the respective mean values of CL number for 12:00 and 00:00 for Moscow and Verkhoyansk stations. It is clear that the amplitude of intraannual variability of this difference does not exceed 0.4 in the layer of 0–10 km and 0.3 at each level.

For the year, standard deviations ( ) of CL number in the layer of 0–10 km for the whole day vary in the range of 1.5–2.5 for all stations. They are equal to 2.0 in mid-latitudes; the ranges of their variations for the Arctic and Antarctic stations are 1.6–2.5 and 1.5–2.0, respectively (see Table 1).

The analysis of the spatiotemporal variability of CL number with account of cloud amount for Moscow station (see Table 2) revealed that for each gradation of cloud amount the ranges of intraannual variations in monthly mean values and the respective mean values of CL number in all considered air layers poorly depend on the observation time. The dependence of CL number on the cloud amount is observed within each layer: the number of CL with the cloud amount of 0–20% and/or 80–100% is maximum and the number of CL with the cloud amount of 60–80% is minimum.

Table 3 provides for the analyzed stations the maximum number of CL with the cloud amount of 0–100% of sky surface determined by the CE method in the layer of 0–10 km for 00:00 and 12:00 UTC. As clear from the table, the maximum number of levels in the aerologic telegram is 60–114 depending on a station, and the maximum CL number is equal to 12–19.

Table 3. The maximum number of cloud layers determined by the CE method for the Russian aerological stations under study (1964–2014)

Station	Winter	Spring	Summer	Autumn	Year	N_T
North European area of the Arctic region of Russia						
Murmansk	16	13	13	12	16	82
Kandalaksha	16	17	16	17	17	103
Shoina	18	16	18	17	18	99
Naryan-Mar	12	13	14	11	14	92
Western Siberian area of the Arctic region of Russia						
Salekhard	13	13	13	12	13	65
Dikson Island	14	17	15	14	17	79
Norilsk	11	12	11	11	12	88
Eastern Siberian area of the Arctic region of Russia						
Olenek	15	17	16	16	17	114
Tiksi	15	13	16	19	19	85
Zhigansk	14	15	14	15	15	84
Verkhoyansk	15	15	15	14	15	87
Mid-latitudes of the European part of Russia						
Moscow	16	14	15	14	16	91
Sukhinichi	14	14	13	14	14	87
Antarctica						
Bellingshausen	12	10	11	9	12	60
Novolazarevskaya	15	15	13	14	15	87
Mirnyi	15	14	15	15	15	82

Note: N_T is the maximum number of levels presented in the aerological telegram.

The analysis of computation of the maximum CL number with account of a cloud level demonstrated that, for example, it is equal to 6, 8, 8 for Sukhinichi station and 5, 6, 6 for Bellingshausen station for the air layers of 0–2, 2–6, and 6–10 km, respectively.

It is rather interesting to compare the above results with the results obtained by other authors based on the data of aircraft sounding, radars, and experiments with free balloons.

For example, according to the aircraft sounding data obtained by A.M. Borovikov and A.A. Fedorova, the maximum number of cloud layers is equal to 6; according to the studies made by L.P. Uporova, it may reach 7–8 [10].

A.M. Baranov studied frontal cloudiness, and A.M. Borovikov, the cloudiness considered regardless of synoptic conditions; they both noted the approximate constancy of the distribution of cloud layers during the year [10].

M.B. Fridzon conducted experiments with free balloons, when high-sensitive and low-inertia radiotechnical devices measuring air humidity and air temperature were synchronously lifted to the height of 30 km together with serial radiosondes [15]. Using the certified precision low-inertia instruments, the layered structure of the atmosphere was detected where the zones of high and low relative humidity alternate. The number of such strongly pronounced zones may reach 10–12 in one air mass [15].

The authors of [32] compared the vertical structure of cloud layers detected over the long-term period using radiosonde and radar data. The method used for the cloud layer separation is based on the existence of the certain critical value of relative humidity. According to the results of this study, the maximum number of layers identified from radiosonde and radar data was equal to 5 and 4, respectively.

The quantitative differences in the estimates of CL number may be explained by the difference in the methods of cloud layer separation and calculation, in the periods, periodicity, and regularity of observations [3, 10, 17] as well as by the summarization of results for the air layer of 0–10 km. It should also be taken into account that the CE method detects humid layers where clouds will be formed in several next hours (these layers are not registered yet during ground-based cloud observations at the given moment due to the small concentration of cloud particles, but they will be registered after the formation (usually with the radar)). The method also detects humid layers which represent the certain form of clouds left after their spreading (in several hours) and which are detected during the aircraft-based sounding with the instrument for the determination of cloud particle image [3, 17].

4. CONCLUSIONS

New data on the vertical structure of the atmosphere were obtained, namely, data on the spatiotemporal variability of the number of cloud layers in the air layer of 0–10 km. It was demonstrated that regional differences and differences for 00:00 and 12:00 in the ranges of intraannual variations in monthly mean and seasonal mean values of CL number are poorly pronounced. They are manifested when the CL number is considered for different cloud levels and with account of cloud amount. The presented data on the CL number qualitatively agree with the results obtained from the data of aircraft-based sounding, radars, and experiments with free balloons.

The statistical characteristics of CL number may be useful for studying the atmospheric radiation energy, for assessing propagation conditions of electromagnetic waves, for supporting the aviation operation, and for interpreting the measurement data on cloud atmosphere parameters obtained by other methods using the ground- and satellite-based instruments.

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