Climatology and interannual variability in statistical characteristics of cloud cover over the North Atlantic during 1950-2017

M Aleksandrova and K Belyaev
Shirshov Institute of Oceanology, 36 Nahimovskiy pr., Moscow, 117997, Russia

E-mail: marina@sail.msk.ru

Abstract. A three-parameter mixed gamma distribution is applied for characterizing the statistical properties of the fractional cloud cover in the North Atlantic using visual cloud cover reports from voluntary observing ships (VOS) for the period from 1950 to 2017. Seasonal climatologies of the distribution parameters and the cloud cover are analyzed. The PDF-based analysis allows for the identification of the areas with different probability distributions even under the same mean total cloud cover. Analysis of interannual variability shows that in different regions of the North Atlantic, there are noticeable changes in the form of the distribution over time. In some regions, these changes are coincident with significant trends in the total cloud cover and result in changes in the distribution shape.

1. Introduction
Clouds over the ocean play a key role in the climate system determining shortwave and longwave radiation [1] and being an effective indicator of climate variability [2]. While in the most applications cloud cover analysis is limited to the mean cloud amount, probabilities different cloud fractions are also important for understanding cloud-related physical mechanisms, for instance for identifying cloud regimes.

For analyzing characteristics of fractional cloud cover and variability in different cloud fractions, the probability distribution of cloud cover is required. Distribution-based approaches are quite effective for the other marine meteorological variables such as winds [3] and surface fluxes [4]. Earlier works (e.g. [5]) argued a two-parameter beta distribution for fractional cloud cover. However, beta distribution has infinities at 0 (clear sky) and/or 1 (overcast) what doesn’t agree with observations. Aleksandrova et al. [6] suggested and justified an alternative probability, which allows for the approximation of all possible cloud conditions and gives finite values at 0 (clear sky) and 1 (overcast). Here we apply this distribution for the detailed analysis of cloud cover characteristics over the North Atlantic Ocean including also climate variability in different cloud amounts.

2. Probability distribution of fractional cloud cover and visual cloud data over the ocean
A new probability distribution of fractional cloud cover over the ocean [6] represents a three-parameter mixed gamma distribution and in continuous form can be expressed by the following equation:

\[ P(x) = C(\alpha, \beta) \times \{\theta (1 - x)^\alpha \exp[-\beta(1 - x)] + (1 - \theta)x^\alpha \exp(-\beta x)\} \]  

(1)
where \( P(x) \) is a probability density function, variable \( x \) - fractional cloud cover distributed on the \([0,1]\) interval, \( \alpha \) and \( \beta \) \((\alpha>0, \beta>0)\) are the shape and scale parameter respectively, \( \theta \) is steering parameter which can be estimated as

\[
\theta \approx p(0) \times [p(0) + p(1)]^{-1} \tag{2}
\]

where \( p(0) \) and \( p(1) \) are estimations of the probability of the probability of clear sky and overcast conditions respectively. Steering parameter \( \theta \) controls mixing of two gamma distributions and can be obtained directly from the observations. Parameters \( \alpha \) and \( \beta \) cannot be estimated directly from the data. For the estimations of these parameters, the descent minimization procedure has been used. The normalizing constant \( C \) from (1) is expressed as

\[
C(\alpha, \beta) = \beta^{\alpha+1} \gamma^{-1}(\alpha + 1, \beta), \tag{3}
\]

where \( \gamma(\alpha, \beta) \) is lower incomplete gamma function. In order to apply new distribution to the discrete cloud cover estimates, expressed in octas, Aleksandrova et al. [6] suggested a discrete form of (1):

\[
P_d(k) = \beta^{\alpha+1} \gamma^{-1}(\alpha + 1, \beta) \times \frac{1}{n} \times \left[ \theta \left( 1 - \frac{k}{n} \right)^\alpha \exp \left[ -\beta \left( 1 - \frac{k}{n} \right) \right] + (1 - \theta) \left( \frac{k}{n} \right)^\alpha \exp \left[ -\beta \frac{k}{n} \right] \right] \tag{4}
\]

where \( k \) is a cloud octa (from 0 to 8), \( n \) is denominator which equals the number of discrete bins (if fractional cloud cover is expressed in octas then \( n=9 \)).

The probability mass function (PMF) (4) has been further applied to the voluntary ship observation (VOS) which are available from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS: [7]). This dataset has the longest record (from the mid-nineteenth century) and provides quite good coverage of the North Atlantic after World War II. In this respect, VOS data have advantages compared to satellite records, which are still short [8] and re-analyses, which require extensive validation [9].

We use here visual cloud cover observations data from ICOADS for the period 1950-2017. The VOS data are characterized by considerable heterogeneity in space and time [10]. While in the North Atlantic data coverage is better compared to the other regions, even here most reports are concentrated along the main ship routes. Considering time changed in the data amount, most reports collected during the period from the late 1960s to the late 1980s when the number of observations is typically twice as high compared to the 1950s, 1990s, and 2000s.

We analyze cloud cover over the North Atlantic from 20°N to 80°N. In the midlatitudes and near the coasts of North America, Europe, and Africa, the mean seasonal number of reports is typically around 200 reports per 2° grid cell with the local maxima exceeding 500 in the best sampled 2° grid cells. Tropical regions are characterized by somewhat poor sampling with 20 to 100 reports per season per 2° grid cell. Nevertheless, this sampling density remains sufficient for the analysis of variability. The poorest sampling is observed in the Greenland Sea where the mean seasonal number of reports per 2° grid cell drops to less than 20.

3. Characteristics of the distribution of cloud cover over the North Atlantic

We first demonstrate characteristics of PMF (4) as revealed by VOS observations for the period 1950-2017. All computations are performed for individual seasons [January-March (JFM), April-June (AMJ), July-September (JAS), October-December (OND)]. The results for JFM and JAS are shown in figure 1.

The climatologies of the mean cloud cover (figures 1a and 1b) show maximum cloud fraction of 6.5-7.5 octas north of the 40°N in JFM and north of the 50°N in JAS. In the tropics total cloud cover does not exceed 5 octas in both seasons. The seasonal march in the total cloud cover in the latitudinal zone from 25°N to 50°N is estimated at 1-1.5 octas. The smallest cloud amounts (2.5-3.5 octas) at JFM observed in the tropics near the coast of Africa over the Canary Current.
Figure 1. Climatology of the total cloud cover (a,b) and the parameters of the discrete mixed gamma distribution of the fractional cloud cover (4) for shape parameter $\alpha$ (c,d), scale parameter $\beta$ (e,f), steering parameter $\theta$ (g,h) for JFM (a,c,e,g) and JAS (b,d,f,h) in the North Atlantic for the period 1950-2017.

In most areas from 20°N to 50°N as well as around Iceland in all years, the goodness of fit of PMF (4) estimated using the chi-square test exceeds 99%. The lower goodness of fit is observed in some 2° grid cells in the eastern part of tropics and over the Greenland Sea (figure not shown). In this area, the
percentage of years with the goodness of fit of 99% decreases to 70-80%. However, in this area almost in all years, the goodness of fit exceeds 95%.

The distribution of the parameters of PMF (4) is shown in figures 1c-1h. Spatial distribution of the shape parameter $\alpha$ (figures 1c and 1d) shows that in the North Atlantic, this parameter varies from 0.5 to 5. The maximum values of the parameter $\alpha$ are observed in the Greenland Sea in JAS, but our results in this region should be considered with caution because of the considerable undersampling here. In the well-sampled regions, maximum values of parameter $\alpha$ exceed 4 north of the Newfoundland in JFM and south of Greenland in JAS. The minimum values of $\alpha$ in the tropics are typically lower than 1 in both seasons.

Spatial distribution of the scale parameter $\beta$ is shown in figure 1e and 1f. The largest values of the parameter $\beta$ are observed in JAS in the tropics with the local maxima of more than 2. Minima of the $\beta$ parameter is close to 0 and observed in the North Atlantic mid-latitudes. In case of a very small value of $\beta$, the distribution (4) transforms into a power function (steered by parameters $\alpha$ and $\theta$).

Spatial distribution of parameter $\theta$ (figures 1g and 1h) resembles a reversed spatial distribution of the mean total cloud cover (figures 1a and 1b) in agreement with the equation (2). The largest values of parameter $\theta$ (up to 0.5) are observed in the tropics. In winter (JFM) maximum $\theta$ identified around 20°N while in summer there is a shift in the location of maximum. Minimum values of $\theta$ parameter below 0.1 are identified in the mid- and high latitudes, where the probability of clear sky condition is very small.

Of a specific interest is the eastern ocean subtropical regions, characterized by the high occurrence of stratocumulus clouds, e.g. near the coast of North Africa [11]. This area exhibits distinct differences from the other tropical areas. The minimum in the total cloud cover in winter (JFM) here is consistent with local maxima in the $\theta$ parameter, which increases here up to 0.8. Also, we note, local maxima of the $\alpha$ parameter (2-2.5) in this area and the regional minimum of parameter $\beta$ (of about 0.05) in this area in summer (JAS).

For a better understanding of the role of the distribution parameter figure 2 shows examples of the empirical histograms of the fractional cloud cover in octas and their approximation by the PMF (4) for the period 1950-2017 for selected 10° grid cells over the North Atlantic.

Figure 2 shows that the $\alpha$ parameter is controlling the concavity and convexity of the distribution. With increasing the $\alpha$ parameter, the convex form of PMF transforms into the concave. Parameter $\beta$ is responsible for the skewness of the distribution. The parameter $\theta$ defines the occurrence of clear skies and overcast. The shape of the distribution is remarkably changing from the north to the south. In the mid-latitudes were the $\beta$ parameter is quite small (regions 1 and 2), the distribution is characterized by the increasing occurrence of overcast conditions in both seasons. Region 3 in the Central Atlantic demonstrates a remarkable seasonal change in the shape of the distribution, implied by a strongly growing the $\beta$ parameter in summer. This is also the case for region 5, however here the change of the shape of the distribution is controlled by the $\alpha$ parameter. In the latitudinal zone 40°N-30°N as well as at the western tropical Atlantic, the distribution is convex with the higher frequency of the moderate cloud cover. This form of distribution is associated with increasing both $\beta$ and $\theta$ parameters. At the same time over the Canary Current in summer (JAS) the distribution has a concave form with the higher occurrence of clear sky and overcast conditions and the smaller occurrence of moderate cloud cover.
Figure 2. Empirical histograms (green) and their approximations by the mixed gamma distribution (4) (blue) of the fractional cloud cover (octas) for selected North Atlantic regions (shown on the map (k)).

4. Temporal variability in the distribution of cloud cover over the North Atlantic

To analyze the interannual variability of cloud characteristics over the North Atlantic, we first computed linear trends and their statistical significance. Figures 3a and 3b show estimates of linear trends in the total cloud cover that are significant at 95%-significance level according to Student’s t-test. In the tropics, linear trends in the total cloud cover are significantly positive, likely implying the extension of the Hadley cell over the last decades [12]. The most evident pattern of growing cloud cover is observed in summer (JAS) (figure 3b) when the area of positive trends spreads over the whole Atlantic tropics and subtropics with the maximum trends being 0.2 octas per decade (more than 1 octa over the period 1950-2017). Also, remarkably strong positive trends are found in the Mediterranean and over the eastern subtropical Atlantic. Positive trends in most grid cells in the North Atlantic are consistent with the results obtained in [11], which shows that the annual global-average cloud amount increases over the period 1954-1998. Positive trends in the tropics also coincide with the results obtained in [13], where it is shown that in all latitudinal zones of the northern hemisphere up to 60°N the trends of the total cloud are positive, with the maximum values are observed in the tropics.

Statistically significant negative trends in the total cloud cover are locally observed in the subpolar regions near Newfoundland and in the Labrador Sea with the strongest trend magnitude 0.2 octas per decade in summer (JAS). Due to the lack of data for this area, our results for high latitudes should be considered with caution. Nevertheless, these results coincide with the results obtained in [2].
shows that in the Atlantic Arctic, there are negative trends in the total cloud cover according to station observations above the open water during 1936-2013.

**Figure 3.** Linear trends in the total cloud cover (a,b) and the parameters of the discrete mixed gamma distribution of the fractional cloud cover (4) for shape parameter α (c,d), scale parameter β (e,f), steering parameter θ (g,h) for JFM (a,c,e,g) and JAS (b,d,f,h) in the North Atlantic for the period 1950-2017.

Analysis of linear trends in the total cloud cover can be also considered in a view of the tendencies of parameters of PMF (4). Tropical signals (figures 3a and 3b) are closely coordinated with the changes...
in the $\beta$ parameter (figures 3e and 3f). Parameter $\beta$ increases over the most North Atlantic in both winter and summer. Maximum trend values reach 0.3 per decade (15-20%) in the tropics south of 30°N. Positive trends in the $\beta$ parameter imply the changing in the skewness of the distribution with the increasing convexity under the convex form of PMF and decreasing concavity in case of the concave form of distribution. Linear trends in parameter $\alpha$ in both seasons are remarkably negative along the coasts of North America, Europe and Africa (figures 3c and 3d). Here the decrease is characterized by the values of 0.3 per decade (equivalent to 10-30% of the mean values). Also, positive trends (of about 0.3 per decade) are observed in the western Atlantic subtropics and tropics. These trends are especially pronounced in summer, extending also to the Central Atlantic. In some regions, significant trends in parameter $\alpha$ are observed over the areas which do not indicate significant trends in the total cloud cover (western North Atlantic mid-latitudes). Here the change in the form of distribution occurs (implied by $\alpha$ parameter), while the mean cloud cover remains relatively stable. Figures 3g and 3h demonstrate linear trends in the $\theta$ parameter, which are negative over the most North Atlantic with the strongest tendencies in the tropics being 0.1 per decade in JAS. This implies the decrease in the occurrence of the clear sky conditions and is generally consistent with the increase of the total cloud cover in the same regions. Thus, positive trends in the total cloud cover in the tropics especially in summer are clearly associated with the growing parameter $\beta$ and the decreasing parameter $\theta$. This shows that the increase in the mean total cloud cover is consistent with the growing probability of moderate cloud cover and the decreasing probability of conditions close to the clear sky.

For the detailed regional analysis of interannual variability, we analyzed a regionally-integrated time series of cloudiness and the associated parameters of the probability distributions. Figure 4 shows two-dimensional diagrams of the occurrence anomalies for different cloud fractions and associated time series for selected 5° grid cells.

In winter in the central subpolar North Atlantic (figure 4a) trends in the total cloud cover are slightly positive implying the decline of the occurrence of clear sky conditions and the increase of the occurrences of the conditions close to overcast. This tendency is associated with the coordinated changes in $\alpha$ and $\theta$ parameters and small and practically unchangeable $\beta$ parameter. Maximum values of cloud cover, of $\alpha$ and $\theta$ parameters, are observed from the late 1970s to the early 1990s. In this period, the frequency of overcast conditions reaches its maximum. In the next years, the probability of conditions close to overcast slightly decreases but the probability of small amount of clouds with octas from 0 to 3 decreases as well, with the simultaneous increase in the occurrence of moderate cloud cover (octas from 4 to 7).

Figure 4b presents the changes in the western mid-latitude North Atlantic in the summer. In this region, linear trends in the total cloud cover are not statistically significant while linear trends in $\alpha$ and $\theta$ parameters are significantly negative. In this region in the 1950s and in the early 1960s, there was a higher frequency of the clear sky conditions and the conditions close to overcast with a rare occurrence of moderate cloud cover. This implied a concave form of the PMF for this period. In the 1980s and 1990s, the frequencies of clear sky and overcast conditions decreased while the frequency of scattered clouds with octa range from 1 to 4 increased. As a result, the concavity of the PMF in this period was getting smaller. This also correlates with the decreasing $\theta$ parameter (figure 4b). During the recent decade, the frequency of small cloud amounts, as well as the frequency of the overcast conditions, decreased at the expense of the increase in the occurrence of moderate cloud cover. As a result, in this period the distribution remains concave, but the concavity significantly decreases compared to the earlier decades.

In the western tropical Atlantic in summer, there is a clear change in the occurrence of conditions close to overcast (towards increasing large cloud amounts from the 1950s to 2000s). This happens at the expense of decreasing occurrence of small cloud amounts and results in the positive trend in the mean total cloud cover estimated at the level of 1 octa over the observational period. These changes go hand in hand with the positive trend in the $\alpha$ parameter and the negative trend in the $\theta$ parameter (see, figure 4c). While the shape of the distributions for different decades remains qualitatively stable (convex form), there a change towards the higher occurrence of overcast conditions in the latest decade of the record.
A statistically significant trend in the total cloud cover in the eastern subtropical Atlantic (figure 4d) implying more than 1 octa growing total cloud cover over the last 6 decades (0.186 octas per decade), is associated with the decreasing $\alpha$ parameter by 0.228 per decade and the decreasing $\theta$ parameter by 0.05 per decade. The maximum frequency of the clear sky conditions here is observed in the 1970s when the distribution has a concave form. In the 1980s, the frequency of the clear skies remains still large but

![Figure 4. Interannual variability of the occurrence anomalies for different cloud fraction; time series for the total cloud cover and the distribution parameters; PMF for the different time period for selected regions. The occurrence anomalies were calculated around the mean value of each octa for 1950-2017.](image)
also the probability of the overcast conditions increases. Under these conditions, the distribution form remains concave. At the beginning of the 21st, however, the probability of clear sky conditions significantly decreases with the increasing occurrence of moderate cloud cover (octas from 3 to 6). This results in the change of the shape of the distribution from concave to convex for the last decades.

In summary, our analysis shows that in different regions of the North Atlantic in the last several decades, there has been an increase of the occurrence of moderate cloud cover and a decrease in the probability of both clear sky and overcast conditions.

5. Discussion and conclusions
We analyzed characteristics of the probability distribution of cloud cover and its temporal variability over the North Atlantic using visual VOS reports for the period from 1950 to 2017. The use of probability distribution developed for the fractional cloud cover [6] clearly allows us to enrich the analysis of the long-term variability of cloud cover. Specifically, we were able to attribute the observed changes in the total cloud cover to the tendencies on distribution parameters and in the shape of the three-parameters mixed gamma distribution. Our approach helps to identify the areas characterized by almost similar mean total cloud cover but demonstrating different distributions associated with the different cloud regimes. Analysis of the temporal variability in the distribution parameters identified the areas where the form of the distribution is changing over time being coordinated with the changes in the total cloud cover. For example, in the eastern subtropical North Atlantic, the distribution transforms from the concave to the convex form during the last two decades. Also, analysis of the temporal variability demonstrated that the increase in the total cloud cover in some regions of the North Atlantic occurs due to the increase in the frequency of moderate cloud cover with octas from 4 to 7. These results largely coincide with the previous studies (for example, [2] and [13]) based on other data samples.

In the future, application of the probability distribution of the fractional cloud cover can be used for intercomparision and validation of cloud cover data from satellite missions and reanalyses. However, scaling is different in the different data set. This problem is well highlighted in [14], where it is shown how the averaging scale affects the shape of the cloud distribution. This analysis based on the images of cloudiness from satellites over the European part of the USSR in 1979-1981. The distributions were compared for different scales of averaging from 0° (at the zenith point) to 10° grid cells. It is shown that on a small scale (up to 2° grid cells) the distribution has a concave shape. With the increasing averaging scale (8° and 10° grid cells), the distribution takes a convex shape. At the same time, with visual observations of clouds, one can estimate the number of clouds in a section with a diameter of about 15 km (which corresponds to approximately 0.2° grid cells at 50°N). On this basis, it becomes clear that a direct comparison of the distributions obtained from visual observations, satellite data, and reanalysis data is impossible. This intercomparison requires in-depth analysis of scaling.

Also, the use of statistical distributions of fractional cloud cover is effective for estimation and minimization of sampling errors in VOS cloud data in the areas of the undersampling area (for example, in the Southern Ocean and in the subpolar regions of the North Atlantic) as well as for the early decades of the 20th century.

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