Exploiting the synergy of GOME and ATSR-2 for the retrieval of aerosol properties over land and ocean

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Abstract

Currently satellite observation of aerosols is limited to either the oceans or to UV-absorbing aerosols. To overcome these restrictions the new aerosol retrieval method SYNAER (SYNergetic AErosol Retrieval) was developed within the ESA-AO2 project PAGODA (Project for ATSR and GOME Data Application). SYNAER delivers boundary layer aerosol optical thickness (BLAOT) and type over both land and ocean, the latter as BLAOT percentage contribution of 10 representative components from the OPAC (Optical Parameters of Aerosols and Clouds) dataset. The high spatial resolution of ATSR-2 permits cloud detection, BLAOT calculation over automatically selected dark pixels and surface albedo correction for a set of different boundary layer aerosol mixtures. After spatial integration to GOME pixels these parameters are used to simulate GOME spectra for the same set of different aerosol mixtures. A least square fit of these spectra to the measured spectrum delivers the BLAOT value and - if a uniqueness test is passed - the aerosol mixture. Within the ESA-AO3 project PAGODA-2 (Extending the Applicability of New Methods from PAGODA) SYNAER will be validated. First case studies using ground based sun-photometer measurements of the spectral aerosol optical thickness from NASA's Aerosol Robotic Network (AERONET) show a good agreement.

Introduction

Aerosol particles affect climate directly by interacting with solar and terrestrial radiation and indirectly by their effect on cloud microphysics (aerosols act as cloud condensation nuclei), albedo and pre-cipitation [Refs. 9, 10]. Tropospheric aerosol forcing is comparable to global net cloud forcing of approximately -1 Wm^{-2} [Ref. 1]. However, on regional scale the mean direct radiative forcing by aerosols can be as large as -10 Wm^{-2} (mineral dust over ocean [Ref. 24]). Anthropogenic changes of the global aerosol distribution may delay or temporarily mask greenhouse warming. Our understanding of aerosol impact is extending beyond the sulfate aerosol which has been used as sole aerosol component in climate models upto now: It is recognized that smoke aerosol and mineral dust are equally important and may regionally enhance greenhouse warming. For a review of aerosol impact on climate see Charlson and Heintzenberg [Ref. 1].

In order to assess the impact of aerosols on climate there is thus a growing need for more detailed information on the aerosol spatial distribution and variation together with its composition. More specifically, we need to know aerosol optical thickness (AOT), its absorption, scattering properties, vertical profiles, size distributions and chemical composition. Currently there is only limited capability for aerosol moni-toring. Available products are restricted to the oceans (NOAA [Refs. 8, 22]; planned: GOME/SCIAMACHY [Ref. 3]), UV absorbing aerosols (TOMS [Ref. 4]) or the stratosphere (SAGE). With the exception of singular case studies only values of the aerosol optical thickness can be derived so far.

Within the next few years a number of new spaceborne instruments promises a large step forward in the aerosol monitoring capabilities. Among these are SCIA-MACHY and AATSR onboard ENVISAT (with their predecessors GOME and ATSR-2 onboard ERS-2), POLDER, TOMS and OCTS onboard ADEOS-2 (ADEOS-1 was active for 8 months in 1996/97) and MISR and MODIS onboard the EOS-AM-1. In principle aerosol retrieval can be exhibited by inversion from data of several groups of sensors: (1) Multispectral near nadir viewing (MODIS [Ref. 23]; SCIA-MACHY), (2) multiangle, multispectral viewing (MISR [Ref. 11]; AATSR), (3) multiangle, multispectral viewing with polarization (POLDER [Ref. 16]), (4) limb viewing (SCIAMACHY, SAGE). A detailed summary of the current status and plans on aerosol retrieval can be found in Kaufman et al. [Ref. 12].

In order to overcome restrictions due to current monosensoral methods a new synergetic aerosol retrieval method was developed at the German Remote Sensing Data Center (DFD) of the German Aerospace Center (DLR).

The new method

ATSR-2 measures radiances in 7 spectral bands with a ground resolution of approximatelly 1.1 km. GOME observes near-nadir reflection in the range from 240 nm to 790 nm with a spectral resolution of 0.2 nm to 0.4 nm and a pixel size of 320 x 40 km^2 or 80 x 40 km^2. Both instruments measure the solar illumination regularly . Thus reflectances can be calculated with reduced calibration errors significantly as compared to the use of calibrated radiances.

Aerosol parameters are retrieved from a combination of simultaneous ATSR-2 and GOME data with the software SYNAER (SYNergetic AErosol Retrieval [Refs. 19,7]): First of all a cloud detection is performed for all ATSR-2 pixels. Boundary layer aerosol optical thickness (BLAOT) values are derived from automatically selected dark ATSR-2 nadir pixels (dark forest, water bodies) for which the surface albedo can be estimated with good accuracy. Using the atmospheric correction scheme EXACT [Ref. 18] which has been validated with Landsat-TM and NOAA-AVHRR data, BLAOT can be estimated for the dark fields and interpolated to all cloudfree ATSR-2 nadir pixels. Then the surface albedo values for the 3 wavelengths 560 nm, 670 nm and 870 nm are obtained for all pixels. The ATSR-2 derived data are colocated to GOME pixels and interpolated spectrally. Using the ATSR-2 calculated values of optical thickness and surface albedo, GOME spectra for different mixtures are simulated. A least square fit of the simulations to the measured GOME spectrum results in the selection of the most plausible type of aerosol and its corresponding BLAOT value in a GOME pixel. Finally, an ambiguity test is applied. Figure 1 gives an overview of processing steps in SYNAER.

Clouds are detected by the well established APOLLO (AVHRR Processing Scheme Over CLoud Land and Ocean [Refs. 21, 2, 15]) software extended to ATSR-2 data. APOLLO/ATSR-2 [Ref. 7] exploits reflectances and temperatures in the solar and terrestric spectral range. Five ATSR-2 channels which are equivalent to the AVHHR spectral bands are used for cloud detection. A number of threshold tests is applied to differentiate types of clouds. APOLLO yields cloud fraction, 4 cloud layers and cloud optical parameters.

Dark land ATSR-2 pixels are selected on the basis of the 1.6 μm channel. As the aerosol effect at this wavelength can be neglected for most aerosol types, all cloud/snowfree pixels with a 1.6 μm reflectance below a given threshold are selected. To reject wet bare soil pixels which are also dark in the 1.6 μm channel but brighter in the visible the normalized differential vegetation index (NDVI) must be larger than a preset minimum value. For the pixels selected through this scheme the dark field albedo values at 560 nm and 670 nm can then be estimated from the 1.6 μm reflectance by application of a conversion factor. Kaufman et al. [Ref. 13] suggest a similiar selection scheme based on the 2.1 μm and 3.8 μm channels of the MODIS sensor onboard the EOS-A platform. Water pixels are exploited over deep ocean only with a fixed albedo.

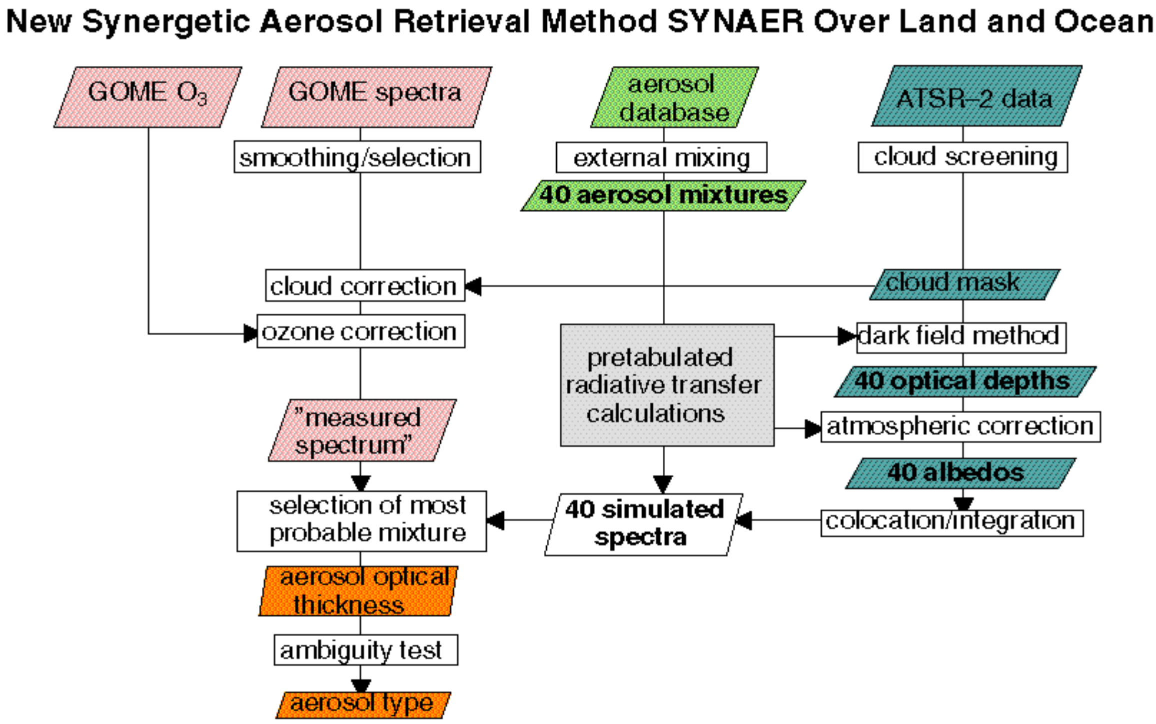

Figure 1: Flow chart of the aerosol retrieval major steps.

The accuracy of the retrieved spectral optical thickness values depends highly on the exact knowledge of the surface albedo of the dark fields and decreases with increasing surface albedo. The BLAOT retrieval based on dark field selection and estimation of their surface albedo values from the 1.6 µm channel shows a significant scatter in the retrieved values of neighbouring pixels. Therefore, a minimum number of adjacent pixels must be exploited to allow for an appropriate averaging. In areas with sparse dark fields singularities must be rejected. To overcome these difficulties dark fields are grouped into 4 different classes with increasing surface albedo, i. e. decreasing retrieval accuracy. For boxes of 25x25 ATSR-2 pixels only dark pixels of the lowest available, i. e. most accurate category are exploited. Furthermore, pixels are rejected if their retrieved values differ by more than the local variance from the average of their neighbourhood. The range for this variance test is increased stepwise until a minimum pixel number guarantees statistical significance.
Aerosol optical thickness and surface albedo values are derived for 40 different boundary layer aerosol mixtures because the retrieved values depend strongly on the type of aerosol. For the modelling of aerosols the external mixing approach [Ref. 25] based on 10 components from the OPAC database (Optical properties of aerosols and clouds [Ref. 5]) is used in the boundary layer. The same set of 40 mixtures is used in the ATSR-2 BLAOT and albedo retrieval and the GOME simulations. For humidity dependent components two models with 50% and 95% relative humidity have been included. The free tropospheric and the stratospheric aerosol are fixed based on World Climate Program [Ref. 25].
In the current version GOME spectra are calculated at 10 wavelengths which are free of severe instrument errors (e.g. noise in band overlap regions) and gas absorption lines. The broad ozone absorption in the Chappuis band is corrected utilizing GOME retrieved ozone columns. The ambiguity test checks if the GOME fit error value of the best and second best mixtures differ at least by a noise induced error value. This test refuses pixels with large cloud fraction, radiometric differences or bright surface because their aerosol sensitivity is low. A

before-hand refusal is impossible because of the complex geometry dependent influence of the interaction between atmosphere and surface on the radiance field.

All radiative transfer calculations are conducted with an iterative code (successive orders of scattering, SOS; [Ref. 17]) which includes full multiple scattering. They assume the surface at sea level. For a fast application the actual radiative transfer calculations in EXACT and SOS are replaced by interpolations using pre-calculated tables.

Nadir and forward ATSR-2 gridded brightness temperature (GBT) products were used but forward reflectances seem to be uneligible for our aerosol retrieval scheme. First validation results have shown no further improvement and sometimes even poor results if the forward reflectances were taken into account. Missregistrations between nadir and forward view in the gridded data product and therefore physical information content of different air masses at one grid point seems to be the reason. Parallax maps of ATSR-2 nadir and forward view were generated to try a stereo approach for cloud detection. With a good co-registration between nadir and forward view these images should possess parallaxes only in flight direction, but the results clearly shows significant parallaxes perpendicular to the flight direction.

Within the project PAGODA-2 (Extending the Applicability of New Methods from the Project for ATSR and GOME Data Application) accepted in the 3. ERS AO we will further improve and validate the aerosol retrieval method. Furthermore, we will investigate the possibilities for aerosol retrieval from partly cloudy GOME pixels in order to assess the interaction between clouds and aerosols directly. The basic idea is to look inside large GOME pixels with the high ATSR-2 resolution and to use the APOLLO derived cloud parameters on the ATSR-2 grid to characterize the cloud influence as it is seen by GOME with high accuracy. Having created cloud-corrected GOME spectra the aerosol retrieval in partly cloudy GOME pixels will be possible. We will also revise the set of predefined aerosol mixtures.

The method will be adapted to similiar sensors AATSR and SCIAMACHY onboard ENVISAT-1 (launch planned end of 2000) and applied within the accepted ENVISAT-AO proposal SENECA (Synergetic ENVISAT Data Exploitation for Cloud, Aerosol and Ozone Retrieval). SCIAMACHY and AATSR provide some valuable additional features for global aerosol monitoring in comparison to GOME and ATSR-2: As far as SCIAMACHY is concerned, there is the wider spectral range (upto 2400 nm, GOME upto 790 nm) which enables a better investigation of the type of aerosol especially for large particles and the additional limb viewing geometry for stratospheric aerosol retrieval. Both AATSR and SCIAMACHY offer an improved data transmission rate with small SCIAMACHY pixels throughout the entire mission and orbitwise AATSR products which will be much easier to handle than ATSR-2 framewise products. Furthermore, other ENVISAT instruments (MERIS, MIPAS) also measure parts of the global aerosol distribution and may be used for comparisons.

First validation results

The validation of SYNAER results has been started. For the first case studies ground based measurements taken by the AERONET (AErosol RObotic NETwork) stations were used. The objective of AERONET [Ref. 6] is to monitor aerosols by ground based spectral radiometers. It was especially designed for the validation needed for all upcoming satellites like ENVISAT, EOS-AM 1 and ADEOS-2 that will be capable of retrieving aerosol information. The measurements are processed in near real-time, archived and made available to the public by NASA’s Goddard Space Flight Center through their www pages (http://aeronet.gsfc.nasa.gov: 8080). AERONET provides spectral aerosol optical thickness (AOT) values and aerosol size distributions taken by automatic sun-sky scanning spectral radiometers since 1993 at approximately 50 ground stations worldwide.

So far, about 2500 GOME pixels were analysed, but only 66 pixels include ground stations inside the pixel boundaries. Additional criteria for validation pixels (cloudfree ground based measurements, less than 15% cloud coverage inside the GOME pixel, a maximum of 15 minutes difference between ground measurement and satellite overpass) left four pixels with corresponding ground measurements of spectral aerosol optical thickness values. For these pixels ground measurements of size distributions are not available.

In all four cases the SYNAER retrieval was driven by land dark fields. The specifications of the four test cases are given in table 1. All GOME pixels have a size of 80x40 km^2. Figure 2 shows the retrieved AOT values at 3 wavelengths against the groundbased sun-photometer measurements from the AERONET database. A good agreement with errors less than 0.05 for the AOT values can be seen. However, for one case the 500 and 870 nm values show a significant deviation indicating the detection of a wrong aerosol mixture. Direct validation of the retrieved mixing contributions of the basic aerosol components is planned through the exploitation of airborne measurements acquired in August 1998.

pixel	1	2	3	4
date	15/8/97	5/10/97	15/11/97	14/7/98
UTC	9:39	9:36	10:24	14:28
latitude	45:18N	45:18N	45:48N	16:00S
longitude	12:30E	12:30E	8:37E	62:01W
altitude	10m	10m	235m	500m
orbit	12129	12859	13446	16898
number	818	589	419	1596
location	Venice	Venice	Ispra	Concep-cion
country	Italy	Italy	Italy	Bolivia
clouds	5.4%	11.4%	6.1%	0.0%
author	GZ	GZ	GZ	BH
type	nadir	nadir	west	nadir

Table 1: Specifications of validation pixels (authors: GZ=Giuseppe Zibordi/JRC, BH=Brent Holben/NASA-GSFC)

Conclusions

A new unsupervised retrieval method SYNAER for aerosol optical thickness and type in the boundary layer over cloudfree land and ocean from GOME and ATSR-2 data was delevoped and applied.

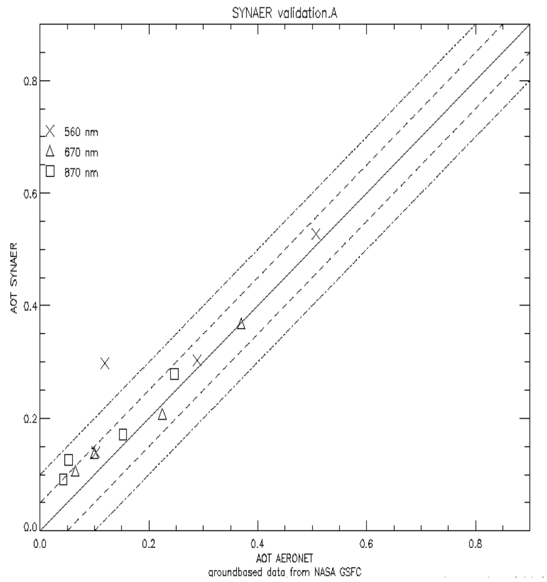

Figure 2: First validation results: Comparison of spectral AOT values measured by the groundbased AERONET stations at Ispra, Venice and Concepcion to AOT values retrieved by SYNAER. AERONET data were acquired through the AERONET website of NASA-GSFC (http://aeronet.gsfc.nasa.gov:8080).

Nadir and forward ATSR-2 reflectances were used but forward reflectances seem to be uneligible for our aerosol retrieval scheme. Misregistrations between nadir and forward view in the gridded data product and therefore physical information content of different air masses seem to be the reason. A first case study validation showed good agreement of retrieved spectral aerosol optical thickness values to ground based sun photometer measurements (error below 0.05 at 560, 670 and 870 nm). Difficulties in the selection of the right aerosol mixture, i. e. the correct spectral dependence of AOT values occur which have to be addressed in the future. Due to a very small number of exploitable ground measurements only four case studies could be performed so far. We plan a more detailed validation of this approach with airborne measurements that were conducted in August 1998. Additionally the AERONET data base was completed remarkably and therefore, the availability of ground measurements has been improved much.

Within the setup of a processor for atmospheric value added products DFD will operationalize the SYNAER method. Our aim is to contribute a satellite based climatology of tropospheric aerosols from 10 years of ERS-2 and ENVISAT data (7/1995 to 6/2005) to improve the understanding of the global temporal-spatial distribution of aerosol loading and its major components. The direct implementation of the SYNAER resulting climatology dataset in the global circulation model ECHAM [Ref. 20] is prepared as our dataset follows the characteristics of the groundbased dataset GADS (Global Aerosol Data Set [Ref. 14]) which is currently under implementation in ECHAM. Thus this dataset may easily enable a more detailed treatment of aerosols in climate models. Furthermore, a direct comparison of the groundbased GADS and the satellite derived SYNAER climatologies is possible since both datasets rely on the same set of representative aerosol components from the OPAC database.

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References

1. Charlson, R. J., Heintzenberg, J. (Eds.), Dahlem Workshop Report on Aerosol Forcing of Climate, 416 pp., John Wiley, New York, 1995
2. Gesell, G., An Algorithm for Snow and Ice Detection using AVHRR data: An Extension to the APOLLO Software Package, *Int. J. Rem. Sens.*, 10, 897-905, 1989
3. Guzzi, R., Burrows, J., Cattani, E., Kurosu, T., Cervino, M., Levoni, C., Torricella, F., GOME Cloud ans Aerosol Data Products Algorithm Development - Final Report, ESA Contract 11572/95/NL/CN, 1998
4. Herman, J. R., Bhartia, P. K., Torres, O., Hsu, C., Seftor, C., Celarier, E., Global distributions of UV-absorbing aerosols from NIMBUS 7 TOMS data, *J. Geophys. Res.*, 102, 16911-16922, 1997
5. Hess, M., Köpke, P., Schult, I., Optical Properties of Aerosols and Clouds: The Software package OPAC, *Bull. Am. Met. Soc.*, 79, 831-844, 1998
6. Holben, B. N., Eck, T. F., Slutsker, I., Tanre, D., Buis, J. P., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y. J., Nakajima, T., Lavenu, F., Iankowiak, I., Smirnov, A., AERONET - A Federated Instrument Network and Data Archive for Aerosol Characterization, *Rem. Sens. Environ.*, 66, 1-16, 1998
7. Holzer-Popp, Th., Kriebel, Th., Böttger, U., Dameris, M., Gesell, G., König, Th., Meerkötter, R., Rother, T., Schroedter, M., PAGODA final report, Schriften des Deutschen Fernerkundungsdatenzentrums Nr.1, DLR, Oberpfaffenhofen, 1998
8. Husar, R. B., Prospero, J. M., Stowe, L. L., Characterization of tropospheric aerosols over the oceans with the NOAA advanced very high resolution radiometer optical thickness operational product, *J. Geophys. Res.*, 102, 16889-16909, 1997
9. IPCC (Intergovermental Panel on Climate Change), Climate Change: the 1990 and 1992 IPCC assessments, WMO/UNEP, June, 1992
10. IPCC (Intergovermental Panel on Climate Change), Climate Change 1994, Cambridge Univ. Press, 1995
11. Kahn, R., West, R., McDonald, D., Rheingans, B., Mishchenko, M. I., Sensitivity of multiangle remote sensing observations to aerosol sphericity, *J. Geophys. Res.*, 102, 16861-16870, 1997
12. Kaufman, Y. J., Tanre, D., Gordon, H. R., Nakajima, T., Lenoble, J., Frouin, R., Grassl, H., Herman, B. M., King, M. D., Teillet, P. M., Passive remote sensing of tropospheric aerosol and atmospheric correction for the aerosol effect, *J. Geophys. Res.*, 102, 16815-16830, 1997
13. Kaufman, Y. J., Tanre, D., Remer, L. A., Vermote, E. F., Chu, A., Holben, B. N., Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectrometer, *J. Geophys. Res.*, 102, 17051-17067, 1997
14. Köpke P., Hess, M., Schult, I., Shettle, E. P., Global Aerosol Data Set, Max-Planck-Institut für Meteorologie, Report No. 243, 1997

15. Kriebel, K. T., Saunders, R. W., Gesell, G., Optical Properties of Clouds Derived from Fully Cloudy AVHRR pixels, *Beitr. Phys. Atmos.*, 62, 165-171, 1989
16. Leroy, M., Deuze, J. L., Breon, F. M., Hautecoeur, O., Herman, M., Buriez, J. C., Tanre, D., Bouffies, S., Chazette, P., Roujean, J. L., Retrieval of atmospheric properties and surface bidirectional reflectances over land from POLDER/ADEOS, *J. Geophys. Res.*, 102, 17023-17038, 1997
17. Nagel, M. R., Quenzel, H., Kweta, W., Wendling, P., Daylight Illumination-Color-Contrast-Tables, New York, Academic Press, 1978
18. Popp, Th., Correcting atmospheric masking to retrieve the spectral albedo of land surfaces from satellite, *Int. J. Rem Sens.*, 16, 3483-3508, 1995
19. Popp, Th., Gesell, G., König, Th., Kriebel, Th., Meerkötter, R., Mannstein, H., Exploiting GOME and ATSR-2 data: First results of the PAGODA project, in: *Proc. 3rd ERS Symp. on Space at the service of our Environment*, Florence, Italy, 17-21 March 1997, ESA SP-414, Vol II, 761-766, 1997
20. Röckner, E., Arpe K., Bengtsson, L., Brinkop, S., Dümenil, L., Esch, M., Kirk, E., Lunkeit, F., Ponater, M., Rockel, B., Sausen, R., Schlese, U., Schubert, S., and Windelband, M., Simulation of the present-day climate with the ECHAM model: Impact of model physics and resolution. Max-Planck-Institut für Meteorologie, *Report No.* 93, 171pp, 1992
21. Saunders, R. W., Kriebel, K. T., An Improved Method for Detecting Clear-Sky and Cloudy Radiances from AVHRR-data, *Int. J. Rem. Sens.*, 9, 123-150, 1988
22. Stowe, L. L., Ignatov, A. M., Singh, R. R., Development, validation, and potential enhancements to the second-generation operational aerosol product at the National Environmental Satellite, Data, and Information Service of the National Oceanic and Atmospheric Administration, *J. Geophys. Res.*, 102, 16923-16934, 1997
23. Tanre, D., Kaufman, Y. J., Herman, M., Mattoo, S., Remote Sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances, *J. Geophys. Res.*, 102, 16971-16988, 1997
24. Tegen I., Lacis A.A., Fung I., The influence on climate forcing of mineral aerosols from disturbed soils, *Nature*, 380, 419-422, 1996
25. World Climate Program (WCP), A Preliminary Cloudless Standard Atmosphere for Radiation Computation, WCP-112, *WMO/TD* No. 24, Boulder, 1986