# PROGRESS IN ATMOSPHERIC OPTICS AND MONITORING OF THE PHYSICAL STATE OF THE ATMOSPHERE

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*Retrospective review of the results of research in atmospheric optics is presented including the spectral transmittance of the atmosphere, the patterns of transfer of optical radiation and image through scattering media, and the refraction of light in the Earth's atmosphere. Advances in experimental procedure and optical technology are discussed as well as the prospects for their application to integrated climatic–ecological monitoring. Results of processing of homogeneous series of observations on the individual climatic–ecological parameters of the atmosphere are given.*

## INTRODUCTION

Atmospheric optics gave the bulk of the evidence of forming an independent branch of exact science (physics) in the first half of the present century. It was then that advances in interdisciplinary branches of exact sciences lent impetus to a transition from basically qualitative description of atmospheric–optical phenomena to their quantitative analysis. Attempts were made to apply the powerful mathematical apparatus of radiative transfer theory to a description of optical phenomena associated with the radiation regime of the atmosphere.[1] Approaches were developed to describe quantitatively the absorption functions of atmospheric gases.[1,2] The use of exact theory of light scattering by spherical particles (Mie theory[3]) for a description of optical wave scattering by atmospheric aerosol provides physically well grounded quantitative approach to the interpretation of such atmospheric optical phenomena as spectral dependence of the transmittance of atmospheric haze, fog, and clouds; spectral patterns of rainbow and glory; polarization effects due to scattering.[4–6] Over these years similar attempts have been made in other areas of atmospheric optics.

Atmospheric optics has made the greatest progress in the last few decades due to increasing practical application of opto–electronic and laser technology intended to operate in the atmosphere and beyond it. The experimental technology in atmospheric optics is correspondingly updated, quickly excluding visual observations and optical devices of older generation. Progress in computing machinery and computerization of scientific investigations have opened up new opportunities for mathematical and physical modeling of atmospheric–optical processes and phenomena.

The above–mentioned opportunities along with some other new opportunities were most effectively employed by the scientific staff of the Joint Institute of Atmospheric Optics of the Siberian Branch of the RAS established in 1969 and headed by Academician V.E. Zuev. Results of investigations performed by this scientific team, most powerful in Russia among those engaged in atmospheric optics, were summarized in a unique collection of monographs on the current problems in atmospheric optics[7] as well as in many other monographs by V.E. Zuev and his scholars, to which I also belong.

In recent years the environmental effect of man's economic and industrial activities has brought the threat to life and concerns not only some countries and regions but also the whole world community about its hazards. As a consequence of this concern, various regional, national, and international programs for monitoring of different environmental components, over which the Earth's atmosphere (atmospheric air) takes priority, have been set up. Such studies are recognized to be very urgent for survival and stable development of the whole of civilization.[8] Atmospheric optics bears a direct relation to the solution of such urgent problems for the reasons of not only high potential of atmospheric–optical techniques for efficient monitoring of essentially all atmospheric parameters, but also of a wide arsenal of opto–electronic means of monitoring, among which means of laser remote sensing occupy a special position.[9]

The present review deals with some fundamental results of investigations on atmospheric optics obtained with my participation in the last few decades. The objective of this review is not so much to illustrate the results themselves as to show promise of technical means, developed in the process of data retrieval, for integrated atmospheric monitoring.

Drawing up of the program on such monitoring is now terminating under my supervision as part of Interdepartmental Project on Climatic–Ecological Monitoring of Siberia, whose brief description is also given in the review.

## SOME FUNDAMENTAL RESULTS OF ATMOSPHERIC–OPTICAL RESEARCH

The fundamental results of atmospheric–optical research obtained in the last few decades, including the results obtained with my participation, are interesting from two viewpoints. First, the investigations performed over a period of many years provided a new knowledge of unknown patterns of interaction of optical radiation with the constituents of the Earth's atmosphere and of its optical–physical properties. Second, such studies generally employ ingenious methods and devices under field conditions, has undergone the long–standing tests, and has been updated to the point of being able to obtain homogeneous series of observations. These new scientific results significantly increase the importance of the methods

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and advances in atmospheric optics for the solution of current problems in atmospheric physics.

## 1. Spectral atmospheric transmission

Molecular absorption by atmospheric gases and aerosol extinction make primary contribution to the spectral atmospheric transmission. In the last few decades, when lasers have been increasingly employed, the studies of the first component have been concentrated on the problems of spectroscopy of high and superhigh resolution.[10] These laser applications provide new knowledge and new methods for atmospheric gas monitoring. A path laser gas analyzer for atmospheric gaseous pollutant monitoring by differential absorption technique is an example of recent developments completed at the IAO of the SB of the RAS. The vigorous scientific supervision of Academician V.E. Zuev over the studies of atmospheric transmission associated with molecular absorption has predetermined the acquisition of the above–indicated and many other important scientific results on spectroscopy of the atmosphere. At the same time, I focused my attention on spectral transmission associated with aerosol extinction.

One fundamental result of long–standing experimental studies of atmospheric transmission is the spectral dependence of aerosol extinction coefficients in atmospheric haze. The atmospheric haze is understood as such atmospheric–optical situation in the ground layer of the atmosphere for which the meteorological visibility range $S_m = 3.9/\kappa$ exceeds 1 km, where $\kappa$ is the aerosol extinction coefficient at the wavelength $\lambda = 0.55$ μm. Such situations are typical of the real atmosphere and are encounted in more than 90 per cent of time in most geographical regions.

Typical result of statistical measurements in continental atmospheric haze are depicted in Fig. 1. High selectivity of aerosol extinction coefficient $\kappa(\lambda)$ in the wavelength range 0.4–2 μm and less pronounced wavelength behavior between 2 and 12 μm are characteristic of coastal (Crimea), arid (Balkhash), and continental (Tomsk) atmospheric haze. Also shown in Fig. 1 by dashed lines is the spectral dependence of the aerosol extinction coefficients calculated from the measurements of the fraction of dry aerosol particles with radii between 0.3 and 4 μm. As is evident from the figure, optical measurement data (measurements) and microphysical data (calculations) agree well in the 2–5 μm wavelength range. The marked difference between the two data sets in short–wave (<2 μm) and long–wave (>5 μm) regions is reasonably explained by neglect of small (<0.3 μm) and large (>4 μm) particles, respectively, in calculations.

An analysis of optical and microphysical measurement statistics shows that the spectral transmittance of atmospheric haze in the short–wave region ($\lambda$<2 μm) is governed by the submicron aerosol fraction, and in the long–wave region – by coarsely dispersed fraction which exists sufficiently independently of the submicron one, has a different chemical composition, and responds in a different way to environmental changes. Thus to analyze the optical properties of atmospheric haze over a wide spectral range it is insufficient to classify them under types by the optical parameters in the visible range (e.g., by meteorological visibility data), because at least in the infrared long–wave range the nature of aerosol extinction proves to be quite dissimilar.

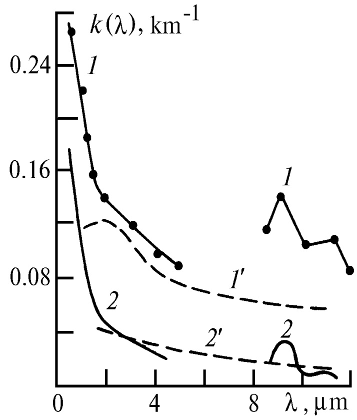


*FIG. 1. Spectral dependence of aerosol extinction coefficients for atmospheric haze: 1 and 2) measurements, 1′ and 2′) calculations.*

Another important result of experimental studies of the spectral atmospheric aerosol transmittance is the advent of unique multiwavelength spectrophotometers for 0.4–12 μm wavelength region in the process of modernization of experimental procedure and technology over a period of many years on the basis of accumulated practical experience. A device for atmospheric spectral transmittance measurements on near–ground horizontal paths is described in Ref. 11. Here we only note that this automated spectrophotometer is supplied with special software package for measurement data processing and selection of the aerosol component of atmospheric haze transmittance. In addition, a solar spectrophotometer has been developed and tested for atmospheric aerosol depth measurements on slant paths over a wide spectral range (0.4–12 μm); in addition to two measurement channels, the photometric complex of the instrument includes an automatic sun tracking system and a television control system.

## 2. Atmospheric transmission fluctuations

Not only widely varying energy losses but also spatiotemporal fluctuations in attenuated signal accompany the propagation of optical waves through the Earth's atmosphere. The signal fluctuations are unavoidable in a turbid atmosphere due to statistical nature of optical radiation scattering by statistical ensemble of particles. Turbulent inhomogeneities in the refractive index also significantly affect the optical wave parameters in the atmosphere. Given the energy losses in the turbulent atmosphere are small, it is commonly said about the intensity (or phase) fluctuations of optical waves. In the real atmosphere, the aerosol extinction and turbulent fluctuations act simultaneously during optical wave propagation, engendering the fluctuations of optical signal recorded from a distant source of radiation. They are perceived as fluctuations of atmospheric transmission.

Long–term experimental studies of atmospheric transmission for various turbidity types have shown the transmission fluctuations to be strongest in precipitation. In this case, transmission fluctuation spectra measured before and during precipitation differ drastically, so that one can readily identify their high–frequency portion attributed to scattering by hydrometeors alone (precipitation particles). These striking differences were first found in Refs. 12 and 13 and then were considered at length with my participation.[14]

Figure 2 illustrates the characteristic deformation of the fluctuation spectrum as a function of the intensity of precipitation (in snowfall). It is seen from the figure that as the intensity of precipitation increases, the second maximum (due to hydrometeors) occurs at frequencies of the order of 1 kHz, whereby the maximum due to turbulence becomes less pronounced. In heavy precipitation, the latter maximum disappears at all to yield the unimodal spectrum. In two–phase precipitation (rain with snow), trimodal spectra occur with two hydrometeor peaks corresponding to two types of precipitation.

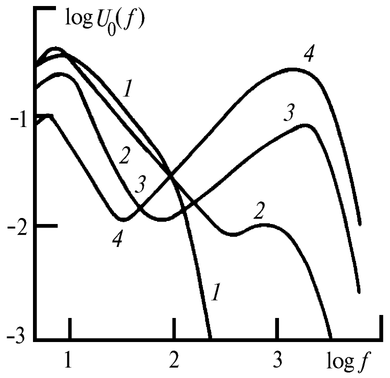


*FIG. 2. Frequency spectrum of atmospheric transmission fluctuations: 1)* $\tau < 0.02$, *2)* $\tau = 0.02$, *3)* $\tau = 0.05$, *and 4)* $\tau = 0.2$.

Analysis of many spectra shows that in the real atmosphere the above–described simple mechanism of spectrum transformation is modified due to the other factors involved, such as the conditions of experiment and more detailed precipitation characteristics. In principle, by choosing suitable conditions and scheme of experiment one can solve the inverse problem, that is, determine the intensity and microstructure parameters of hydrometeors as well as the characteristics of atmospheric turbulence from the fluctuation spectrum of atmospheric transmission.[15] A stationary instrumental complex, capable of performing such measurements not only in principle but in practice as well, has been developed and now operates at the Institute of Atmospheric Optics of the SB of the RAS. This result of long–term measurements seems to be important for effective monitoring of atmospheric precipitation being part of integrated monitoring of the environment.

### 3. Optical radiation transfer through the atmosphere

Like nonoptical radiative transfer through various media, attenuation of optical radiation in the atmosphere is described completely by radiative transfer equation in generalized form or in the optical–ray approximation in some particular cases.[16,17] Integro–differential equation of radiative transfer is solved by numerical techniques in most practical cases.[6,18] Merely at small optical depths the transfer equation for optical radiation in the atmosphere reduces to the approximate formula of exponential attenuation (Bouguer's law), while at very large optical depths – to the exponential formula with "depth–regime" parameters.[16,19,20]

My efforts to solve the problem at moderate optical depths in a scattering atmosphere led to analytical formula derived in the single–scattering approximation and to determination of the applicability limits for Bouguer's law.[16,19] The brightness $B$ of a point source is attenuated in a homogeneous scattering atmosphere according to the formula

$$B = B_0\, e^{-\tau}(1 + \Lambda\tau\, D)\ , \tag{1}$$

where $\tau = \kappa L$ is the optical depth of the atmosphere, $\kappa$ is the coefficient of total extinction, $L$ is the path length between a source and a receiver, and $\Lambda$ is the probability of photon survival (single scattering albedo). The parameter $D$ in Eq. (1) is determined by the scattering properties of a medium and is given by the formula

$$D = \frac{1}{2}\int_0^{\Psi}\int_0^{\Theta} f(\psi + \theta,\ \rho)\ d\psi\, d\theta\ , \tag{2}$$

where $\Psi$ and $\Theta$ are the receiver field of view and the angle into which the point source radiates, respectively; $\psi$ and $\theta$ are the integration variables; $f(\psi + \theta,\ \rho)$ is the scattering phase function; the parameter $\rho = 3\pi a/\lambda$; $a$ is the radius of scatterers; $\lambda$ is the wavelength.

Special experimental studies in artificial fog and smoke have shown the formula to be applicable at much larger optical thicknesses than Bouguer's law, up to $\tau = 9$. Of course, so wide range of applicability of formula (1) is fundamentally important for practice of optical measurements in a turbid atmosphere. As to scientific importance, the system of formulas (1) and (2) with some others obtained in the same approximation[16,19] provides a basis for the theory of optical measurements in scattering media.

One more fundamental result was obtained in experiments on laser beam propagation through scattering media.[19] These studies have shown that the brightness of a laser source (brightness of direct radiation) attenuated according to Bouguer's law exceeds that of background or multiply scattered radiation up to unexpectedly large optical depths. Figure 3 shows the measurement results for narrow beam of a He–Ne laser radiation with $\lambda = 0.63$ μm, beam diameter of 8 mm, and angular beam divergence of 6′. Straight lines *1* and *2* in the figure on semilogarithmic scale refer to Bouguer's exponential attenuation of direct and background laser radiation, respectively. Curves *3* and *4* show measurements of background and forward scattered radiation in evaporation fog and woody smoke, respectively. As is obvious from the figure, the laser beam intensity follows the exponential attenuation law, while the forward scattered intensity remains practically unchanged at depths from $\tau = 22$. Subsequent more detailed studies have shown that the revealed effect is due to small size of illuminated scattering volume, where the multiply scattered radiation background, which determines the limits of applicability of Bouguer's law, is formed.

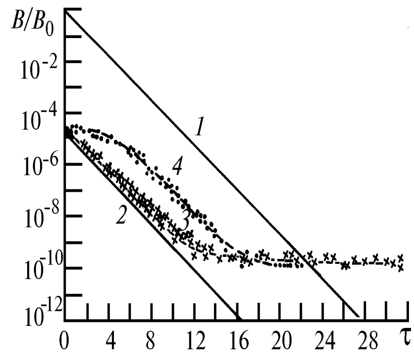


*FIG. 3. Decrease in the brightness of direct and scattered laser radiation in artificial fog: 1) direct radiation brightness, 2) background radiation brightness, 3) multiply scattered radiation brightness,* and *4) singly scattered radiation brightness.*

In practice the above effect implies that the brightness contrast of a laser source remains constant up to abnormally large optical depths, and thus the application of such sources offers few advantages over thermal ones in observations under adverse meteorological conditions. Laser navigation systems developed at the Joint Institute of Atmospheric Optics of the SB of the RAS under the scientific supervision of Academician V.E. Zuev were field tested and proved to be efficient for limited visibility range both for ship steering and aircraft landing.[21]

### 4. Optical image transfer through the atmosphere

Scattering of optical waves by atmospheric aerosol and turbulent inhomogeneities causes not only energy losses obeying generally the radiative transfer equation, but also temporal fluctuations of atmospheric transmission. Simultaneous recording of direct and forward scattered radiation causes further reduction of the brightness contrast of an observed object. In the real atmosphere strong angular dependence of forward scattered radiation intensity is responsible for strong dependence of the contrast distorted by the atmosphere on the size of the object or its elements. In this connection in the last few decades a consideration of the apparent brightness contrast transfer (optical image transfer) through the atmosphere as a process of frequency modulation of optical signals has received wide acceptance.

The fundamental scientific result in the problem of vision through the atmosphere obtained with my participation for a quantitative description in the single–scattering approximation is that we succeeded in the derivation of the optical image transfer equation and the formula for optical transfer function[19] for dispersed media.

Of particular interest for solving the problems of vision through the turbid atmosphere is the so–called $t$–effect which is manifested in observations through a thin scattering layer. The effect of the position of a thin scattering layer on brightness contrast of a self–illuminating half–plane (with a broad spectrum of spatial frequencies) was first investigated with my participation in 1972. Those studies have shown that a minimum contrast is observed for intermediate scattering layer position between a receiver and an object. The scattering layer position is conventionally specified by the ratio $t = l/z$, where $l$ is the distance to the receiver and $z$ is the distance between the receiver and the observed object. That is why the extreme dependence of the apparent contrast on the layer position was referred to as $t$–effect, which is clearly illustrated in Fig. 4. In the figure the right and the left photographs refer to the extreme positions of the scattering layer, while the central photograph – to the layer position with minimum apparent contrast.

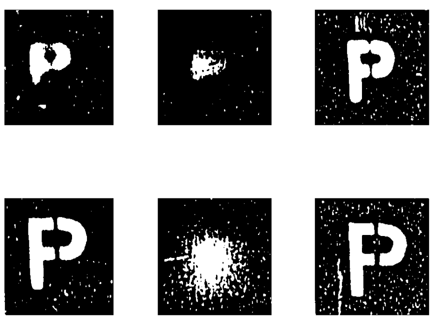

*FIG. 4. Examples of quality of optical images recorded through a scattering layer: upper raw is for milky medium and lower is for mat glass.*

Further more detailed numerical experiments with my participation yielded a fuller pattern of the $t$–effect. Figure 5 shows the results of calculations of the optical transfer function $K$ of a scattering layer at different spatial frequencies, in rad$^{-1}$ (indicated by the numbers adjacent to each curve). The results of calculations analogous to that shown in Fig. 5 indicate that the $t$–effect must be taken into account as in ground–based as in aerospace observations in the continuously and substantially inhomogeneous atmosphere.[22]

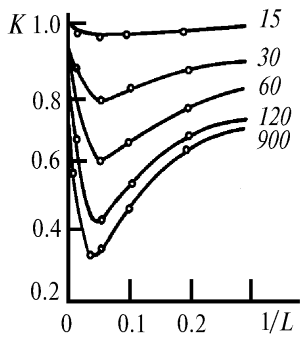


*FIG. 5. Calculated dependence of the OTF on spatial frequency for different positions of scattering layer.*

### 5. Aerosol scattering in the atmosphere

Some more effects exist, in addition to the above–considered, which accompany aerosol scattering in the atmosphere. Among these, most pronounced are the oreol, backward, and lateral scattering, as well as polarization effects due to atmospheric aerosol scattering. All optical effects due to aerosol scattering degrade the performance of optical–electronic systems operating through the atmosphere by introducing the atmospheric optical noise.[14] However, by solving inverse problems, these optical effects may be used and are now being widely used for diagnostics of the physical state of the atmosphere. Many results of investigations conducted in this direction under the scientific supervision of Academician V.E. Zuev over the last few decades have become a decisive factor for physical foundations of remote optical sensing of the atmosphere and practical applications of laser sounding systems.[13] Here we discuss only the results obtained with my participation.[14]

Among most important are the results of investigation of the applicability limits of the optical sensing equation for various turbidity types. As an example, Figure 6 shows measurements and results of calculations of the brightness of backscattered radiation $B$ as functions of the scattering coefficient $\kappa_s$ for fixed parameters of laser radar system (curve *1* shows the results of calculations from the formulas derived in the single scattering approximation and curve *2* – calculations considering double scattering in sounded volume). As is seen from the figure, only curve *3* for the brightness of doubly scattered radiation in the near field fits well the experimental data for $\kappa_s > 0.3$ m. The experimental points in the figure were obtained for lidar configuration with sounded volume at a distance of 7 m. In the case at hand, the comparison of calculations with experimental data gives the applicability limits of the formulas obtained in the single ($\tau < 1.5$) and double ($\tau < 4.5$) scattering approximations in optical sensing within fog or cloud.

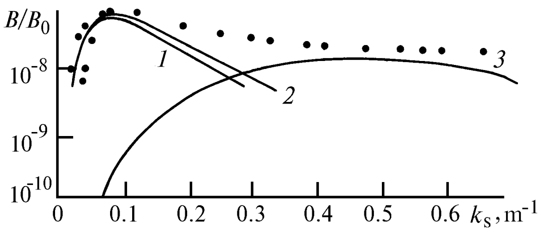


*FIG. 6. Dependence of calculated and measured backscattered radiation brightness on the scattering coefficient: 1) calculations from the formulas derived in the single scattering approximation, 2) calculations considering double scattering in sounded volume, and 3) calculations considering double scattering in the near field; dots are experimental data.*

Figure 7 shows the experimental dependence of the polarization degree of backscattered radiation on the scattering coefficient $\kappa_s$. Curves *1* and *2* are for measurements of the polarization degree for total and multiply scattered (without singly scattered) radiation fluxes. Dashed line *3* is for the calculated polarization degree due to single scattering by uniform spherical particles, while small crosses adjacent to it indicate the processed experimental data. As seen from the figure, the degree of polarization for backscattered radiation decreases with increasing optical density of the medium due to increasing contribution from multiple scattering which becomes pronounced even for optically thin layers of scattering medium ($\tau$ = 0.1–0.2).

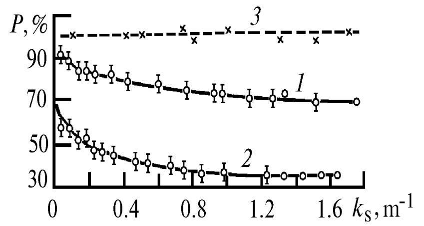


*FIG. 7. Dependence of the polarization degree of backscattered radiation in fog on the scattering coefficient: 1) total backscattered radiation, 2) multiply backscattered radiation, and 3) singly backscattered radiation.*

As a whole, the results reviewed as well as other experimental studies of aerosol scattering for model and real conditions have laid the physical foundations for further successive development of new methods and technical means of atmospheric optical sensing. The latter include aureol photometers, nephelometers, and aerosol lidars, whose recent scientific–technical updating has brought the complex of instrumentation for studies of the scattering atmosphere, both in the expedition and monitoring regimes, into being.

### 6. Optical refraction in the atmosphere

In the last few decades real impetus was given to centuries–old studies of optical refraction in the Earth's atmosphere in response to new advances in atmospheric sciences as well as to current practical problems concerning extending applications of opto–electronic devices. The results of those studies are of fundamental value since they provide a new insight into the correlation between the angular beam deflections (refraction angles) and the physical state of the atmosphere.

The optical beam refraction was investigated on horizontal paths located in the ground layer of the atmosphere or above the water surface, and was found to be substantially affected by turbulent regime in the lower atmosphere.[24,25] The following approach was developed to assess this effect. The theory of atmospheric turbulence states that the vertical distribution of air temperature $T(z)$ can be described using the notion of temperature ($T^*$) and length ($L^*$) scales and universal function $\Phi(z/L)$, namely,

$$\frac{dT}{dz} = \Phi\left(\frac{z}{L^*}\right)\frac{T^*}{z}, \qquad (3)$$

where $z$ is the altitude above the Earth's surface. The function $\Phi(z/L^*)$ is specified by boundary layer stratification (steady with $z/L^* > 0$, unsteady with $z/L^* < 0$, and neutral with $z/L^* < 0$). It is seen from Eq. (3) that the value of temperature gradient for fixed beam altitude above the Earth's surface is characteristic of suffuciently extended paths in contrast with the same value measured in one point of the path. So the developed algorithms for optical refraction calculations considering the atmospheric stratification prove to be more correct for homogeneous paths and indispensable for inhomogeneous ones.

The approach to the evaluation of refraction angles on horizontal paths considering atmospheric stratification, which was developed with my participation, provides physically well grounded interpretation of the dependence of the optical refraction on the atmospheric turbulence observed for a long time. The approach affords the detailed formulas confirmed by experiments on the paths located above the ground and the sea surface.[24] Thus, the new knowledge of atmospheric physics provided the basis for not only new approach to the solution of direct problem, but also opened new ways to solve such inverse problems as assessment of temperature and turbulence regimes in the atmosphere from measurements of optical refraction angles.

On slant paths the refraction angles are more difficult to evaluate due to technical problems associated with the determination of the atmospheric physical parameters. Classical approach to the solution of the problem is based on global atmospheric models involving either physical parameters or refraction angles themselves.[26] In the last few decades new methods and means of aerological (weather–balloon) atmospheric sensing have been developed and widely used. They provide qualitatively new approach to the solution of the problems of optical refraction. Aerological atmospheric sensing and supporting *in situ* optical observations ensure the maximum possible accuracy of evaluation of refraction angles for a given geographic location; otherwise, long–standing aerological data alone allow more adequate refraction models of the atmosphere to be constructed. In the latter case, the accuracy of estimation of the refraction angles is determined by the estimated spatial scales on which a given statistical model of the atmosphere remains adequate. It was precisely this problem which was investigated with my participation.[27]

The results of studies performed in Ref. 27 indicated the possibility of calculating the refraction angles with intermediate accuracy between that calculated from the data of direct aerological sensing (Fig. 8, curve *1*) and from the statistical (standard for the Earth) atmospheric models (Fig. 8, curve *3*). Such intermediate calculations are performed for regional atmospheric models (Fig. 8, curve *2*) relying upon long–standing data of aerological sensing in a given region of the Earth. The distance of applicability of regional atmospheric models was typically several hundreds of kilometers for examined regions. In these circumstances new requirements to the information about mean and maximum possible values of refraction angles are formulated for any climatic zones and meteorological conditions. An effort in this direction was first made in Ref. 28 where we compiled the tables of total and astronomical refraction angles. Application of the results of investigations on optical refraction along slant paths is as yet at the methodical stage. An exception is the temperature profile retrieval in the upper atmosphere from satellite observations of refractive distortions of solar disc.[29]

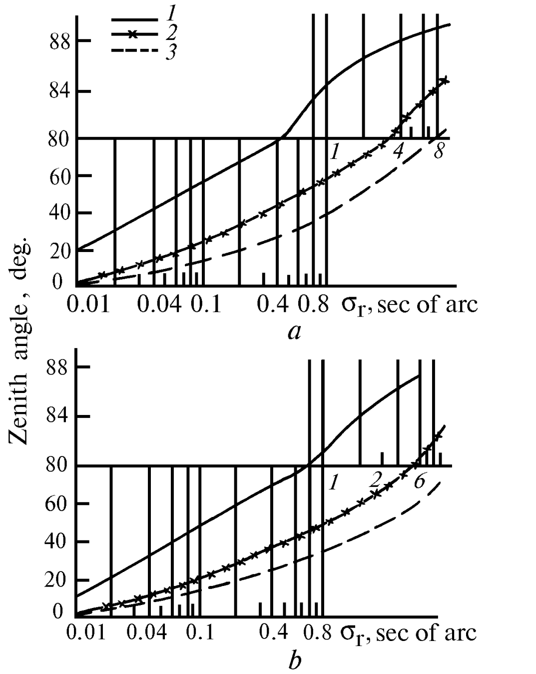


*FIG. 8. The* rms *error* $\sigma_r$ *in the estimation of the angle of optical refraction using: 1) aerological sensing data, 2) regional atmospheric model, and 3) standard atmospheric model, in summer (a) and winter (b).*

## MONITORING OF PHYSICAL STATE OF THE ATMOSPHERE

At the end of the twentieth century the totality of the fundamental results of investigations on atmospheric optics changes profoundly not only the arsenal of methods and experimental means but also the methodological concept of monitoring of the physical state of the atmosphere. The formation of the latter implies clarification of the spatial scales of monitoring (global, regional, and local), allowance for correlation between climatic and ecological factors in the Earth's atmosphere, and consideration of the interaction of physical, chemical, and biological processes in the atmosphere.

The new concept of integrated monitoring of the Earth's atmosphere meets completely the requirements stemming from basic directions of technological development within the scope of the general problem of stable development on the Earth[8] and provides a basis for many international and national programs. This new concept underlies the Project on Climatic–Ecological Monitoring of Siberia (CEMS) drawn up under my scientific supervision in 1993 (see Ref. 30).

The Project CEMS is primarily aimed at systematic and integrated monitoring of physical–chemical state of the Siberian air basin to reveal the long–term climatic–ecological changes in the region (scientific purposes of the Project) and to provide forecast of their consequences upon long–term program of social–economic development of Siberia (practical purposes of the Project).

The Project CEMS by its scientific–methodical content incorporates 12 key objects of monitoring, chosen so as to characterize fully the physical state of the Earth's atmosphere and to reveal long–term climatic–ecological changes. In so doing, by the effect of these changes is meant not only their recording, but also their unumbiguous interpretation required for further scientifically–grounded forecast of significant trends. By way of illustration, let us give some specific results obtained as part of the Project CEMS.

Figure 9 shows average–annual air temperatures measured at the meteorological station in Tomsk over the period from 1875 to 1993 (see Ref. 31). The dashed line in the figure is plotted from the data averaged by the method of least squares. As seen from Fig. 9, a trend of increasing average–annual temperature at the end of the last century vanishes.

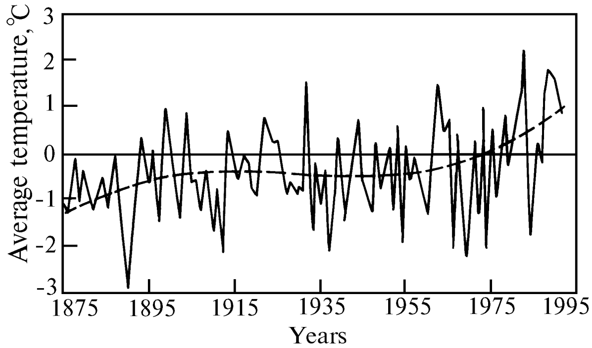


*FIG. 9. Average–annual temperature (Tomsk).*

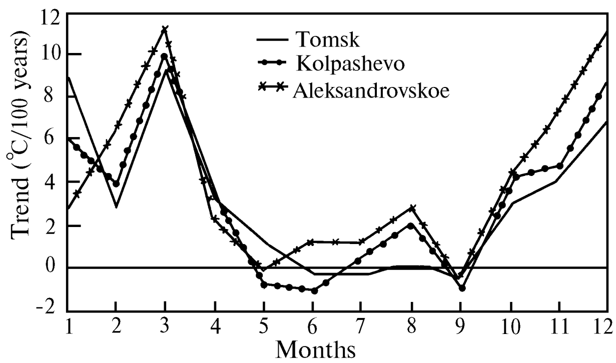


*FIG. 10. Trends in the average monthly temperature in the Tomsk Region.*

Since the 60s of the present century the average–annual temperature starts to grow again and is above zero (in °C) in the 70s. As a whole, the average–annual temperature changes by about 2°C over the period of observations. Mechanism of so considerable change in the average–annual temperature becomes clear from Fig. 10 which shows the trends in the average monthly daytime temperatures from the data obtained at three meteorological stations in the Tomsk Region (Tomsk, Kolpashevo, and Aleksandrovskoe) over the last 40 years. As seen from the figure, for all meteorological stations the temperature trends are nearly zero during summer months and exceed 8°C/100 years in winter. Thus warming–up in the Tomsk Region over 120 years is connected with winter months without noticeable change of temperature regime in summer.

The reason for such behavior has yet to be studied in the course of climatic–ecological monitoring.

One more interesting result was obtained for annual variations of atmospheric aerosol content. Figure 11 shows the data of airborne measurements of the number density of aerosol particles in the lower 3 km atmospheric layer.[32] As seen from the figure, aerosol content in the troposphere over West Siberia changes substantially from year to year. Decrease in the aerosol number density in the 80s is followed by its increase in the early 90s, with the amount of this increase still remaining less than its initially recorded value. For comparison, Figure 11 shows aerosol optical thickness over Moscow as a function of time. The pronounced maximum in aerosol concentration in 1988 occurs in the year of increased smoke content over Moscow due to fires in forests near Moscow. Forest fires are probably responsible for increased number density of aerosol particles in 1989 over West Siberia. Possible impact of annual changes in atmospheric aerosol content on thermal regime in the region is currently clarified by more detailed statistical data processing.

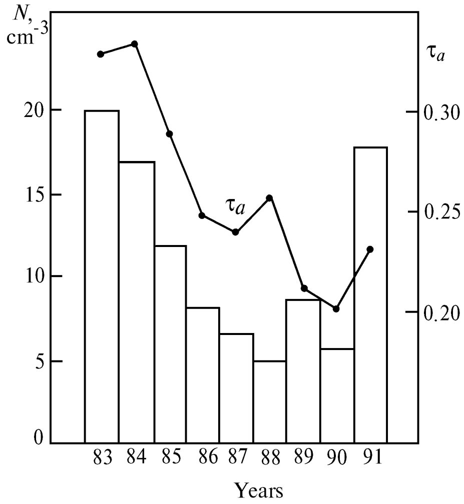


*FIG. 11. Annual variation of number density of aerosol particles over West Siberia.*

Somewhat surprising result was obtained in flux measurements of radio–wave radiation by a special radio–engineering complex designed for broadband measurements of radio–wave radiation flux. In addition, this complex was capable of filtering out low–frequency envelope in all high–frequency channels, including broadcasting ones. Figure 12 shows a record of signal for such a low–frequency envelope in a certain broadcasting channel of the short–wave range. Striking is the presence of repeatedly recorded signal in the region of several tens of hertz, where men's biosignals are observed and studies are conducted on electromagnetic safety (at the information level).

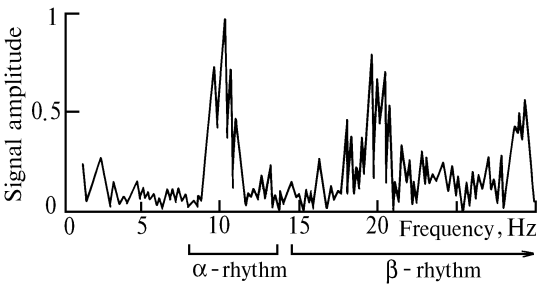


*FIG. 12. A particular record of low–frequency signal by radio–engineering complex (October 18, 15:00, local time).*

The above–discussed and some other specific results obtained at the initial stage of climatic–ecological monitoring show the scientific and practical value of the Project CEMS. The organization and scientific–research work of 1993 is continued in 1994 with focus on the following topics:

– creation of the network of the climatic–ecological monitoring of Siberia which includes a system of observation stations and posts for measurements under urban (industrial) and rural (background) conditions;

– measurements of the key atmospheric parameters and information–analytical investigations of fundamental atmospheric processes and phenomena, as well as analysis and interpretation of long–term regional changes in physical state of the atmosphere;

– international cooperation including intercalibration of instrumentation with further certification of the climatic–ecological monitoring network as regional incorporated in the international network of global monitoring;

– organization of annual Siberian conferences summarizing the results of climatic–ecological monitoring of Siberia and publication of annual information bulletins.

## CONCLUSION

The present review covers only some results obtained in atmospheric optics and prospects for their application. Undoubtedly, such purely "internal" problems as interaction of optical waves with different atmospheric constituents, atmospheric optical properties, atmospheric–optical phenomena, and so on still remain fundamental problems of atmospheric optics. At the same time, some new urgent problems have emerged recently in atmospheric optics which call for attention but can be regarded as "external."

As the above sections indicate, many principal results of atmospheric–optical research have wide and firm prospects for successful application to integrated monitoring of physical state of the atmosphere. In the last few decades progress in atmospheric optics significantly extends the class of objects of such monitoring. From methodical viewpoint this means that monitoring of physical state of the atmosphere has become an urgent problem of atmospheric optics.

Of the objects for climatic–ecological monitoring listed above, the object named "Physical state of the underlying surface" should be specially mentioned. In the context of regional monitoring (of air basin of Siberia), this object is understood as the Earth's surface of various types (soil, vegetation, snow cover, and so on). In the context of global monitoring, the concept also includes the sea surface. New methods and technical means of atmospheric optics provide grounds, both theoretical and experimental, for efficient studies of the sea surface as well as ocean–atmosphere interaction. Such interaction is important in studies of global climate change and renders a new urgent problem of atmospheric optics.

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