ENHANCEMENT OF THE TURBIDITY OF THE ATMOSPHERE OVER THE ATLANTIC IN THE POST MT. PINATUBO ERUPTION PERIOD

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The results of investigations of the atmospheric optical depth in the spectral range 0.447 *to* 1.061 μm *carried out in some regions over the central Atlantic after Mt. Pinatubo eruption are discussed. These results clearly show that an essential increase of the atmospheric turbidity took place over the Atlantic due to the eruptive cloud of atmospheric aerosol. The strongest changes of the atmospheric optical depth occurred in the short–wave region of the spectral range under study.*

As known, the powerful volcanic eruptions (Agung – 1963, Fuego – 1971, El–Chichon – 1982, and others) resulted in substantial and long–term variations in turbidity of the atmosphere on a planet scale thus changing its radiative regime and climate.[1,2] The eruption of Mt. Pinatubo volcano on June 15, 1991 should be classified as one of the most powerful eruption known in the last decades.[3] The high–power eruptions are characterized by the three basic stages of volcanic aerosol evolution. The first stage is specified by an explosive emission of SO_2, ashes, and other components into the atmosphere which then propagate over the Earth under the effect of stratospheric transport (for Mt. Pinatubo eruption it took a three–week period). The second stage can be described by latitudinal expansion of the volcanic layer, physicochemical transformations of volcanic products and their maximum concentrations in the stratospheric layer during 2 to 3 months. The third stage is marked by slow (to an year and longer) relaxation of the stratospheric volcanic layer to the initial "background" state.

Our measurements of the aerosol optical depth (AOD) of the atmosphere were carried out at the second stage where the stratospheric volcanic layer with maximum concentrations within 20°South – 30°North had already been formed in the atmosphere.[4]

The AOD investigations were made from board the research vessel "Akademik Vernadskii" (its 43 rd mission) from July 4 to October 2, 1991 within 25–42°North in some regions of the Central Atlantic (Fig. 1). An automated wide–range (0.4–12 μm) solar photometer[5] was used in the measurements. The instruments were calibrated by the "long" Bouguer method using a specially developed algorithm. The Rayleigh and gas components of the optical depth (Table I) were determined based on the LOWTRAN–7 model taking into account the light filter contours, the Sun spectrum, and the photodetector spectral sensitivity. This paper is concerned with the preliminary analysis of the results only for shortwave spectral regions. It should be noted that the results for 869 and 1061 nm channels must be refined within 0.01–0.04 accuracy.

To provide calibration the repetition frequency of measurements during a day was irregular, i.e., from 5–15 min^{-1} at lower Sun to 40–60 min^{-1} at noon. Therefore for the results to be statistically processed the individual AOD measurements during two hours were averaged.

Preliminary analysis of data made it possible to divide the entire region into three districts characterized by different optical weather:

I. The Canary polygon being 600–1500 km from the Western coasts of Sahara (region 1).

II. The open ocean in the Central Atlantic (regions 2 and 4).

III. The coasts of North America (regions 3 and 5).

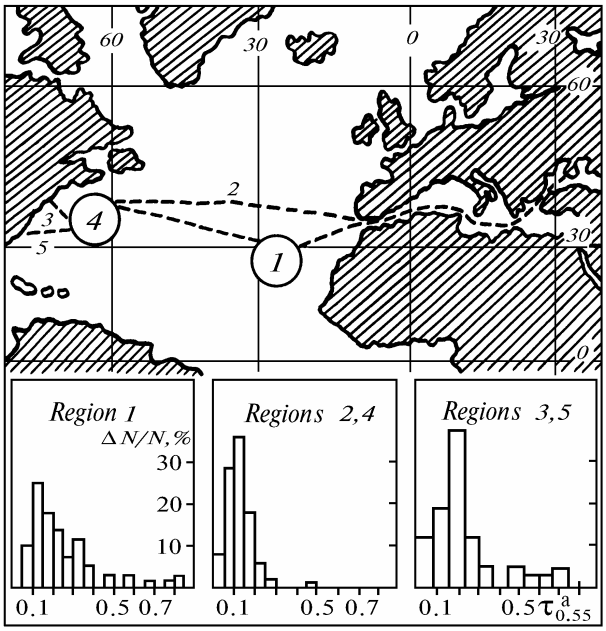

FIG. 1. Navigational chart showing the regions of our experiments carried out during the 43 rd *mission of the vessel and histograms of the AOD recurrences (1 – the Canary polygon, 2 – the Central Atlantic, 3 – Man Bay, 4 – "Gulf–stream" polygon, and 5 – Chesapeake Bay).*

TABLE I. Characteristics of spectral channels.

λ, nm	447	484	552	674	869	1061
$\Delta\lambda_{0.5}$, nm	38	8	10	12	16	22
$\tau^{Re} + \tau^{gas}$	0.233	0.178	0.127	0.089	0.088	0.074

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TABLE II. Characteristics of the results obtained in the regions.

Region	I. Canary polygon	II. Open ocean	III. Coastal regions	IV. Entire passage
Coordinates of the regions	25–33°North 22–31°West	33–41°North 15–68°West	36–42°North 68–76°West	25–42°North 15–76°West
Date	July 4–August 3	August 4–10 August 17 – September 8 September 19–26	August 11–16 September 9–18	July 4 – September 26
The number of days	28	32	14	74
The number of AOD spectra averaged over 2–h periods	125	117	43	286

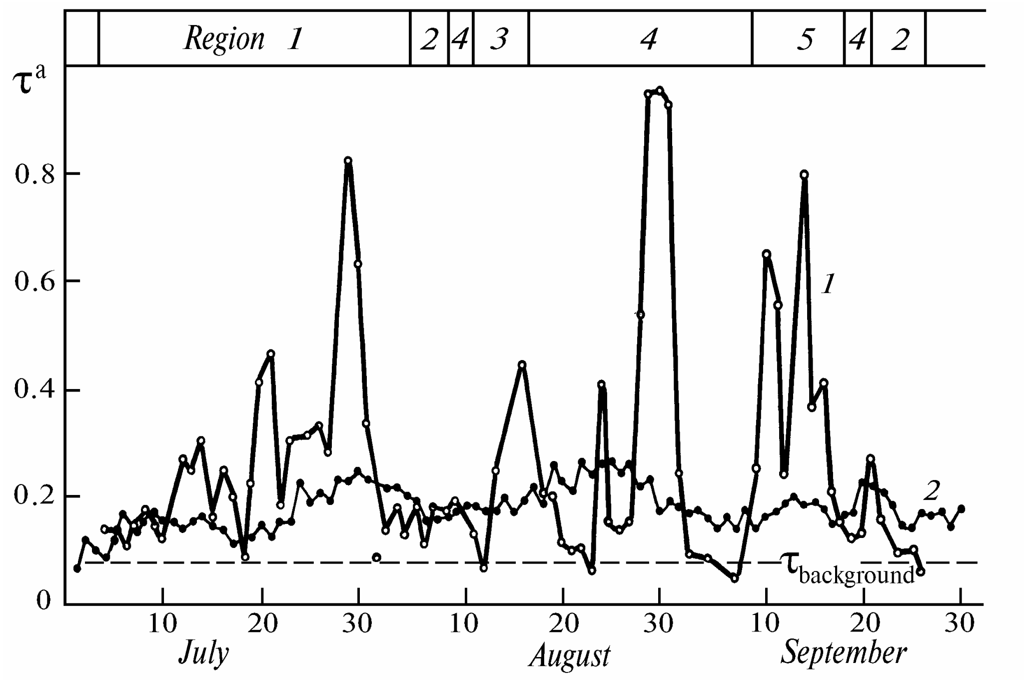

FIG. 2. Dynamics of temporal AOD variability of the marine atmosphere based on shipborne (curve 1, λ = 0.484 μm) and spaceborne (curve 2, NOAA–11, λ = 0.5 μm, 20–30°North, Ref. 4) measurements.

Characteristics of the regions and statistical support of the experimental results are given in Table II.

The general behavior of the AOD variability (λ = 484 nm) is depicted in Fig. 2. There also the satellite (NOAA–11, λ = 0.50, Ref. 4) AODs of the marine atmosphere at 20–30°North averaged over the entire planet are presented. Due to different scales of spatiotemporal averaging the satellite data and those obtained onboard the vessel are not expected to fully coincide. Nevertheless, over the regions far from a continent (the Northern part of the Canary polygon and the Central Atlantic, in the first decades of July and August) the results coincide sufficiently well at the local and global levels.

This figure shows that during the entire period of measurements the atmospheric turbidities were higher than the level of the background state for the open ocean (0.07–0.08, Refs. 6 and 7). The largest AODs of the atmosphere were observed on 14, 20–23, and 30 July near Western Africa, on 16, 29–31 August and 10, 11, and 14 September near North America. The AOD values on those days exceeded 0.3, i.e., they were 1.5–2 times greater than the corresponding values from the models of the marine atmosphere available. To evaluate the effect of the volcanic layer correctly the situations with a foggy haze in the lower layer of the atmosphere were excluded from the analysis. Let us analyze the AOD statistics of the marine atmosphere in the aforementioned regions separately.

In the region of the Canary polygon the spatiotemporal variability of the atmospheric turbidity was formed by two basic factors: the action of North–West emissions from Sahara which is characteristic of this region and the contribution from the aerosol and gas volcanic layer. It is not inconceivable that in spring––summer period of 1991 the fire emissions from Kuwait had significant impact on the atmospheric turbidity. These factors are difficult to be reliably separated without some additional information.

Comparing the statistical AOD parameters (Table III) we see that the region of the Canary polygon is marked by maximum turbidities in the IR spectral region and low selectivity of spectral behavior (Fig. 3) which is usually characterized by the Angström parameter α (α is the parameter entering into the Angström approximation formula $\tau_\lambda^a \sim \lambda^{-\alpha}$ and depending on aerosol particle size distribution). Small α values can be explained by an enhanced content of the coarse aerosol fraction in the aerosol ensemble, i.e., the dust from Sahara is most likely to be present in this region. However, it should be noted that the region under study is in the periphery of dust emissions from Sahara (10–30°North, Ref. 8), therefore its effect must be primarily observed in the southern part of the polygon.

TABLE III. Statistical characteristics of the AOD in the post–volcanic atmosphere of the Central Atlantic.

Number of region	λ, nm	$\overline{\tau}^a_\lambda$	σ_s	$\sigma_s/\overline{\tau}$	τ_{min}	τ_{max}	α
	447	0.253	0.161	0.637	0.077	0.847	
	484	0.250	0.161	0.645	0.064	0.845	
I	552	0.236	0.157	0.665	0.070	0.818	0.71
	674	0.181	0.150	0.828	0.031	0.750	
	869	0.132	0.144	1.087	–0.014	0.685	
	1061	0.161	0.137	0.852	0.005	0.746	
	447	0.426	0.231	0.542	0.141	0.847	
	484	0.424	0.232	0.548	0.146	0.845	
I*	552	0.411	0.224	0.544	0.137	0.818	0.39
	674	0.357	0.210	0.588	0.097	0.750	
	869	0.302	0.198	0.655	0.050	0.685	
	1061	0.331	0.188	0.567	0.090	0.941	
	447	0.140	0.083	0.594	0.035	0.698	
	484	0.140	0.077	0.550	0.032	0.657	
II	552	0.123	0.064	0.518	0.032	0.465	1.15
	674	0.085	0.055	0.647	0.013	0.280	
	869	0.040	0.048	1.217	–0.032	0.215	
	1061	0.076	0.041	0.541	0.018	0.256	
	447	0.301	0.218	0.725	0.055	0.902	
	484	0.287	0.200	0.697	0.050	0.846	
III	552	0.232	0.164	0.704	0.046	0.705	1.83
	674	0.158	0.117	0.736	0.014	0.487	
	869	0.068	0.076	1.122	–0.029	0.271	
	1061	0.080	0.054	0.679	0.004	0.243	

The latter assumption can be confirmed if we analyze the latitude dependence of AOD based on shipborne measurement data (Fig. 4) and satellite data[4] on the mean values of τ^a_{NOAA} for 20–30° and 10–20°North. As the satellite measurements showed, the increase in turbidity reached ~ 0.01 per one latitude degree. The results obtained from the vessel revealed that during the period from July 10 till July 31 when the vessel sailed to the southward the latitudinal gradient was 0.04 (without regard for bursts τ^a – 0.03), i.e., an obvious action of a local factor on the atmospheric turbidity, the approaching to the zone of dust emissions from Sahara, took place.

On the way of the vessel back to the North latitudes (32°North, August, 1–2) the atmospheric optical depth returned to its initial values at the level of 0.1. Thus the postvolcanic increase of the mean atmospheric turbidity for the Northern part of the polygon did not exceed 0.03–0.05 and the total commensurable action of the volcanic layer and tropospheric emissions of dust from Sahara in the Southern part (25–26°North) resulted in the AOD increase, on the average, to 0.4 with extremal turbidities of more than 0.7.

Histogram of the AOD recurrences (Fig. 1) is broad with the most probable values of turbidity being in the region 0.1–0.15. In the range of AOD values 0.3–0.35 there is the second maximum. The same peculiarity can also be found in Fig. 2. These are bursts of atmospheric turbidity $\tau^a_{0.55} > 0.3$ with 7–9 day period. Periodic increases in the atmospheric AOD exceed the synoptic scale of variability and can be caused by a cyclic character of dust emissions or peculiarities in the evolution of the volcanic layer. To analyze this fact we examined the spectral AODs observed during the events of increased turbidity (collection of data I* in Table III). The Angström parameter for these situations was about 0.39 what corresponds to a quasineutral spectral behavior of AOD. Thus the bursts of atmospheric turbidity can be explained by the coarse aerosol fraction and their most probable source is dust emission.

The atmosphere over open ocean is characterized by the AOD values that occurred to be minimum for the whole 43 rd mission of the vessel in the IR spectral range with a relatively selective spectral behavior (Table III and Fig. 3). By way of example, Fig. 3 depicts a mean spectral behavior of AOD obtained from our measurements in the Central Atlantic in 1989 ($\overline{\tau}^a_{0.55}$ = 0.078, $\overline{\alpha}$ = 0.57). The values close to ours are also given in Ref. 7 for the Pacific Ocean ($\overline{\tau}^a_{0.55}$ = 0.07, $\overline{\alpha}$ = 0.4). Since these measurements were made in the "intervolcanic" period their results can be related to a background state of the atmosphere of the open ocean. Comparison of the curves $\tau^a(\lambda)$ 1 and 2 shows that the largest variations in AOD occurred in the short–wave spectral range. The same also follows from a twofold increase (from 0.57 to 1.15) of the Angström parameter.

To evaluate the AOD spectral behavior of the volcanic layer let us use the spectral behaviors $\tau^a(\lambda)$ of the background (1989) and postvolcanic (summer 1992) atmosphere over the ocean. Subtraction of the two spectra gives for $\tau^{volc}(\lambda)$ (dashed curve in Fig. 3) the spectral dependence with very high selectivity (α^{volc} = 2.45) what is indicative of enhanced content of small particles in the layer. It should be noted that the obtained estimate for α^{volc} exceeds significantly the mean values of the Angström parameter for the continental atmosphere which is enriched with a submicron aerosol fraction as compared to the marine one (α^{cont} = 1–1.7).

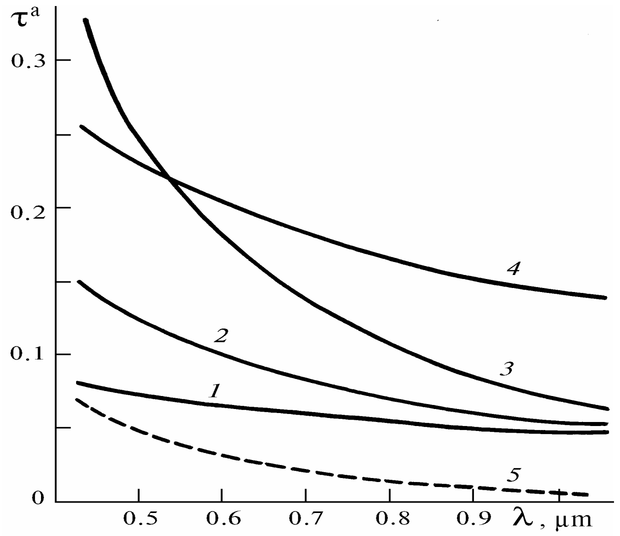

FIG. 3. Mean spectral AOD dependences in the oceanic atmosphere in different regions: background (open ocean (1)) and postvolcanic (open ocean (2), coastal regions (3), and Canary polygon (4)) states and τ(λ) of the volcanic layer (5).

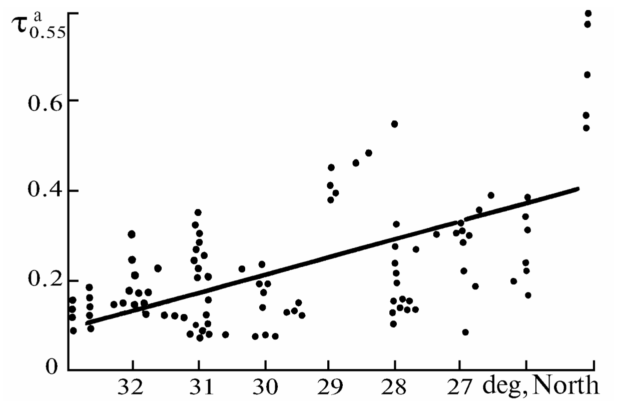

FIG. 4. Latitudinal dependence of $\tau^a_{0.55}$ variability at the Canary polygon.

The histogram of recurrences of $\tau^a_{0.55}$ in the open ocean preserved a relatively narrow single–mode character but the most probable values displaced from 0.05–0.08 (Refs. 6 and 7) to ~ 0.12 (Fig. 1).

Atmosphere over the coastal regions of North America was characterized by increased turbidity in the short–wave spectral region due to joint action of submicron aerosol both in the stratospheric layer and in the continental aerosol of the tropopause. The Angström parameter near the continent takes maximum values ($\alpha = 1.83$) thus showing high selectivity of the spectral behavior. It should be noted that in the IR range the AOD values are commensurable with those in the atmosphere over the open ocean, and in the violet spectral range they exceed the corresponding values τ^a for the most turbid atmosphere of the Canary polygon. The coastal regions are also distinguished by higher variability of the turbidity (σ_s and $\sigma_s/\bar{\tau}$) even under conditions when no fogs or haze occur.

The histogram of recurrences $\tau^a_{0.55}$ demonstrates high probability of the turbidity within the region 0.15–0.25 and a long–term "plume" of equally probable values up to very high $\tau^a_{0.55} = 0.75$.

The analysis of AOD of the marine atmosphere makes it possible to draw the following conclusions:

1. Formation of the stratospheric volcanic layer after the eruption of Mt. Pinatubo volcano resulted in a substantial increase of the atmospheric turbidity over all regions of the Central Atlantic.

2. The greatest changes of the atmospheric AOD occurred in the short–wave spectral range (e.g., the Angström parameter for the open ocean increased by a factor of two from 0.4–0.6 to 1.15) what is indicative of the situation where a submicron aerosol fraction dominated in the volcanic layer.

3. The effect of the stratospheric layer in the "coastal" regions turned out to be obscured but commensurable with the contributions from local sources, i.e., different emissions of continental aerosol.

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