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VARIABILITY OF RADIATIVE PROPERTIES OF CLOUDS FROM AIRCRAFT MEASUREMENTS

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RESUMEN

Utilizando las mediciones realizadas durante el Primer Experimento Global del GARP (FGGE) en diferentes condiciones geográficas, se discuten las propiedades radiativas de las nubes estratiformes. Se describen sus rasgos característicos, en particular las características radiativas espectrales y totales de estas nubes sobre áreas urbanas y rurales, la cubierta de hielo del Artico y cuerpos acuosos en dependencia del espesor óptico de las nubes y la elevación del Sol. Asimismo se analiza la dependencia de la emisividad de las nubes y su espesor en latitudes altas, medias y tropicales.

La variabilidad de las propiedades radiativas de las nubes estratos en diferentes condiciones, requiere de un mayor cúmulo de datos observacionales y búsqueda de técnicas para su parametrización al considerar la interacción entre las nubes y la radiación en el modelado numérico de la circulación general y del clima.

Los resultados muestran que el albedo total de las nubes es algo menor que su albedo en el visible, sin embargo, con una precisión cercana al 10 por ciento, éstos pueden considerarse idénticos, lo cual es esencial para la energética radiativa de la atmósfera. Las nubes bajas se caracterizan por absorción de radiación de onda corta, no solamente en las bandas de absorción molecular sino también en el espectro visible. Como regla general, el calentamiento de las nubes inducido por absorción es menor que el enfriamiento debido al intercambio de calor radiativo, con excepción de nubes sobre grandes áreas industriales, en las regiones de incendios de bosques y de nubes interaccionando con aerosoles ópticamente activos en el caso de transportes masivos de polvo de los desiertos.

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La absortividad de las nubes sobre el agua, áreas rurales y hielo, no excede 0.05 . . . 0.15, pero para nubes ópticamente espesas con $\tau > 30$, puede llegar a 0.20 . . . 0.30. El albedo, A, de una atmósfera nubosa sobre cuerpos acuosos disminuye al aumentar la latitud, con un razón de cambio cercana a 0.003 km^{-1}; y sobre el mar cercana a 0.01 km^{-1}. Para una elevación del Sol $h_{\odot} = 15 - 18^{o}$, el gradiente $\Delta A/\Delta h_{\odot}$ cambia de signo, lo cual se conecta con el efecto de la macro-inhomogeneidad de las nubes para elevaciones bajas del Sol.

Los resultados de comparar datos calculados con observaciones de la evolución de niebla advectiva y nubes sobre hielo, así como experimentos complicados subsatelitarios, indican la necesidad de considerar la divergencia radiativa del flujo de calor en una atmósfera nubosa. Se encuentra una disminución de ésta, por fuera de la emisividad de las nubes, en las altas latitudes, al compararla con la divergencia en las latitudes medias y tropicales. Los datos sobre la dependencia de la emisividad de las nubes se expresan con su espesor óptico y nivel.

ABSTRACT

Radiative properties of stratiform clouds in different geographical conditions have been discussed using FGGE data. Characteristic features have been described, in particular, of the spectral and total radiative characteristics of clouds over urban and rural areas, Arctic ice, and water bodies depending on the optical thickness of clouds and sun elevation. The dependence of emissivity of clouds in high, middle and tropical latitudes on their thickness has been analyzed.

Variability of radiative properties of stratus clouds in different conditions requires further accumulation of observational data and a search for techniques for their parameterization to consider the interaction between clouds and radiation in numerical modeling of the general atmospheric circulation and climate.

The results of studies have shown that the total (full spectrum) albedo of clouds is somewhat less than the albedo in the visible, but within an accuracy of about 10 per cent they can be considered identical, which is essential for radiative energetics of the atmosphere. Low-level clouds are characterized by shortwave radiation absorption not only in the molecular absorption bands but also in the visible spectrum. The absorption-induced cloud warming is smaller, as a rule, than cooling due to radiative heat exchange, with the exception of clouds over large industrial areas, in the regions of forest fires, and clouds interacting with optically active aerosoles in the case of strong dust transport from deserts.

Cloud absorptivity over water, rural areas and ice does not exceed 0.05 . . . 0.15, but for optically thick clouds with $\tau > 30$ it may reach 0.20 . . . 0.30. The albedo of a cloudy atmosphere, A, over water bodies decreases with increased altitude, with a lapse rate of about 0.003 km^{-1}, and above the sea about 0.01 km^{-1}. At a sun elevation $h_{\odot} = 15 - 18^{o}$ the gradient $\Delta A/\Delta h_{\odot}$ changes its sign which is related to the effect of clouds macro-inhomogeneity at low sun elevations.

The results of comparing calculated data with observations of the evolution of advective fog and clouds over ice as well as complex sub-satellite experiments indicate the necessity of consideration of radiative heat flux divergence in a cloudy atmosphere. A decrease has been found of clouds emissivity in high latitudes as compared to that in middle and tropical latitudes. Data are given on the dependence of clouds emissivity on their thickness and level.

INTRODUCTION

Systematic studies of radiative properties of clouds have been carried out in the USSR during more than 30 years. The purpose of these studies in the first stage was the development of instruments and measurement techniques, in addition to obtaining and preliminary analysis of the observational data (Koptev and Voskresensky, 1960; Chapursky, 1966). Subsequent improvement of techniques and instruments has ensured accumulation of a reliable data base of radiative properties of clouds depending on their thickness, water content, sun elevation, and surface albedo, which has made it possible to substantiate a model of an average stratus cloud (Goissa, 1968; Goissa and Shoshin, 1974; Cheltsov, 1952). A third stage was marked by complex studies of clouds not only stratus (Binenko and Piatovskaya, 1982; Kondratyev and Binenko, 1981), but also cumulus (Kondratyev *et al.*, 1981; Goissa and Corb, 1974; Feigelson, 1981) and cirrus (Kondratyev and Binenko, 1981; Kondratyev and Ter-Markaryants, 1976) clouds. The processes were studied which determine the urban impact on radiative properties of extended cloudiness (Kondratyev *et al.*, 1981), and transformation of stratus clouds over the Arctic ice (Buikov *et al.*, 1981) as a result of dynamics-radiation interaction.

The present paper discusses some results from the third stage of studies carried out within the CAENEX (Kondratyev and Ter-Markaryants, 1976), GAAREX (Kondratyev *et al.*, 1980), and FGGE (Kondratyev and Binenko, 1981) programs.

The basic means of observations was, as a rule, two flying laboratories, IL-18 and IL-14, the first measured spectral and total radiances, and the second observed micro- and macroparameters of clouds, aerosols, condensation nuclei, and the chemical composition of cloud liquid water.

In some cases one succeeded in making complex sub-satellite observations at the locations where ground-truth measurements were also possible (for instance, over the region of the drifting station Severny Polyus-22, SP-22). Total radiative characteristics of clouds (reflectivity, R, transmissivity, T, absorptivity, A) were estimated from measurements of hemispherical shortwave (SW) radiation fluxes and used, first of all, to study the radiative energetics of clouds.

Cloud emissivity, ε, is an important radiative characteristic of the longwave (LW) radiation transfer in the atmosphere. With scattering on cloud particles neglected, the value of in a wavelength interval, $\Delta\lambda$, can be estimated from measurements of LW radiation fluxes $F\downarrow\uparrow$ and is called flux emissivity, and in the case of the emission measured within small solid angles - directed emissivity. The thermal emission measured with airborne pyrgeometers and IR radiometers near the top (H_{top}) and bottom (H_{bott}) of clouds, as well as the temperature data obtained with thermohygrometers made it possible to estimate the upward and downward emission fluxes, $F_{\Delta\lambda}\downarrow\uparrow$ as well as the blackbody emission, $B_{\Delta\lambda}$, for the temperature of the cloud layer boundaries, and then to calculate the cloud emissivity.

RADIATIVE CHARACTERISTICS OF CLOUDS

Analysis of spectral measurements of the angular distribution on the radiation reflected by clouds has shown that reflectivities are characterized by a strong anisotropic distribution, especially in the solar vertical plane. The anisotropy is most pronounced for specular reflection angles toward horizon at low sun elevations. As the wavelength increases, the reflectivity phase function becomes more elongated (outside the molecular absorption bands). Molecular absorption reduces reflection anisotropy as compared to anisotropy at adjacent wavelengths outside the absorption bands for oxygen and water vapour. Multiple scattering in the visible spectrum smoothes the angular distribution of the light reflected from clouds (Kondratyev *et al.*, 1981; Kondratyev and Ter-Markaryants, 1976). This conclusion is confirmed by aircraft photometry of effective path lengths of photons, ℓ_{eff}, for reflection and transmission, varying from 0.2 . . . 0.5 km to 10 . . . 15 km, and depending strongly on clouds' macro-structure and surface albedo (Grechko *et al.*, 1975). The path length reaches a maximum in multi-layered cloud systems of great optical thickness and a minimum in thin cloud layers over sea surface.

The specific character of macrostructure and scattering in clouds over the sea (larger droplets, smaller number concentration, greater water content and optical thickness), as compared to clouds over land (smaller contribution from reflection from the surface), determines non-selectivity of the albedo, R_λ, transmission, T_λ, and absorptivity, A_λ in the visible spectrum, a slight decrease in R_λ in the 0.35 – 0.4 μm interval, and wavelength dependence in the molecular absorption bands in the IR spectrum. The same spectral dependence of R_λ, T_λ, A_λ is typical of clouds (with $\tau > 15$) over land and ice. Some decrease in R_λ of ice crystal cirrus clouds with increased wavelength is connected with stronger scattering on large ice particles, fewer number of scattering centers, smaller optical thickness of clouds ($\sim 1 \div 2$), and with the effect of the underlying atmospheric layer and the surface. Laboratory measurements of the attenuation coefficient in the wavelength region 0.63 - 4.5 μm for plate-crystals 20 μm by 30 μm, and columns 30 μm by 100 μm have shown that its spectral dependence is of slightly oscillating character, except for a narrow band centered at 2.8 μm, where attenuation decreases sharply (Dugin *et al.*, 1976). The values of the backscattering coefficient, $\rho\pi$, of crystal cirrostratus (Cs) clouds (from lidar measurments at $\lambda_1 = 0.53$ μm and $\lambda_2 = 1.06$ μm) varies within 10^{-2} and 10^{-1} $km^{-1}sr^{-1}$($\lambda = 0.53$ μm). The ratio $\alpha = \rho\pi\lambda_1/\rho\pi\lambda_2$, being a sensitive indicator of variations in scattering particles' size distribution (for instance, in the case of transition from cloud droplets to larger crystal-type scattering particles), decrease in the case of crystal clouds down to 0.9 - 1.4 for Cs clouds (Kondratyev and Binenko, 1981). The crystal-cloud albedo is small, as a rule, constituting 0.10 . . . 0.30 (except for the ITCZ, where A can reach 0.7 (Welch and Davis, 1980).

Current total and spectral irradiance measurements indicate a relationship between the total and spectral albedo of clouds (Binenko, 1980). The total cloud albedo is somewhat below the albedo in the visible, but with an accuracy of about 10 per cent they can be considered identical, which is essential for radiative energetics of the atmosphere.

The most important factors determining the cloud albedo are their optical thickness, τ, particle size distribution and phase state, sun elevation (especially, in the 10^o - 40^o interval) as well as surface albedo (for optically thin clouds, $\tau<10$).

The absorption of SW radiation by clouds is well pronounced: at optical thickness 20 and greater a cloud absorbs about 10 per cent of the incident radiation. Even in the visible spectrum the absorptivity (intensified by multiple scattering) can reach 5 per cent and more, especially if there is an optically active aerosol substance in the cloud (Kondratyev and Binenko, 1981; Griffith and Knollenberg, 1980).

Low level clouds are characterized by the presence in their upper part of the zone of active absorption of SW radiation, with maximum radiative heating due to absorption in the H_2O bands ψ, Ω, χ, which, as a rule, is compensated for by LW radiation-induced cooling, the contribution to radiative cooling in the 8 - 12 μm transparency window reaching 90 - 95 per cent (Kondratyev and Binenko, 1981; Khvorostyanov, 1981). The inner part of the cloud is characterized by radiative equilibrium, and weak radiative heating due to both solar and LW radiation is observed near the clouds' bottom. On the whole, as a result of radiative heat exchange an average cloud is subject to radiative cooling even at high sun elevations. Radiation measurements during CAENEX and GATE have confirmed these conclusions.

Complex studies of sub-inversion stratiform clouds under urban (Zaporozhye-Donetsk) and non-urban conditions have made it possible to analyze basic differences between polluted and relatively pure clouds over rural areas (Kondratyev *et al.,* 1981). The results of chemical analysis of the urban cloud water have shown its high mineral content, a decrease in pollutants concentration in cloud water with altitude of its sampling. Analysis of soluble admixtures revealed the presence of $(NH_4)_2SO_4$, $CaSO_4$, and sulphuric acid. The cloud-water samples under investigation were of dark coloration, and, together with high concentration of soluble admixtures, they contained an abundance of unsoluble soot particles. The contribution of organic substances containing carbon compounds is rather substantial, reaching 30 - 50 per cent of the mass of an unsoluble sediment. The spectroscopic and neutron-activation analysis of the unsoluble sediment revealed the presence of iron, zink, chromium with mass concentrations about 1400, 900, and 400 mg/m^3, respectively, as well as silicon, copper and aluminium. The mineralization level and concentration of organic matter in rural clouds is 2.3 times less than in urban clouds.

The number density of Aitken nuclei under cloudy weather conditions was 3-7 times less than in clear-sky weather, when it varied within $(3\text{-}21)\cdot 10^4$ cm^{-3}, and decreased toward the cloud bottom. The size spectrum of aerosol particles was close to log-normal, and showed itself as bimodal.

The effect of hygroscopic admixtures and higher concentration of condensation nuclei in urban clouds increase the concentration and enlarge the fraction of smaller cloud droplets (as compared to rural clouds with the same liquid water content) and should have intensified the reflection and decreased the transmission and absorptivity of urban clouds. But, as seen from Table 1, due to the presence of absorbing polluting particles (soot, iron oxides), the absorption grows, and the albedo decreases. Therefore, it turns out that the role of pollutants is dominant as compared to the contribution of small-sized droplets, in the case of sufficiently thick clouds, with $\tau > 16$. The difference between the cloud albedo over the city, R_c, and outside it, R_T, varied from 0.08 to 0.14 depending on the optical thickness of clouds.

Figure 1 illustrates a comparison of measurements and calculations of the absorptivity of stratiform clouds depending on relative optical thickness of the cloud (Kondratyev and Binenko, 1981). A normalization was made with regard to mean optical thickness $\tau_{av} = 23$. Curve 1 includes aerosol absorption in the cloud, curve 2 includes only water vapour and 'dirty' water absorption in the 0.3 - 2.5 μm wavelength region at $\cos\Theta_0 = 0.5$ (Θ_0 is the solar zenith angle). Fig. 1 also contains the results of pyranometric measurements (3); the data for clouds over the sea (Kondratyev and Ter-Markaryants, 1976) obtained during CAENEX in 1971/ 72, the data for Zaporozhye in 1978 (4), as well as the results of simultaneous measurements of hemispherical SW radiation at $\lambda = 0.5$ μm (6,7).

As is seen, the measured absorptivity of clouds over the sea at $\lambda = 0.5$ μm is comparable to molecular absorption (curve 2); the integral data (3,5) agree better with the calculations considering aerosol absorption in the case of thinner clouds, but these measurements have not been accompanied by aerosol measurements. Total (4) and spectral (7) observational data on absorption in the cloud-aerosol layers agree qualitatively with calculations (curve 1) (Grassl, 1976; Twomey, 1976). The differences are largely caused by rough determination of the absorptivity, and

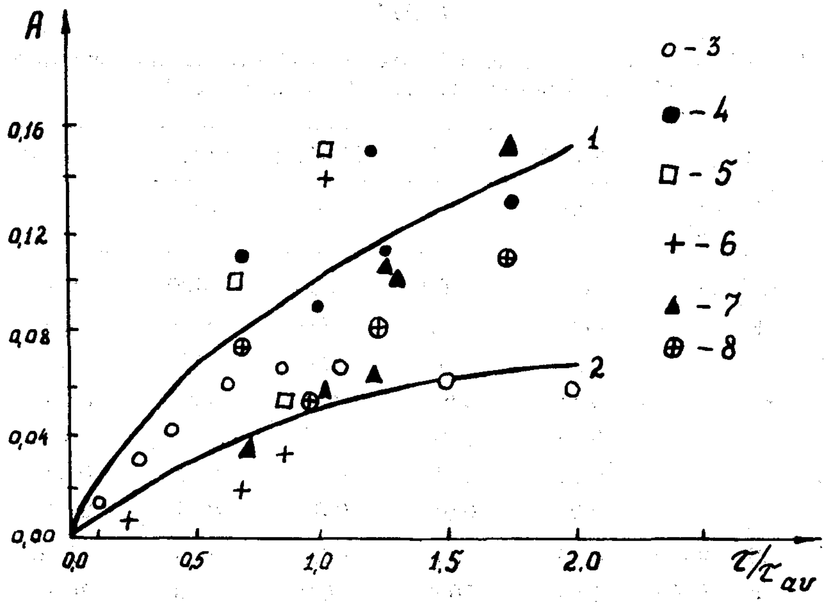
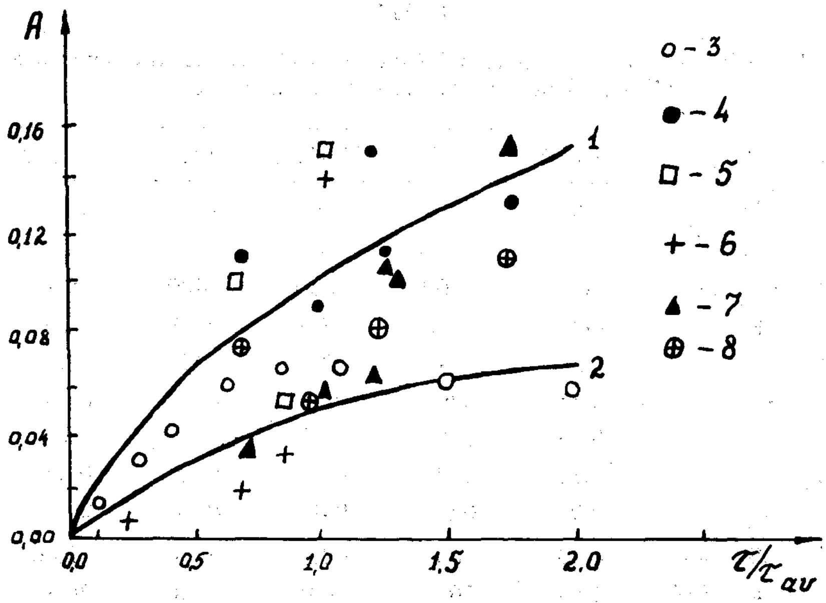


Fig. 1. The dependence of absorptivity, A, on relative optical thickness of clouds τ/τ_{av} (τ_{av} = 23).
1 - calculations including aerosol absorption;
2 - including molecular total absorption in a cloud;
3 - observational data on the total A according to (Goissa, 1968; Goissa and Shoshin, 1969);
4 - pyranometric data over the urban area (the last two right-hand side values are higher by a factor of 2 than is shown in the Figure);
5 - observed data;
6 - observations at 0.5 μm (over the Black Sea);
7 - observations at 0.5 μm (over the urban area);
8 - actinometric data outside the urban area.

different initial data used in the calculations as compared to observational conditions. The aerosol absorption in clouds in the visible spectrum varied from 0.05 to 0.11 and was less than that in the 0.3 - 3.0 μm wavelength region. The value of the imaginary part of the complex index of refraction for aerosol particles over Zaporozhye was about 0.03, which explains the rather strong absorption in the visible spectrum.

Measurements of SW and LW irradiances enabled one to calculate the radiative heat flux divergence and the rate of radiative temperature change for the entire cloud layer. Radiative cooling of the whole cloud in a polluted zone can be followed by heating of the same cloud over the city (Table 1).



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The dependence of the albedo and absorptivity of clouds on their optical thickness under different conditions (varying surface albedo, sun elevation) is shown in Fig. 2. The albedo of stratiform clouds over the ice (curve 1) at low sun elevations is greater than over the land (2), rural area (3), city (3'), and water (4). The albedo of water surface was 0.04, rural area 0.13, city 0.20, and ice 0.70. The surface albedo decreases with increased optical thickness of the cloud. Knowledge of the mean values of the attenuation coefficient $\bar{\gamma}$ (km^{-1}) and geometrical thickness of stratiform clouds in different geographical regions (Buikov *et al.*, 1981) permits the optical thickness $\tau = \bar{\gamma}\Delta H$ and radiative characteristics of cloud to be estimated.

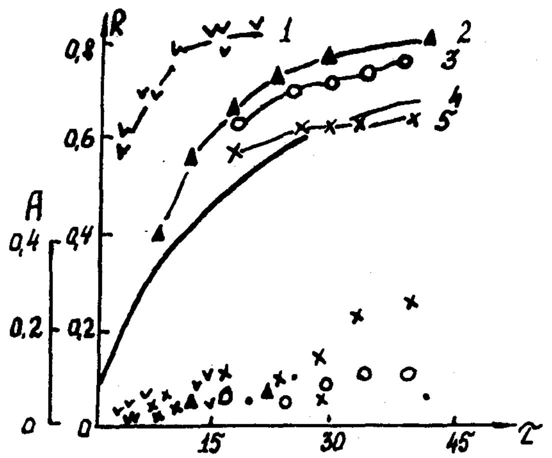

Fig. 2. The dependence of albedo, R, and absorptivity, A, of stratus clouds on their optical thickness, τ.

1 - over ice at $h_{\odot} = 32^{\circ}$;
2 - over land at $h_{\odot} = 50^{\circ}$ (Goissa and Shoshin, 1969);
3 and 3' - over suburban and urban areas, respectively (Kondratyev *et al.*, 1981);
4 - over water bodies at $h_{\odot} = 50^{\circ}$ (Kondratyev and Ter-Markaryants, 1976).
Asterix (5) indicates R and A of clouds in the presence of fumarole plume in the region of the Aldair volcano-island.

From CAENEX and GATE measurements the albedo of average stratiform clouds ($\Delta H \sim 400$ m) increases slightly at sun elevations decreasing from 90^o to 50^o, the gradient $\Delta A/\Delta h_\odot$ not exceeding 0.001 deg^{-1} in the region $h_\odot = 50^o \ldots 20^o$, and 0.002 deg^{-1} (Kondratyev *et al.*, 1981; Feigelson, 1981) at $h_\odot < 20 \ldots 15^o$. In the Arctic, the cloud albedo decreases due to a macro-inhomogeneous cloud top surface (other things being equal).

Thus, the absorptivity of stratiform clouds is maximum over the city, which is connected with the effect of an optically active hydrophobic aerosol (soot, iron oxides) whose contribution to absorption is greater than the effect of hygroscopic inactive particles. Cloud absorptivity over water bodies, rural areas and ice does not exceed 0.05 - 0.10. Radiative heating of clouds due to SW radiation is, as a rule, less than LW cooling. An exception is with clouds over large industrial cities, regions of forest fires and clouds interacting with optically active aerosols due to strong dust transport from deserts. On an average, absorptivity of such polluted clouds with $\tau > 30$ does not exceed 0.20 - 0.30 (with a relative error of 50 per cent in estimating A).

RADIATIVE CHARACTERISTICS OF THE SURFACE-ATMOSPHERE SYSTEM

Figure 3 shows the vertical profiles of the surface-atmosphere system albedo for different conditions, in clear-sky and cloudy weather. For weakly-reflecting surfaces the albedo increases with increased altitude, particularly in the presence of atmospheric haze or atmospheric aerosol layers. The system albedo over Sea of Okhotsk increases with height, z, in the 0.2 ... 8.4 km layer with a gradient $\Delta R/\Delta z = 0.004$ km^{-1} at $h_\odot \sim 42^o$, and in the presence of thin haze over the Chuckchee Sea at $h_\odot \sim 35^o$ $\Delta R/\Delta z \sim 0.006$ km^{-1}. From observations during CAENEX over the Azov Sea at $h_\odot \sim 38^o$ and in the presence of aerosol layers $\Delta R/\Delta z \sim 0.006$ km^{-1}, and over the Atlantic Ocean at $h_\odot \sim 80^o$, in the clear-sky weather $\Delta R/\Delta z \sim 0.009$ km^{-1}, while with dust transported from the Sahara it is about 0.037 km^{-1}.

The surface-atmosphere system albedo over strongly reflecting surfaces, such as ice and cloudiness, especially sharply decreases with height in the 200 ... 500 m layer, near the surface. For instance, the ice albedo, from the SP-22 data, was 0.77-0.79, and at the 200 m altitude it decreased to 0.70 - 0.72, with an albedo gradient $\Delta R/\Delta z \sim 0.01$ km^{-1} over the ice in the 0.2 ... 8.4 km interval. The system albedo in a cloudy atmosphere over water bodies decreases with a gradient $\Delta R/\Delta z \sim 0.003$ km^{-1}. In the presence of an aerosol layer or haze the vertical change of the system albedo can be more complicated.

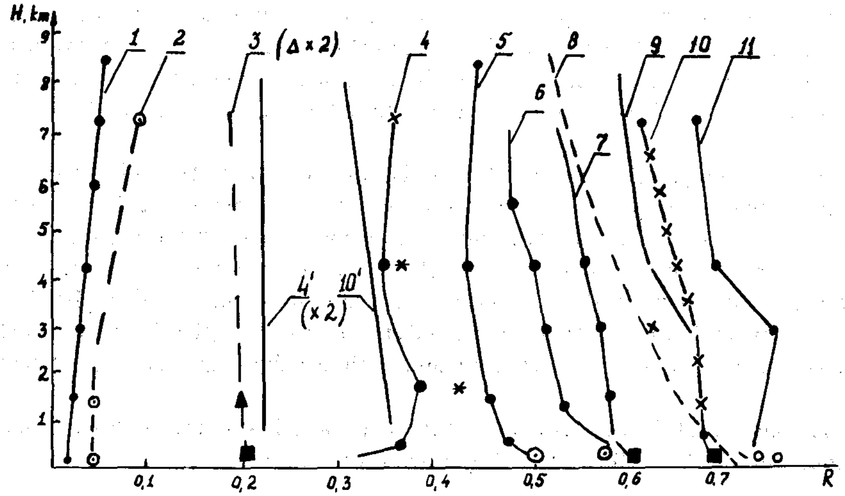

Fig. 3. Vertical profiles of the surface-atmosphere system albedo (Kondratyev and Binenko, 1981).

1 - water surface of Sea of Okhotsk at $h_\odot=42^\circ$ (May 28, 1979);

2 and 3 - water and ice 0.7 - 0.8 concentration in the Chuckchee Sea at $h_\odot= 35^\circ$(June5, 1979);

4 - fog, ΔH = 200 m, and the fumarole plume above it (*) at $h_\odot= 44^\circ$(May 28, 1979);

4' and 10' - stratus clouds over water and ice at $h_\odot=30^\circ$;

5 and 6 - drifting melting ice 0.8 - 0.9 concentration at $h_\odot=36^\circ$(June 4, 1979), and 0.9 - 1.0 at $h_\odot=32^\circ$ (June 2, 1979);

7 - stratocumulus cloudiness at ΔH=200 m at $h_\odot=30^\circ$ over pack ice;

8 - stratus, ΔH = 300 m, and straticirrus, ΔH = 800 m clouds at $h_\odot = 30^\circ$ over pack ice (June 9, 1979);

9 - stratus cloud, ΔH = 250 m at $h_\odot=34^\circ$ over SP-22 (glacier ice, June 7, 1979);

10 - stratus cloud, ΔH = 200 m (Ac, 0.8) at $h_\odot=24^\circ$ over SP-22 (glacier ice, June 2, 1979);

11 - glacier ice (SP-22), stratus cloud, ΔH = 250 m (As, 0.9, ΔH = 500 m) at $h_\odot= 34^\circ$ (June 1-2, 1979).

A square marks the ice albedo from the 200 m height.

Albedo values for curves 3, 4' and 10' have to be multiplied by 2.

It is seen from comparison of the cloud albedos at a 1 km level over the water and ice (curves 4 and 9, 4' and 10', Fig. 3) that an increase of cloud albedo (at similar $h_\odot$ and τ) due to increasing surface albedo (from 0.05 to 0.80) can reach 0.3. The contrast between stratiform cloud albedos over the water and over the ice is related to differences in the surface albedo, the droplets size distribution, the clouds' phase state, and the ratio between liquid and solid phases of the cloud particles.

The role of the phase composition of arctic clouds is more substantial for middle and upper clouds. The presence of crystals in clouds leads to stronger forward scattering, which causes a decrease in the albedo of one-layer clouds: Ac and As (0.5 - 0.65); Cs (0.15 - 0.30) over water as compared to lower clouds (0.5 - 0.7).

In the tropics (within the ITCZ), crystal cirrus clouds can play an important role in the radiative energetics of the atmosphere. Their microstructure determines optically thicker crystal clouds as compared to similar clouds in the European USSR territory and in the Arctic (Kosarev *et al.*, 1978). At the same time, lower concentrations of cloud particles, prevalence of crystals and supercooled droplets in the Arctic apparently cause a decrease in cloud emissivity ($\varepsilon < 1$) (the thinner and higher the clouds, the lower decrease), as compared to similar clouds in the tropical Atlantic.

The albedo of Ac and As clouds over the ice and lower stratus clouds layer is, respectively, 0.60 . . . 0.76; 0.52 (Fig. 3, curves 10, 11, 9).

One of the purposes of complex studies of clouds in the Arctic was a study of the dynamics of formation and development of fog and clouds during a polar day over the SP-22, as well as comparison of calculated and observed characteristics of advective fog and stratus clouds over the ice (Buikov *et al.*, 1981). Analysis of the results obtained revealed different macroparameters of the calculated and observed clouds. Namely, an actual transition from clear-sky weather to clouds takes more time than is indicated from numerical experiments and is characterized by a slower increase in the geometrical thickness of the cloud whose life-time may reach 3 days.

The results of comparing the observed and calculated radiation fluxes in the presence of advective fog and stratus clouds revealed their quantitative agreement (within the limits of the uncertainty in estimation of radiative characteristics). In the course of transformation of clear-sky weather and formation of fog and stratus clouds, the rate of radiative temperature change increases due to both SW and LW radiation. But the contribution from cooling in the atmospheric cloud layer prevails in the total rate of radiative temperature change. In this connection, the role of different heat flux divergences is of great interest in the dynamics of lower stratus clouds development.

In the initial stage of cloud formation, the LW cooling and the downward eddy heat flux due to the temperature inversion is compensated for by latent heat flux and solar heating by 30-40 per cent, and the total rate of cooling is 1 - 3^{o}C/hr. As the cloud matures and the sun elevation increases, the temperature stratification changes leading to a change of sign of the sensible heat flux divergence. The latter, together with the latent heat released and increased solar heat flux convergence, overcompensates the LW cooling. Therefore, the total rate of temperature lowering decreases by an order of magnitude and is 0.1 - 0.3°C/hr. Temperature changes due to advection and vertical motions are of the similar order of magnitude. Thus, both calculations and observations reveal the possibility of a quasi-stationary existence of low-level clouds determined by compensation of LW cooling by heat release due to phase transitions and solar heating.

Complex sub-satellite experiments on simultaneous vertical sounding of the atmosphere in the region of the drifting SP-22 station from the IL-18 flying laboratory during a pass of a meteorological satellite (MS) permitted the dependence of the ice-atmosphere system albedo on sun elevation to be analyzed (Binenko and Pyatovskaya, 1982). Figure 4 shows the respective dependences for stratus clouds with geometrical thickness $\Delta H \sim 300$-500 m (1) (aircraft data); for cloudy (2) and cloud-free (3) conditions (MS data); as well as for ice (4) from the 200 m height and from SP-22 (5). In the case of strongly reflecting surfaces, such as ice and clouds, the sign of the gradient $\Delta R/\Delta h_{\odot}$ changes within $h_{\odot} \sim 15 \ldots 20^{\circ}$ (from aircraft data) and $h_{\odot} \sim 25 \ldots 30^{\circ}$ (from satellite data).

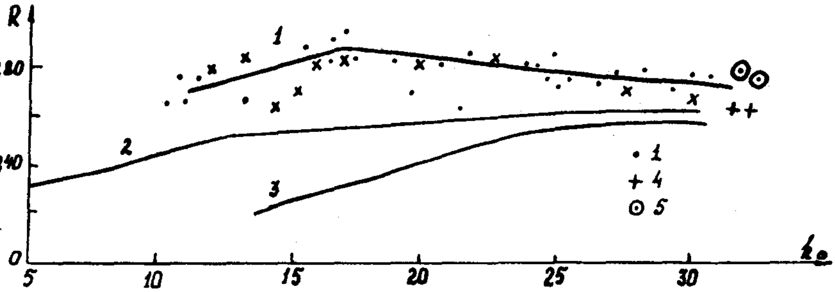

Fig. 4. The dependence of the albedo of clouds (1) and ice-atmosphere-cloud (2) and ice-atmosphere (3) systems on Sun elevation, $h_{\odot}$(4 - ice from the 200 m height, 5 - from SP-22 observations).

Table 2a lists the averaged data on the rate of radiative temperature change $\partial T/\partial t$ for the SW and LW radiation in the Arctic in the presence of clouds over ice, and water in clear-sky weather for different atmospheric layers.

In Arctic conditions $\partial T/\partial t$ depends substantially on sun elevation (Table 2b). At low sun elevations, radiative cooling down to 0.04 ... 0.05°C/hr due to LW radiation is observed, and at $h_{\odot} \sim 35^{\circ} \ldots 45^{\circ}$ radiative warming up to 0.04 ... 0.05°C/hr occurs due to SW-radiation absorption.

Tabla 2

The Rate of Radiative Temperature Change, —, in Different Atmospheric Layers (a) and for the Whole Atmosphere Depending on Sun Elevation, $h_\odot$(b)

Table 2a

ΔH, Km	Ice + St, Sc		Water + O^2	
	$\frac{\partial T}{\partial t}$ SW	$\frac{\partial T}{\partial t}$ LW	$\frac{\partial T}{\partial t}$ SW	$\frac{\partial T}{\partial t}$ LW
0 – 2	0.2	–0.7	0.15	–0.14
2 – 8	0.03	–0.07	0.03	–0.04
8 – 300	0.04	–0.02	0.03	–0.01
0 – 300	0.045	–0.07	0.07	–0.04

Table 2b

$h_\odot$	$\frac{\partial T}{\partial t}$ SW	$\frac{\partial T}{\partial t}$ LW	$\frac{\partial T}{\partial t}$ NET
14 – 25°	0.04	–0.05	–0.01
25 – 35°	0.07	–0.05	0.02
35 – 45°	0.10	–0.07	0.03

EMISSIVITY OF CLOUDS

During the 1971-1979 period in accomplishing the CAENEX, GATE, POLEX, GAAREX, FGGE programmes, an extensive data base has been accumulated, with the IL-18 flying laboratory, on the thermal emission of clouds from pyrgeometric measurements of hemispherical LW radiation fluxes and directed upward emission in the 10-12 μm wavelength region.

During airborne soundings, measurements were made near cloud layer boundaries (at a distance of 10 - 50 m) and cloud thicknesses were then estimated. This enabled one to plot the dependence of cloud emissivity at lower (1), middle (2) and upper (3) levels, in different geographical zones, polar ("), middle (') and equatorial (1, 2, 3) latitudes, on the geometrical thickness of clouds (Fig. 5).

St, Sc, Ns clouds were grouped as low level clouds, As, Ac ($Cu_{cong.}$ in the GATE area) as middle level clouds, and Ci, Cs as upper level clouds.

Figure 5 shows the data on directed emissivity of clouds, rms deviations (vertical lines) of which give an idea of the data scattering relative to each averaged curve. An error in estimation of the flux emissivity is greater than that in calculating the directed emissivity and, as a rule, its values are higher than those of directed emissivity (within 10 per cent).

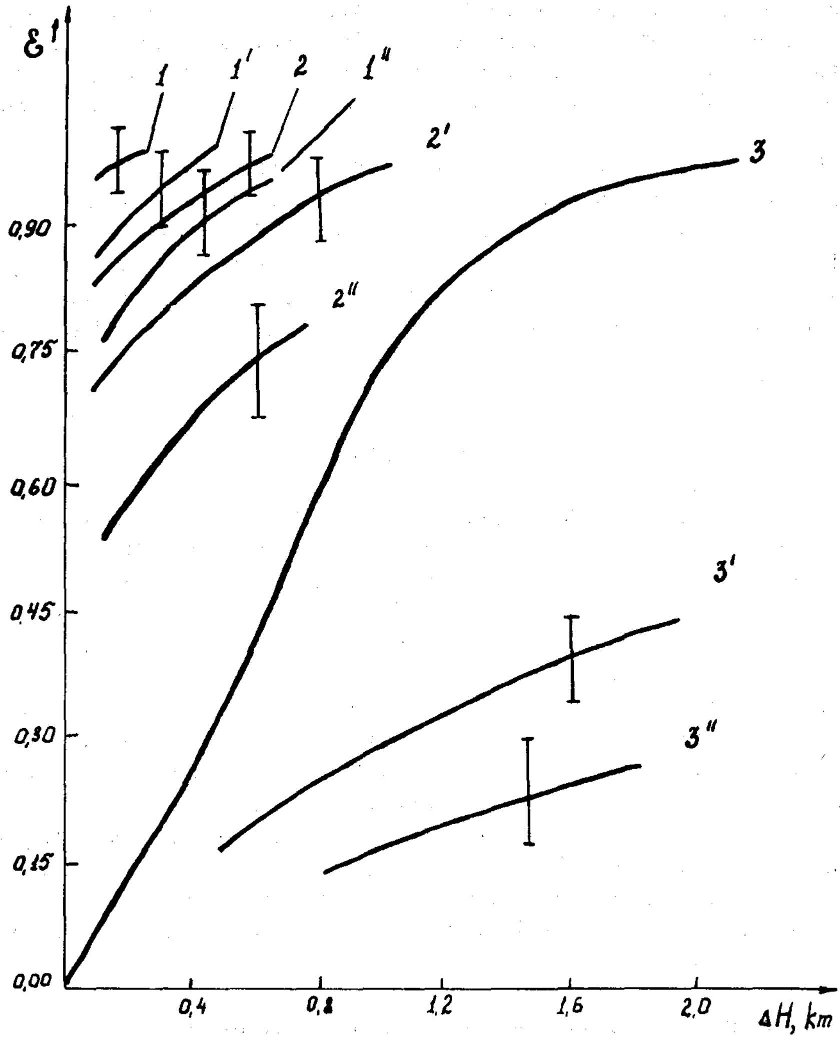

Fig. 5. The dependence of directed emissivity of clouds, ε↑, of low (1), middle (2) and upper (3) levels in different geographical regions - in high (1", 2", 3"), middle (1', 2', 3') and tropical (1, 2, 3) latitudes of geometrical thickness of clouds, ΔH.

Characteristic features of the data in Fig. 5 are as follows: (i) an increase in directed emissivity, $\varepsilon\uparrow$ with increased cloud thickness; (ii) a decrease in $\varepsilon\uparrow$ with increased height of the cloud layer; (iii) lower emissivity of high-latitude clouds as compared to similar clouds in middle and tropical latitudes. So, for instance, the emissivity of the Arctic clouds changed from 0.75 to 0.95 (for characteristic thicknesses of St, Sc clouds; from 0.45 to 0.70 for As, Ac, and for Ci, Cs within 0.10 - 0.35 (Kondratyev and Binenko, 1981). At the same time, crystal clouds in the GATE tropical area, according to (Kosarev *et al.*, 1978), are characterized by much higher values of $\varepsilon\uparrow$ as compared to similar clouds in middle and high latitudes. With the geometrical thickness ~2 km, $\varepsilon\uparrow \sim 1$ i.e. in this case a cloud emits as a blackbody.

The differences observed in emissivities of clouds of the same type and thickness are, apparently, connected with different liquid water content, specific character of their microphysical and optical parameters (Feigelson, 1981; Kosarev *et al.*, 1978; Paltridge and Platt, 1981). A wide range of cloud emissivity variations points to strong variability of LW radiation fluxes in a cloudy atmosphere and to the fact that IR optical properties of clouds contribute much to their role as an ERB modulator.

CONCLUSION

The results of our studies have shown that the total albedo of clouds is somewhat less than the albedo in the visible. But with an accuracy of about 10 per cent they can be considered identical, which is essential for radiative energetics of the atmosphere. Low-level clouds are characterized by SW radiation absorption not only in the molecular absorption bands but also in the visible spectrum. The absorption-induced cloud warming is smaller, as a rule, than cooling due to radiative heat exchange, with the exception of clouds over large industrial areas, in regions of forest fires, and clouds interacting with optically active aerosols associated with strong dust transport from deserts. Cloud absorptivity over water, rural areas and ice does not exceed 0.05 . . . 0.15, but for optically thick clouds with $\tau > 30$ it may reach 0.20 . . . 0.30. The albedo of a cloudy atmosphere, R, over water bodies decreases with increased altitude, with a lapse rate of about 0.003 km^{-1}, and above the sea, about 0.01 km^{-1}. At the sun elevation $h_{\odot} = 15 - 18^{o}$ the gradient $\Delta R/\Delta h_{\odot}$ changes its sign, which is connected with the effect of the clouds' macro-inhomogeneity at low sun elevations.

The results of comparing calculated data with observations of the evolution of advective fog and clouds over ice, as well as complex sub-satellite experiments, indicate the necessity of consideration of radiative heat flux divergence in a cloudy atmosphere (radiation-cloudiness interaction).

Variability of radiative properties of stratus clouds under different conditions requires further accumulation of observational data and a search for techniques for their parameterization to consider the interaction between clouds and radiation in numerical modeling of the general atmospheric circulation and climate.

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