Cloud identification using actinometrical data

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Abstract. A technique for automated cloud identification by analyzing measurable direct and diffuse radiation is proposed.

1. Introduction
Having determined the form of a cloud cover, one can get an idea of the processes leading to its formation in the atmosphere and predict their further development. Particular attention should be paid to convective cloudiness, which is a powerful carrier of atmospheric moisture and a regulator of radiation balance and, due to its proximity to the Earth's surface and high frequency in the warm time of the year, has a great influence on the formation of weather and climate and is a major source of hazardous meteorological and emergency situations. Satellite observations for various reasons cannot always provide information on the state of the lower layers of the atmosphere in which such cloudiness is formed and, therefore, ground observations are of great importance in this case. Regular visual observations of basic parameters of cloudiness (shape, amount and cloud base height) are carried out at weather stations 8 times a day, which is clearly not enough, because low clouds are very dynamic formations and can change the state of the sky from clear to completely covered by clouds within 20-30 minutes.

At present, as part of a modernization of the actinometric network, weather stations are being equipped with automatic actinometric complexes (AACs), which allow us to obtain continuous series of measurements of major elements of the radiation mode which directly depend on the state of the atmosphere and primarily on the shape and amount of cloudiness. With series of measurements of the direct $S$ and diffuse $D$ irradiances, it is possible, with some assumptions, to restore the state of the sky that caused a particular combination of the $S$ and $D$ values on the Earth's surface that are naturally and conveniently used as initial parameters.

2. Theory
The standard methodology to determine cloud shapes is based on aer morphological classification which makes it possible to define the shape of clouds by their appearance [1]. The use of such classification in automated systems is difficult, primarily, because for this purpose, in addition to a matrix photodetector for direct monitoring of the sky condition, considerable computing and, hence, energy resources are required to implement complex and time-consuming algorithms for image processing and image recognition. In contrast, for a broad automation of the cloud shape determination process, inexpensive systems that can classify cloudiness by other (non-morphological) features, for example, actinometrical features, are needed. Table 1 shows typical and usual distinctive features of basic cloud shapes [1], according to which all clouds may be subdivided with respect to their optical...
thickness into three classes: transparent, semi-transparent, and non-transparent ones. Within each of the classes, three groups of clouds may be defined according to the degree of influence on direct irradiance and four groups of clouds according to their effects on diffuse irradiance.

Table 1. Typical and usual features of basic cloud types.

| Cloud optical thickness | Cloud forms | Decrease of direct irradiance $S$ | Change of diffuse irradiance $D$ |
|-------------------------|-------------|----------------------------------|----------------------------------|
|                         |             | weak    | significant | strong | increase | weak    | significant | strong | decrease |
| Transparent clouds      | $Ci$        | x       |             |        |          | x       |             |        |          |
|                         | $Cc$        | x       |             |        |          | x       |             |        |          |
|                         | $Cs$        | x       |             |        |          | x       |             |        |          |
| Semi-transparent clouds | $Ac$        | x       |             |        |          | x       |             |        |          |
|                         | $As$        | x       |             |        |          | x       |             |        |          |
| Non-transparent clouds  | $As$        | x       |             |        |          | x       |             |        |          |
|                         | $Ns$        | x       |             |        |          | x       |             |        |          |
|                         | $Sc$        | x       |             |        |          | x       |             |        |          |
|                         | $St$        | x       |             |        |          | x       |             |        |          |
|                         | $Cu$        | x       |             |        |          | x       |             |        |          |
|                         | $Cb$        | x       |             |        |          | x       |             |        |          |

Thus, each type of cloudiness can be described by specific, unique amplitude and temporal actinometrical features. The amplitude features depend on the effect this particular type of cloudiness has on direct and diffuse irradiances. These are described by the transmission ratio of direct irradiance $C_S = \frac{S}{S_0}$ and the ratio of change of diffuse irradiance $C_D = \frac{D}{D_0}$, where $S$ and $D$ are mean values measured in some time period, and $S_0$ and $D_0$ are the values of direct and diffuse irradiances in clear sky and at the same Sun altitude. These ratios allow us to probe the clouds not only in terms of the throughput, but also in terms of their ability to re-emit solar radiation. Such an approach was proposed in [2], where the authors only use the transmission ratio of direct irradiance $C_S$, that is, the cloud is examined only to transmit direct radiation. Since clouds are not stationary and always in motion and development, they form their own temporal actinometrical features which can be described by the coefficients of variation of direct $V_S = \frac{\sigma_S}{S}$ and diffuse $V_D = \frac{\sigma_D}{D}$ irradiance, characterizing the homogeneity of cloud optical thickness and its speed. One can find such an approach in [3], where, as an amplitude feature, the average value of the total irradiance $Q = S' + D'$ scaled to a value of 1400 W·m$^{-2}$ and, as a temporal feature, the standard deviation in a 21-minute period are used. The distinctive feature of cumulus cloudiness, for example, is its ability to change the solar disk type with some frequency from a completely open ($S = S_0$) to a completely shadowed ($S = 0$), and also to significantly increase the diffuse irradiance $D$ (up to 3-3.5 times). In this case there may be situations when a reduction in the direct irradiance, when a cumulus cloud is covering the Sun disk, will be considerably compensated by an increase in the diffuse irradiance from the same cloud, thus making the total irradiance decrease insignificant, which is typical not only for cumulus, but also for
altocumulus clouds. This uncertainty in the identification of cloud types can be avoided by using separate analyses of the direct $S$ and diffuse $D$ irradiances.

The technique to define cloud types using an optical thickness classification proposed below involves measuring the direct $S$ and diffuse $D$ irradiances within a certain period of time, determining their mean values, calculating the coefficients $C_S V_S C_D V_D$ and comparing them with reference values for some shapes and types of clouds. For cumulus cloudiness the technique assumes determining the mean values of these coefficients for each cloud amount.

3. Raw data and measurement results

To apply this technique for automated cloud detecting in practice, it is necessary to solve two problems. The first is to choose (or create) a model of diurnal variation of the direct $S_0$ and diffuse $D_0$ clear-sky irradiances for the measurement point, season, and Sun altitude considered. In [3], to model the diurnal total clear-sky irradiance $Q_0$, a complex analytical expression is used which includes both empirical and measured coefficients of absorption and diffusion in atmospheric gases, atmospheric pressure, and dew point. In our case, interpolated average long-term values for clear sky of the warm period of the year for a given point are used to model the clear-sky diurnal variation of the $S_0$ and $D_0$ irradiances [4].

The second problem is determining the mean values of the coefficients $C_S V_S C_D V_D$ for each type of clouds and separately for each cumulus cloud amount, which demands continuous synchronous series of instrumental measurements of the direct and diffuse irradiances and of visual observations of cloud shapes for comparison. As the series, one-minute measurements of the direct and diffuse irradiances from the AAC of the Ogurtsovo meteorological station (Novosibirsk, WMO 29638) for May-August 2016 were used [5]. The mean values of $\bar{S}$ and $\bar{D}$ were calculated for 20-minute periods with a single shape of cloudiness on with clear sky. The shape and cloud amount were identified from panoramic images of the sky from a television meter of the cloud parameters [6] set up near the AAC. Figure 1 shows an example of processing of a panoramic image when there were only cumulus clouds in the sky.

![Figure 1. Original and processed all-sky image.](image-url)
The thus obtained mean values of the coefficients $C_S V_S C_D V_D$ for the main shapes and types of clouds are presented in Table 2, where the clear sky condition is described similarly to the cloud condition.

**Table 2. Average coefficients of basic cloud types.**

| Cloud optical thickness | Cloud forms (sky condition) | Average coefficients |
|-------------------------|-----------------------------|----------------------|
|                         |                             | $C_S$  | $V_S$  | $C_D$  | $V_D$  |
| Full transmission       | Clear                       | 1.0    | 0.01   | 0.9    | 0.04   |
| Transparent clouds      | $Ci$, $Cc$, $Ac$ trans.     | 0.7    | 0.7    | 2.2    | 0.06   |
|                         | $Cs$                        | 0.7    | 0.5    | 2.1    | 0.02   |
| Semi-transparent clouds | $Ac$, $Ci$ sp., $Sc$ trans. | 0.5    | 0.7    | 2.6    | 0.10   |
|                         | $As$                        | 0.5    | 0.5    | 3.8    | 0.04   |
| Non-transparent clouds  | $Sc$, $Ac$ op., $Ac$ lent.  | 0.1    | 0.89   | 3.2    | 0.15   |
|                         | $St$, $As$ neb. op., $As$ ind. op. | 0.3 | 0.5    | 2.1    | 0.02   |
|                         | $Cu$, $Ci$ ing.             | 0.6    | 0.62   | 1.8    | 0.18   |
|                         | $Cb$, $Ns$                  | 0.0    | 0.9    | 1.5    | 0.21   |

It can be seen that a small coefficient of variation of the diffuse irradiance ($V_D \leq 0.05$) is characteristic for clear sky and for stratiform clouds ($Cs$, $As$, $St$), which is explained by the homogeneity of the optical thickness of the cloud layer (or the atmosphere in the case of clear sky) and by the low speed of its motion across the sky. A large coefficient of variation of the direct irradiance ($V_S > 0.6$) is characteristic for cumuliform clouds ($Cc$, $Ac$, $Sc$, $Cu$, $Cb$), which is explained by the "trigger" condition of the solar disk, which can change its state from shadowed to open at some frequency depending on the cloud amount and velocity.

**Table 3. Average coefficients of cumulus clouds.**

| Cumulus cloud amount $n$ | $C_S$ | $V_S$ | $C_D$ | $V_D$ | Number of measurements $N$ |
|-------------------------|-------|-------|-------|-------|----------------------------|
| 0                       | 1.0   | 0.01  | 0.8   | 0.04  | 32                         |
| 1                       | 0.9   | 0.13  | 1.1   | 0.05  | 94                         |
| 2                       | 0.9   | 0.19  | 1.2   | 0.10  | 331                        |
| 3                       | 0.8   | 0.31  | 1.3   | 0.12  | 919                        |
| 4                       | 0.7   | 0.48  | 1.5   | 0.13  | 1082                       |
| 5                       | 0.6   | 0.74  | 1.8   | 0.13  | 907                        |
| 6                       | 0.5   | 0.94  | 2.0   | 0.13  | 840                        |
| 7                       | 0.3   | 1.17  | 2.1   | 0.14  | 835                        |
| 8                       | 0.2   | 1.68  | 2.0   | 0.16  | 528                        |
| 9                       | 0.1   | 1.87  | 1.9   | 0.19  | 200                        |

In view of the fact that under cumulus cloudiness the range of values of the coefficients $C_S V_S C_D V_D$ is quite large, it is advisable to divide the interval of their values into several domains for each cloud amount. To calculate the average values of the coefficients, a 20-minute measurement interval was
also used, when there was only a certain amount of cumulus cloudiness in the sky. The average values of the coefficients $C_S V_S C_D V_D$ obtained for various cumulus cloud amounts are given in Table 3.

It is well-known that the magnitude of the diffuse irradiance depends to a large extent on the shape and amount of cloudiness. With clear sky it depends on the Sun altitude angle, atmospheric conditions and surface albedo and $D = D_0$. High-level clouds typically cause an insignificant increase in the diffuse irradiance compared to its value for clear sky and $D = D_0 + D_h (D_h > 0)$. Middle-level clouds, depending on their type, can cause both large and small increase in the diffuse irradiance (for example, Ac trans. or Ac op., accordingly) and $D = D_0 + D_m$, where $D_m = (1.6 \div 5)D_0$. Low-level clouds and clouds of vertical development can both increase and decrease (in case of rain clouds) the diffuse irradiance. Located at low altitudes (the cloud base height under 1500 m), such clouds cover clear-sky areas and have a significant effect on $D_0$, which must be taken into account. Therefore, for low-level clouds $D = (1 - b)D_0 + D_h$, where $b$ is the cloud amount in fractions of units. In general, the cloud amount can be considered as a function of the diffuse irradiance $b = f(D)$. With average values of the $C_D$ (from Table 3), it becomes possible to estimate the cumulus cloud amount $[7]$. This dependence is shown in Figure 2.

\[
y = -0.0044x^3 + 0.0427x^2 + 0.0835x + 0.8578
\]

$R^2 = 0.9864$

Figure 2. Coefficient $C_D$ versus cumulus cloud amount.

4. Conclusions
Clouds are a natural regulator of the solar radiation coming to the Earth’s surface. All major types of cloudiness can be described by their unique amplitude and temporal actinometrical features, which characterize their ability to transmit and re-emit solar radiation. Cumulus cloudiness is of great significance for the process of weather and climate formation of a territory, since it is dynamically unstable and can carry large amounts of water over long distances both horizontally and vertically. Besides, this type of cloudiness is the basis for the formation of cumulonimbus clouds, which are most dangerous in terms of emergency situations in the sky and on the Earth. The paper presented a technique to determine the cloud shape by its amplitude and temporal actinometrical features based on an analysis of continuous series of data for the direct and diffuse irradiances. This approach allows us to formalize and automate the process, which in most cases is carried out visually. Also, making separate analyses of the constituents of the total irradiance allows determining not only the type of cloudiness, but also its amount by the magnitude of the diffuse irradiance.
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