OPTICAL INVESTIGATIONS OF THE ATMOSPHERE DURING THE 35th MISSION OF THE RESEARCH VESSEL *AKADEMIK MSTISLAV KELDYSH*

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Received June 30, 1995

Here we describe optical investigations of the atmosphere conducted from January to April 1995 in some regions of the Atlantic Ocean from the equator to the English Channel. Certain meteorological peculiarities of the regions investigated are considered together with the volume of experimental data and their statistical significance. We also present in this paper preliminary results on space-time variability of the aerosol number density in the adjacent to water layer as well as the aerosol optical depth and total moisture content. The continental aerosol is shown to influence greatly on the oceanic atmosphere characteristics.

It is known that in complicated processes of interactions and circulations in the "ocean–atmosphere" system the aerosol plays an important role participating both in the atmospheric circulation and in energy exchanges as a factor of climate formation and as a regulator of radiation effect on bioorganisms. The substance exchange is in generation of salt aerosol from the sea surface and in the natural and anthropogenic aerosol sink undergoing different physicochemical transformations in the atmosphere.

Taking into account high sensitivity of aerosol to various environmental influences, an important factor in aerosol investigation is obtaining of a full set of data on the parameters measured (chemical and disperse composition, characteristics of scattering and spectral transmission, meteorological parameters, etc.) and from the viewpoint of observation representation. It should be noted that this is not a simple task under the marine conditions.

The state of the art of aerosol investigations under marine conditions can be estimated using as an example measurements of aerosol optical depths (AOD). Despite of the fact that the number of publications on this problem reaches some tens, the investigations remain irregular and not always complete. From the literature available[1–6] it follows that, on the average, only one expedition a year is normally performed, the number of measurement days is about 10 to 30, and the degree of observation regularity P_0 (the ratio of measurement days to the overall measurement period) is 30 to 60%, that is, the investigations are irregular in a narrow sense: series of measurements are short, broken and refer to separate regions of the World Ocean.

GENERAL CHARACTERISTICS OF THE RESEARCH

In January–April 1995 the authors have performed optical investigations of the atmosphere during the mission of the research vessel *Akademik Mstislav Keldysh* to further study aerosol above the ocean as well as total content of water vapor and some gaseous components (CO_2, CH_4, N_2O) in the atmosphere. The program of the research included the investigation of chemical composition and aerosol number density in the water–air interface, spectral transmittance of the atmosphere (STA) in the spectral range from 0.37 to 4.0 μm, and the aureole part of the scattering phase functions.

Chemical composition of aerosol was determined using the Petryanov-filter sampling (AFA-VP-20) and the disperse composition was determined using two standard photoelectric AZ-5 particle counters with 12 measuring limits for the particle diameters from $d > 0.4$ to $d > 10$ μm. To increase the accuracy of the counters, the Ch3-63 and Ch3-57 electronic frequency meters were used. The disperse composition was determined during daytime every two hours and occasionally in nighttime.

When measuring the spectral atmospheric transmittance the AMSF-3 and AMSF-4 multiwave solar photometers were used. These photometers have been described in Ref. 7, and their specifications are given in Table I. The measured signals and service information, including the navigation data of the vessel, were recorded with a computer PC/AT-386(387) and an analog-to-digital converter (16 channels, 12 bits). Preliminary processing of the data was performed in a real time with the data, displayed in the digital and graphic form, on atmospheric mass, atmospheric optical depth, moisture content, and so on. Methods of calibration, calculation of atmospheric masses, Rayleigh and gas components of the atmospheric optical depth have been described earlier.[8,9] The total moisture content of the atmosphere W was determined by the three-channel spectroscopic method in the region of the H_2O absorption band at 0.94 μm (Ref. 10).

0235-6880/95/12 981-08 $02.00

TABLE I. Specifications of the AMSF-3 and AMSF-4 photometers.

Characteristics	AMSF-3		AMSF-4
	Short-wave channel	Long-wave channel	Short-wave channel
Field of view angle, deg.	0.75	1	0.75
Number of spectral channels	12	5	8
Maxima (and halfwidths) of light filters transmission, μm	0.370 (0.22) 0.409 (0.30) 0.425 (0.013) 0.439 (0.006) 0.485 (0.007) 0.514 (0.022) 0.553 (0.008) 0.638 (0.005) 0.673 (0.010) 0.870 (0.011) 0.940 (0.010) 1.061 (0.019)	2.182 (0.029) 2.32 (0.04) 2.06 (0.04) 3.9 (0.04) 4.0 (0.04)	0.368 (0.019) 0.438 (0.008) 0.485 (0.008) 0.552 (0.008) 0.633 (0.009) 0.869 (0.015) 0.934 (0.010) 0.1060 (0.020)
Error of photometric measurements, %	1	3–5	1
Time of single measurement series, min	1–2		1
Range of aureole angles, deg.	–		0.75–6
Angular resolution in aureole, deg.	–		0.25
Parameters (characteristics) of the atmosphere measured	AOD (0.37–4.0 μm); Integral contents of H_2O, CO_2, CH_2, N_2O		AOD (0.37–1.06 μm); Aureole scattering phase functions

Measurements of the spectral atmospheric transmittance have been carried out as a continuous series of 10–30 minutes duration every hour under conditions of clear sky. In the subsequent data processing the mean hour values of the atmospheric optical depth and moisture content were used.

In this paper we present the first and most general results of atmospheric research during the 35th mission concerning the disperse composition of aerosol, atmospheric optical depth in the spectral range 0.37–1.06 μm, and moisture content of the atmosphere. It should be noted that in rapid processing of the spectral atmospheric transmittance data the results of preliminary photometer calibration were used, gas components of the optical depth were considered for the conditions of tropical zone, and in some cases false sampling could not be eliminated.

Five regions with the uniform characteristics of aerosol and moisture content of the atmosphere (Fig. 1) have been isolated on the basis of the previous investigations and the results of operative analysis of the data obtained. The regions of research and the experimental data are briefly described in Table II. A comparison with the data of analogous investigations[1–6] makes it possible to note long duration of regular observations; as a rule, the time of absence of regular observations does not exceed 10 per cent.

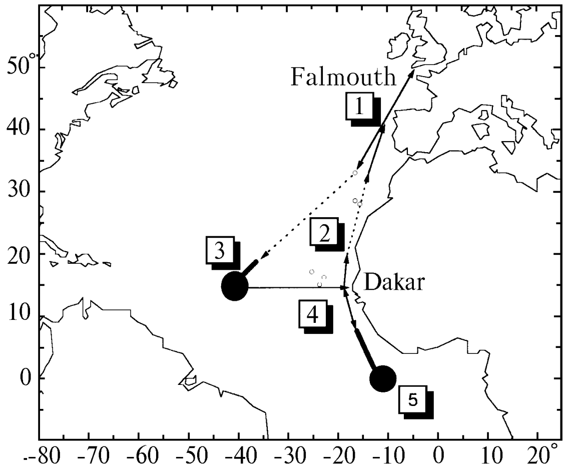

FIG. 1. Chart of research areas in the 35th voyage of the research vessel Akademik Mstislav Keldysh.

DISPERSE COMPOSITION OF AEROSOL

When investigating microphysical characteristics two tasks were achieved: 1) investigation of variations in aerosol concentration over different ocean regions; 2) methodical experiments on estimating the distorting effects from the environment and altitude of the observation point.

TABLE II. Characteristics of the regions under study and of the data bulk obtained and the degree of the observation regularity of R_0.

Conventional symbol and characteristics of the region	Aerosol disperse composition (AZ-5)			Aerosol chemical composition		AOD AMSF-3			Aureole AMSF-4	
	n	p_0	m	n	m	n	p_0	m	n	m
1 "Europe." North of the Central Atlantic close to western coast of Europe. Low moisture content, irregular transport of continental aerosol.	9		41	2	2	8	0.89	1163	–	–
2. "Canaries." Region of northern tropic in the vicinity of the Canaries. Low moisture content, irregular transport of aerosol from Western Africa.	9		73	8	13	7	0.88	1638	–	–
3. "Trade Wind." (I polygon). Tropical region of the Atlantic in the zone of stable northeastern trade wind. Moderate moisture content, long-range transport of aerosol from Sahara.	23	1.0	280	19	19	23	1.0	3501	8	53
4. "Sea of Darkness." Region of enhanced atmospheric turbidity in the zone of high-power dust escapes from Western Sahara.	10	0.77	97	10	8	12	0.92	2307	7	44
5. "Equator." (II polygon). Tropical equatorial region at periphery of the Gulf of Guinea. High moisture content, stable south-eastern trade wind.	30	1.0	242	8	6	23	0.77	3428	9	90
Data bulk	82		733	47	48	73	0.88	12037	24	187

Note. n is the number of measurement days, m is the number of series.

TABLE III. Average integral number densities N, liter^{-1}, $(d > d_i)$ *and the difference in number densities* Δ *at heights* 7.5 m *and* 13 m *above the sea level.*

Height of measurement	Scales in the AZ-5 meter, d_i, μm											
	0.4	0.5	0.6	0.7	0.8	0.9	1	1.5	2	4	7	10
Port side, 7.5 m	12784	9792	7772	6207	5014	4023	3213	1964	1184	101	3.9	0.18
Starboard, 13 m	11980	9861	7675	5946	4768	3704	3055	1905	1158	99	3.11	0.12
Δ	–804	69	97	261	246	319	158	59	26	2	0.79	0.06

The distorting factors are the following: smoke plumes emitted from stacks, temperature gradients of air in the vicinity of the aerosol sampling point due to radiation heating of the vessel hull, eddies at the lee side, and so on. The experiments have shown that the most favorable conditions are those when the measurements are conducted from the shadow side of the vessel and on its windward side with the resulting wind on the forecastle side. Taking into account the above factors, five of measurement points were chosen and used on the right and left sides at the heights from 2 m to 18.5 m above the sea level.

The experiments on the altitude dependence of the concentration, $N_i(h)$, were caused by the following circumstances. It is known that one of the main fractions of aerosol in the marine atmosphere is presented by salt particles generated from the surface.[11,12] It is obvious that for different size of salt aerosol and meteorological conditions (wind velocity, turbulent regime, and so on) one can assume different rate of generation and particle sedimentation, namely, variation of their microstructure as they move away from the surface. Besides, the estimates of altitude dependence of disperse composition are interesting from the standpoint of a correct choice of altitudes where the AZ-5 counters are located. The experimental procedure apart, we note that different approaches to the estimate of the altitude behavior of N_i show either the lack of the dependence $N_i(h)$ or a slight decrease of the concentration with the altitude. For example, from a comparison of the averaged (over the entire set) integral concentrations of aerosol for the two basic altitudes of measurements (Table III) it follows that for particles with the diameter more than 0.5 μm an 8% decrease in N_i is observed with the increase of height in the size range $d > 0.9$ μm.

TABLE IV. Statistical characteristics of the integral aerosol number densities N, liter^{-1}, *($d > d_i$) for different regions.*

d, μm	"Europe"			"Canaries"			"Trade wind"			"Sea of Darkness"			"Equator"		
	$\bar{N}$	max	min	$\bar{N}$	max	min	$\bar{N}$	max	min	$\bar{N}$	max	min	$\bar{N}$	max	min
0.4	8535	37231	1144	7231	14951	2468	12150	32689	1334	19584	50027	4344	3949	12000	1025
0.5	4579	16923	701	5518	17956	1983	9795	33279	1141	15880	42731	3158	2898	10466	643
0.6	3013	10037	507	4444	13283	1438	7747	24653	859	12558	35008	2593	2276	8548	436
0.7	2081	6547	401	3582	10940	1227	6113	21320	734	9950	28760	2068	1871	7438	351
0.8	1487	4490	248	2710	9271	850	4945	18788	485	7929	26176	1540	1535	5885	263
0.9	1021	3228	176	2186	7124	626	3919	15931	387	6225	20159	1024	1248	4500	201
1	718	1965	67	1782	5838	538	3174	14569	224	5071	18438	764	1005	4000	128
1.5	319	828	36	1001	3472	211	1968	11889	151	3035	12491	277	630	2875	78
2	143	351	8	579	2390	67	1187	8014	21	1830	8968	109	370	1607	32
4	9	34	0	41	269	4	77	882	0	136	1143	4	13	124	0
7	1	9	0	1	12	0	2	20	0	6	100	0	0	10	0
10		3	0	0	1	0	0	3	0	0	5	0	0	0	0

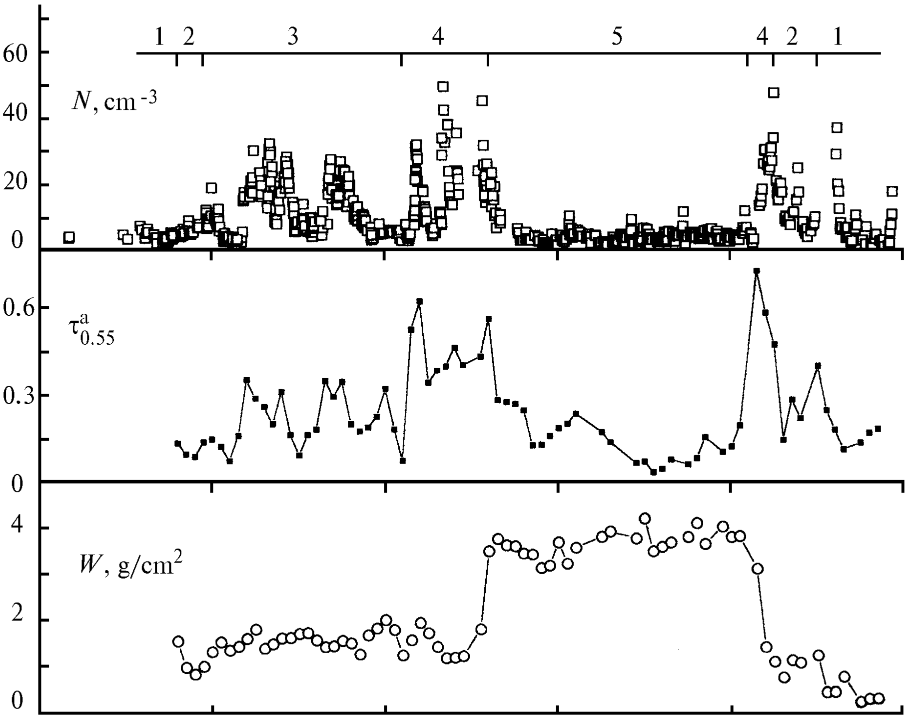

FIG. 2. Time behavior of the total concentration of near water aerosol N($d > 0.4$ μm), aerosol optical depth $\tau^a(\lambda = 0.553$ μm$)$*, and total moisture content W of the atmosphere along the route (the regions of the route are given in the upper part of the figure). Digits in the upper part of the figure denote regions.*

General view of the time variability of $N(d > 0.4)$ is given in Fig. 2, and Table IV presents statistical characteristics of the variations of integral concentrations of aerosol: mean, minimum, and maximum values, as well as rms deviations.

As one would expect, the region of the "Sea of Darkness" stands out because of its anomalously high aerosol content. This region is well known[13,14] for the increased turbidity of air as a result of regular excursions of dust aerosol from the deserts of Western Sahara. Extremal values of the concentration ($N > 45$ cm^{-3}) were recorded on February 28, March 5, and April 7 and 8.

Lower values of the aerosol concentration (about 33 cm^{-3}) were observed in the "Trade wind" region located in the western periphery of the "Sea of Darkness" at a distance of 2.5 thousand km from Africa. Long-range dust transfers to this area are due to the action of eastern and northeastern trade winds.[19] Note that in the period of measurements at this polygon the mean wind velocity was 10 m/s and the wind direction was within 45°–90° for 70 per cent of cases.

Splashes of the increased concentration of aerosol were observed along the western shore of Europe. Maximum values $N = 37.231$ cm^{-3} were recorded, in particular, on April 15 in the northwestern part of Pyrenees peninsula.

The minimum aerosol content, which did not exceed $N = 12$ cm^{-3}, was observed in the "Equator" region. Statistical characteristics of the concentration, N, for "Canaries" are intermediate in their values.

More comprehensive information on the disperse composition of aerosol in the Atlantic Ocean regions under study is given by the particle size distribution function (Fig. 3):

$$f(r) = \log(\Delta N/\Delta \log r),$$

where r is the particle radius; $\Delta N = N(d > d_i) - N(d > d_{i+1})$. As follows from Fig. 3, in the functions $f(r)$ in all regions the distribution function has its maximum at r ~1.5 μm. This maximum is more distinct in the particle distribution over volume (see insertion in Fig. 3) what is in a good agreement with the results of similar studies.[13,20] The above maximum is accounted for by two factors, namely, generation of salt particles from the ocean surface and for the regions 3 and 4 – by the additional availability of large particles of dusty aerosol in air.

Functions $f(r)$ for regions 2–5 are of similar shape, namely, practically parallel transfer of distribution curves as the total concentration N decreases. In the regions "Sea of Darkness" and "Trade wind" one more maximum can be seen in the size range from 0.4 to 0.5 μm.

Based on the shape of the function $f(r)$ for the "Europe" region one can judge on large content of the fine aerosol fraction comparable in value with the largest dust content in the ocean region "Sea of Darkness". The particle size distribution in the "Europe" is close to the results obtained over continents and coastal regions.[20,21]

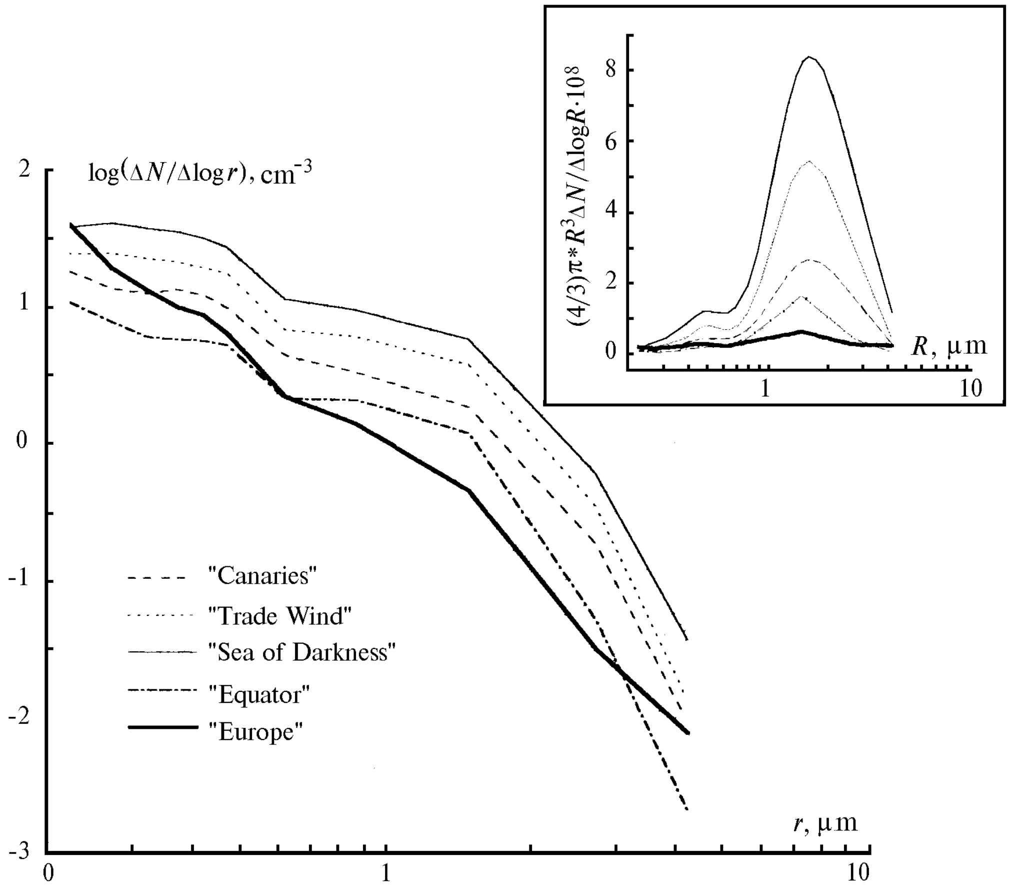

FIG. 3. Mean values of the distribution functions of concentrations and volumes (in the insertion) of aerosol particles for different regions.

AEROSOL OPTICAL DEPTH OF THE ATMOSPHERE

Comparison of the data on spatial variability of AOD of the atmosphere and the aerosol concentration N (Fig. 2) reveals similarity of their distributions in the regions under study. Besides, from the preliminary qualitative analysis of the observation series of N_i and AOD it follows that their basic variability and correlation are due to the variation of synoptic situation with the periods from 3 to 6 days. The degree of correlation of the integral (over the entire atmosphere) optical characteristics, $\tau^a_{0.55}$, and the aerosol concentration in the near water layer is illustrated in Fig. 4.

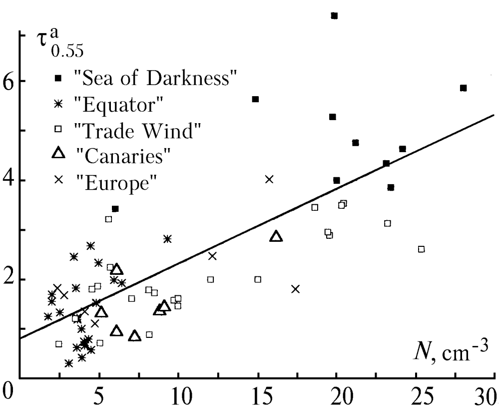

FIG. 4. The correlation of total concentration of the near water aerosol and AOD of the atmosphere.

The crosscorrelation coefficient for the whole array of daily mean values of $\tau^a_{0.55}$ and N turned out to be sufficiently high, namely, 0.734, and the approximation of the dependence is expressed as:

$$\tau^a_{0.55} = (0.80 \pm 0.0121) + (0.015 \pm 0.002)\,N .$$

In similar investigations,[13] larger correlation values, 0.89 and 0.91, have been obtained, but in this case we notice that the above values refer to specific phases of the experiment. According to the scatter diagram of the values τ^a and N for all phases of the experiment the correlation coefficient should be estimated within 0.7–0.8.

The greatest atmospheric turbidities were typical for the "Sea of Darkness" (Figs. 2 and 5). The mean level of AOD of the atmosphere in the "Sea of Darkness" in the entire spectral range exceeded the maximum values of the atmospheric turbidity in other regions. The experimental values of AOD ($\tau^a_{0.55} > 0.6$) were recorded on February 26 and April 6 and 7 when the research vessel was at a short distance from the Cape Verde Islands and crossed the "Sea of Darkness" on its back way.

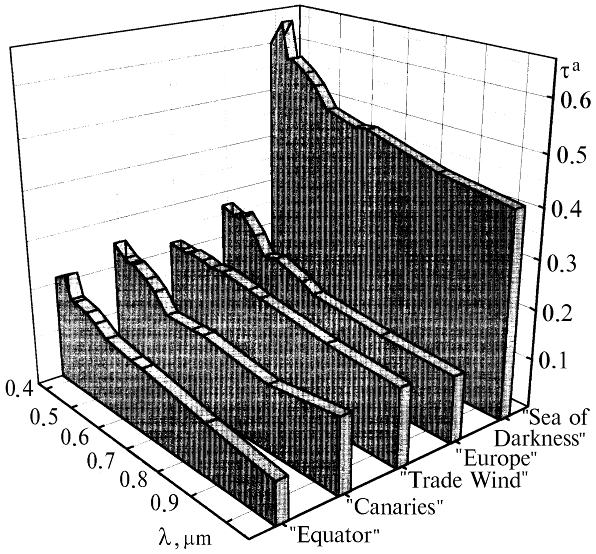

FIG. 5. Spectral dependences of AOD of the atmosphere for different research areas.

Another important property characteristic of the atmosphere over "Sea of Darkness" is small values of the Angström parameter α, characterizing the relative selectivity of the AOD spectral behavior according to the formula:

$$\tau^a_\lambda = \beta\lambda^{-\alpha} .$$

Comparison with the results of previous investigations by different groups (Table V) enables one to draw a conclusion on the constancy, in this region, of high atmospheric turbidities and quasineutral spectral behavior of AOD because of a large number of coarse particles of dust.

TABLE V. Comparison between the values of $\bar{\tau}_{0.55}$ and $\bar{\alpha}$ obtained in the region of "Sea of Darkness" with the data of earlier investigations.

Characteristic	Ref. 15	Ref. 16	Ref. 3	35th mission
$\bar{\tau}_{0.55}$	0.42	0.32–0.36	0.39	0.494
$\bar{\alpha}$	0.45	0.36–0.61	0.37	0.407

In the "Trade Wind" region the atmosphere is cleaner (see Figs. 2, 5). In this case the AOD does not exceed 0.38 in the ultraviolet spectral range and 0.3 in the infrared spectral range. At the same time, based on the low values of the parameter α one can conclude that this region is also characterized by the high content of coarse aerosol particles.

For estimating the long-distance transport of dust aerosol westward of Sahara the meridional dependence of AOD was analyzed during the mission of the research vessel at 15°N from 45°W to the seaport of Dakar. The effect of temporal variability of AOD was decreased in advance by data averaging over 10 points of hourly mean values τ^a (Fig. 6).

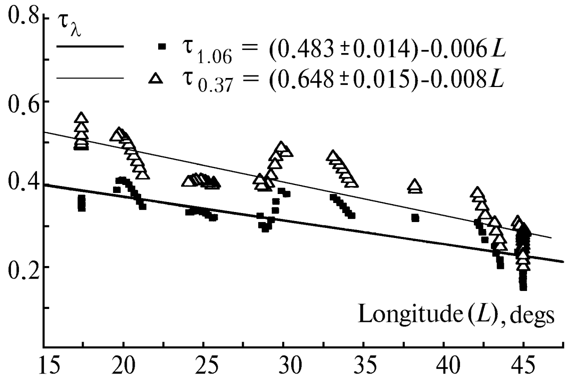

FIG. 6. Meridional dependence of τ^a_λ *along* 15°N.

The approximation dependences, given in the figure, determine the mean gradient of τ^a at the level 0.006–0.008 per one degree of longitude. The "Equator" region is characterized by the AOD minimum values in the infrared spectral range (the values of $\tau^a_{1.06}$ do not exceed 0.16) and relatively large selectivity of the spectral behavior ($\bar{\alpha} \approx 0.94$).

From the comparison of AOD with the data on disperse composition (see Fig. 3) it follows that in this region we observe certain data divergence. The data correlate well in relation of small values of AOD and concentrations N, and discrepancy between the data is in a considerable selectivity of τ^a_λ at a relatively small content of fine aerosol.

Note that peculiarities in geophysical conditions of the "Equator" region are the following (Ref. 13, 19, etc.):

– the intertropical convergence region (ICR) in the north, which is characterized by the developed convection, increased cloudiness which actually separates the regions 4 and 5 as well as prevents the penetration and decreases the concentration, first of all, of large size aerosol fraction;

– irregular "Khartman" wind-blown fine desert loess dust from Central and Southwestern Africa;

– prevailing onshore winds (southern and southeastern directions);

– regular clearing of the atmosphere as a result of washing by tropical rains.

Priority in the action of one or another factor and, hence, explanation of the divergences in the behavior of τ^a_λ and N can be determined later based on the data on synoptic processes and chemical composition of aerosol.

Atmospheric turbidities in the regions "Canaries" and "Europe" are, on the average, of intermediate values between those considered previously. A peculiarity of the "Canaries" is large relative variability of AOD and the Angström parameter. The values of variation coefficients τ^a and α in this region are maximum within 50%–100%. Considerable variability of characteristics can be explained by incidental intrusions of reduced dust escapes from the Sahara Desert into a relatively clean region.

The "Europe" region is characterized by high selectivity of spectral behavior and greatest values of AOD (except for "Sea of Darkness") in the short-wave spectral range. This is in a good agreement with the above results of investigations of disperse composition, i.e., the enhanced content of fine aerosol escaped from the European continent.

It should be noted that the greatest part of the research regions on the route of the 35th mission (except for the "Trade Wind" area) is located in the 500 km zone along the western sea shore of Africa and Europe. In this connection the peculiarities of aerosol characteristics considered are mostly due to the effect from different continental aerosols. This problem will be considered in more detail when chemical analysis of aerosol samples will be completed.

MOISTURE CONTENT OF THE ATMOSPHERE

Because of different physical nature, the spatial distribution of moisture in the atmosphere differs from the zoning for AOD and aerosol concentration (see Fig. 2). The mean values of W in the regions under study were: "Europe" – 0.53, "Canaries" – 1.04, "Trade Wind" – 1.55, "Sea of Darkness" – 1.75, "Equator" – 3.66 g/cm^2. The results obtained indicate that the latitude dependence prevails in the moisture content distribution. The decrease in W with the increase in latitude is traced easily over the period of April 4 to 18 (see Fig. 2) during the voyage from equator to the seaport of Falmouth (50°N, Great Britain). Specific feature of the latitude distribution of W is its zonal nature, i.e., high moisture content in equatorial zone decreases stepwise to 1.2 g/cm^2 when crossing the intertropical zone of convergence, and then a monotonic decrease in W at a mean rate of 0.017 g/cm^2 per one degree of latitude occurs.

The greatest relative variability of the moisture content of the atmosphere was typical for "Sea of Darkness" reaching 45%, while in other regions the variation coefficient of W did not exceed 25%. It is evident that large variation of moisture content in the atmosphere of "Sea of Darkness" is caused by two factors, tradewind transports of dry air from Africa and intrusion of moist equatorial air masses formed in the intertropical zone of convergence.

Based on earlier investigations (see, e.g., Refs. 17, 18) the existence of correlation between the total moisture content and the surface absolute humidity or the water vapor partial pressure e is well understood. To evaluate the above relationship, we have analyzed the hourly mean values W and e for all regions. The dependence obtained turned out to be close to linear one with the correlation coefficient at the level of 0.93.

BASIC CONCLUSIONS

1. During the three-month period of investigations in the 35th mission of the research vessel *Akademik Mstislav Keldysh* we have obtained a continuous series of observations and a complete set of data (chemical and disperse composition of aerosol, spectral AOD and the scattering phase function, moisture content and meteorological parameters), necessary for obtaining interconnections between atmospheric parameters and for determining their space-time variability.

2. Uniformity of microphysical and optical parameters of aerosol atmosphere within separate parts of the route has made it possible to isolate five typical regions in the Atlantic Ocean. The peculiarities of the characteristics being studied in these regions are due to the difference of meteorological conditions and the influence of different sources of continental aerosol.

3. Basically the scale of time variability of aerosol characteristics and of the moisture content is the synoptic scale with the period of 3 to 6 days. No regular diurnal behavior has been revealed in preliminary analysis. The spatial variability of W is mostly of zonal character with latitude, and the horizontal inhomogeneities of concentration N_i and AOD are determined by the proximity to different aerosol sources.

4. The relation of integral characteristics of AOD and the moisture content of the atmosphere W with their close local analogs in the near water layer N_i and e turned out to be sufficiently high; the crosscorrelation coefficients were 0.73 and 0.93, respectively.

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