About investigation results on the atmosphere aerosol optical depth in circumnavigation around Antarctica (the 53d RAE)

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The results are presented of new cycle of investigations of the aerosol optical depth (AOD) of the atmosphere, carried out aboard of the research vessel *Akademik Fedorov* at the first stage of the 53d Russian Antarctic Expedition (November, 2007 – March, 2008). Statistical characteristics of spectral AOD, Angström exponent and columnar water vapor of the atmosphere in some regions of Southern Hemisphere are discussed. Generalized data on latitudinal dependence of aerosol turbidity over ocean, obtained in several expeditions, are presented. The data show a linear decrease of AOD by approximately 5 times during moving from equator to Antarctica. It is noted than AOD of the atmosphere near Antarctica in the post-volcanic period (1995–2008) is characterized by stably low values (about 0.025) in the center of the visible range at a value of spatial-temporal variability (rmsd) of 0.01–0.02.

Two approaches are combined now in investigations of the aerosol optical depth over ocean: the global coverage and regular manner of satellite observations (AVHRR/NOAA, MODIS, MISR, etc.[1–4]), including episodic, but more precise measurements aboard a ship.[5] Thus, ship-based measurements of the atmosphere AOD continue to play an important role in decreasing the deficiency of the data on the aerosol radiative properties in different regions of the World Ocean. In order to integrate and systematize measurements, as well as to standardize the processing of data, the AERONET Maritime Aerosol Network website (http:// aeronet. gsfc.nasa.gov /new_web /maritime_aerosol_network. html) was created,[6] where the measurements of AOD are presented with calibration references to the AERONET technique.

In connection with International Polar Year, observations of AOD in the cleanest regions of the planet, such as South Ocean and Antarctica, have gained the especial importance. Investigations in the region of Antarctica make it possible to estimate tendencies in the change of global aerosol background under conditions of the increasing anthropogenic loading and climate changes. In this paper we discuss the results of measurements of the atmospheric AOD in winter 2007/2008 at the first stage of the 53d Russian Antarctic Expedition onboard the research vessel *Akademik Fedorov*.

1. Characteristics of experiments

The portable sunphotometer Microtops II [Ref. 6], supplemented by the coordinate meter GPS-12, was used in measurements of the atmosphere spectral transparency. Specifications of the Microtops II are the following: the angle of the field of view is 2.5°, maxima of the transmission bands of the light filters are 440, 500, 675, 870, and 940 nm, the error in measuring is 1%. Before the expedition, the device was calibrated by means of comparison with the network photometer Cimel CE-318. The atmospheric AOD and columnar water vapor (from the recorded signals of the transparency) were calculated upon the standard technique accepted in AERONET.[8] Photometric measurements were conducted as short series (5–15 readings) under conditions of the free-of-cloud sun. When analyzing the obtained data, daily average values of AOD τ^a_λ, as well as the Angström exponent α, which characterizes the selectivity of the spectral dependence of AOD, were used:

$$\tau^a(\lambda) = \beta\lambda^{-\alpha}. \quad (1)$$

The parameters α and β were calculated by the least squares method after taking logarithm of the relation (1) in wavelength range 440–870 nm.

As for the β, let us remind[9,10] that it is mainly determined by the content of large aerosol particles in the atmosphere and can be used for estimation of the coarse component of AOD τ_c ($\beta \approx \tau_c$).

The route of the vessel (Fig. 1) included crossing the Atlantic Ocean (Saint Petersburg – Cape Town) and the circumnavigation around Antarctica with approaches to Russian Antarctic stations, Australia (Melbourne) and South Africa (Cape Town).

Measurements started on November 16, 2007 near Gibraltar and finished on March 6, 2008 near Cape Town. The total data array, obtained during 69 days, consists of 3549 individual readings, 300 hourly

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average spectra of AOD. The manner of variations of the atmospheric AOD and columnar water vapor during the whole period of measurements is shown in Fig. 2. The increase of the aerosol turbidity in the northern trade wind zone (dust emissions from the Sahara) and at approaches to continents (Melbourne and Cape Town) are well seen).

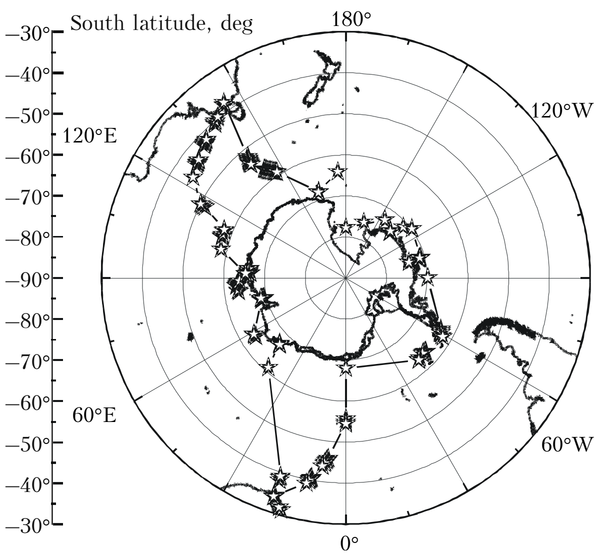

Fig. 1. The route of RV *Akademik Fedorov* at the first stage of 53d RAE (asterisks mark the regions of measuring AOD).

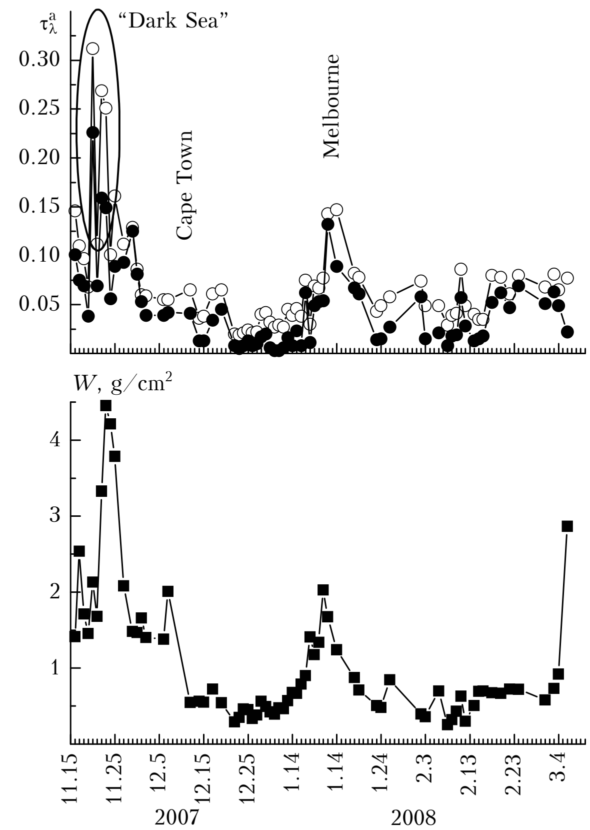

Fig. 2. Variations of AOD (440 and 870 nm) and columnar water vapor of the atmosphere during the measurement period.

The most part of data was obtained at latitudes higher than 35°S (52 measurement days) and near Antarctica (34 measurement days). Five regions (data subarrays) were selected for analysis of the data obtained in the Southern Hemisphere: 1) South Ocean (at latitudes higher than 55°S, beyond the coastal zone); 2) coastal (~100 miles) zone of Antarctica; 3) the station Mirny; and the ship passages in moderate latitudes; 4) Antarctica – Melbourne; 5) Antarctica – Cape Town. The characteristics of the data obtained in these regions are presented in Table 1.

Table 1. The quantity of data obtained in different regions

region	Individual series	Days of measurements
1. South Ocean	241	7
2. Antarctica (~100 mile zone)	1723	34
3. station Mirny	506	4
4. passage to Melbourne	430	7
5. passage to Cape Town	171	11

2. Discussion of results

2.1. Statistical characteristics

The calculated characteristics of the selected regions (Table 2) evidence small aerosol turbidity of the atmosphere at high latitudes of the Southern Hemisphere and are in agreement with previous results.[11–13] The well known zonal dependence of the columnar water vapor of the atmosphere is observed, i.e., the decrease of the moisture with latitude (W in the mid-latitudes is about 1.4 g/cm^2, and 0.5 g/cm^2 near Antarctica). The same dependence is also the characteristic of AOD (see below in detail).

The data presented at the site of Maritime aerosol network and in the review[14] made it possible to compare the obtained values of AOD near Antarctica with data of other researches in these region (Fig. 3).

It follows from the presented results that mean values of AOD at a wavelength of 500 nm at high latitudes of the Southern Hemisphere vary in the range ~0.02–0.08. The lowest AOD values (0.015) are observed over continental regions of Antarctica,[14] and the highest values refer to the ocean mid-latitudes. For example, mean τ^a_{500} over Amsterdam island is about 0.08 (http://aeronet.gsfc.nasa.gov). The results of measurements of AOD in 53d RAE lie in the center of this range and are in agreement with the data of other scientific groups in Antarctica.

Let us consider two peculiarities in AOD characteristics observed at high latitudes (> 65°S). The minimal average AOD values (even lower than at South Pole[14]) were recorded near station Mirny. However, because of short period of observations, this property, most likely, is a favorable concurrence of circumstances, but not the characteristic of this region.

Table 2. Statistics of AOD and atmospheric moisture content at the Southern Hemisphere

Region	Parameter						
	τ^a_{440}	τ^a_{500}	τ^a_{675}	τ^a_{870}	α	$\beta(\approx\tau_c)$	W, g/cm^2
1. South Ocean	0.056 ± 0.015	0.035 ± 0.017	0.035 ± 0.018	0.031 ± 0.021	0.95 ± 0.74	0.028 ± 0.020	0.69 ± 0.11
2. Antarctica	0.043 ± 0.019	0.027 ± 0.020	0.024 ± 0.019	0.022 ± 0.019	1.16 ± 0.63	0.018 ± 0.018	0.51 ± 0.14
3. station Mirny	0.028 ± 0.003	0.011 ± 0.004	0.008 ± 0.003	0.005 ± 0.002	2.38 ± 0.47	0.003 ± 0.002	0.44 ± 0.04
4. passage to Melbourne	0.078 ± 0.034	0.059 ± 0.031	0.064 ± 0.034	0.061 ± 0.036	0.35 ± 0.39	0.059 ± 0.036	1.35 ± 0.41
5. passage to Cape Town	0.075 ± 0.027	0.056 ± 0.025	0.058 ± 0.029	0.055 ± 0.031	0.46 ± 0.52	0.052 ± 0.031	1.45 ± 0.65
Total data (>55°S)	0.046 ± 0.019	0.029 ± 0.019	0.026 ± 0.019	0.024 ± 0.019	1.14 ± 0.65	0.020 ± 0.018	0.54 ± 0.15

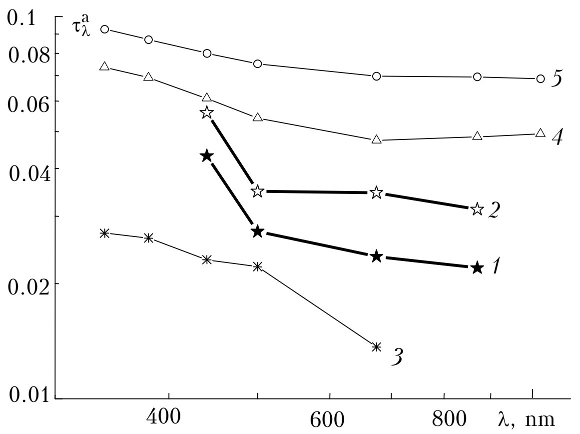

Fig. 3. Mean spectral dependences $\tau^a(\lambda)$ over South Ocean (*1*); near Antarctica (*2*) in comparison with the data of AERONET (http://aeronet.gsfc.nasa.gov): South Pole 90°S, 70°E (*3*); Crozet island 46°S, 51°E (*4*); Amsterdam island 37°S, 77°E (*5*).

The second peculiarity is related with relatively great values of the Angström exponent (index of selectivity) near Antarctica (subarrays 2 and 3) in comparison with clean regions of the World Ocean, where α value is, on the average,[10,15] 0.4–0.6. The data of observations at other Antarctic stations[14] also evidence great values of the Angstrom exponent, comparable with the continental data (α ~ 1.3). According to them, average values of α lie in range from 0.73 to 1.75. The main reasons of the enhanced α can be the following.

First, the value of α mainly depends on the ratio of the optical contributions into AOD of fine (submicron) and coarse aerosol.[9] The fraction of the coarse aerosol generated by sea surface under conditions of the open ocean (subarrays 1, 4, and 5) ($\tau_c \approx$ 0.03–0.06) is relatively large (for example, no less than 50% at a wavelength of 440 nm). Therefore, α values are small. The content of marine aerosol decreases in the regions, covered with ice (2 and 3) ($\tau_c \approx$ 0.003–0.018), in comparison with the fine aerosol, that leads to increase of the selectivity index.

Second, it follows from the shape of the spectral dependence $\tau^a(\lambda)$ (see data of the 53d RAE in Fig. 3) that the selectivity is mainly observed at the first part of 440–500 nm region because of the enhanced values at λ = 440 nm (or decreased values at λ = 500 nm). This means that the systematic error, i.e., the overestimation of AOD at 440 nm can cause a false increase of α values at small values of AOD close to the error in its determination (~ 0.01–0.02).

In principle, there may be physical reasons of appearance of AOD selectivity only in range 440–500 nm: such behavior of $\tau^a(\lambda)$ can be realized at low concentrations of fine aerosol and/or less size of this fraction of particles in the Antarctic atmosphere. In this case, the fall in selectivity of AOD with growing λ, caused by the fine aerosol, practically stops in the middle of the visible wavelength range.

Additional investigations are necessary for clarification and justification of true reasons of the noted peculiarities in the $\tau^a(\lambda)$ spectral behavior, desirably at a greater number of wavelengths in the violet spectral range.

2.2. AOD spatial distribution in the atmosphere

Measurements of AOD and columnar water vapor during circumnavigation in South Ocean made it possible to consider their longitudinal distributions. It follows from the results shown in Fig. 4 that the greater turbidity of the atmosphere is observed in the Western Hemisphere (Pacific sector). For example, AOD values at 440 nm are (mean ± rmsd): 0.034 ± 0.013 in the Eastern Hemisphere and 0.055 ± 0.02 in the Western one. This difference is statistically significant with confidence probability more than 0.999. Such a peculiarity is not observed for the columnar water vapor of the atmosphere.

However, the presence of latitudinal dependence of $\tau^a(\varphi)$ over the ocean in the Southern Hemisphere is more evident (it was mentioned for the first time in Ref. 13). New results make it possible to refine and generalize the aforementioned regularity, taking into account the data of four expeditions: the 19th cruise of RV *Akademik Sergey Vavilov*, as well as the 51st, 52nd, and 53d RAEs (Fig. 5).

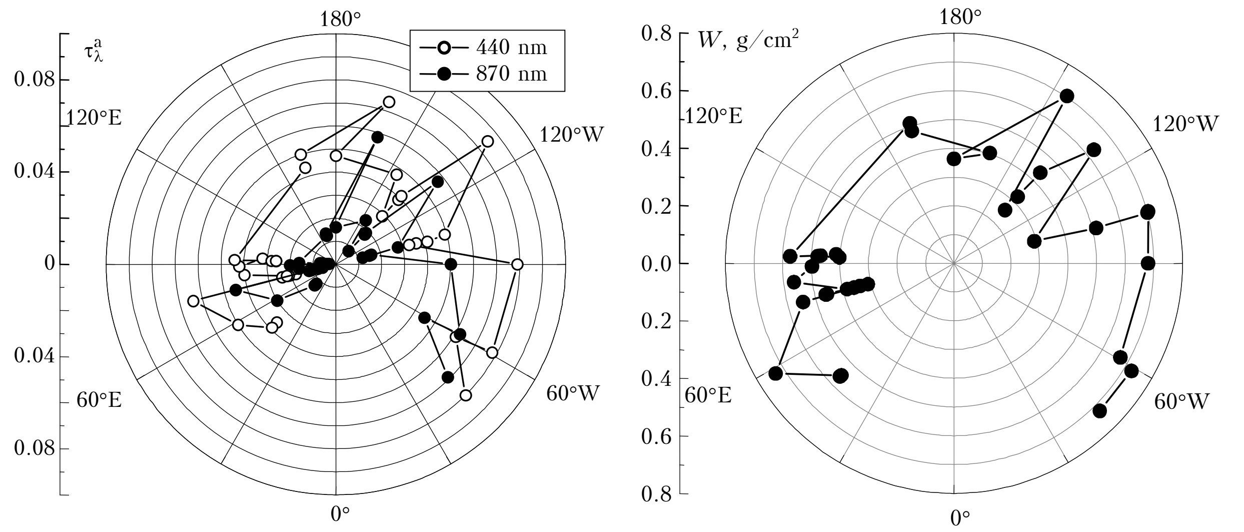

Fig. 4. Longitudinal distribution of AOD and columnar water vapor of the atmosphere at high latitudes of the Southern Hemisphere.

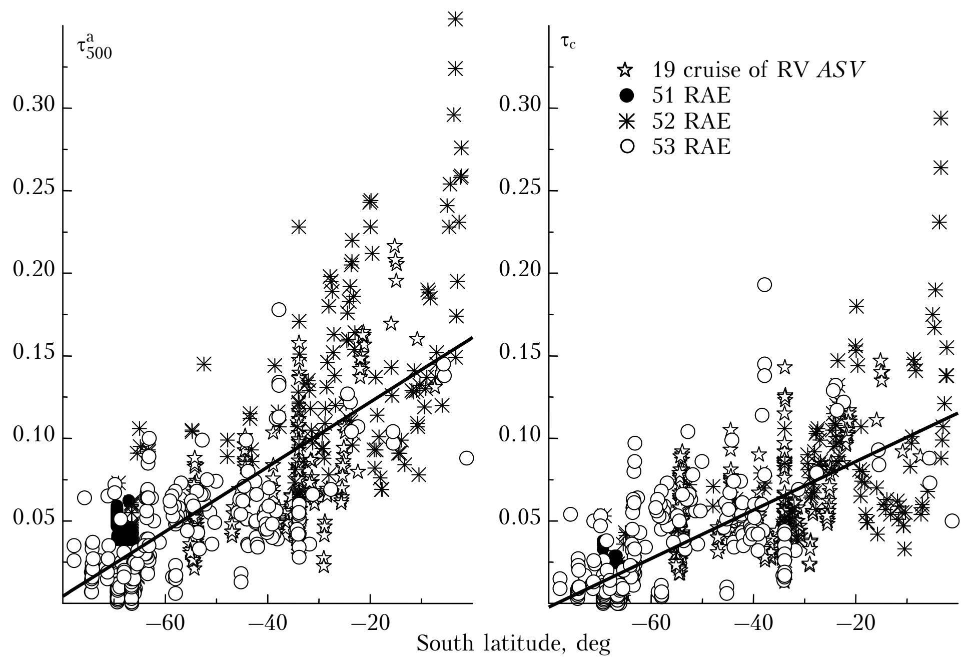

Fig. 5. Latitudinal behavior of AOD (τ_{500}^a and τ_c) and linear fitting of their latitudinal dependence.

The decrease of the aerosol turbidity, when moving from equator, is observed at all wavelengths and two components of AOD, caused by the fine and coarse aerosol. For example, AOD in the middle of the visible wavelength range decreases by 5 times, from 0.16 in tropics to ~0.03 near Antarctica. The comparison of linear approximations of $\tau^a(\varphi)$ for different expedition has shown that the difference between them is small and is caused by different latitude measurement range, and some differences in the aerosol turbidity in different periods. It is also important to emphasize that the latitudinal decrease of AOD is also observed in the Pacific sector of South Ocean.

The generalization of results of several expeditions has confirmed that the linear latitude dependence can be applied to model description of the τ_λ^a spatial distribution over ocean in the Southern Hemisphere (beyond coastal zones), which for the central part of the visible range takes the form:

$$\tau_{500}^a(\varphi) = \tau_{500}^a(0°) - k\varphi° = 0.161 - 0.002\varphi°. \quad (2)$$

The error of the empirical dependence is 0.021.

2.3. Comparison with long-term data on AOD over Antarctica

It was interesting to compare the results of measurements of AOD aboard RV *Akademik Fedorov* near Antarctica (approximately in 100-mile zone) with data of stationary observations at the station Mirny.[14,16] Mean values of AOD at 500 nm obtained in the 51st, 52nd, and 53d RAEs are shown in Fig. 6, as well as the long-term behavior of AOD at the station Mirny.

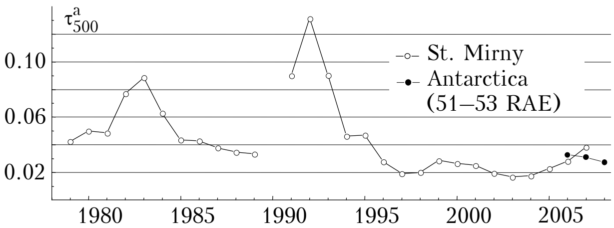

Fig. 6. Long-term variability of AOD of the atmosphere over the station Mirny and average data of ship-born measurements near Antarctica in 51–53 RAEs.

The well-known peaks of the aerosol turbidity after Mt. El-Chichon (1982) and Pinatubo (1991) eruptions are well seen. If to exclude the periods of volcanic disturbances, then a small negative trend of the long-term variability by approximately 2.4% is observed (see Ref. 14 for detail), i.e., the level of the global background aerosol, at least has not been increased for the last 30 years.

It is seen that in the post-volcanic period (1996–2008) the AOD is characterized by quite low values (0.024 ± 0.006) without some significant trend. It is seen in Fig. 6 that average AOD values at the station Mirny somewhat differ from the data of ship-born measurements. The greatest difference ($\Delta\tau$ less than 0.01) can be explained by different periods and regions of measurements: annual averaging in one case (st. Mirny) and spatial-temporal averaging in the coastal zone during shorter periods in another case. It can be concluded that the values of inter-annual variations (rmsd) and spatial inhomogeneities of AOD near the coast of Antarctica (see also Table 2) are comparable and do not exceed 0.02 in the middle of the visible wavelength range.

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