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Integrated Ground-Based and Satellite Remote Sensing of the Earth Surface and Atmosphere in East and West Antarctica with Lidar and Radiometric Systems †

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Abstract: We have developed remote ground-based and satellite methods, hardware and software for studying atmospheric aerosols, clouds and the underlying surface in Eastern and Western Antarctica. The ground-based equipment includes: (1) a CIMEL solar spectrum photometer, which measures the spectrum of solar radiation transmitted and scattered by the atmosphere, (2) a multi-wavelength Raman lidar, which measures the vertical backscatter profile, (3) an albedometer, which measures the spectral albedo of the surface, primarily snow, (4) a reflectometer, which measures the directional spectral reflectance of snow. The ground-based measurement data were integrated with data from satellite radiometers MODIS or OLCI and the satellite lidar CALIOP. A synergy of the manifold data results in retrieval of various atmosphere and surface characteristics such as the aerosol optical depth, profiles of concentration of the fine and coarse aerosol fractions, spatial distribution of the effective snow grain size, fraction of outcrops etc.

Keywords: East and West Antarctica; snow cover; atmospheric aerosols; AERONET; lidar sounding; satellite sounding

1. Introduction

Research by Belarusian scientists in Antarctica began in 2006, when the Belarusian scientific group began measuring the ozone content in the atmosphere as part of the 52nd Russian Antarctic Expedition. In 2008, Belarusian scientists created the radiometric sounding station Vechernaya_Hill (67.66° S, 46.16° E) near Mount Vechernyaya [1], which became part of the AERONET global radiometric network [2,3].

In 2011–2015, the program of observations at the Belarusian scientific station, besides the solar radiometric observations, included measurements of the altitude dependence of optical parameters of the atmosphere by means of a lidar. A spectral albedometer for measuring the reflectance spectra of the earth's surface was also made, and its performance was successfully tested in Antarctica [4].

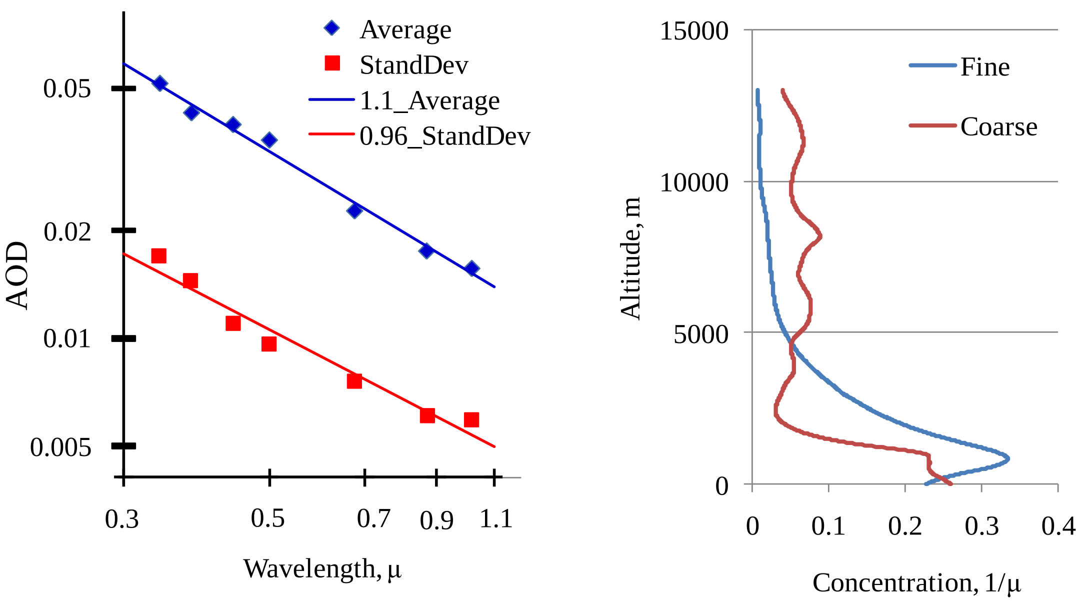
Turkey has been conducting regular expeditions to the Antarctic since 2016 and plans to establish a stationary research station on the Antarctic Peninsula [5,6].

An important role in the formation of a monitoring system for the atmosphere and underlying surface in Antarctica is assigned to space observation systems. Algorithms to retrieve parameters of the snow surface from satellite measurements were developed [7,8]. The degree of coverage of the territory by snow and its average spectral albedo, as well as the level of pollution and the size of snow granules are the most important parameters that determine the radiation balance of polar regions. These data are necessary for studying the processes of metamorphism in the snow and ice cover of Antarctica.

2. Combined Ground-Based and Satellite Investigations of Atmospheric Aerosols in the Region of Belarusian Antarctic station *Gora Vechernyaya*

The methodology for aerosol sounding with ground- and satellite-based lidars and solar spectrometric systems (hereinafter called LRS, for Lidar & Radiometer Sounding) uses a synergistic approach to organization of measurements and development of algorithms to process the combined data. The result of a complex experiment is a complete set of parameters of an optical aerosol model required to describe the process of radiative transfer in an aerosol layer stratified along height [9–11]. Whereas the sources of radiometric data in the LRS are stations of the AERONET, lidar data are provided by stations of lidar networks (EARLINET, AD-Net, CIS-LiNet) and the satellite lidar CALIOP. Nowadays, the LRS is successfully used to study Eurasian aerosols [12]. In 2018, the first LRS measurements in Antarctica to study a long-range smoke transport to Enderby Land were performed at the Belarusian Antarctic station *Gora Vechernyaya* [13], and since than the LRS became a part of regular observations in Belarusian Antarctic expeditions.

Figure 1 shows some results of optical observations at the *Gora Vechernyaya* station.



(**a**) (**b**)

Figure 1. Results of optical measurements at station *Gora Vechernyaya:* (**a**) AOD spectrum. Markers denote the measured spectral AOD and its standard deviations for the measurement period 2008–2021. Straight lines are the linear regression of the spectral dependences in the logarithmic scale; the slopes are indicated in the legend. (**b**) Altitude distributions of the fine and coarse fractions averaged over 2019–2021.

Observation seasons usually last from December to early March. The spectral distribution of the AOD (Aerosol Optical Depth) have been averaged first across a season and then across years. The standard deviation refers to the dispersion of the season-averaged values over years. The spectral dependences are approximated by a power law and represented in the plot by straight lines, the line slope shown in the legend being the exponent of the power law.

Figure 1b presents the average height profiles of the volume concentration of fine and coarse particles according to terminology used in AERONET [2]. In this plot, the concentration profiles are normalized by the column amount, which is an integral of the concentration over height.

The average column amount of the fine fraction is about 0.05 μm as compared to 0.005 μm for the coarse one, i.e., the column amount of the fine mode at the region of Mount Vechernyaya is about 10 times higher than that of the coarse one.

3. Snow Cover Studies in the Regions of East and West Antarctica Using Satellite Data

3.1. Algorithm ASAR

The snow cover has a significant influence on the Earth's albedo and, accordingly, on its climate. The development of satellite sensing methods, in particular, monitoring of snow age, degree of pollution and grain size, becomes especially important for the polar regions, where direct measurements are difficult.

The main feature of the snow cover of Antarctica is its purity. According to [14], the average concentrations of black carbon are 0.1–0.3 ng/g at the South Pole station and 0.6 ng/g at the Vostok station (coast). The peak concentration at the Vostok station reached 7 ng/g, which is still too low to show up in optical measurements.

On the other hand, strong winds over Antarctica in winter, as well as snowmelt in summer, result in rock outcrops. The outcrops can be fragmented, i.e., occupy limited areas of several hundred square meters. Since satellite radiometers, such as MODIS, have a spatial resolution of about 1×1 km^2, a pixel may be mixed: partly occupied by snow, partly by rocks, which can significantly reduce the pixel albedo in the visible range. Thus, to correctly determine the size of snow grains, it is required to estimate the fraction of a pixel that is free of snow.

An algorithm to retrieve the effective snow grain size, rock fraction, and albedo of a mixed snow/rock pixel from satellite data over Antarctica was developed at the Institute of Physics of NAS of Belarus and implemented in the form of the ASAR code (Antarctic Snow Albedo Retriever).

The first feature of the ASAR algorithm is to take into account the purity of the snow cover in Antarctica. In this modification of the algorithm, the concentration of black carbon is assumed to be zero. The second feature is that the rock fraction per pixel is estimated from satellite data. For such a bright surface as snow, the angular dependence of reflectance may be significant, because of the anisotropy of the phase function of light scattering by snow grains. Since the shape of the snow grain is not known a priori, the angular dependence of reflectance cannot be predicted either and therefore it is to be estimated from the satellite data as well. This comprises the third feature. Data on the angular distribution of reflectance by rocks are rather scarce; however, their albedo is quite low and the contribution of reflectance from rocks is much lower than that from snow. Thus, reflection from rocks are considered to obey Lambert's law.

The algorithm does not use any specific snow model or a priori information about the shape of snow grains. It uses only the spectral information obtained by a satellite radiometer and is based on the asymptotic dependence of the bidirectional reflectance of a semi-infinite snow layer on the particle size [7,8].

This implementation of the method, results of which are presented herein, uses the MODIS spectroradiometer [15], but a version that processes the OLSI [15] data has also been developed. Herein, MODIS channels no. 2, 3 and 5 are used, because rocks reduce albedo mainly in the visible range (#3, 469 nm), while snow noticeably absorbs light in the near infrared (#5, 1.24 μm). Channel 2 (859 nm) is an additional channel that eliminates the uncertainty associated with the angular dependence of the snow brightness. In addition, none of these channels matches the absorption bands of atmospheric gases, in particular, ozone.

3.2. Spatial Distribution of the Snow Grain Size in East and West Antarctica

MODIS radiometer data are available on the official website of the LAADS (The Level-1 and Atmosphere Archive & Distribution System) [17]. The original MODIS data files in the HDF4 format, after being converted to the modern HDF5 format, are processed by the ASAR software package. As a result of processing, a set of statistical information is obtained in the form of maps of various parameters of the underlying surface, such as the effective size of snow grains, rock fraction, and average pixel albedo. The retrieved data are saved in the HDF5 format and can be used for further processing and analysis.

Figure 2 show maps of the spatial distribution of snow grain sizes in West and East Antarctica, retrieved with the ASAR algorithm from satellite data related to the beginning of 2022. The red line on the maps indicates the coastline of Antarctica. Note that in the images taken by the Terra satellite, the north is at the bottom of the map, whereas in the images taken by the Aqua satellite, it is at the top, because Terra and Aqua move in opposite directions.

Figure 2 demonstrates significant differences in the state of the snow cover of Antarctica depending on the region. According to Terra data (Figure 2b), the size of snow grains in Enderby Land (the area of *Molodyozhnaya* and *Gora Vechernyaya* stations) does not exceed 100 μm, which corresponds to fresh snow that has not undergone metamorphism [18]. On the Antarctic Peninsula (Figure 2a,c), snow grains are much larger, especially on the western coast of the peninsula, including the location of the Turkish station (about 300 μm and above), which indicates significant metamorphism due to melting, temperature gradient, or other reasons [18,19]. However, the largest grains (larger than 400 μm) are observed on the coast of the Prydz Bay (Figure 2b, the *Progress* station area). Such values could have been taken as an "artifact" associated with the data unreliability at the edge of the satellite image, however, the data from the MODIS Aqua radiometer (Figure 2d) confirm the anomalously high values of the snow grain size in this area. Hence, the difference in the effective size of snow grains in these regions during the current Antarctic summer can be considered reliably established. Probably, this difference may be due to the ocean influence, which is stronger in the "more maritime" regions of the Antarctic Peninsula and Prydz Bay than in the "more continental" Enderby Land.

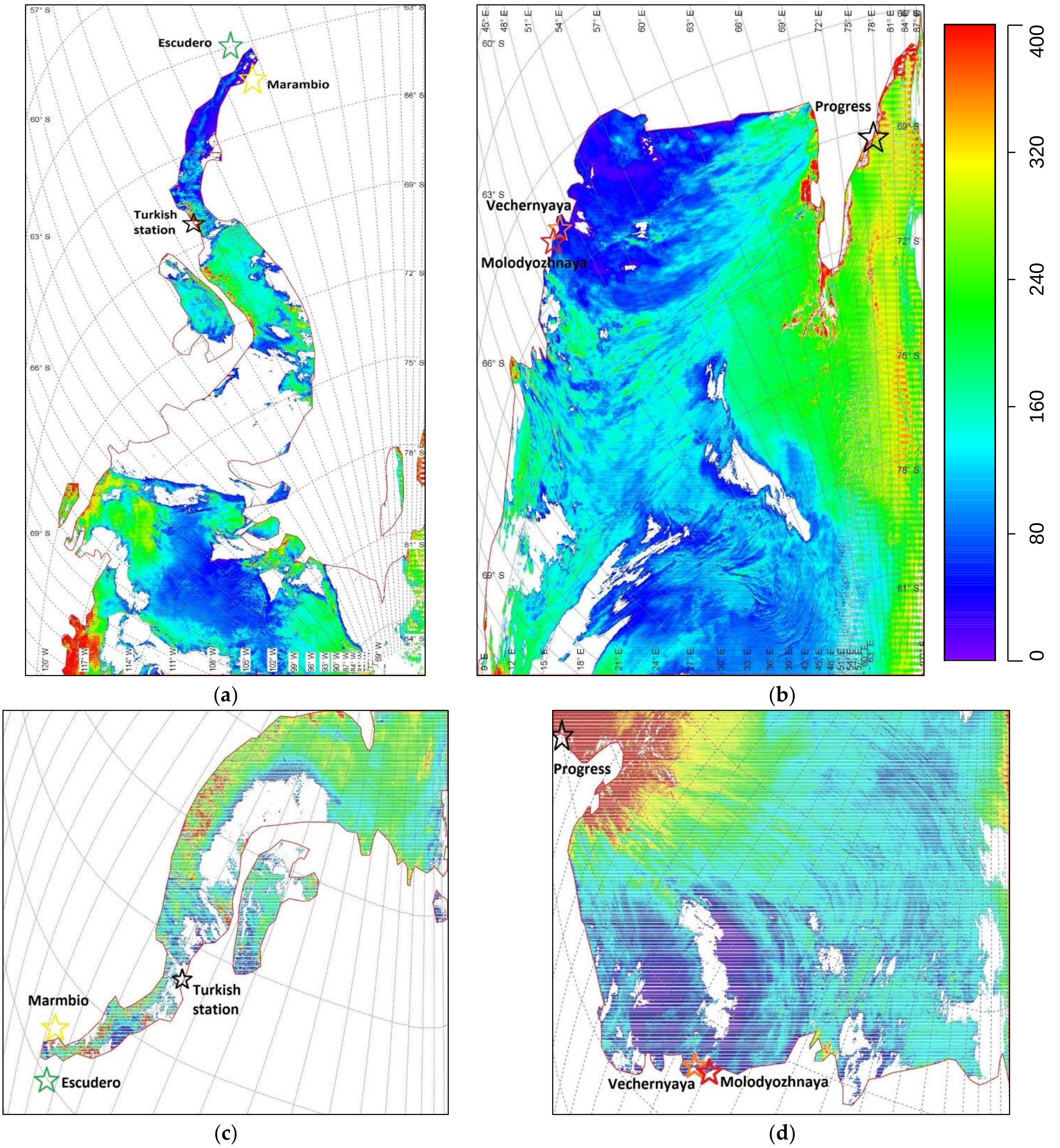


Figure 2. Maps of the effective grain size: (**a**) Antarctic Peninsula, Terra, 01/07/2022; (**b**) East Antarctica, Terra, 01/07/2022; (**c**) Antarctic Peninsula, Aqua, 01/08/2022; (**d**) East Antarctica, Aqua, 01/07/2022. The color scale is in micrometers.

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