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Modern Climate Change in Georgia. Radiatively Active Small Atmospheric Admixtures.

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Modern Climate Change in Georgia.
Radiatively Active Small Atmospheric Admixtures.

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კლიმატის თანამედროვე ცვლილება საქართველოში. ატმოსფეროს მცირე რადიაციულად აქტიური მინარევები.

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Современное изменение климата в Грузии.
Радиационно-активные малые примеси в атмосфере.

Summary

The book presents the results of many years of the investigations of some radiatively active small atmospheric admixtures (RASAA). The data on the anthropogenic emissions of CO_2, CH_4, N_2O, NO_X, SO_2 and aerosols are presented. The distribution of the number concentration of aerosols in the troposphere over various regions of Georgia is studied in detail. A detailed analysis of the long-term variations of total ozone, aerosol optical depth of the atmosphere and other RASAA is given. Estimations of the effect of some RASAA on the direct and diffuse solar radiation in Georgia are presented.

For scientists and engineers working on problems of atmospheric physics and climate change.

ანოტაცია

წიგნში წარმოდგენილია საქართველოში ზოგიერთი ოპტიკურად აქტიური მცირე ატმოსფერული მინარევის მრავალწლიური კვლევის შედეგები. წარმოდგენილია მონაცემები CO_2, CH_4, N_2O, NO_X, SO_2 და აეროზოლების ანთროპოგენური ემისიების შესახებ. დაწვრილებითაა შესწავლილი აეროზოლების თვლადი კონცენტრაციის ვერტიკალური განაწილება ტროპოსფეროში საქართველოს სხვადასხვა რეგიონისთვის. ჩატარებულია ოზონის საერთო რაოდენობის, ატმოსფერული აეროზოლების ოპტიკური სიმკვრივის და სხვა ნართების გრძელვადიანი ვარიაციების დეტალური ანალიზი. წარმოდგენილია ზოგიერთი ნართის გავლენის თეორიული შეფასება საქართველოში მზის პირდაპირი და გაბნეული რადიაციის რეჟიმზე.

განკუთვნილია მეცნიერ-მუშაკებისთვის და ინჟინრებისთვის, რომელთა საქმიანობა დაკავშირებულია ატმოსფეროს ფიზიკისა და კლიმატის ცვლილების პრობლემებთან.

Аннотация

В книге представлены результаты многолетних исследований в Грузии некоторых радиационно-активных малых примесей в атмосфере (РАМПА). Представлены данные об антропогенной эмиссии CO_2, CH_4, N_2O, NO_X, SO_2 и аэрозолей. Подробно изучено распределение счетной концентрации аэрозолей в тропосфере над различными районами Грузии. Приведен детальный анализ долговременных вариаций общего содержания озона, аэрозольной оптической толщи атмосферы и других составляющих РАМПА. Представлены теоретические оценки влияния некоторых РАМПА на режим прямой и рассеянной радиации в Грузии.

Предназначена для научных работников и инженеров, связанных в своей деятельности с проблемами физики атмосферы и изменения климата.

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Оглавление

Introduction

In the last years the problem of the forthcoming climate change under the conditions of growing anthropogenic impact on the environment has been drawing an increasing attention. This problem acquires a particular importance for Georgia, where almost all climate types are encountered except of savannahs and tropical forests. Georgia is located in the South-West part of Europe, to the South from the Main Caucasian Ridge between the Black and Caspian Seas. The area of the country amounts to 69700 km^2, only 46% of which is at elevations from 0 to 1000 m above the sea level. The territory of Georgia in its middle part is almost meridianwise divided by the Likhi Ridge into two different from the climatic point of view areas: a constantly humid area of the marine subtropical climate (Western Georgia) and an area transitional from the continental dry subtropical climate to the marine climate (Eastern Georgia). Each of these areas consists of zones and subzones. The mean annual temperature in the coastal zone of the Black Sea amounts to 14-15°C, the amount of precipitation - 1500-2500 mm. On the lowlands of Eastern Georgia the mean annual air temperature is between 11 and 13°C, while the amount of precipitation - 400-600 mm. In the mountainous regions the annual precipitation amount reaches 800-1200 mm.

In the winter for the whole Georgian territory a steady snow cover is not formed at locations below 400 m above the sea level. The sunshine duration on the most part of the country's territory is between 1900-2200 hours. The period of air temperature warming up to 10°C in the lowland area amounts to 120-160 days, while in the mountainous regions reaches 220-320 days [56].

The multiformity of the climatic conditions in Georgia is determined by the interaction of global and local atmospheric circulation processes over its territory. Therefore it should be expected that even an inconsiderable global climate change will quickly find a response in a change of the Georgian climate, not to mention the forecast considerable warming of the atmosphere in the nearest decades as a result of the greenhouse effect. From this point of view the Georgian territory represents a natural laboratory for the indication and study of global and local climatic effects.

In Georgia there are rich traditions of investigations of the climate and also separate climate-forming factors of this country. However intensive studies of the modern climate change in Georgia were started in 1996 by leading scientists of the Georgian Academy of Sciences (Institute of Hydrometeorology, Institute of Geography, Institute of Geophysics), Department of Hydrometeorology (National Climate Research Centre) and Tbilisi State University. A strong stimulus for carrying out these

investigations was the adoption of the United Nations Framework Convention on Climate Change in 1992 in Rio de Janeiro, which Georgia joined on 27 October 1994. During the last four years for the territory of Georgia long-term variations (60-100 years) of such climate elements as the near-ground air temperature, soil temperature [54, 64, 138, 140], air humidity and precipitation [32, 53], atmospheric aerosols and ozone [16, 20, 25, 82, 83], etc. have been studied.

One of the main reasons for the modern climate change represents the human activity related to the energy consumption. Therefore a considerable attention was paid to the inventory of the anthropogenic emissions of the greenhouse gases and aerosols, having a direct effect on the climate formation, in Georgia [36, 37, 56].

After the collapse of the former Soviet Union in Georgia during the following decade a strong fall-down in the industry took place. Correspondingly the energy consumption also decreased considerably. Thus, at the end of 1980-s at the average in the world the anthropogenic emission of the main greenhouse gas CO_2 per capita per year amounted to about 4.5 tons, while in Georgia - about 6.4 tons. In the middle of 1990-s this index in Georgia fell down almost five times. Correspondingly considerably decreased the anthropogenic emissions of such important for the climate formation radiatively active small atmospheric admixtures (RASAA) as CH_4, N_2O, NO_X, CO, SO_2, aerosols (sulphates, nitrates, soot, solid emissions). Thus, in the last years in the climate change in Georgia an intensification of the role of external anthropogenic RASAA emission sources, located in neighbouring industrially developed countries must have been taking place.

The present book is one of the components of the book series "Modern Climate Change in Georgia", in which it is assumed to highlight the tendencies of the change of practically all main climate elements for the last 60-100 years. The book presents the results of many years of the investigations of some radiatively active small atmospheric admixtures in the atmosphere (aerosols, CO, SO_2, NO_X, O_3), the data on the anthropogenic RASAA emissions (CO_2, CH_4, N_2O, NO_X, etc.) and the tendencies of long-term variations of their content in the atmosphere, theoretical estimations of the variability of some RASAA on the short-wave solar radiation.

The book consists of six chapters.

The first chapter gives the modern concepts on the role of RASAA in the processes occurring in the atmosphere, their effect on the global, regional and local climate change. The data on the main anthropogenic RASAA emissions in Georgia are also presented.

The second chapter is dedicated to an analysis of the particularities of the variations of the anthropogenic emissions of CO_2, CH_4, N_2O, CO, SO_2, NO_X, aerosols in Georgia for the two last decades.

In the third chapter the data on the spatial-temporary variations of CO, SO_2, NO_X, ozone and aerosols in the near-ground atmospheric layer and in the troposphere are given. The main attention is paid to the issues related to the generation of the secondary aerosols according to the scheme gas → particle, aerosol-cloud interaction.

The results of the investigations of the total ozone on the Georgian territory are presented in the fourth chapter.

In the fifth chapter the data on the spatial-temporary characteristics of the aerosol optical depth of the atmosphere over the Georgian territory are presented.

The sixth chapter gives theoretical estimations of the effect of the variations of water vapour, ozone, aerosol content in the atmosphere and underlying surface albedo on the direct and diffuse solar radiation in Georgia.

Chapter I

The role of radiatively active small atmospheric admixtures (RASAA) in the formation of climate change

1.1   Effect of RASAA on the atmospheric processes, energy level formation at the Earth's surface, climate sustainability and change

The main importance in the climate formation and its change is attributed to the speed of the heat transfer to the Earth's climatic system (ECS). The only source of this energy represents the solar radiation. The atmosphere and ocean react to this heating by forming systems of air and oceanic flows, which redistribute heat energy on the Earth among regions with its excess and deficit.

According to Budyko's scheme [41] the Earth as a planet (together with the atmosphere) at the average per year absorbs 237.2 W/m^2 of heat radiation. Out of this amount 156.4 W/m^2 is absorbed by the Earth's surface, while 80.8 W/m^2 - in the atmosphere [41].

The radiation balance of the Earth's surface equals at the average per year to 104.7 W/m^2, while the effective radiation from the Earth's surface, corresponding to the difference of the absorbed radiation and radiation balance amounts to 51.7 W/m^2. The total amount of the outgoing Earth's long-wave radiation equals to the absorbed radiation amount (237.2 W/m^2). In addition the ratio of the effective radiation from the Earth's surface to the outgoing long-wave radiation of the Earth is much less than the ratio of the long-wave radiation absorbed by the Earth's surface to the solar radiation absorbed by the Earth as a planet (21.8% and 65.9% respectively), which well characterizes the "greenhouse" effect on the Earth's radiation balance. Another characteristic of the "greenhouse" effect is the value of the radiation balance near the ground (104.7 W/m^2).

The energy of this balance is consumed for the evaporation (87.5 W/m^2) and turbulent heat exchange between the Earth's surface and atmosphere (17.2 W/m^2). The atmosphere receives heat energy from three sources: absorbed short-wave radiation (80.8 W/m^2), vapour condensation heat (87.5 W/m^2), turbulent heat transfer flux from the Earth's surface (17.2 W/m^2). The sum of these values amounts to 185.5 W/m^2 and equals to the loss of heat due to the outgoing long-wave radiation corresponding to the difference between the outgoing long-wave radiation of the Earth as a planet and effective radiation near the ground [41].

Stability of the mentioned energy balance of the Earth and ratio of its components determines stability of the global climate. The violation of this stability may be caused by the following main climateforming factors

[2-4,26,27,41,43,50,55,72-74,84,85,97,98,101,139,144]: changes in the solar energy flux (solar constant changes); variations of the cloudiness; changes of the underlying surface albedo; changes in the parameters of the Earth's orbit; changes of the water exchange in the atmosphere; variations of the background stratospheric and volcanic aerosol concentration; variability of the tropospheric aerosol content; changes of the content of some "greenhouse" gases in the atmosphere; variability of the systems of oceanic and air flows (ocean-atmospheric interactions).

During many years an opinion dominated that the modern global climate is more or less stable and its changes in the nearest future would not exceed the level of the natural variations. However in the recent decades the climate change due to anthropogenic factors has become obvious.

The generalization by WMO of the opinions of the meteorological services from 50 countries enabled to classify the factors of the annual variability of the global climate: 1) ocean-atmospheric interactions; 2) destruction of forests, solar activity; 3)variability of the snow and ice cover; 4) others (urbanization, CO_2, aerosols, desertification, stratospheric aerosols, soil humidity). At a scale of decades the priority is given to: 1) CO_2; 2) destruction of forests; 3) urbanization, ocean-atmospheric interaction; 4) others (aerosols, solar activity, desertification, volcanic eruptions, stratospheric ozone, anthropogenic heat emissions, snow and ice cover) [98].

Thus, changes in the global climate occurring at present are conditioned to a significant extent by the changes of the contents of radiatively active admixtures of an anthropogenic origin in the atmosphere. These admixtures are carbon dioxide (CO_2), methane (CH_4), nitrogen protoxide (N_2O), halocarbons (CFCs), tropospheric and stratospheric ozone and aerosols. Except of nonsoot aerosol particles and stratospheric ozone all other mentioned components play the role of heat accumulators in the formation of the energy level of the Earth.

CO_2, CH_4, N_2O, CFCs, tropospheric ozone together with water vapour, whose radiative properties are quite well studied [4,106,107], absorb long-wave radiation emitted by the Earth's surface and create the "greenhouse" effect. Soot aerosols actively absorb solar radiation and warm the atmosphere by reemitting it. Nonsoot aerosol particles mainly scatter solar radiation thus diminishing its flux to the Earth's surface. In addition aerosols interacting with clouds change their microphysical and electrical characteristics, which finally results in changing of the optical properties of these mixed aerodiperse systems. Considering that cloudiness represents one of the most important factors affecting the radiation and climate, the role of aerosols in indirect radiative effects in the atmospheric and Earth's energy level formation turns out to be very significant.

1.2 The effect of RASAA variations on global, regional and local climate change

In the last decades due to the intensive development of industry, power industry, transport in developed industrial countries the emission of radiatively active small admixtures in the atmosphere have also considerably increased. For example during the last 1000 years the volume concentration of the main "greenhouse" gas CO_2 near the ground fluctuated within the ranges $\pm$ 10ppm from the mean value 280 ppm. However, the data of the organized in March 1958 monitoring of CO_2 content in the atmosphere, already after 10-15 years, convincingly showed that the carbon dioxide concentration was considerably increasing in time. In 1994 at the station Mauna-Loa it amounted to 358 ppmv. The rate of the annual increment of the CO_2 concentration in the atmosphere is also growing and its increase is tightly related to the intensification of fossil fuel consumption (the rate of the annual increment in 1960 amounted to 0.83 ppm, in 1970 - to 1.28 ppmv, in 1980 - to 1.53 ppmv, in 1994 - to 1.6 ppmv). In 2050-2100 a doubling of the carbon dioxide concentration in the atmosphere is expected [27,41,74].

The content of methane in the atmosphere increased from 700 ppbv in the preindustrial period (1860-1880) to 1721 ppbv in 1994. The rate of the methane concentration increase from 1980 to 1990 amounted to 1.1-1.3% per year. In 2030-2050 the volume concentration of methane in the air should reach 2000-2500 ppbv [74,78].

The volume concentration of N_2O in the preindustrial period amounted to 275 ppbv and in 1992 reached the value of 311 ppbv. It is expected that in 2030-2050 the N_2O content in the air will amount to 350-400 ppbv [74,78].

The total concentration of $CFCl_3$ and CF_2Cl_3 in the atmosphere in 1980 was about 0.450 ppbv and in 2030-2050 it is expected to reach 1 ppbv [74,78].

At present in comparison to the preindustrial period in the Northern Hemisphere the content of tropospheric ozone have increased almost twice. For the Southern Hemisphere a similar effect have not been detected, possibly because of the small number of observations [74].

As it was mentioned above, atmospheric aerosols play a significant role in direct and indirect radiative effects and in general a growth of their content reduces the incident solar radiation flux. One of the most important aerosol components represent secondary sulphate formations of natural and anthropogenic origin, which have a high scattering ability and good condensation properties. Secondary nitrate aerosols play at a global scale in direct radiative effects an insignificant role. However, like sulphates,

having good condensation properties can considerably affect microphysical characteristics of clouds, thus indirectly affecting also the formation of the energy level near the ground [2,3,46,68,88].

The sources of secondary sulphate and nitrate aerosols in the atmosphere are natural and anthropogenic gaseous compounds of sulphur (SO_2, CS_2, H_2S, etc.) and nitrogen (NO_X). These gases as a result of a number of photochemical reactions, particularly in humid media in presence of ozone and other admixtures, transform into aerosol particles with sizes considerably affecting the optical properties of the atmosphere [2,3,46,65,75,110,145]. Ionizing radiation of radon significantly accelerates these reactions [99].

Like the "greenhouse" gas emissions in the postindustrial period the emission of anthropogenic aerosols and aerosolforming gases in the atmosphere has also considerably increased. For example, in comparison to the preindustrial period the emission of SO_2 in the middle of 1980-s increased from 4-5 Tg/year to 125-130 Tg/year.

Table 1.1 presents the data on the emissions in the atmosphere of natural and anthropogenic aerosols and their mean global optical characteristics for the last decade [26,48,74]. As it follows from this table the share of the anthropogenic aerosol emission amounts to only 11% of the total annual amount of aerosols from all sources. However, the share of anthropogenic aerosols in the mean global value of the atmospheric aerosol optical depth τ_{ag} amounts to $\cong 45\%$. It is noteworthy also that the share of anthropogenic sulphate aerosols in the value of τ_{ag} amounts to 19%, while the share in the total emission being only 4.1%. The share of all sulphate aerosols in τ_{ag} is 33%, the emission share being 7%. The emission of natural mineral and marine aerosols per year amounts approximately to 2800 Tg (or 83% of the total emission), while their share in the value of τ_{ag} is only 26% (23% and 3% respectively). Industrial dust, nitrates, volcanic dust, biological debris, soot particles do not contribute considerably in τ_{ag} (about 13% in the aggregate). A more significant contribution in the τ_{ag} value is made by organic matter from biogenic VOC and biomass burning (28%).

According to Table 1.1 the mean global value of the atmospheric aerosol optical depth amounts to 0.100 (or for the wavelength $\lambda=1.0$ mcm $\tau_{ag} \approx 0.055$). These data are mainly in a good agreement with the data on τ_{ag} and background values of τ_a by other authors, which are in the ranges 0.016-0.100 [3,19,91,92,109,112,142].

In the past the Earth climate changed many times not being or being slightly affected by anthropogenic sources of RASAA [2,27,41,43,84,98]. Therefore, it is very important to estimate quantitatively the influence of the increase of anthropogenic RASAA emissions on the radiative forcing

Table 1.1

Source strength, atmospheric burden, extinction efficiency and visible optical depth τ_{ag} due to the various types of aerosol particles [26,48,74].

Source	Flux (Tg/yr)	Ratio per Total Emission (%)	Global Mean Column Burden (mg/m^2)	Mass Extinction Coefficient (Hydrated) (m^2/g)	Global Mean Optical Depth τ_{ag}	Ratio of τ_{ag} per Total Value (%)
Natural						
Primary						
Soil Dust (Mineral Aerosol)	1500	43.72	32.2	0.7	0.023	
Sea Salt	1300	39.70	7.0	0.4	0.003	29
Volcanic Dust	33	0.96	0.7	2.0	0.001	
Biological Debris	50	1.46	1.1	2.0	0.002	
Secondary						
Sulphates from Natural Precursors, as (NH$_4$)$_2$SO$_4$	102	2.97	2.8	5.1	0.014	
Organic Matter from Biogenic VOC	55	1.60	2.1	5.1	0.011	26
Nitrates from NO$_X$	22	0.64	0.5	2.0	0.001	
Total Natural	3062	89.25			0.055	55
Anthropogenic						
Primary						
Industrial Dust, etc.	100	2.91	2.1	2.0	0.004	
Soot (Elemental Carbon) from Fossil Fuels	8	0.23	0.2	10.0	0.002	7
Soot from Biomass Combustion	5	0.15	0.1	10.0	0.001	
Secondary						
Sulphates from SO$_2$ as (NH$_4$)$_2$SO$_4$	140	4.08	3.8	5.1	0.019	
Biomass Burning	80	2.33	3.4	5.1	0.017	38
Nitrates from NO$_X$	36	1.05	0.8	2.0	0.002	
Total Anthropogenic	369	10.75			0.045	45
Total	3431	100			0.100	100

both at global and regional scales. Table 1.2 presents the data for main RASAA on the mean global changes of the values of anthropogenic components of radiative forcing F in the middle of 1990-s in comparison to the preindustrial period [73,74]. As it follows from the table, during the indicated time period (140-150 years) as a result of "greenhouse" gases the values of F(+) increased in the aggregate by 3.25 W/m^2. At the same time the change of the stratospheric ozone content and growth of aerosol emissions in the atmosphere resulted in an increase of F(-) by 1.45 W/m^2 too. Thus, the total effect of the increase in F amounted to about +1.80 W/m^2.

Table 1.2

Mean global change of the anthropogenic components of radiative forcing in the middle of 1990-s in comparison to the preindustrial period for main RASAA [73,74]

Global - Mean Radiative Forcing (F), W/m^2					
+			-		
RASAA	W/m^2	Ratio per F_+ (%)	RASAA	W/m^2	Ratio per F_- (%)
CO_2	1.6	49	Stratospheric Ozone	0.10	7
CH_4	0.45	14	Sulphate	0.40	28
N_2O	0.15	5	Biomass Burning	0.20	14
Halocarbons (CFCs)	0.25	8	Tropospheric Aerosols - Indirect Effect	0.75 (0÷1.5)	52
Tropospheric Ozone	0.40 (0.2÷0.6)	12			
Fossil Fuel Soot	0.10	3			
Cl/Br Direct	0.30	9			
Total	3.25	100	Total	1.45	100

The main role among "greenhouse" gases in the increase of radiative forcing is played by carbon dioxide (about 50%). The decrease of F(-) is mainly conditioned by sulphates and tropospheric aerosols (about 80%). It is noteworthy that at present the share of tropospheric ozone in the increase of F(+) is almost the same as that of methane (12% and 14% respectively). The ratio between F(-) and F(+) at present amounts to about 45%.

Table 1.3 presents the predicted values of the variations of anthropogenic components of the mean global radiative forcing in 2050 and 2100 in comparison to the preindustrial period. As it follows from the table the total effect of the increase of F in 50 and 100 years may amount to respectively 3.7 W/m^2 and 6.5 W/m^2. In addition the share of CO_2 in the F(+) increase will be growing (66% and 68-74% respectively), the share of methane will change insignificantly (15-13%), the share of tropospheric ozone will decrease to 9-7%. The growth of the aerosol pollution of the atmosphere should result in an increase of F(-) values, which will exceed 2 W/m^2. In addition the share of sulphates and tropospheric aerosols (indirect effects) in the increase of F(-) values will be about 85-90%.

The growth of the aerosol pollution of the atmosphere will be preventing the intensification of the "greenhouse" effect. However the share of F(-) in F(+) will be diminishing in the nearest 100 years and in

Table 1.3

Mean global values of the anthropogenic components of radiative forcing in 2050 and 2100 in comparison to the preindustrial period for main RASAA according to the emission scenario 1S92 [73,74]. In brackets - the share per F in %.

Global - Mean Radiative Forcing (F), W/m^2					
	+			-	
RASAA	2050	2100	RASAA	2050	2100
CO_2	3.80 (66)	5.80÷6.30 (68÷74)	Stratospheric Ozone	0.04 (2)	0 (0)
CH_4	0.84 (15)	1.07 (13)	Sulphate	0.60 (29)	0.60 (29)
N_2O	0.36 (6)	0.53 (6)	Biomass Burning	0.25 (12)	0.25 (12)
Halocarbons (CFCs)	0.11 (2)	0.22 (3)	Tropospheric Aerosols - Indirect Effect	1.2 (57)	1.2 (59)
Tropospheric Ozone	0.50 (9)	0.57 (7)			
Cl/Br Direct	0.15 (3)	0.08 (1)			
Total	5.76	8.27÷8.77 mean - 8.52	Total	2.09	2.05

2050 and 2100 will amount to 36% and 24% respectively. Thus, it is expected that the rate of the growth of the total anthropogenic radiative forcing will be increasing. Table 1.4 gives the data on the variations of F=(F(+)-F(-)) from 1700 to 2100, calculated according to the emission scenario 1S92 [73,74]. As it follows from the table in 1700-1800 the rate of the F increase per century amounted to 0.23 W/m^2, from 1800 till 1900 - 0.12 W/m^2, in 1900-2000 - 1.45 W/m^2. In 2000-2100 the increase rate of F values per century is expected to be within the ranges 2.4-6.1 W/m^2. It is noteworthy also that in the increase of F in the future century, as earlier, the main role, becoming more and more significant with years, will be played by carbon dioxide.

In this connection in predicting models of global anthropogenic climate change, the main attention is paid to the radiative forcing caused by the growth of CO_2 content in the atmosphere. For example, according to the data by various authors in the future century at the moment of a doubling of the atmospheric carbon dioxide content the mean annual near-ground air temperature is expected to elevate by 1.3-4.5 ^{O}C [27,41,42,43,52,73].

While estimating the potential effect of anthropogenic RASAA on climate change it is important to consider that their emission is limited by the man-inhabited territory, which occupies an area of about 15 10^6 km^2 [2,84]. In the beginning - middle of 1990-s the global anthropogenic CO_2

Table 1.4

Mean global change of the total values of anthropogenic radiative forcing in 1700-2100 calculated according to the emission scenario 1S92 [73,74].

Total global mean radiative forcing, W/m^2								
1700	1800	1850	1900	1950	1975	2000	2050	2100
0	0.23	0.33	0.35	0.63	0.90	1.80	3.30-4.10	4.20-7.90

emission in the atmosphere amounted to about $26 \cdot 10^9$ T/year. The data on the natural and anthropogenic aerosol emission are presented in Table 1.1 ($3062 \cdot 10^6$ T/year and $369 \cdot 10^6$ T/year respectively) [74]. In Georgia, which occupies a territory of about 70000 km^2, the anthropogenic CO_2 emission in the end of 1980-s was approximately $35 \cdot 10^6$ T/year [36]. The anthropogenic aerosol emission (Chapter II) at the average was about $484 \cdot 10^3$ T/year.

Table 1.5 presents comparative characteristics of the emissions of anthropogenic carbon dioxide, natural and anthropogenic aerosols from a square km of territory averaged by the area of the whole Earth ($510 \cdot 10^6$ km^2) and by the mean man-inhabited territory ($15 \cdot 10^6$ km^2) with the emissions of the indicated admixtures from the Georgian territory (70000 km^2).

Table 1.5

Emission of CO_2 and aerosols from 1 km^2 of territory (T/year) at the end of 1980-s.

RASAA / Territory	Anthrop. CO_2	Natural Aerosols	Anthrop. Aerosols
Mean Gloabal	50	6	0.7
Mean Global (Man-inhabited Areas)	1700	6	25
Georgia	500	6	7

Table 1.5 clearly demonstrates non-uniformity of the distribution of RASAA emission sources on the Earth's surface. For example, the share of the global anthropogenic aerosol emission in the natural one amounts to only 12%, while on man-inhabited territories the anthropogenic aerosol emission is 4 times higher than the natural. The emission of anthropogenic CO_2 from man-inhabited territories is 34 higher than the global one. This table also shows that from the territory of Georgia even in the Soviet period the RASAA emission was about 3.5 times lower than the emission from the man-inhabited territory throughout the world.

Non-uniformity of the distribution of RASAA emission sources on the Earth surface and also different life times of their components in the atmosphere result correspondingly in a uniform distribution over the Earth of those components of RASAA, whose life time is limited by hours or weeks (sulphates, nitrates, methane, etc.) [2,3,44,46]. For example, the share of sulphate aerosols in τ_{ag} in the visible wavelength range varies from 0.010 over the oceans in the South Hemisphere to 0.050-0.070 over the USA, Central Europe and Russia [3,45]. Because of non-uniformity of the natural and anthropogenic aerosol emissions even over the ocean surface of the Earth the distribution of the atmospheric aerosol optical depth is very inhomogeneous and varies within values different by more than an order [3,109].

In contrast to aerosols and other RASAA with short life times the mean presence time of carbon dioxide in the atmosphere is about two years [44]. Therefore, the distribution of this gas over the Earth's surface is more homogeneous except of its content near large emission sources. Correspondingly the role of carbon dioxide in the global warming is expected to increase in time (Tables 1.2 and 1.3). A similar picture is in the case of e.g. N_2O. However, the share of this "greenhouse" gas in radiative forcing remains inconsiderable.

Non-uniformity of the RASAA distribution in the atmosphere determines local and regional particularities of the anthropogenic climate change. For example, according to the models [73,74], at the moment of a doubling of the CO_2 content in the atmosphere, at the background of a mean global elevation of the near-ground temperature in various regions of the world, variations of this temperature in comparison to the preindustrial period will be within the ranges $-6^O C \div +6^O C$. In other words, whole regions, although not very large, are expected to appear in which the cooling effect will be taking place too. It is noteworthy that for the Caucasian Region at that time the elevation of the near-ground temperature in the model without allowance to the effect of aerosols is expected to be $2-3^O C$ and $>0-2^O C$ - with allowance to this effect.

For Georgia, occupying a small territory, on which almost all types of climate are encountered - from the humid subtropics with a high temperature background to the cold climate of eternal snows and glaciers, not only regional effects of anthropogenic climate change, but also local ones (cities, large RASAA sources, etc.) are very important. The climatic conditions in Georgia formed as a result of the interaction over its territory, having a complex relief and variety of physical-geographical conditions, of global and local atmospheric-circulation processes. Therefore, even inconsiderable anthropogenic changes in the global or regional climate will very quickly find a response if not over the whole Georgian territory, at least for its separate climatic zones. From this point of view the territory of

Georgia and its separate regions can be considered as a natural laboratory for indication and study of climatic effects of various scales and also of separate climateforming factors.

Intensive study of the modern climate change in Georgia was started in 1996 by leading scientists of the Georgian Academy of Sciences (Institute of Hydrometeorology, Institute of Geography, Institute of Geophysics), Department of Hydrometeorology (National Climate Research Centre) and Tbilisi State University. Within a short time period were studied multiyear (60-100 years) variations of the near-ground air and soil temperature for the Georgian territory [54,64,138,140], variations of humidity, water circulation and precipitation [32,53]. The temporary variations of the vertical distribution of temperature and humidity in the atmosphere were also investigated [141]. For separate long-term meteorological stations long-period trends of the near-ground wind were studied [77]. Particular attention was paid to the investigation of temporary variations of such radiatively active small atmospheric admixtures as aerosols [16,23,25,39,132,134,135] and ozone [20,82,83]. For this purpose both the direct radiative effects of aerosols and ozone [17,21,24] and the effects of their interaction with such climate elements as cloudiness, fogs, thunderstorms, hail, etc. [12,15,17,18,22,81,87] were considered. Also considerable attention was drawn to the study of the climate change effect on the Black Sea level variations in the coastal zone of Georgia [58], etc.

One of important results of these works was an empiric model of the near-ground temperature variations for the Georgian territory from 1906 till 1995 [140]. It was established that air temperature trends for various regions of Georgia were inhomogeneous, which resulted in a spotty distribution of the mean annual values of temperature anomalies in these regions within the ranges <-0.3 ^{O}C - >0.5 ^{O}C during 90 years. In the aggregate for Western Georgia a cooling was observed, while for Eastern Georgia - a warming. For Eastern Georgia the maximum increase of the mean annual near-ground air temperature (>+0.5 ^{O}C) in the mentioned period approximately coincides with the value of the mean global temperature growth [73,140]. One of main reasons of such inhomogenity of the temperature trends on the Georgian territory may be the particularities of the distribution of anthropogenic RASAA sources on this territory.

1.3 Main anthropogenic sources of RASAA emissions in Georgia

Georgia is located in the middle and Western parts of the Caucasus, between $41^O07'$ and $43^O47'$ N.L. and $40^O01'$ and $46^O44'$ E.L. (Fig. 1.1). Intermediary geographical location of Georgia at the borders of Europe and Minor Asia, between the Black Sea and dry areas to the East, together with the relief particularities determines a big variety of its nature. Georgia is located in a large belt of foldy mountain systems. Only 12.8% of the whole Georgian territory lies at elevations below 200 m, 33.4% is situated between 200 and 1000 m, while 53.8% of the country's territory is at elevations higher than 1000 m.

The presence of a high barrier in the form of the Main Caucasian Ridge protects Georgia from an immediate invasion of cold air masses from the North. The open area from the Black Sea side conduces the penetration of warm humid air masses. Fig. 1.2 presents a scheme of air mass movements by directions in the atmospheric layer from 0.5 to 5.0 km above the sea level in various regions of Georgia in January and July [90], which clearly demonstrates the above-said.

Main anthropogenic sources of RASAA in Georgia are industry (chemical, food, etc.) and power industry, agriculture, forestry, transport, aviation, waste recycling and biomass consumption.

Fig. 1.1 presents the location of the biggest anthropogenic RASAA emission sources in Georgia (power industry, industry, transport) in Tbilisi, Telavi, Sokhumi, Rustavi, Gardabani, Kaspi, Zestaponi, Kutaisi, Chiatura, Batumi, Tkvarcheli. In this figure the location of six main (Tbilisi, Telavi, Tsalka, Anaseuli, Senaki, Sokhumi) and 2 auxiliary (Jvari Pass, Kazbegi) actinometric stations is presented, whose data were used for the determination of the atmospheric aerosol optical depth (see Chapter IV).

In the last years in Georgia with assistance of the national government, UNDP and GEF a national inventory of sources of "greenhouse" gases and aerosols was carried out for the period from 1980 till 1996. Estimations of anthropogenic emissions of CO_2, CH_4, N_2O, NO_X, CO, NMVOC, SO_2, solid and secondary sulphate and nitrate aerosols were made according to [51,57,62,63,73,101,115,143,147]. Main results of these works are presented in [36,37,56].

Table 1.6 presents the data on the mean annual emission in 1985-1996 of anthropogenic RASAA in Georgia according to [36,37,56]. As it follows from this table, the main anthropogenic "greenhouse" gases in Georgia are CO_2, CH_4 and N_2O. Nitrogen oxides, despite their sufficiently high share in the total emission of "greenhouse" gases (9.4% in CO_2 equivalent), because of the short presence time in the atmosphere play a considerable role in the "greenhouse" effect only at local scales. The total
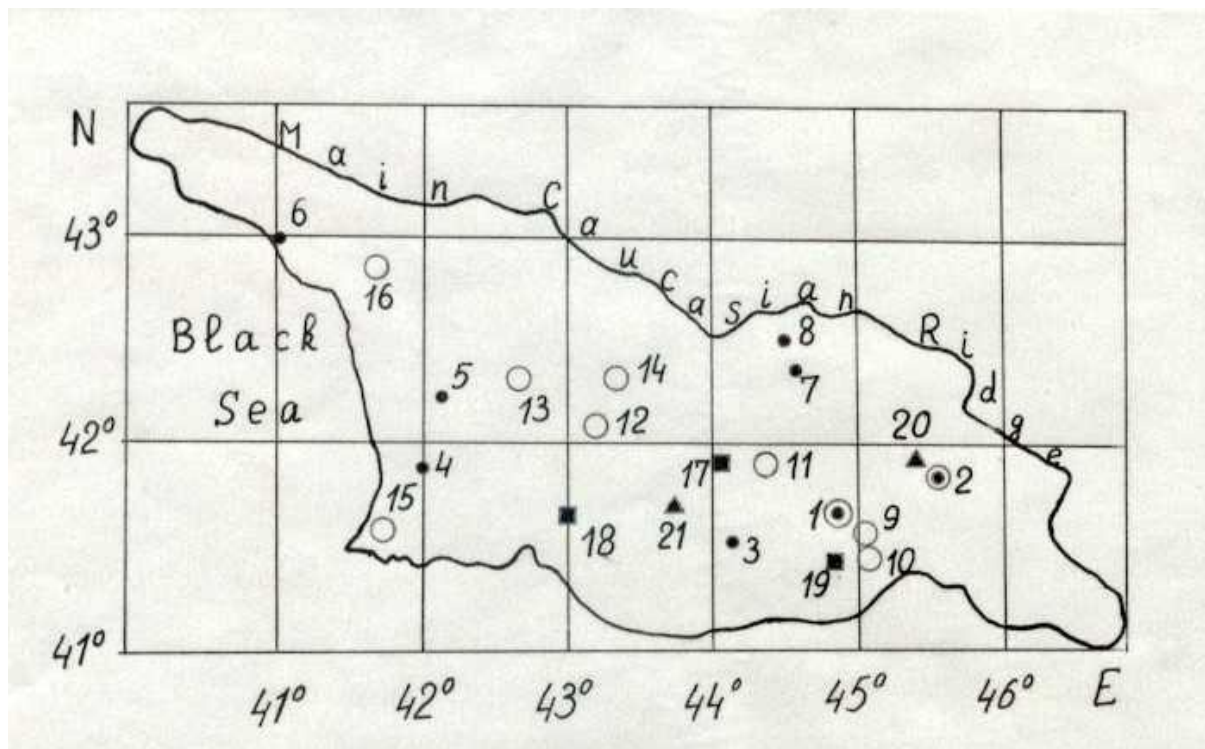
Fig 1.1

Disposition of actinometric stations (•) and main anthropogenic RASAA emission sources (o) on the Georgian territory. 1 - Tbilisi (403 m above the sea level); 2 - Telavi (568 m); 3 - Tsalka (1457 m); 4 - Anaseuli (158 m); 5 - Senaki (40 m); 6 - Sokhumi (116 m); 7 - Jvari Pass (2396 m); 8 - Kazbegi (3656 m). 9 - Rustavi (374 m); 10 - Gardabani (300 m); 11 - Kaspi (522 m); 12 - Zestaponi (200 m); 13 - Kutaisi (116 m); 14 - Chiatura (350 m); 15 Batumi (6m); 16 - Tkvarcheli (418 m); Sign (■) designates air pollution control sites in relatively low polluted towns. 17 - Gori (588 m); 18 - Akhaltsikhe (982 m); 19 - Marneuli (406 m); Sign (▲) designates stations, where total ozone measurements were carried out. 20 - Ruispiri (550 m); 21 - Abastumani (1700 m). There is a similar station in Tbilisi.

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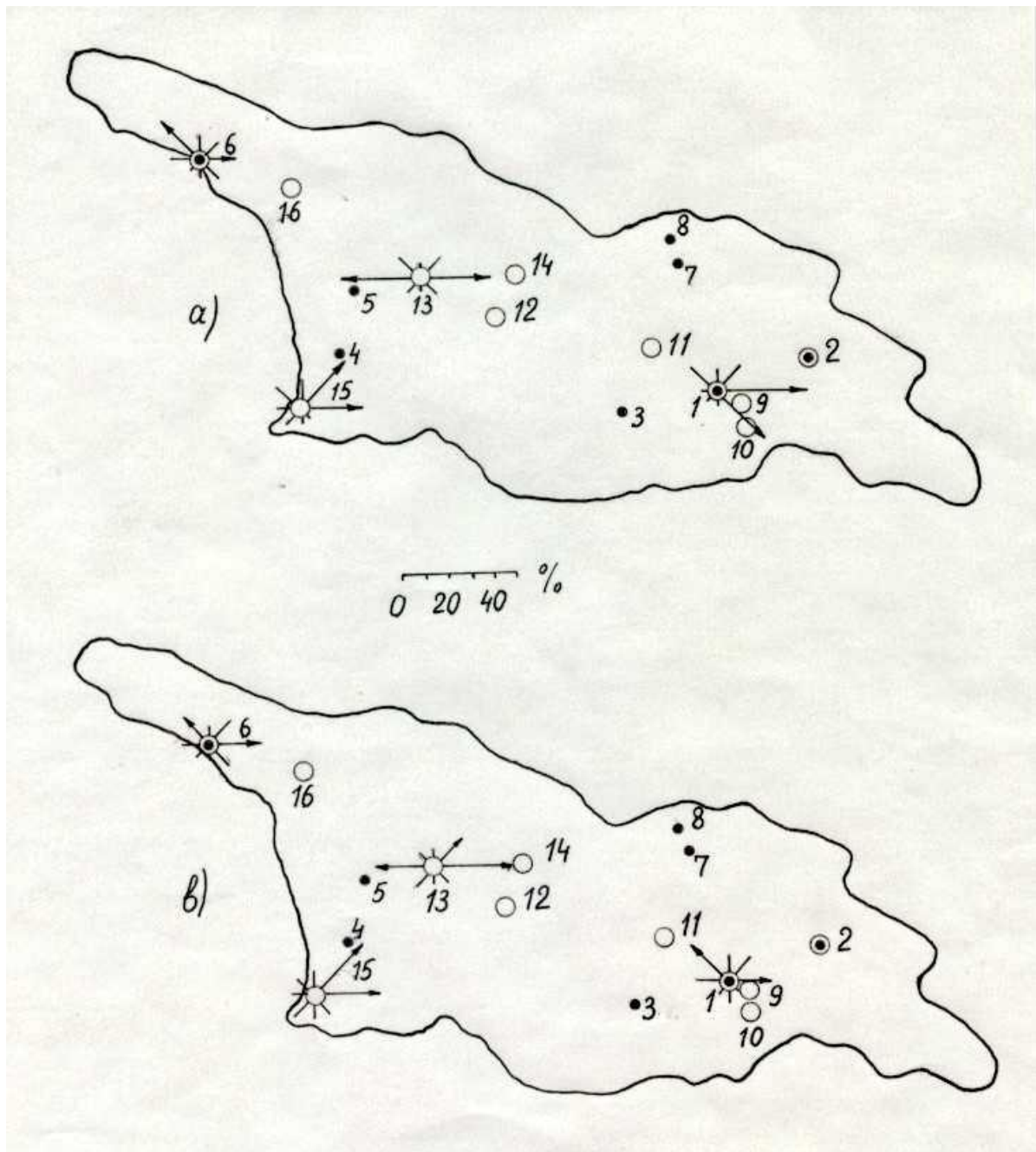
Fig. 1.2

Occurrence of the air mass movement directions in the atmospheric layer 0.5 - 5.0 km above the sea level in various regions of Georgia. a) January, b) July. (Site numbers are the same as in 1.1)

mean annual direct industrial emissions of solid particles and secondary sulphate and nitrate aerosols in the mentioned time period in Georgia amounted to 317 thousand tons. The share of secondary sulphates and nitrates from the total aerosol emission amounts to about 60%, which is in a good agreement with the same ratio for the global emissions of anthropogenic aerosols (Table 1.1).

It is noteworthy that sources of anthropogenic emissions of RASAA on the Georgian territory have a very non-uniform distribution. For example, in Eastern Georgia, the share of anthropogenic RASAA emissions in the total emission amounts to about 66%. In addition to a considerable number of industries and power plants, approximately a quarter of all transport of Georgia is concentrated in Tbilisi. Correspondingly the share of anthropogenic RASAA emissions in the city is about 36% of the total emission in Georgia. It should be noted also that in Eastern Georgia main sources of anthropogenic RASAA emissions are located in a line of 80-100 km in Kaspi, Tbilisi, Gardabani, Rustavi (Fig. 1.1). Considering the character of the air mass dynamics in Eastern Georgia and the fact that RASAA from large anthropogenic sources can be easily transported at distances of several tens and even hundreds of kilometers around the sources in a 2-3 km atmospheric layer [38,67,113], one could presume that all agricultural regions to the East of the Kaspi-Gardabani line (Fig. 1.2) get under the impact of these sources.

Table 1.6

Emission of gaseous and aerosol components of RASAA in Georgia in 1985-1996

RASAA	Thous. T per year	CO_2 equiv. thous. T per year	Ratio in CO_2 equiv. %
Carbon dioxide CO_2	25000	25000	65.4
Methane CH_4	300	6300	16.5
Nitrogen protoxide N_2O	6.6	2050	5.4
Nitrogen oxides NO_X	90	3600	9.4
Carbon oxide CO	430	1300	3.4
NMVOC	25		
Sulphur dioxide SO_2	170		
Solid emissions	122		
Soot	3.5		
Sulphates from SO_2	129		
Nitrates from NO_X	62		
Total of greenhouse gases	25827	38250	
Total of aerosols	317		
Total of secondary aerosols	191		

In Western Georgia anthropogenic RASAA emissions are less concentrated - twice as lower as in Eastern Georgia. Correspondingly local effects of the atmospheric pollution by RASAA in Western Georgia are considerably weaker than in Eastern Georgia.

Chapter II

The particularities of the anthropogenic RASAA emission change in Georgia

2.1   The anthropogenic emission of   some gaseous components of RASAA in Georgia in 1980-1996

Before the collapse of the former Soviet Union in Georgia were quite developed such branches of economy as power industry, light and heavy industry, food industry, transport, agriculture, etc. Table 2.1 presents the data on the mean annual emission of some gaseous components of RASAA in Georgia in 1980-1990 classified according to their sources [36,37,56]. The mean annual CO_2 emission in the mentioned period in Georgia amounted to 37 mln. tons. The main sources of anthropogenic CO_2 emissions were power plants and heating facilities (29.5%), metal production and processing plants including machine industry (20.4%) and accommodational fuel consumption and transport (10.2%). Almost 3/4 of the total emission of CO_2 in Georgia was by the mentioned sources.

The mean annual methane emission in the atmosphere in Georgia from 1980 to 1990 was 391 thousand tons. The main contributions in the methane were made by such sources as waste (38.1%), agriculture and volatile products fuel combustion (27.3% each).

The main sources of N_2O emissions in the atmosphere in the mentioned period were agriculture (79.1%) and industrial processes (15.6%). The total share of these sources was almost 95% from the mean annual N_2O emission in the atmosphere amounting to about 9 thousand tons.

The NO_X emission (Table 2.1) reached 134 thousand tons per year. Main sources of this RASAA component were transport (29.4%), power plants and heating facilities (20.1%), metal production and processing industries including machine industry (18.1%), accommodational fuel consumption (11.4%). Altogether these sources made up almost 80% of the total mean annual NO_X emission.

CO emissions at the average per year amounted to 626 thousand tons. The main part of these emissions was by transport (50%), forest use (33.9%) and agriculture (9.3%). Total - 93.2%.

The major part of NMVOC emissions was attributed to transport (74.4%) and industrial processes (17.7%) the total emission of the mentioned RASAA component being 48 thousand tons per year.

The mean annual SO_2 emission in 1980-1990 amounted to 254 thousand tons. Main emission sources of this gas were power plants and

Table 2.1

Emission of gaseous components of RASAA in Georgia in 1980-1990 (thousand tons). In brackets - ratio per total emission of the corresponding RASAA in %.

RASAA Type of emission per year	CO_2	CH_4	N_2O	NO_X	CO	NMVOC	SO_2
1. Power industry 1.1 Power production and heating	10919 (29.5)	0.206 (0.05)	0.037 (0.4)	27.00 (20.1)	3.02 (0.5)	0.794 (1.7)	93.80 (36.9)
1.2 Metal industry	6052 (16.4)	0.426 (0.11)	0.067 (0.7)	19.53 (14.6)	4.84 (0.8)	0.953 (2.0)	52.00 (20.5)
1.3 Chemical, celulose, paper industry	1238 (3.3)	0.088 (0.02)	0.013 (0.15)	4.00 (3.0)	1.00 (0.15)	0.171 (0.4)	10.61 (4.2)
1.4 Food industry, drinks, tobacco	1330 (3.6)	0.094 (0.02)	0.015 (0.2)	4.29 (3.2)	1.06 (0.2)	0.184 (0.4)	11.42 (4.5)
1.5 Industry of building materials	1462 (4.0)	0.103 (0.03)	0.016 (0.2)	4.71 (3.5)	1.17 (0.2)	0.202 (0.4)	12.55 (4.9)
1.6 Machine industry and metal processing	1469 (4.0)	0.103 (0.03)	0.016 (0.2)	4.74 (3.5)	1.17 (0.2)	0.203 (0.4)	12.61 (5.0)
1.7 Accomodational needs	4725 (12.8)	0.333 (0.09)	0.053 (0.6)	15.24 (11.4)	3.78 (0.6)	0.652 (1.4)	38.6 (15.2)
1.8 Agriculture, forestry, fishery	2246 (6.1)	0.158 (0.04)	0.025 (0.3)	7.24 (5.4)	1.80 (0.3)	0.310 (0.6)	19.08 (7.5)
1.9 Transport and aviation	3778 (10.2)	0.600 (0.15)	0.055 (0.6)	39.42 (29.4)	313.0 (50.0)	35.73 (74.4)	2.2 (0.9)
1.10 Emission from biomass	436 (1.2)	1.573 (0.4)	0.011 (0.1)	0.37 (0.3)	22.95 (3.7)		
1.11 Volatile emissions of fuel (coal, oil, gas)		106.6 (27.3)					
2. Industrial processes	1181 (3.2)	0.300 (0.08)	1.397 (15.6)	0.37 (0.3)	1.82 (0.3)	8.49 (17.7)	1.04 (0.4)
3. Forest use	1360 (3.8)	24.5 (6.3)	0.168 (1.9)	6.09 (4.5)	212.5 (33.9)		
4. Agriculture	806 (2.2)	106.7 (27.3)	7.085 (79.1)	0.96 (0.7)	57.94 (9.3)		
5. Waste		149 (38.1)					
Total	37000	391	8.96	134	626	48	254

heating facilities (36.9%), metal production and processing industries including machine industry (25.5%), accommodational fuel consumption (15.2 %) and agriculture (7.5%). Thus, the share of the mentioned sources in the total SO_2 emission made up a little more than 85%.

After the collapse of the USSR because of the destruction of economical relations, political conflicts and for other reasons in Georgia the level of industrial and agricultural production fell down strongly, the infrastructure changed, an energy-fuel crisis began. Correspondingly the emission of gaseous components of RASAA considerably decreased in 1991-1996 (Table 2.2). The distribution of main emission sources of gaseous components of RASAA and their share in the total emission also changed.

The mean annual emission of CO_2 in Georgia in 1991-1996 amounted to 13 mln. tons. The main CO_2 emission sources according to

their shares in the total emission of this gas redistributed in the following order: power and heat production (35.9%), accommodational fuel consumption (15.5%) and transport (12.0), metal production and processing industries including machine industry (11.9%). As in the first time period (1980-1990) the emissions from these sources in the second period (1991-1996) made up 3/4 of the total CO_2 emission. However, the share of CO_2 emissions due to power and heat production and also accommodational fuel consumption and transport increased considerably. At the same time the CO_2 emissions by metal production and processing decreased almost twice.

Table 2.2

Emission of gaseous components of RASAA in Georgia in 1991-1996 (thousand tons). In brackets - ratio per total emission of the corresponding RASAA in %.

RASAA Type of emission per year	CO_2	CH_4	N_2O	NO_X	CO	NMVOC	SO_2
1. Power industry 1.1 Power production and heating	4673 (35.9)	0.087 (0.04)	0.016 (0.4)	11.40 (23.6)	1.27 (0.5)	0.336 (10.2)	39.63 (47.7)
1.2 Metal industry	1207 (9.3)	0.085 (0.04)	0.013 (0.3)	3.84 (7.8)	0.95 (0.4)	0.168 (5.1)	10.32 (12.4)
1.3 Chemicals, celulose, paper industry	147 (1.1)	0.008 (0.004)	0.002 (0.05)	0.47 (1.0)	0.12 (0.05)	0.02 (0.6)	1.24 (1.5)
1.4 Food industry, drinks, tobacco	293 (2.3)	0.021 (0.01)	0.003 (0.07)	0.93 (1.9)	0.23 (0.09)	0.040 (1.2)	2.48 (3.0)
1.5 Industry of building materials	113 (0.9)	0.008 (0.004)	0.002 (0.05)	0.36 (0.7)	0.09 (0.04)	0.015 (0.5)	0.96 (1.2)
1.6 Machine industry and metal processing	343 (2.6)	0.024 (0.01)	0.004 (0.09)	1.09 (2.3)	0.27 (0.1)	0.047 (1.4)	2.91 (3.5)
1.7 Accomodational needs	2015 (15.5)	0.140 (0.07)	0.022 (0.5)	6.42 (13.3)	1.59 (0.6)	0.274 (8.3)	16.7 (20.1)
1.8 Agriculture, forestry, fishery	957 (7.4)	0.067 (0.03)	0.011 (0.3)	3.05 (6.3)	0.76 (0.3)	0.129 (3.9)	8.12 (9.8)
1.9 Transport and aviation	1558 (12.0)	0.369 (0.2)	0.029 (0.7)	17.53 (36.3)	122.0 (48.8)	0.878 (26.6)	0.4 (0.5)
1.10 Emission from biomass	58 (0.4)	0.200 (0.1)	0.002 (0.05)	0.06 (0.1)	3.00 (1.2)		
1.11 Volatile emissions of fuel (coal, oil, gas)		32.95 (16.3)					
2. Industrial processes	312 (2.4)	0.057 (0.03)	0.858 (19.9)	0.15 (0.3)	0.73 (0.3)	1.384 (41.9)	0.13 (0.2)
3. Forest use	731 (5.6)	8.900 (4.4)	0.060 (1.4)	2.93 (6.1)	77.95 (31.2)		
4. Agriculture	593 (4.6)	73.87 (36.6)	3.291 (76.4)	0.07 (0.1)	41.38 (16.6)		
5. Waste		85.18 (42.2)					
Total	13000	202	4.31	48.3	250	3.3	83

Emissions of CH_4 in the second time period at the average per year in Georgia amounted to 202 thousand tons. Approximately 95% of this emission was determined by the same sources as in 1980-1990. However the share of CH_4 emissions by waste increased up to 42.2%, while by

agriculture - to 36.6%. At the same time the share of methane emissions due to volatile products of fuel combustion decreased down to 16.3%.

The emission of N_2O in 1991-1996 at the average per year amounted to 4.31 thousand tons. As in the first time period the main sources of the mentioned RASAA component were agriculture and production (76.4% and 19.9 % of the total N_2O emission respectively).

In the second time period the NO_X emission in the atmosphere in Georgia amounted at the average per year to 48.3 thousand tons (Table 2.2). In comparison to the previous time period the NO_X emission by transport rose up to 36.3%, to 23.6% - by power and heat production, to 13.3% - by accommodational fuel consumption. At the same time the share of NO_X emissions by metal production and processing industry including machine industry decreased to 10.1%. In the aggregate for the mentioned sources the NO_X emission share in the second time period changed insignificantly and amounted to 83.3% versus 80% in 1980-1990.

Emissions of CO at the average per year in 1991-1996 amounted to 250 thousand tons. The share of transport and forest use emissions diminished to a certain extent (48.8% and 31.2% respectively). At the same time the share of CO emissions by agriculture rose up to 16.6%. The total share of the mentioned sources in the CO emissions amounted to 96.6%.

Emissions of NMVOC in the second time period decreased at the average per year to 3.3 thousand tons. The share of emissions due to production was 41.9%, transport - 26.6%, power and heat production - 10.2%.

The mean annual SO_2 emission in 1991-1996 decreased in Georgia to 83 thousand tons. The share of the emissions of this gas by power and heat production rose up to 47.7%, by accommodational fuel consumption - to 20.1%, by agriculture - to 9.8%. At the same time the share of SO_2 emissions by metal production and processing industry fell down to 15.9% versus 25.5% in the previous time period. The share of the mentioned sources in the total SO_2 emission in the second time period amounted to 93.5%, which is approximately by 8.5% higher than the same figure in 1980-1990.

In the aggregate the ratio of the emissions of the gaseous components of RASAA in Georgia in 1991-1996 to their emissions in 1980-1990 was: for CO_2 - 35.1%, CH_4 - 51.7%, N_2O - 48.1%, NO_X - 36.0%, CO - 39.9%, NMVOC - 6.9%, SO_2 - 32.7%. It means that the emission of CO_2, NO_X, CO and SO_2 in the second time period in comparison to the first one decreased approximately three times, while CH_4 and N_2O - two times. Thus, in 1991-1996 in comparison to the previous period an increase in the share of methane and N_2O in the total "greenhouse" gas (CO_2, CH_4, N_2O, NO_X, CO) emission took place, which is clearly demonstrated in Fig. 2.1 and Table 2.3.

Fig. 2.1 presents the dynamics of the variations of the annual anthropogenic emission of the mentioned "greenhouse" gases in Georgia in 1980-1996 in CO_2 equivalent. The same picture gives the data on the total
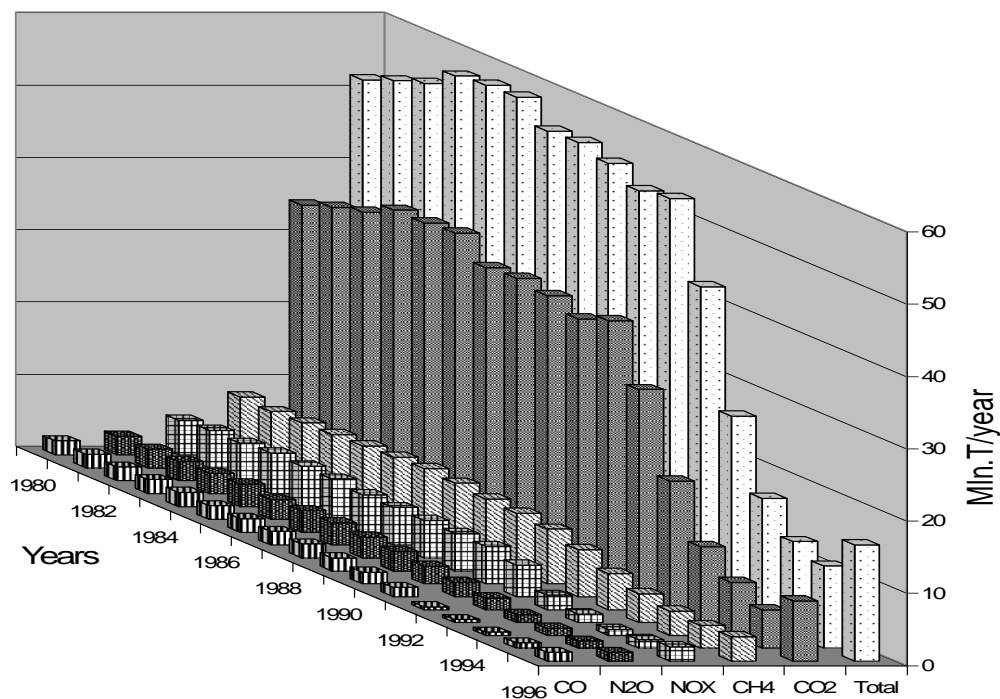
Fig. 2.1

Emission of greenhouse gases in Georgia in 1980-1996
in CO_2 equivalent (mln. T/year)

emission of these gases. Table 2.3 presents the data on the mean annual values of the "greenhouse" gas emissions in Georgia in 1980-1990 and 1991-1996 in CO_2 equivalent. It follows from the table that in the second period in comparison to the first one the share of NO_X and CO emissions in the total "greenhouse" gas emission in CO_2 equivalent changed inconsiderably. At the same time the share of N_2O rose up a little (by 1.3%), considerably increased the share of methane (by 5.1%) and correspondingly reduced the share of carbon dioxide (by 5.9%).

It is noteworthy that in the last period the CO_2 emission from $1km^2$ of Georgian territory fell down to 185 tons per year versus 500 tons in the middle of 1980-s (Table 1.5). Thus, at present from the Georgian territory in the atmosphere gets at the average 9 times less of anthropogenic carbon dioxide than from the man-inhabited territory. Considering the close location of Georgia to highly developed industrial countries of Europe and Asia and Aslo the air mass movement dynamics (Fig. 1.2) one can maintain that the content of "greenhouse" gases in the atmosphere on this territory is

Table 2.3

Mean annual anthropogenic emission of CO_2, CH_4, N_2O, NO_X and CO in Georgia in 1980-1990 and 1991-1996 in CO_2 equivalent (thous. T).

RASAA	CO_2	CH_4	N_2O	NO_X	CO	Total
I) 1980-1990	37000	8211	2778	5360	1878	55227
Ratio per total emission (%)	67.0	14.9	5.0	9.7	3.4	100
II) 1991-1996	13000	4242	1336	1932	750	21260
Ratio per total emission (%)	61.1	20.0	6.3	9.1	3.5	100
Ratio (II/I) (%)	35.1	51.7	48.1	36.0	39.9	38.5

mainly determined by external sources of their emission. As an example it can be mentioned that these countries contribute almost a half in the global "greenhouse" gas emission [49]. In particular, in the Netherlands only the transport emission of CO_2 in the atmosphere in 1995 amounted to 27 mln. tons [71]. This is more than two times higher than the whole mean annual anthropogenic CO_2 emission in Georgia in 1991-1996. Thus, it can be presumed that the effect of local emission sources of "greenhouse" gases in Georgia on their content in the atmosphere has a local character (Fig. 1.1). It seems that their impact is significant for areas from several hundreds to several thousand square kilometers [38,44]. However, due to the fact that Georgia occupies only about 70 thousand square kilometers, even local changes in climatic elements carry a big importance for the economy of this country.

2.2 The anthropogenic emission of the aerosol component of RASAA in Georgia in 1985-1996

In Georgia the main anthropogenic sources of aerosol emissions in the atmosphere represent fuel combustion for accommodational and production purposes, transport, combustion of waste, emissions due to the technological cycles, etc. Estimation of the share of the aerosol component of RASAA is associated with certain difficulties and in a number of cases is even impossible. However, generally such estimations can be made [51,56,57,73,101,115,143,147].

Table 2.4

Emission of anthropogenic aerosols in Georgia (thous. T/year) by main industries, power industry and transport

Years	Solid Emissions	Soot	Secondary Aerosols		Total Amount of Emissions
			Sulphates from SO_2	Nitrates from NO_x	
1985	188	3.9	208	94	494
1986	241	3.9	194	90	529
1987	223	4.0	196	90	513
1988	201	4.2	194	90	489
1989	173	4.3	189	88	454
1990	145	4.3	189	87	425
1991	90	6.3	147	76	319
1992	80	No data	103	32	≥215
1993	47	1.3	54	22	124
1994	30	0.3	36	14	80
1995	24	1.8	15	18	59
1996	15	4.4	23	34	76
1985-1990 (I)	195	4.1	195	90	484
1991-1996 (II)	48	≥2.8	63	33	≥147
II/I (%)	25	>68	32	37	≥30
Ratio per Total Aerosol Content (%)					
1985-1990	40	1	40	19	100
1991-1996	33	2	43	22	100

Table 2.4 presents the data on the emissions in Georgia of solid aerosols by industry, power industry and heating facilities, soot particles by transport using petrol and dizel fuel, secondary sulphate and nitrate aerosols formed from sulphur dioxide and NO_X emitted by the sources indicated in Tables 2.1 and 2.2. As it follows from Table 2.4 in 1991-1996 the total emission of all aerosols at the average per year amounted to 147 thousand tons per year and made up about 30% of the emission in the first period. The share of solid particles in the total aerosol emission in 1985-1990 was 40%, soot particles - 1%, secondary sulphate and nitrate aerosols
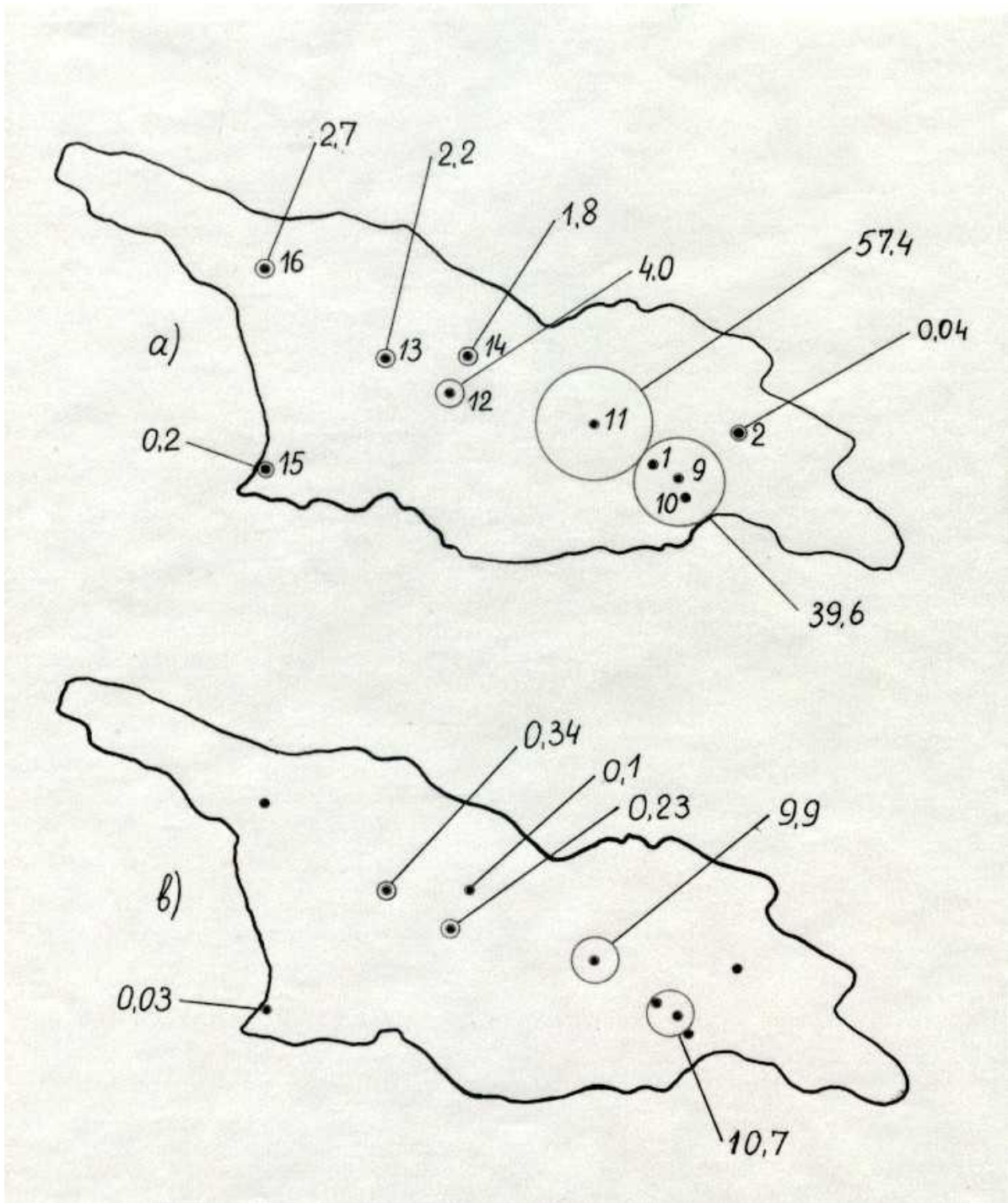
Fig. 2.2

Mean annual emission of aerosols (in thous. tons) by large industries in Georgia in 1985-1990 (a) and 1991-1996 (b). (The numbers of towns are the same as in Fig. 1.1.) (For N 2 - Telavi, the data on aerosol emissions due to the hail prevention activities in Kakheti are presented.)

- 59%. In 1991-1996 the share of solid particles fell down to 33%, the share of soot particles rose up to 2%, secondary sulphate and nitrate aerosols increased to 65%.

Fig. 2.2 as an illustration presents the data on the mean annual emission of solid aerosols by large industries in Georgia in 1985-1990 and 1991-1996. In the second time period in comparison to the first one the emission of solid aerosols decreased four times, while the emission of secondary sulphates and nitrates - three times (Tables 2.4, Fig. 2.2). It is noteworthy also that in 1985-1990 direct emissions of solid aerosols by industries in Eastern Georgia amounted to 90% of the emission by all large industries. In 1991-1996 this share rose up to 97% (Fig. 2.2).

As in the case of "greenhouse" gases the atmospheric pollution over the Georgian territory by anthropogenic aerosols is mainly determined by external emission sources located in developed industrial countries of Europe and Asia (Table 1.5, Fig.1.2). Local sources of anthropogenic aerosols in Georgia affect their content in the atmosphere over local areas near these sources (Fig.1.1 and 2.2).

Chapter III

Spatial-temporary characteristics of the distribution of some RASAA in the troposphere over the Georgian territory

The information on the vertical distribution of various microadmixtures in the atmosphere can be acquired by aircraft, balloon, lidar, satellite, etc. measurements [2,12,31,38,76,81,113,116,133,144,145]. For example, it has been established [35,38,146] that within the 50 kilometer atmospheric layer the volume concentration of CO_2 in middle latitudes varies little with elevation (relative variation range is only 9%). The volume concentration of CO in comparison to the near-ground values increases up to the elevation of 2.0 km by 28%, then decreases up to the elevation of approximately 25.0 km by 82%. In the layer 25-50 km the CO content varies little with height and amounts approximately to 19% of the near-ground concentration. The main part of total ozone ($\geq$ 90%) is concentrated in the stratosphere. In the troposphere the ozone content varies inconsiderably with elevation. Significant variations of tropospheric ozone take place during winds, thunderstorm processes, photochemical smogs [9,81,144]. During photochemical smogs elevated concentrations of ozone are observed up to the height of 3 km. The ozone content in this atmospheric layer decreases approximately linearly and at the height 3 km it amounts to about 40% of the near-ground concentration [114].

In Georgia investigations of various RASAA components drew particular attention [1,7,9,10,12,16,17,19,24,25,28-31,39,59,60,69,81-83,95,96,118,128,133,134,136-138]. A considerable part of these works is related to the study of physical properties of aerosols, the effect of meteorological conditions on their content in the atmosphere [9,10,12,28-31,59,60,69,95,118]. Attention was paid also to the study of the distribution of natural radioactive aerosols in the atmosphere and various aspects of their use as passive tracers for the investigation of some atmospheric processes [6,7,12,117,119]. In the last years the "passivity" in the atmosphere of natural and artificial origin has been revised and their role in the formation of the microphysical and electrical structure of clouds, secondary aerosols, etc. has been studied [70,99,111]. Similar investigations have been started also in Georgia [12,15].

A number of works is dedicated to questions related to the problems of the air pollution by aerosol and gaseous admixtures, monitoring and prediction of this pollution [1,29,30,59,60,69,94]. Since 1975 in Georgia systematic measurements of the content in the atmosphere of CO, SO_2, NO_X, dust and other admixtures in big cities have been carried out [59,60].

Georgia has rich traditions also in the field of atmospheric ozone investigations, which have been carried out since 1957. An important role in these investigations belongs to the Institute of Geophysics of the Georgian Academy of Sciences, where during a long time spatial-temporary variations of total ozone, its vertical distribution and near-ground concentration in Georgia have been studied [9,81-83].The next chapter of this book gives a detailed description of the results of the recent investigations of the total ozone variability over the territory of Georgia.

Wide-scale investigations have been carried out in the field of the study of optical properties of atmospheric aerosols, spatial-temporary variations of the atmospheric aerosol optical depth over the territory of Georgia, direct and indirect climatic effects of atmospheric aerosols [16-19,23-25,39,50,54,87,126-128,131-134,136,137]. The priority in these investigations in Georgia belongs to the Institute of Geography of the Georgian Academy of Sciences. In Chapter V of this book the latest results of the investigations of the dynamics of the aerosol pollution of the atmosphere in Georgia are presented.

3.1 The content of some RASAA near the ground and in the troposphere in various regions of Georgia

The distribution of RASAA near the ground on the Georgian territory, as well as their emission sources, also has a non-uniform character. Table 3.1 presents the data on the mean annual content of dust, CO, SO_2, NO_X and soluble sulphates near the ground in various towns of Georgia in 1985-1990 [60,69]. As it follows from this table depending on a site location and the strength of a RASAA emission source the content of dust near the ground varies from 0.2 to 1.0 mg/m^3, CO - from 2 to 5 mg/m^3, SO_2 - from 0.03 to 0.18 mg/m^3, NO_X - from 0.05 to 0.14 mg/m^3, soluble sulphates - from 0.010 to 0.040 mg/m^3. The ozone concentration near the ground at 15 o'clock at the average per year in 1985-1990 amounted to 0.038 mg/m^3.

Table 3.1

Mean annual contents of some RASAA in the near-earth atmospheric layer in various towns of Georgia in 1985-1990 [60,69] in mg/m^3.

Town	N on Fig.1.1	Dust	CO	SO_2	NO_X	Solvable sulphates
Tbilisi	1	0.5	5	0.11	0.09	0.015
Sokhumi	6	0.3	3.5	0.08	0.06	0.015
Rustavi	9	0.6	3	0.15	0.14	0.020
Kaspi	11	0.5	3	0.08	0.07	0.010
Zestaponi	12	0.5	4	0.10	0.07	0.040
Kutaisi	13	1.0	5	0.11	0.06	0.030
Batumi	15	0.2	3	0.11	0.07	0.015
Tkvarcheli	16	0.2	2	0.18	0.06	-
Gori	17	0.3	2	0.03	0.05	-
Akhaltsikhe	18	0.3	2	0.03	0.05	-
Marneuli	19	0.3	4	0.03	0.05	-

It is noteworthy that the main sources of anthropogenic RASAA emissions are not located in Gori, Akhaltsikhe and Marneuli. Nevertheless their concentrations here are though lower than in large industrial centers, still sufficiently high. This indicates once more that in Georgia with its small territory the effect of industrial regions on the atmosopheric pollution level in agricultural areas is quite essential.

The content of the mentioned RASAA near the ground varies during a day. Table 3.2 presents the data on variations of the mean annual concentrations of dust, CO, SO_2, NO_X and ozone from 07 till 21 o'clock local time in Tbilisi. The data are normed by the value of the mean daily concentrations of the corresponding admixtures. As it follows from this

Table 3.2

Daily content variations of some RASAA in the near-earth atmospheric layer in Tbilisi [60,81]. Normed per mean daily concentration (%).

RASAA	Time (hours)					
	07	10	13	15	18	21
Dust	88	108	106	102	102	92
CO	75	100	125	117	108	92
SO_2	95	101	107	110	102	98
NO_X	97	103	109	108	100	98
O_3	83	76	121	131	109	79

table the amplitude of the oscillations in the near-ground layer in Tbilisi of dust amounts to 88-108% at 07 and 10 o'clock respectively; CO - 75-125% at 07 and 13 o'clock; SO_2 - 95-110% at 07 and 15 o'clock; NO_X - 97-109% at 07 and 13 o'clock; ozone - 76-131% at 10 and 15 o'clock. Such daily variations of the mentioned RASA near the ground is quite characteristic for industrial cities and is related mainly to the industrial activity and transport[12,44,59]. The minimum ozone content at 10 o'clock coincides with the maximum dust content in the air. The maximum near-ground ozone content at 15 o'clock follows the maximum NO_X content in the air at 13 o'clock and is determined by photochemical transformations of nitrogen oxides into ozone. A more detailed description of the near-ground ozone concentration variations in Georgia under conditions of a photochemical smog can be found in [12,81]. It can be noted only that the ozone content in the atmosphere is in an inverse corelation with the content of aerosols, which represent one of its sink sources. In addition, ozone together with sulphur oxides participates in the secondary aerosol formation according to the scheme gas→particle [12,44,46,99] and its part is consumed during the mentioned chemical transformations. In the second half of a day in the near-ground atmospheric layer during photochemical reactions nitrogen oxides generate more ozone than it is consumed for the secondary particle formation and oxidation of the already existing aerosols. This very fact together with the daily variations of meteorological factors (temperature, turbulence, solar radiation, etc.) determines the maximum near-ground ozone content in the second half of a day. A similar daily variation of the near-ground ozone concentration is inherent to rural areas. However, in different seasons of a year there is a considerable difference between the near-ground ozone concentrations in rural and urban areas. For example, at 15 o'clock from April till August in Tbilisi the atmospheric ozone content according to the data of 1984-1985 amounted at the average to 0.050 mg/m^3, while in the village of Ruispiri (10 km to the West from Telavi) - 0.041 mg/m^3. In other months (September-March) in Tbilisi the ozone content was 0.016 mg/m^3, in Ruispiri - 0.043 mg/m^3 [81]. These data

clearly demonstrate the role of anthropogenic air pollution in the photochemical ozone formation and sink processes in the atmosphere.

Table 3.3 presents the data on monthly dust, CO, SO_2, NO_X and ozone concentrations in some towns in Georgia. In order to be demonstrative the data are given in the form of the relative variation $\left(\dfrac{X\max - X\min}{\overline{X}}\right)\cdot 100\%$. As it follows from this table (with exception of dust in Sokhumi and Rustavi, CO in Tbilisi, Kutaisi and Batumi, NO_X in Batumi and ozone in Tbilisi) monthly variations of the concentrations of the mentioned RASAA near the ground are mainly absent (do not exceed 25% from the mean annual values). The biggest monthly variations were observed in the mean monthly near-ground ozone concentration in Tbilisi (variation - 186%). In Ruispiri the variation of the mean monthly near ground ozone concentration amounts to 111%. Thus, the effect of anthropogenic pollution is well observed in the near-ground ozone concentration.

Table 3.3

Variational scale of mean monthly near-ground concentrations of RASAA in various towns of Georgia [60,81]. Normed per mean annual concentration (%).

RASAA / Town	Dust	CO	SO_2	NO_X	O_3
Tbilisi	25	40	18	17	186
Sukhumi	33	25	12	0	-
Rustavi	38	25	12	17	-
Zestaponi	20	0	18	20	-
Kutaisi	25	40	13	25	-
Batumi	0	33	23	40	-

It is noteworthy that near-ground dust, CO, SO_2, and NO_X control sites are located mainly not far from their emission sources (industries, highways) [59]. Correspondingly the data presented in Tables 3.1-3.3 characterize the mean level of the air pollution by these admixtures and their variations for such large RASAA emission sources as cities.

The decrease of the anthropogenic RASAA emissions after the collapse of the former Soviet Union affected their concentrations near the ground. Table 3.4 presents the data on the mean annual concentrations in the near-ground atmospheric layer of CO, SO_2, NO_X and ozone in Tbilisi and Rustavi in 1991-1996 [60,69]. A comparison of Tables 3.1 and 3.4 shows that in Tbilisi and Rustavi in the mentioned time period in comparison to 1985-1990 the content of dust amounts to 60% and 50% respectively, CO - 60% and 100%, SO_2 - 9% and 27%, NO_X - 44% and

43%. It means that the concentration of SO_2 in the atmosphere decreased most of all. The concentration of the near-ground ozone on the contrary rose up by 42% in 1991-1996 in comparison to the previous period. This effect is probably related to a less consumption of ozone for the aerosol oxidation and secondary particle formation during photochemical reactions.

Table 3.4

Mean annual content of dust, CO, SO_2, NO_X, and ozone in the near-earth atmospheric layer in Tbilisi and Rustavi in 1991-1996 [60,69]. (In mg/m^3).

Town	Dust	CO	SO_2	NO_X	O_3
Tbilisi	0.3	3	0.01	0.04	0.054
Rustavi	0.3	3	0.04	0.06	-

Let's estimate how the amount of secondary sulphate particles near the ground in Tbilisi could change in the last years. For this purpose the data given in [99] are used. In particular as a result of laboratory experiments it was shown in this work that humid air in a presence of SO_2 and ozone (0.53 and 0.1 mg/m^3 respectively) about $8.4 \cdot 10^3$ cm^{-3} Aitken nuclei were observed. A presence of radon in this mixture in the amount 7.4 Bk/m^3 increased the Aitken nuclei concentration in the air approximately 2.9 times. Adding of ethilen in the concentration of 0.12 mg/m^3 to a mixture humid air+SO_2+O_3+radon increased the Aitken nuclei concentration in comparison to a mixture humid air+SO_2+O_3 7.9 times, while to a mixture humid air+SO_2+O_3+ethilen 4.4 times. In a mixture humid air+SO_2+radon Aitken nuclei were not generated. Thus, a presence of radon (or air ionisation) conduces intensification of secondary aerosol formation processes in reactions gas→particle.

The same work [99] presents the data on the mean monthly values of the concentrations of Aitken nuclei (N_A), SO_2, O_3, ethilen and radon near the ground in Trombay (India) during altogether 14 months from 1982 till 1983. The concentrations varied within the following ranges: relative humidity from 40 to 86%, SO_2 from 0.0045 to 0.025 mg/m^3, the mean value being 0.012 mg/m^3, O_3 from 0.002 to 0.057 mg/m^3, the mean value being 0.022 mg/m^3, ethilen from 0.0019 to 0.066 mg/m^3, with the mean value 0.016 mg/m^3, radon from 0.3 to 5.0 Bk/m^3 with the mean value 2.2 Bk/m^3. A statistical analysis of these data in all observation months showed that the content of Aitken nuclei in the air in Trombay is well correlated to the SO_2 and radon concentrations (corelations +0.74 and +0.67 respectively). The corelation of N_A with ethilen and ozone is not important (+0.28 and +0.04 respectively). Thus, a presence of ozone with a

concentration at least 0.002 mg/m^3 conduces the formation from SO_2 in the air of Aitken Nuclei, whose content is practically independent from the near-ground ozone variations. A presence of ethilen creates auspicious conditions for the Aitken nuclei formation but also does not affect their content in the atmosphere. At the same time variations of the SO_2 and radon concentration in the air considerably influence the concentration of Aitken nuclei. A multiregression analysis showed that the aggregate corelation between N_A, SO_2 (N_{SO2}) and radon (N_{Rn}) concentration amounts to +0.82. A multiregression equation of the dependence of the Aitken nuclei concentration on the SO_2 and radon concentrations in Trombay has the following form:

$$N_A = \left(27 + 2900N_{SO_2} + 8.3N_{Rn}\right) \cdot 10^3 \, cm^{-3} \qquad (3.1)$$

where N_{SO2} is in mg/m^3; N_{Rn} - in Bk/m^3.

The mentioned relation allows to estimate the contribution of each component in the N_A variation. For example, for mean values of N_{SO2} (0.012 mg/m^3) and N_{Rn} values between the maximum and minimum (0.3-5.0 Bk/m^3) in Trombay the Aitken nuclei concentration may change from 66 10^3 to 104 10^3 cm^{-3} (or 1.6 times). For mean values of N_{Rn} and N_{SO2} values between the maximum and minimum N_A can be from 59 10^3 to 120 10^3 cm^{-3} (or increase more than twice).

It is noteworthy that in the air ionization near the ground except of radon and short living products of its decay contribute cosmic rays, beta and gama radiation of the Earth's surface. Without radon and products of its decay the ionization intensity near the ground amounts approximately to 5.5 ion couples/cm^3·sec [40]. Radon, radium A and radium C' in the equilibrium radon concentration 1.0 Bk/m^3 creates about 0.8 ion couples/cm^3·sec. Thus in the near-ground layer in Trombay the ionization intensity amounted at the average per month to 7.3 ion couples/cm^3·sec with variations from 5.8 to 9.5 ion couples/cm^3·sec. This means that for mean values of N_{SO2} the growth of the ionization intensity in the near-ground atmosphere in Trombay 1.6 times led to an increase of N_A also 1.6 times.

In Tbilisi the mean monthly relative humidity varies between 57 and 75% [47]. The radon content according to the data of multiyear observations varies at the average per month from 1.8 to 9.3 Bk/m^3 [119]. Correspondingly the ionization intensity in the near-ground air in Tbilisi varies at the average per month approximately from 7.0 to 13 ion couples/cm^3·sec. The SO_2 and ozone content in Tbilisi (Tables 3.1 and 3.4)
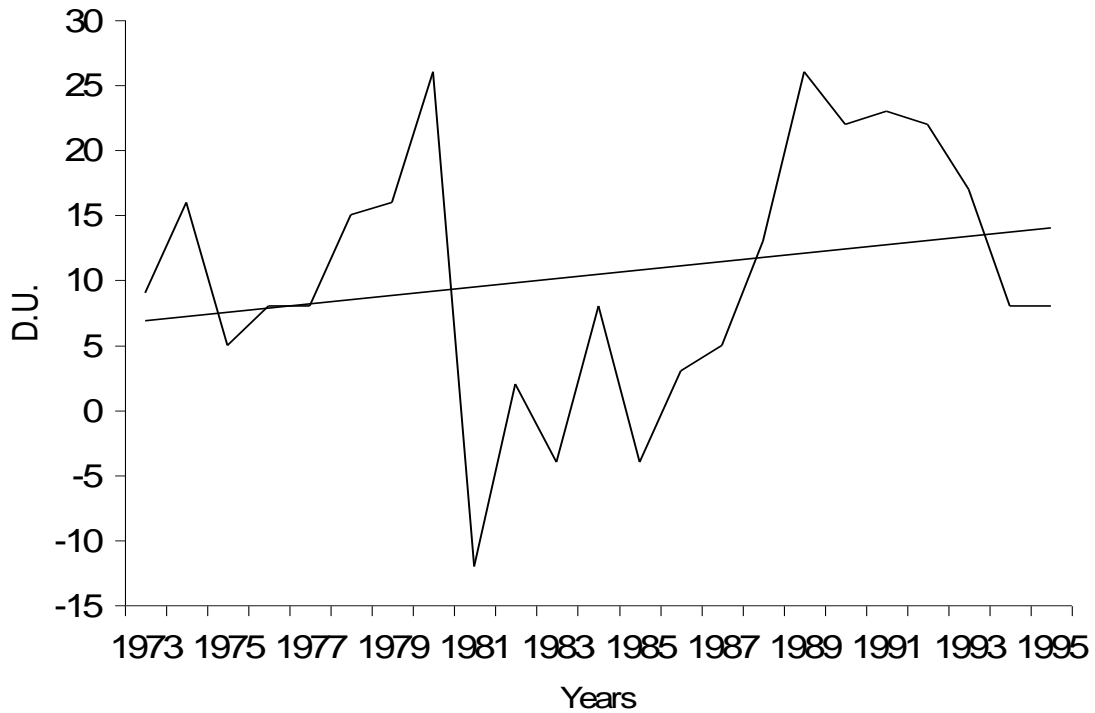
Fig. 3.1

Trend of mean annual total tropospheric ozone in Tbilisi in 1973-1995

is sufficient for secondary aerosol generation. Thus the conditions in Trombay and Tbilisi (at least for the last years) are quite similar. Following this let's assume N_A in Tbilisi depends on N_{SO2} and N_{Rn} in the same way as in Trombay (equation (3.1)). Then in 1985-1990 with the mean SO_2 concentration in Tbilisi 0.11 mg/m^3 the concentration N_A of sulphate aerosols amounted at the average per year to approximately 400 10^3 cm^{-3}, while in 1991-1996 with the mean SO_2 content 0.01 mg/m^3 - about 100 10^3 cm^{-3}.

These estimations may be justified also by the following calculations. The mass of sulphate aerosols of submicron sizes 0.2 10^{-2} - 0.4 10^{-2} mcm makes up about 5% of their total mass [2]. Correspondingly in Tbilisi in 1985-1990 the mean annual amount of sulphates is approximately 0.75 mcg/m^3 (Table 3.1). The density of sulphate aerosols equals to about 1.8 g/cm^3 [2]. Easy calculations show that for the Aitken nuclei concentration in Tbilisi 400 10^4 cm^{-3} their weight content within the mentioned submicron range could vary between 0.24-1.9 mcg/m^3. Thus for rough estimations of the sulphate condensation nuclei content near the ground in Tbilisi the expression (3.1) is quite acceptable. Correspondingly

the decrease 11 times of the SO_2 content near the ground in Tbilisi in 1991-1996 in comparison to 1985-1990 led to the decrease of the sulphate condensation nuclei amount 4 times. This, together with the increase of the total weight concentration of aerosols resulted in an intensive growth of the near-ground ozone concentration in Tbilisi in 1991-1996.

Finally it should be noted that in Tbilisi as well as in other industrial regions of the world in the last decades a positive trends has been observed not only in the near-ground ozone, but also in its column concentration in the troposphere. Fig. 3.1 presents the data on the variations of the difference of the mean annual values of total ozone ΔX in Tbilisi and Abastumani (Fig. 1.1). The ozonometric station in Abastumani is located at the elevation 1700 m above the sea level, approximately 80 km to the West from Tbilisi in a nonindustrial area of Georgia. Therefore the difference between the total ozone in Tbilisi and Abastumani may be considered as a characteristic of the tropospheric total ozone over Tbilisi. As it follows from the Fig. 3.1 in 1973-1995 over Tbilisi a positive trend of ΔX values was observed. Equations of linear regression relating ΔX values with time has the form:

$$\Delta X=0.32(t-1972)+6.5 \text{ D.U.} \qquad (3.2)$$

where t - years, $1973 \leq t \leq 1995$.

3.2   The distribution of aerosols over the Georgian territory in the lower troposphere

At the Institute of Geophysics of Georgian Academy of Sciences during a number of years investigations of the vertical distribution of aerosols and radon decay products in the lower 5 kilometer layer of the atmosphere were carried out by means of a flying laboratory IL-14. The measurements of the number concentration of aerosols were made using membrane filters and impactors with a subsequent determination of the particle concentration and sizes by means of a microscope [7,11,12,31,81,118]. In a number of cases simultaneously the vertical distribution of the weight and number concentrations were measured, which allowed to determine their density at various elevations [95]. Synchronous measurements of the content of radon decay products and small ions in the air allowed to estimate the concentration of condensation nuclei [5,7,40]. In particular, it was shown that cumulus cloudiness conduces an increase of the aerosol content in the lower troposphere [9,12,81]. Later similar results were presented also in [34]. Below are presented the results of a generalized analysis of the existing information on the distribution of aerosols of the radiatively active size range in the free atmosphere over the territory of Georgia.

Table 3.5 presents the data on the vertical distribution in the lower 5 kilometer atmospheric layer of the number concentration of aerosols with radii more than 0.35 mcm over Tbilisi, Zestaponi and Kakheti. Over Tbilisi and Zestaponi the measurements were carried out in cloudless days. The data of the measurements in Kakheti are divided in three groups: cloudless days (I), sunny days with cumulus clouds (II), sunny days with all types of clouds including cumulus (III). As it follows from Table 3.5 the content of aerosols over Tbilisi for cloudless days is higher than their content over Zestaponi and Kakheti at all elevations. The variations of the aerosol concentration in the layer 1.0-3.0 km over Tbilisi and Telavi in cloudless days are approximately similar ($31 \leq C_V \leq 57\%$). Over Zestaponi in the same atmospheric layer the aerosol concentration variations are higher ($48 \leq C_V \leq 104\%$). In cloudy days the number concentration of aerosols over Kakheti considerably increases and becomes practically the same as over Tbilisi in cloudless days. At the same time the variations of the aerosol content in the layer 1.0-3.0 km over Kakheti in cloudy days also increase ($38 \leq C_V \leq 103\%$).

Table 3.6 presents the data on the size distribution of aerosols at various elevations for the vertical profiles of the aerosol concentration given in Table 3.5. These data are presented in the form of number concentrations of aerosols normed by the number concentration of aerosols with sizes more than 0.35 mcm in three size ranges: $0.35 < r \leq 1.0$ mcm,

1.0 < r ≤ 2.0 mcm and r > 2.0 mcm. As it follows from this table within the lower 5 kilometer atmospheric layer the size distribution of aerosols for all observation regions has quite a stable character and varies little with elevation and under the impact of cloudiness. Over Tbilisi the small-disperse fraction prevails to some extent. This seems to be related with a large amount of secondary aerosols here in comparison to other regions.

Table 3.5

Vertical distribution of number concentration of aerosols with sizes r>0.35 mcm over various regions of Georgia according to data 1973-1976 (warm season).

Region	El.s.l. km Param.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Tbilisi (clear days)	cm^{-3}	-	6.1	4.5	4.2	4.9	4.3	-	4.2	-	1.4
	N of cases	-	10	11	11	11	10	-	4	-	1
	σ	-	2.9	2.0	2.0	2.7	1.9	-	1.8	-	-
	c$_V$ (%)	-	48	44	48	55	44	-	43	-	-
Zestaponi (clear days)	cm^{-3}	11.0	3.3	2.9	2.6	2.7	2.7	1.5	1.8	-	-
	N of cases	3	7	6	6	6	7	2	2	-	-
	σ	8.9	1.6	1.9	1.8	1.5	2.8	0.5	0.6	-	-
	c$_V$ (%)	81	48	66	69	56	104	33	33	-	-
Kakheti (I) (clear days)	cm^{-3}	-	2.8	2.1	1.8	1.6	1.4	1.4	1.2	0.4	0.4
	N of cases	-	5	5	5	5	5	2	2	1	1
	σ	-	1.2	0.9	0.7	0.5	0.8	1.4	0.9	-	-
	c$_V$ (%)	-	43	43	39	31	57	100	75	-	-
Kakheti (II) (days with cumulus clouds)	cm^{-3}	-	3.2	2.3	1.8	2.1	2.8	1.4	1.6	2.2	2.3
	N of cases	-	9	9	9	9	9	4	3	2	2
	σ	-	1.2	1.0	1.1	1.5	1.1	0.8	0.4	0.9	2.0
	c$_V$ (%)	-	38	43	61	71	39	47	25	41	87
Kakheti (III) (days with clouds of various types incl.cumulus)	cm^{-3}	12.6	5.6	5.0	3.9	3.5	4.4	4.7	2.3	2.3	2.1
	N of cases	2	20	21	21	21	18	6	5	2	3
	σ	1.5	3.4	3.9	4.0	2.9	3.5	6.5	1.1	0.9	1.6
	c$_V$ (%)	12	61	78	103	83	80	138	48	39	76

The size distribution of aerosols is often presented in the form of Junge's distribution [76]

$$dN/dr = Cr^{-(\beta+1)} \qquad (3.3)$$

where dN is the number of particles in the size range dr, C- constant. The parameter β for the middle and upper atmosphere equals usually to 3. In our case for the lower 5 kilometer atmospheric layer the mean values of β depending on an observation region varies between 1.3 and 1.7 (Table 3.6). It should be noted here also that the estimations of β were carried out quite approximately due to the absence of a large number of particle ranges (only

three). In addition the upper boundary of particle sizes is not fixed. Nevertheless, the value of β gives an idea about the character of the aerosol distribution over industrial and agricultural regions of Georgia and also about the variation of this distribution under the impact of cloudiness. Thus, it follows from Tables 3.5 and 3.6 that cloudiness does not affect the size distribution of aerosols. It changes only their content in the air towards increasing.

Table 3.6

Size distribution of aerosols over various regions of Georgia according to the data 1973-1976 (%)

Region	El.s.l. km / Radius (mcm)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	Mean in layer 0.5÷5.0 km	Junge coeff. β
Tbilisi (clear days)	0.35÷1.0	-	66	64	60	61	56	-	69	-	71	64	
	1.0÷2.0	-	25	27	26	24	30	-	21	-	21	25	1.7
	>2.0	-	9	9	14	15	14	-	10	-	8	11	
Zestaponi (clear days)	0.35÷1.0	62	45	52	54	59	59	53	50	-	-	54	
	1.0÷2.0	27	33	28	27	26	30	33	33	-	-	30	1.5
	>2.0	11	22	20	19	15	11	14	17	-	-	16	
Kakheti (I)	0.35÷1.0	-	64	62	61	56	50	64	58	50	50	57	
	1.0÷2.0	-	25	24	33	25	29	21	25	25	25	26	1.3
	>2.0	-	11	14	6	19	21	15	17	25	25	17	
Kakheti (II)	0.35÷1.0	-	59	52	61	62	64	53	62	55	57	58	
	1.0÷2.0	-	22	26	22	24	22	29	25	30	25	25	1.3
	>2.0	-	19	22	17	14	14	18	13	15	18	17	
Kakheti (III)	0.35÷1.0	53	57	56	59	60	61	47	61	53	52	56	
	1.0÷2.0	31	23	24	26	23	20	21	26	30	38	26	1.3
	>2.0	16	20	20	15	17	19	32	13	14	10	18	

The most radiatively active size range of aerosols is between their radii from 0.1 to 2.0 mcm. Therefore it is very interesting to estimate the amount of aerosols in this range for Georgia. Such estimations require information on the density of aerosols, their number concentration and size distribution. The data on the two last parameters are given in Tables 3.5 and 3.6. The data on the vertical distribution of the aerosol density over Tbilisi are borrowed from [95]. Using these data and assuming that the aerosol density over Tbilisi is the same as in Zestaponi and Kakheti, estimations of the weight concentration of aerosols in the size range from 0.1 to 2.0 mcm by radius were carried out. The results of these calculations are presented in Table 3.7. The same table gives the data on the vertical distribution over Tbilisi of the mean aerosol density and concentration taken from [95]. In the lower row of the table the data on the total mass of

aerosols in an atmospheric column with a 1 m^2 cross-section and 3 and 5 km height are given.

It follows from Table 3.7 that a main part of aerosols (more than 70%) is concentrated in the lower 3 kilometer atmospheric layer. The mass of aerosols with sizes from 0.1 to 2.0 mcm amounts to a little less than 60% of the total aerosol mass (for Tbilisi). The effect of the anthropogenic air pollution and cloudiness on the total aerosol mass in the radiatively active range of their sizes is well observed. For example, over Tbilisi, the total mass of radiatively active aerosols in a vertical air column is higher than the mean global value of the same parameter for natural aerosols approximately 4 times (Table 1.1), over Zestaponi and Kakheti (in cloudless days) - approximately 3 and 1.4 times respectively.

Table 3.7

Vertical distribution of mean density and weight concentration of aerosols over Tbilisi [95] and calculated weight concentration of aerosols in the size range 0.1 ≤ r ≤ 2.0 mcm over some regions of Georgia.

Elev. sea lev. km		Measurement Tbilisi [95]		Calculation according to Table 3.5 and 3.6				
				Tbilisi	Zestaponi	Kakheti(I)	Kakheti(II)	Kakheti(III)
		g/cm^3	mg/cm^3	mg/m^3				
0.5		3.2	0.23	0.125	0.160	0.045	0.062	0.202
1.0		2.5	0.13	0.070	0.053	0.026	0.035	0.058
1.5		2.1	0.08	0.045	0.034	0.019	0.026	0.042
2.0		1.9	0.07	0.042	0.028	0.013	0.013	0.029
2.5		1.6	0.06	0.040	0.020	0.013	0.013	0.019
3.0		1.6	0.05	0.040	0.020	0.013	0.016	0.026
3.5				0.035	0.014	0.010	0.013	0.022
4.0				0.027	0.017	0.010	0.010	0.013
4.5				0.017	0.011	0.003	0.016	0.013
5.0				0.007	0.008	0.003	0.016	0.013
Total in layer (mg/m^2)	0.5÷3.0 km		240	140	112	50	64	131
	0.5÷5.0 km			190	140	66	90	165

The mean ($\bar{r}$) and mean cubic ($\bar{r_3}$) radii of radiatively active aerosols according to our estimations amount respectively: over Tbilisi to 0.23 mcm and 0.40 mcm, over Zestaponi to 0.24 mcm and 0.45 mcm, over Kakheti to 0.28 and 0.50 mcm. Thus, the mean sizes of radiatively active aerosols in various regions of Georgia do not differ much from each other. It is noteworthy that the mean geometric sizes of sulphate aerosols [2] in various regions of the world vary between 0.24-0.66 mcm, which does not disagree with our data on the mean sizes of radiatively active aerosols. Now let's assume that the vertical distribution of sulphate aerosols is proportional to the vertical distribution of the vertical distribution of the

weight concentration of aerosols with sizes from 0.1 to 2.0 mcm. In this case using the data of Tables 3.1 and 3.7 the mass of sulphates in a 5 kilometer atmospheric column over Tbilisi-Rustavi and Zestaponi my be estimated to be 15 mg/m^2 and 16 mg/m^2 respectively. These estimations are also in a good agreement with the data for the global distribution of sulphates in the world according to which over the Caucasian region the mass of sulpahtes amounts to 10-12 mg/m^2 [3].

The share of mineral aerosols in their total amount in various industrial regions of the world amounts to 30-60% [2]. In the Caucasus the near-ground concentration of mineral aerosols with sizes 0.1-100 mcm for April is estimated to be 0.1 mg/m^3 [3]. Considering the relation between the weight concentration of aerosols in the radiatively active size range and their total concentration (Table 3.7), the column concentration of radiatively active aerosols over Tbilisi (and Georgia in general) may be estimated as $\approx$ 100 mg/m^2. Then using the data of Table 1.1, various components of the atmospheric aerosol optical depth τ_a over Tbilisi in the visible wavelength range can be estimated by the following values: τ_a of mineral aerosols $\approx$ 0.070, of sulphates $\approx$ 0.77, τ_a of anthropogenic aerosols $\approx$ 0.150. The total value of τ_a for April amounts approximately to 0.300. For the wavelength λ=1.0 mcm these values amount to: 0.038, 0.042, 0.083 and 0.165 respectively. It is noteworthy that the values of τ_a for April approximately equal to its mean annual values. The content of sulphates in the atmospheric precipitation in Tbilisi in 1972-1978 and from 1982 up to 1987 changed insignificantly [60]. Therefore, one can assume that the content of sulphates in the atmosphere during the period of the aircraft investigations does not differ much from the data of Table 3.1. Thus, in the last decades till 1990 over Tbilisi the atmospheric aerosol optical depth exceeded its mean global value approximately three times (Table 1.1). At the same time in Tbilisi the share in τ_a of mineral aerosols amounted up to 23%, sulphates - 26%, industrial dust, nitrates, etc. - 50%. Considering that almost a half of the sulphate τ_a is anthropogenic (Table 1.1), the share of the anthropogenic component of the atmospheric aerosol optical depth in Tbilisi may be estimated as approximately 60%.

Finally let's estimate the emission of mineral aerosols from the Georgian terriotory using the data on the sedimentation velocity of particles in the radiatively active size range [118] and on their concentration in the near-ground atmosphere [3]. According to [118] the sedimentation velocity of aerosols with sizes up to 2.0 mcm is estimated as 3.1 10^{-3} m sec^{-1}. The concentration of mineral aerosols according to [3] and considering Table 3.7 in the radiativley active size range is about 0.54 mg/m^3. In this case each second the aerosol emission from a square meter of the Earth's surface amounts approximately to 1.7 10^{-4} mg, or 5.4 tons from a square kilometer

per year. This estimation is in quite a satisfactory agreement with the mean global mineral aerosol emission (Table 1.5), which equals to 6 tons from a square kilometer per year.

3.3   The interaction of aerosols with cloudiness

As it was noted in the first chapter in the impact of atmospheric aerosols on climate their direct and indirect radiative effects are distinguished. The scheme of the effect of atmospheric aerosols on radiative forcing [3] is presented in Fig. 3.2. As it follows from the scheme the indirect radiative effects of atmospheric aerosols are mainly related to their influence on the variations of microphysical properties of clouds and fogs. In addition clouds represent accumulators of mineral and generators of secondary aerosols [2,3,10,12,34,81,105,117]. Therefore, after the destruction of clouds, zones with high aerosol concentrations remain in the atmosphere. It is particularly well observed in a presence of "good weather" clouds including convective ones in the atmosphere ([3,12,34], Table 3.5, 3.7). In addition, clouds conduce redistribution of aerosols in the atmosphere transfering them from polluted regions to cleaner ones. At present the share of indirect radiative effects of tropospheric aerosols in the decrease of radiative forcing is the same as of stratospheric ozone, sulphates and biomass burning together. In the next century this share will be increasing (Table 1.2 and 1.3). Therefore, during the last years a particular attention is paid to the study of the indirect radiative effects of atmospheric aerosols.

A detailed analysis of the investigations of aerosol-cloud interactions in the aspect of climate change is presented e.g. in [2,3]. Except of a mechanical accumulation of mineral aerosols in clouds, a number of chemical reactions taking place in them with participation of the short-wave solar radiation and OH radicals, results in generation of additional aerosol particles - condensation nuclei [2,3,65,102]. Thus, not only spatial redistribution of atmospheric aerosols but also generation of new particles occurs according to the scheme gas$\rightarrow$particle.

The formation of particles is very intensive in a humid or liquid droplet system in a presence of SO_2, NO_X, ozone, carbon, etc. [2,3,110]. A presence of carbon particles intensifies the process of the sulphate aerosol formation [110]. The mentioned microadmixtures are present everywhere in the atmosphere and clouds of any type. Correspondingly everywhere takes place the formation of secondary aerosols according to the gas$\rightarrow$particle scheme. Depending on conditions (the concentration of admixtures and their combination, temperature and humidity of the air, cloud aqueousity, solar radiation, etc.) the aerosol particle formation may occur during time from several hours to several days [2,3,110].

As in the near-ground atmosphere (see sec. 3.1) the ionizing radiation of radioactive admixtures (radon, nuclear explosion products, etc.) and cosmic rays should lead to an acceleration of the secondary

aerosol formation in clouds. On the basis of the data on the content in convective clouds of

Atmospheric Aerosols

Stratospheric Aerosols

Tropospheric Aerosols

Direct radiative forcing through reduction in surface insolation and increase in atmospheric absorption of solar radiation

Indirect radiative forcing through modification of cloud and haze micro-physical properties

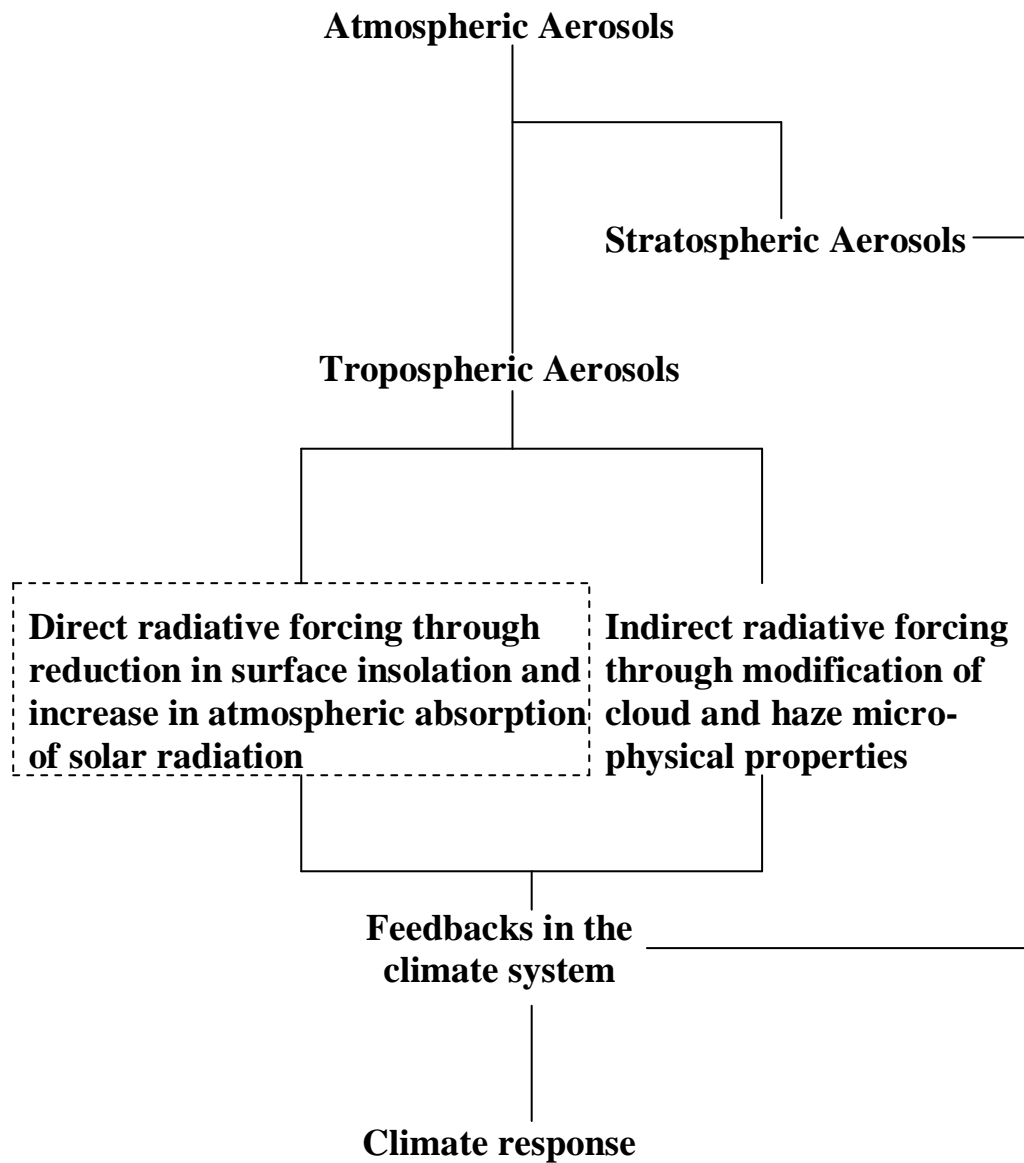**Feedbacks in the climate system**

Climate response

Fig. 3.2

A schematic diagram showing the relationship between the radiative forcing of atmospheric aerosols and climate response [3].

radon, light ions, and also the values of the ionization intensity by cosmic rays [5,7,8,11,117] we estimated the concentration of condensation nuclei N_A in them. The values of N_A were determined from the well-known balance equation relating the formation and disappearing of light ions:

$$q - \alpha'\chi^2 - \beta'N_A\chi = 0 \qquad (3.4)$$

where: q is the intensity of ion formation, χ - the concentration of light lions, α' - recombination coefficient, β' - coefficient of the capture of light ions by condensation nuclei.

In our case all parameters, except β' in the equation (3.4) are known. Therefore, we calculated the values of $\beta'N_A$. Inasmuch as the value of β' for clouds of the same type may be considered a constant N_A can be evaluated in relative units.

Table 3.8 presents the data on the concentration of condensation nuclei in cumulus clouds depending on ionization intensity. The importance level of α according to Student's criterium for differences between N_A in the I and II rows amounts to 0.2, in II and III rows - to 0.25, in I and III rows - to 0.01. Thus, Table 3.3 clearly demonstrates a direct dependence of the concentration of condensation nuclei on the ionization intensity. It is noteworthy that for the cases presented in Table 3.8 the share of the ionization intensity by radon and its decay products did not exceed 10%.

Table 3.8

Concentration of condensation nuclei (in relative units) in cumulus clouds with various levels of ionization intensity.

N	Number of cases	Condensation nuclei concentration N_A			Ionization intensity q ($cm^{-3}sec^{-1}$)		
		N_A (%)	σ	C_V(%)	q	σ	C_V(%)
I	12	100	33	33	5.75	0.37	6.4
II	5	125	40	32	6.4	0.22	3.4
III	7	156	45	29	8.0	0.65	8.1

A direct dependence of N_A on q is observed under the conditions of a high ionization. For example, calculations of N_A, carried out using the data from [13] show that in the New-Athon cave at almost 100% air humidity variations of q from 126 ion couples per cm^3/sec to 1041 ion couples per cm^3/sec leads to an increase of N_A almost four times. The main source of air ionization in the cave represents radon and its decay products. Thus, cosmic and radioactive air ionization can considerably affect the processes of the secondary aerosol formation in the atmosphere and clouds changing indirectly their radiative properties too.

In addition to the effect on the condensation nuclei formation radioactive substances conduce the processes of crystallization of water droplets [111] affect the intensity and duration of thunderstorm processes, hail activity of clouds [15,70]. Considering that in thunderstorm clouds due to electric discharges a considerable amount of nitrogen oxides and ozone is generated [81,93], they create particularly auspicious conditions for the condensation nuclei generation. For example, according to the data of [14] in the precipitation from thunderstorm clouds in comparison to nonthunderstorm ones the content of NO_3^- is elevated by 147%, NH_4^+ - by 102%, SO_4^{2-} - by 51%. Thus, in thunderstorm clouds in comparison to nonthunderstorm intensification of the secondary aerosol formation takes place.

The processes of aerosol-cloud interactions are generally quite complex. There are several schemes of such interactions. For example in [3,102] schemes of the generation in the atmosphere, marine and continental clouds of condensation nuclei from natural and anthropogenic aerosolforming gases (SO_2, NO_X, etc.) are presented. [12] offers a scheme of the stimulation of the heterogenic ice nucleation in clouds due to oxidation of aerosols and ozone. The thunderstorm processes are also considered in this scheme. Fig. 3.3 presents a specified in comparison to [12] scheme of aerosol-climate interactions.

This scheme shows how versatile the relations between processes in clouds and the clear atmosphere are. On one hand aerosols being modified in the atmosphere and getting into cloud media as a result of being humidified or interacting with cloud droplets conduce the generation of ice crystals. A change in the phase state of the cloud media leads to a change in its electric activity (cloud-to-cloud, intracloud, cloud-to-ground discharges). Discharging activity changes the chemical composition of the cloud media (formation of nitrogen oxides, ozone, etc.). The mentioned gases together with radon, sulphur oxides and other components under conditions of a high humidity and cosmic ionization lead to an intensive generation of condensation nuclei. Condensation of water vapour on these nuclei leads to local oversaturations, activation of inactive aerosols in the interdroplet media and generation of crystallization nuclei and ice crystals, i.e. again to a change in the phase state of the cloud media. At the same time the effect of high ozone concentrations on inactive soil aerosols in the interdroplet media activates them in the sense of the ice formation [12,81]. Phase transformations and ionization processes lead to changing of the electric activity of a cloud and the cycle repeats anew.

Breaking through the troposphere strong vertical air flows can carry into the stratosphere considerable amounts of water vapour, aerosols,
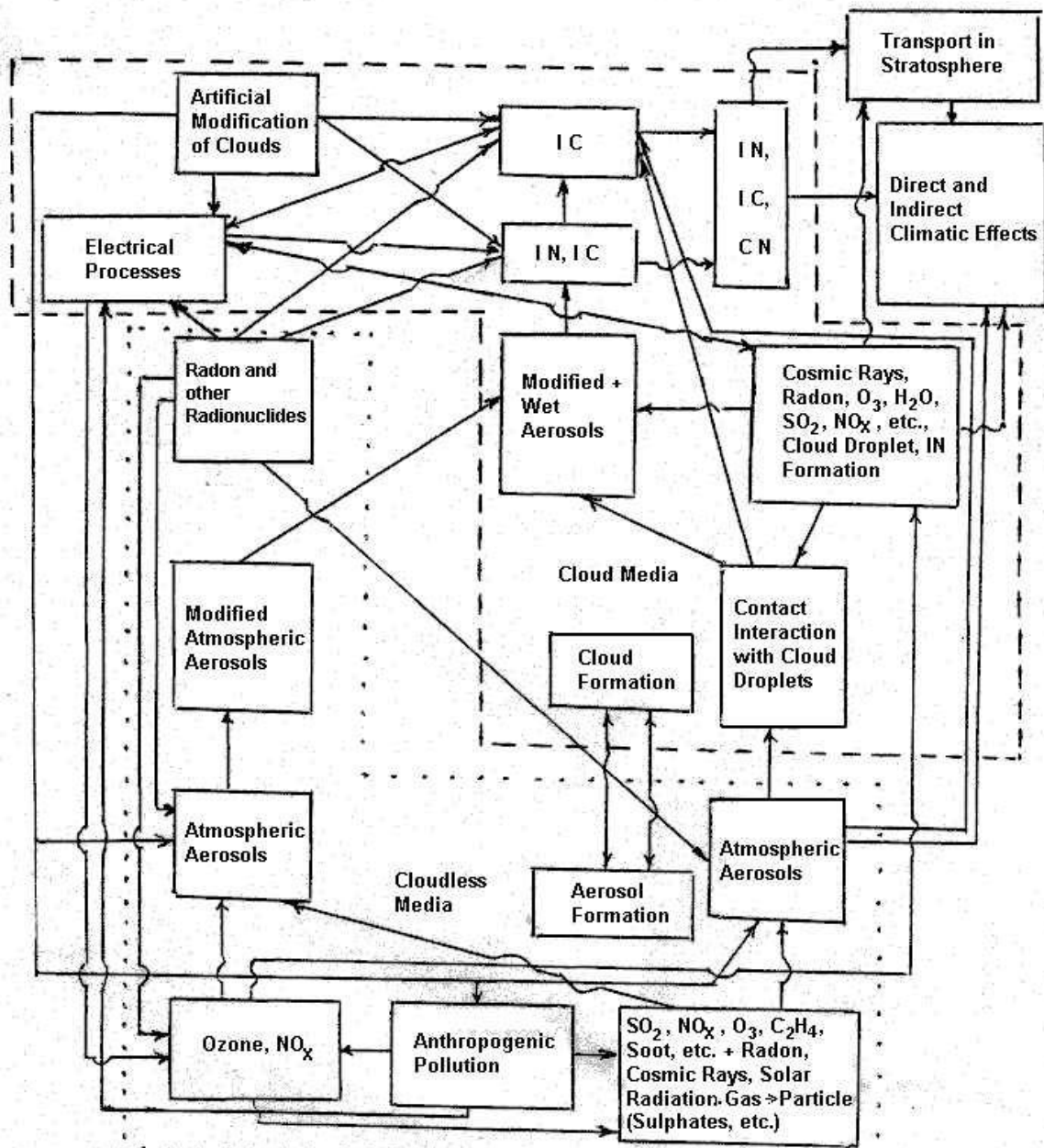
Fig. 3.3

A scheme of the convective clouds - aerosol interaction and formation of condensation and crystallization nuclei and ice crystals in the atmosphere and clouds. IN - ice nuclei; IC - ice crystals; CN - condensation nuclei; MIF - modification by ice-forming reagents.

ozone, SO_2, NO_X and other admixtures. Thus cumulus, big convective and thunderstorm clouds in addition to direct climatic effects (solar radiation attenuation, precipitation, near-ground temperature changes, etc.) can considerably contribute to variations of the chemical composition of the atmosphere and the content of aerosols in it. The latter also affect radiative forcing and climate change.

The effect of convective cloudiness on the content of aerosols in the atmosphere in various regions can manifest itself in different ways. In Georgia this effect appears both for cumulus cloudiness (Table 3.5 and 3.7) and for big thunderstorm-hail clouds [22]. According to the data of [22] an increase of the number of thunderstorm-hail clouds in the warm season over the territory of Kakheti 3 times leads to an increase of the mean seasonal values of the column concentration of radiatively active aerosols in the atmosphere 1.5 times. Thus, cloudiness as well as atmospheric aerosols affect radiative forcing in a direct and indirect ways.

Chapter IV

The particularities of the total ozone distribution and variability in Georgia

4.1   The distribution of total ozone

Total ozone (TO) varies both in time and depending on latitude and longitude. In addition local geographical conditions and orography also affect it in some extent [89].

As a result of the study of the spatial and temporary variations of ozone, distribution maps of the mean annual and seasonal values of TO in 1973-1995 were composed. Considering that TO observations in Georgia were carried out mainly in Abastumani, Tbilisi and Ruispiri (in Ruispiri only in the warm season) the data of 13 nearest to Georgia ozonometric stations were also used. This allowed to compose approximate large-scale maps of the TO distribution for the Caucasian territory. Using these large-scale maps and the data of short period (up to several months) observations carried out in various times and locations in Georgia, an attempt was made to compose relatively small-scale TO distribution maps for the territory of Georgia. In addition, in order to determine the magnitude and direction of the TO variations in time the data of the multiyear observations in Tbilisi and Abastumani were used.

The determination of the long-term change of TO was considerably complicated by a clear, complex structure of the annual, seasonal and daily variations of TO. Attempting to reveal the tendency of the TO variations investigators often used only mean annual values of TO and did not consider its short period variations receiving therefore weak negative (sometimes zero) trends of TO. On the basis of an analysis of 50 year data (1932-1982) it was claimed in [61] that the stratospheric ozone layer represented a stable formation and the strength of modern anthropogenic factors was not sufficient to cause significant TO changes.

Important results of TO investigations were achieved as a result of a fundamental study of its seasonal and monthly variations.

Attempts to determine the global change of TO were complicated also by many other reasons. Among others it was important to establish the TO variations versus latitude. It is already known at present that the minimum of TO is observed on the equator, while the maximum - near the poles. The mean annual minimum of TO on the equator amounts to 262 D.U., the maximum at 80° N.L. - 415 D.U. and 60° S.L. - 360 D.U. [66]. The variability versus longitude is characterized by two maxima: in Sibiria and the West of Greenland. According to [66] the TO maximum is possibly

related to quasistationary systems of low atmospheric pressures in the mentioned regions. It is interesting that the maximum of TO in the West of Greenland and Canada, established by satillite and ground observations, is concentrated near the magnetic pole where almost constantly an invasion of charged particles occurs. These particles cause perturbations of the F layer of the ionosphere. It is noteworthy that TO practically does not change during a year in the West of Greenland.

Total ozone in the atmosphere depends also on orography. In [86] the TO magnitude of 120 D.U. observed in Kabul in 1950, which did not agree with the latitudinal TO distribution, was explained by the orographic effect.

In [86] it was established that the Asian Mountain System plays a considerable role in the TO distribution. In particular, in the upper layer of the troposphere ozone is destroyed due to the interaction with water vapour and aerosols [86].

In [89] it was proved that in comparison to the coastal zone TO decreases inside the continent, for example in the Caucasus and Alma-Ata. This effect, which is observed mainly in the summer is called the continental effect. In [79] it was shown, on the basis of quite a large amount of statistical data, that the corelation between TO and vertical air flows is negative and varies between 0.6 and 0.9. This means that downflows are related to a TO increase, while upflows - to a decrease. It is known that when there are downflows in the atmosphere they carry to lower layers air masses relatively rich with ozone and vice versa [103] (this process is known as the Dobson-Normand principle). This effect was confirmed experimentally in [79]. Thus, TO variations can be caused by those atmospheric processes, which generate vertical air flows in the stratosphere. One of such atmospheric processes represents the "jet flow", which is observed mainly in lower stratospheric and upper tropospheric layers. A jet flow arises in the area of atmospheric fronts. On its left side a downflow, while on the right an upflow prevails. Due to these very flows on the left side of a jet flow a TO increase, while on the right side a TO reduction is observed [80,81,103].

A map of the geographical distribution of TO for the Northern Hemisphere was for the first time presented in [86]. There were three continental maxima in this map: to the North-East of America (TO>460 D.U.); North-Eastern Europe (TO>420 D.U.) and North-Eastern Asia (TO>420 D.U.). Such maxima were clearer in the spring than autumn.

In [104] maps of the monthly distribution of TO are presented. For this purpose the data of 114 observatories for 1957-1964 were used. According to these maps over North-Eastern Asia a TO maximum was observed in the winter-spring season (TO varied between 450 and 463 D.U.). A second weaker maximum was over Canada, a third still weaker

maximum over Scandinavia in the spring, while a TO minimum was observed over Middle Asia in the spring (the mean value of TO in Dushanbe was 226 D.U.).

In [33] maps of the TO distribution and variability in the Northern Hemisphere are presented. For this purpose the data of world-wide observations for 1957-1983 were used. A map for the Southern Hemisphere was also composed using the data of the world network and Nimbus-4 satellite. According to these maps the main maximum of TO except of the spring season is located in the region of Akhot Sea. A second relatively weaker maximum is over the East of Canada. The main minimum is in Europe [33].

In order to compose TO distribution maps for Georgia the data of TO observations in 1973-1995 were used (the data before 1973 were considered invalid [33]). At first a climatic TO map was composed for the region located between 35-54° N.L. and 22-77° E.L. The data of the following stations were used: Abastumani, Tbilisi, Ruispiri, Pheodosia, Odessa, Tsimliansk, Guriev, Samara, Ashkhabad, Chardjou, Dushanbe, Aral Sea and Alma-Ata.

First of all for the mentioned stations periods with synchronous observations were selected and using them a large-scale total ozone distribution map was composed for the Caucasus and nearby territories. Then out of the 13 stations those with relatively complete observational data were singled out (Abastumani, Tbilisi, Pheodosia, Odessa, Kuibishev, Ashkhabad, Alma-Ata). Corelations between them were established and small missing periods were recovered by the method of splitting of random functions into orthogonal vectors [100]. Using the recovered homogeneous data, maps of the mean annual and seasonal distribution of TO were composed for the mentioned region (Fig. 4.1 a-e).

On the basis of the composed large-scale maps relatively small-scale maps of the TO distribution were composed (Fig. 4.2 a-e) for the Georgian territory, for which all the existing data of ozone observation in Georgia in 1973-1995 were used.

Fig. 4.1 (a-e) clearly demonstrates the latitudinal character of the ozone distribution with a maximum over Samara and minimum over Ashkhabad. These variations, which manifested themselves as a result of the composition of small-scale maps of TO in Georgia were probably caused by the orography and related atmospheric processes (jet flows, foehn winds, atmospheric fronts, etc.).

a

б

в
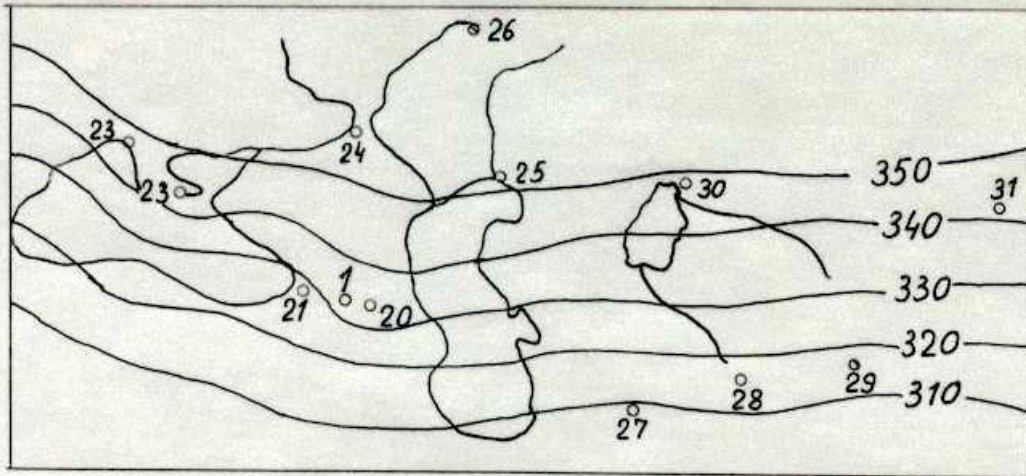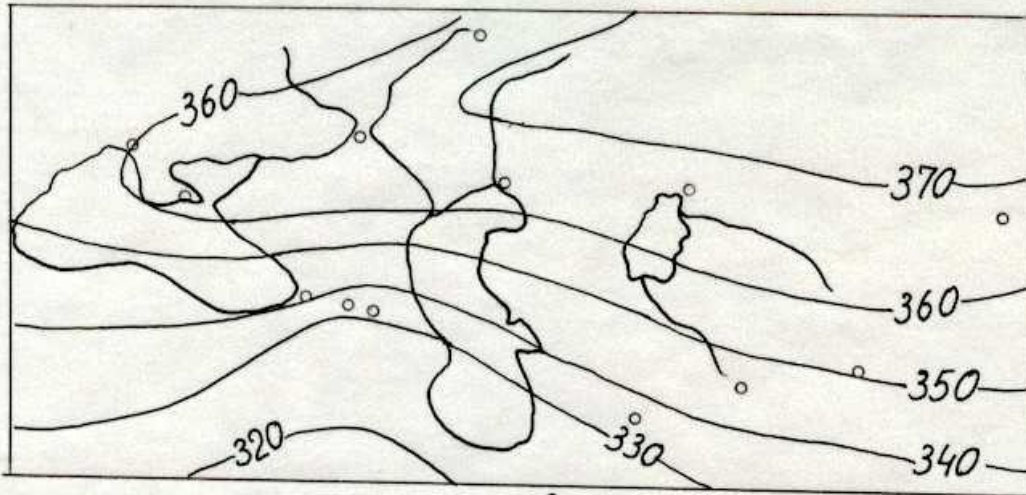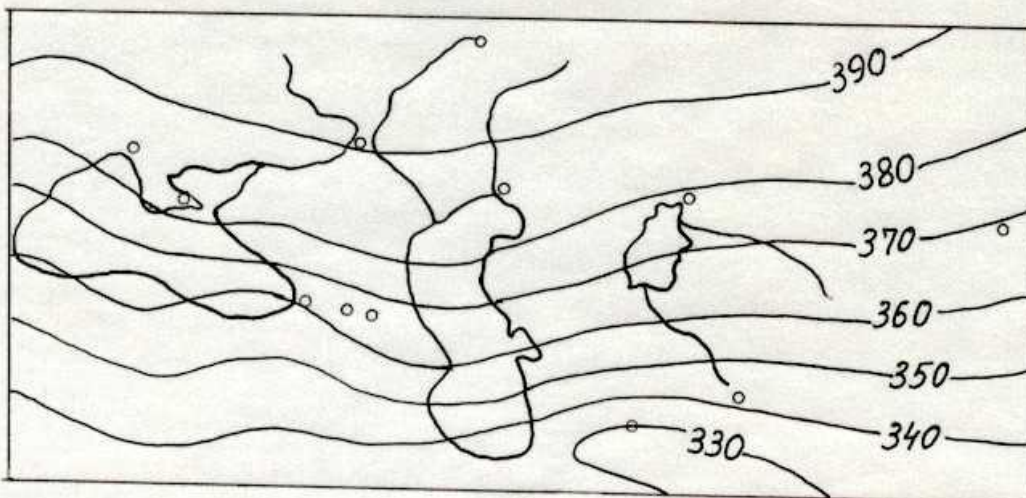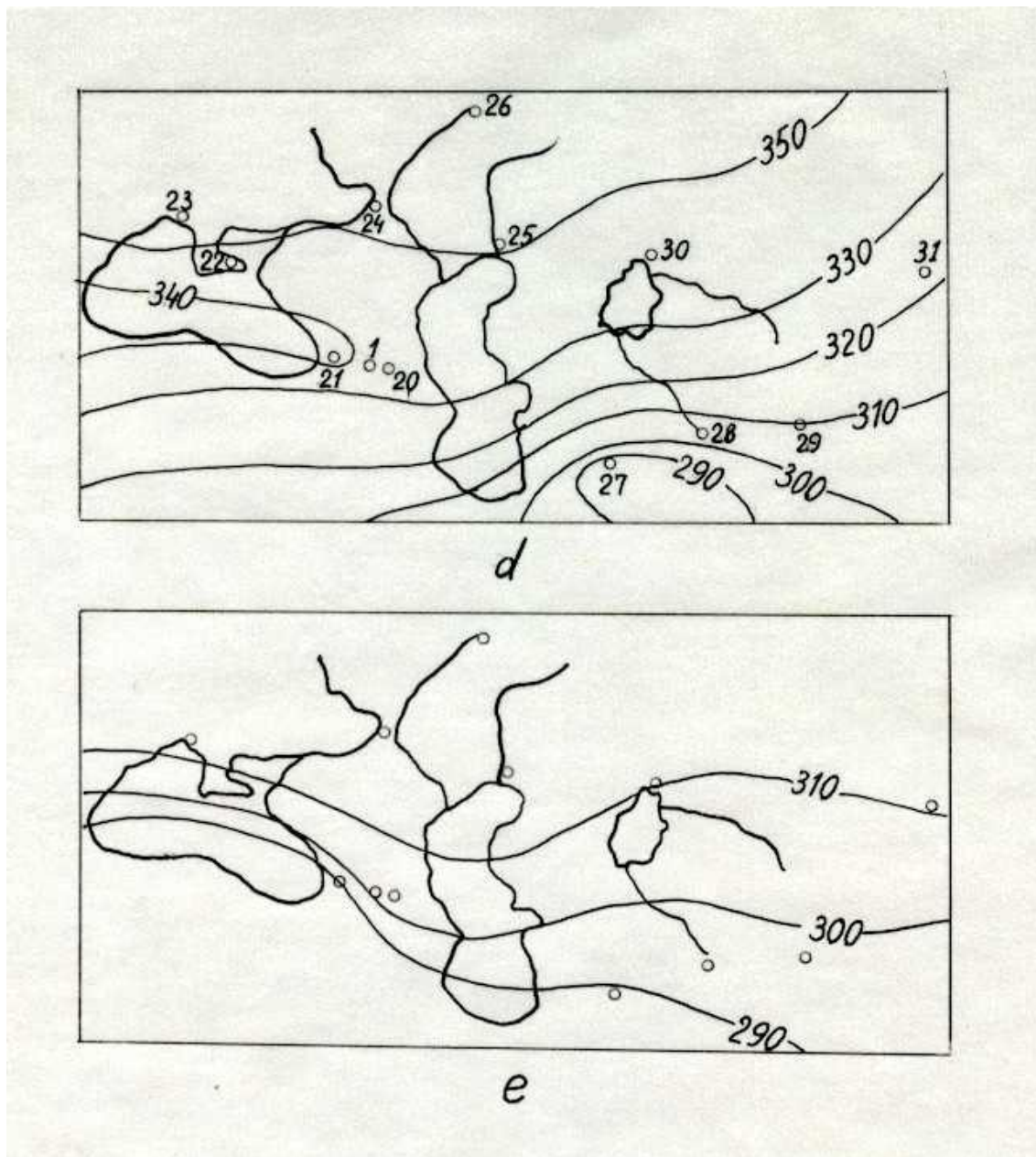
Fig. 4.1

Mean annual (a), winter (b), spring (c), summer (d) and autumn (e) total ozone distribution in the atmosphere between 35-55° N.L. and 30-80° E.L. 1 - Tbilisi, 20 - Ruispiri, 21 - Abastumani, 22 - Pheodosia, 23 - Odessa, 24 - Tsimliansk, 25 - Guriev, 26 - Samara, 27 - Ashkhabad, 28 - Chardjou, 29 - Dushanbe, 30 - Aral Sea, 31 - Alma-Ata.

Fig. 4.2

Mean annual (a), winter (b), spring (c), summer (d) and autumn (e) total ozone distribution in the atmosphere in Georgia.
1 - Tbilisi, 20 - Ruispiri, 21 - Abastumani.

4.2 The variability of total ozone in Georgia and its relation to the global processes of the ozone variability

In order to establish the tendency of the total ozone variations in Georgia the data of Abastumani and Tbilisi observations were used. For an analysis of the observational data, as it was mentioned above, also the data from the stations Pheodosia, Odessa, Samara, Ashkhabad, Alma-Ata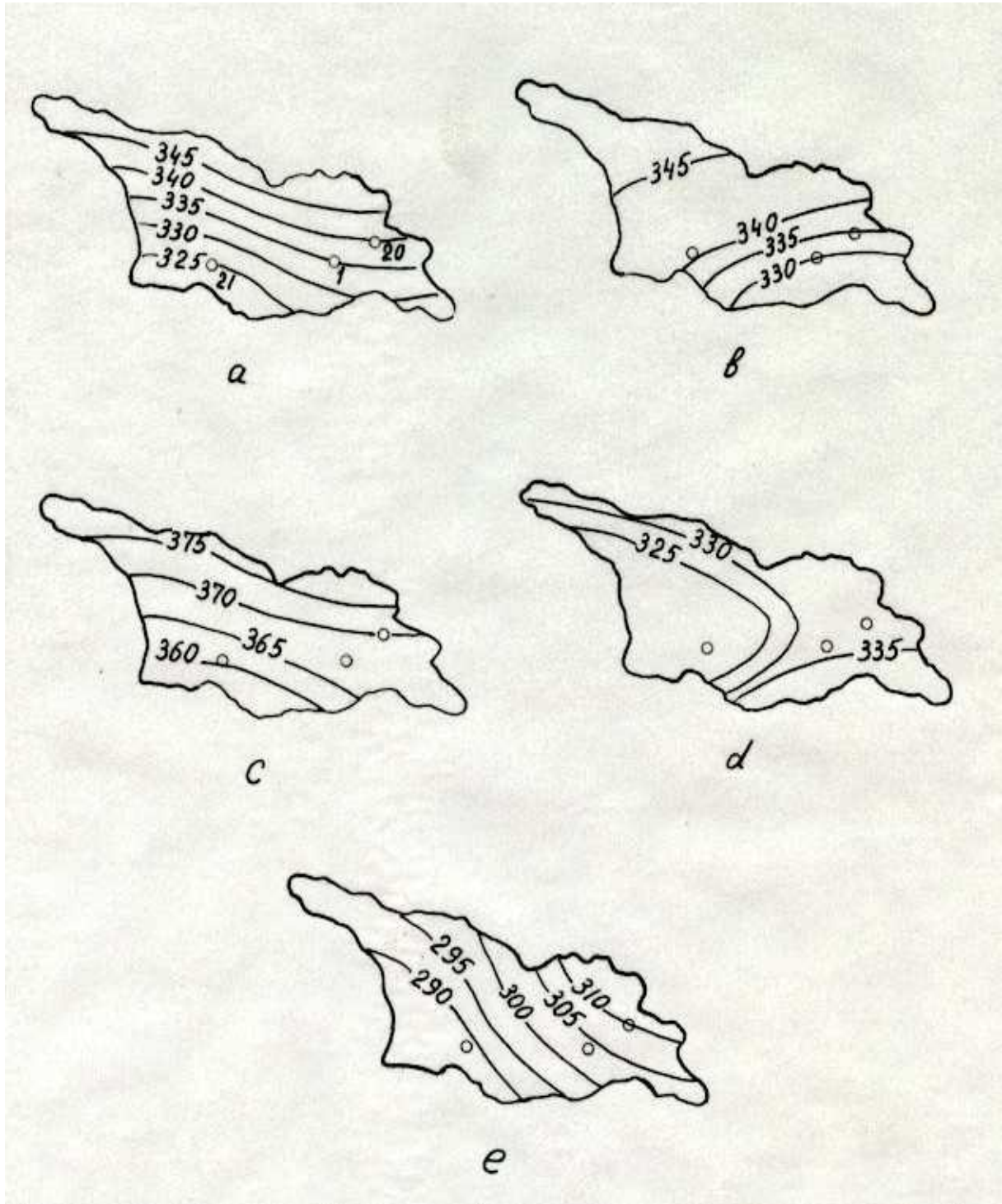, Tsimliansk, Guriev, Aral Sea, Chardjou and Dushanbe, the corelations between them and the method of splitting of a random function into orthogonal vectors were used.

At first the data for the whole observational period (1957-1995) were taken. An analysis showed a tendency of increase. But considering the fact that the data of the ozonometric network of the former USSR before 1973 are not sufficiently reliable [33], only the data after 1973 were used. The mean annual and seasonal (winter, spring, summer, autumn) variations were studied for the period 1973-1995 (Fig. 4.3 a-e).

The dependence of TO on time was approximated by a linear equation:

$$U = U_0 + K (\tau - 1973)$$

where U and U_0 are the mean annual (seasonal) TO value for any year of the period and for the beginning of the period respectively. K - the mean variation of total ozone per year during the period, while τ - years between 1973 and 1995. Table 4.1 presents the mean annual and seasonal calculated values of U_0 and K for Georgia and observational stations near the country.

Fig. 4.2 (a-e) and Table 4.1 show that in Abastumani the TO maximum (375 D.U.) is in the spring, while the minimum (306 D.U.) - in the autumn. Ozone decreases throughout a year with the maximum intensity in the spring (K=-1.32 D.U. per year), and minimum in the summer. Least of all TO decreases in Odessa in the autumn (-0.41 D.U.), then in Tbilisi in the autumn (-0.45 D.U.) and in Abastumani in the summer (-0.50 D.U.). The ozone reduction is mainly more intensive in the winter-spring season, which is in a good agreement with the results by other authors for other regions.

Table 4.1 shows that the annual reduction of TO in Tbilisi amounts to -0.2%, while in Abastumani it equals -0.3%. This means that in Tbilisi smog ozone compensates the global ozone reduction. The most intensive decrease of TO in Abastumani is observed in the spring and amounts to -0.35%. In the summer the TO reduction in Abastumani and Tbilisi is the same and amounts to -0.18%. Such low value of the TO reduction in Abastumani must be caused by a compensation of the global ozone

reduction by ozone generated from gases of the methane group (methane, isoprene, terpene, etc.) emitted by plants. As regards Tbilisi, the global reduction is compensated by smog ozone.

Table 4.1

Variations of total ozone in 1973-1995

Observation point	Season	TO - U$_{1970}$ D.U.	K D.U./year	K - %
Abastumani	Annual	334	-1.00	-0.30
	Winter	353	-1.04	-0.29
	Spring	375	-1.32	-0.35
	Summer	311	-0.50	-0.16
	Autumn	306	-1.27	-0.42
Tbilisi	Annual	340	-0.68	-0.20
	Winter	341	-1.04	-0.30
	Spring	378	-0.50	-0.13
	Summer	338	-0.54	-0.16
	Autumn	308	-0.45	-0.15
Odessa	Annual	369	-1.77	-0.48
	Winter	347	-1.09	-0.31
	Spring	408	-1.82	-0.45
	Summer	355	-0.77	-0.22
	Autumn	317	-0.41	-0.13
Samara	Annual	363	-0.73	-0.20
	Winter	372	-1.36	-0.36
	Spring	409	-1.23	-0.30
	Summer	363	-1.41	-0.39
	Autumn	325	-0.91	-0.28
Ashkhabad	Annual	325	-1.35	-0.42
	Winter	347	-1.04	-0.30
	Spring	352	-1.95	-0.55
	Summer	308	-1.91	-0.62
	Autumn	301	-1.18	-0.39
Alma-Ata	Annual	354	-1.09	-0.31
	Winter	390	-1.36	-0.35
	Spring	379	-1.00	-0.26
	Summer	338	-1.36	-0.40
	Autumn	317	-0.59	-0.19

Thus, in Georgia as well as globally a reduction of total ozone in the atmosphere takes place, which is to a significant extent determined by the growing global atmospheric pollution.

The near-ground ozone concentration has regular daily and seasonal variations, which depend on atmospheric processes, variations of meteorological elements and the atmospheric pollution and relief.

Total ozone has seasonal variations with a maximum in the spring and minimum in the autumn.
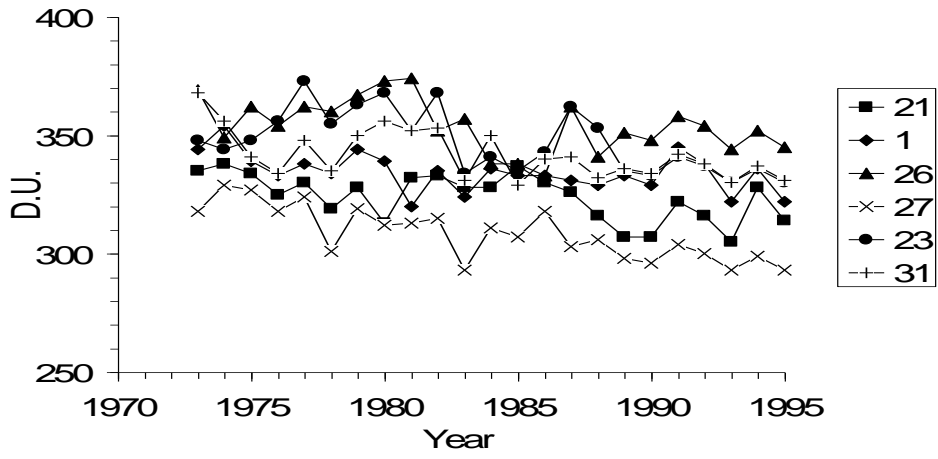
(a)
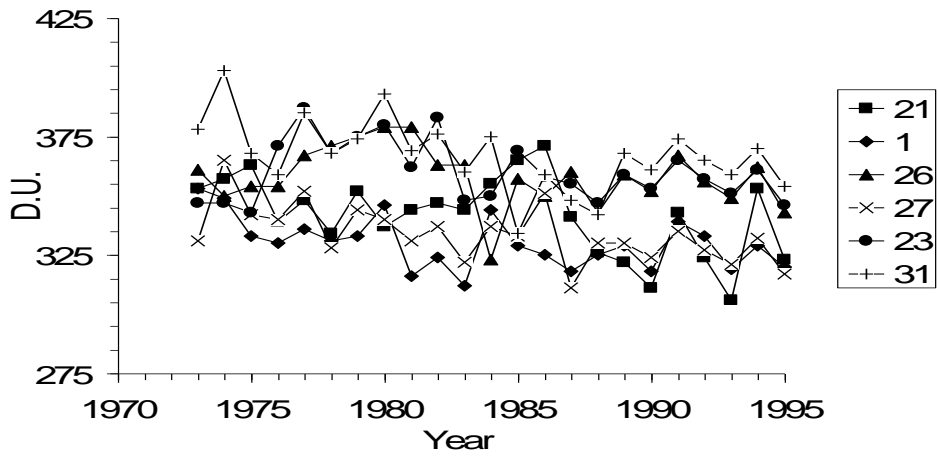
(b)
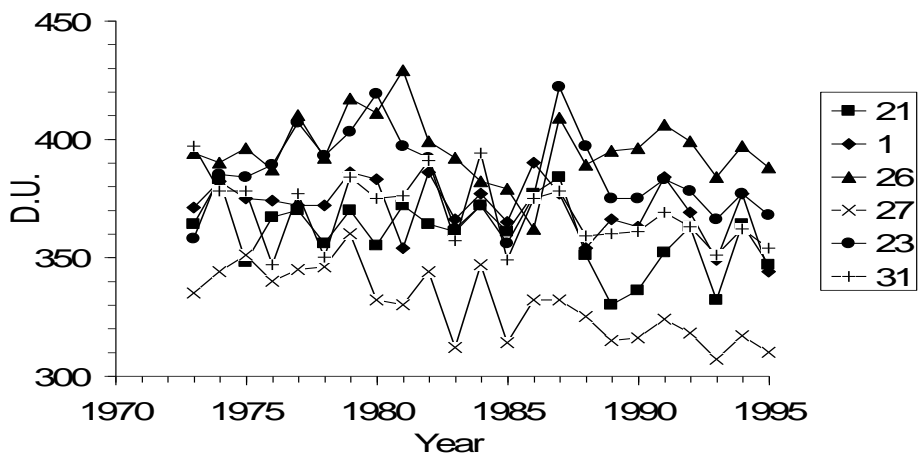
(c)
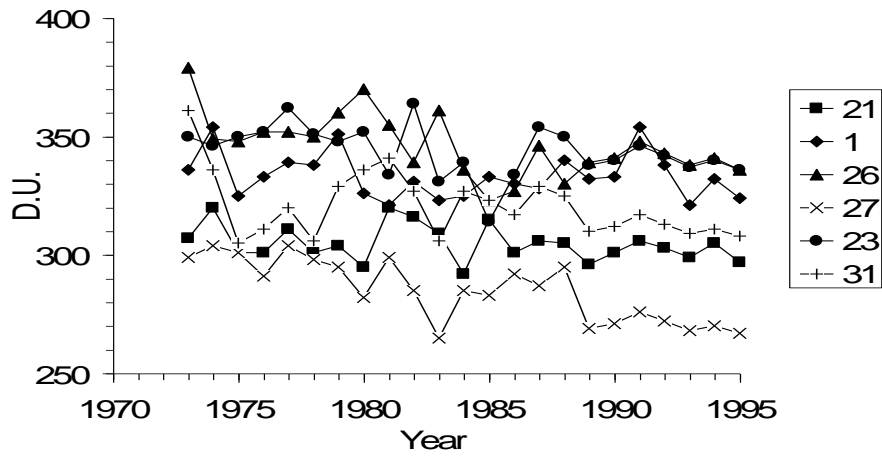
(d)
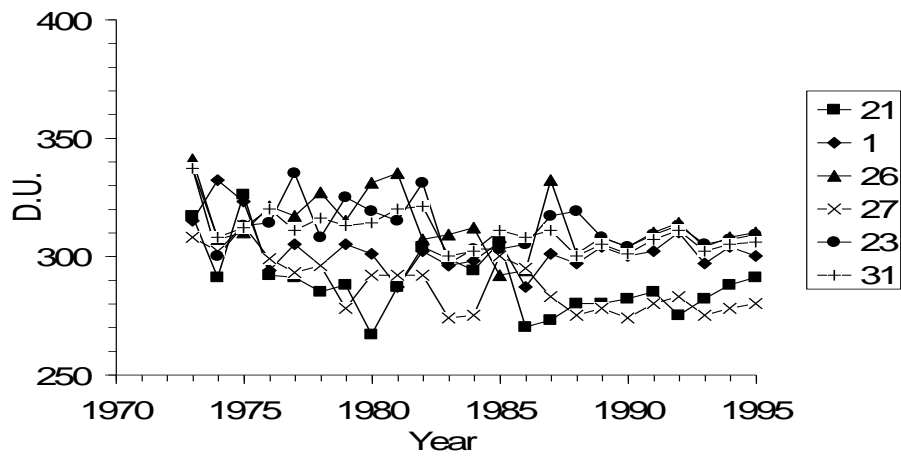
(e)

Fig. 4.3

Mean annual (a), winter (b), spring (c), summer (d) and autumn (e) total ozone variations in 1973-1995 (1 - Tbilisi, 21 - Abastumani, 23 - Odessa, 26 - Samara, 27 - Ashkhabad, 31 - Alma-Ata)

Chapter V

Spatial-temporary characteristics of the atmospheric aerosol optical depth in Georgia.

As it was mentioned above, one of important atmospheric components directly affecting the climate formation and change represent atmospheric aerosols [2,50,96]. In order to study the effect of aerosols on climate four main problems should be solved [2]: 1. Determination of the spatial-temporary variability of aerosols in the atmosphere; 2. creating aerosol-radiation models necessary for climate modeling; 3. consideration of aerosols in the climate formation theory; 4. study of the interaction of aerosols and main climateforming processes and factors (transformation of the underlying surface, icing, precipitation and cloud formation, etc.).

Activities in this direction have been carried out in Georgia since long ago. In the beginning of 1960-s, when the modern climate warming was already undoubted F. Davitaia was one of the first scientists in the world who presented a hypothesis that the process of climate warming was mainly caused by atmospheric aerosols [50]. According to this hypothesis the growing atmospheric pollution and circulation processes should cause a reduction of the underlying surface albedo at the global scale. This, of course, is followed by a warming process till the aerosol concentration has reached a critical value, when the effect of aerosol scattering of the radiation begins to prevail. The subsequent growth of the aerosol concentration radically changes the climate change direction and causes a strong cooling. This theory is already undoubted at present and is known in literary sources as "nuclear winter".

A quantitative estimation of the effect of both atmospheric aerosols and all other factors on the climate change processes was possible only by creating a Sun-atmosphere-Earth energy-balance model. In the 1960-s this turned out to be impossible due to the absence in literary sources of any information on the optical properties of aerosols. Owing to F. Davitaia's assistance and leadership, for the first time in the world, a study of the optical properties of marine and continental aerosols began in Georgia. With this purpose in Adjaria (the Black Sea coast) a special experimental base was established, which is still functioning at present. A special method and appropriate equipment were developed for the study of the optical properties of aerosols [122-125,130]. During years experimental and theoretical investigations were carried out, as a result of which optical-meteorological models of marine and continental atmospheric aerosols were created [126,127], effects of meteorological elements and atmospheric processes on them were established [128,129], which gave a

possibility to create an energy-balance model. It is noteworthy that the results were used abroad.

The main indicator of the air pollution represents the atmospheric aerosol optical depth (τ_a). It characterizes the total attenuation of the solar radiation for the whole atmospheric height for all types of aerosols (natural, anthropogenic, generated from the gaseous phase, mineral, marine, organic, etc.). Determination of τ_a values is possible under "clear sky" conditions by the data of observations on the direct solar radiation and a number of other physical parameters of the atmosphere [133]. In this chapter τ_a values are given for the wavelength $\lambda=1$ mcm and midday hours.

τ_a was determined at six main actinometric stations of Georgia - Tbilisi, Telavi, Anaseuli, Senaki, Sokhumi, Tsalka and two auxiliary - Kazbegi and Jvari Pass (Fig. 1.1). For Tbilisi the data of actinometric observations includes the period 1928-1990; for Telavi, Anaseuli, Senaki, Sokhumi, Tsalka - 1956-1990; for Kazbegi - 1955-1964; for Jvari Pass - 1969-1985. For the mentioned 5 main actinometric stations the data on τ_a for 1928-1955 were recovered using the method [100,133] and data of Tbilisi. An application of these methods became possible due to high corelations of the τ_a data between the stations. Corelations between Tbilisi and other stations in those years, for which synchronous data on τ_a are available amounted to: 0.89 for Telavi, 0.75 for Tsalka, 0.82 for Sokhumi, 0.85 for Anaseuli, 0.78 for Senaki. The recovering accuracy was: 95% for Telavi, 91 for Tsalka, 90% for Sokhumi, 88% for Anaseuli, 87 for Senaki.

5.1   The method of determination of the atmospheric pollution level

As it was mentioned above, the role of aerosols in the climate formation is quite essential. Another very important problem is the adaptation of the biosphere to the growing atmospheric pollution. A lot of cases of a highly negative effect of the air pollution on the human health are known [51,96]. The atmospheric pollution negatively affects also water and soil surfaces, conduces the destruction of plants and forests on considerable territories. Together with water and food hazardous substances can get into the human organism. Pollutants considerably damage buildings, various building materials and products. For example the rate of the corrosion of iron and its alloys in industrial centers is 20 times, while of aluminum 100 times higher than in rural areas [51].

All the above-mentioned emphasizes the social and economic importance of the atmospheric pollution problem.

Since long ago it has been known that small invisible particles can get into the atmosphere from the space or Earth's surface and staying for years in the atmosphere determine global or regional atmospheric pollution levels. But there were no grounds to think that these particles (aerosols) had any effect on atmospheric processes. Therefore, till 1950-s there were no systematic observations on atmospheric aerosols. As far as it is known first in 1959 in Germany a short information was published that in one of industrial regions during the last 20 years the amount of aerosols in the atmosphere had grown 3 and more times and this was attributed to an anthropogenic effect [108]. Later in 1964, as it has been already mentioned, F. Davitaia presented a hypothesis, according to which the modern climate warming was caused by the growth of the atmospheric pollution.

At present atmospheric aerosols draw a world-wide attention. By a proposal of the World Meteorological Organization a special monitoring has been established, which systematically controls the concentration of aerosols in the atmosphere. This organization suggested two methods. One of them foresees sampling and a subsequent laboratory analysis of the near-ground air. The other - determining of the atmospheric aerosol optical depth (τ_a) by measuring the spectral Sun radiation. The first one enables to determine the chemical composition of aerosols, but is informative only for the near-ground atmospheric layer being at the same time not quite accurate due to the destruction of the natural aerosol structure during sampling. The other one (s.c. "actinometric monitoring") determines the aerosol concentration sufficiently accurately without destroying their natural structure, but can not distinguish their chemical composition. At the same time it requires a complex equipment and qualified personnel.

Considering these difficulties at the Institute of Geography of Georgian Academy of Sciences a method was developed, which allows to determine the atmospheric aerosol optical depth using the integral solar radiation [121,122]. The latter is measured systematically in the world actinometric network. The method was subsequently specified [130,133] and is presently used for the study of the aerosol pollution of the atmosphere. The main idea of the method is described below.

The irradiance of the direct integral solar radiation I(m) with an incidence angle ϑ after going through an atmospheric mass m can be expressed as:

$$I(m) = \int_0^\infty I_0(\lambda) P(\lambda, m) P_a(\lambda, m) d\lambda \qquad (5.1)$$

where m=sec ϑ; $I_0(\lambda)$ - the spectral solar constant; $P(\lambda, m)$ - transmittance of an "aerosol-free" atmosphere; $P_a(\lambda, m)$ - transmittance of atmospheric aerosols; λ - wavelength.

If $P(\lambda, m)$ is known, then in (5.1) remains unknown $P_a(\lambda, m)$. Due to the fact that the equation belongs to ill posed problems an additional condition is required for its solution. This condition can be the Angstroem formula for the dependence of P_a on λ:

$$P_a(\lambda, m) = \exp\left(-\frac{a}{a_0}\left(\frac{\lambda_0}{\lambda}\right)^n \cdot m\right) \qquad (5.2)$$

where a and n represent the s.c Angstroem parameters, while a_0 and λ_0 are fixed values. In order to facilitate calculations it is usually assumed that n=1 (this assumption is used almost in all model calculations). Considering this assumption and (5.2) only one unknown parameter a is left in (5.1) (it is proportional to the aerosol concentration). After certain transformations (5.1) can be reduced to a form easy for computer calculations, which require a measured irradiance of the integral solar radiation, total column concentrations in the atmosphere of ozone, water vapour and carbon dioxide and their absorption coefficients for the whole spectral range, the vertical distribution of temperature and absolute humidity and the elevation above the sea level (for calculating the molecular diffusion of radiation). The derived parameter a enables to determine τ_a for any wavelength. The aerosol optical depth calculated by the mentioned method is in a good agreement with the same parameter derived by spectral measurements under clear sky conditions in any optical situation [123,133].

Considering the fact that the atmospheric aerosol optical depth represents one of the first indicators of the atmospheric pollution level the

Institute of Geography of the Georgian Academy of Sciences proposed a special scale for atmospheric pollution estimation (Table 5.1) [16].

Table 5.1

Scale of atmospheric pollution level

N	I	II	III	IV	V	VI	VII	VIII	IX
τ_a	<0.050	0.050÷0.080	0.081÷0.110	0.111÷0.130	0.131÷0.150	0.151÷0.190	0.191÷0.230	0.231÷0.310	>0.310
Pollution Level	Ideally Clean	Very Clean	Clean	Mainly Clean	Normal	Slightly Turbid	Fairly Turbid	Turbid	Very Turbid
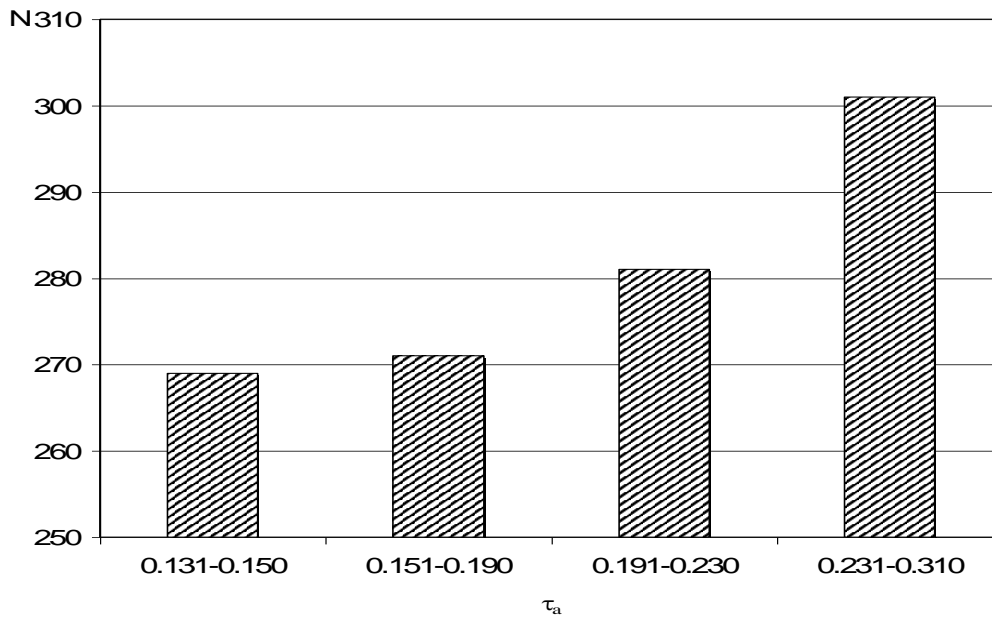
Fig. 5.1

Dependence of the mortality due to cardiovascular diseases per million inhabitants in Tbilisi (N) on atmospheric pollution level (τ_a)

Table 5.1 shows that atmospheric pollution is divided in 9 categories from "ideally clean" to "very turbid". In order to test the validity of the scale (Table 5.1) the data of the mean monthly mortality due to cardiovascular diseases per million inhabitants in Tbilisi in 1980-1990 were analyzed. In the cold season and at a background of considerable variations of the main meteorological elements it is difficult to distinguish the effect of the pollution. Another picture is observed in the warm season of a year, particularly from June till September. In this period in Tbilisi the mortality decreases down to the minimum and, as it turned out, one of the main risk-

factors affecting the human health together with meteorological elements, magnetic disturbances, thunderstorms, etc. was the atmospheric pollution.

Fig. 5.1 presents histograms of the dependence of the mortality due to cardiovascular diseases on the air pollution in Tbilisi from June till September. As the figure shows the maximum intensification of the mortality takes place at a "turbid" atmosphere and in comparison to the "normal" pollution level this growth amounts to 12%. Thus, the scale is quite representative for the estimation of an atmospheric pollution state in the medical and biological aspect and can be used in medical meteorology. At the same time the importance of the monitoring of the atmospheric aerosol optical depth by the actinometric network is confirmed [16].

5.2 The annual variations of the atmospheric pollution in some regions of Georgia in 1928-1990 and the role of background, anthropogenic and strong random pollution sources in the formation of the total pollution level

An analysis of the data on τ_a variations showed that from 1928 till 1990 for the whole territory of Georgia a growth of the atmospheric pollution level had been taking place. It is noteworthy that in Tbilisi in 1928-1965 τ_a increased linearly [122], while in 1965-1985 - exponentially [39]. According to the specified data of the last years (Fig. 5.2 c) in 1986-1990 some reduction of the τ_a values occurred. In order to compare with the Tbilisi data (the highest pollution level in Georgia) Fig. 5.2 a,b presents the mean annual τ_a values for Tsalka (the lowest pollution level in Georgia) and Anaseuli (a middle pollution level characteristic for Western Georgia).

Fig. 5.3 a, b, c present the τ_a variations in 1928-1990 in Tsalka, Anaseuli and Tbilisi in the four seasons of a year.

As a first approximation the τ_a variations in Georgia may be presented in a linear form:

$$\tau_a = a{\cdot}t + b \qquad\qquad (5.3)$$

where t designates years beginning from 1928, while a and b are empiric coefficients. Their values were determined by the least square method and are presented in Table 5.2.

Fig. 5.2-5.3 and Table 5.2 show that the character of the annual and seasonal τ_a variations in Georgia is the same for the whole territory of Georgia - a gradual increase in 1928-1990. The highest increase rate of τ_a (for both seasonal and annual values) is observed in Tbilisi, while the lowest in Tsalka. In Western Georgia (Anaseuli, Senaki, Sokhumi) the pollution variations are not very considerable. τ_a here is lower than in Eastern Georgia (Tbilisi, Telavi), but higher than in Tsalka.

In comparison to 1928 the mean atmospheric pollution growth per year for various regions of Georgia amounts to: 13% in Tbilisi, 15% in Telavi, 8.7% in Anaseuli, 5.5% in Senaki, 6.6% in Sokhumi, 3.6% in Tsalka, 8.8% at the average for Georgia. In other words in 1990 the air pollution grew in comparison to 1928: in Tbilisi 8 times, in Telavi 9 times, in Anaseuli 5.4 times, in Senaki 6 times, in Sokhumi 4.1 times, in Tsalka 2.2 times. According to the scale presented in Table 5.1 at the average per year a "clean" atmosphere ($\tau_a<0.110$) was observed till: 1969 in Tbilisi, 1973 in Telavi, 1984 in Anaseuli and Sokhumi, 1988 in Senaki. If the rate

(a)

(b)
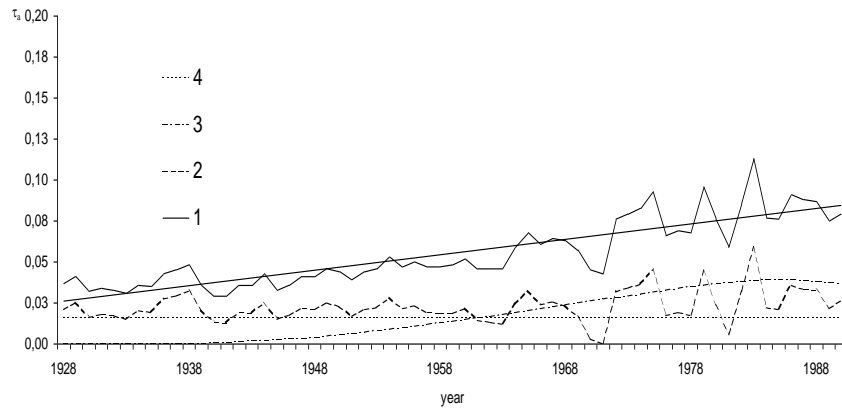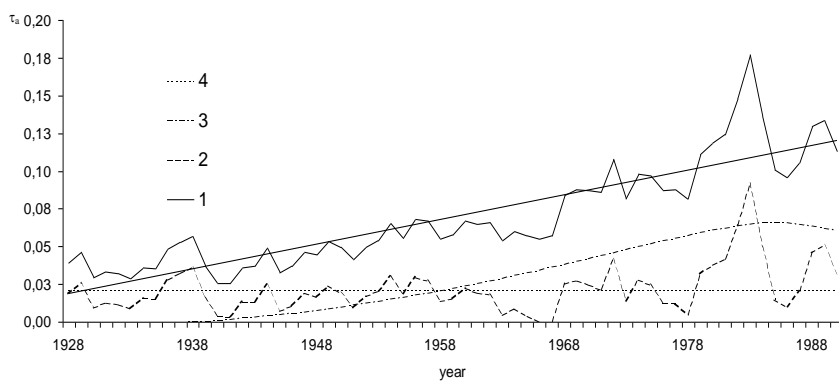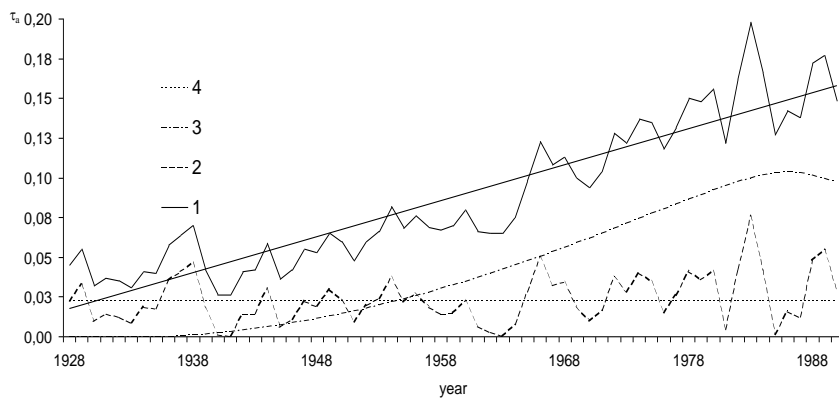
Fig. 5.2

Variations of mean annual values of τ_a in (a) Tsalka, (b) Anaseuli, (c) Tbilisi in 1928-1990. 1 - total, 2 - random, 3 - anthropogenic, 4 - background τ_a levels.

of the pollution increase remains the same in the nearest future, a "clean" atmosphere in Tsalka will last till 2017.

<div align="right">Table 5.2</div>

Values of a and b coefficients of (5.3) for the six actinometric stations of Georgia in 1928-1990 (monthly, seasonal, annual)

Station / Mon./Seas.		Tbilisi	Telavi	Tsalka	Anaseuli	Senaki	Sokhumi
I	a	0.00156	0.00148	0.000644	0.000959	0.000776	0.00101
	b	0.0107	-0.000729	0.00990	0.00840	0.0137	0.0113
II	a	0.00197	0.00174	0.000852	0.00118	0.00122	0.00132
	b	0.0126	-0.000300	0.00928	0.00664	0.0173	0.0126
III	a	0.00215	0.00194	0.000929	0.00174	0.00123	0.00152
	b	0.0134	0.0106	0.0214	0.0131	0.0236	0.0189
IV	a	0.00246	0.00237	0.00104	0.00192	0.00153	0.00170
	b	0.0181	0.0146	0.0279	0.0218	0.0260	0.0256
V	a	0.00272	0.00248	0.00107	0.00229	0.00174	0.00201
	b	0.0193	0.00986	0.0348	0.0262	0.0318	0.0301
VI	a	0.00268	0.00253	0.00115	0.00219	0.00197	0.00208
	b	0.0224	0.0180	0.0408	0.0272	0.0330	0.0330
VII	a	0.00308	0.00302	0.00135	0.00234	0.00200	0.00223
	b	0.0225	0.0358	0.0475	0.0293	0.0396	0.0361
VIII	a	0.00287	0.00267	0.00119	0.00220	0.00202	0.00213
	b	0.0208	0.0377	0.0451	0.0280	0.0358	0.0330
IX	a	0.00248	0.00241	0.00104	0.00177	0.00165	0.00168
	b	0.0148	0.0244	0.0331	0.0190	0.0264	0.0234
X	a	0.00196	0.00194	0.000807	0.00136	0.00125	0.00111
	b	0.0126	0.00431	0.0149	0.0123	0.0190	0.0170
XI	a	0.00163	0.00158	0.000645	0.000928	0.000799	0.000857
	b	0.0110	0.00203	0.00779	0.00781	0.0147	0.0121
XII	a	0.00157	0.00144	0.000616	0.000797	0.000744	0.000899
	b	0.0098	-0.000609	0.00593	0.00767	0.0121	0.00960
Winter	a	0.0017	0.0015	0.0007	0.00098	0.0009	0.0011
	b	0.0110	-0.0033	0.0085	0.0076	0.0143	0.0111
Spring	a	0.0024	0.0023	0.0010	0.0020	0.0015	0.0017
	b	0.0017	0.0116	0.0281	0.0203	0.0271	0.0249
Summer	a	0.0029	0.0027	0.0012	0.0022	0.0020	0.0021
	b	0.0220	0.0305	0.0445	0.0283	0.0361	0.0340
Automn	a	0.0020	0.0020	0.0008	0.00135	0.0012	0.0012
	b	0.0128	0.0103	0.0183	0.0129	0.0200	0.0173
Annual	a	0.00231	0.00214	0.000941	0.00164	0.0014	0.00155
	b	0.0154	0.0118	0.0250	0.0173	0.0243	0.0220

It is very interesting to compare the rate of the pollution increase in Georgia to similar data from other regions of the world, particularly those with a low pollution level. Table 5.3 presents the mean values of τ_a for six regions of Georgia and Tibet (Mt. Qomolungma) [92], derived as a result of observations carried out in 1966-1986, and also τ_a increase rates in
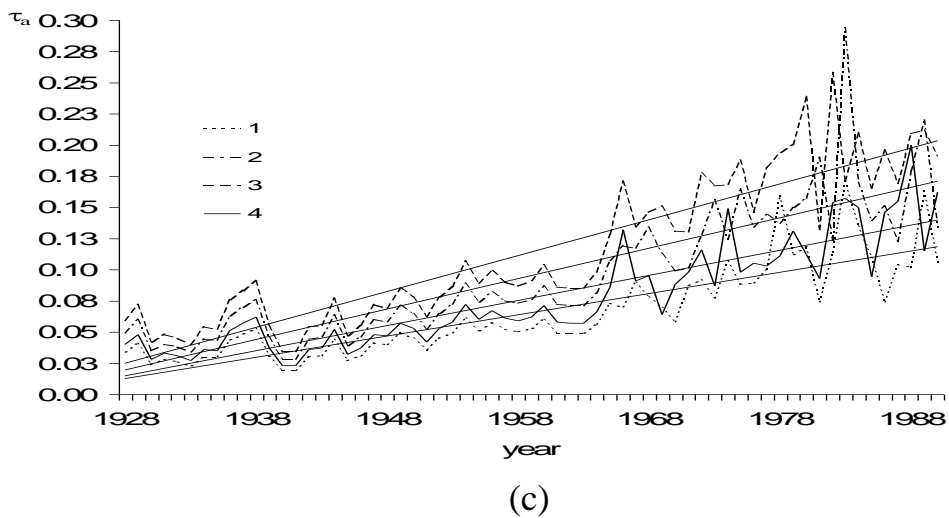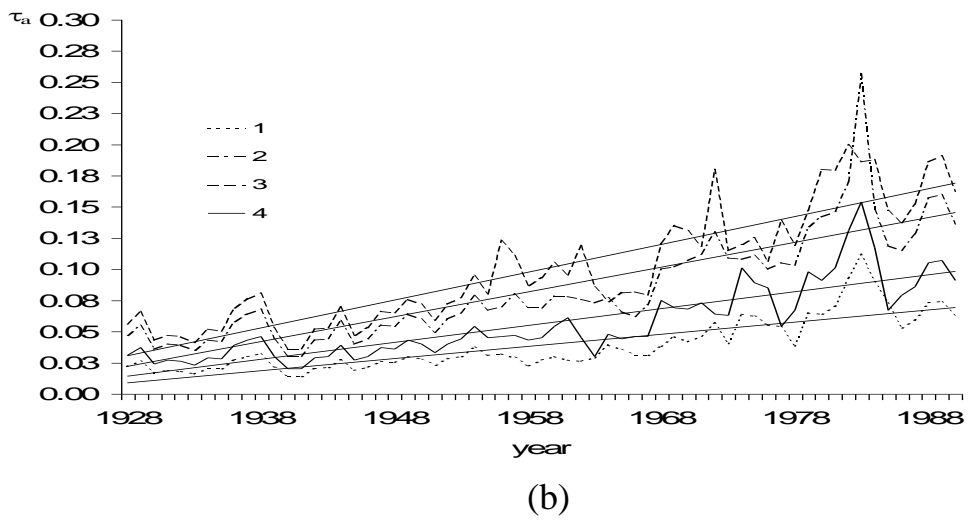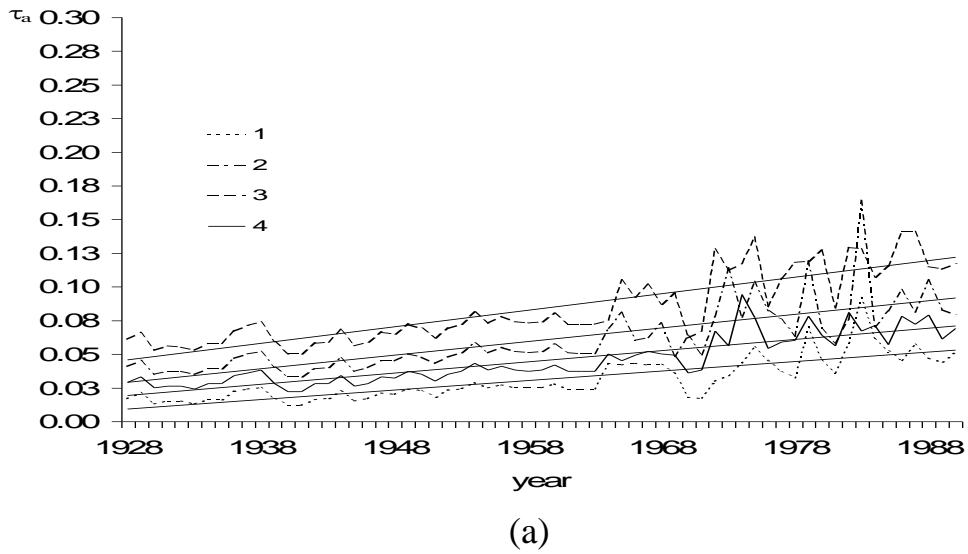
Fig. 5.3

Variations of mean seasonal values of τ_a in (a) Tsalka, (b) Anaseuli, (c) Tbilisi in 1928-1990. 1 - winter, 2 - spring, 3 - summer, 4 - autumn

comparison to 1966. It is noteworthy that at the high-mountain stations of Georgia the mean annual τ_a values amounted for the Jvari Pass to 0.066 (1969-1985) and for Kazbegi 0.049 (1955-1964).

<div align="right">Table 5.3</div>

<div align="center">Mean values of τ_a and their increase rates in 1966-1986
in Georgia and Tibet</div>

Station	Tbilisi	Telavi	Tsalka	Anaseuli	Senaki	Sokhumi	Tibet
Elev. above Sea Lev. (m)	403	568	1457	158	40	116	6300
τ_a (1966-1986)	0.127± 0.037	0.120± 0.031	0.073± 0.017	0.096± 0.035	0.089± 0.033	0.096± 0.033	0.024± 0.009
τ_a Increase Rate (%)	2.7	5.7	2.8	4.8	5.0	3.7	1.8

Table 5.3 shows that the pollution level in Georgia is higher than in Tibet: for low pollution regions (Tsalka) approximately 3 times, for highly polluted regions (Tbilisi, Telavi) 5 times and more. The increase rate in 1966-1986 is also higher (at the average in Georgia 4.1%, in Tibet 1.8%). All this indicates that in Georgia together with global pollution sources a considerable role is played by local sources of air pollution.

5.3 The dynamics of the random and anthropogenic components of the atmospheric aerosol optical depth in 1928-1990.

In order to estimate the effect of various factors in the formation of the atmospheric pollution level an attempt was made to establish the role of background, anthropogenic and random sources in the total pollution.

The following considerations were taken into account: 1. The background pollution always exists in the atmosphere and its value (τ_b) is invariable, therefore as a τ_b value for a certain region is taken the minimum τ_a in 1928-1990. 2. Also random sources of pollution (forest fires, volcanoes, nuclear explosions, etc.) always exist and vary in a wide range. But considering their nature, their variation range is invariable too. 3. Anthropogenic pollution sources (industries, transport, etc.) represent main contributors into the total atmospheric pollution level. Considering the above-mentioned, if on a curve of τ_a variations the minimum points are selected and connected by a line, the profile of the background+anthropogenic pollution will be derived. Such curves and approximating functions were found in an empiric way and using the least square method:

$$\tau_{ant+b} = \begin{cases} \tau_b & \text{when } t < T \\ \dfrac{A}{(58 - |1985 - t|)^{\frac{1}{2}}} e^{B(|1985 - t|)^{\frac{4}{3}}} & \text{when } t \geq T \end{cases} \quad (5.4)$$

where τ_b is a background value of τ_a for any region, T - certain year, t - years from 1928 to 1990, A and B - coefficients. Using τ_{ant+b} it is very easy to find anthropogenic and background levels:

$$\tau_{ant} = \tau_{ant+b} - \tau_b; \quad \tau_r = \tau_a - \tau_{ant+b};$$

The results of these estimations are given in Fig. 5.2 (curves 2, 3, 4) and Tables 5.4-5.5.

Table 5.5 shows that the background level varies little for the whole territory of Georgia: not more than 21% from the mean value. Random pollution levels also changed inconsiderably in 1928-1970. In 1971-1990 an increase of about 45% was observed in the random pollution level. A particular contribution into this increase was made by the El-Chichon volcano erupted in 1982. It is noteworthy that in 1970-1990 the highest values of the random pollution was observed in Telavi. This was probably caused by such sources as hail prevention activities, which had a random

character in comparison to industrial, transport and other constant anthropogenic sources. However the highest after Tbilisi level of pollution in Telavi is in our opinion mainly caused by the transport of RASAA from Tbilisi, Rustavi, Kaspi, Gardabani (Fig. 1.1 and 1.2).

Table 5.4

Values of A and B coefficients and T and τ_b parameters of (5.4) for the six actinometric stations of Georgia in 1928-1990

Station Parameter	Tbilisi	Telavi	Tsalka	Anaseuli	Senaki	Sokhumi
A	1.029	0.890	0.518	0.713	0.739	0.760
B	-0.013	-0.013	-0.010	-0.012	-0.011	-0.011
T	1935	1935	1937	1936	1936	1936
τ_b	0.0227	0.0152	0.0159	0.0205	0.0212	0.0160

Table 5.5

Background, random and anthropogenic levels of the atmospheric pollution in various regions of Georgia

Period (Years)	Station	Tbilisi	Telavi	Tsalka	Anaseuli	Senaki	Sokhumi	Mean for Georgia
1928-1950	Backgr.	0.023	0.015	0.016	0.020	0.021	0.016	0.019
	Random	0.019±0.012	0.023±0.011	0.020±0.005	0.017±0.009	0.021±0.007	0.023±0.008	0.021±0.008
	Anthr.	0.004±0.005	0.003±0.004	0.001±0.002	0.003±0.003	0.002±0.003	0.002±0.003	0.003±0.003
	Total	0.046±0.013	0.041±0.012	0.038±0.005	0.040±0.009	0.044±0.008	0.042±0.009	0.042±0.009
1951-1970	Random	0.020±0.013	0.023±0.010	0.020±0.006	0.017±0.010	0.021±0.007	0.029±0.007	0.022±0.009
	Anthr.	0.037±0.014	0.032±0.012	0.016±0.006	0.026±0.010	0.024±0.009	0.026±0.010	0.027±0.010
	Total	0.080±0.020	0.071±0.013	0.051±0.008	0.063±0.012	0.066±0.011	0.071±0.014	0.067±0.013
1971-1990	Random	0.032±0.018	0.042±0.017	0.028±0.014	0.032±0.021	0.025±0.021	0.031±0.021	0.032±0.019
	Anthr.	0.090±0.013	0.077±0.011	0.035±0.004	0.058±0.007	0.056±0.007	0.060±0.008	0.063±0.008
	Total	0.144±0.023	0.134±0.025	0.079±0.015	0.111±0.025	0.102±0.028	0.106±0.025	0.113±0.022

The background and random pollution levels do not differ much from each other, while the anthropogenic pollution level in comparison to the background increases intensively. For example, in 1971-1990 this increase amounted to: 470% in Tbilisi, 400% in Telavi, 180% in Tsalka,

300% in Anaseuli, 315% in Sokhumi, 255% in Senaki. Thus, in the growth of τ_a in Georgia contribute mainly global and local anthropogenic sources.

The random component of the atmospheric aerosol optical depth is determined mainly by volcanic activity. As an example Fig. 5.4 and 5.5 present the mean annual values of τ_r in Tbilisi and the relative mean monthly variations of the atmospheric aerosol optical depth in Anaseuli. The times of volcanic eruptions and amounts of emitted aerosols are also given [84]. Fig. 5.4 shows that in 1928-1990 an intensive increase of τ_a is observed after a strong volcanic eruption. The same picture indicates an intensification of the volcanic activity in the last three decades.

In contrast to anthropogenic changes of aerosols variations caused by strong random pollution sources (volcanic eruptions, forest fires, nuclear explosions, etc.) are not monotonous and occur during relatively short time intervals. As an illustration Fig. 5.5 presents the relative monthly pollution variation in 1980-1990. This is the period when as a result of an eruption of the El-Chichon volcano in Mexico (February 1982) a particularly large amount of aerosols got in the stratosphere and raised intensively the global pollution level during 3-4 years. The figure clearly shows that in Georgia, namely in Anaseuli (approximately the same picture was detected at other actinometric stations of Georgia), the pollution effect manifested itself about 5-6 months after the eruption and the atmosphere cleaned only in more than 2 years.

As it was mentioned above there are stable corelations between the mean annual values of the atmospheric aerosol optical depth in various regions of Georgia. In Table 5.6 corelation matrices of the mean annual values of τ_a and its random component in 1955-1990 for the six actinometric stations of Georgia are presented.

According to the table even for the random values of τ_a quite high corelations are observed. This indicates that in the random component of τ_a contribute mainly global sources of pollution.

At the same time local factors also considerably affect the random levels of τ_a. This is indicated by higher corelations between stations located close to each other in comparison to corelations between stations located at large distances. As regards the total τ_a values (Table 5.6) in this case high corelations are observed between all stations i.e. variations of the atmospheric pollution for the whole territory of Georgia are approximately similar. The temporary variations of the anthropogenic component of τ_a is in a good coherence with the change of the anthropogenic emissions of the aerosol component of RASAA in Georgia (Table 5.7). However, the rate of the reduction of the aerosol emissions from 1986 till 1990 is considerably higher than the rate of the τ_a decrease.
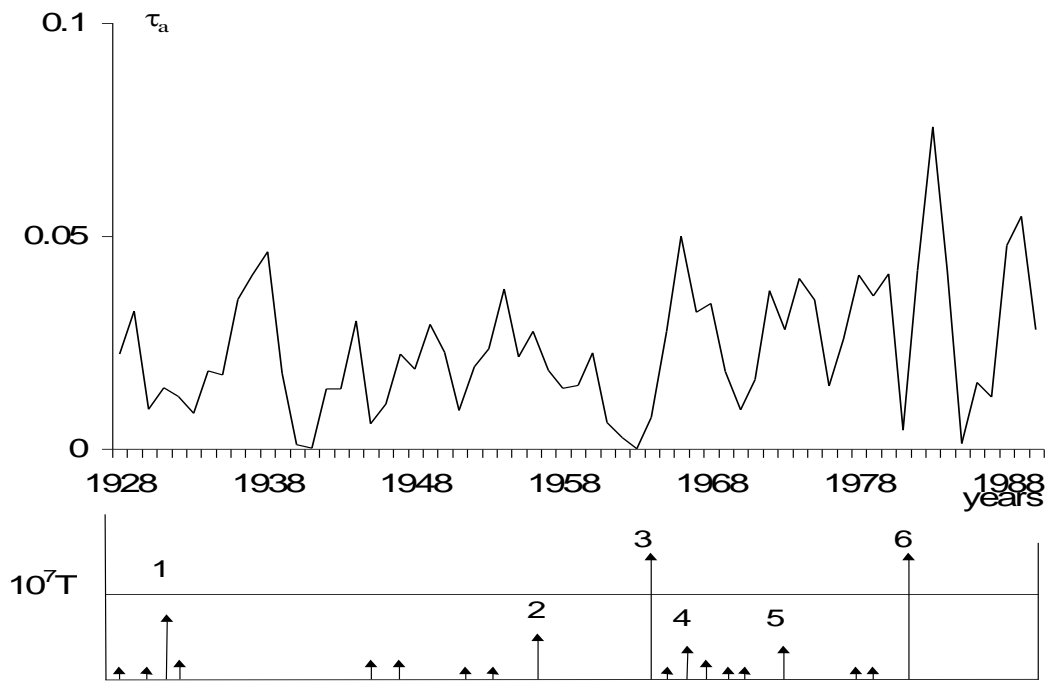
Fig. 5.4

Variations of the atmospheric aerosol optical depth levels caused by strong random sources of pollution in 1928-1990 in Tbilisi. Arrows indicate volcanic eruptions and amounts of emitted aerosols according to [84]. Numbers indicate strong volcanic eruptions.

1 - Sierra Asul   10.04.1932, 7.8 mln.T.
2 - Nameless   30.03.1956, 4.9 mln.T.
3 - Agung   17.03.1963, 15 mln.T.
4 - Avu   12.08.1966, 4.4 mln.T.
5 - Fuego   17.10.1974, 4.5 mln.T.
6 - El Chichon   04.04.1982, 10-15 mln.T.

$\Delta\tau_{a(rand.)}=0.000273\cdot(t-1927)+0.0147$
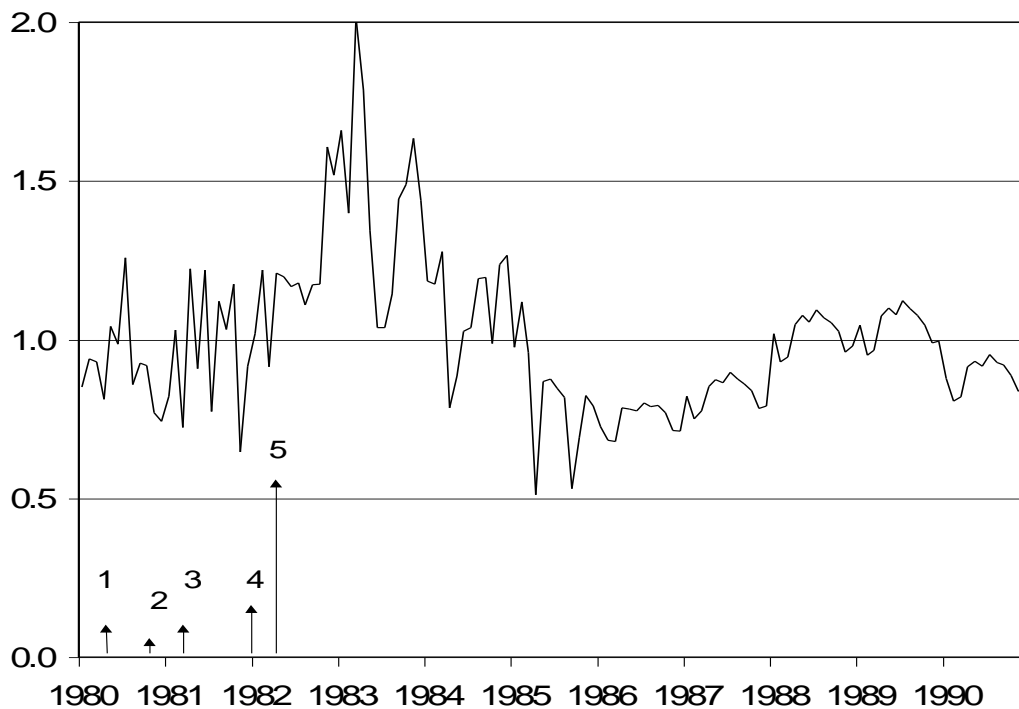
Fig. 5.5

Variations of relative ($\tau_a/\Delta\tau_a$) values of atmospheric aerosol optical depth from January 1980 till December 1990 in Anaseuli. Arrows and numbers indicate volcanic eruptions and amounts of emitted aerosols according to the data of [84].

1 -	St. Helens	18.05.1980, 0.32-0.5 mln.T.
2 -	Ulawun	10.1980, 0.25 mln.T.
3 -	Alaid	27.04.1981, 0.5 mln.T.
4 -	Nameless	01.1982, 1.0 mln.T.
5 -	El Chichon	04.04.1982, 10-15 mln.T.

This confirms a considerable role of global anthropogenic RASAA emission sources in the air pollution in Georgia (Table 1.5).

Table 5.6

Corelation matrix for six actinometric stations of Georgia according to mean annual values of the atmospheric aerosol optical depth (upper right part) and τ_a caused by strong random pollution sources (left lower part)

Station	Tbilisi	Telavi	Tsalka	Anaseuli	Senaki	Sokhumi
Tbilisi	1	0.92	0.87	0.87	0.83	0.84
Telavi	0.61	1	0.81	0.84	0.86	0.81
Tsalka	0.63	0.47	1	0.75	0.71	0.72
Anaseuli	0.58	0.50	0.39	1	0.81	0.89
Senaki	0.46	0.57	0.31	0.51	1	0.89
Sokhumi	0.49	0.38	0.32	0.69	0.70	1

Table 5.7

Variations of anthropogenic emissions of aerosols (Table 2.4) and mean value of the anthropogenic component of τ_a in Georgia in 1985-1990 (normed per 1986)

Year \\ Parameter	1985	1986	1987	1988	1989	1990
$\tau_{a(anthr.)}$ %	99.6	100	99.3	96.8	95.9	93.6
Aer. em. %	93.4	100	97.0	92.4	85.8	80.3

Finally it is noteworthy that the approach used in this chapter for the estimation of the background, random and anthropogenic components of the atmospheric aerosol optical depth is not very rough. For example in Tbilisi (Table 5.5) the share of the anthropogenic component of τ_a in the total value of the atmospheric aerosol optical depth in 1971-1990 amounted approximately to 60%. This figure is in a good agreement with the analogous estimation of the aerosol content over Tbilisi, carried out in Chapter 3. The share of the anthropogenic τ_a in its total value at the global scale is 45% (Table 1.1). A similar figure (44%) is observed at the station Tsalka in 1971-1990 (Table 5.5), which also confirms a satisfactory accuracy of the mentioned method.

5.4   The monthly variations of the atmospheric pollution in some regions of Georgia in 1928-1990.


        Investigation of the monthly variations of the mean monthly values of the atmospheric aerosol optical depth are of a considerable interest.
        Fig. 5.6 presents the mean monthly variations of τ_a in 1928-1990 at three actinometric stations of Georgia. Fig. 5.7 presents the dynamics of the mean monthly values of τ_a for the same three actinometric stations in three time periods from 1928 till 1990. The figures show that the highest level of the atmospheric pollution and its increase rate is observed in Tbilisi, the lowest - in Tsalka. In Western Georgia (Anaseuli) the variations of the atmospheric pollution level is quite homogeneous for the whole territory. τ_a values are lower here than in Tsalka. The τ_a variations (Fig. 5.6-5.7) have a clear seasonal profile with a maximum in the summer (mainly in July) and a minimum in the winter. The highest increase rate of τ_a in Georgia is observed in the summer (Fig. 5.3, Table 5.2).
   Table 5.8 presents the data on the occurrence of the mean monthly τ_a values in three periods for the six actinometric stations of Georgia. According to the scale of air pollution presented in Table 5.1, for various regions of Georgia the following picture is observed: in 1928-1950 a "clean atmosphere" ($\tau_a \leq 0.110$) was on the whole territory of Georgia. In 1951-1971 a considerable growth of the air pollution occurred. The pollution level up to the gradation "clean atmosphere" amounted approximately to 86% of cases in Tbilisi, 87% in Telavi and Sokhumi, 91% in Anaseuli, 93% in Senaki. "Clean atmosphere" practically remained in Tsalka - 99% of cases. In 1971-1990 the pollution level increased intensively again. In Tbilisi the atmospheric pollution level up to the gradation "clean atmosphere" amounted already to only 32% of cases, while in Telavi - 38%. In Western Georgia "clean atmosphere" was still observed in more than a half of cases (Anaseuli - 53%, Senaki - 66%, Sokhumi - 55%). In Tsalka the occurrence of the mean monthly values up to this gradation amounted to 79%.
        The biggest amplitude of the mean monthly variations of τ_a in 1971-1990 was observed in Tbilisi (all 9 gradations of atmospheric pollution, Table 5.1). In Tsalka this amplitude varied within I-VII, while in other towns - within I-VIII gradations. In the mentioned time period the highest occurrence was observed for "slightly turbid" in Tbilisi, "clean" and "slightly turbid" in Telavi, "very clean" in other towns.
        In comparison to the second period in 1971-1990 considerable inhomogenities of the τ_a distribution according to the gradations (Table 5.8) took place. For example, in the second period at all six stations one
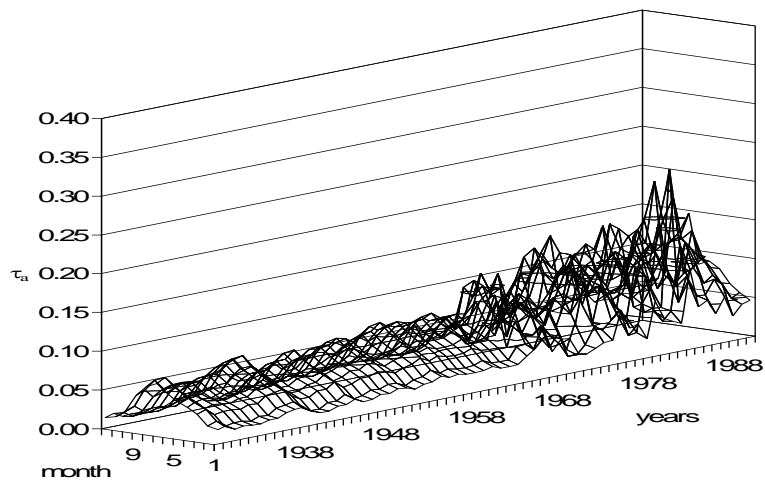
(a)
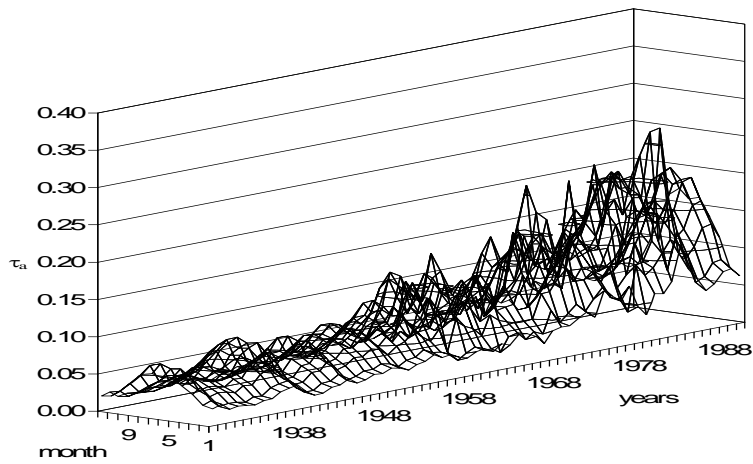
(b)
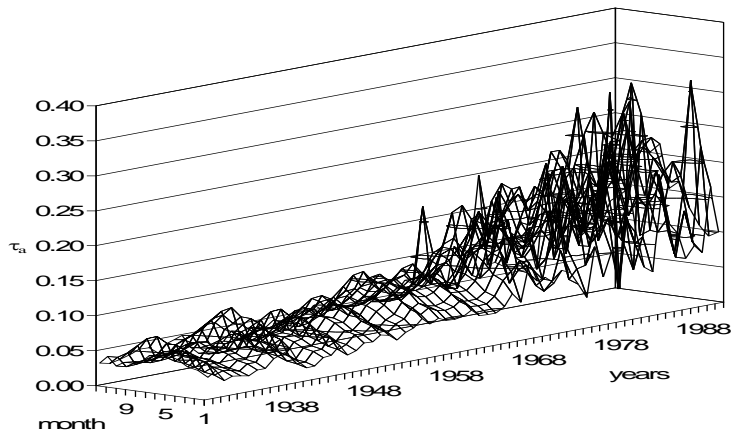
(c)

Fig 5.6

Variations of mean monthly values of atmospheric aerosol optical depth in
1928-1990 in (a) Tsalka, (b) Anaseuli, (c) Tbilisi

Fig 5.7

Monthly variations of mean monthly values of atmospheric aerosol optical depth averaged for three 20 year periods in (a) Tsalka, (b) Anaseuli, (c) Tbilisi. 1 - 1928-1950; 2 - 1951-1970; 3 - 1971-1990.

Table 5.8

Occurrence of mean monthly values of τ_a in three time periods for six stations of Georgia. I) 1928-1950; II) 1951-1970; III) 1971-1990 (%)

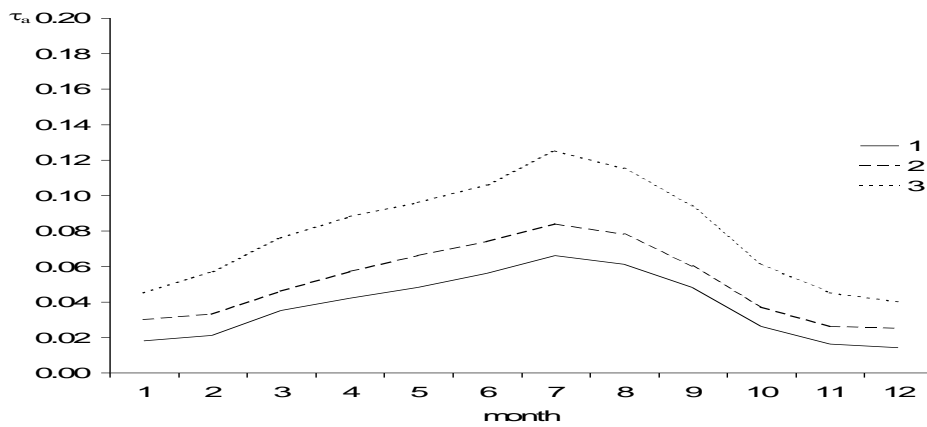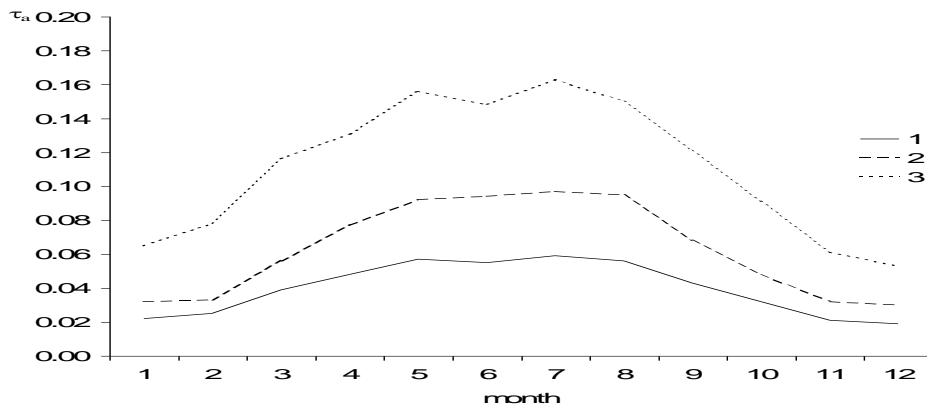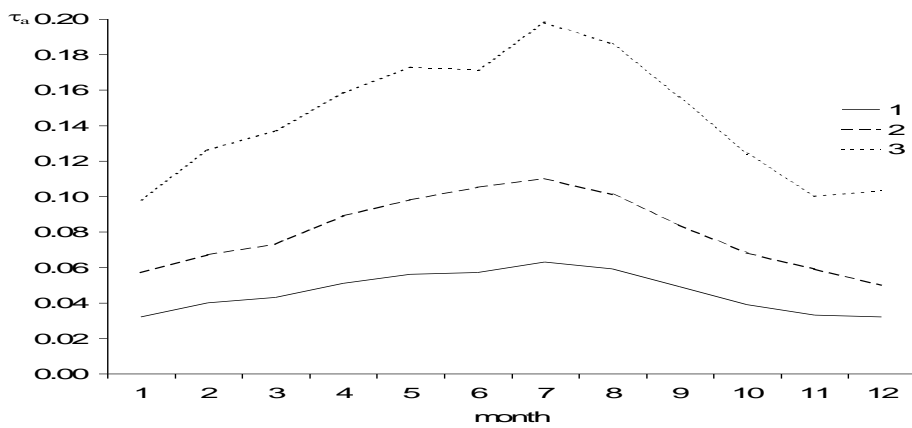| τ_a / Periods	0.010÷0.050	0.051÷0.080	0.081÷0.110	0.111÷0.130	0.131÷0.150	0.151÷0.190	0.191÷0.230	0.231÷0.310	0.311÷0.325
Tbilisi									
I	65.22	31.16	3.62						
II	15.00	41.67	29.17	6.67	3.75	3.75			
III	1.67	11.67	18.33	13.75	11.25	21.67	15.42	5.00	1.25
Telavi									
I	67.03	26.45	6.52						
II	32.92	31.67	22.50	8.33	3.33	0.83	0.42		
III	3.75	15.00	19.17	13.33	12.08	19.17	12.50	5.00	
Tsalka									
I	70.29	29.71							
II	50.42	40.83	7.50	1.25					
III	26.67	28.33	25.42	12.08	5.42	1.25	0.83		
Anaseuli									
I	72.10	27.54	0.36						
II	42.92	30.42	17.50	7.92	1.25				
III	9.17	22.92	20.83	14.17	11.67	14.58	5.42	1.25	
Senaki									
I	65.22	32.61	2.17						
II	34.17	35.00	23.33	6.67	0.83				
III	13.75	25.83	25.00	9.17	6.67	12.08	6.67	0.83	
Sokhumi									
I	68.84	29.35	1.81						
II	33.33	30.00	23.33	7.92	5.42				
III	8.75	26.67	19.17	15.42	12.92	12.92	3.75	0.42	

Table 5.9

Corelation matrix of mean monthly values of τ_a for Tbilisi in 1928-1990

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
I	1	0.825	0.797	0.865	0.889	0.844	0.797	0.779	0.781	0.712	0.845	0.794
II		1	0.851	0.817	0.891	0.811	0.880	0.852	0.815	0.788	0.823	0.835
III			1	0.862	0.813	0.804	0.842	0.842	0.794	0.741	0.820	0.863
IV				1	0.902	0.869	0.860	0.822	0.829	0.846	0.859	0.873
V					1	0.915	0.910	0.908	0.865	0.830	0.869	0.888
VI						1	0.843	0.821	0.857	0.805	0.881	0.889
VII							1	0.924	0.872	0.840	0.838	0.873
VIII								1	0.843	0.815	0.820	0.839
IX									1	0.872	0.929	0.866
X										1	0.848	0.865
XI											1	0.905
XII												1

extremum was observed, while in the third period one extremum was observed only in Tsalka. In other towns two extrema of the τ_a distribution were detected, one of which was in the II or III gradation, while the other one in the gradation "slightly turbid atmosphere".

Table 5.9 presents a corelation matrix of the mean monthly values of τ_a for all months in 1928-1990 in Tbilisi. The table shows that a high corelation is observed among all months. This verifies a high stability of the aerosol pollution of the atmosphere. In addition this matrix can be used for prediction of mean monthly values of the air pollution by means of the data of observations in previous periods.

Chapter VI

Estimations of the effect of some RASAA on the direct and diffuse solar radiation regime in Georgia

6.1   Methods of the calculation of the direct and diffuse solar radiation

The process of the transfer of electromagnetic radiation in disperse media is described by the following equation:

$$\frac{\cos\vartheta}{\rho}\frac{\partial I}{\partial z} = kE + \frac{\sigma}{4\pi}\int I(z,s')\gamma(z,s,s')d\omega' - (k+\sigma)I \qquad (6.1)$$

Considering the atmosphere as a disperse media and the Sun as a radiation source the parameters of the equation acquire the following sense: I - irradiance of the direct monochromatic Sun radiation on a surface perpendicular to the rays, E - irradiance of the thermal monochromatic radiation of the atmosphere, z - vertical coordinate directed upwards (the atmosphere is considered to be a plane homogeneous system, therefore the parameters of (6.1) do not change along x and y axes), ρ - density of the media at the z elevation, k - absorption, while σ - diffusion coefficients, $\gamma(z,s,s')$ - scattering indicatrix at the z elevation in the s direction, when a ray comes from the s' direction in the atmosphere, $d\omega'$ - space angle in the s' direction.

If the terms corresponding to the diffuse and thermal radiation are neglected, the equation has the form:

$$\frac{\cos\vartheta}{\rho}\frac{\partial I}{\partial z} = -(k+\sigma)I \qquad (6.2)$$

whose solution with the boundary condition

$$I\big|_{z=\infty} = I_0 \qquad (6.3)$$

is

$$I = I_0 e^{-m\int_z^\infty \rho(k+\sigma)dz} \qquad (6.4)$$

where $m = \dfrac{1}{\cos \vartheta}$, while the expression $\displaystyle\int_{z}^{\infty} \rho(k + \sigma)dz$ represents the atmospheric optical depth in the vertical direction beginning from the z elevation. If this expression is designated by τ, then it is composed of the following components:

$$\tau = \tau_z + \tau_{O_3} + \tau_{CO_2} + \tau_{\omega} + \tau_a \qquad (6.5)$$

where $\tau_z, \tau_{O_3}, \tau_{CO_2}, \tau_{\omega}, \tau_a$ are respectively the optical depths of an ideally clean atmosphere, ozone, carbon dioxide, water vapour and atmospheric aerosols.

They can be determined by the following formulas:

$$\tau_z = 0.00879 \cdot \lambda^{-4.09} \cdot e^{-\frac{z}{h}} \cdot A(z) \qquad (6.6)$$

λ - wavelength (mcm), h - reduced height of the atmosphere (~ 8 km), A(z) - considers the nonisothermity of the free atmosphere.

$$\tau_{O_3} = k_{O_3} \cdot u \qquad (6.7)$$

k_{O_3} - absorption coefficient of ozone in a narrow range of wavelengths, while u - total ozone in the atmosphere (atm·cm).

$$\tau_{CO_2} = k_{CO_2} \cdot v \qquad (6.8)$$

k_{CO_2} and v - absorption coefficient and total content of carbon dioxide.

$$\tau_{\omega} = k_{\omega} \cdot \omega \qquad (6.9)$$

k_{ω} and ω - absorption coefficient and total content of water vapour.

$$\tau_a = \frac{a}{\lambda} \qquad (6.10)$$

a - aerosol extinction coefficient.

After determining the corresponding optical depths by (6.2-6.10) the integral irradiance on a surface perpendicular to the radiation direction can be calculated by the following expression:

$$I(m) = \int_0^\infty I_0(\lambda) \cdot e^{-m\tau(\lambda)} d\lambda \qquad (6.11)$$

At a given m the irradiance of the direct solar radiation on a horizontal surface is determined by the equation

$$I'(m) = I(m) \cdot \cos\vartheta \qquad (6.12)$$

$I'(m)$ is calculated for five values of m at 6^{30}, 9^{30}, 12^{30}, 15^{30}, 18^{30} o'clock and then considering the times of the sunrise and sunset daily sums are determined. Ranges of the division of the integral according to wavelengths and the absorption coefficients in the corresponding ranges and also the values of the solar constant (I_0) are given in [133].

In order to test the model monthly sums of the direct solar radiation on a horizontal surface under the clear sky conditions were calculated for 1954, 1960 and 1965 in Tbilisi. The results are presented in Fig. 6.1 a,b,c and Table 6.1

Table 6.1

Comparison of the calculated and actual monthly sums of the direct solar radiation (MJ/m^2)

Month	1954			1960			1965		
	Actual	Calc.	Diff. %	Actual	Calc.	Diff. %	Actual	Calc.	Diff. %
1	191.90	192.32	-0.22	214.53	184.36	14.06	178.49	188.13	-5.40
2	313.83	267.74	14.69	308.38	274.45	11.01	274.45	275.28	-0.31
3	530.04	499.87	5.69	390.93	531.71	-36.01	442.46	513.69	-16.10
4	626.41	624.73	0.27	667.89	603.36	9.66	559.37	601.27	-7.49
5	623.05	710.21	-13.99	748.33	622.22	16.85	653.22	609.23	6.74
6	696.80	714.81	-2.58	711.46	621.38	12.66	692.61	607.13	12.32
7	602.52	670.82	-11.34	670.82	604.62	9.87	653.22	581.99	10.90
8	532.55	588.70	-10.54	624.73	544.70	12.81	580.32	523.75	9.75
9	514.95	495.26	3.82	457.97	503.64	-9.97	461.74	504.06	-9.17
10	320.95	392.18	-22.19	355.73	318.86	10.37	358.66	325.56	9.23
11	212.85	271.93	-27.76	233.38	206.57	11.49	228.36	213.69	6.42
12	155.03	175.14	-12.97	134.08	157.54	-17.50	174.30	156.71	10.10
Year	5320.88	5603.29	-5.31	5518.23	5173.39	6.25	5257.19	5100.49	2.98
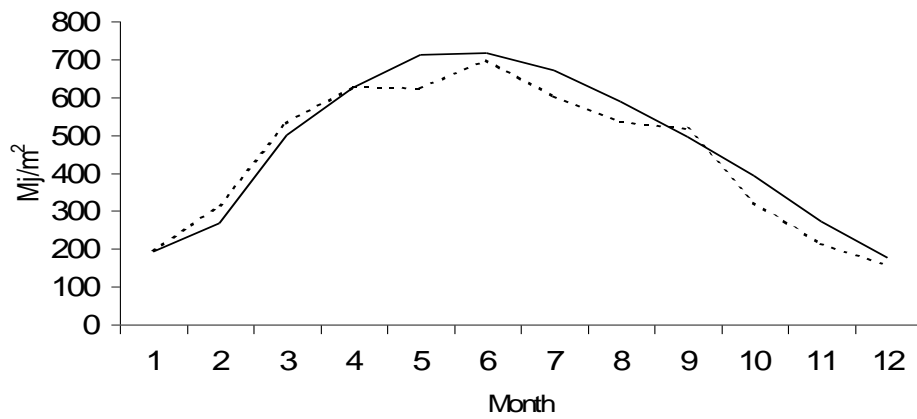
(a)
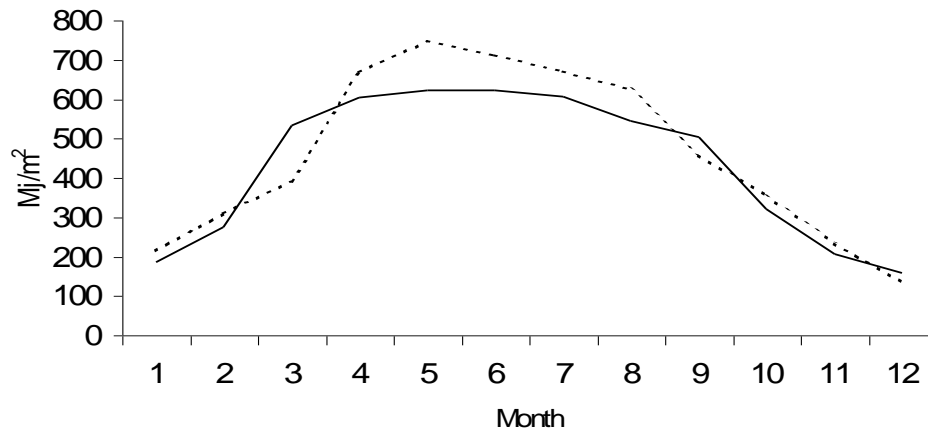
(b)
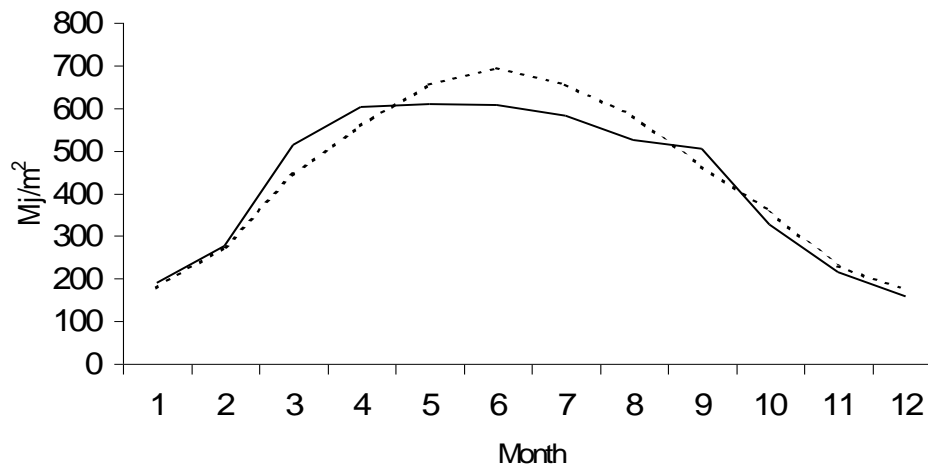
(c)

Fig. 6.1
Actual (dashed curve) and calculated values of the monthly sums of the
direct solar radiation in Tbilisi: a - 1954, b - 1960, c - 1965

Mathematical modeling of the diffuse radiation in the atmosphere is based on the solution of the integral differential equation (6.1) using boundary conditions. In the approximation of the nonpolarization of the radiation and a nonradiating atmosphere the equation has the following form [120]:

$$\begin{cases} \mathbf{D}\psi = \mathbf{S}\psi \\ \psi^+\big|_{\Gamma_{z_0}} = \pi S_\lambda \delta(s - s_0); \psi^-\big|_{\Gamma_{z_H}} = q\mathbf{R}_{z_H}\psi^+ \end{cases} \qquad (6.13)$$

here

$$\mathbf{D} \equiv \mu\frac{\partial}{\partial z} + (k+\sigma)\rho; \mathbf{S}\psi = \sigma\iint_\Omega \psi(z,s')\gamma(z,s,s')ds'; \mathbf{R}_{z_H}\psi = \frac{1}{\pi}\iint_{\Omega^+} \psi(z_H,s')\mu'ds';$$

$$ds = d\mu d\varphi; \Omega = \Omega^+ \cup \Omega^- = \{(\mu,\varphi): \mu \in [-1,1], \varphi \in [0,2\pi]\};$$

and $\psi, z, \mu, \varphi, \gamma, q, \rho$ and S_λ represent respectively the irradiance function, elevation from the ground, zenith angle cosine, azimuth, scattering indicatrix, albedo of the underlying surface, media density and solar constant. The boundary conditions in (6.13) physically mean that outside the atmosphere the downward radiation equals to the solar constant, while the upward radiation near the ground complies with the s.c. Lambert low, i.e. is the same in all directions and equals to the flux of the downward radiation per a space angle unit.

For practical calculations it is convenient to introduce new variables and namely using the following equation:

$$d\tau = (k+\sigma)\rho dz \qquad (6.14)$$

where τ is the optical depth of the atmosphere, the differential and integral operators in (6.13) have the form:

$$\mathbf{D}\tau \equiv \mu\frac{\partial}{\partial \tau} + 1; \mathbf{S}\psi = \omega(\tau)\iint_\Omega \psi(\tau,s')\gamma(\tau,s,s')ds' \qquad (6.15)$$

where $\omega(\tau) = \dfrac{\sigma}{k+\sigma}$ represents the s.c. scattering albedo and actually determines the share of the extinction by scattering in the total extinction.

It is impossible to solve (6.13) analytically and therefore numerical methods should be used. The traditional way of the solution represents the

s.c. method of iterations according to scattering multiplicity [120]. Its scheme has the form:

$$\psi^{(N+1)} = \mathbf{D}^{-1}\mathbf{S}(\psi^{(N)} + \psi_0) \qquad (6.16)$$

In order to get (6.16) explicitly, the solution of (6.13) should be rewritten in a semi-analytical form. Integrating a differential equation of the first order easily gives:

$$\begin{cases} \psi^+(\tau,s) = \int\limits_0^\tau \frac{\omega(\tau')}{\mu^+} \iint\limits_\Omega \psi(\tau',s')\gamma(\tau',s,s')ds'\, e^{\frac{\tau'-\tau}{\mu^+}}\, d\tau' + \psi_{\tau_0}{}^+ \cdot e^{-\frac{\tau}{\mu^+}} \\ \\ \psi^-(\tau,s) = \int\limits_{\tau_H}^\tau \frac{\omega(\tau')}{\mu^-} \iint\limits_\Omega \psi(\tau',s')\gamma(\tau',s,s')ds'\, e^{\frac{\tau'-\tau}{\mu^-}}\, d\tau' + \psi_{\tau_H}{}^- \cdot e^{\frac{\tau_H-\tau}{\mu^-}} \end{cases} \qquad (6.17)$$

where ψ^+ and ψ^- represent respectively the upward and downward radiation functions, $\mu^+ \in [0,1]$, $\mu^- \in [-1,0]$, while $\psi^+{}_{\tau_0} = \pi S_\lambda \delta(s - s_0)$ and $\psi^-{}_{\tau_H} = q\mathbf{R}_{\tau_H}\psi^+$.

Let us reduce (6.17) to a form convenient for numerical calculations. With this purpose the τ argument of ψ^+ and ψ^- functions is incremented by an arbitrarily small value Δ and the following designations are introduced:

$$\begin{cases} \mathbf{S}^+ \equiv \iint\limits_{\Omega^+} \psi(\tau,s')\gamma(\tau,s,s')ds'; \\ \\ \mathbf{S}^- \equiv \iint\limits_{\Omega^-} \psi(\tau,s')\gamma(\tau,s,s')ds'; \end{cases} \qquad (6.18)$$

It gives:

$$\begin{cases} \psi^+(\tau+\Delta,s) \approx \psi^+(\tau,s) \cdot e^{-\frac{\Delta}{\mu^+}} + \Delta \cdot \frac{\omega(\tau)}{\mu^+}[\mathbf{S}^+\psi^+ + \mathbf{S}^-\psi^+]; \\ \\ \psi^-(\tau+\Delta,s) \approx \psi^-(\tau,s) \cdot e^{\frac{\Delta}{\mu^-}} - \Delta \cdot \frac{\omega(\tau)}{\mu^-}[\mathbf{S}^+\psi^- + \mathbf{S}^-\psi^-]; \end{cases} \qquad (6.19)$$

Finally introducing a grid $\{\tau_i, s_j\}$ an iteration scheme is derived:

$$
\begin{cases}
\psi^+_{i+1,j}{}^{(N+1)} = \psi^+_{i,j}{}^{(N)} \cdot e^{-\frac{\Delta_i}{\mu^+_j}} + \Delta_i \cdot \frac{\omega_i}{\mu^+_j}[\mathbf{S}^+\psi^+_{i,j}{}^{(N)} + \mathbf{S}^-\psi^+_{i,j}{}^{(N)}]; \\[2em]
\psi^-_{i-1,j}{}^{(N+1)} = \psi^-_{i,j}{}^{(N)} \cdot e^{\frac{\Delta_i}{\mu^-_j}} - \Delta_i \cdot \frac{\omega_i}{\mu^-_j}[\mathbf{S}^+\psi^-_{i,j}{}^{(N+1)} + \mathbf{S}^-\psi^-_{i,j}{}^{(N)}];
\end{cases}
\tag{6.20}
$$

here the upper index in parentheses designates the number of an iteration.

The condition of stopping the iterations is :

$$
\left|\frac{\psi^{(N+1)} - \psi^{(N)}}{\psi^{(N)}} < \varepsilon\right|
\tag{6.21}
$$

where ε is an arbitrarily small number. During computer calculations due to large computing errors at big N-s the process may not converge. Therefore along with (6.21) the following condition is also used:

$$
\left|\iint_{\Omega^-}\psi^-(0,s)\mu^- ds\right| + (1+q)\iint_{\Omega^+}\psi^+(\tau_H,s)\mu^+ ds = \pi\mu_0 S_\lambda e^{-\frac{\tau_H^a}{\mu_0}}
\tag{6.22}
$$

where τ_H^a is the absorption part of the optical depth. (6.22) follows from the energy conservation low: a sum of the reflected, transmitted and absorbed radiation should be equal to the initial radiation flux.

The scattering indicatrix was borrowed from [145]. It has the following analytical form:

$$
\frac{3}{16\pi}\tau_R(1+\cos^2\varphi) + \frac{\left(\tau - \frac{15}{16}\tau_R\right)}{4\pi(e^{-\pi} - 0.009)}(e^{-3\varphi} - 0.009);
\tag{6.23}
$$

where τ_R can be calculated by (6.6), while τ is the optical depth of the atmosphere.

Finally in order to test the model in Fig. 6.2 a and b and Table 6.2 the actual and calculated diffuse radiation values under the clear sky conditions for 1980 and 1981 in Tbilisi are given.

Table 6.2

Comparison of actual and calculated diffuse radiation values for 12^{30} o'clock in Tbilisi (KW/m^2)

Month	1980			1981		
	Actual	Calc.	Diff. %	Actual	Calc.	Diff. %
1	0.120	0.079	34	0.076	0.080	-05
2	0.120	0.101	16	0.113	0.100	12
3	0.120	0.104	13	0.126	0.123	2
4	0.190	0.173	9	0.150	0.143	5
5	0.150	0.173	-15	0.118	0.159	-35
6	0.170	0.198	-16	0.175	0.144	18
7	0.210	0.253	-20	0.136	0.137	-1
8	0.130	0.195	-50	0.153	0.139	9
9	0.110	0.140	-27	0.132	0.116	12
10	0.110	0.110	0	0.147	0.111	24
11	0.070	0.060	15	0.082	0.093	-13
12	0.090	0.071	21	0.077	0.073	5
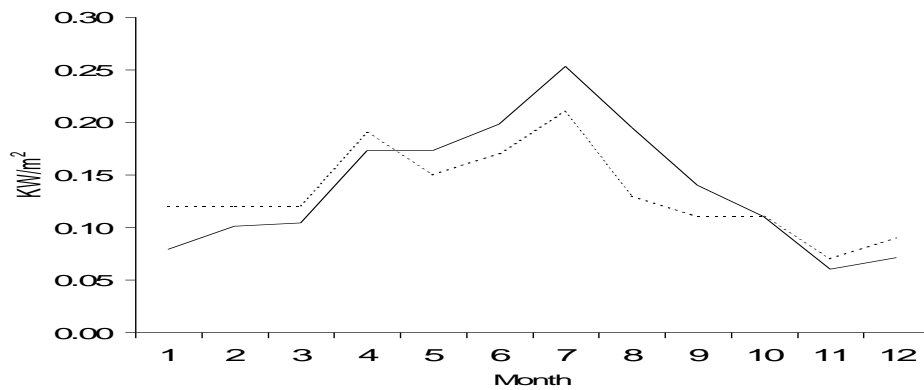
(a)
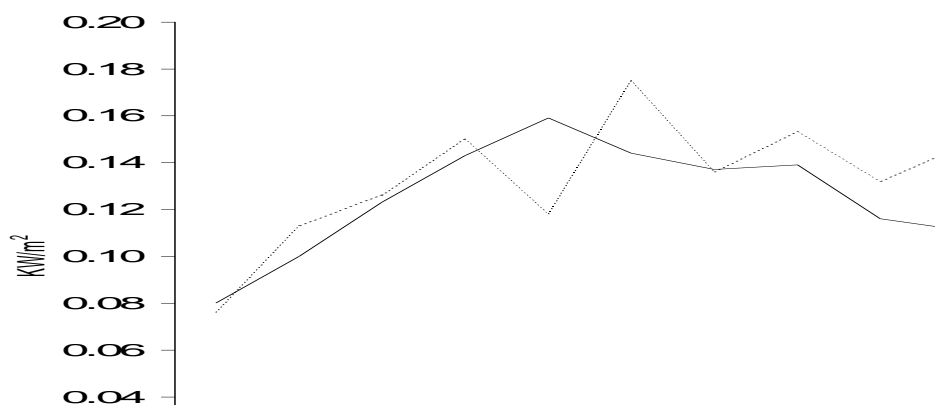
(b)

Fig. 6.2

Actual (dashed curve) and calculated values in Tbilisi of the diffuse radiation in Tbilisi. a - 1980, b - 1981

6.2 The effect of atmospheric aerosols on the attenuation of the direct solar radiation in Georgia

In this part of the book using the methods of the calculation of the solar radiation (part 6.1) and the data on the atmospheric aerosol optical depth (part 5.3) the results of the estimations of the aerosol attenuation of the direct solar radiation in Georgia from 1928 to 1990 are presented. The ozone content in the atmosphere was considered constant and equaled to 0.3 atm·cm. The water vapour content was calculated using the mean annual values of the air humidity according to the method [133]. The calculations were carried out for 12^{30} o'clock.
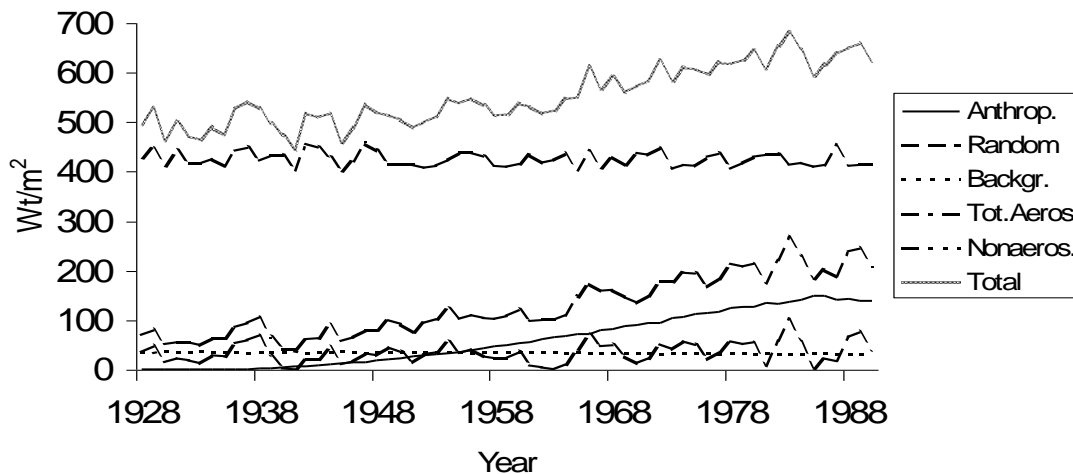

Fig. 6.3

Attenuation of the direct solar radiation by aerosol components, nonaerosol components of the atmosphere and real atmosphere in 1928-1990 in Tbilisi

Fig. 6.3 and 6.4 present the dynamics of the mean annual values of the direct solar radiation attenuation by various aerosols, nonaerosol components and real atmosphere in 1928-1990 in Tbilisi and Tsalka respectively. An analogous picture is observed for the other 4 actinometric stations of Georgia (Telavi, Anaseuli, Senaki, Sokhumi).

Fig. 6.3 and 6.4 show that an increase of the direct solar radiation attenuation in the atmosphere during the last 20-30 years is caused by an increase of the anthropogenic aerosol content. Other factors (nonaerosol components, aerosols generated by background and random sources) cause though sometimes strong but still short-term variations of the direct solar radiation attenuation and have little effect on the long-term variations. However it should be mentioned that in Tsalka despite a quite clear increasing trend in the direct solar radiation attenuation, it does not yet

affect the whole atmospheric attenuation dynamics. This is caused by the fact that in Tsalka in comparison to the other five stations the atmospheric pollution level is considerably lower, besides this station is located at 1457 m above the sea level, due to which the effect of the atmospheric aerosols on the solar radiation attenuation is considerably less in comparison to the other atmospheric components.
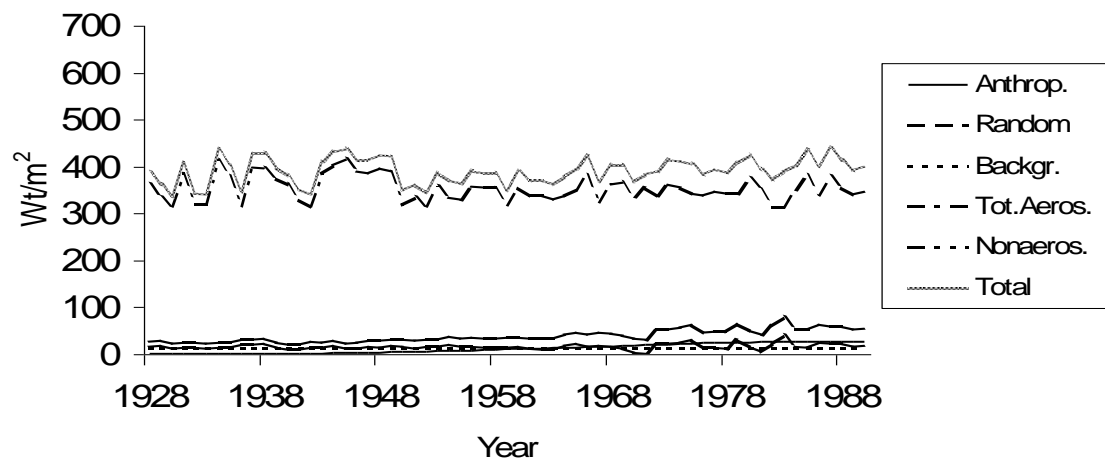
Fig. 6.4

Attenuation of the direct solar radiation by aerosol components, nonaerosol components of the atmosphere and real atmosphere in 1928-1990 in Tsalka

The dynamics of the direct solar radiation attenuation was approximated linearly:

$$y = a \cdot (t - 1927) + b \qquad (6.24)$$

where t is a year from 1928 to 1990, y - approximated attenuation, while a and b - empirical coefficients.

Table 6.3 presents the values of a and b coefficients from (6.24) for the aerosol and total atmospheric attenuation at the six actinometric stations of Georgia.

A comparison of a coefficients for the aerosol and total atmospheric attenuation shows that on the Georgian territory the increase of the direct solar radiation attenuation is mainly determined by the anthropogenic aerosols. It may be seen also that in the case of Tsalka the atmospheric aerosols do not yet dominate in the direct solar radiation variations at this station.

Table 6.3

Values of a and b coefficients from (6.24) for the aerosol and total atmospheric attenuation at the six actinometric stations of Georgia

Coefficient	Tbilisi		Telavi		Tsalka		Anaseuli		Senaki		Sokhumi	
	a	b	a	b	a	b	a	b	a	b	a	b
Aerosol attenuation	3	30	2.6	20	0.6	17	2.6	37	2.4	53	2.5	45
Atmospheric attenuation	2.9	458	2.6	439	0.4	378	2.6	495	2.4	523	2.3	515

According to Table 6.3 the mean annual aerosol attenuation in Tbilisi in 1990 increased by 279% in comparison to 1928, which corresponds to an increase of the total atmospheric attenuation by 37% in the same period. In Telavi the same values amount to: 289% and 35%; in Tsalka - 156% and 6%; in Anaseuli - 234% and 31%; in Sokhumi - 208% and 27%; in Senaki - 181% and 26%. According to this at five actinometric stations of Georgia (except of Tsalka) in 1928-1990 an increase of the aerosol attenuation at the average 2-2.5 times caused an increase of the total atmospheric attenuation approximately by a third.

It is interesting to check how significant statistically the mentioned attenuation is. With this purpose in Table 6.4 the mean annual values of the total atmospheric attenuation of the direct solar radiation averaged for three 20 year periods are presented together with their corresponding dispersions in the ultraviolet, visible and infrared wavelength ranges.

The table shows that in Tbilisi, Telavi, Anaseuli, Senaki and Sokhumi the increase in the total atmospheric attenuation of the direct solar radiation is statistically significant in all mentioned wavelength ranges, while in Tsalka does not exceed the ranges of the mean square deviation. It should be mentioned also here that the increase of the aerosol attenuation of the direct solar radiation in Tsalka is doubtless. Simply it does not have a considerable effect on the total atmospheric attenuation variations.

Table 6.4
Values of the direct solar radiation attenuation (W/m^2) in various regions of Georgia in three twenty year periods

Period	Range	Tbilisi	Telavi	Tsalka	Anaseuli	Senaki	Sokhumi
1928-1950	UV	65±4	63±3	57±3	65±2	67±2	66±3
	Vis.	137±17	124±12	91±10	140±10	153±11	146±14
	IR	293±8	285±6	241±28	323±6	331±18	331±6
	Total	495±28	472±19	389±36	528±18	551±28	543±21
1951-1970	UV	66±3	66±3	58±3	68±3	69±2	68±3
	Vis.	160±17	148±16	97±10	164±12	177±12	174±16
	IR	304±8	292±8	244±16	332±6	343±7	337±5
	Total	530±27	506±26	399±29	564±20	589±19	579±22
1971-1990	UV	73±2	70±3	60±3	72±3	73±3	72±3
	Vis.	217±19	193±22	110±8	213±22	217±29	213±24
	IR	327±9	313±10	229±12	351±10	358±13	350±10
	Total	617±29	576±34	399±17	636±34	648±44	635±36

Table 6.5 gives the results of the calculations of the ratio of the aerosol and total atmospheric attenuation of the direct solar radiation averaged for the period 1928-1990 to the values in 1928.

Table 6.5
Increase of the mean attenuation of the direct solar radiation in 1928-1990 in comparison to 1928 (%)

Attenuation	Range	Tbilisi	Telavi	Tsalka	Anaseuli	Senaki	Sokhumi
Aerosol	UV	268	260	150	226	174	189
	Vis.	276	286	152	231	178	205
	IR	289	302	169	242	188	221
Total	UV	17	18	8	17	14	15
	Vis.	87	90	33	74	61	71
	IR	18	16	4	13	12	9

Thus, according to Tables 6.4 and 6.5 in Georgia the increase of the atmospheric pollution in 1928-1990 caused a considerable decrease in the direct solar radiation irradiance. This effect manifested itself most intensively in Tbilisi and Telavi. The least attenuation of the direct Solar radiation was observed at station Tsalka.

6.3   Effect of the variability of some RASAA on the short-wave solar radiation fluxes.

Short-wave direct (S) (also on a horizontal surface (S')) and diffuse (D) solar radiation coming to the Earth's surface depend on the content in the atmosphere of water vapour (ω) and ozone (u), optical depth of atmospheric aerosols (τ_a) and also the albedo of the underlying surface (A_k) (for D) [2,133]. Schemes of the calculation of S, S' and D considering ω, u, τ_a and A_k are given in 6.1. In 6.2 the direct solar radiation attenuation was studied depending on τ_a and considering the total ozone invariability (u=0.3 atm·cm) and inconsiderable variations of water vapour. In particular it turned out that an increase in τ_a from 0.025 to 0.200 (for the wavelength λ=1 mcm the direct solar radiation attenuation increases linearly.

In this part the results of S, S' and D calculations are presented for a wide range of variations of atmospheric aerosol (τ_a) and ozone content at various levels of ω and A_k. The mentioned calculations are carried out for January and July for the conditions of Tbilisi.

Fig. 6.5 a and b give the dependence of S' on the atmospheric aerosol optical depth at various values of ω and for u=0.3 atm·cm in January and July respectively. Fig. 6.6 a and b present the dependence of the diffuse radiation (D) on the atmospheric aerosols optical depth at various values of water vapour and short-wave albedo (A_k) in January and July. Finally Fig. 6.7 a and b present the dependence of the total radiation (Q=S'+D) on the atmospheric aerosol optical depth at various values of ω and A_k and for u=0.3 atm·cm. All calculations were carried out for the clear sky conditions. Mean monthly values of S', D and Q are given in Mj/m^2.

As the calculations showed, S and S' depend considerably on ω and τ_a and insignificantly on the total ozone. Diffuse radiation increases significantly with τ_a and A_k. D does not depend on the total ozone. The total radiation decreases with τ_a and increases with A_k (Fig. 6.5-6.7, Table 6.6). The dependence of S and S' on u and D on A_k has a linear character at fixed values of ω and τ_a. S, S', D and Q variations at variations of u from 0.2 to 0.4 atm·cm and A_k from 0.1 to 0.7 are presented in Table 6.6. As the table shows the relative differences $\frac{S_{u=0.2} - S_{u=0.4}}{S_{u=0.3}} 100\%$ and $\frac{S'_{u=0.2} - S'_{u=0.4}}{S'_{u=0.3}} 100\%$ vary at various values of τ_a and ω in January and July from 0 to 2.4%. The effect of the underlying surface albedo on δD relative difference variations are much more considerable. δD values in January and July vary from 2.3 to 11.8% at various values of τ_a and ω (Table 6.6). Finally, the effect of A_k on δQ variations for u=0.3 atm·cm and various values of τ_a and ω are not considerable - 1.3-3.4%.
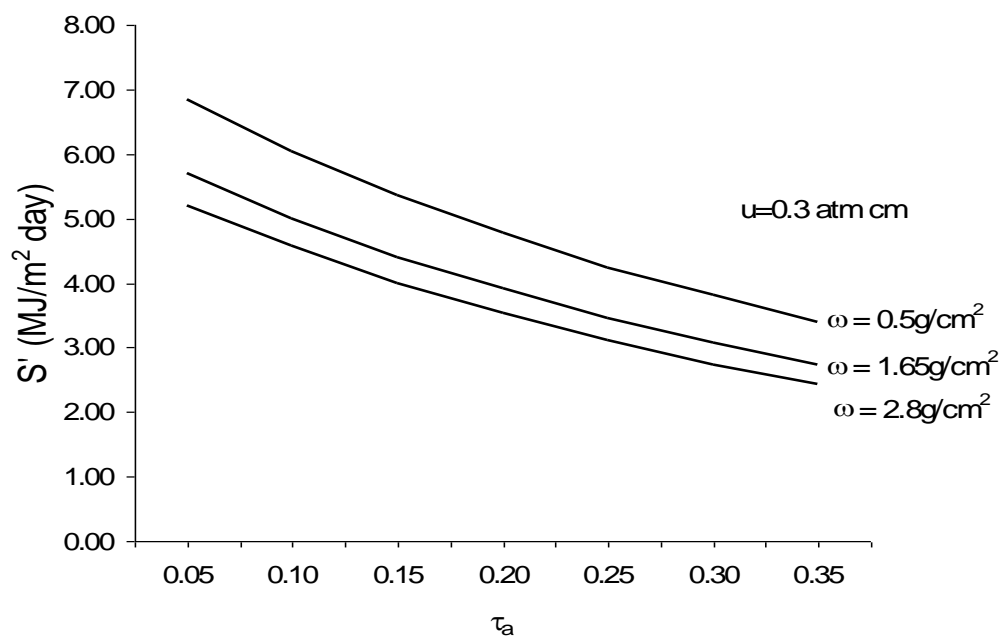
(a)
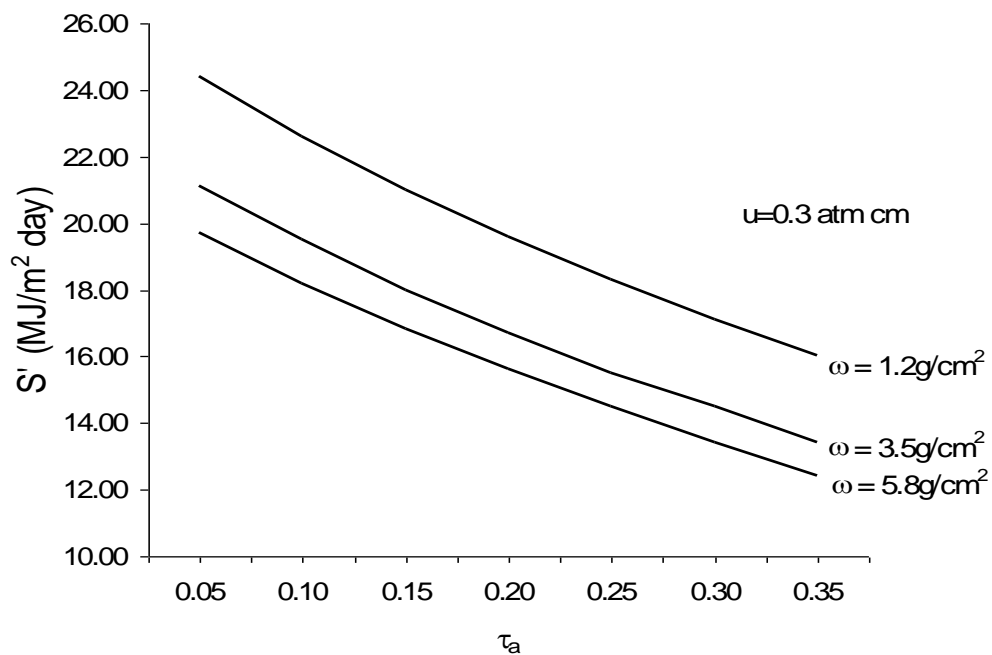
(b)

Fig. 6.5

Dependence of the direct solar radiation on a horizontal surface on the atmospheric aerosol optical depth at various values of water vapour and for the total ozone 0.3 atm·cm. a - January, b - July

(a)
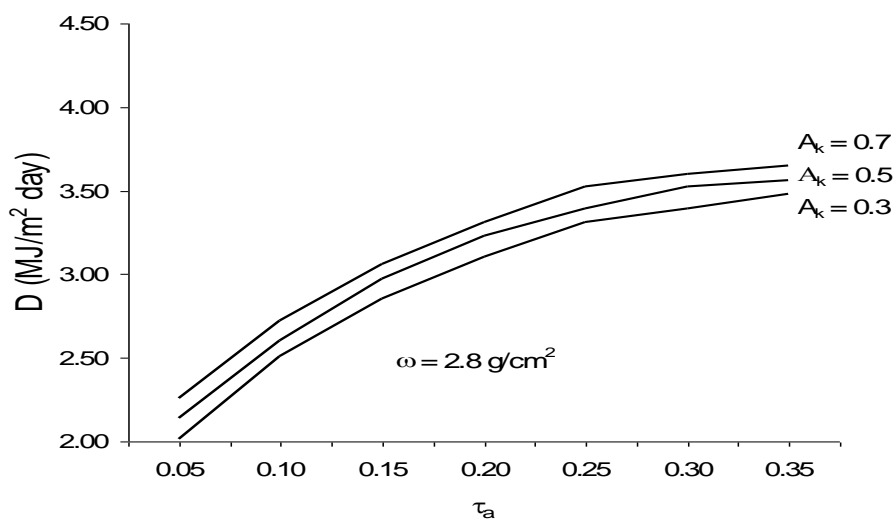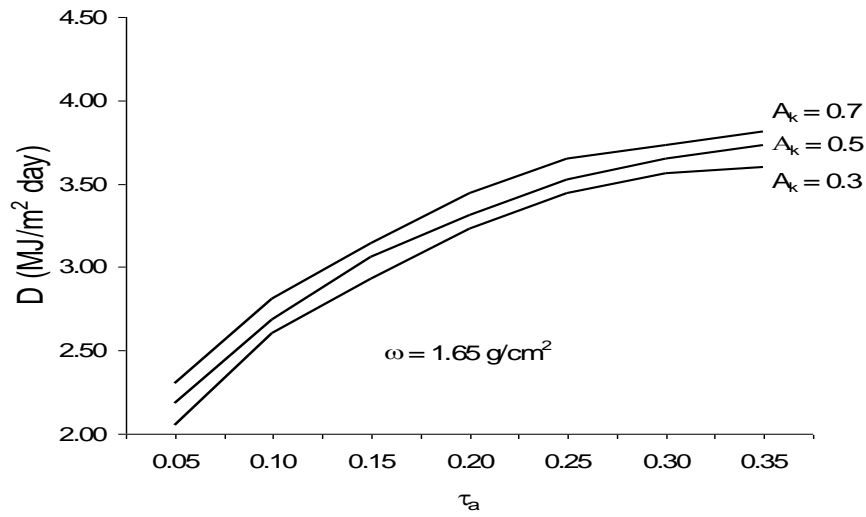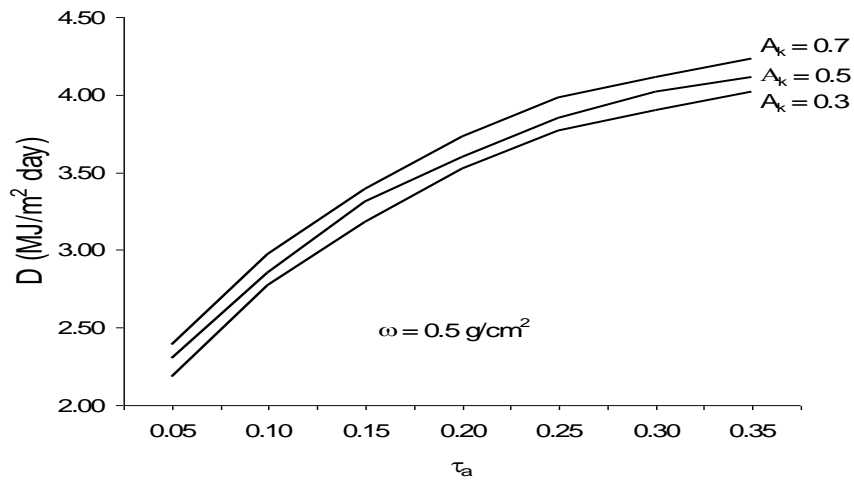
Fig. 6.6
Dependence of the diffuse solar radiation on the atmospheric aerosol
optical depth at various values of water vapour and albedo
a - January, b - July.

(a)

(b)

Fig. 6.7
Dependence of the total solar radiation on the atmospheric aerosol optical
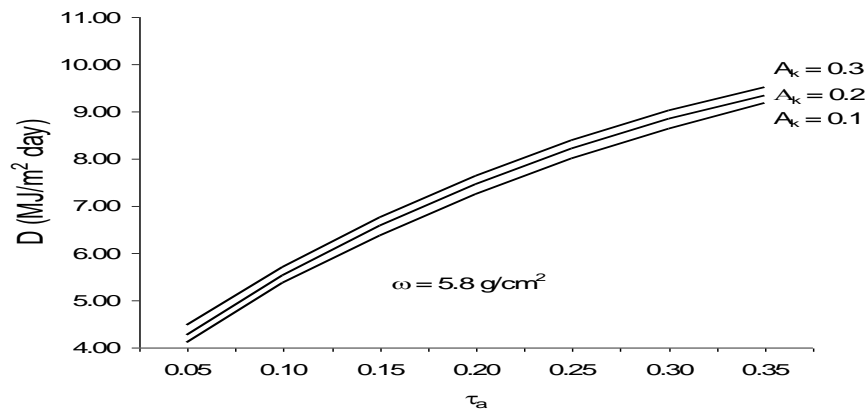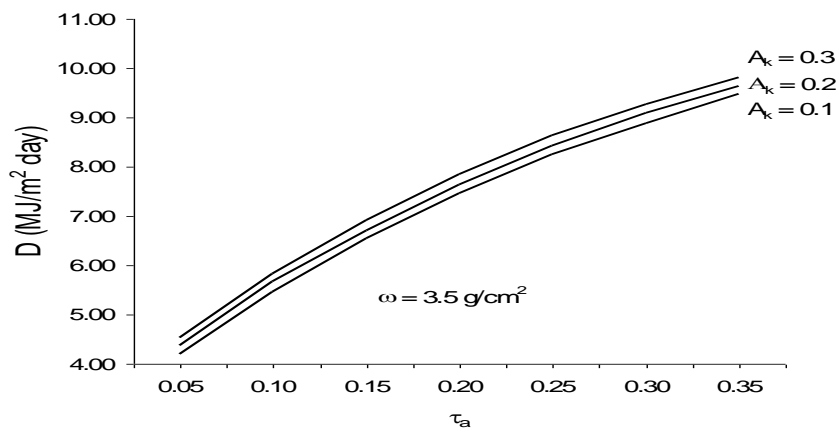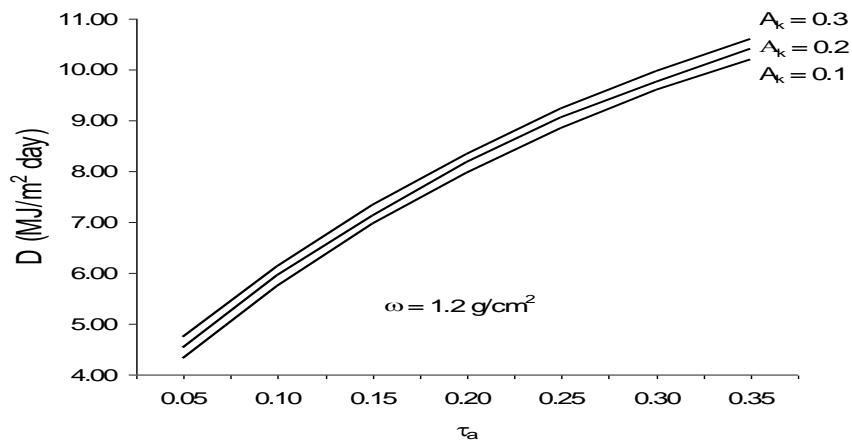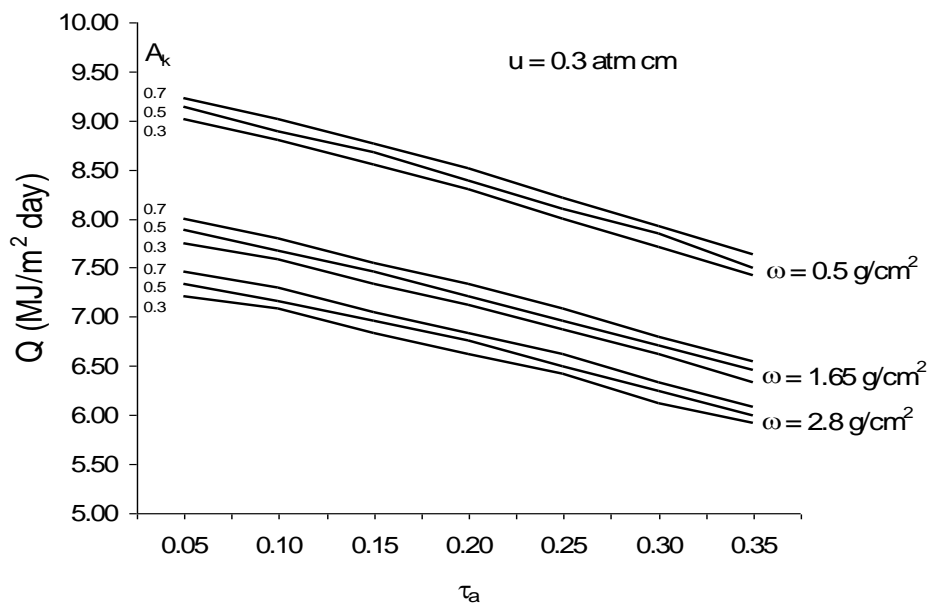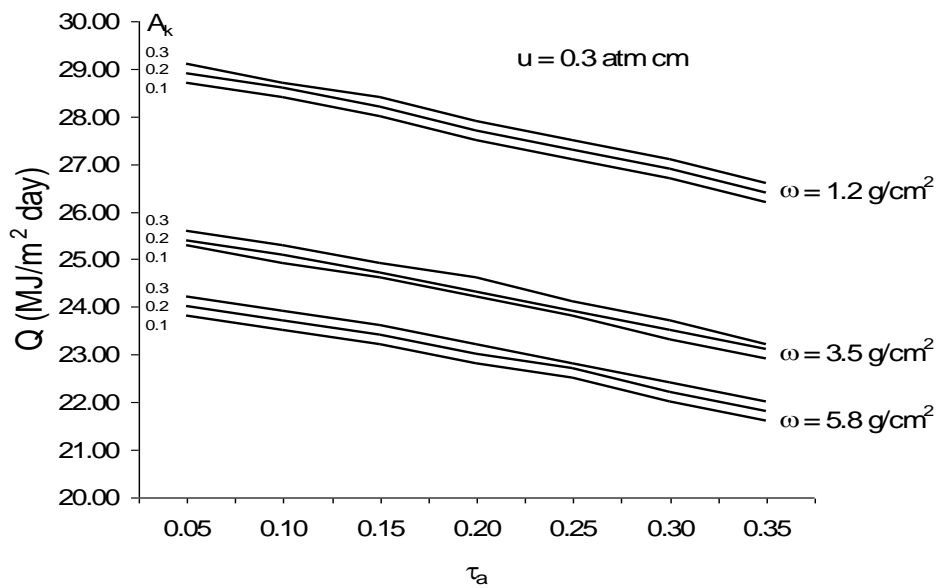depth at various values of water vapour and albedo.
Total ozone is 0.3 atm·cm. a - January, b - July.

Table 6.6

Variations of S and S' - (X) and D and Q - (Y)

$$\delta X = \frac{X_{u=0.2} - X_{u=0.4}}{X_{u=0.3}} 100\% \; ; \delta Y = \frac{Y_{A_k=0.7} - Y_{A_k=0.3}}{Y_{A_k=0.5}} 100\% \; \text{(January)}$$

$$\delta Y = \frac{Y_{A_k=0.3} - Y_{A_k=0.1}}{Y_{A_k=0.2}} 100\% \; , \text{(July). u=0.3 atm·cm}$$

ω g/cm^2	τ_a	$\delta S(\%)$	$\delta S'(\%)$	$\delta D(\%)$	$\delta Q=\delta(S'+D)(\%)$
January					
0.5	0.05	1.7	1.2	9.1	2.3
	0.35	0.9	1.2	5.1	2.8
1.65	0.05	1.8	1.5	11.5	3.2
	0.35	1.2	0.0	5.6	3.2
2.8	0.05	2.0	2.4	11.8	3.4
	0.35	1.9	1.7	4.7	2.8
July					
1.2	0.05	1.2	0.9	9.3	1.4
	0.35	0.8	0.8	3.6	1.4
3.5	0.05	1.4	1.0	7.7	1.3
	0.35	0.9	0.6	3.5	1.5
5.8	0.05	1.4	1.1	8.8	1.6
	0.35	1.2	1.0	3.6	1.5

The calculation results enabled to establish empirical expressions for calculating the direct and diffuse solar radiation considering the water vapour and ozone content in the atmosphere and optical depth of atmospheric aerosols. The expressions have the following form:

$$\text{Jan.: } S=(19.9\omega^{-0.145}-1.76u)\exp(-2.595\tau_a\omega^{0.049})$$
$$\text{Jul.: } S=(39.7\omega^{-0.119}-2.18u)\exp[-(1.676+0.0105\omega)\tau_a]$$
$$\text{Jan.: } S'=(7.0\omega^{-0.141}-0.59u)\exp(-2.4\tau_a\omega^{0.050}) \qquad (6.25)$$
$$\text{Jul.: } S'=(27.0\omega^{-0.126}-1.17u)\exp(-1.4\tau_a\omega^{0.054})$$
$$\text{Jan.: } D=4.60\omega^{-0.090}+0.453\omega^{-0.0736}A_k+0.876\omega^{-0.137}\ln\tau_a$$
$$\text{Jul.: } D=13.0\omega^{-0.0722}+2.0\omega^{-0.0451}A_k+3.105\omega^{-0.0933}\ln\tau_a$$

where S, S' and D are in Mj/m^2 per day; ω is in g/cm^2; u(O$_3$) is in atm·cm; January: $0.5 \le \omega \le 2.8$, $0.3 \le A_k \le 0.7$; July: $1.2 \le \omega \le 5.8$, $0.1 \le A_k \le 0.3$; $0.2 \le u \le 0.4$; $0.05 \le \tau_a \le 0.35$. $\omega^k \approx 1+k\cdot\ln\omega$, if $k\cdot\ln\omega<<1$ and in this case the expressions (6.25) can be considerably simplified.

Using (6.25) it is possible with quite a high precision (Table 6.7) to calculate S, S', D and Q values at stations where actinometric observations are not carried out. Therefore they have a significant practical value in determining the radiation fluxes.

Table 6.7

Accuracy of (6.25) expressions with respect to the calculated values of S, S' and D. ($C_v = \frac{\sigma}{x} 100\%$); n - number of cases.

Jnuary			July		
S	S'	D	S	S'	D
n=27			n=27		
0.85	0.73	1.4	0.94	0.33	4.1

Thus, the main factors affecting the solar radiation attenuation are atmospheric aerosols and water vapour. S and S' decrease 2.0 - 2.3 times with an increase in τ_a from 0.05 to 0.35 in January at ω from 0.5 to 2.8 g/cm^2 and 1.5 - 1.7 times in July, at ω values from 1.2 to 5.8 g/cm^2. S and S' decrease 1.3 - 1.4 times with an increase in ω from 0.5 to 2.8 g/cm^2 in January and 1.2 - 1.3 times in July with an increase from 1.2 to 5.8 g/cm^2 at τ_a values from 0.05 to 0.35.

Variations of the diffuse radiation depend first of all on the aerosol optical depth, then on the albedo of the underlying surface and finally on the water vapour content. Besides τ_a and A_k increase causes a D increase, while it decreases versus ω.

The main factors affecting the total radiation in the atmosphere are water vapour and atmospheric aerosols. Thus an increase in τ_a from 0.05 to 0.35 causes a decrease in Q approximately 1.22 times for ω values from 0.5 to 2.8 g/cm^2 and A_k values from 0.3 to 0.7 in January and 1.1 times for ω from 1.2 to 5.8 g/cm^2 and A_k from 0.1 to 0.3 in July. Q decreases 1.25 times with an ω increase from 0.5 to 2.8 g/cm^2 in January and 1.21 times at ω from 1.2 to 5.8 g/cm^2 in July (A_k varies from 0.3 to 0.7 and from 0.1 to 0.3 respectively) at τ_a values from 0.05 to 0.35.

Finally using the expressions (6.25) it is possible to estimate the decrease of the total solar radiation near the ground in various regions of Georgia as a result of the atmospheric pollution elevation in the period from 1928 till 1990. The results of the calculations are presented in Table 6.8. It is noteworthy that the mean values of ω, A_k and u for the corresponding stations in the periods indicated in the table differ insignificantly from each other.

This table shows that at the end of 1980-s due to an increase of the atmospheric pollution on the whole Georgian territory a decrease of the total radiation Q occurred in comparison to the periods with a "very clean" atmosphere (Table 5.1). The increase of the aerosol pollution of the atmosphere occurred mainly due to an increase in its anthropogenic component and also some increase in the random component (Part 5.3). Considering the results presented in Table 5.4 it is possible to estimate the share of the anthropogenic component in the variations of the atmospheric aerosol optical depth in Table 6.8. In January in Tbilisi this share amounted

to 100%, in Telavi - 80%, in Tsalka - 67%, in Western Georgia - at the average 70%. In July in Tbilisi and Telavi the share of the anthropogenic increase in τ_a amounted to about 89%, in Tsalka - 68%, in Western Georgia - 83%. Correspondingly the decrease ΔQ due to the anthropogenic increase in τ_a amounts in January: in Tbilisi to 2.2, in Telavi to 1.1, in Tsalka to 0.5, in Western Georgia to 0.6 W/m^2, while in July: to 12.5, 11.5, 5.5 and 7.5 W/m^2 respectively.

Table 6.8

Aerosol effect of the decrease of the total solar radiation near the ground in various regions of Georgia in 1986-1990 in comparison to the period with a "very clean" atmosphere. $\Delta Q = Q_{\tau_a 2} - Q_{\tau_a 1}$, W/m^2.

Stations	January				July			
	Period	τ_{a1}	τ_{a2}	ΔQ	Period	τ_{a1}	τ_{a2}	ΔQ
Tbilisi	Beginning of 1950-s	0.050	0.100	-2.2	Beginning of 1930-s	0.060	0.220	-14
Telavi	Middle of 1960-s	0.050	0.080	-1.4	Middle of 1960-s	0.070	0.220	-13
Tsalka	Middle of 1970-s	0.050	0.065	-0.8	Middle of 1970-s	0.050	0.150	-8.0
W.Georgia (Anaseuli, Senaki, Sokhumi)	End of 1960-s Beginning of 1970-s	0.050	0.070	-0.8	End of 1960-s Beginning of 1970-s	0.060	0.175	-9.0

In Tbilisi the share of the anthropogenic sulphate component of τ_a amounts approximately to 20% of its total anthropogenic component (Part 3.2). Therefore the decrease of Q due to the anthropogenic sulphates in Tbilisi may be estimated as 2.5 W/m^2 in July and 0.4 W/m^2 in January. The value ΔQ for January coincides with the mean global decrease of the sulphate component of radiative forcing (Table 1.2). In the Central Europe and over Eastern China, where the industry is developed considerably more than in Georgia, the decrease of the sulphate radiative forcing in July equals respectively to 11 and 7.2 W/m^2 [73,74]. In the future it is planned to specify the mentioned estimations with allowance to the variations of water vapour, ozone in the atmosphere and also the albedo of the underlying surface.

Conclusion

The present book is a result of many years of the investigations of some radiatively active small atmospheric admixtures (RASAA) in Georgia.

A detailed analysis of the particularities of the variations of the anthropogenic RASAA emissions in Georgia during the last two decades has been made. Thus, the share of various RASAA components in the period of 1991-1996 in comparison to 1980-1990 amounted to: CO_2 - 35.1%, CH_4 - 51.7%, N_2O - 48.1%, NO_X - 36.0%, CO - 39.9%, SO_2 - 32.7%, aerosols (sulphates, nitrates, soot, solid emissions) - about 30%. This is related to a considerable fall-down in the industry of Georgia after the collapse of the former USSR. Correspondingly in industrial cities the near-ground concentrations of dust, CO, SO_2, NO_X decreased. Thus, in Tbilisi in the period from 1991 till 1996 in comparison to the previous six year period the content of dust and CO amounted to 60%, NO_X - 44%, SO_2 - 9%. The content of the near-ground ozone increased on the contrary by 42%. In the same time period in comparison to 1985-1990 the amount of the generated secondary sulphate condensation nuclei decreased four times.

The vertical distribution of the number concentration of aerosols with sizes more than 0.35 mcm in radius has been studied for various regions of Georgia. In particular it was shown that within the lower five kilometer atmospheric layer the size distribution of aerosols is quite steady and varies little with elevation and under the influence of cloudiness. However at days with cumulus clouds in comparison to cloudless days the mass of aerosols in the lower five kilometer layer increases approximately 1.4 times, while at days with clouds of various types including cumulus - 2.5 times.

A scheme of the interaction of atmospheric aerosols and convective clouds and also generation in the atmosphere and clouds of condensation, crystallization nuclei and ice crystals with allowance to ionization and electrization processes occurring in the atmosphere has been proposed.

The variations of total ozone from 1973 till 1995 have been studied. It was shown that in the mentioned period of time both in Georgia and in neighbouring regions (Odessa, Samara, Ashgabad, Alma-Ata) negative trends of total ozone both for the mean monthly and for the mean annual values were observed.

A detailed analysis of the spatial-temporary characteristics of the aerosol optical depth of the atmosphere τ_a over Georgia has been carried out. For the whole territory of Georgia from 1928 till 1990 considerable positive trends of the aerosol optical depth of the atmosphere, determined by an increase in the anthropogenic pollution of the atmosphere, were observed. Estimations of the dynamics of the background, anthropogenic

and random components of the aerosol optical depth of the atmosphere were given. Thus, if in 1928-1950 in various regions of Georgia the share of the anthropogenic component of τ_a amounted to 3-9% of its total value, in 1971-1990 this share amounted to 44-63% (Tsalka and Tbilisi respectively).

For the estimation of the atmospheric pollution by the aerosol optical depth a nine grade scale has been used. The representativity of the scale was confirmed by an increase of the mortality by cardio-vascular diseases in Tbilisi versus an increase of τ_a values in the scale.

Calculations of the effect of some RASAA on the direct and diffuse solar radiation in Georgia have been carried out for the clear sky conditions. In particular it was shown that as a result of an increase in the atmospheric pollution level in 1990 in comparison to 1928 in Tbilisi the attenuation of the direct solar radiation increased by 37%, in Telavi by 35%, in Western Georgia (Anaseuli, Senaki, Sokhumi) by 28%, in Tsalka by 6%. Estimations of the effect of the variations of water vapour, ozone, aerosols in the atmosphere and underlying surface albedo on the short-wave solar radiation were given. In particular, by the end of 1980-s due to the anthropogenic increase in the atmospheric pollution in January the short-wave radiation in Tbilisi decreased by 2.2 W/m^2, in Telavi by 1.1 W/m^2, in Western Georgia by 0.6 W/m^2, in Tsalka by 0.5 W/m^2. In July this decrease amounted respectively to: 12.5, 11.5, 7.5 and 5.5 W/m^2.

<center>დასკვნა</center>

წინამდებარე მონოგრაფია წარმოადგენს საქართველოში ზოგიერთი რადიაციულად აქტიური მცირე ატმოსფერული მინარევის მრავალწლიური კვლევების შედეგს.

მოყვანილია საქართველოში ამ მინარევების ანთროპოგენური ემისიების თავისებურებების დაწვრილებითი ანალიზი ბოლო ორი ათწლეულისთვის. ასე, რადიაციულად აქტიური მცირე ატმოსფერული მინარევების სხვადასხვა შემადგენლის ემისიების წილმა 1991-1996 წლების პერიოდში 1980-1990 წლებთან შედარებით შეადგინა: 35.1%, CO_2-სთვის, 51.7% CH_4-სთვის, 48.1% N_2O-სთვის, 36.0% NO_X-სთვის, 39.9% CO-სთვის, 32.7% SO_2-სთვის, 30% აეროზოლებისთვის (სულფატები, ნიტრატები, ჭვარტლი, მყარი გამონაბოლქვი). ეს დაკავშირებულია საქართველოში წარმოების მნიშვნელოვანი დაქვეითებით საბჭოთა კავშირის დაშლის შემდეგ. შესაბამისად, სამრეწველო ქალაქებში მიწისპირა ჰაერში შემცირდა მტვრის, CO-ს, SO_2-ის და NO_X-ის შემცველობა. ასე, თბილისში 1991-1996 წლების პერიოდში წინა ექვს წელთან შედარებით მტვრისა და CO-ს შემცველობამ შეადგინა 60%, NO_X - 44%, SO_2 - 9%. მიწისპირა ოზონის შემცველობა, პირიქით, გაიზარდა ოთხჯერ 42% - ით. ამავე პერიოდში 1985-1990 წლებთან შედარებით ოთხჯერ შემცირდა მეორადი სულფატური აეროზოლების წარმოქმნა.

შესწავლილია 0.35 მკმ-ზე მეტი რადიუსის მქონე აეროზოლების თვლადი კონცენტრაციის ვერტიკალური განაწილება საქართველოს სხვადასხვა რეგიონის თავზე. კერძოთ, დადგინდა, რომ ატმოსფეროს ქვედა ხუთკილომეტრიანი ფენის ფარგლებში აეროზოლების ზომების მიხედვით განაწილებას საკმარისად მდგრადი ხასიათი აქვს და ნაკლებად იცვლება სიმაღლესთან ერთად და ღრუბლიანობის გავლენით. თუმცა, გროვა ღრუბლიან დღეებში უღრუბლო დღეებთან შედარებით აეროზოლების მასა ქვედა ხუთკილომეტრიან ფენაში იზრდება დაახლოებით 1.4-ჯერ, ხოლო სხვადასხვა ტიპის (მათ შორის გროვა) ღრუბლიან დღეებში - 2.5-ჯერ.

შემოთავაზებულია ატმოსფერული აეროზოლებისა და კონვექტური ღრუბლების ურთიერთქმედების და, ასევე, ატმოსფეროში და ღრუბლებში კონდენსაციის, კრისტალიზაციის ბირთვების და ყინულის კრისტალების წარმოქმნის ბლოკ-სქემა ატმოსფეროში იონიზაციისა და ელექტრიზაციის პროცესების გათვალისწინებით. ნაჩვენებია, რომ მძლავრ კონვექტურ და საელჯექო ღრუბლებს მნიშვნელოვანი წვლილი შეაქვთ პირდაპირ და არაპირდაპირ რადიაციულ ეფექტებში.

გამოკვლეულია ოზონის საერთო რაოდენობის ვარიაციები 1973-1995 წლებში. ნაჩვენებია, რომ დროის ამ პერიოდში როგორც საქართველოში, ისევე ახლომდებარე რეგიონებში (ოდესა, სამარა, აშხაბადი, ალმა-ატა) დაიმზირებოდა ოზონის საერთო რაოდენობის

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უარყოფითი ტრენდი, როგორც საშუალო სეზონური, ისე საშუალო წლიური მნიშვნელობებისთვის.

ჩატარებულია ატმოსფერული აეროზოლების ოპტიკური სიმკვრივის τ_a-ს სიერცულ დროითი მახასიათებლების დაწვრილებითი ანალიზი საქართველოს ტერიტორიისთვის. ნაჩვენებია, რომ მთელი საქართველოსთვის 1928-1990 წლებში დაიმზირებოდა ატმოსფერული აეროზოლების ოპტიკური სიმკვრივის მნიშვნელოვანი დადებითი ტრენდები, რომლებიც ატმოსფეროს ანთროპოგენური გაჭუჭყიანებით იყო განპირობებული. მოყვანილია აეროზოლების ოპტიკური სიმკვრივის ფონური, შემთხვევითი და ანთროპოგენური მდგენლების დინამიკის შეფასება. ასე, თუ 1928-1950 წლებში საქართველოს სხვადასხვა რეგიონში τ_a-ს ანთროპოგენური მდგენლის წილი მის საერთო მნიშვნელობაში 3-9%-ს შეადგენდა, 1971-1990 წლებში ეს წილი 44 - 63%-მდე (წალკა და თბილისი შესაბამისად) გაიზარდა.

ატმოსფერული აეროზოლების ოპტიკური სიმკვრივის მნიშვნელობებით ატმოსფერული გაჭუჭყიანების დონის შესაფასებლად შემოთავაზებული იქნა ცხრა დიაპაზონიანი სკალა. სკალის რეპრეზენტატულობა დადასტურდა ქ. თბილისში გულ-სისხლძარღვთა დაავადებებით გამოწვეული სიკვდილიანობის ზრდით τ_a-ს მნიშვნელობების სკალაში მოყვანილი გრადაციების მიხედვით ზრდასთან ერთად.

ჩატარებულია ზოგიერთი რადიაციულად აქტიური მცირე ატმოსფერული მინარევის მზის პირდაპირი და გაბნეული რადიაციის რეჟიმზე გავლენის თეორიული გამოთვლები საქართველოს ტერიტორიისთვის მოწმენდილი ცის პირობებში. კერძოდ, ნაჩვენებია, რომ ატმოსფერული გაჭუჭყიანების ზრდის შედეგად 1990 წელს 1928 წელთან შედარებით თბილისში მზის პირდაპირი რადიაციის შესუსტება გაიზარდა 37%-ით, თელავში 35%-ით, დასავლეთ საქართველოში (ანასეული, სენაკი, სოხუმი) - 28%-ით, წალკაში - 6%-ით. მოყვანილია მზის მოკლეტალდიან რადიაციულ ნაკადებზე ატმოსფეროში წყლის ორთქლის, ოზონის, აეროზოლების შემცველობის და ქვეფენილი ზედაპირის ალბედოს გავლენის შეფასება. კერძოდ, მიდებულია, რომ 1980-იანი წლების ბოლოს ატმოსფეროს ანთროპოგენური გაჭუჭყიანების ზრდის გამო იანვარში მზის მოკლეტალდიანი რადიაციის ინტენსიურობა შემცირდა თბილისში 2.2 ვტ/მ^2-ით, თელავში 1.1 ვტ/მ^2-ით, დასავლეთ საქართველოში 0.6 ვტ/მ^2-ით, წალკაში 0.5 ვტ/მ^2-ით. ივლისის თვეში ეს შემცირება შესაბამისად შეადგენდა: 12.5, 11.5, 7.5 და 5.5 ვტ/მ^2-ს.

Заключение

Настоящая книга является итогом многолетних исследований некоторых радиационно-активных малых примесей в атмосфере (РАМПА) в условиях Грузии.

Проведен подробный анализ особенностей изменения антропогенной эмиссии РАМПА в Грузии в течении последних двух десятилетий. Так, доля эмиссии различных составляющих РАМПА в период с 1991 по 1996 г.г. по сравнению с периодом с 1980 по 1990 г.г. составила: для CO_2 - 35.1%, CH_4 - 51.7% N_2O - 48.1%, NO_X - 36.0%, CO - 39.9%, SO_2 - 32.7%, аэрозолей (сульфаты, нитраты, сажа, твердые выбросы) - около 30%. Это связано с существенным падением в Грузии промышленного производства после распада Советского Союза. Соответственно в промышленных городах в приземном слое воздуха уменьшилось содержание пыли, CO, SO_2, NO_X. Так в Тбилиси в период с 1991 по 1996 г.г. по сравнению с предыдущей шестилеткой содержание пыли и CO составляло 60%, NO_X - 44%, SO_2 - 9%. Содержание приземного озона, напротив, возросло на 42%. В этот же промежуток времени по сравнению с 1985-1990 г.г., количество образующихся вторичных сульфатных ядер конденсации уменьшилось в четыре раза.

Изучено вертикальное распределение счетной концентрации аэрозолей размерами более 0.35 мкм по радиусу над различными районами Грузии. В частности получено, что в пределах нижнего пятикилометрового слоя атмосферы распределение аэрозолей по размерам имеет достаточно устойчивый характер и мало меняется с высотой и под влиянием облачности. Однако в дни с кучевыми облаками по сравнению с безоблачными днями масса аэрозолей в пятикилометровом слое атмосферы растет примерно в 1.4 раза, а в дни с облаками различных типов, включая и кучевые - в 2.5 раза.

Предложена блок-схема взаимодействия атмосферных аэрозолей и конвективных облаков, а также образования в атмосфере и облаках ядер конденсации, кристаллизации и ледяных кристаллов с учетом протекающих в атмосфере процессов ионизации и электризации. Показано, что мощные конвективные и грозовые облака способны вносить существенный вклад в прямые и косвенные радиационные эффекты.

Исследованы вариации общего содержания озона в период с 1973 по 1995 г.г. Показано, что в указанный период времени как

в Грузии, так и в прилегающих регионах (Одесса, Самара, Ашхабад, Алма-Ата) наблюдаются отрицательные тренды обшего содержания озона как для среднесезонных, так и среднегодовых значений.

Проведен подробный анализ пространственно-временных характеристик аэрозольной оптической толши атмосферы τ_a над Грузией. Показано, что для всей территории Грузии в период с 1928 по 1990 г.г. наблюдались сушественные положительные тренды аэрозольной оптической толши атмосферы, обусловленные ростом антропогенного аэрозольного загрязнения атмосферы. Приведены оценки динамики фоновой, случайной и антропогенной составляюшей аэрозольной оптической толши атмосферы. Так, если в период с 1928 по 1950 г.г. в различных районах Грузии доля антропогенной составляюшей τ_a составляла от ее обшей величины 3-9%, то в период с 1971 по 1990 г.г. эта доля составляла 44-63% (Цалка и Тбилиси соответственно).

Для оценки уровня загрязненности атмосферы по значениям аэрозольной оптической толши атмосферы предложена девяти диапазонная шкала. Репрезентативность шкалы подтверждается ростом спертности в Тбилиси от сердечно сосудистых заболеваний с ростом указанных в ней значений τ_a по градациям.

Проведены теоретические расчеты влияния некоторых РАМПА на режим прямой и рассеянной солнечной радиации в Грузии в ясные дни. В частности показано, что в результате роста аэрозольного загрязнения атмосферы в 1990 году по сравнению с 1928 годом в Тбилиси ослабление интенсивности прямой солнечной радиации увеличилось на 37%, в Телави на 35%, в Западной Грузии (Анасеули, Сенаки, Сухуми) - на 28%, в Цалке - на 6%. Приведены оценки влияния на потоки коротковолновой солнечной радиации изменчивости содержания в атмосфере водяного пара, озона, аэрозолей и величин коротковолнового альбедо подстилающей поверхности. В частности получено, что к концу восьмидесятых годов в результате антропогенного роста аэрозольного загрязнения атмосферы в январе месяце интенсивность коротковолновой солнечной радиации уменьшилась в Тбилиси на 2.2 вт/м^2, в Телави на 1.1 вт/м^2, в Западной Грузии на 0.6 вт/м^2, в Цалке на 0.5 вт/м^2. В июле месяце это уменьшение соответственно составило: 12.5, 11.5, 7.5 и 5.5 вт/м^2.

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СОВРЕМЕННОЕ ИЗМЕНЕНИЕ КЛИМАТА В ГРУЗИИ.
РАДИАЦИОННО-АКТИВНЫЕ МАЛЫЕ ПРИМЕСИ В АТМОСФЕРЕ.

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