Cloud Properties from Observations in Different Spectral Ranges

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The Earth's radiation energy balance and hydrological cycle are fundamentally coupled with the distribution and properties of clouds. The ability to remotely infer cloud properties and their variation in space and time is crucial for establishing climatology as a reference for validation of present-day climate models and in assessing future climate change. Remote cloud observations also provide data sets useful for testing and improving cloud model physics, and for assimilation into numerical weather prediction models. The accurate determination of the cloud liquid water content (LWC) profile from one single remote sensing instrument is not possible. The combination of all of the measured properties of the clouds, surface and atmosphere allows for a diagnosis of the effects of cloud variations on the planetary and surface radiation budgets. A ground based system combining active and passive remote sensing instruments from different spectral ranges is used to investigate cloud processes. The observations of clouds are carried out by microwave meteorological radar operating at wavelengths of 3 and 10 cm. This information is merged with the physical characteristics of clouds retrieved from the radiance data displayed in series of digital photographs of the clouds taken in short time intervals. The radar and visible images are transformed into the same geographic projection format and displayed simultaneously for qualitative evaluation.

Visible images

The broadband observations of clouds in visible spectrum are justifiable because the extinction coefficient does not depend on the wavelength, and depends only on the ratio of liquid water content to the effective radius of particles. The extinction coefficient of cloudy media slightly increases with the wavelength in the visible and near infrared. This is the reason why the satellite methods of cloud microstructure determination are concerned mostly with the retrievals of values of the effective radius and the liquid water path.

The visible flux is more sensitive than the IR flux to variability in the water content and in the base and top heights of observed clouds. The technique for extraction of information about cloud properties in visible range uses series of digital images of clouds. Observations from earth surface give the possibility to operate with the transmitted light, which is directly related to the light extinction, and consequently, to the optical thickness of clouds that is governed mostly by values of effective radius and liquid water content independently of the particle-size distribution [1]. Therefore, the high time resolution in observable variations of cloud properties such as optical thickness allows for assessing the rates of microphysical processes in clouds. Optical thicknesses of clouds characterize the interaction of clouds with both solar (shortwave) and terrestrial (long wave) radiation.

There is a rough factor of two in difference between the ISCCP (International Satellite Cloud Climatology Project) results, based on measured visible reflectance, and the surface-based results, based on diffuse broadband transmission. Since the latter quantity is very sensitive to the absorption in the cloud outside the visible wavelength range (which is represented in the surface analysis only by a climatology), the difference may be accounted for, in part, by errors in absorption and, in part, by the effects of cloud variations over larger satellite spatial scales of 100 - 300 km [2].

The most important area of the application of the optical properties of clouds lies in the field of remote sensing. From point of view of the image transfer in cloudy media, cloud is a high-frequency filter. As a result of light scattering, the transmission function of high-frequency signals in time and space domains is reduced considerably. The lost of contrast is higher for thicker cloudy media with lower transmission and smaller droplets or crystals. An analytical relationship is obtained between values of Optical Transfer Function and cloud microphysical parameters [1]. There the influence of the shape of particles on the radiation transfer in clouds is studied. It was found that clouds with non-spherical particles have lower transmittance (larger values of reflectance) as compared to clouds with spherical droplets with the same value of volume to particle surface area ratio.

The variability of the optical thickness and the type of cloud particles affects the intensity and polarization of the transmitted light, so the ground-based measurement of cloud brightness in appropriate time intervals may be a useful method for studying the processes of cloud formation.

Meteorological radar

The meteorological radar that operates at 3 and 10 cm wavelengths provides continuous vertical profiles of clouds as they drift over the site. The radar reflectance is more sensitive to large cloud particles with effective radius $r_{eff} \sim 35$ µm and larger. Such sizes of hydrosols are predominantly related to precipitation. Normal refraction of radar waves through the atmosphere prevents radar data at distant ranges from being quantitatively representative unless precipitation-related processes are taken into account. At some conditions, radar data give very accurate estimates of cloud base and cloud top heights, and therefore of cloud physical or geometrical depth D. Since radar reflectivity is proportional to the 6th power of drop diameter a very small number of drizzle sized drops produce a detectable back scattering signal. The backscattering signal in the visible to near infrared wavelengths (as detected by the ceilometer) on the other hand, increases only with the square of the droplet diameter. This is why the ceilometer does not detect those drizzle sized drops, since their number density is not high enough. The latter exhibits the general problems with radar reflectivity if drizzle sized droplets are present. For characterizing cloud properties in more details, a set of attendant meteorological parameters including ceilometer estimate of the lower cloud boundary at visible wavelengths is used. The vertical structure of clouds is exclusively determined by the temperature and water vapor mixing ratio at the lower cloud boundary. The horizontal (temporal) structure is a strong function of the cloud boundaries. When comparing the remotely sensed values of Liquid Water Content (LWC) with in situ measured LWC it becomes evident that the methods combining different parameters are much closer to the in situ measured properties [3].

Perspectives of ground-based joint observations

The distribution of cloud properties and their correlated variations is best illustrated either from satellite or from surface measurements by two-dimensional frequency distributions (histograms) of the cloud top pressure (radar) and visible optical thickness. Later we will add two other cloud properties to these results, cloud particle size which indicates the microphysical behavior of the cloud and precipitation. Also we will add the results of the analysis of cloud vertical structures. Combined optical and microwave remote sensing data are used, for example, in the ISCCP and Special Sensor Microwave/Imager for estimation of the liquid water path (water content in a vertical cloud column) and rainfall rate of oceanic clouds [4].

The ray optics results have a high accuracy for large droplets with size parameters larger than 400, and consequently, for particle effective radius r_{eff} ~ 35 μm for visible range represented by 0.55 μm wavelength. It is obtained direct relationship between observable quantities, such as visible cloud reflection and transmission functions, with microphysical parameters of clouds - the size and refractive index of particles.

At the same time, the radar reflectance from cloud layers at cm wavelengths that is much larger than the size of hydrosols with diameter not exceeding 1 mm is described by the theory of Rayleigh scattering. Thus the different aspects of joint investigation concerning cloud properties by means of observations in visible and cm spectral ranges can provide more thorough answer to the questions about climatologic significance of clouds.

Cloud variations exhibit regional dependence that is much larger and is hidden in the global averages. Thus, regional variations must be examined to diagnose the controlling processes. Local (small horizontal scales) vertical motions caused by hydrostatic instability produce cumuliform clouds, and much larger scale wave motions from a variety of source produce stratum form clouds. Two key features that follow from these facts are that the vertical structure is particularly diagnostic of the motions producing the clouds. Thus, understanding how the atmospheric circulation leads to the cloud properties observe, it is crucial to examine the correlated variations of cloud properties, especially their vertical structure, that is better observable from surface. The ISCCP datasets are obtained from passive measurements of radiation reflected and emitted by the clouds, so that they cannot provide information about the vertical distribution of cloud mass. Satellite measurements have been extended to include cloud base-height and cloud optical thickness, available from surface observations [2].

Ground-based regional observations of clouds on short space-time scale provide valuable detailed information about atmospheric dynamics and cloud properties, allow for turning to good advantage the information content of both transmission and reflection functions in respect to microphysical characteristics of clouds, and are used as a complementary tool to the global satellite observations.

First data and results

In Fig. 1 fast forming cyclone clouds during the lowering pressure P from 1019 to 1005 hPa (at sea level) for less than three hours are shown. Visible images indicate the high rate of the growing optical thickness – the linear average of the brightness decreases by 49% in 4 minutes, while still no data about radar reflectance (Fig. 1.2 below). At this stage of cloud formation, the size of hydrosols is too small to give detectable radar reflectance. Nevertheless, radar measurements indicate relatively high top height of clouds – about 6000 m (Fig. 1.2. up), and ceilometer determined base height is ~1800 m above ground level that makes over 4000 m physical thickness of cloud layer. About two hours later it began to rain, and in the course of six hours the amount of precipitation was 6 litre/m^2.

Fig.1.1. Visible images taken in time interval of 4 minutes; The skies are mostly cloudy and the optical thickness grows very fast by 49%

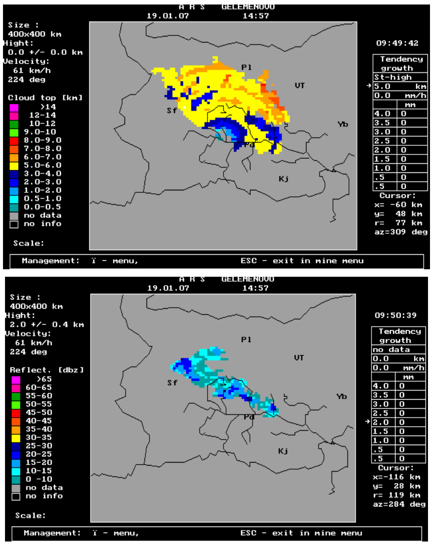
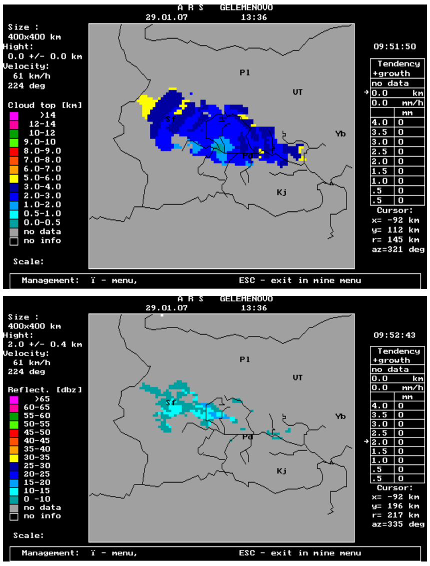


Fig. 1.2. Meteorological and radar data: Base height ~1800 m, Top ~6000 m, Thickness >4000 m, T=15^o C, RH=45%, P=1005 hPa (« norm)

Fig. 2 1. Visible images: In two hours the clouds get larger and darker in view of the prolonged exposition of the right picture



A R S GELEMENOVO 29.01.07 13:36

Size : 400x400 km
Hight: 0.0 +/- 0.0 km
Velocity: 61 km/h 224 deg
09:51:50
Cursor: x= -92 km y= 112 km r= 145 km az=321 deg

A R S GELEMENOVO 29.01.07 13:36

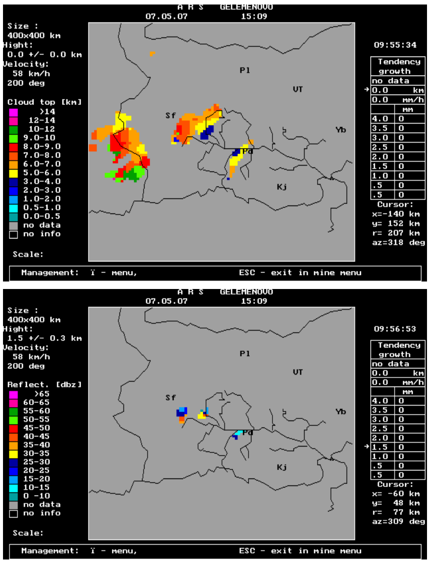
Size : 400x400 km
Hight: 2.0 +/- 0.4 km
Velocity: 61 km/h 224 deg
09:52:43
Cursor: x= -92 km y= 196 km r= 217 km az=335 deg

Fig. 2.2. Meteorological and radar data: Base height ~1500 m, Top ~4000 m, Thickness ~2500 m, $T=4^o$ C, RH=56%, P=1010 hPa (< norm), Reflectance: 10-15

The visible images in Fig. 2.1 show the early formation and the appearance of clouds during their development for more than two hours (Fig. 2.1. left and right). The radar images register lesser top height (Fig.2.2. up) and thickness of clouds as compared with the previous example, but the mixed phase ice-water hydrosols are large enough to be detected by radar. The low radar reflectance R=10-15 (Fig. 2.2. below) is an indication of relatively poor precipitation potential of these clouds – 1 litre/m^2.

The last example displays fast formation of dark convective clouds surrounded by bright aerosol veil that is a sign of probable thunderstorms. The visible images in Fig. 3.1 are taken in only two minutes. The larger radar reflectance R=20-25 (Fig. 3.2 below) and thickness than in the previous example are related to the higher liquid water path in these clouds. Two hours later began thunderstorm and rainfall of amount 3 litre/m^2.

Fig.3.1. Visible images present the quick darkening of clouds in only two minutes



A R S GELEMENOVO 07.05.07 15:09

Size : 400x400 km
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Cursor: x=-140 km y= 152 km r= 207 km az=318 deg

A R S GELEMENOVO 07.05.07 15:09

Size : 400x400 km
Hight: 1.5 +/- 0.3 km
Velocity: 58 km/h 200 deg
09:56:53
Cursor: x= -60 km y= 48 km r= 77 km az=309 deg

Fig. 3.2. Meteorological and radar data: Base height ~1300 m, Top ~8000 m, Thickness >6500 m, $T=21^o$ C, RH=56%, P=1008 hPa (<norm), Reflectance:20-25

The digital processing of the visible images allows for assessing the variability of macro- and the rate of changes of some micro-physical parameters of clouds. The integrated use of remote sensing instruments operating in the visible and microwave spectral ranges make it possible to develop an efficient approach for cloud investigations, and related climate and weather changes.

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