SPATIAL DISTRIBUTION OF AN AEROSOL COMPONENT OF ATMOSPHERIC TRANSMITTANCE OVER THE ATLANTIC OCEAN

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This paper proposes the genetic classification of areas of the Atlantic Ocean characterizing the spatial distribution of atmospheric turbidity due to aerosol over the ocean. Zoning is based on the results of many-month measurements of atmospheric transmittance performed during five sea missions (1989–1996). It takes into account basic factors of aerosol field formation over the ocean, as well as data of preceding atmospheric investigations. Quantitative data on atmospheric aerosol optical thickness and the Angstrom parameter are presented for different areas of the Atlantic Ocean in the latitude zone from 10°S *to* 60°N.

INTRODUCTION

Results of many-year observations at the continental network of actinometric and ozonometric stations have made it possible to reveal and characterize quantitatively properties and regularities of atmospheric transmittance variability in different areas and under different atmospheric conditions.[1–4, etc.] The situation with investigation of atmospheric transmittance and aerosol optical thickness (AOT) of the marine atmosphere is completely different. Because of lack of meteorological stations and high cost and complexity of marine experiments, investigations are of irregular character. They have been carried out in separate regions; observation series are discontinuous and short. The analysis of a review of marine investigations of AOT, made for the 30-year period,[5] enables the conclusion that in the most thoroughly investigated part of the World Ocean – the Atlantic Ocean – about twenty expeditions were carried out and the total volume of data obtained is comparable with a two-year cycle of observations at a single continental station, while the degree of regularity of observations (the ratio between the number of days of measurements and the measurement periods) is 0.3 to 0.6.

The geographic distribution of AOT over the ocean is diversified, and its value varies within two orders of magnitude.[4–10] In this case, differences are not only in the AOT value but also in the character of its variability and in the spectral behavior. Even mean AOT values reported by different authors are widely scattered – from 0.05 to 0.5 and more. This gives rise to doubts about the quality of some measurements or their representation, but the main reason for such a scatter is objective. On the large territory of the ocean bordering both unpolluted polar areas and the continents, which produce aerosols of different types,[11] identical characteristics of atmospheric turbidity can hardly be expected. The results given in Figs. 1 and 2 illustrate the variability range of AOT τ^A_λ and the Angstrom parameter α, characterizing the selectivity of the spectral behavior $\tau^A(\lambda) = \beta\lambda^{-\alpha}$.

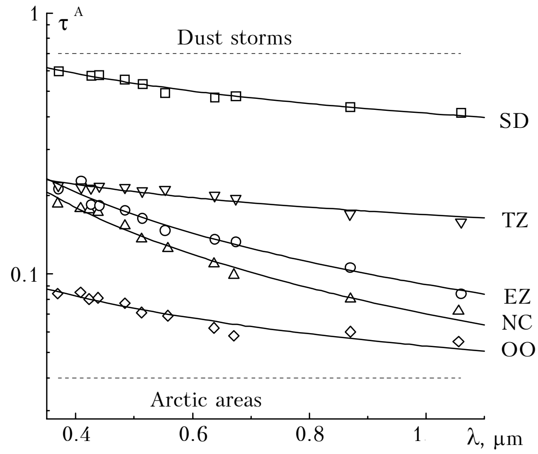

FIG. 1. Mean spectral behaviors of atmospheric AOT over the ocean.

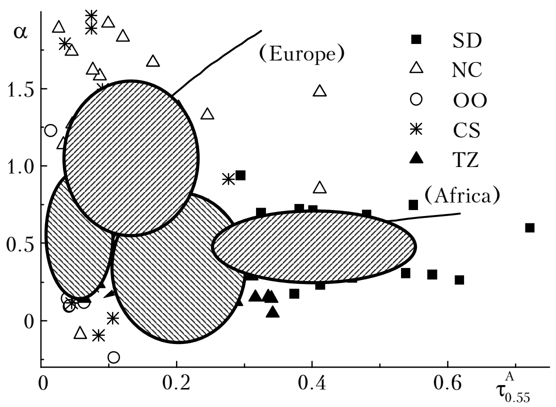

FIG. 2. Combined regions of values of $\tau^A_{0.55}$ and the Angstrom parameter α in the basic areas of the Atlantic Ocean.

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At such a variety of characteristics of spectral AOT the necessity of zoning seems rather evident.

PRINCIPLES OF ZONING

The works by O.D. Barteneva and K.S. Shifrin with co-authors[4,6, etc.] undoubtedly have played a prominent role in investigations of optical characteristic of the marine atmosphere. A large body of studies made in 1970–1980 have revealed variability peculiarities and characteristics of atmospheric turbidity due to aerosol in different areas. They also has laid the groundwork for all the subsequent physical generalizations.

In the period of 1989–1996, during five missions in the Atlantic Ocean, we have performed a new cycle of studies of the spectral transmittance.[7–10, etc.] This cycle is rather representative in the regularity of observations (0.9) and the volume of data obtained (264 days of measurements in addition to 600 days reported in all the other papers). A wide range and variety of atmospheric transmittance characteristics in different areas (from 10°S to 60°N) have required solution of a methodical problem: separation of space and time variations or isolation of areas with similar AOT characteristics. The geographic classification of data in this field carried out earlier by L.I. Ivanov[12] seems contradictory. One of disadvantages of its “latitude–longitude conceptB is that the model of spatial distribution of thermodynamic characteristics by three latitude zones: 0–30°, 30–50°, and 50–70°, has been taken as a basis for zoning of aerosol characteristics. Thus, the role of centers of air mass formation and atmospheric circulations was actually belittled.

The existing methods of climatic zoning can be subdivided into two groups of classifications: indicatory and genetic ones.[13] It is clear that for aerosol as an element of the climatic system the approaches should be similar. As to the atmospheric AOT, fundamentals of the indicatory classification were proposed in Ref. 6: three most contrast regions of the ocean were separated based on values of τ^A and α. They are the Sea of Darkness, the central-oceanic region, and the coastal one. However, vast expanses of other oceanic regions remained unclassified, and the transmittance characteristics typical of these regions are still to be determined.

The genetic classification seems preferable for the water area of the ocean, because it reveals the basic processes of formation of atmospheric physical fields and allows (with deficient information) extension of regularities revealed to less investigated areas.[13–15] Below we describe an attempt to apply this approach to the aerosol component of atmospheric transmittance. When defining the principles of AOT zoning, the following considerations have been taken into account.

In many genetic classifications (those by Alisov, Flon, Vitvitskii, et al.[13–15]) atmospheric circulations and features of the underlying surface play a large or even crucial part. Most aerosol sources are also governed by a type of the underlying surface, and the spatial spread of aerosol depends on motion of air masses. Under oceanic conditions, the underlying surface (generator of marine aerosol) is rather homogeneous and variations of meteorological fields are smoothed. Nevertheless, microphysical and optical investigations of aerosol over the ocean[4–11] have indicated that variations of atmospheric transmittance characteristics are considerable and mostly caused by invasions of aerosol of different kind from the continents.

It follows herefrom that AOT spatial inhomogeneities over the ocean present the problem of transfer of just the continental aerosol. Thus, the classification of aerosol fields should take into account the joint effect of the two main factors: sources or types of continental aerosol, which prevail in each latitude zone, and prevailing circulations or air mass transports, which determine direction and depth of aerosol penetration into the oceanic area.

RESULTS OF ZONING

Relative arrangement of the considered “aerosolB areas is explained in Fig. 3.

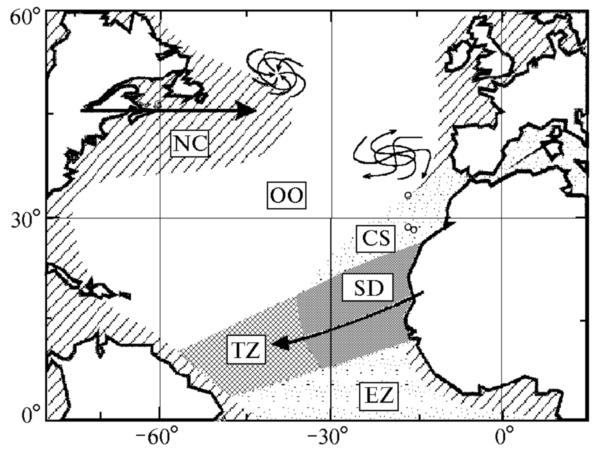

FIG. 3. Geographic arrangement of the aerosol zones on the territory of the Atlantic Ocean.

A dominant aerosol in the mid-latitudinal atmosphere (Europe, America) is more finely disperse as compared to a marine aerosol.[11] A narrow coastal zone (CZ) lies as a belt with the width of tens kilometers along the coast. This zone is characterized by a breeze circulation, which favors regular mixing of the continental aerosol with the marine one, enriching the latter with a finely disperse fraction. Further transport of the continental aerosol to the oceanic zone is due to the cyclone activity developed in these latitudes and the west transport. In the near zone, areas near the continents (NC) should be separated out, while in the far zone we should separate the central oceanic areas or open ocean (OO). Due to remoteness of the OO area, the continental air masses (and aerosol) coming there are strongly transformed. The lack of data and random character of aerosol transport prevent strict determination of the extent of NC area deep into the ocean. Thus we can use a semiqualitative estimate based on the scale of cyclonic formations. Taking into account the different (in latitude) intensity of aerosol sources and transports, the extent can be estimated as 100 to 200 km at boundaries of the moderate zone and up to 1000 km in the central part.

The next area occurs in tropical latitudes. The stable tradewind transport with arrival of the dust coarse-disperse aerosol from the Sahara Desert predominates here. From the results of continental and shipborne investigations[4,14] it is known that the content of the Sahara aerosol in the atmosphere gradually decreases, but it can be followed up to the coasts of America. The contributory factors, characteristic of the tradewind zone (TZ), are the inversion and relatively high rates of aerosol transport in the 2–4-km layer. From the viewpoint of aerosol characteristics, TZ can be considered as extending to western coastal areas of the Atlantic Ocean. The OO area gradually narrows in the south direction and is limited by TZ. The TZ area, most saturated with dust aerosol (to the east of ~ 35°W), is well known in the literature as the "Sea of DarknessB (SD). The natural south boundary of SD and TZ is the intratropical zone of convergence (IZC), whose annual mean position is about 7°N (Refs. 13, 14, and 16). The axis of IZC, as well as the axis of the tradewind transport, is deflected in the direction from east-northeast to west-southwest.

Mixed areas: the Canaries (CS) and the Mediterranean Sea (MS), should be separated out on the north of the tradewind zone. Depending on seasonal circulation conditions, these areas are under variable action of arrivals of coarse-disperse and fine-disperse aerosols from the two continents. Alternation of circulations here is conditioned by neighborhood of the northeast tradewind with one of the basic centers of atmospheric effect – the Azores Anticyclone.

Finally, in the southern part there is the equatorial zone (EZ) or IZC. The following geophysical conditions are typical for this area: calm wind, developed convection, filtration of the continental aerosol by cloudiness and frequent precipitation.[4,13] Closer to Africa, we should note the action of the Harmatan wind,[4,14] carrying away the mineral aerosol, which is more finely disperse as compared with the Sahara aerosol. All these conditions together form here the atmospheric turbidity, which differ in its character from that in the adjacent tradewind zone.

The quantitative characteristics of AOT for the above-mentioned oceanic areas are given in Table I. Note that for the statistical characteristics we did not perform generalization (averaging) with the results of other authors by methodical reasons: different methods of accounting for gas components (in some papers absorption was not excluded at all), different statistics collected, different averaging methods, and so on. Because our measurements near coasts for the CZ areas are few, in Table I we present the data from Ref. 6.

From Table I it follows that the main differences between the aerosol zones manifest themselves in the following characteristics: the mean AOT values, the variation coefficients V_τ, and the Angstrom parameter. The increased atmospheric turbidity obviously occurs near the continents – in the SD, NC, and CS areas. It is clear that in the temperate latitudes the Angstrom parameter increases, as approaching the continent, from purely oceanic values $\alpha = 0.6$ to continental values as high as $\alpha_{cont} \approx 1.3$ (Ref. 4). In the tradewind zone these tendency is not observed since the turbidity increases due to enrichment with the coarse-disperse aerosol fraction as Africa is approached.

Of some doubts is the fact that the minimal mean values of α are observed in the TZ area, rather than in the Sea of Darkness, which is characterized by the maximum dust concentration. The matter is that content of mineral aerosol fraction actually decreases in the west direction due to aerosol spatial scattering and sink into the ocean. According to the data from Ref. 17, adhesion of small dust particles into conglomerates and sedimentation occur in the process of aerosol transport. That is, farther from the continent the aerosol particle size spectrum is transformed due to decrease in content of small particles. The content of another coarse-disperse aerosol fraction, salt particles, in air is governed by the character of sea roughness and wind velocity.[11] As follows from Ref. 16 and the results of our measurements, as the distance from Africa increases, the wind velocity grows and, consequently, generation of marine aerosol intensifies.

TABLE I. Statistical characteristics (the means, standard deviations, and variation coefficients) of τ^A_λ and α in different areas of the Atlantic Ocean.

Areas (*N* days of measurements)	$\bar{\tau}_{0.55}$	σ_τ	V_τ	$\bar{\alpha}$	σ_α	V_α
OO (26)	0.076	0.047	0.62	0.59	0.47	0.80
NC (25)	0.149	0.097	0.65	1.11	0.50	0.45
CZ (Ref. 6)	0.20	0.10	0.49	0.90	0.43	0.48
CS (31)	0.135	0.081	0.60	0.73	0.54	0.74
MS (6)	0.072	0.048	0.66	1.0	0.60	0.60
SD (32)	0.381	0.143	0.38	0.50	0.22	0.45
TZ (23)	0.196	0.095	0.49	0.31	0.34	1.11
EZ (25)	0.141	0.073	0.52	0.85	0.55	0.65

(The central part of the Atlantic Ocean in the tradewind zone is characterized by most strong and stable winds as compared with other areas.) In this area sinking inversions are weaker and upward flows prevail, what contributes to the process of atmosphere filling with the marine aerosol in TZ.

Thus, the joint action of the above factors results in significant reduction of the content of small particles when passing from SD to TZ, while the decrease in the content of large particles is compensated by the coagulation process and generation of salt particles. Transformation of the aerosol disperse composition leads to the change of optical characteristics in TZ (see Fig. 1): AOT in the UV range becomes comparable with that in the other oceanic areas, while in the near IR range AOT remains at a relatively high level.

In general, the overall range of AOT characteristics over the Atlantic Ocean ($<\tau> = 0.01 - 0.7$; $<\alpha> = -0.24 - 2.42$) is comparable with the variability range under conditions of the continental atmosphere,[1–4,18] but the repetition histograms of τ^A (except for SD) are shifted toward smaller values (Fig. 4). The repetition histograms of AOT in the OO, NC, SD areas are unimodal with the most probable values of τ^A close to the mean values. The frequency diagrams of τ^A in the TZ, EZ, and CS areas are more diffused, and the second mode can be followed in them. This mode is caused by irregular invasions of dusty air from the Sea of Darkness.

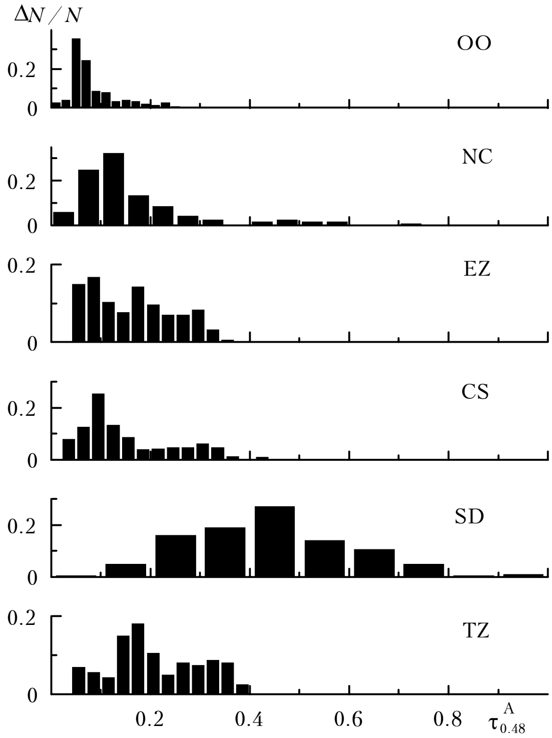

FIG. 4. Repetition histograms of hourly mean values of $\tau^A_{0.48}$ in the separated oceanic areas.

The zoning made it possible to distinguish and consider peculiarities of time behavior of AOT in different areas. The spatial distribution of absolute daily variability (σ_τ) follows roughly the distribution of AOT mean values. The values of σ_τ are comparable with the continental ones,[18] and the relative variability ($V_\tau = \sigma_\tau / \bar{\tau}$) is higher because of lesser turbidity of the marine atmosphere. The maximum variation coefficients V_τ = 60 to 80% are typical of the OO, NC, and CS areas, which are the zone of intense cyclonic activity. Variations of the Angstrom parameter (especially relative – V_α) are higher than in the continental atmosphere: 0.45 – 1.11 as compared with 0.3 – 0.4 under conditions of Tomsk.

Two notes about the characteristics considered should be made:

1. When calculating the AOT statistics (see Table I) the results of 1991 were used,[19] which have been obtained one to three months after the Mt. Pinatubo eruption. The characteristics of AOT in this period in the CS, n n , and NC areas also agree with the above classification, but the values of τ^A and α were distorted by a supplementary contribution of the volcanic layer.

2. Because our data are few, the characteristics of transmittance in the MS area remained not commented. Values of AOT, which are too small for an inland sea (as compared with the data from Refs. 5 and 6), were conditioned by both short duration of observations and circulation peculiarities of this area near the Azores maximum. In different seasons and synoptic periods, unpolluted air masses from the open ocean (as in our case) or continental dust arrivals from Europe or the Sahara Desert prevail in the MS area.

VALIDATION AND COMPARISON OF THE RESULTS

The correctness of the approach to zoning in a methodical aspect is confirmed by the agreement with the results of the indicatory classification by values of τ^A, α, and V_τ. The ranges of values "τ^A–α" (see Fig. 2) are localized in accordance with peculiarities of each area. The area overlap and point spread are rather natural because of synoptic variability of AOT (invasions of various air masses to the areas). The classification of the areas based on "τ^A–α" is supported additionally by differences in the variation coefficients (see Table I).

The zoning carried out is in a good agreement with the spaceborne data on atmospheric turbidity due to aerosol over the ocean. Figure 5 shows, as an example, the spatial distribution of AOT from the AVHRR/NOAA-11 radiometer data (the results were presented by the American colleagues when performing subsatellite experiments[20]). Despite the fact that the spaceborne sensing is conducted only at a single wavelength (spectral differences in AOT cannot be followed up), main peculiarities and positions of the areas are consistent with the classification considered.

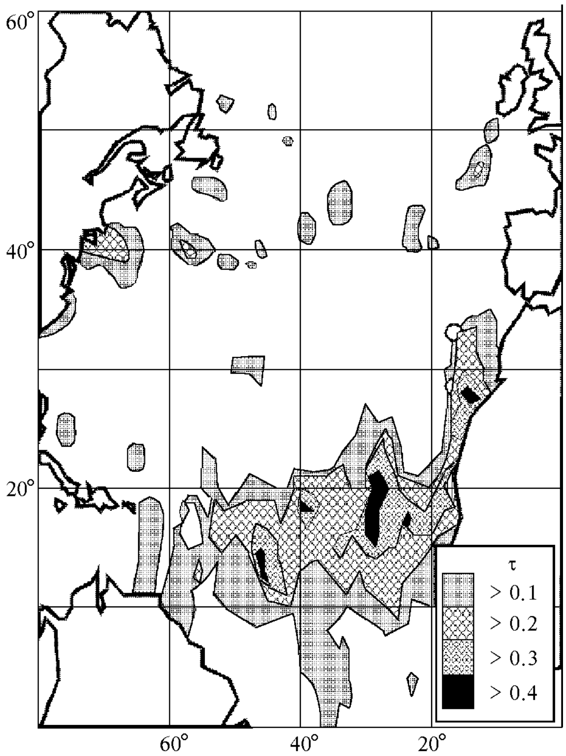

FIG. 5. Spatial distribution of atmospheric AOT over the ocean from the data of spaceborne sensing (NOAA–11, September 21, 1989).

One more verification of the zoning and quantitative characteristics may be the comparison with results by other authors. For brevity we restrict our consideration to only those papers and areas where most detailed statistical and spectral data have been obtained (Table II).

Comparison of the results for the OO area indicates that in most cases our data fall in the mid-range of τ^A and α values obtained by other authors: $<\tau^A>_{00} = 0.067–0.087$ and $<\alpha>_{00} = 0.1–0.66$. The exception is the results of Ref. 21, as well as Refs. 5 and 22 for 1985 and 1988. The data of Ref. 21 are doubtful since the AOT values in the middle of the Atlantic Ocean (to the north of 30°N) were found in the range of 0.11 to 0.61. Such values are, in fact, comparable with those in a zone of intense dust arrivals. In the second case, measurements were carried out to the northwest of the Straits of Gibraltar, therefore the continental arrivals from the Pyrenees and Africa could affect the results. According to our classification, this area is rather NC than OO. With this comment, when comparing the data in the NC area, our results again occupy the intermediate position in the entire range of values: $<\tau^A>_{NC} = 0.097 - 0.21$; $<\alpha>_{NC} = 0.1 - 1.17$.

The scatter in data in the relatively small SD area – $<\tau^A>_{SD} = 0.24 - 0.54$, $<\alpha>_{SD} = 0.3 - 0.6$, represents the seasonal variability and cyclicity of dust escapes from the Sahara Desert. In our earlier studies,[7,8] mean values of AOT for different periods differ as well. In October 1989 $\tau^A = 0.36$; in November–December 1989 $\tau^A = 0.28$; in March–April 1995 $\tau^A = 0.48$; and the common average ($\tau^A = 0.38$) occupies the intermediate position among all the results.

TABLE II. Mean values of τ^A_λ and α obtained by different authors in the three areas (is for our data).*

Area	Ref.	Year	Area	*N*, days	$\tau^A_{0.55}$	α
OO	*	1989–1996	Atlantic Ocean	26	0.076	0.59
	4	1979	"	–	0.071	0.1
	4	1987	"	–	0.087	0.3
	5	1989/90	"	12	0.07	0.34
	6	1982, 1986	Pacific Ocean	33	0.07	0.40
	4	1981	Indian Ocean	15	0.067	0.60
	21	1988	Atlantic Ocean	6	0.16	1.0
OO/NC	5	1985	East Atlantic	11	0.18	0.56
	22	1988	"	15	0.12	0.66
NC	*	1989–1996		25	0.149	1.11
	4	1979	Caribbean Sea	–	0.097	0.1
	4	1983	Norwegian Sea	–	0.201	0.3
	6	1986	Mediterranean Sea	27	0.20	1.17
	22	1988	East Atlantic	19	0.21	0.86
SD	*	1989–1995	Sea of Darkness	32	0.381	0.50
	6	1986	"	9	0.42	0.45
	4	1972	"	–	0.24	0.6
	4	1986/87	"	–	0.535	0.3
	21	1988	"	–	0.37	0.33
	23		"	–	0.382	–

CONCLUSION

Experimental data on atmospheric transmittance over the ocean are still insufficient for development of qualitative experimental models. Because of low activity of the Russian scientific research fleet since 1990s, we think that in the nearest future oceanic investigations will remain rare, and so results will be only fragmentary. Therefore, without having pretensions to completion of the model, the aim of our investigation was to formulate and justify the principles of zoning of the ocean (for AOT) in order to analyze consistently separate results obtained for different areas. Comparison of average τ^A and α characteristics with the data from other papers gives grounds to believe that estimates of spectral AOT for separated areas of the Atlantic Ocean, which result from our investigations, are most justified.

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