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Characteristics of the Snow Cover in East and West Antarctica and Their 20-Year Trends Retrieved from Satellite Remote Sensing Data †

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Abstract: The aim of this study was to make a comparative analysis of the state of the snow surface in East and West Antarctica, including changes in snow cover characteristics during the past two decades. To do so, we used the ASAR (Antarctic Snow Albedo Retriever) algorithm, which processes satellite data and retrieves an effective snow grain size and a fraction of rocks not covered by snow, to process the MODIS data throughout the entire period of its operation (up to now). We have chosen several test areas (approximately 30 × 30 km^2) to study the state of the snow cover on Enderby Land (East Antarctica), on the coast of the Ross Sea (the Transantarctic Mountains), and the Antarctic Peninsula (West Antarctica). As a result, we have plotted and analyzed the time series of the effective snow grain size and rock fraction in these areas across the last 20 years. We have found weak negative trends for the effective grain size on the coast of Enderby Land and the Ross Sea. The rock fraction does not demonstrate any trend. The study of snow cover trends on a continental scale can contribute to the investigation of environmental changes in Antarctica.

Keywords: snow cover; remote sensing; East and West Antarctica

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1. Introduction

The need to study Antarctica has originated from its importance in the formation of climatic and weather processes on the planet. Polar regions have a critical impact on the Earth's climate. To quantify and predict the consequences of anthropogenic and natural impacts on Antarctica, it is necessary to monitor its environment and study the patterns of its transformation. One of the most important environmental components is the snow cover.

The snow cover has a significant effect on the Earth albedo and, accordingly, on its climate. At the same time, the snow cover is a system with strong feedback: temperature rise speeds up melting, which increases the absorption of sunlight, and which in turn speeds up melting. This feedback may be greatly enhanced by the presence of pollution, especially soot, which is mainly the result of industrial emissions.

Fortunately, a feature of the snow cover in Antarctica is its purity. According to Grenfell et al. [1], 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 has reached 7 ng/g. A recent study [2] has reported that black carbon content has been rising, particularly in areas surrounding research facilities and popular shore tourist-landing sites, showing the median concentration of 3 ng/g and the peak concentration of 8 n/g. Nevertheless, these "dirty" regions are rather local and concentrated mainly at the tip of the Antarctic Peninsula, where a great number of stations and tourist routes are located. The rest of the Antarctic snow cover remains rather pure: at least its contamination is too low to appear in optical measurements.

On the other hand, summer melting, as well as strong winds in autumn and spring, results in rock outcrops, which reduce the snow cover albedo. The rock outcrops can be fragmented, occupying plots with an area of several hundred square meters. Since satellite radiometers used for the remote sensing of large areas (e.g., MODIS) have a spatial resolution of the order of 1×1 km^2, snow coverage in a pixel may be incomplete. Thus, to correctly determine the snow grain size and surface albedo, it is required to estimate the snow coverage as well.

2. Method

Earlier, we developed the ASAR algorithm (Antarctic Snow Albedo Retriever), which processes satellite radiometer data and maps the main snow cover characteristics, such as the effective snow grain size, the fraction of rocks free of snow, and the pixel albedo. ASAR 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 semi-infinite snow layer reflectance on the particle size. The ASAR input is an original MODIS data file in HDF format, and the output is a map of the retrieved parameters in H5 format intended for further statistical processing and analysis, as well as for visualization. The algorithm details will be published elsewhere.

3. Results

3.1. Maps

3.1.1. Enderby Land

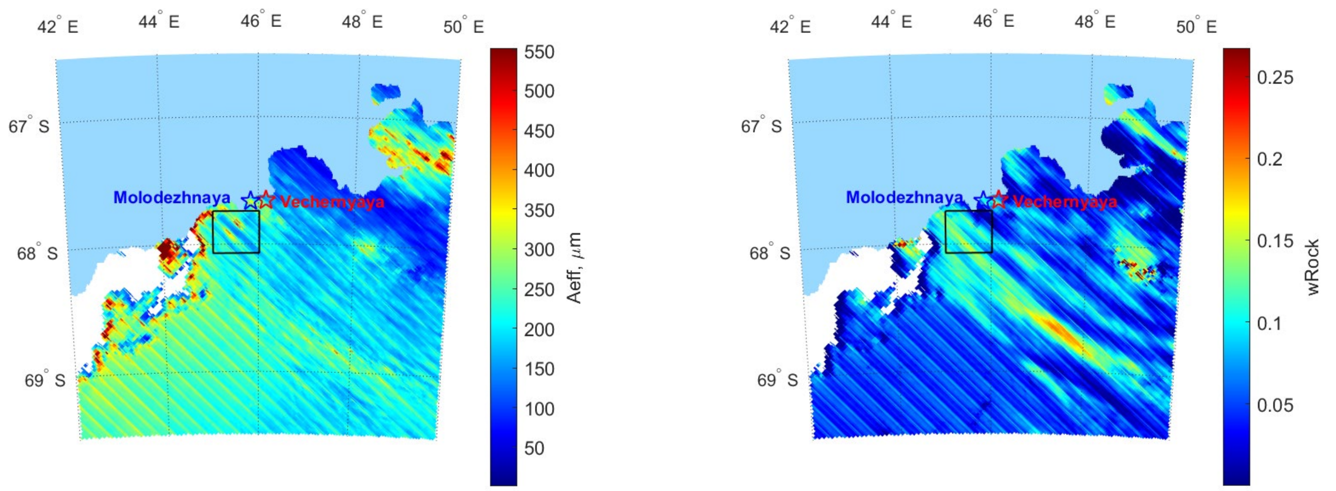
In Enderby Land, a piece of a typical snow surface was chosen for study, located in the region of the Vechernyaya Mountain and Molodyozhnaya stations near the coast. The site is a rectangle with spherical coordinates bounded by parallels 67.74° S and 68.07° S and meridians 45.05° E and 46.02° E. The site size is approximately 40 km × 40 km.

Figure 1 shows the spatial distributions of the effective snow grain size (Aeff) and the naked rock fraction (wRock = 1 − snow coverage) in Enderby Land retrieved from the Terra data on 25 December 2020, at 04:30. The selected area is shown in the figure with a black rectangle. The site is quite homogeneous and adjacent to the coast, which will allow us to study how the proximity of the ocean affects the melting of the snow cover. White patches represent pixels discarded because of clouds or bad data.

3.1.2. Ross Sea Coast

To build a time series of snow cover characteristics, one should choose a surface area that will be sufficiently homogeneous and will represent a typical surface for a given region. To ensure the stability of the data, the desired area must be, on the one hand, sufficiently homogeneous and, on the other hand, sufficiently large. A reasonable size seems to be about 30–40 km.

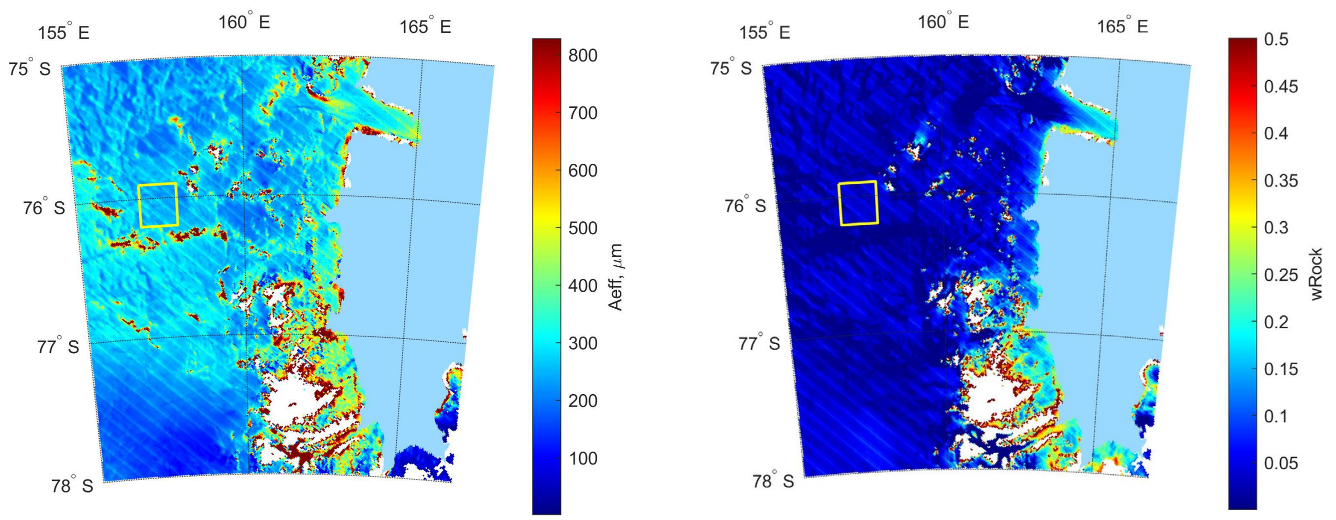
On the coast of the Ross Sea, there are the Transantarctic Mountains, which divide West Antarctica and East Antarctica. They make a significant contribution to the surrounding climate. There is notable ice movement in this area, especially on the seaside of the ridge, where glaciers slide into the Ross Sea. The abundance of glaciers makes it difficult to find a stable snow surface. Another effect is katabatic winds formed because of strong air cooling near the glacier surface. They reach very high speeds and carry a large volume of cold air from mountain tops. These winds also have an impact on the snow surface, forming either snow sastrugi, which affect the retrieval, or areas completely free of snow—the so-called Antarctic oases.



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

Figure 1. Example of the retrieval of the snow cover characteristics from satellite data (Terra, 25 December 2020, at 04:30): (**a**) the effective snow grain size and (**b**) the rock fraction. The test plot is shown with a black rectangle. The stripes are associated with an artifact of MODIS Terra.

In light of the above facts, in order to analyze the trends of the snow cover characteristics, we decided to consider a site to the east of the Transantarctic Mountains with the least ingress of moving glaciers, rock outcrops, and the impact of winds. The plot is a rectangle in spherical coordinates, bounded by parallels 75.9° S and 76.2° S and meridians 156.9° E and 158.0° E. An example of satellite data processing in the selected area is shown in Figure 2. The selected area is indicated by the yellow square.



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

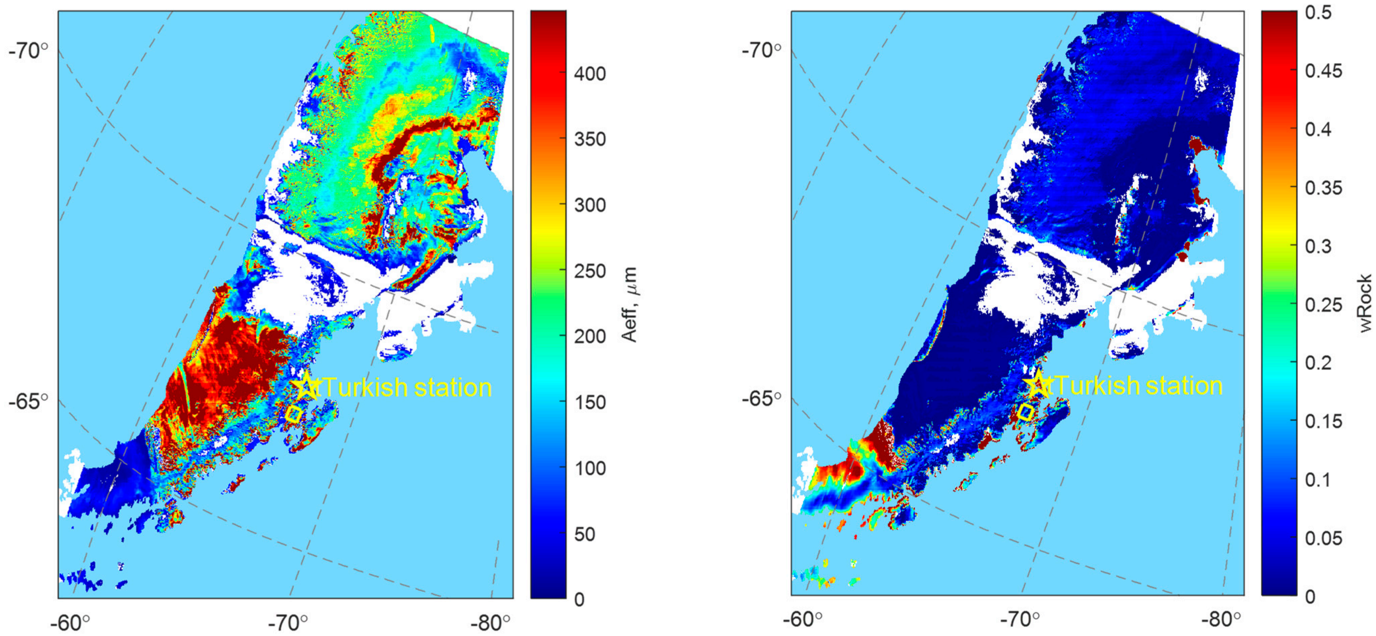
Figure 2. Example of the retrieval of the snow cover characteristics from satellite data (Terra, 10 December 2021, 21:05): (**a**) the effective snow grain size and (**b**) the rock fraction. The test plot is shown with a yellow rectangle.

3.1.3. Antarctic Peninsula

The Antarctic Peninsula, in fact, is a mountain range stretching from north to south, which in its geomorphology is a continuation of the South American Andes. The central part of the peninsula is occupied by a glacial plateau, the height of which is from 1.5 to 2 km. A part of the coast of the peninsula, especially the northwestern part, is occupied by the Antarctic tundra. The climate of the Antarctic Peninsula is the mildest on the entire continent; hence, it has a large number of research stations and tourist routes. The climate on the western coast of the peninsula is characterized as maritime Antarctic and is the mildest.

Closer to the central part of the peninsula, there are areas with the least impact of the movement of ice masses. Also, due to the absence of sharp elevation changes, there is no such phenomenon as katabatic winds.

In order to analyze the trends in changes in the characteristics of the snow cover, it was decided to select, for further analysis, a site in the center of the peninsula, on the western coast, near the area where the Turkish research station is located. The site is a rectangle with parallels 67.15° and 67.40° S and meridians 66.85° and 67.45° E. Figure 3 shows an example of the snow cover characteristics retrieval and also indicates the location of the Turkish station and the selected plot.

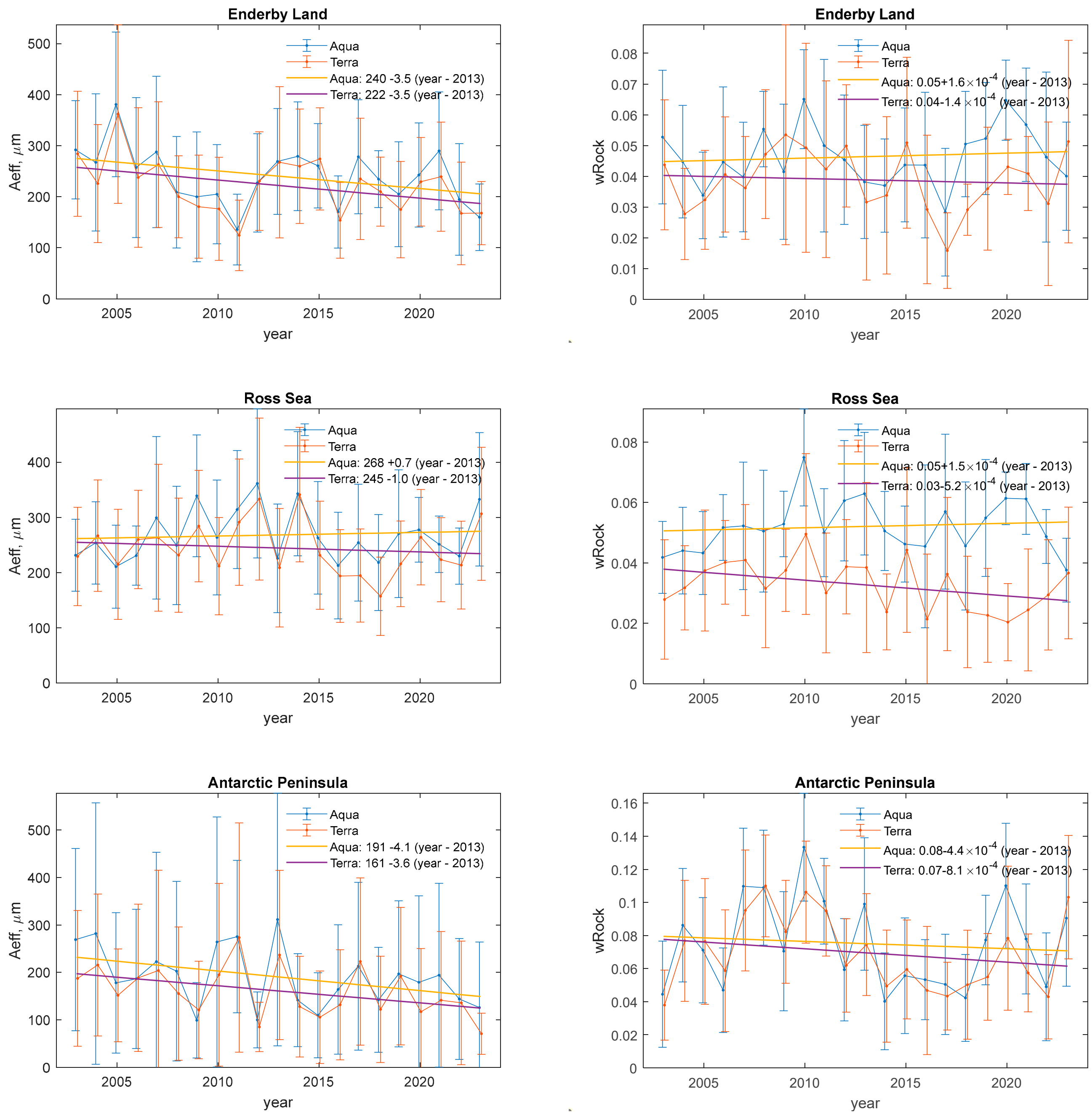


(**a**) (**b**)

Figure 3. Example of the retrieval of the snow cover characteristics from satellite data (Aqua, 1 January 2023 19:29): (**a**) the effective snow grain size and (**b**) the rock fraction. The test plot is shown with a yellow rectangle.

3.2. Trends

Satellite images of areas that include the test plots were processed for the entire observation period from 2002 to 2023 (5076 scenes in total). The retrieved values of Aeff and wRock were averaged over the months. The time series of the January averaged values is shown in Figure 4. The figure separately shows the results of processing data from the Terra and Aqua satellites [3]. The straight lines show the linear trends for the entire period.



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

Figure 4. Times series and trends of the snow cover characteristics for three test plots in Enderby Land, near the Ross Sea coast, and the Antarctic Peninsula: (**a**) the effective snow grain size and (**b**) the rock fraction.

4. Discussion

Enderby Land is rather inhomogeneous and shows uneven melting, quite natural for the coast of Antarctica in summer (see Figure 1). In contrast, the area located east of the Transantarctic Mountains is quite homogeneous (see Figure 2). The effective grain sizes/rock fractions are about 231 ± 107 μm/4.3 ± 2.1% on the coast of Enderby Land and 256 ± 99 μm/4.2 ± 1.8% near the Ross Sea. The relative standard deviation for Aeff in the Ross Sea plot is lower than that on the Enderby Land coast (39% vs. 46%). A reason for this may be due to the fact that the plot near the Ross Sea is protected from the ocean by the mountain range and is therefore less prone to melting, resulting in smaller grains and higher homogeneity. At the same time, the Antarctic Peninsula demonstrates even smaller grains (176 ± 160 µm), despite being warmer. This can be due to the fact that the area on the west coast of the peninsula experiences not only stronger melt but also more frequent snowfalls caused by a warmer ocean, which provide new, small grains. The greatest scatter is seen on the Antarctic Peninsula (up to 100%), which together with the high rock fraction (7 ± 3%) confirms the idea of the rapid changes in the snow cover state.

The time series of both Aeff and wRock in Enderby Land are quite uniform. One can notice a slight decrease in the effective grain size in 2008–2011 to values below 200 µm, which corresponds to a slightly aged but not melting snowpack. The test plot near the Ross Sea coast shows no trends. The rock fraction on the coast of the Antarctic Peninsula demonstrates something like an oscillation with a notable increase in 2008–2013 and a maximum in 2010.

The time series in Enderby Land and on the Antarctic Peninsula show negative trends for Aeff, although quite small compared to the spread of the values. In Enderby Land, the Aeff linear regression provides the total 20-year change, $\delta = 70$ µm, which is comparable to the absolute standard deviations, $\sigma = 107$ µm. On the plot near the Ross Sea, the total change is negligible ($\delta = 6$ µm vs. $\sigma = 99$ µm). On the Antarctic Peninsula, the Aeff linear decrease is 77 µm at $\sigma = 160$ µm. The rock fraction demonstrates no trends in all the considered areas. To conclude, the negative trends for the effective grain size on the coast of Enderby Land and the Ross Sea can be considered reliably established, albeit weak in magnitude. Additionally, some oscillations were observed in the snow coverage in the west coast of the Antarctic Peninsula from 2002 to 2023.

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