# ON THE CORRELATIONS IN SPECTRAL BEHAVIOR OF THE AEROSOL OPTICAL DEPTH IN SOME REGIONS OF ATLANTICS

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*Variations in the spectral behavior of the aerosol optical depth of the atmosphere observed in some regions of Atlantics during the 40th expedition of the research vessel "Akademik Vernadskii" are analyzed. A comparison of statistical characteristics of the Angstrom parameter for three regions with the data by other authors is conducted. Correlations between the spectral behavior of the optical depth of the atmosphere, Angstrom parameter, and meteorological parameters are discussed.*

Spectral behavior of aerosol optical depths (AOD) of the marine atmosphere became quite an interesting object in connection with the development of spaceborne methods for oceanological studies and the account of the atmospheric distortions of observations in different spectral ranges.

This paper presents the analysis of the AOD measurements at four wavelengths (0.48, 0.55, 0.67, and 1 μm) in several regions of Atlantics during the 40th voyage of the research vessel "Akademik Vernadskii" in 1989 (see Ref. 1). Specifications of the instrumentation, the observational conditions, and the methods of calibration and account of gas components have been discussed earlier (see Refs. 2 and 3).

The results of the analysis of statistical characteristics and histograms of AOD reproducibility[1,3] enabled us to combine the regions under study into three specific regions (an open ocean, "a darkness sea", and coastal regions) what coincides with the classification given in Ref. 4. The first region, in our case, covers distant regions of Central and North Atlantics (at a latitude of 17–60°north). As the second region, we consider the tropical zone of Atlantics near the Western coast of Africa where we have collected two data sets during different periods of observations (from 12 till 26 of October and from November 11 till December 4). The third region contains the areas along the North–West coast of Europe and the Mediterranean Sea. However because of the lack of spectral components of AOD at the first stage of our studies the analysis of the spectral behavior was made only based on the data obtained in the Mediterranean Sea.

Figure 1 depicts the AOD spectral behavior based on the mean values $\bar{\tau}_\lambda^a$ and rms deviations (RMSD) $\sigma_\tau$ for each of the above three regions. The results show that in all the three regions the AOD decreases with the wavelength increase with only inessential variations of the RMSD and variation coefficient $V_\tau = \dfrac{\bar{\tau}}{\sigma_\tau}$. The agreement of the data for the open ocean and the Mediterranean Sea, in contrast to Ref. 4, is accounted for by different "optical weather" during different voyages. In our case it was characterized by a high transmission typical of the atmosphere over the open ocean. High transmission of the atmosphere in this region in winter also follows from the data[6] obtained in the Mediterranean Sea during the same period and is explained by characteristic circulation of air masses which is favorable for cleaning the atmosphere from dust emissions from the continent. The effect of these emissions is most evident in summer and fall.[4,5]

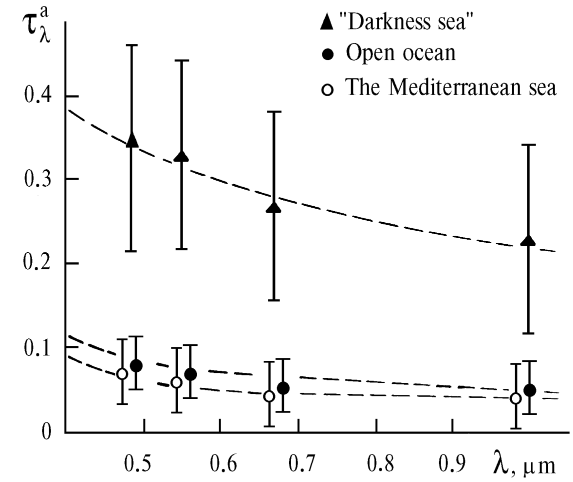


*FIG. 1. The spectral behavior of AOD of the atmosphere ($\tau_\lambda^a$ and $\sigma_\tau$) for three regions. The approximated Angstrom dependence is shown by dashed curves.*

Most reasonable approximation of the AOD spectral behavior can be done with a power dependence, i.e., with the Angstrom formula

$$\tau_\lambda^a = \beta \cdot \lambda^{-\alpha}, \quad (1)$$

where $\alpha$ is the Angstrom parameter characterizing the selectivity (relative) of the AOD spectral behavior and related to the particle size–distribution, $\beta$ is the turbidity factor related to the aerosol concentration. The parameter $\alpha$ is found by the method of least squares after taking the logarithm of dependence (1). The values $\tau_\lambda^a$ averaged over a half–day period were used in calculations.

Two facts should be noted in relation to the Angstrom formula:

1) as was noted by other authors, real spectral dependences of AOD and their averaged values correspond to the Angstrom formula only approximately;

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2) relative selectivity of the spectral behavior expressed by the power function changes within the aforementioned wavelength range and, as a consequence, the value of α depends on the spectrum boundaries.

The latter fact is particularly important when one compares the results of investigations by different authors. By way of example of α variations Table I lists its values found based on our results for the "darkness sea" in different spectral intervals.

*TABLE I. Angstrom indices in different spectral ranges.*

| λ, μm | 0.48–0.55 | 0.55–0.67 | 0.67–1 | 0.48–1 |
|---|---|---|---|---|
| α | 0.48 | 1.22 | 0.33 | 0.61 |

Statistical characteristics of the Angstrom parameter variability for the three regions are given in Table II, and averaged dependences (1) are depicted by dashed line in Fig. 1. Prior to the analysis and comparison with the results of other researchers[4,8] it is necessary to discuss the differences in the techniques used which must be taken into account. In Ref. 4 the spectral range under study is somewhat wider (0.44–1.02 μm) (ours is 0.40–1.0 μm), the approach to zoning of the ocean regions under study is the same, but at the same time we have studied the atmosphere over different oceans. In Ref. 8 the spectral range is 0.38–0.78 μm while zoning has been done not geographically but according to the type of air mass determined from airborne measurements of the aerosol composition at four pressure levels in the atmosphere (from 1000 to 500 mbar).

*TABLE II. Statistical characteristics of the Angstrom parameter.*

| Region | Statistical characteristics | | | |
|---|---|---|---|---|
| | $\bar{\tau}^a_{0.55}$ | $\bar{\alpha}$ | $\sigma_\alpha$ | $\nu_\alpha$ |
| Open ocean | 0.08 | 0.75 | 0.76 | 1.02 |
| Ref. 4 | 0.07 | 0.39 | 0.38 | 0.97 |
| Ref. 8 | 0.16 | 1 | – | – |
| The Mediterranian Sea | 0.06 | 0.72 | 0.63 | 0.88 |
| Ref. 4 | 0.2 | 1.17 | 0.3 | 0.26 |
| "Darkness sea" | 0.32 | 0.61 | 0.29 | 0.48 |
| | (0.36) | (0.36) | (0.25) | (0.69) |
| Ref. 4 | 0.42 | 0.45 | 0.12 | 0.26 |
| Ref. 8 | 0.39 | 0.37 | – | – |

The analysis of a histogram of the Angstrom parameter reproducibility (Fig. 2) and its statistical characteristics (Table II) in different regions reveals that α can vary in a wide range and mainly being in the interval 0.2–1.1. The maximum relative variability of α ($V_\alpha$ reaches unity) is observed in the open ocean what is caused, to a certain extent, by small values of $\tau^a_\lambda$ and the increasing role of errors. Disagreement between the mean values of α obtained in our study and the results obtained in Refs. 4 and 8 is accounted for not only by different atmospheres over the Atlantic and Pacific oceans and possibly, by certain differences in the measurement techniques (different spectral ranges, account of gas components, etc.) which become serious at small values of $\tau^a_\lambda$.

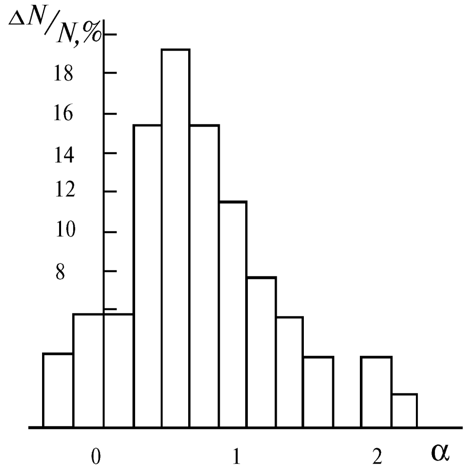


*FIG. 2. Histogram of the Angstrom parameter reproducibility over the entire period of measurements.*

Disagreement between our data on the statistical characteristics of the Angstrom parameter and the results obtained in the Mediterranean sea[4] is explained by two different types of "optical weather" occurring in this region during different seasons, that is, the turbid atmosphere due to dust emissions from Africa in the warm season and clear atmosphere in winter[6] because of cyclonic processes.

The best agreement of the results for α is observed in the Tropical Atlantic region near the Western coast of Africa. This region is characterized by a sufficiently stable enhanced turbidity due to systematic dust emissions from Sahara whose traces are found as far as American continent. The TROPEX–72 National Experiment (Refs. 9 and 10) showed that the dust emissions result in a significant increase of aerosol concentration and of a fraction of large particles of a mineral origin. As a consequence, the mean turbidity increases and the spectral behavior selectivity decreases (see Table II). The mean Angstrom parameter $\bar{\alpha} = 0.61$ is somewhat larger than the data in Refs. 4 and 8 and coincides with the results from Ref. 11, according to which the value $\bar{\alpha}$ averaged over the entire period of the TROPEX–72 expedition in this region was 0.6. To explain the observed disagreements let us analyze the curve of α value reproducibility for the first period of observations (October) and for the total observation time (October–December) for $\Delta\alpha = 0.1$ (Fig. 3). In the resulting histogram there are two well–defined modes of α values which correspond to two types of the AOD spectral behavior typical of this region. The first maximum ($\alpha \approx 0.4$–$0.45$) coincides with the results from Ref. 4 and corresponds to almost neutral spectral behavior of $\tau^a_\lambda$ caused by an increased role of the coarse fraction of aerosol. The second maximum ($\alpha \simeq 0.8$) coincides with our results for the ocean ($\alpha = 0.75$) and demonstrates larger selectivity of the spectral behavior and the weaker effect of large particles. Thus, because of much larger statistics of our data (23 measuring cycles in contrast to 12 in Ref. 4 and only 2 in Ref. 8), we think that most likely the observed differences can be explained by the fact that the measurements[4,8] have been carried out under conditions of "optical weather" of the first type with the AOD spectral behavior characteristic of this region. Separate consideration of the values α for the first period of measurements (October) also supports this conclusion. In this case in the histogram of $\alpha$ value reproducibility (Fig. 3) the second maximum practically disappears, and the mean values of $\overline{\tau}^a_{0.55}$ and $\overline{\alpha}$ (the results are given in parentheses in Table II) approach to those from Refs. 4 and 8.

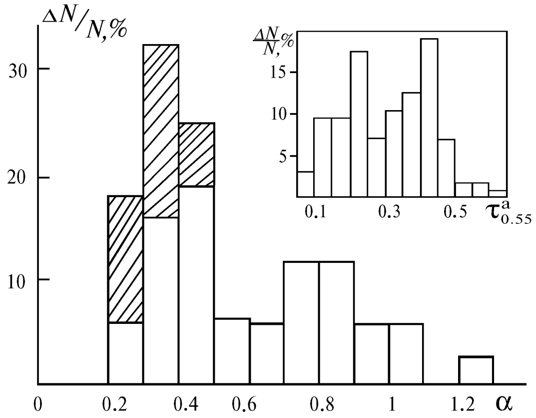


*FIG. 3. Histogram of $\alpha$ parameter reproducibility over the entire period of measurements in the "darkness sea" and during the first stage (a hatched portion). Histogram of $\tau^a_{0.55}$ reproducibility in the same region is shown at the top of figure.*

Bimodality is also characteristic of the histogram of the AOD value reproducibility drawn for the atmosphere in this region[1] (see Fig. 3). It is reasonable to assume that every typical spectral behavior of AOD is somehow related to one of the typical situations with the atmospheric turbidity. Search for such dependence revealed its nonunique and complicated character what was confirmed by a low level of correlation $r(\tau^a_{0.55}, \alpha)$ equal to 0.311 for this region. To reveal such an obscured and complicated relation ($\tau^a_{0.55}$, $\alpha$) the AOD referring to the first ($0.2 < \tau^a_{0.55} < 0.25$) and second ($0.4 < \tau^a_{0.55} < 0.45$) maxima in the histogram of $\alpha$ value reproducibility were analyzed separately. As a result, it turned out that 89% of the values $\tau^a_{0.55}$ within the first maximum corresponded to the values of $\alpha$ from 0.6 to 1.3 with the most probable value $\alpha \simeq 0.85$, i.e., they were from the second mode of the histogram of Angstrom parameter reproducibility. Similarly, for the second mode of $\tau^a_{0.55}$, 68% of its values corresponded to the values $\alpha$ from 0.2 to 0.5 with the most probable value $\alpha \simeq 0.45$ which was close to the first maximum in the histogram of $\alpha$ values reproducibility.

Thus, based on the results obtained for the "darkness sea" during the 40th expedition it is possible to assume that each of the typical situations[1] with respect to the level of $\tau^a_{0.55}$ values is characterized by its own spectral behavior: for weaker turbidity it is primarily more selective, and for a strong turbidity it is close to a neutral one.

Taking into account the existence of relationship between $\tau^a_\lambda$ and $\alpha$ it is interesting to analyze correlation between parameters $\alpha$ and $\beta$ in order to seek a possibility of using a single parameter model for describing $\tau^a_\lambda(\lambda)$ at least in some regions. It should be noted that similar attempts have been undertaken earlier[13] but no unique relations have been revealed.

First of all, we have analyzed the $\alpha$ and $\beta$ values themselves compiled in three data sets, that is, the data for the open ocean, "darkness sea", and all measurements in the ocean. To increase the statistical support in the analysis we used all individual spectral data of AOD without their averaging over time. The values of the correlation coefficients $r_{\alpha,\beta}$ (Table III) were significant and negative. Moreover the correlation in some subsets of data was higher than that in the general array. This means that there exist regional peculiarities in the correlation. It follows from the negative values of $r_{\alpha,\beta}$ that an increase of the turbidity coefficient $\beta$ (concentration) is accompanied, as a rule, by a decrease of the parameter $\alpha$ or increase of the relative contribution of large particles. Taking into account this fact we wrote the parameter $\alpha$ in terms of $\beta$ as follows:

$$\alpha^0 = a\,\beta^{-b}. \qquad (2)$$

The correlation coefficients $r_{\alpha,\alpha 0}$ together with corresponding values $a$ and $b$ are given in Table III. A sufficiently high level of the correlation $r_{\alpha,\alpha 0}$, at least for individual regions, allows one to hope that based on data of more long observations it would be possible to reveal and validate a single parameter spectral behavior and determine its applicability limits.

*TABLE III. Values of the correlation coefficients $r_{\alpha,\beta}$, $r_{\alpha,\alpha 0}$, and the parameters a and b.*

| Region | $r_{\alpha,\beta}$ | $\alpha^0 = a\beta^{-b}$ | | |
|---|---|---|---|---|
| | | $r_{\alpha,\alpha 0}$ | $a$ | $b$ |
| Open ocean | –0.492 | 0.743 | 0.025 | –0.957 |
| "Darkness sea" | –0.476 | 0.858 | 0.255 | –0.510 |
| The whole data set | –0.249 | 0.571 | 0.293 | –0.292 |

The analysis of the coefficients of correlation between AOD at different wavelengths (Table IV) has revealed higher correlation than that obtained in earlier studies.[4,11] As it should be expected, an increase of the wavelengths separation $\lambda_i - \lambda_j$ is accompanied by a decrease of the coefficient $r(\tau^a_{\lambda_i}; \tau^a_{\lambda_j})$ from 0.995 to 0.948. Note that the correlation significance in our case is 0.135 (within the confidence interval of 0.95).

*TABLE IV. Matrix of the correlation coefficients.*

| | $\tau_{0.48}$ | $\tau_{0.55}$ | $\tau_{0.67}$ | $\tau_1$ | $T$ | $R$ | $e$ | $V$ | $W$ | $\alpha$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $\tau_{0.48}$ | 1 | 0.995 | 0.982 | 0.448 | 0.421 | 0.007 | 0.479 | –0.142 | 0.547 | –0.075 |
| $\tau_{0.55}$ | | 1 | 0.990 | 0.962 | 0.417 | –0.005 | 0.469 | –0.128 | 0.518 | –0.091 |
| $\tau_{0.67}$ | | | 1 | 0.980 | 0.379 | 0.003 | 0.451 | –0.103 | 0.432 | –0.143 |
| $\tau_1$ | | | | 1 | 0.378 | 0.009 | 0.432 | –0.053 | 0.313 | –0.261 |
| $T$ | | | | | 1 | –0.402 | 0.926 | –0.214 | 0.581 | 0.038 |
| $R$ | | | | | | 1 | –0.036 | –0.115 | 0.046 | –0.114 |
| $e$ | | | | | | | 1 | –0.293 | 0.626 | –0.091 |
| $V$ | | | | | | | | 1 | –0.491 | 0.007 |
| $W$ | | | | | | | | | 1 | 0.279 |
| $\alpha$ | | | | | | | | | | 1 |

The equations of regression relating the values $\tau^a_{0.55}$, which is chosen as a reference one, with the AOD at other wavelengths are listed in Table V. The confidence intervals for the regression parameters were obtained with the accuracy of 0.95. In Table V there are also the rms errors in the extrapolation $\sigma_i = \sigma_0 \sqrt{1 - r^2(\tau^a_{\lambda_i}; \tau^a_{\lambda_j})}$ and relative errors $\Delta_i = \sigma_i \,/\, \overline{\tau}^a_{\lambda_i}$.

*TABLE V. Regression equations for the correlation $\tau^a_{0.55}$ and $\tau^a_i$ and the values of the errors $\sigma_i$ and $\Delta_i$.*

| Regression equation | $\sigma_i$ | $\Delta_i$ |
|---|---|---|
| $\tau^a_{0.48} = (1.05 \pm 0.02)\tau^a_{0.55} + (0.00 \pm 0.01)$ | 0.02 | 0.10 |
| $\tau^a_{0.67} = (0.89 \pm 0.03)\tau^a_{0.55} - (0.02 \pm 0.01)$ | 0.02 | 0.14 |
| $\tau^a_1 = (0.72 \pm 0.05)\tau^a_{0.55} - (0.01 \pm 0.05)$ | 0.04 | 0.31 |

The relationship between $\tau^a_\lambda$ and meteorological parameters [(the temperature ($T$), relative ($R$) and absolute ($e$) humidity of air, wind velocity ($V$), and density of water vapor column of the atmosphere ($W$), as well as the Angstrom parameter ($\alpha$)] is more complicated. The absence of correlation between $\tau^a_\lambda$ and parameters $R$ and $V$ is obvious, while for the parameter $\alpha$ the weak negative correlation can be observed. As to the remaining meteorological parameters ($T$, $e$, and $V$), the correlation with these parameters is significant, and it increases monotonically going from $\tau^a_{1.0}$ in the IR to $\tau^a_{0.48}$ in the short–wave portion of the visible range. This peculiarity can be explained by a stronger dependence of a small–size aerosol on meteorological situation. The maximum correlation (to 0.547) is typical of water vapor column density $W$. This is caused by the fact that both $W$ and AOD are integral characteristics of the whole atmospheric column.

However, the significance of the correlation coefficients observed does not enable one to find simple unique relationships. A synoptic period of $\tau^a_\lambda(t)$ variability presented in our results (not discussed in this paper) allows us to assume that the most probable explanation for the significant correlation (with the parameters $T$, $e$, and $V$) is the change of air masses, each of which is characterized by its own set of optical and meteorological parameters.

Disagreement between the results obtained by different authors (see, e.g., Refs. 11 and 12) concerning the correlation between $\tau^a_\lambda$ and meteorological parameters does not allow an objective comparison to be performed, therefore further studies using, first of all, synoptic information are needed.

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