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Abstract

Full Text

Geophysics

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On the Application of Radar to the Study of Cloud Structure

(Presented by Academician E. K. Fedorov, March 31, 1961)

1. The modern application of radar in aerology makes it possible to record radio-echo signals from clouds of various forms at different stages of their development. The substantial advantages of radar methods of observation compel one to investigate every possibility of extracting meteorological information from signals reflected by a meteorological object.

It is known that, in the general case, the magnitude of the signal reflected from droplet clouds, when the Rayleigh scattering law is satisfied, is proportional to the so-called radar reflectivity

$$z = \int_0^{\infty} n(r) r^6 dr,$$

where $n(r)$ is the density of the size distribution of cloud droplets (cm^{-4}). On the other hand, one of the most important microphysical characteristics of clouds, namely the liquid water content, is related to $n(r)$ by the obvious relation

$$W = \frac{4}{3} \pi \gamma_w \int_0^{\infty} r^3 n(r) dr.$$

Here W is the liquid water content of the cloud ($\text{g} \cdot \text{cm}^{-3}$), and γ_w is the density of water ($\text{g} \cdot \text{cm}^{-3}$).

The first attempt to relate z and W was made by Atlas ⁽¹⁾, using the experimental data of Diem ⁽²⁾ and Boucher ⁽³⁾ on the size distribution of cloud droplets. He calculated that, with an error not exceeding 53%*, the liquid water content can be found from the relation

$$z = 0.048 W$$

(here z is in $\text{mm}^6 \cdot \text{m}^{-3}$, W in $\text{g} \cdot \text{m}^{-3}$).

Another attempt to justify the possibility of radar determination of liquid water content was undertaken by Donaldson ⁽⁴⁾, who, assuming the constancy of z

Fig. 1. Schematic structure of a cloud and its relation to the radio-echo signal.

Figure 1: Fig. 1. Schematic structure of a cloud and its relation to the radio-echo signal.

along the path of signal propagation, related W to the magnitude of radio-wave attenuation in clouds.

2. The absence in the literature of data on an experimental verification of the conclusions of Atlas and Donaldson, and the great practical importance of developing radar methods for determining the liquid water content of clouds, prompted us in 1959-1960 to carry out special expeditions for parallel radar and aircraft observations.

The special apparatus developed for this purpose made it possible, with sufficient accuracy (up to 2.5 db), to determine by means of radar the value of z^{**} .

* We note that such accuracy in determining W is quite satisfactory for most applied problems.

** The value of z is determined from the power of the received signal P_r , which, in turn, depends on a number of unstable station parameters. Therefore the accuracy achieved here may be regarded as very high.

The aircraft itself was equipped both with the usual set of aerological instruments, which made it possible to measure the concentration of droplets with radii from 4 to 30 μ , and with an instrument designed by A. N. Nevzorov ⁽⁵⁾, intended for measuring the concentration of particles with $r = 75\mu$.

The data obtained from numerous simultaneous measurements of liquid-water content (from the aircraft) and of the quantity z (by radar), carried out in clouds of various forms, indicate the absence of any pronounced relationship between these quantities*. Moreover, calculations of z , based on known empirical relations for the form of the function $n(r)$ ^(6, 7), lead to values of the order of $10^{-17} \div 10^{-15} \text{ cm}^3$, whereas radar measurements give, as a rule, significantly higher values, reaching in individual cases 10^{-13} cm^3 and more, even in clouds that do not produce visible precipitation.

Fig. 1. Schematic structure of a cloud and its relation to the radio-echo signal. a: 1 –visual boundaries of the cloud, 2-3 –zone of existence of large particles, 1a –upper radar boundary of the cloud, 3, 3a –lower radar boundary of the cloud, 4 –radar station; b –distribution of radio-echo intensity with height.

Such a discrepancy between the new experimental data and earlier ideas is explained by the presence in clouds of large particles with sizes greater than 200 μ , which was not taken into account in ^(1, 2). Because of their low concentration (from units to thousands per 1 m^3), these particles have almost no effect on the optical density and liquid-water content of clouds; however, they make the principal contribution to the radio-echo signal, determined by the value z . No

rigid relationship has been found between the usual microphysical parameters of clouds and the concentration and size distribution of large particles, which fluctuate strongly in space and in time.

The results obtained make it possible to draw important conclusions that differ from the ideas mentioned above (¹, ²):

- a) Remote determination of the liquid-water content of clouds, based on data on the magnitude of the radio echo from them, is impossible.
- b) The estimate of attenuation (and of the liquid-water content associated with it) from the ratio of radio-echo signals received from two volumes of a cloud separated from one another by some distance must be considered invalid. This random quantity z does not characterize the attenuation introduced by the cloud, since clouds are highly inhomogeneous from the point of view of the distribution of large particles in them; i.e., even as a rough approximation the quantity z cannot be taken as constant.
- c) Large particles are detected both beneath clouds and in layers between cloud strata. As a consequence, the contours of the region of the detected signal do not coincide with the visually observed boundaries of clouds.

* For a detailed description of the methodology and results of the observations, see (⁵).

With very good agreement between the heights of the upper cloud boundary determined by radar and by aircraft, the lower boundaries are determined with a large error, sometimes reaching several kilometers (⁸).

In the most general case, the relation between the structure of a cloud and the magnitude of the signal reflected from it may be expressed by the scheme of Fig. 1, which summarizes the results of the first carefully conducted set of parallel aircraft and radar measurements of cloud parameters.

The possibility, from the magnitude of z (sometimes $z > 10^{-15} \text{ cm}^3$), of detecting the presence of large particles in clouds opens prospects for applying radar to broaden our understanding of the processes of precipitation formation. This question lies beyond the scope of the present article and deserves special study.

- 3. Large particles in clouds do not exert any appreciable influence on the attenuation of radio waves, since, so long as the sizes of cloud droplets are smaller than the wavelength, the attenuation coefficient depends substantially only on the liquid-water content of the clouds. This circumstance indicates the possibility of carrying out radar measurement of the liquid-water content and boundaries of clouds, provided a method is developed for reliably determining the attenuation of radio waves in clouds.

Two ways of solving the problem may be proposed:

- a) Observation through a cloud of an isotropically reflecting and space-moving target*—a standard with a constant reflection cross section

substantially exceeding the radar cross section of the clouds. The relationships in this case are obvious; the method makes it possible to determine both the cloud boundaries and their mean liquid-water content. The quality of the measurement results depends on the range, the accuracy with which the standard is tracked in direction, errors in determining the lower cloud boundary, and the type of flight trajectory of the target.

- b) A method that will apparently have certain advantages is to eliminate from the measurement results the fluctuating value of the radio echo by carrying out measurements of this value at two wavelengths reflected from one and the same volume. Without dwelling on the technical side of carrying out such observations, we note that in this case, by fixing the elevation angle, it is possible rather simply to determine the change in W along the sounding direction. Indeed, let us write the power of the signal received from a cloud at range R in the form

$$P_r(\lambda, R) = A(\lambda, R)z \exp \left[-K(\lambda) \int_0^R W(x) dx \right].$$

Assuming that, in practically simultaneous measurements at two wavelengths, the radar reflectivity does not change**, we easily find that

$$\int_0^R W(x) dx = \frac{\ln \left[\frac{P_r(\lambda_2 R) A(\lambda_1, R)}{P_r(\lambda_1, R) A(\lambda_2, R)} \right]}{K(\lambda_1) - K(\lambda_2)} = f(R)$$

By differentiating the experimental curve $f(R)$, one can obtain the value of the cloud liquid-water content at range R along the sounding path, i.e.,

$$W(R) = \frac{df(R)}{dR}.$$

If the Rayleigh scattering law is obeyed, the proposed method should possess high accuracy and rapidity. Naturally, constructing the curve $W(R)$ makes it possible to establish easily the distance to the visual boundary of the cloud, since on one side of this boundary $W = 0$.

* This target may, for example, be carried by a pilot balloon.

** Obviously, this is possible for wavelengths λ_1 and λ_2 for which the Rayleigh scattering law from the ensemble of cloud droplets may be regarded as valid.

By varying the direction of sounding, it is not difficult to determine both the height of the lower boundary of the cloud and the heights of the boundaries of cloud layers, as well as the spatial oscillations of these heights, which is important both for aviation and for a number of other problems in cloud physics.

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