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Calculation of Probability of Cloud–Free Lines–of–Sight at Given Heights in Foshan, China

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ABSTRACT

Based on Lund and Shanklin's work (1972), methods of calculating Probability of Cloud–Free Lines–of–Sight (PCFLOS), Persistence Probability of Cloud–Free Lines–of–Sight (PPCFLOS) and Recurrence Probability of Cloud–free Lines–of–Sight (RPCFLOS) at given heights are presented. PCFLOS, PPCFLOS and RPCFLOS are calculated in Foshan, China by conventional observation data from 1961 to 1990. The conclusions are:

(1) The higher the elevations, the smaller the PCFLOS and the larger the view angles, the larger the PCFLOS.

(2) PPCFLOS and RPCFLOS decrease with the increase of elevation and the delay of time.

(3) RPCFLOS is always equal to or larger than PPCFLOS at lag times.

Key words: Probability of cloud–free lines–of–sight, Persistence probability of cloud–free lines–of–sight, Recurrence probability of cloud–free lines–of–sight, Cloud climate

1. Introduction

Whether or not there are clouds on a line as we looking at a point on the ground from a point in the space or in reverse order is important for such purpose as determining the utility of optical and infrared searching and tracking systems. Probability of Cloud–Free Lines–of–Sight (PCFLOS) throughout the atmosphere is the probability of cloud–free lines–of–sight from ground to the top of the atmosphere. In reality, however, PCFLOS at different levels is more important for the above military actions. Not only the appearance of clouds on the lines–of–sight but also their lasting time and re–appearing probability are necessary in flying reconnaissance and bombardment. Persistence Probability of Cloud–Free Lines–of–Sight (PPCFLOS) is the probability of an uninterrupted sequence of cloud–free lines–of–sight. Recurrence Probability of Cloud–Free Lines–of–Sight (RPCFLOS) is a conditional probability of cloud–free lines–of–sight recurring at lag time. PCFLOS, PPCFLOS and RPCFLOS are all needed for the governmental and military actions.

PCFLOS, PPCFLOS and RPCFLOS cannot be obtained directly from conventional observation data because they are related to view angles and azimuths. There were lots of works done on their calculation. Lund and Shanklin (1972) presented an efficient method, which was cited frequently in meteorological society. Nevertheless, Lund and Shanklin's method can only be used to calculate PCFLOS, PPCFLOS and RPCFLOS throughout the atmosphere, not be used to limited altitudes. In this paper, the methods of calculating PCFLOS, PPCFLOS and RPCFLOS at different levels are provided and their values are calculated in Foshan, China by conventional cloud data from 1961 to 1990.

2. General method for calculating PCFLOS at given heights

2.1 *PCFLOS throughout the atmosphere*

Assuming that PCFLOS is unique at same elevation in different direction, Lund and Shanklin (1972) used the following formula to calculate PCFLOS throughout the atmosphere:

$$P_a = \sum_{N=1}^{6} c_{\alpha k}^{N} f_k^N \ , \tag{1}$$

where N is the superscript notation, it represents cloud-form category. p_α is a column vector of α rows, each row for each view angle α (10°, 20° ··· 90°), the p values represent PCFLOS throughout the atmosphere. $c_{\alpha k}^1, c_{\alpha k}^2 \cdots c_{\alpha k}^6$ are six matrices of α rows and k columns for six cloud-form categories, each row for each angle α and each column for each sky cover k(0, 1, 2···10). These six cloud-form categories are shown in Table 1.

Table 1. Cloud-form categories

Category	Cloud Form	Cloud types
1	Cirriform	Cirrocumulus, Cirrostratus, Cirrus
2	Middle	Altocumulus, Altostratus, Altocumulus castellanus
3	Cumuliform	Cumulonimbus, Cumulonimbus mammatus, Cumulus
4	Stratiform	Fractocumulus, Fractostratus, Nimbostratus, Stratus, Stratocumulus
5	Mixed	Mixtures of more than one form
6	None	No clouds of any type reported

f with subscript k and superscript N are frequencies of each N cloud-form categories and each k tenths of cloudiness.

The c values are probabilities of cloud-free lines-of-sight at angle α and cloudiness k. Matrix c was extracted from whole-sky photographs, which were taken in Columbia from 1966 to 1969. The values of $c_{\alpha k}^1, c_{\alpha k}^2 \cdots c_{\alpha k}^6$ can be referred to Lund and Shanklin (1972), these values can be applied to all geographical locations since the definitions of cloud types around the world are the same. Shawn Yu et. al. (1985) also testified this conclusion by data in Hamburg, Germany.

2.2 *PCFLOS at given heights*

Eq.(1) can be used to calculate PCFLOS throughout the atmosphere, it needs total cloud amount and cloud types from the conventional cloud data if $c_{\alpha k}^N$ are known. In real application, however, we need PCFLOS from ground to different levels because planes usually bomb at a definite elevation, which means the cloud heights have to be considered in Eq.(1). When cloud amount, cloud heights and cloud types are considered simultaneously, PCFLOS at different levels can be calculated by the following equation assuming $c_{\alpha k}^N$ are independent on cloud height:

$$p_{\alpha l} = \sum_{N=1}^{6} c_{\alpha k}^{N} f_{kl}^N \ , \tag{2}$$

where l is the given height, k is the total cloud amount below height l. $p_{\alpha l}$ is the PCFLOS at angle α and height l. f_{kl}^N are frequencies of cloud categories N, cloud base height l and total

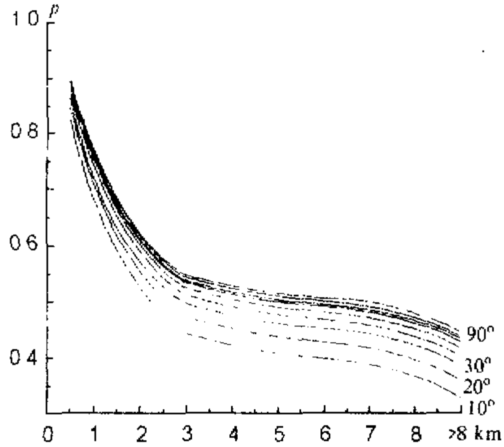

Fig. 1. PCFLOS at 10 different levels in Foshan, China.

cloud amount k below height l. If there is no cloud below level l, cloud–form category belongs to 6; if there are clouds only on one level below l, cloud–form category belongs to 1,2,3 or 4; and if there are clouds on two or more levels below l, cloud–form category belongs to 5. p, c, f are all matrices. Other terms are with the same meanings as those in Eq.(1).

$f_{kl}^1, f_{kl}^2 \cdots f_{kl}^6$ in Eq.(2) are obtained from the conventional surface observational data in Foshan, from 1961 to 1990. The results are omitted here for saving pages. l is divided into 10 levels in this paper. PCFLOS at ten different levels in Foshan are calculated by Eq.(2) and the results are listed in Table 2, which are further smoothed as shown in Fig. 1.

Table 2. PCFLOS at 10 different levels in Foshan

	0.5 km	1 km	2 km	3 km	4 km	5 km	6 km	7 km	8 km	>8 km
10°	0.824	0.641	0.490	0.442	0.417	0.406	0.398	0.390	0.378	0.326
20°	0.847	0.668	0.519	0.471	0.446	0.435	0.427	0.419	0.407	0.358
30°	0.865	0.688	0.541	0.495	0.470	0.459	0.451	0.444	0.432	0.385
40°	0.876	0.701	0.556	0.510	0.486	0.475	0.467	0.459	0.447	0.402
50°	0.887	0.713	0.568	0.523	0.498	0.488	0.480	0.472	0.460	0.416
60°	0.893	0.719	0.576	0.532	0.508	0.497	0.490	0.482	0.470	0.427
70°	0.894	0.722	0.580	0.536	0.512	0.501	0.494	0.486	0.474	0.432
80°	0.901	0.728	0.586	0.542	0.518	0.508	0.500	0.492	0.480	0.439
90°	0.902	0.731	0.590	0.546	0.523	0.513	0.505	0.505	0.486	0.444

Figure 1 shows that the largest PCFLOS is 0.902 at angle 90°, and the smallest is 0.326 at angle 10°. The higher the elevations, the smaller the PCFLOS and the larger the view angles, the larger the PCFLOS. It is understandable that the opportunity of cloud appearance below l will increase if l is higher and the distance between a point at the ground and a point at the certain level in the atmosphere is longer at lower angle than that at higher angle. For example, at the angle of 40°, PCFLOS is 0.876 at height of 0.5 km, while at 8 km its value is less than half of that. At the height of 3 km, PCFLOS is 0.546 at angle 90°, but it is only 0.442 at angle 10°.

3. PPCFLOS and RPCFLOS at given heights

3.1 *Concept of persistence and recurrence*

Since conventional observations are taken hourly, the duration of cloud-free lines-of-sight between hours is unknown. We cannot assume cloud is free on the line-of-sight between hours if it is cloud-free at initial and terminal time since clouds vary rapidly in very short periods. Lund (1973) defined persistence for this study as an uninterrupted sequence of cloud-free or cloudy lines-of-sight. Hourly persistence is defined as an uninterrupted sequence of cloud-free or cloudy lines-of-sight spaced 1-hour apart. 5-minute persistence is defined likewise but the interval is 5 minutes.

Lund defined recurrence as the relative frequency (an estimate of conditional probability) of an event recurring at some later hours, given that the event occurred at the initial hour. This implies that another event could have occurred in the intervening time. Recurrence relative frequencies equal or exceed persistence relative frequencies at all lag times except the first when they are uniform.

3.2 *Method of calculating PPCFLOS and RPCFLOS at given heights*

We only calculate 5-minute PPCFLOS and RPCFLOS in this paper. Lund (1973) used the following formula to calculate PPCFLOS and RPCFLOS throughout the atmosphere:

$$p_t = E_{tk} f_k \ , \tag{3}$$

where t is 5-minute lag time (5, 10, ··· 55), k is total cloud amount, p_t is a column vector of t rows, each row for each 5-min lag time in an hour considered, E_{tk} is a matrix of t rows and k columns, each column for each sky cover category and f_k is a column vector of k rows, the elements of column vector f_k are frequencies of each k tenths of cloudiness. p_t is PPCFLOS or RPCFLOS at lag time t, and matrices E_{tk} are frequencies of persistence or recurrence at lag time t for each k tenths cloudiness when cloud is free on lines-of-sight at the initial time. The values of E matrices are extracted from the photograph data in Columbia, America in summer, 1969. The values of E matrix can be referred to Lund (1973). The calculation scheme was described in detail by Charles and MacNichol (1990).

In order to get PPCFLOS and RPCFLOS at different levels, the following equation can be derived from Eq.(3), which is more reasonable at given heights:

$$p_{tl} = E_{tk} f_{kl} \ , \tag{4}$$

where p_{tl} is the PPCFLOS or RPCFLOS at given height l at lag time t, f_{kl} represents the frequency of k tenths cloudiness below l. p,E,f are all matrices. Other terms are the same as those in Eq.(3).

Assuming that (1) for a given tenth of cloudiness, the character of the sky is essentially the same anywhere in the world, and (2) sky cover changes within 1 hour are similar everywhere, Eq.(4) can be applied widely to different geographical locations as long as the conventional cloud observations are available. In order to get the frequency f_{kl} in Eq.(4), the cloud observational data from 1961 to 1990 in Foshan are used for statistical processing. The model height l was divided into 10 levels with lag time of 5 minutes. Matrices E are still used the values in Columbia because of deficiency of data in China, error will be produced probably. In spite of this error, tendency variations of PPCFLOS and RPCFLOS with elevations and lag times will not change. PPCFLOS and RPCFLOS at different levels and times within an hour can be calculated by Eq.(4). The calculated results are listed in Table 3 and Table 4; the values are further smoothed as shown in Fig. 2 and Fig. 3.

Table 3. PPCLFOS at 10 given heights in Foshan

Minute	0.5 km	1 km	2 km	3 km	4 km	5 km	6 km	7 km	8 km	>8 km
5	0.97	0.93	0.90	0.88	0.88	0.88	0.87	0.87	0.87	0.85
10	0.95	0.88	0.82	0.80	0.79	0.78	0.78	0.78	0.77	0.75
15	0.93	0.84	0.76	0.74	0.72	0.72	0.71	0.71	0.70	0.67
20	0.91	0.80	0.72	0.69	0.67	0.66	0.66	0.65	0.65	0.61
25	0.90	0.78	0.68	0.65	0.63	0.62	0.62	0.61	0.60	0.57
30	0.89	0.76	0.66	0.62	0.60	0.59	0.59	0.58	0.57	0.53
35	0.89	0.75	0.63	0.60	0.58	0.57	0.56	0.56	0.55	0.50
40	0.88	0.74	0.62	0.58	0.56	0.55	0.54	0.54	0.53	0.48
45	0.88	0.73	0.60	0.57	0.54	0.53	0.53	0.52	0.51	0.46
50	0.86	0.71	0.59	0.55	0.53	0.52	0.51	0.50	0.49	0.44
55	0.86	0.70	0.58	0.53	0.51	0.50	0.50	0.49	0.48	0.43

Table 4. RPCFLOS at 10 given heights in Foshan

Minute	0.5 km	1 km	2 km	3 km	4 km	5 km	6 km	7 km	8 km	>8 km
5	0.97	0.93	0.90	0.88	0.88	0.88	0.87	0.87	0.87	0.85
10	0.97	0.91	0.87	0.86	0.85	0.84	0.84	0.84	0.84	0.82
15	0.96	0.90	0.85	0.84	0.83	0.83	0.82	0.82	0.82	0.80
20	0.96	0.90	0.84	0.83	0.82	0.81	0.81	0.81	0.80	0.78
25	0.96	0.89	0.83	0.82	0.81	0.80	0.80	0.80	0.79	0.77
30	0.95	0.88	0.82	0.81	0.80	0.79	0.79	0.79	0.78	0.76
35	0.95	0.88	0.82	0.80	0.79	0.78	0.78	0.78	0.77	0.75
40	0.95	0.87	0.81	0.79	0.78	0.77	0.77	0.77	0.76	0.74
45	0.95	0.87	0.80	0.78	0.77	0.77	0.76	0.76	0.75	0.73
50	0.94	0.86	0.80	0.77	0.76	0.76	0.75	0.75	0.74	0.72
55	0.94	0.86	0.79	0.77	0.76	0.75	0.75	0.74	0.74	0.71

Figure 2 shows that PPCFLOS decreases with the increase of lag times and heights if cloud is free on a line–of–sight at initial time. In an hour, it reduces 30% on the average. The lower the level, the smaller it reduces, or the higher the levels, the more it reduces. For example, PPCFLOS only reduces 0.11 in an hour at 0.5 km, but reduces 0.42 at height above 8 km.

Figure 3 also shows that RPCFLOS decreases with the increase of lag times and heights. The reducing rate is smaller as compared with that of PPCFLOS because it is recurrence probability. It reduces only 0.03 at 0.5 km level in an hour and only 0.14 at height above 8 km. Compare Fig. 2 with Fig. 3, it is clear that RPCFLOS is in general equal to or large than PPCFLOS at given height and lag time. If the cloud free line–of–sight at the initial hour is known, PPCFLOS and RPCFLOS at any 5–minute lag time in an hour on different levels can be available in Table 3 and Table 4. These values are needed for aviation and military applications.

Based on the conventional cloud observation data from 1961 to 1990 in Foshan, china, two calculation schemes are presented to get PCFLOS, PPCFLOS and RPCFLOS at different levels in the atmosphere. The main conclusions are:

(1) The higher the elevations, the smaller the PCFLOS and the larger the view angles, the larger the PCFLOS.

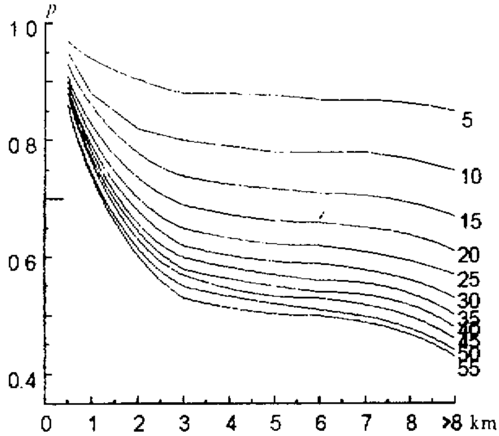

Fig. 2. PPCFLOS at 10 given heights in Foshan.

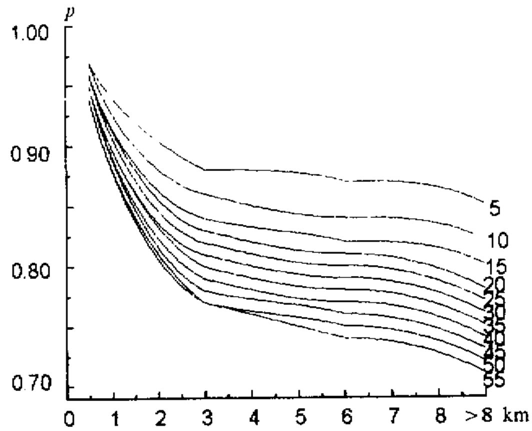

Fig. 3. RPCFLOS at 10 given heights in Foshan.

4. Conclusions and discussion

Based on the conventional cloud observation data from 1961 to 1990 in Foshan, China, two calculation schemes are presented to get PCFLOS, PPCFLOS and RPCFLOS at different levels in the atmosphere. The main conclusions are:

(1) The higher the elevations, the smaller the PCFLOS and the larger the view angles, the larger the PCFLOS.

(2) PPCFLOS and RPCFLOS decrease with heights and lag times.

(3) RPCFLOS is always equal to or large than PPCFLOS at lag times.

There are few questions to be declared in the present study: The values of Matrix E in Eq.(4) are extracted from the Columbia photographic data in summer, 1969. The data from a specific place in one year are not sufficient to represent the climatic values. If the Chinese climate data related to the view angle are available, it should be used in the present model and the results might be slightly different. The values of PCFLOS, PPCFLOS and RPCFLOS at different levels in Foshan must be different from those in other regions because of different geographic locations, diurnal cycles and weather conditions. They will be compared furthermore.

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