ISSN 1068-3739, Russian Meteorology and Hydrology, 2020, Vol. 45, No. 4, pp. 227–238. Allerton Press, Inc., 2020.
Russian Text The Author(s), 2020, published in Meteorologiya i Gidrologiya, 2020, No. 4, pp. 18–32.

Long-term Estimates of the Number of Cloud Layers from Radiosonde Data for 1964–2017 in Different Latitudinal Zones

I. V. Chernykh[a]* and O. A. Aldukhov[a]

[a]*All-Russian Research Institute of Hydrometeorological Information–World Data Center, ul. Koroleva 6, Obninsk, Kaluga oblast, 249035 Russia*

**e-mail: civ@meteo.ru*

Received December 14, 2018
Revised August 8, 2019
Accepted October 1, 2019

Abstract—The statistical characteristics are computed for the number of cloud layers based on radiosonde data from 965 aerological stations located at different latitudes of the globe for the period of 1964–2017 and on the CE method for the determination of cloud boundaries and cloud amount from the temperature and humidity profiles retrieved from radiosonde data. The calculations are performed for the atmospheric layer from the surface to the height of 10 km. The geographic distribution of seasonal and annual mean values as well as of standard deviations is obtained for the number of cloud layers. The amplitude of their regional variations is determined, that allowed specifying the spatiotemporal features of atmospheric layering into cloud and intercloud layers. The results agree with data of aircraft-based sounding, radar data, radiosonde data, and the results obtained from free balloon experiments.

DOI: 10.3103/S1068373920040020

Keywords: Number of cloud layers, vertical distribution of temperature and humidity, CE method for the determination of cloud boundaries and cloud amount

1. INTRODUCTION

Many studies investigated the vertical structure of the atmosphere based on observational data [3–7, 10, 11, 17, 23–27, 30–34, 38, 40–45]. Such great attention is caused by the importance of this information for scientific and applied problems, for example, for studying the radiant heat transfer in the atmosphere, for assessing the conditions of electromagnetic wave propagation, and for aviation needs [10, 12, 15, 21, 22, 24, 26, 27]. In particular, the investigation of the cloud vertical macrostructure retrieved from radiosonde data is needed to determine its long-term characteristics as radiosonde data were collected for a rather long observation period [1, 2, 18, 33]. The authors of this paper used radiosonde data on temperature and humidity to obtain the global estimates of the total thickness and boundaries of retrieved cloud layers [3, 24] and presented station estimates for these parameters as well as for the number of cloud layers for 1964–2014 [4, 26].

This paper invrstigates the temperature-humidity layering of the atmosphere in the layer of 0–10 km above the surface into cloud and intercloud layers determined from radiosonde profiles of temperature and humidity by the CE method [3, 25, 32]. The spatiotemporal variability is considered for the number of cloud layers retrieved from radiosonde data from the global network of aerological stations for 1964–2017. It was studied by the calculation of global long-term estimates and by the construction of geographic distributions for the long-term statistical characteristics of the number of cloud layers. Their analysis was performed, and the variation ranges were determined for the long-term statistical characteristics for the whole globe. The results are presented for different gradations of cloud amount and for different atmospheric layers for seasons and years.

2. DATA AND METHODS

Data for 1964–2017 from CARDS (Comprehensive Aerological Reference Dataset) [2, 33] complemented with current data from AEROSTAB [1] and AEROSTAS [18] datasets formed the information base. The data passed the procedure of complex quality control [2]. The stations located at different latitudes of the globe with the sufficient amount of data for the formation of 965 time series (some of them include the observations of two or three stations due to their opening, closure, or relocation) were selected from the list of the global aerological network stations. The period from 1964 was chosen for calculations, because radiosonde data from the global aerological network for the Southern Hemisphere for the late 1950s–1960s are insufficient for long-term calculations [19].

The conditions for the use of sparse and, therefore, extremely valuable data in the poorly covered regions were less strict than in the previous papers (for example, [3, 4, 24]). Firstly, the inclusion of long-term statistical characteristics for the number of cloud layers into calculations required that the time series for every season had data for at least 15 of 54 analyzed years for each station, provided that the last year of observations was not before 2014; the availability of data for a half of the analyzed observation period was required in the previous studies. Secondly, all radiosonde data which passed the quality control were used both for temperature and for humidity in all atmospheric layers from the surface to the height of 10 km; therefore, the number of profiles used for different layers can slightly differ. Previously, the calculations considered only radiosonde observations which contained data on temperature and humidity for the whole atmospheric layer from the surface to the height of 10 km. The extension of the observation period to 2017, the softening of data application conditions, the execution of calculations for seasons and years allowed obtaining geographic distributions for the statistical characteristics of the number of cloud layers in different atmospheric layers, with the detailing of cloud amount gradations.

Observational data in the troposphere are more “favorable” than in the stratosphere both from the point of view of the amount and in terms of the errors of calculation based on these data, which are related to the small height of radiosonde flight [2, 4, 19]. One of the main characteristics of upper-air sounding is its vertical resolution, it may vary in time in the long-term datasets [3, 25, 30, 42]: it basically increases as the radiosonde system develops. In 1964–2017, the long-term global mean resolution is ~0.7 km for the atmospheric layer of 0–30 km and ~0.4 km (i.e., much higher) for the lower tropospheric layer; the long-term global mean number of observations levels is 42 and 8, respectively.

Historical data on humidity are inhomogeneous in most countries for the following reasons: firstly, different countries use different sensors; secondly, there are no international standards for the conversion of relative humidity into dew point; thirdly, the replacement of humidity sensors was carried out; fourthly, the precision of relative humidity measurement (regardless of the sensor model) is influenced by the value of relative humidity, pressure, and solar radiation as well as by the value and/or sign of the temperature gradient [3, 13, 25, 28, 30, 33, 35–37, 39].

In accordance to the KN-04 code [16], the values of temperature T and relative humidity R in the aerological telegram are presented with the accuracy to 0.1 C and 0.1%, respectively. It should be recalled that the time constant for temperature sensors usually does not exceed 5 s at the level of 1000 hPa and 13.5 s at 100 hPa. For most humidity sensors, measurement errors do not exceed 5% under the positive values of temperature but increase essentially at the temperature of –20 to –40 C. The values of the time constant for different humidity sensors may differ significantly: for example, from 0.3 s at 20 C for the thin-film carbon sensor used for the VIZ and AIR radiosondes to 200 s at –30 C for the film sensor used in China, Russia, and France [3, 13, 25].

Numerous studies [5, 6, 11, 12, 17, 41, 43–45] noted that the presence of cloud layers mainly affects the value of air temperature and air humidity. Hence, their crossing by radiosondes should lead to the changes in the readings of corresponding sensors. For the long-term studies of parameters of the vertical macrostructure of cloud layers, it is desirable to use a method for their determination which is poorly sensitive to the inhomogeneities of long-term aerological datasets caused by the change of sensors and by the technology of radiosonde observations, in particular, by the possible change in the resolution of sounding. The results of applying the methods for the determination of cloud boundaries and cloud amount based on the direct use of the measured values of temperature and humidity highly depend on the inertial properties of sensors [13, 39]. Using them, it is often impossible to detect intercloud layers as well as thin and few-cloud layers in case of multilayer cloudiness, hence, the correct determination of the number of layers and the thickness of clouds is also impossible [3, 5, 12, 41–45].

The CE method was used to retrieve cloud boundaries and cloud amount from radiosonde profiles of temperature and humidity. The method was specially developed for the long-term studies of cloud layers based on global long-term radiosonde data [33]. The main idea of the method consists in the determination of height intervals, where the temperature and humidity profiles are affected by cloud layers. Due to the measurement data presentation accuracy and the inertia of instruments, the response of the sensors may have a weak or almost no effect on the absolute values of temperature and humidity [13, 17]. However, according to [3, 25, 32, 37, 39], it is almost always manifested in relative changes (the derivatives along the profile which correspond to the rate and acceleration of temperature and humidity variation in the certain interval of the vertical profile). The approximation of radiosonde data on temperature and humidity using cubic splines with smooth variation in derivatives along the profile gives a more plausible pattern of vertical variations in the meteorological parameters than the approximation with a broken line. The values of derivatives along the profile which indicate the impact of external forces, in case of spline approximation are determined by observations not only at the nearest points of the profile but also at the next points. This allows reducing the effect of the sensor inertia during the analysis of the vertical profile segment under study.

The detection of cloud layers by the CE method includes two stages. At the first stage, the cloud boundaries are determined using the second height derivatives of temperature T and relative humidity R along the profiles. The idea is that the features of the rate of vertical variations in temperature and humidity may be caused by changes in these parameters, when a radiosonde crosses the cloud layer boundaries. The following conditions were taken as a criterion of cloud layer existence:

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

It is required to change the sign of the corresponding second derivative to the opposite one at the boundary points h_1 and h_2. This means that the points h_1 and h_2 are the points of inflection for 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 the minimum of T at the point h_1 and, on the contrary, the minimum of R and the maximum of T at the point h_2). These conditions were determined as a result of the comparison of temperature and relative humidity profiles and their second derivatives with ground-based observations of clouds [3, 25, 32]. The approximation of measurement data on meteorological parameters with an Akima cubic spline with zero boundary conditions for the second derivatives is applied to obtain the continuous second derivatives along the vertical profile [9, 20, 29, 32]. The possible false oscillations arising from the application of the standard cubic spline at the dramatic change in the value at close distances are damped by the Akima spline as well as by the requirement that the used profile points had the vertical distance of at least 10 m at the given accuracy of presentation of the values of meteorological parameters.

At the second stage, the degree of the sky coverage was determined for the gradations of 0–20, 20–60, 60–80, and 80–100% for each detected cloud layer. It was based on the values of temperature and dew point at the level of maximum relative humidity within this layer using the piecewise-linear approximation of the Arabei–Moshnikov diagram [3, 32]. The maximum cloud amount in the layers situated within the corresponding altitude ranges (0–2, 2–6, and 6–10 km) is taken as the cloud amount in each layer [7, 23].

Different aspects of the CE method testing for dense and thin cloud layers, for cases of cloudless sky are discussed in detail in [3, 25, 30, 32, 40]. The authors and independent experts demonstrated that the results obtained using it indicate the presence of individual cloud and intercloud layers; this allows the objective estimation of the number of layers [3, 25, 30, 40].

To assess a possibility of using the time series of retrieved cloud parameters for the long-term studies, the sensitivity of the methods for the cloud layer determination from radiosonde data (including the CE method) to the sounding resolution variation was studied, and the results of cloudiness retrieval by the other methods using the SHEBA (Surface Heat Budget of the Arctic Ocean, USA) experiment data were compared [3, 25, 30]. The comparison of the cloud layer boundaries predicted by the CE method and the clouds detected by the cloud-range meter, radar, lidar, satellite and aircraft instruments revealed the following. Firstly, the results of the CE method poorly depend on the resolution of humidity and temperature profiles (in the framework of standard radio sounding) and on the minimum permissible cloud layer thickness. Secondly, the change in the sounding resolution from 0.4 to 0.7 km under the minimum permissible cloud layer thickness of 0.1 km has little effect on the results of cloud layer boundary prediction. Thirdly, the best result of retrieval of cloud layer boundaries in the atmospheric layer below 0.5–0.6 km was obtained for the temperature and humidity profile resolution of 0.1 km and for the minimum permissible cloud layer thickness of 50 m. In this case, a need in the higher resolution is explained by the smaller scale of physical processes in the lower troposphere as compared to the free troposphere [3, 23, 30].

The use of more detailed profiles (with the resolution of 1 m) for the analysis is limited by the accuracy of presentation of temperature and humidity values in the aerological telegram [3, 25]. The upper estimate of the error of gradient calculation using two neighboring observed values of temperature with the resolution h is determined from the formula $T = 0.1/ h$. If the resolution h varies within 0.4–0.7 km, the error of temperature gradient due to the accuracy of presentation of T varies from 0.025 to 0.014 C/m that makes up about 4 and 2% of the mean tropospheric temperature gradient (0.65 C/100 m). This is an acceptable accuracy. If $h = 1$ m, the error of the temperature gradient determination caused by the accuracy of temperature presentation equal to 0.1 C is 0.1 C/m, which is by 15 times higher than its mean tropospheric value. Hence, to solve the problems implying the calculation of derivatives using detailed radiosonde profiles, for example, of GPS sounding profiles, the values of temperature and relative humidity should be presented in the aerological diagram with the accuracy at least to 0.001 C and 0.001%. This may have no added value to the accuracy for transmitted values (due to the observation errors) but will allow obtaining a more precise profile of gradients due to the high correlation of observation errors which cancel each other during the calculation of gradients [3].

The long-term mean values of the number of layers with the cloud amount of 0–20, 20–60, 60–80, and 80–100% for the atmospheric layers of 0–2, 2–6, 6–10, and 0–10 km for the seasons and the whole year and the respective standard deviations were computed for each station to study variations in the number of cloud layers depending on the cloud amount, atmospheric layer, and season. The cloud layers detected by the CE method with the thickness of at least 50 m were considered. The existence of other layers was permitted during the analysis of cloud layers with the fixed cloud amount. The cloud amount of 0–20% is few clouds, 20–60% is scattered clouds, 60–80% is broken clouds, and 80–100% is overcast.

To visualize and to analyze the geographic distribution of statistical characteristics, it is more convenient to use fields on a regular grid than values on an irregular set of stations. The method of weighted anisotropic interpolation [10] was used to interpolate the long-term statistical characteristics of the number of cloud layers to the 2 2 grid:

$$\hat{f}_0 = \frac{\sum_{i=1}^{m} a_i f_i}{\sum_{i=1}^{m} a_i}$$

where a_i is the weight of each of the neighboring stations for a regular grid point. The estimates show [8] that it is sufficient to use the 5–8 closest stations to the point of interest which homogeneously or symmetrically surround it from all sides, for the horizontal interpolation. Every time the values of a_i are found as the solutions to the system of linear equations

$$\sum_{i=1}^{m} a_i r_{ij} = r_{0j} \quad \text{for} \quad j = 1, \ldots, m$$

where r_{ij} is the distance between the ith and jth stations, r_{0j} is the distance between the zero grid point and the jth station. For most meteorological parameters, the method of anisotropic interpolation gives almost the same accuracy (in terms of minimizing the mean squared interpolation error) as the optimum interpolation [9, 14], but it has an essential advantage over the optimum interpolation as its application does not require the knowledge of statistical structure of the interpolated parameters. However, the anisotropic interpolation does not provide the estimates of the interpolation error [2, 3].

The geographic distributions of the mean values and standard deviations of the number of cloud layers for the seasons and the whole year with account of the cloud amount gradation and atmospheric layer were constructed to study the spatiotemporal variability of the number of cloud layers.

3. NUMBER OF CLOUD LAYERS

Tables 1 and 2 present the estimates of variation ranges for the long-term statistical characteristics of the number of cloud layers in the above atmospheric layers on the territory of the globe for different gradations of cloud amount. The estimates were obtained by the analysis of the corresponding geographic distributions for the seasons and the whole year. For the mean values of the number of cloud layers with the cloud amount of 0–100% in different atmospheric layers, they are presented in Figs. 1 and 2 for different seasons.

The data in Table 1 and Figs. 1 and 2 show that the global seasonal and annual mean values of the number of cloud layers with the cloud amount of 0–100% in the layers of 0–2, 2–6, 6–10, and 0–10 km vary within 1.0–3.1, 1.2–5.0, 1.2–4.1, and 2.1–10.7; the amplitudes of their variations are equal to 2.1, 3.8, 2.9, and 8.6, respectively. For the respective standard deviations, the ranges of their global variation are 0.1–1.6, 0.4–2.8, 0.5–2.5, and 0.9–5.5 (Table 2), and the amplitudes of variations are 1.5, 2.4, 2.0, and 4.6.

Table 1. The variation ranges of global long-term seasonal mean and annual mean values of the number of cloud layers retrieved from the radiosonde profiles of temperature and humidity for the atmospheric layers of 0–2, 2–6, 6–10, and 0–10 km above the surface with account of cloud amount, 1964–2017

Cloud amount, %	Winter	Spring	Summer	Autumn	Year	Number of observations, 10^3
0–10 km						
0–20	1.6–7.0	1.6–7.2	1.6–8.0	1.7–8.0	1.7–7.3	1.2–36.3
20–60	1.1–2.0	1.1–2.0	1.1–2.0	1.1–2.0	1.1–2.0	0.5–21.6
60–80	1.0–1.4	1.0–1.4	1.0–1.4	1.0–1.4	1.0–1.4	0.3–13.1
80–100	1.4–4.9	1.4–4.6	1.2–4.7	1.3–4.4	1.4–4.5	0.7–31.6
0–100	2.3–10.7	2.3–10.8	2.1–10.6	2.2–10.6	2.2–10.5	1.5–37.9
6–10 km						
0–20	1.2–3.0	1.2–3.1	1.2–3.1	1.2–3.0	1.2–3.0	0.5–32.9
20–60	1.0–1.6	1.0–1.5	1.0–1.5	1.0–1.5	1.0–1.5	0.2–15.5
60–80	1.0–1.3	1.0–1.2	1.0–1.2	1.0–1.2	1.0–1.2	0.1–9.9
80–100	1.1–2.5	1.1–2.6	1.1–2.7	1.1–2.6	1.1–2.6	0.2–25.4
0–100	1.3–3.9	1.3–4.0	1.2–4.0	1.3–4.1	1.3–4.0	1.4–37.5
2–6 km						
0–20	1.1–3.5	1.2–3.9	1.2–3.6	1.2–3.7	1.2–3.5	1.1–35.3
20–60	1.0–1.5	1.0–1.5	1.0–1.5	1.0–1.5	1.0–1.5	0.3–9.8
60–80	1.0–1.2	1.0–1.2	1.0–1.1	1.0–1.1	1.0–1.2	0.1–7.0
80–100	1.1–2.5	1.1–2.6	1.1–2.5	1.1–2.5	1.1–2.5	0.5–25.0
0–100	1.2–4.9	1.2–5.0	1.2–4.8	1.2–4.7	1.2–4.6	1.5–37.7
0–2 km						
0–20	1.0–2.5	1.0–2.3	1.0–2.4	1.0–2.4	1.0–2.4	0.8–29.0
20–60	1.0–1.3	1.0–1.3	1.0–1.3	1.0–1.3	1.0–1.3	0.1–10.5
60–80	1.0–1.1	1.0–1.1	1.0–1.1	1.0–1.1	1.0–1.1	0.1–5.9
80–100	1.0–2.1	1.0–2.0	1.0–2.1	1.0–2.1	1.0–2.1	0.2–31.3
0–100	1.1–3.0	1.0–3.1	1.0–3.1	1.0–3.1	1.0–3.1	1.4–37.9

For the seasons, the variation ranges of global long-term mean values of the number of cloud layers and standard deviations for each gradation of cloud amount in each analyzed atmospheric layer differ little.

For all seasons and for the whole year, the variation ranges of global long-term statistical characteristics for the number of cloud layers for the analyzed atmospheric layers are highly dependent on the cloud amount. The geographic distribution of long-term statistical characteristics for the number of cloud layers with account of the cloud amount gradation for the whole year is presented in Fig. 3. Their maximum values were basically registered in the low latitudes in case of few clouds and in the high latitudes in overcast conditions.

Figures 1 and 2 demonstrate that the minimum mean values of the number of cloud layers with the cloud amount of 0–100% for all seasons and atmospheric layers are discovered in the area of the Himalayas, and the location of several zones with their maximum values depends on a season and an atmospheric layer. For example, the maximum seasonal mean values of the number of cloud layers in the atmospheric layers of 0–2 and 0–10 km are found in autumn and winter in the southwestern Atlantic Ocean (Figs. 1a, 1g, 2b, and 2h). The analysis of data revealed that in the lower tropospheric layer in the area of the Himalayas the annual mean number of the sounding levels is about 2, whereas it is equal to ~13 in the southwestern Atlantic Ocean under the global mean value of ~8.

Data in Table 3 show that the global statistical characteristics of the number of retrieved few-cloud layers are maximum in all seasons and for the whole year in each analyzed atmospheric layer; they decrease

Table 2. The variation ranges of global long-term seasonal and annual standard deviations of the number of cloud layers for the atmospheric layers of 0–2, 2–6, 6–10, and 0–10 km above the surface with account of cloud amount, 1964–2017

Cloud amount, %	Winter	Spring	Summer	Autumn	Year
			0–10 km		
0–20	0.9–4.1	0.8–4.2	0.8–4.2	0.8–4.2	0.8–4.2
20–60	0.4–1.2	0.4–1.2	0.3–1.2	0.4–1.3	0.4–1.2
60–80	0.2–0.6	0.2–0.6	0.1–0.6	0.2–0.6	0.2–0.6
80–100	0.7–3.5	0.6–3.5	0.5–3.6	0.6–3.2	0.7–3.5
0–100	1.0–5.5	0.9–5.4	1.0–5.2	0.9–5.4	1.0–5.4
			6–10 km		
0–20	0.5–1.7	0.4–1.8	0.4–1.8	0.4–1.8	0.4–1.7
20–60	0.2–0.9	0.2–0.8	0.2–0.8	0.2–0.8	0.2–0.8
60–80	0.1–0.5	0.0–0.4	0.0–0.4	0.1–0.4	0.1–0.4
80–100	0.3–1.6	0.3–1.7	0.3–1.7	0.3–1.6	0.3–1.6
0–100	0.5–2.1	0.5–2.2	0.5–2.2	0.5–2.5	0.5–2.2
			2–6 km		
0–20	0.4–2.3	0.4–2.4	0.4–2.4	0.4–2.4	0.4–2.3
20–60	0.1–0.9	0.1–0.7	0.1–0.7	0.2–0.9	0.2–0.9
60–80	0.0–0.4	0.1–0.4	0.0–0.4	0.1–0.4	0.1–0.4
80–100	0.3–1.7	0.3–1.7	0.3–1.8	0.3–1.7	0.3–1.7
0–100	0.4–2.7	0.5–2.8	0.5–2.5	0.5–2.8	0.5–2.6
			0–2 km		
0–20	0.2–1.3	0.1–1.2	0.1–1.2	0.1–1.3	0.2–1.3
20–60	0.0–0.6	0.0–0.5	0.0–0.5	0.0–0.5	0.1–0.5
60–80	0.0–0.3	0.0–0.3	0.0–0.3	0.0–0.3	0.0–0.3
80–100	0.1–1.2	0.1–1.2	0.1–1.2	0.2–1.2	0.1–1.2
0–100	0.2–1.6	0.2–1.6	0.1–1.5	0.2–1.5	0.2–1.5

as the cloud amount increases to 60–80% and increase (but remain smaller than the number of few-cloud layers) for the overcast layers. For example, in the layer of 0–10 km for the whole year the global mean number of cloud layers with few, scattered, broken clouds, and overcast is equal to 4.2, 1.5, 1.2, and 2.6; for the gradation of 0–100%, the mean number of the cloud layers is 6.5; for the low, middle, and high levels, the mean number of cloud layers with the cloud amount of 0–100% is 2.1, 2.8, and 2.3, respectively. According to Table 3, the global long-term seasonal mean values and standard deviations of the number of cloud layers with the fixed gradation of cloud amount inside each layer do not depend on a season. For all seasons, the variation ranges of global long-term mean values and standard deviations of the number of cloud layers with account of the cloud amount gradation for different levels are:

—1.1–1.9 and 0.3–1.0 for the high level;

—1.1–2.3 and 0.2–1.3 for the middle level;

—1.0–1.6 and 0.2–0.8 for the low level.

The highest amplitudes of variations in long-term statistical characteristics of the number of cloud layers depending on the cloud amount gradation are registered for the middle-level cloud layers.

The presented results agree with aircraft, radar, free balloon, and radiosonde data [12, 26, 45]. Based on the aircraft data [12, 26], A.M. Baranov and A.M. Borovikov noted an approximate constancy of the distribution of cloud layering during a year; according to the results of the studies by L.P. Uporova, the number of cloud layers can reach 8. M.B. Fridzon [22, 26] used free balloons and certified precision fast-response instruments to register the layered structure of the atmosphere, where the zones of high and low relative hu-

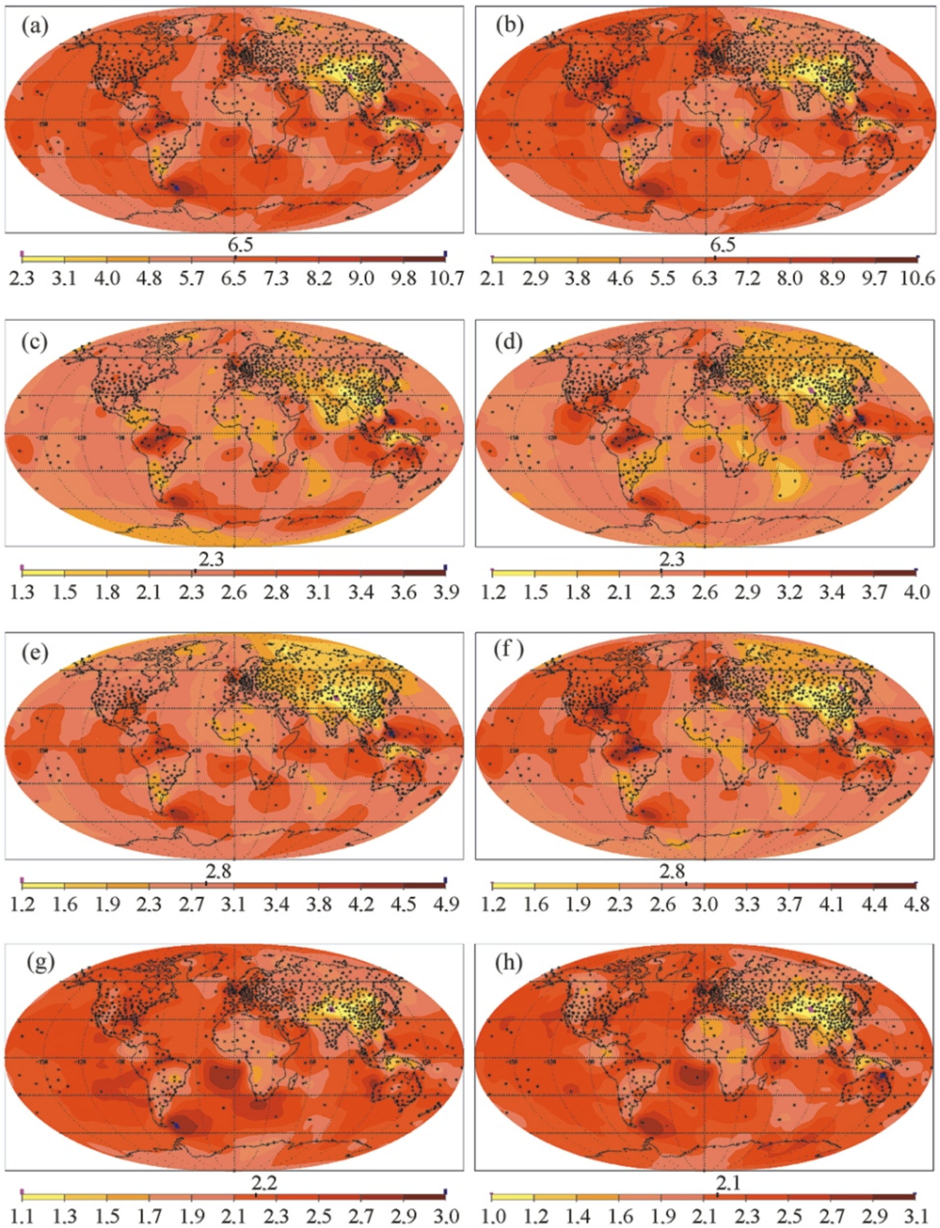

Fig. 1. The geographic distribution of long-term mean values of the number of cloud layers with the cloud amount of 0–100% in different atmospheric layers: (a, b) 0–10, (c, d) 6–10, (e, f) 2–6, and (g, h) 0–2 km above the surface for (a, c, e, g) winter and (b, d, f, h) summer. Here and in Figs. 2 and 3, radiosonde data from 965 stations for 1964–2017 are used; the blue and pink segments are corresponding maximum and minimum values; the asterisks are aerological stations. The winter includes December, January, and February; the summer includes June, July, and August.

midity alternate as the height increases; their number can reach 10–12. In [45] the number of cloud layers reached 5 based on radiosonde data and on the certain critical value of humidity for the identification of cloud layers and 4 based on the data of quasisynchronous radar measurements.

The possible reasons for differences in the estimates of the number of cloud layers are differences in the methods for their determination and calculation, in observation periods, periodicity, and regularity of observations [3, 12, 26] and, evidently, in the study region. The comparison of results of the cloud layer retrieval using the CE method, ground-based observations of clouds, aircraft, radar, and lidar data revealed [25, 30] that the CE method detects the cloud and humid layers registered during ground-based observations which can form clouds during the next hours (they will be detected after the formation, usually by the

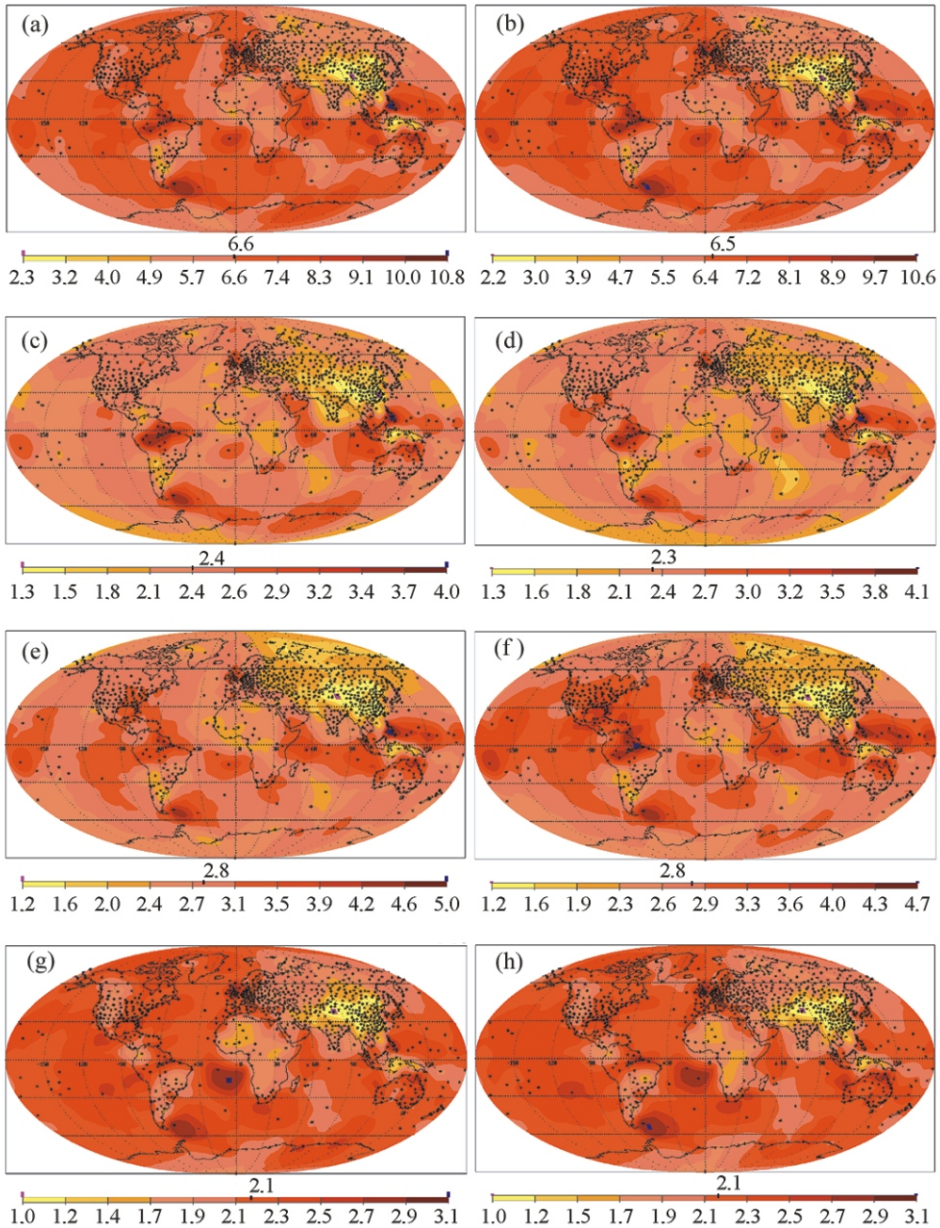

Fig. 2. The geographic distribution of long-term mean values of the number of cloud layers with the cloud amount of 0–100% in different atmospheric layers: (a, b) 0–10, (c, d) 6–10, (e, f) 2–6, and (g, h) 0–2 km above the surface for (a, c, e, g) spring and (b, d, f, h) autumn. The spring includes March, April, and May; the autumn includes September, October, and November.

radar), as well as the layers being a certain form of the clouds remained after their spreading (they are detected using an instrument for the determination of cloud particle images during the aircraft sounding).

4. CONCLUSIONS

New data on the vertical macrostructure of clouds, namely, on the number of cloud layers in the height range from the surface to 10 km are presented using radiosonde data for 1964–2017 and the CE method for the determination of cloud boundaries and cloud amount based on the temperature and humidity profiles.

The long-term estimates of global statistical characteristics were obtained for the number of cloud layers depending on a season, cloud amount, and atmospheric layer. Their analysis revealed that the seasonal differences in the global mean values of the number of cloud layers with account of cloud amount in each in-

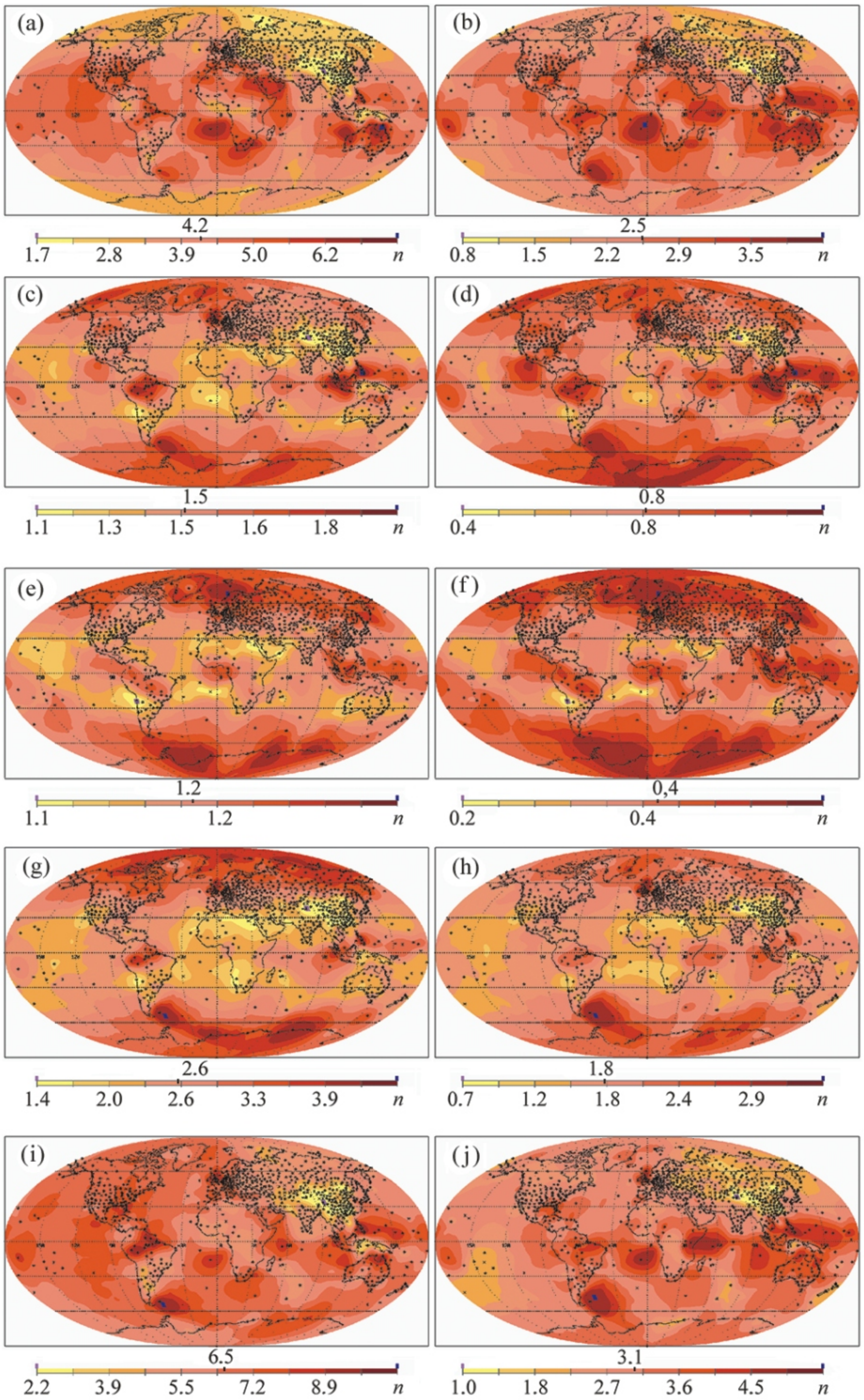

Fig. 3. The geographic distribution of (a, c, e, g, i) long-term annual mean values and (b, d, f, h, j) standard deviations of the number of cloud layers in the atmospheric layer of 0–10 km above the surface with different cloud amounts: (a, b) 0–20%, (c, d) 20–60%, (e, f) 60–80%, (g, h) 80–100%, (i, j) 0–100%.

vestigated atmospheric layer as well as in the variation ranges of the seasonal mean number of layers depending on the cloud amount in the analyzed atmospheric layers are poorly pronounced.

The analysis of geographic distributions of the seasonal mean number of cloud layers localized the zones of the maximum and minimum number of cloud layers in different atmospheric layers.

Table 3. The global long-term seasonal and annual mean values of the number of cloud layers ($\overline{X}$) for the atmospheric layers of 0–2, 2–6, 6–10, and 0–10 km above the surface with account of cloud amount and the respective standard deviations ( ), 1964–2017

Cloud amount, %	Winter		Spring		Summer		Autumn		Year	
	$\overline{X}$		$\overline{X}$		$\overline{X}$		$\overline{X}$		$\overline{X}$	
					0–10 km					
0–20	4.2	2.4	4.2	2.5	4.3	2.5	4.2	2.5	4.2	2.5
20–60	1.5	0.8	1.5	0.8	1.5	0.8	1.5	0.8	1.5	0.8
60–80	1.2	0.4	1.2	0.4	1.2	0.4	1.2	0.4	1.2	0.4
80–100	2.7	1.8	2.6	1.8	2.5	1.7	2.5	1.8	2.6	1.8
0–100	6.5	3.0	6.6	3.1	6.5	3.1	6.5	3.1	6.5	3.1
					6–10 km					
0–20	1.9	1.0	1.9	1.0	1.9	1.0	1.9	1.0	1.9	1.0
20–60	1.2	0.5	1.2	0.5	1.2	0.5	1.2	0.5	1.2	0.5
60–80	1.1	0.3	1.1	0.3	1.1	0.3	1.1	0.3	1.1	0.3
80–100	1.7	0.9	1.7	0.9	1.6	0.9	1.6	0.9	1.6	0.9
0–100	2.3	1.2	2.4	1.2	2.3	1.2	2.3	1.2	2.3	1.2
					2–6 km					
0–20	2.2	1.3	2.3	1.3	2.3	1.3	2.3	1.3	2.3	1.3
20–60	1.2	0.5	1.2	0.4	1.2	0.4	1.2	0.5	1.2	0.5
60–80	1.1	0.2	1.1	0.2	1.1	0.2	1.1	0.3	1.1	0.3
80–100	1.6	0.9	1.6	0.9	1.6	0.9	1.6	0.9	1.6	0.9
0–100	2.8	1.5	2.8	1.5	2.8	1.5	2.8	1.5	2.8	1.5
					0–2 km					
0–20	1.6	0.8	1.6	0.8	1.6	0.8	1.6	0.8	1.6	0.8
20–60	1.1	0.4	1.1	0.4	1.2	0.4	1.1	0.4	1.1	0.4
60–80	1.0	0.2	1.0	0.2	1.0	0.2	1.0	0.2	1.0	0.2
80–100	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7
0–100	2.2	1.0	2.1	1.0	2.1	1.0	2.1	1.0	2.1	1.0

The estimates of the number of cloud layers may be useful for studying the radiant heat transfer in the atmosphere, for assessing conditions for the propagation of electromagnetic waves, and for aviation needs.

FUNDING

The development of the CE method for the retrieval of cloud boundaries and cloud amount from radiosonde data and its testing were supported by the Soros grant (Z1000) and by the Russian Foundation for Basic Research (grants 01-05-65285 and 02-05-64088).

REFERENCES

1. O. A. Aldukhov, V. A. Orzhekhovskaya, T. O. Sadovnikova, and T. V. Rudenkova, *AEROSTAB: Archive of Current Aerological Information. Description of the Archive* (VNIIGMI-MTsD, Obninsk, 1990) [in Russian].
2. O. A. Aldukhov and I. V. Chernykh, *Methods of Analysis and Interpretation of Upper-air Sounding Data*, Vol. 1: *Quality Control and Data Processing* (VNIIGMI-MTsD, Obninsk, 2013) [in Russian].
3. O. A. Aldukhov and I. V. Chernykh, *Methods of Analysis and Interpretation of Upper-air Sounding Data*, Vol. 2: *Retrieved Cloud Layers* (VNIIGMI-MTsD, Obninsk, 2013) [in Russian].

4. O. A. Aldukhov and I. V. Chernykh, *Methods of Analysis and Interpretation of Upper-air Sounding Data*, Vol. 3: *Humidity and Temperature in the Atmosphere: Statistical Characteristics* (VNIIGMI-MTsD, Obninsk, 2015) [in Russian].
5. E. N. Arabei, "Radiosonde Data as a Tool for Cloud Layer Detection," Meteorol. Gidrol., No. 6 (1975) [in Russian].
6. A. M. Baranov, *Upper-level Clouds and Flight Conditions in Them* (LKVVIA im. Mozhaiskogo, Leningrad, 1960) [in Russian].
7. D. P. Bespalov, A. M. Devyatkin, Yu. A. Dovgalyuk, V. I. Kondratyuk, Yu. V. Kuleshov, T. P. Svetlova, S. S. Suvorov, and V. I. Timofeev, *Cloud Atlas* (D'ART, St. Petersburg, 2011) [in Russian].
8. L. S. Gandin and R. L. Kagan, *Statistical Methods for Interpretation of Meteorological Data* (Gidrometeoizdat, Leningrad, 1976) [in Russian].
9. V. A. Gordin, *Mathematical Problems of Hydrodynamic Weather Forecasting. Computational Aspects* (Gidrometeoizdat, Leningrad, 1987) [in Russian].
10. G. M. Grechko, A. S. Gurvich, Yu. V. Romanenko, S. V. Sokolovskii, and M. S. Tatarskaya, "Layered Structure of Temperature Field in the Atmosphere Retrieved from Refraction Measurements from Salyut-6 Orbital Station," Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 2, **17** (1981) [in Russian].
11. L. R. Dmitrieva-Arrago, L. F. Koloskova, and L. S. Orlova, "Testing of the Plot by J. Smagorinsky for the Cloud Amount Determination," Trudy GGO, No. 236 (1969) [in Russian].
12. L. S. Dubrovina, *Clouds and Precipitation Retrieved from Aircraft Sounding Data* (Gidrometeoizdat, Leningrad, 1982) [in Russian].
13. N. A. Zaitseva, *Aerology* (Gidrometeoizdat, Leningrad, 1990) [in Russian].
14. V. V. Kostyukov, *Objective Analysis and Coordination of Meteorological Fields* (Gidrometeoizdat, Moscow, 1982) [in Russian].
15. Z. M. Makhover and L. A. Nudel'man, *Aviation-climatic Characteristics of the Northern Hemisphere*, Vol. 1: *Clouds* (Gidrometeoizdat, Moscow, 1987) [in Russian].
16. *Manual for Hydrometeorological Stations*, Issue 4: *Aerological Observations at Stations*, Part 3a: *Temperature-wind Sounding of the Atmosphere with the Meteorit–RKZ System* (Gidrometeoizdat, Leningrad, 1973) [in Russian].
17. G. D. Reshetov, "Cloudiness at Large Heights," Sov. Meteorol. Gidrol., No. 4 (1962) [in Russian].
18. T. V. Rudenkova, "Archiving Format of Current Aerological Data Transmitted via Communication Channels for PC," Trudy VNIIGMI-MTsD, No. 174 (2010) [in Russian].
19. A. M. Sterin, "Analysis of Linear Trends in Free Atmosphere Temperature Series, 1958–1997," Meteorol. Gidrol., No. 5 (1999) [Russ. Meteorol. Hydrol., No. 5, **24** (1999)].
20. S. B. Stechkin and Yu. N. Subbotin, *Splines in Numerical Mathematics* (Nauka, Moscow, 1976) [in Russian].
21. E. M. Feigel'son, *Radiant Heat Exchange and Clouds* (Gidrometeoizdat, Leningrad, 1970) [in Russian].
22. M. B. Fridzon, *Methodology of Upper-air Sounding and Reliability of Data on Vertical Profiles of Temperature and Humidity to the Height of 35–40 km*, Abstract of Doctor's Thesis (Moscow, 2004).
23. A. Kh. Khrgian and N. I. Novozhilov, *Cloud Atlas* (Gidrometeoizdat, Leningrad, 1978) [in Russian].
24. I. V. Chernykh and O. A. Aldukhov, "Long-term Estimates of Parameters of the Vertical Distribution of Cloud Layers from Atmospheric Radiosounding Data," Meteorol. Gidrol., No. 4 (2016) [Russ. Meteorol. Hydrol., No. 4, **41** (2016)].
25. I. V. Chernykh and O. A. Aldukhov, "Vertical Distribution of Cloud Layers from Atmospheric Radiosounding Data," Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 1, **40** (2004) [Izv., Atmos. Oceanic Phys., No. 1, **40** (2004)].
26. I. V. Chernykh and O. A. Aldukhov, "Estimating the Number of Cloud Layers through Radiosonde Data from Russian Aerological Stations for 1964–2014," Meteorol. Gidrol., No. 3 (2018) [Russ. Meteorol. Hydrol., No. 3, **43** (2018)].
27. N. P. Shakina, E. N. Skriptunova, and A. R. Ivanova, "Conditions Associated with Freezing Precipitation at Airports of Russia and the CIS. 1. Airports of the Moscow Air Zone," Meteorol. Gidrol., No. 6 (2003) [Russ. Meteorol. Hydrol., No. 6 (2003)].
28. O. A. Alduchov and R. E. Eskridge, "Improved Magnus from Approximation of Saturation Vapor Pressure," J. Appl. Meteorol., **35** (1996).
29. R. H. Bartels, J. C. Beatty, and B. A. Barsky, *An Introduction to Splines for Use in Computer Graphics and Geometric Modeling* (Morgan Kaufman Publishers, Los Altos, 1987).
30. I. V. Chernykh, O. A. Alduchov, and R. E. Eskridge, "Reply to Comments of D. J. Seidel and I. Durre on "Trends in Low and High Cloud Boundaries and Errors in Height Determination of Cloud Boundaries"," Bull. Amer. Meteorol. Soc., **84** (2003).
31. I. V. Chernykh, O. A. Alduchov, and R. E. Eskridge, "Trends in Low and High Cloud Boundaries and Errors in Height Determination of Cloud Boundaries," Bull. Amer. Meteorol. Soc., **82** (2001).
32. I. V. Chernykh and R. E. Eskridge, "Determination of Cloud Amount and Level from Radiosonde Soundings," J. Appl. Meteorol., **35** (1996).

33. R. E. Eskridge, O. A. Alduchov, I. V. Chernykh, P.-M. Zhai, A. C. Polansky, and S. R. Doty, “A Comprehensive Aerological Reference Dataset (CARDS): Rough and Systematic Errors,” Bull. Amer. Meteorol. Soc., **76** (1995).
34. N. Ferlay, F. Thieuleux, C. Cornet, A. B. Davis, P. Dubuisson, F. Ducos, F. Parol, J. Riedi, and C. Vanbauce, “Toward New Inferences about Cloud Structures from Multidirectional Measurements in the Oxygen A Band: Middle-of-cloud Pressure and Cloud Geometrical Thickness from POLDER-3/PARASOL,” J. Appl. Meteorol. Climatol., **49** (2010).
35. D. J. Gaffen, *Historical Changes in Radiosonde Instruments and Practices*, Instruments and Observing Methods, Rep. No. 50 (WMO, Geneva, 1993).
36. D. J. Gaffen and R. J. Ross, “Climatology and Trends of U.S. Surface Humidity and Temperature,” J. Climate, **12** (1999).
37. L. Garand, C. Grassotti, J. Halle, and G. L. Klein, “On Differences in Radiosonde Humidity-reporting Practices and Their Implications for Numerical Weather Prediction and Remote Sensing,” Bull. Amer. Meteorol. Soc., **73** (1992).
38. P. J. McBride, K. S. Schmidt, P. Pilewskie, A. Walther, A. K. Heidinger, D. E. Wolfe, C. W. Fairall, and S. Lance, “CalNex Cloud Properties Retrieved from a Ship-based Spectrometer and Comparisons with Satellite and Aircraft Retrieved Cloud Properties,” J. Geophys. Res., Atmos., No. D21, **117** (2012).
39. J. Nash, M. Kitchen, and J. F. Ponting, “Comparisons of Relative Humidity Measurements from Phase I of the WMO International Radiosonde Comparison,” in *Instruments and Observing Methods. Third WMO Technical Conference on Instruments and Methods of Observation*, Rep. No. 22 (WMO, Geneva, 1985).
40. C. M. Naud, J. P. Muller, and E. E. Clothiaux, “Comparison between Active Sensor and Radiosonde Cloud Boundaries over the ARM Southern Great Planes Site,” J. Geophys. Res., No. D4, **108** (2003).
41. W. B. Rossow, Y. Zhang, and J. Wang, “A Statistical Model of Cloud Vertical Structure Based on Reconciling Cloud Layer Amounts Inferred from Satellites and Radiosonde Humidity Profiles,” J. Climate, **18** (2005).
42. D. J. Seidel and I. Durre, “Comments on “Trends in Low and High Cloud Boundaries and Errors in Height Determination of Cloud Boundaries,” Bull. Amer. Meteorol. Soc., **84** (2003).
43. J. Wang and W. B. Rossow, “Determination of Cloud Vertical Structure from Upper-air Observations,” J. Appl. Meteorol., **34** (1995).
44. J. Wang, W. B. Rossow, and J. Zhang, “Cloud Vertical Structure and Its Variations from a 20-yr Global Rawinsond Dataset,” J. Climate, **13** (2000).
45. J. Zhang, Z. Li, H. Chen, and M. Cribb, “Validation of Radiosonde-based Cloud Layer Detection Method against a Ground-based Remote Sensing Method at Multiple ARM Sites,” J. Geophys. Res., Atmos., **118** (2013).