Trends in low and high cloud boundaries and Errors in height determination of cloud boundaries

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ABSTRACT

Clouds are important to climate and climate trends. To determine trends in cloud base height and cloud top heights, the Comprehensive Aerological Reference Data Set (CARDS) and the method of Chernykh and Eskridge (1996) are used to diagnose cloud base, top, and amount. Trends in time series of cloud bases and tops at 795 radiosonde stations from 1964 to 1998 are presented.

It was found that trends in cloud base height and cloud top height are seasonally dependent and a function of cloud cover amount. There was a small increase in multilayer cloudiness in all seasons. Geographical distributions of decadal changes of cloud bases and tops were spatially non-uniform and depended upon the season.

To estimate the errors made in calculating the heights of cloud boundaries, an analysis was made of the response of the thermistors and hygristors. Thermistors and hygristors are linear sensors of the first order. From this it is shown that the distance between calculated inflection points (cloud boundaries) of observed and real values is exactly equal to the time constant of the sensor times the balloon speed. More accurate cloud boundaries can be determined using this finding.

1. Introduction

Clouds affect the radiation balance and therefore surface temperature. Changes in the height of cloud bases, tops, and thickness should be related to temperature change. Karl and Steurer (1990) showed that cloud cover in the US has been increasing since 1948, but cloud cover observations in the US are not homogeneous because of changes in observing procedures. Karl et al. (1993) showed that the decrease in mean monthly diurnal temperature range maybe related to an increase in cloud coverage, particularly low clouds

To estimate cloud trends, it is necessary to have long time series of accurate cloud data. Surface observations do not furnish such a database and have subjectivity problems. The only two choices are satellite data and radiosonde data, and satellite data are only available from 1984. From radiosonde data, there are several methods for determining cloud boundaries and cloud amount (Chernykh and Eskridge, 1996; Dmitrieva-Arrago and Shatunova, 1999; Poore et al., 1995; Wang and Rossow, 1995).

The Comprehensive Aerological Reference Data Set (CARDS) project has created probably the most complete upper-air dataset (Eskridge et al., 1995; Alduchov and Eskridge, 1996). In this paper, CARDS data were used to create time series of cloud layers. Results are categorized by cloud amount, atmospheric layer, and season. The findings of this research will be useful in modeling the atmospheric circulation and in climate change analysis.

2. Data

From the 2500 globally distributed radiosonde stations in the CARDS database, 967 stations have been chosen based on data quality and completeness, which were used to produce 795 time series (see Fig. 1). Standards for data acceptance were relaxed in data sparse regions. Some time series consist of observations from two or three stations due to stations opening, closing, or moving. The restriction is that concatenated stations are not more than 150 km apart. The analysis was restricted to the troposphere (0-10 km) for the central months of all four seasons, January, April, July, and October.

Only soundings with both temperature and humidity data from the surface to 10 km were included in the study of trends. Cubic spline approximations are made to the observed values of temperature and humidity. This produces continuous values of the first and second derivatives for the whole vertical profile.

Because clouds may not be present at the time of a sounding, cloud layers are not diagnosed in each sounding; only those months (January, April, July, and October) that contain at least 10 soundings with clouds were included in the time series. Time series were developed for each cloud coverage interval predicted by the Chernykh and Eskridge (1996) method: 0 to 20%, 20 to 60%, 60 to 80%, and 80 to 100%. In this paper, 0-20% is called few, 20-60% is scattered, 60-80% is broken, and 80-100% is overcast. Clouds are also categorized by height: 0 to 2 km for low clouds, 2 to 6 km for middle clouds, and 6 to 10 km for high clouds. A further

restriction was that the time series for the months (January, April, July, and October) must have data in at least 18 years of the 35-year period at each station.

3. Method

The method for predicting cloud bases, tops, and amount developed by Chernykh and Eskridge (1996), CE, was used. The main idea of the CE method is that cloud layers will affect the humidity and temperature profiles jointly. Due to the time lag of the thermistors and hygristors, the cloud boundary may not be evident in the absolute values of temperature and humidity, but the boundary is almost always evident in the rate of change (derivatives) of temperature and humidity in both profiles. Criteria for predicting cloud layers are

$$T''(z) \geq 0 \text{ and } R''(z) \leq 0, \qquad (1)$$

where T”(z) and R”(z) are the second derivatives of the vertical profile of temperature and relative humidity, respectively. Figs. 2 through 5 of Chernykh and Eskridge (1996) show that cloud boundaries correspond to points where T” and R” change signs. In other words, these points are inflection points for temperature and relative humidity. The inflection points are generated by the temperature and humidity gradients as the radiosonde crosses the cloud boundary. It should be noted that the main source of error in determining cloud boundary height and amount is the large time constant for hygristors. But these humidity errors cancel out in the first and

second derivatives. Hence, the first and second derivatives of humidity and temperature are more accurate than the observed values.

The CE method was shown to be accurate 95% of the time in predicting cloud bases. Cloud amount, in the CE method, is determined by a relation between temperature and dewpoint depression. Cloud amount was found to be correctly predicted in 70 to 80% of the observations. Errors in cloud amount are due to humidity errors caused by the large time constants of humidity sensors. Time constants of hygristors range from 0.3 s for carbon hygristors at 20 °C to 200 s for Goldbeater's skin hygristors at –30 °C. An advantage of the CE method is that it will work with equal accuracy for all humidity sensors in determining cloud bases and tops, while the method of Wang and Rossow (1995), for example, is tuned to the VIZ carbon hygristor.

Because of lag error in temperature and humidity measurements, the observed values are not equal to the true values. An important question is how much error is made in calculating cloud boundaries from observed values. We show (see appendix) that inflection points of the observed values correspond to inflection points of the true values and that the difference between the calculated inflection points for the observed values and those of the true values is exactly equal to the sensor's time constant. Changing radiosonde model sensors will introduce small systematic errors in the cloud base and top heights determined with the CE method. These systematic errors can be removed using the approach given in the appendix. The arguments developed in the appendix are outlined below.

Since temperature and humidity sensors are linear sensors of the 1st order Brock (1993), Gandin and Kagan (1976), and Zaitseva (1990), their time response can be described by

$$\frac{\partial f_O(t)}{\partial t} = \frac{f_t(t) - f_O(t)}{\tau(t)}, \qquad (2)$$

where $f_t(t)$ and $f_O(t)$ are the true and observed values of the variable and (t) is the sensor's time constant. When the second derivative of $f_o(t)$ equals 0, the first derivatives of both the true and observed values are equal and independent of the value of the time constant. For those points, the observed variables have inflection points that reflect the rapid changes of the temperature and relative humidity in crossing bases and tops of humid layers. There is a one to one correspondence between inflection points for the true and observed profiles shifted by a constant distance (τ times balloon speed). Because the balloon, and hence the sensors, are assumed to be moving at a constant speed, time dependence may be replaced by height dependence. Using this result in conjunction with the instrument response time it is possible to improve the calculated height of cloud bases and tops.

Global trends were calculated by simple averaging the data from all stations. This method emphasizes regions with a dense network of stations (e.g. temperate latitudes of the Northern hemisphere).

For data visualization and geographical analysis, it is easier to work with a gridded field instead of values at an irregular set of stations. To interpolate cloud trends to a 5X5 degree grid, the method of weighted anisotropic interpolation (WAI) was used:

$$\hat{f}_0 = \frac{\sum_{i=1}^{m} a_i \times f_i}{\sum_{i=1}^{m} a_i} \tag{3}$$

where a_i are the weights for each of the m neighboring stations for the grid point, o. The weights a_i are found as a solution of linear equation system

$$\sum_{i=1}^{m} a_i \times r_{ij} = r_{0j}, \quad \text{for} \quad j = 1, \ldots, m \tag{4}$$

where r_{ij} is the distance between i-th and j-th stations and r_{0j} is the distance between the 0-grid point and j-th station. For most upper-air variables (Kostyukov, 1982), this method is nearly as accurate as optimum interpolation (OI). But WAI has a great advantage with respect to OI; one does not need to know the statistical structure of the interpolated values. The price for simplicity is that the WAI-method does not produce an estimate of the interpolation error.

4. Results

Fig.2 and Table 1 show that the global mean for cloud bases decreased at about 44 m/decade and cloud tops rose at about 154 m/decade from 1964 to 1998 for all cloud amounts and heights. However, global mean decadal changes of cloud bases (Δh_L) and cloud tops (Δh_H) depend on cloud amount and season (Table 1). Table 1 shows that for every gradation of cloud amount, decadal changes of cloud bases and tops have some seasonal dependence.

In all seasons, cloud categories of few and overcast make the major contribution to the decrease of cloud bases (Table 1). The frequency of low (0-2 km) and middle

(2-6 km) clouds increases for all months (Table 2). The frequency of scattered and broken clouds in the low and middle levels increases slowly or even decreases for some cases of broken clouds (Table 2). Cloud base heights for scattered and broken clouds are stable or even increasing except for April, when scattered cloud bases are decreasing.

Except for overcast conditions, cloud top heights are increasing in all seasons. Overcast frequencies are increasing significantly for low and middle layers. High cloud frequencies for all seasons are increasing with a maximum in the few cloud category. In addition, there is a tendency for multilayer cloudiness to increase. The frequency of clouds is increasing about 1.7% per decade.

Figs. 3 and 4 show that the geographical distribution of decadal change of cloud boundaries for July is spatially nonuniform. Most areas of the Northern Hemisphere have decreasing cloud base heights and increasing cloud top heights. Limited data in the Southern Hemisphere make it difficult to draw conclusions, but the data indicate similar trends as are found in the Northern Hemisphere. The analysis shows that trends in cloud base boundary heights depend on the season (results not shown). For all seasons, cloud top heights are increasing over most of the globe except for high and middle latitudes of the Eastern Hemisphere. The area of decreasing trends of cloud top heights is greatest in July.

In a recent paper, Easterling et al. (1997) examined trends in surface maximum and minimum temperature for the globe. They found that the diurnal temperature range is decreasing over most of the globe; due in large part to increasing minimum temperatures and increasing cloudiness is a factor. The results of this study are in

qualitative agreement with Easterling et al (1997). This study found that global cloudiness is increasing as indicated by decreasing heights of cloud bases, increasing heights of cloud tops, and the number of cloud layers is increasing during the 1964 to 1998 period.

5. Summary

Radiosonde data were analyzed to calculate cloud trends. It was found for all cloud amounts (0 to 100%) that cloud bases are decreasing in all seasons. The decrease in base height is about 150 m from 1964 to 1998. Cloud top heights have increased about 540 m during this period. Cloud frequencies have increased in each cloud height category by about 5%. Trends depend on cloud cover amount, season, and cloud layer height and are consistent with the decrease in diurnal temperature range evident over most of the globe.

It was shown that the error made in calculating cloud base and top height is equal to the time constant of the sensor multiplied by the balloon speed. From this finding, more accurate cloud base and tops can be calculated.

Table 1. Decadal changes of mean height in m/decade for cloud bases (Δh_L) and cloud tops (Δh_H) calculated by linear regression for various cloud amounts in the troposphere. Underlined values were not significant at the 95% level.

Cloud amount	***January***		***April***		***July***		***October***		***Total***	
	Δh_L	Δh_H	Δh_L	Δh_H	Δh_L	Δh_H	Δh_L	Δh_H	Δh_L	Δh_H
0-20%	-15.1	223.2	-35.6	226.2	-42.0	147.8	-29.3	213.4	-30.6	204.2
20-60%	6.7	129.8	-5.6	102.0	7.2	12.5	3.1	83.8	3.0	83.4
60-80%	63.6	73.0	62.6	65.6	51.0	11.3	61.8	58.7	59.8	53.6
80-100%	-26.6	-78.5	-26.9	113.5	-19.2	123.8	-24.8	117.6	-24.1	108.8
0-100%	-35.0	157.7	-49.0	159.6	-50.6	136.2	-41.4	159.5	-43.8	154.1

Table 2. Decadal changes (%/decade) of cloud frequency with cloud coverage 0-20%, 20-60%, 60-80%, 80-100%, 0-100% of the sky for various atmospheric layers. Underlined values were not significant at the 95% level.

Cloud amount (% of the sky)	***Atmospheric layer 0-2 km***					***Atmospheric layer 2-6 km***				
	January	***April***	***July***	***October***	***Total***	***January***	***April***	***July***	***October***	***Total***
0-20%	6.1	6.4	4.8	6.1	5.9	7.5	7.1	6.1	6.1	7.1
20-60%	2.1	1.8	2.0	1.9	1.9	2.2	2.3	2.8	2.1	2.4
60-80%	<u>-0.1</u>	-0.4	-0.4	-0.5	-0.4	0.6	0.5	0.4	<u>0.2</u>	0.4
80-100%	5.1	4.0	4.2	3.8	4.2	3.4	4.4	4.8	3.7	4.1
0-100%	6.5	5.5	4.1	4.8	5.3	4.9	4.8	4.3	4.8	4.6

Cloud amount (% of the sky)	***Atmospheric layer 6-10 km***					***Whole atmospheric layer 0-10 km***				
	January	***April***	***July***	***October***	***Total***	***January***	***April***	***July***	***October***	***Total***
0-20%	7.5	7.1	6.8	6.1	7.1	6.5	6.9	4.3	6.1	6.4
20-60%	4.0	3.8	3.3	3.5	3.6	6.1	5.7	5.5	5.5	5.8
60-80%	2.0	1.5	1.0	1.4	1.4	2.0	1.4	1.0	1.1	1.4
80-100%	<u>1.5</u>	1.9	3.7	1.8	2.2	4.3	4.3	5.0	3.8	4.3
0-100%	6.6	6.0	5.2	5.6	6.0	1.8	1.7	1.5	1.6	1.7

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Appendix

The equation for linear sensors of the first order is

$$\frac{\partial f_o(t)}{\partial t} = \frac{f_t(t) - f_o(t)}{\tau(t)}, \tag{a.1}$$

where $f_t(t)$ and $f_o(t)$ are the true and observed values of the variable and (t) is the sensor's time constant. The sensor is not actually a function of time, but temperature and humidity. However, as the balloon has a nearly constant speed at any given location this dependence can be expressed as a time dependency (time variable t may be replaced by height, z, when the balloon speed is assume to be constant).

From (a.1) it follows

$$f_t(t) = f_o(t) + \tau(t) \cdot f_o^{'}(t). \tag{a.2}$$

Assume that $\tau(t)$ is a constant and also assumed that the profiles of humidity and temperature are continuous as well as their first and second derivative with respect to t or z. Let t_0 to be a point where $f_o^{''}(t_0)$ is equal to 0. From (a.2) it follows

$$f_t^{'}(t) = f_o^{'}(t) + \tau \cdot f_o^{''}(t), \tag{a.3}$$

and at t_0

$$f_t^{'}(t_0) = f_o^{'}(t_0) + \tau(t_0) \cdot f_o^{''}(t_0) = f_o^{'}(t_0). \tag{a.4}$$

Which means that the first derivatives of true and observed values are equal at the t_0 point and its value is independent of the time constant, τ .

Since the functions describing the observed variables have continuous first and second derivatives, they may be approximated by a cubic polynomial (cubic spline approximation is used for $f_o(t)$ in the CE method). Therefore,

$$\begin{aligned} f_o(t) &= a + b \cdot t + \frac{c}{2} \cdot t^2 + \frac{d}{6} \cdot t^3, \\ f_o^{'}(t) &= b + c \cdot t + \frac{d}{2} \cdot t^2, \\ f_o^{''}(t) &= c + d \cdot t. \end{aligned} \quad . \qquad \text{(a.5)}$$

From a.2 and a.5 it follows that

$$\begin{aligned} f_t(t) &= (a + b \cdot t) + (b + c \cdot t) \cdot t + \frac{(c + d \cdot t)}{2} \cdot t^2 + \frac{d}{6} \cdot t^3 \\ f_t^{''}(t) &= c + d \cdot t + d \cdot t \end{aligned} \quad . \qquad \text{(a.6)}$$

If $f_o^{''}(t_0) = 0$ at t_0, then from (a.5) it follows that

$$t_0 = -\frac{c}{d}. \qquad \text{(a.7)}$$

From (a.6), the point t_1 where $f_t^{''}(t_1) = 0$ is

$$\begin{aligned} & c + t \cdot d + t_1 \cdot d = 0 \\ & or \\ & t_1 = -\frac{c}{d} - t \end{aligned} \qquad \text{(a.8)}$$

Hence, the distance between points of inflection for true and observed values is exactly equal to the time constant t. Moreover, it means that if an infection point exists for the observed function $f_o(t)$, then an infection point exists for function $f_t(x)$ of the true values and vice versa. Finally, calculated boundary heights can be

improved using the time constant for the hygristor and thermistors used on each radiosonde.

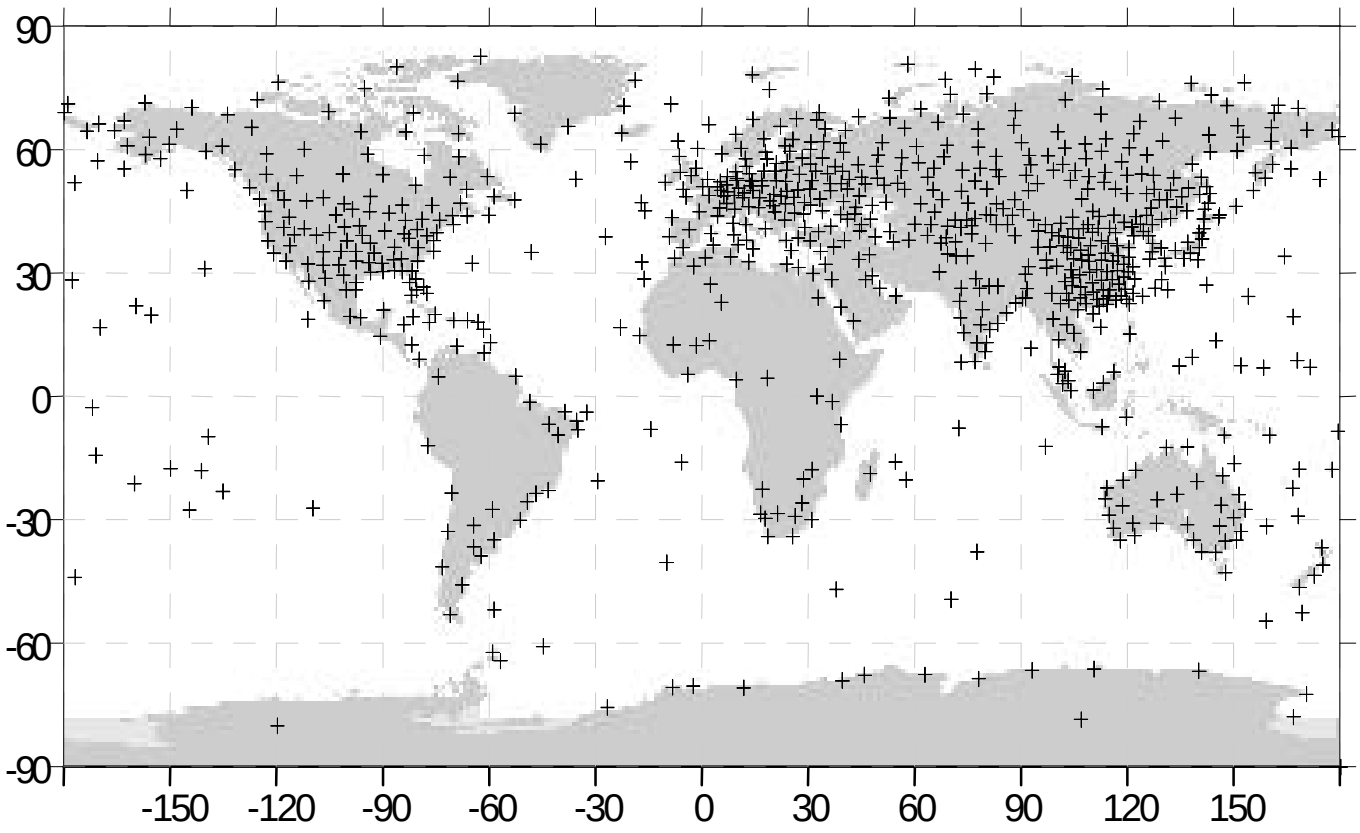

Figure 1. Distribution of the radiosonde stations used in this study.

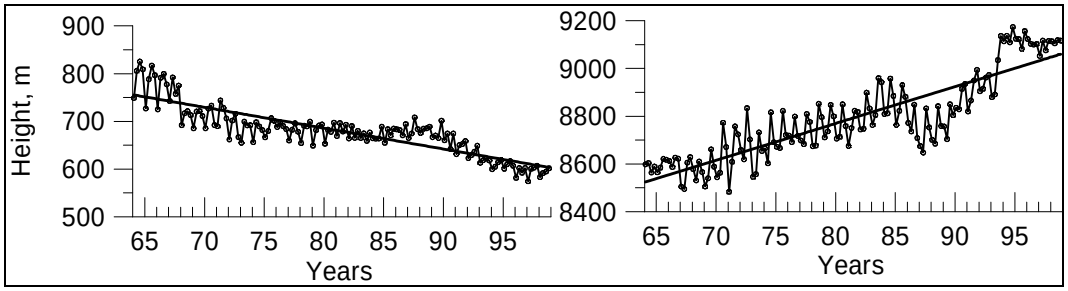

Figure 2 Ceiling (left) and top (right) means and corresponding linear trends for reconstructed cloud layers with 0-100% cloud coverage. Values determined from the central months of the seasons from 1964 to1998.

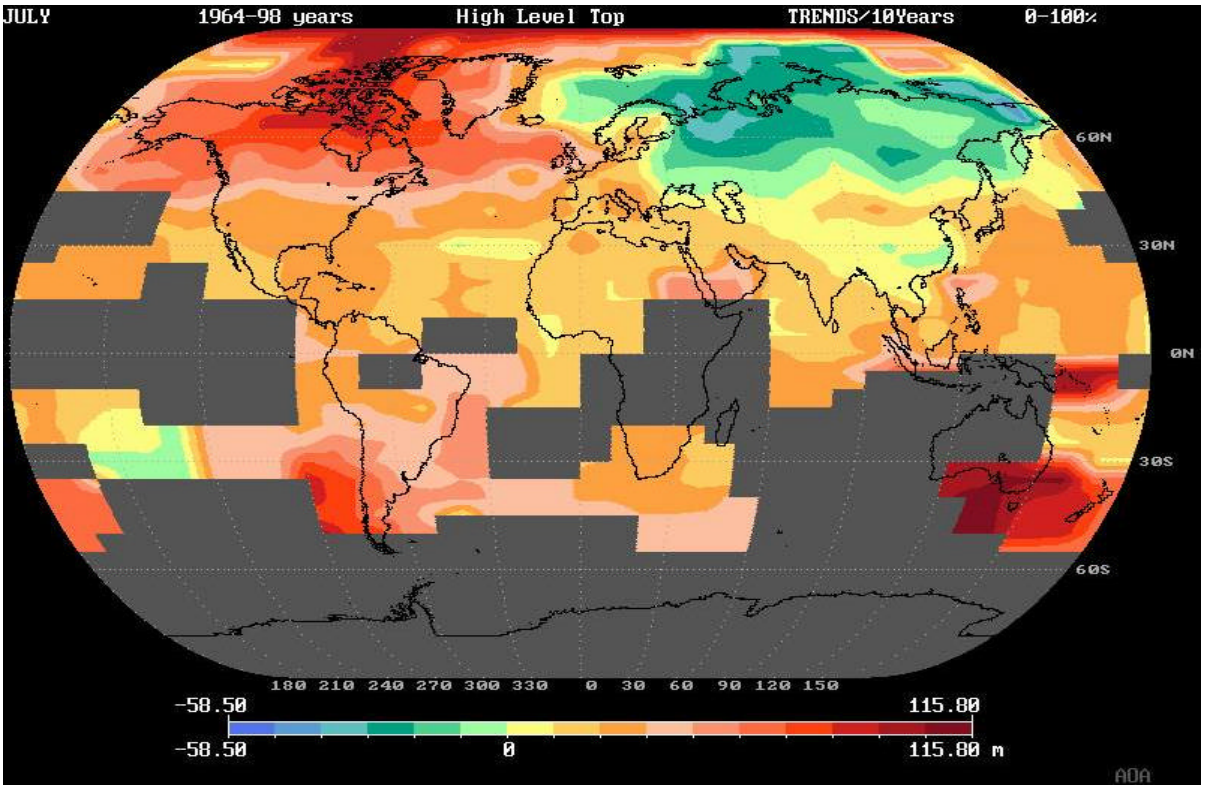

Figure 3. Geographical distribution of trends in cloud top heights for July, 1964 to1998.

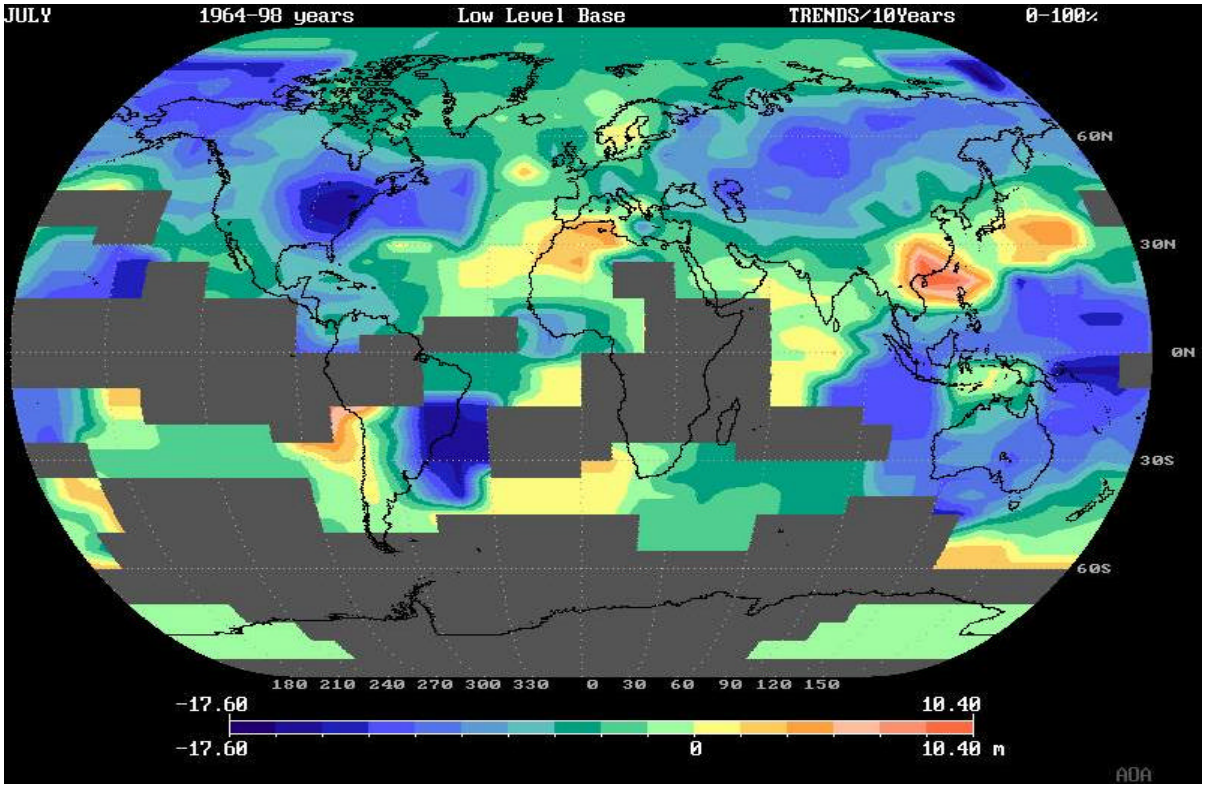

Figure 4. Geographical distribution of trends in cloud base heights for July, 1964 to1998.