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Giacomo TRAVERSA [1,2], Davide FUGAZZA [2], Antonella SENESE [2*] &
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PRELIMINARY RESULTS ON ANTARCTIC ALBEDO FROM REMOTE SENSING OBSERVATIONS

Abstract: Traversa G., Fugazza D., Senese A. & Diolaiuti G.A., *Preliminary results on Antarctic albedo from remote sensing observations.* (IT ISSN 0391-9838, 2019).

The aim of the study is to analyse the surface albedo of the Antarctica and investigate eventual signals of variations in space and time between summer 2000/2001 and 2011/2012 by means of the GLASS albedo product. We followed a step-by-step procedure from micro- to macro-scale. At first, we analysed 95 glaciers around the continent, and we found limited temporal variability. Then, looking at spatial variations, we divided Antarctica based on oceanic basins and by continentality. We found spatial signals, since mean albedo values range between 0.79 (Pacific and Atlantic basins) and 0.82 (Indian basin) and between 0.76 (along the shore) and 0.81 (inner continent). An increasing variability was found from the inner continent to the shore, and heterogeneous patterns among the basins, most likely due to meteorological and environmental conditions (mainly: temperature, precipitation, katabatic winds).

Finally, the general patterns observed (considering the specific glaciers, the three basins and the three continentality sectors) were verified by the analysis of the whole continent and we did not find a significant change of summer averages over time, as they range between 0.79 and 0.80.

Key words: Antarctic albedo, Remote sensing, GLASS.

Riassunto: Traversa G., Fugazza D., Senese A. & Diolaiuti G.A., *Risultati preliminari sull'albedo dell'Antartide da osservazioni di telerilevamento.* (IT ISSN 0391-9838, 2019).

Lo scopo dello studio è analizzare l'albedo dell'Antartide e studiare eventuali segnali di sue variazioni nello spazio e nel tempo tra l'estate 2000/2001 e 2011/2012 mediante il prodotto albedo di GLASS. Abbiamo seguito una procedura "*step by step*" dalla micro alla macro scala. Inizialmente, abbiamo analizzato un campione di ghiacciai in tutto il continente e abbiamo riscontrato una limitata variabilità temporale. Successivamente, investigando l'eventuale presenza di variazioni spaziali, abbiamo suddiviso l'Antartide in base ai bacini oceanici e per caratteristiche di continentalità. I valori medi di albedo variano tra 0.79 (bacini Pacifico e Atlantico) e 0.82 (bacino Indiano) e tra 0.76 (lungo la costa) e 0.81 (continente interno), confermando quindi la presenza di trend spaziali. È stata riscontrata una crescente variabilità dal continente interno verso la costa e si osservano situazioni eterogenee tra i bacini, molto probabilmente a causa delle condizioni meteorologiche e ambientali (principalmente: temperatura, precipitazioni, venti catabatici).

Infine, gli andamenti generali osservati (considerando i ghiacciai specifici, i tre bacini e i tre settori di continentalità) sono stati verificati dall'analisi di tutto il continente e non abbiamo riscontrato un cambiamento significativo delle medie estive nel tempo, poiché variano tra 0.79 e 0.80.

Termini chiave: Albedo antartica, Telerilevamento, GLASS.

INTRODUCTION

Antarctica is the fourth continent by width and is almost entirely covered by snow and ice (King & Turner, 1997). The inner continent presents almost entirely snow as superficial cover and the coastline shows only 5% (1656 km) of rock surface (Drewry, 1983). Antarctica is one of the widest and most reflective surfaces of the planet and thus an eventual variation of its albedo could be a crucial issue in the Earth energy balance, by controlling the absorption of solar radiation at the surface, leading to significant effects on sea level. The continent is a heat sink for the Southern Hemisphere and thus exerts considerable control over the circulation of the atmosphere at high and mid-latitudes (King & Turner, 1997). Unlike the high latitude landmasses of the Northern Hemisphere, characterized by large areas of seasonal snow cover, and thus a rapid response to temperature changes, the Antarctica is covered by a permanent highly reflective surface. For these reasons, albedo is an important feature that needs to be investigated in detail, considering its relations with surface variations from a spatial and temporal point of view. In particular, here

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light-absorbing impurities are few, and thus snow albedo is mostly determined by the size of snow grains (Grenfell & *alii*, 1994; Gay & *alii*, 2002; Warren & *alii*, 2006; Gallet & *alii*, 2011; Picard & *alii*, 2016), regulated by snow metamorphism (i.e. the process of grain coarsening). In addition, the effects of various morphologies owing to strong and persistent winds (e.g. sastrugi, snow dunes and wind glaze areas), or the presence of blue ice, can considerably affect the surface albedo (Frezzotti & *alii*, 2002; Scambos & *alii*, 2012; Das & *alii*, 2013). In turn, the rate of snow metamorphism is influenced by temperature, relative humidity and wind (Pirazzini, 2004; Picard & *alii*; 2012; Lenaerts & *alii*, 2017).

The first measurements of Antarctic surface albedo date back to the past century; in fact, direct surveys of the incoming solar radiation and albedo were performed during the US-IGY-Antarctic Expedition 1957/58. During this campaign, measurements of the albedo at the South Pole and at Byrd Station (80° S, 120° W, 1515 m a.s.l.) gave a mean value of 0.89, with a range between 0.84 and 0.93 (Hoinkes, 1960). Since these first surveys, several field campaigns have been carried out; among others, field observations showed mean albedo values of 0.76 at Faraday (1963-1982), 0.82 at Halley (1963-1982) and 0.85 at Vostok (1963-1972) (King & Turner, 1997), 0.80-0.85 at Scott South Pole and Vostok stations (average of spectral albedo in summer 1985-1986 and 1990-1991, Grenfell & *alii*, 1994), 0.58-0.82 at Hells Gate, Neumayer, Concordia and Reeves Névé stations (between 1994 and 1998, Pirazzini & *alii*, 2004), 0.80-0.90 on the Antarctic Plateau (Dalrymple & *alii*, 1966; Dolgina & *alii*, 1976; Gardiner & Shanklin, 1989). Presently, the best way to acquire albedo data over wide areas of Antarctica is via remote sensing, which also allows investigating longer periods of time. However, few studies have actually used remote sensing for this purpose: Laine (2008) found a range of 0.75-0.90 for the entire Ice Sheet between 1981 and 2000 from AVHRR Pathfinder data; Gallet & *alii* (2011) found values of 0.79-0.83 from MODIS MCD43C3 along a transect from Dome C to Dumont d'Urville.

Considering the scarcity of existing literature, the aim of this study is to analyse the variability of Antarctic albedo in space and time with remote sensing, focusing on inter- and intra-annual variations, from summer 2000-2001 to summer 2011-2012, and across different sub-zones, to obtain a complete overview of the continent. Firstly, starting from a micro-scale analysis, we investigated a subsample of glaciers (fig. 1A) in order to investigate temporal variability in detail; then, dividing the continent based on oceanic basins (i.e. Indian, Pacific and Atlantic) and continentality (i.e. continent, transition and shore), see fig. 1B, we analysed changes in space to verify the presence of spatial signals.

Several existing global albedo products are available, but we chose to discard most of them for different reasons: CLARA-A2 has a coarse resolution (25 km), MCD43A3 and MOD10A1 are affected by data gaps owing to clouds; in addition, while it is also possible to retrieve the albedo from Landsat or Sentinel-2 satellites (e.g. Fugazza & *alii*, 2019), the fine resolution and low spatial coverage of single scenes imply a long processing time, which was unsuitable for our large scale preliminary analysis. Thus, for the aims of this study, the GLASS product derived from MODIS was chosen as the main data source. In fact, considering its spatial and temporal resolutions (described in detail in Methods and Data section), we considered GLASS as the most suitable product for our research, also thanks to its efficient cloud screening algorithm (Liang & *alii*, 2012; Zhao & *alii*, 2013).

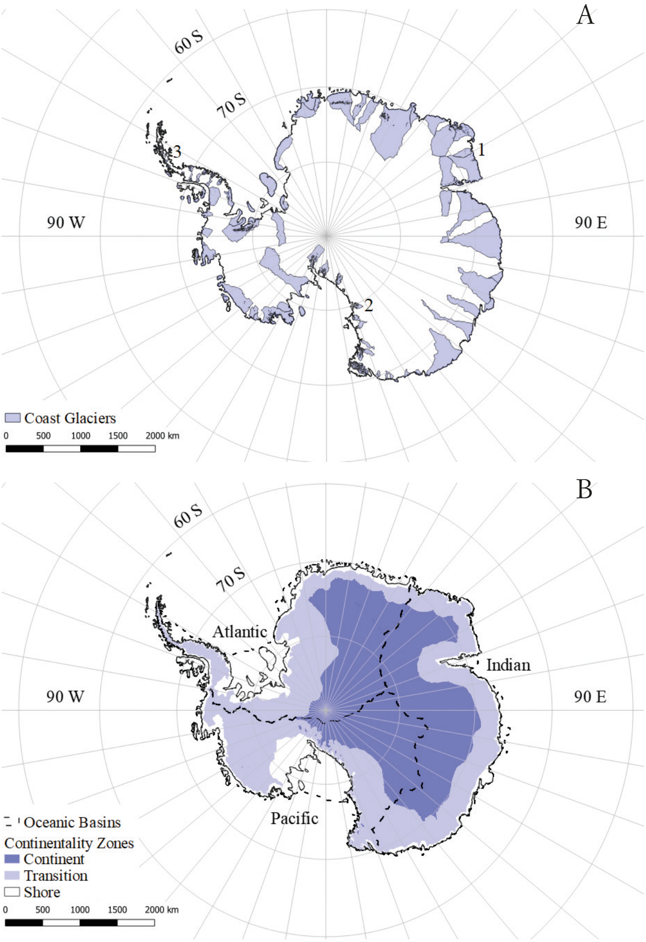

FIG. 1 - The 95 investigated glaciers, including Dovers and Cosgrove g. (1), Darwin g. (2) and Evans g. (3) (A) and Antarctica divided into the 3 oceanic basins by the dashed lines and into continentality zones by different coloured areas (B).

METHODS AND DATA

To obtain the albedo values, we used the GLASS product (Liang & *alii*, 2012), derived from MODIS. This product had an 8-day temporal resolution between 2000 and 2012 and a spatial resolution of 5.6 km for the continental zone (ice shelves and sea ice are not included). GLASS is based on pre-processed MODIS data (i.e. MOD09A1, MOD09GA, MCD43B3 and MOD02), with the addition of a snow- and cloud-mask used to identify different pixels and remove cloud and cloud-shadows effect to increase the overall quality. Each GLASS scene is obtained by merging the 1-day broadband albedo derived from top-of-atmosphere directional reflectance, corrected for the solar/view angle dependence of the surface in a 16-day window through a Statistics-Based Temporal Filtering algorithm (Zhao & *alii*, 2013). We analysed 16 images per season from November 2000 to February 2012. From the original products, downloaded from the GLCF (Global Land Cover Facility), we extracted black-sky albedo (or directional hemispherical reflectance, DHR, that is inherent to specific locations and is linked with the structure and optical properties of the land cover; Schaaf & *alii*, 2011), as proposed by Tedesco & *alii* (2016). Each layer was extracted and cut, considering only the South Polar region (coordinates: C_1 (180° W, 60° S); C_2 (180° E, 90° S)) and then re-projected into the Antarctic Polar Stereographic coordinate system. The uncertainty of individual pixels as reported in the quality control layer of the GLASS product is ±0.10. GLASS products have already been tested using spatial quality verification processes, consisting of different components (Zhao & *alii*, 2013): a spatial quality check-up (i.e. screening for missing data or bands, spatial discontinuity problems) and a numerical accuracy assessment (i.e. comparison between the GLASS product with data measured on the ground).

For each date and each of the following analysis steps, i.e. glacier subsample, basin and continentality division, and whole Antarctica, we applied zonal statistics in QGIS software to obtain mean, median, maximum, minimum and standard deviation of all the considered pixels. In addition, we calculated the uncertainty for each average albedo estimate, using the standard error of the mean (σ_x) (Fugazza & *alii*, 2019), as:

$$\sigma_x = \frac{\sigma}{\sqrt{n}}$$

where σ is the standard deviation of albedo values (for each date and each step) and n is the number of pixels considered.

Firstly, to investigate temporal variability, 95 coastal glaciers were randomly selected from the ice features catchments polygon shapefile by the British Antarctic Survey (BAS). In particular, we analysed 46 glaciers of the Atlantic basin, 30 of the Pacific one and 19 of the Indian one (fig. 1A). We chose a different number of glaciers in each ocean basin to consider approximately the same total glacier area for every basin. In fact, even if the area of the widest glacier for each basin has the same magnitude, ranging between 140,000 km^2 (Pacific) and 300,000 km^2 (Atlantic), the Atlantic basin also presents much smaller glaciers, with areas of 150 km^2, compared to the Pacific and Indian sectors, where the smallest glaciers average 1,200 km^2. Then, in order to divide the Antarctica into the 3 oceanic basins (dashed lines in fig. 1B), we used i) the shapefile of the Antarctic drainage system from Zwally & *alii* (2012), which separates the continent by drainage basins, ice sheets and ice shelves and ii) a shapefile by Natural Earth Data, separating the world waters into individual oceans and seas. Although previous studies used a simpler approach based on longitude zones (Brandt & *alii*, 2005; Laine, 2008), we chose to consider drainage basins for a more accurate subdivision. Considering the continentality zones (i.e. continent, transition and shore), we classified a DEM (Cryo Sat DEM of Antarctica created by the CPOM - Centre for Polar Observation and Modelling, Helm & *alii*, 2014), based on altitude: shore below 800 m a.s.l., transition between 800 and 2500 m a.s.l. and continent above 2500 m a.s.l. (coloured areas in fig. 1B). These altitude ranges are based on the morphology of the surface. In fact, the elevation belt between 800 and 2500 m a.s.l. is characterized by significant changes in topography, with very steep slopes encircling the continent and marking the separation of the inner area from the coast. By combining information on continentality and oceanic basins, we obtained a polygon of the Atlantic basin divided into continentality zones.

Finally, to extract the albedo of the whole Antarctica, we used the coastline shapefile provided by the SCAR (Scientific Committee on Antarctic Research).

The climatological dataset RACMO2.3 (an update of Regional Atmospheric Climate MOdel 2) described by Van Wessem & *alii* (2014a, b) was used to investigate the influence of meteorological conditions on albedo values, by calculating correlation with our albedo data. RACMO2.3 includes 5 different raster maps at 35 km spatial resolution available at https://www.npolar.no/quantarctica/, providing the climatic mean 1979-2011 of: i) annual cumulative precipitation (rain and snow) in kg m^{-2} yr^{-1}, ii) annual total (surface and drifting snow) sublimation rate in kg m^{-2} yr^{-1} where positive values indicate sublimation and negative ones indicate deposition, iii) annual surface mass balance in kg m^{-2} yr^{-1}, iv) annual average temperature in K 2 m above the surface, and v) annual average wind speed in m s^{-1} 10 m above the surface. Our albedo maps were resampled to 35 km spatial resolution by averaging albedo values in the finer grid. Correlation was calculated using Pearson's r between each climatological parameter and separate albedo datasets using every pixel of the raster maps, with significance calculated using a two-tailed student's T-test. Specifically, for each correlation we considered the mean albedo of: i) entire season (November-February), ii) beginning of summer (November), iii) central summer period (December-January), and iv) end of summer (February). Every mean considers the whole period 2000-2012.

RESULTS

The results are shown here following 5 steps, from micro- to macro-scale. Thus, the initial analysis at the scale of individual glaciers allowed us to identify the presence or absence of temporal variations and provided insights into more relevant spatial trends, which were then evaluated in more detail at the macro-scale. In all the analyses, the standard error is low ($\sigma_x < 0.001$), which suggests that all the albedo variations are statistically significant.

Analysis of individual glaciers

We analysed individual glaciers that presented a portion of their outlines directly exposed to the sea or ice-shelves. Hence, we randomly chose 95 glaciers around the continent, studying their albedo variations. As concerns temporal trends of the entire period (average albedo from November 2000 to February 2012), none is evident for any of the glaciers, since the albedo changes are <0.0005 y^{-1} and significance is below the 95% confidence level. However, focusing on a spatial pattern, we found a general low variability in albedo of the Indian glaciers (with a range of 0.03 and an average of 0.79, tab. 1) compared to the other two oceanic basins. Glaciers in the Pacific basin feature an albedo range of 0.10 (with a mean albedo of 0.76) and in the Atlantic basin a range of 0.18 (with a mean albedo of 0.74), which make it the most heterogeneous basin and with the lowest values. The standard deviation confirms this variability: 0.01 (Indian), 0.03 (Pacific) and 0.04 (Atlantic).

TABLE 1 - Mean, maximum, minimum and standard deviation (StD) of albedo of analysed individual glaciers, divided into the three oceanic basins (i.e. Indian, Pacific and Atlantic).

	Mean	Maximum	Minimum	StD
Indian	0.79	0.81	0.78	0.01
Pacific	0.76	0.80	0.70	0.03
Atlantic	0.74	0.80	0.62	0.04

Analysing in more details one representative glacier of each basin provides more information supporting our results. For example, observing the albedo of the Dovers and Cosgrove glacier (fig. 2A), about 400 km away from the Amery Ice Shelf (Indian basin, fig. 1A), we did not identify any significant variation over time and the values are always high (mean of 0.81, ranging from 0.79 to 0.84). Conversely, the time series of the Darwin glacier (fig. 2B), in the proximity of the Ross Ice Shelf (Pacific basin), is more heterogeneous with lower albedo values compared to Dovers and Cosgrove glacier, a mean of 0.7 and an absolute range of 0.13 (0.63-0.76). Here it is also possible to observe, intra-annually, a weak seasonal cycle, where the albedo tends to increase in early summer, with the maximum generally at the end of November, followed by a period of decrease until the end of summer. Finally, in the Atlantic basin, a notable glacier is Evans (fig. 2C) in the Antarctic Peninsula, 50 km from the Larsen Ice Shelf. This glacier provides evidence of the sea proximity effect: the range of values is particularly wide, ranging from 0.6 to 0.83, reaching albedo values typical of blue ice (Bintanja, 1999). In addition, the seasonal cycle is stronger for this glacier.

Analysis by Oceanic basins

Now, focusing on the study of spatial variations, we started by dividing Antarctica in its 3 oceanic basins: Indian, Pacific and Atlantic (fig. 3). The first one shows a higher mean albedo (0.81) compared to the other two basins, a maximum of 0.82 (17/11/2001) and a minimum of 0.79 (26/02/2007). The seasonal cycle of the Indian basin mimics the one previously observed for individual glaciers. Compared to the Indian basin, the Pacific and Atlantic basins show different patterns, but similar between each other. The mean albedo of the Pacific basin is 0.79, the maximum is 0.81 (25/11/2001) and the minimum is 0.76 (06/02/2001), confirming the higher variability also seen for Darwin glacier. Unlike in the analysis of individual glaciers, the Atlantic basin is more homogeneous than Pacific one, with an average albedo of 0.79, and lower range between maximum and minimum (0.80 on 25/11/2001 and 0.77 on 26/02/2007). The seasonal cycle replicates the previous ones, but the inter-annual variation shows larger heterogeneity among the different summers (e.g. summer 2009-2010 when the range is much lower than the previous and following summer). In summary, we found higher values in the Indian basin and a similar range in the Pacific and Atlantic basins, with larger variability in the Pacific one. In comparison, Laine (2008) found the highest average albedo values in the Indian and Pacific basins (average of 0.85) between 1981 and 2000, with slightly higher variability in the Indian basin. Lower values were instead found in the Weddell Sea (WS), Ross Sea (RS) and Bellingshausen-Amundsen Sea (BS) with 0.84, 0.80 and 0.78, respectively. The differences with respect to our results can be explained by the different definitions of basins used by Laine (2008), e.g. our definition of the Pacific includes RS and BS, lowering the overall albedo.

Analysis by continentality sectors

For this analysis, we divided the data based on the three continentality sectors (fig. 4): continent, transition and shore. We did not observe significant inter-annual trends in any sector, but we found evidence of intra-annual patterns, with all three continentality zones showing an albedo range typical of snow (King & Turner, 1997; Picard & *alii*, 2012). The first sector has limited absolute variations, with a maximum of 0.83 (17/11/2001), a minimum of 0.79 (26/02/2009) and a mean value of 0.81. The albedo has the same seasonal cycle as found for the previous analyses, with a second local maximum between January and February (excluding the summer 2009-2010). In the transition sector, maximum, minimum and mean albedo are 0.02 lower compared to the values of the continental sector: the maximum is 0.81 (25/11/2001), the minimum 0.77 (26/02/2007) and the mean value 0.79. The transition sector has the same seasonal pattern as the continental one, but the second peak has a lower duration, limited to January, and does not involve all the summers. The coastal sector shows the lowest values compared to the other sectors: 0.77 (09/11/2001), 0.73 (26/02/2007) and 0.76 for maximum, minimum and average albedo, respectively. The intra-annual variability is similar to the two other sectors, in particular to the continental one, showing a pronounced second peak in January-February.

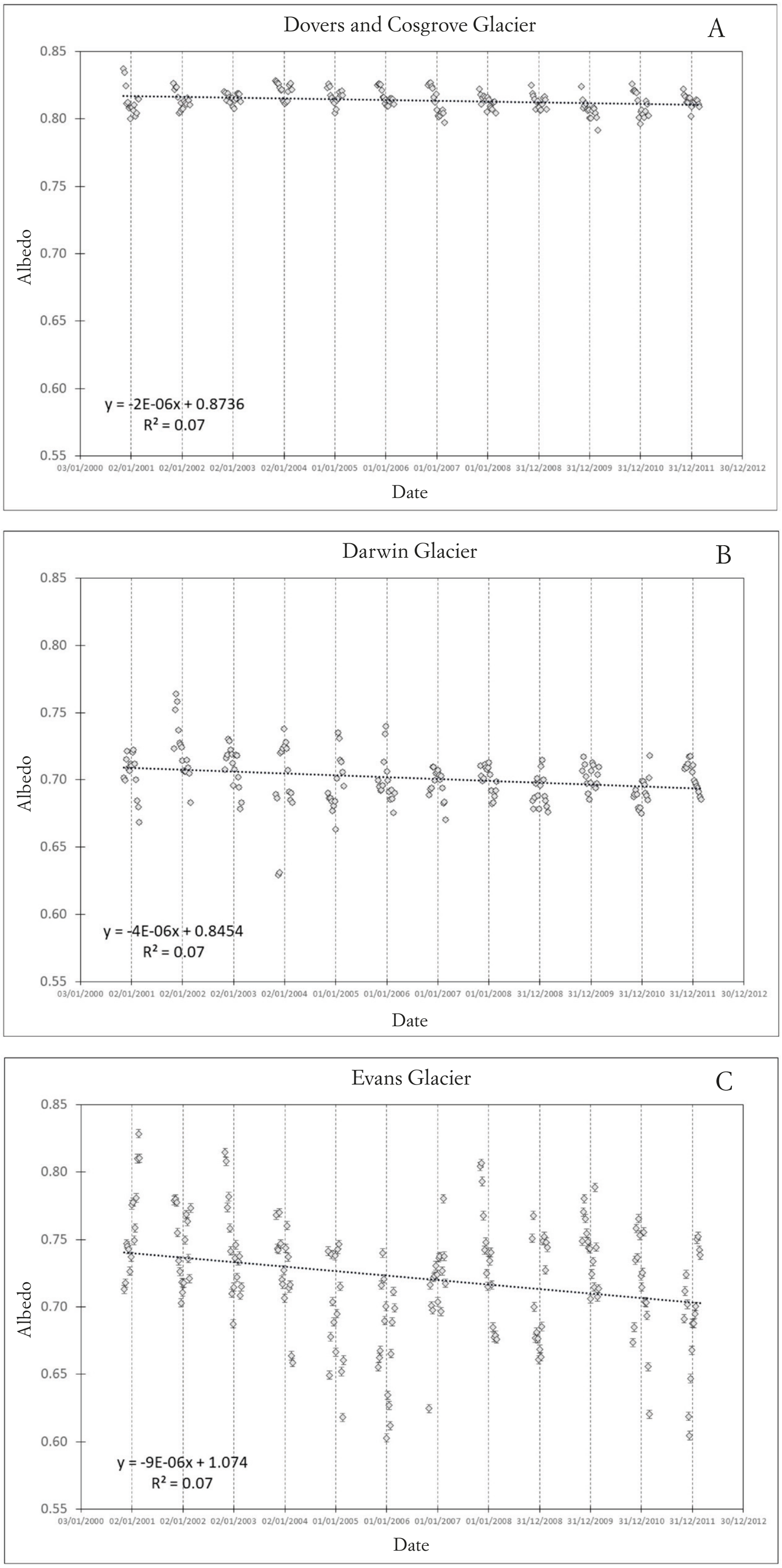

FIG. 2 - Albedo values of Antarctica from 08/11/2000 to 26/02/2012 of Dovers and Cosgrove glacier in the Indian basin (A), Darwin glacier in the Pacific basin (B) and Evans Glaciers in the Atlantic basin (C). Error bars represent the standard error of the mean.

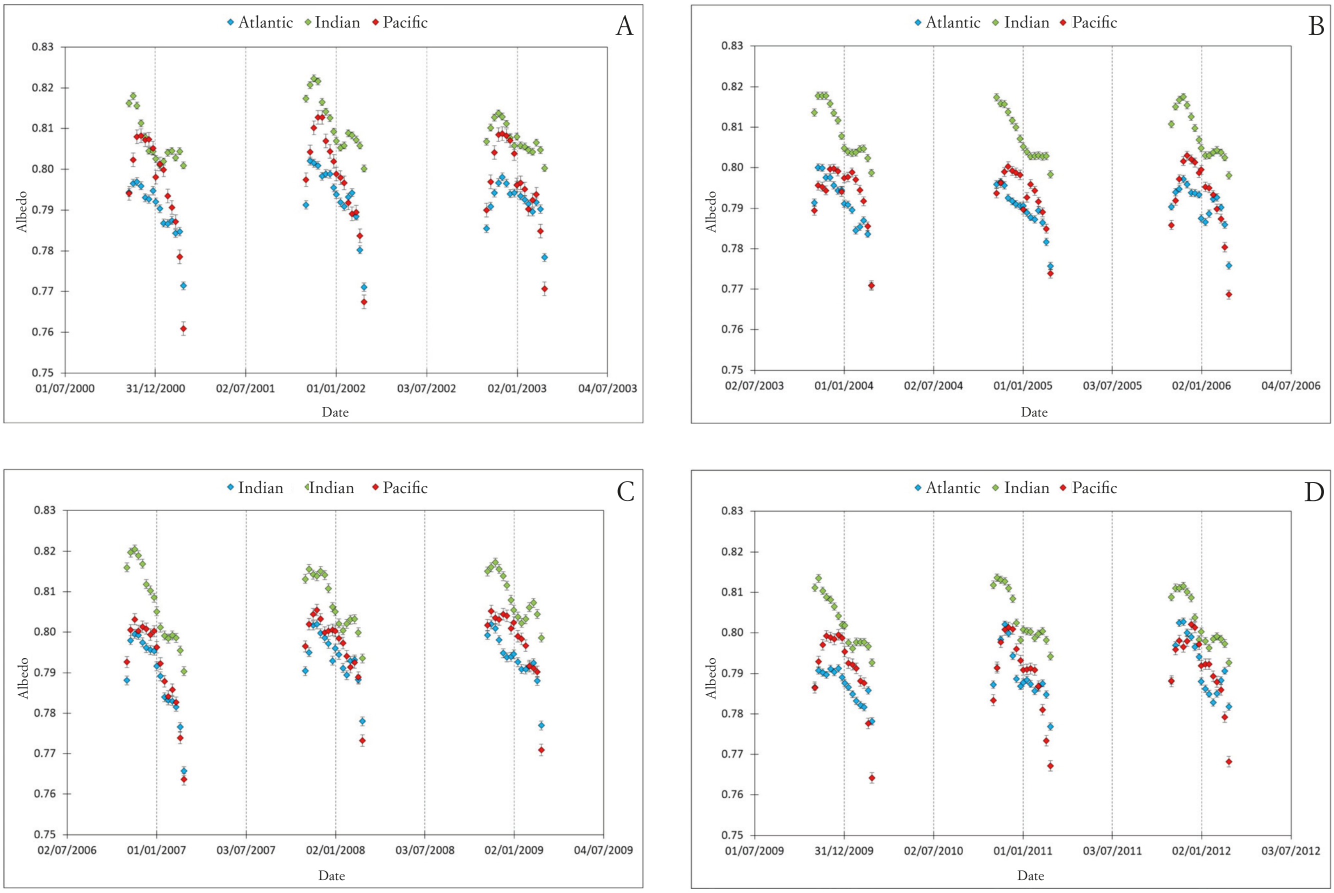

FIG. 3 - Albedo values from 08/11/2000 to 26/02/2012 of Antarctica, divided by oceanic basins: from summer 2000/2001 to 2002/2003 (A), from summer 2003/2004 to 2005/2006 (B), from summer 2006/2007 to 2008/2009 (C) and from summer 2009/2010 to 2011/2012 (D). Error bars represent the standard error of the mean.

Analysis of the Atlantic basin by continentality sectors

Since the Atlantic basin is found to be the most heterogeneous analysing individual glaciers but not at macro-scale, we studied this basin in more detail, dividing it into the three continentality sectors. The continental sector of the Atlantic basin shows a very similar range to the continental sector of the entire Antarctica. We found a mean of 0.81, the same maximum of 0.83 (17/11/2001) and a minimum of 0.78 (26/02/2004), -0.01 lower than the value for continental Antarctica. Here, we observed the same seasonal cycle as the continental sector for the whole Antarctica, again with the exception of summer 2009/2010 when the values are on average lower. Also in the Atlantic transition sector, we did not find a different cycle, but similar patterns to the transition sector of Antarctica. In addition, the mean is once more equal to 0.79, the maximum, dated 25/11/2001, is almost the same with a value of 0.8. Conversely, the minimum is slightly lower than the whole continent transition sector, with a value of 0.75 (26/02/2007). Finally, the Atlantic coastal sector shows a different picture with a higher heterogeneity. It shows the same mean value (0.76) and the same maximum (0.77, on 17/11/2011) of the Antarctic coastal sector and a similar minimum (0.74, on 26/02/2007). Unlike the three continentality sectors, oceanic basins, and Atlantic continental and transition sectors, the intra-annual cycle of the Atlantic shore is not well defined. This might be explained by the very variable climate on the Western side of the Antarctic peninsula (King & Turner, 1997).

Analysis of the entire continent

In the last step, we analysed the albedo variations of the whole Antarctica. We did not find a significant change of the summer averages over time; in fact, the values ranged between 0.79-0.81, with an average of 0.8. Again, the seasonal cycle previously observed is present. Inter-annually, no significant trends are seen between 2000 and 2012. The absolute maximum, for the entire period 2000-2012, occurred on 25/11/2001 with an albedo value of 0.81 and the absolute minimum, on 26/02/2007, with a value of 0.77. The albedo of the whole continent is thus slightly lower than the "Snow on the plateau" albedo range (Dalrymple & *alii*, 1966; Dolgina & *alii*, 1976; Gardiner & Shanklin, 1989).

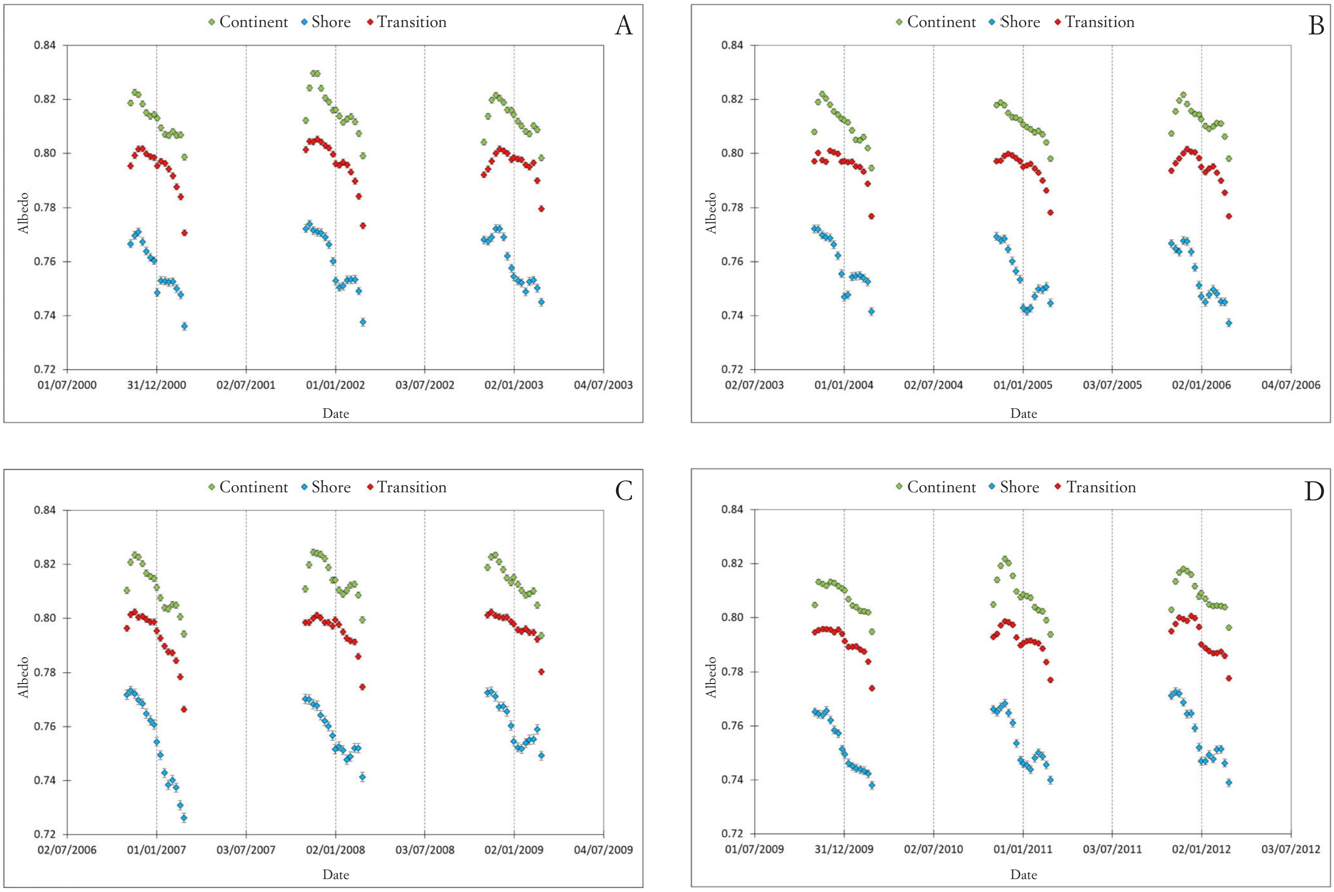

FIG. 4 - Albedo of Antarctic sectors based on continentality from November 2000 to February 2012: from summer 2000/2001 to 2002/2003 (A), from summer 2003/2004 to 2005/2006 (B), from summer 2006/2007 to 2008/2009 (C) and from summer 2009/2010 to 2011/2012 (D). Error bars represent the standard error of the mean.

DISCUSSION

In our analysis, we found limited temporal variability which does not lead to significant trends and a larger spatial variability. In fact, we observed changes from a basin to another and from the continental sector to the shore. In particular, we identified i) a pattern from homogeneous and higher albedo in the Indian basin to more heterogeneous and lower values in the Pacific and Atlantic basins, and ii) an evident decreasing of albedo from inland (i.e. continental zone) to the coastal sector, through the transition zone. In each case, a typical seasonal cycle is observed (increasing albedo in the first half of summer, followed by a decrease during the last months).

This seasonal albedo cycle might be due to the dependence of the albedo on the solar zenith angle (SZA). For instance, Picard & *alii* (2016) found an inverse relationship between albedo and SZA in Antarctica from the analysis of automatic weather station data. A similar relationship was found by Cao & *alii* (2010) by using seven satellite datasets, including Landsat 7 ETM+, MODIS and AVHRR. Therefore, the SZA causes a seasonal albedo cycle, as observed by Pirazzini (2004), since it is higher at the beginning and end of summer. Consequently, the albedo cycle observed in our datasets is probably due to the SZA influence on raw data acquired by MODIS and used in the GLASS algorithm.

As concerns spatial variations, the differences among the basins can be explained from a meteorological and environmental point of view. The results of the correlation analysis between albedo and climatological parameters from RACMO2.3, presented in tab. 2, show negative correlations (except wind speed), with the strongest *r* between albedo and temperature (from -0.52 to -0.62). All correlations are significant at the 99% confidence level. Considering the central summer period, the correlations generally become stronger, especially with precipitation with a value of -0.46. All other correlations, including wind speed and sublimation rate are always lower than ±0.2. The only positive correlation is between albedo and wind speed thus suggesting that an increase of wind speed would lead to increasing albedo. We also calculated correlations for specific dates, obtaining again similar values (see example in tab. 2).

It has to be noted that RACMO2.3 provides only means of yearly observations, and correlation indexes might become higher when comparing e.g. the average of summer climatological data with mean summer albedo. The strongest controls on the albedo at the continent scale, where local conditions are negligible, are therefore temperature (-0.56) and precipitation (-0.39). In fact, the albedo generally depends on the temperature, which controls the morphogenesis stage of snow and ice, and on precipitation, which regulates the presence of fresh snow on the surface (Nakamura & *alii*, 2001).

TABLE 2 - Correlation indexes between albedo (α) and Wind-Speed (WS), Precipitations (P), Sublimation Rate (SR), Surface Mass Balance (SMB) and Temperature (T). All correlations are significant at the 99% confidence level.

	α - WS	α - P	α - SR	α - SMB	α - T
Entire summer season	0.15	-0.39	-0.19	-0.31	-0.56
19/12/2011	0.13	-0.44	-0.21	-0.36	-0.55
Beginning of summer	0.18	-0.38	-0.13	-0.32	-0.52
Central summer period	0.14	-0.46	-0.24	-0.38	-0.62
End of summer	0.13	-0.39	-0.17	-0.31	-0.56

At the local scale, however, other meteorological and environmental factors become important. Concerning continentality, the proximity to the oceans appears to affect Antarctic albedo. Cloudiness, originated from the offshore persistence of low-pressure systems (King & Turner, 1997), has been proposed as an explanation for higher variability in albedo measured at weather stations on the shore (Pirazzini, 2004). However, this assumption cannot be valid in our study as GLASS images are cloud-free. Again, the effect of ocean proximity can be traced back to temperature and precipitation. To further confirm that, we compared the three sectors with the climate zones found by Wagner & *alii* (2018), who divided Antarctica into 12 temperature zones and 5 precipitation zones. The zones with temperatures lower than -43 °C and precipitation lower than 25 mm correspond approximately to the continental sector defined in our study, while the areas with temperatures above -18 °C and precipitation above 500 mm are in agreement with our coastal sector.

In addition, wind, for which contrasting effects have been reported, can also have an important role. Pirazzini (2004) showed that katabatic winds (i.e. winds with very high speed) can increase albedo by limiting snow metamorphism, above all when the absence of warm temperature does not lead to snowmelt. However, most studies report a lowering effect of wind speed on the albedo. In fact, a higher frequency and intensity of katabatic winds can decrease albedo: i) by shaping snow on sloping surfaces and creating sastrugi (i.e. meter-scale longitudinal erosional features, whose axes align with the direction of strong winds, Warren & *alii*, 1998; Frezzotti & *alii*, 2002); ii) by increasing surface melt, and iii) by exposing blue ice through snow erosion (e.g. Victoria Land area, in proximity to David glacier) (Winther & *alii*, 2011).

Lenaerts & *alii* (2017) focused on the double role of katabatic winds near the grounding zone of ice shelves. They found that katabatic winds increase near-surface temperatures by 3 K through disruption of the surface-based temperature inversion, leading to a doubling of surface melt; these winds continuously scour the surface exposing blue ice and firn. Further still, katabatic winds can also shape the surface, creating wind glaze areas that show lower albedo than snow (e.g. in mega-dune fields, on the Antarctic plateau, associated also with sastrugi) (Frezzotti & *alii*, 2002; Scambos & *alii*, 2012; Das & *alii*, 2013). From the positive correlation index between wind speed and albedo, we can hypothesize that, at the macro-scale (i.e. 35 km spatial resolution in our case), the effect of limiting metamorphism by strong katabatic winds leads to an increase of albedo, taking over all other negative effects. An example of local scale effects is instead on the coast of Ross Sea, where temperatures near the melting point and the decreased intensity and frequency of katabatic winds during the summer allow a strong metamorphism of the snow (Pirazzini, 2004), lowering the albedo.

Meteorological and environmental factors also explain the differences seen among the oceanic basins. For instance, the Indian sector includes the Antarctic plateau, with a high average altitude, thus lower temperatures and reduced snow metamorphism. The Pacific basin consists of the area to the west of the Transantarctic Mountains with a wide coastal zone, including the Ross coast, where Pirazzini (2004) found high albedo variability. The Atlantic basin is characterized by slightly different albedo values compared to the Pacific one. This might be due to the combination of two opposite factors: i) the presence of the Antarctic Peninsula, which reaches the lowest latitude of the continent and thus shows the highest temperatures, and ii) the occurrence of cyclones and easterly winds, producing frequent snowfall and almost continuous drifting snow, which supply the surface with small and highly reflective snow grains (Pirazzini, 2004).

Finally, as regards the analysis of the Atlantic basin by continentality zones, we observed a similar variation in the albedo of the continental and transition zone and a different situation in the Atlantic coastal zone. This difference could be due to the mixing of the heterogeneous meteorological and geographical conditions (e.g. temperature, precipitation, wind speed, proximity to the ocean, etc.) occurring in the Atlantic coastal zones, unlike the other sectors. Values seen in the Atlantic coastal zone however do not affect patterns in the other areas: the whole Atlantic basin, the whole shore sector and the whole continent.

CONCLUSION

In this study, we analysed the surface albedo of Antarctica between summer 2000/2001 and summer 2011/2012 by means of the GLASS product. We found limited temporal variability from the micro-scale analysis of individual glaciers. Considering the spatial variability, mean albedo ranges from 0.79 (Pacific and Atlantic basins) to 0.82 (Indian basin) and from 0.76 (shore) to 0.81 (continent).

This decrease in albedo from the inner areas to the shore can be explained by sea proximity and larger meteorological variability (in temperature, precipitation and wind speed influencing the presence of fresh snow and its metamorphism; Nakamura & *alii*, 2001). This is further demonstrated by the comparison between GLASS albedo dataset and RACMO2.3 climatological product (Van Wessem & *alii*, 2014a, 2014b), where we found good correlations especially with temperature and precipitation. Other factors might include the presence of exposed ice or nunataks close to the coast (Stenmark & *alii*, 2014), lowering albedo at the scale of GLASS pixels and topography (less constant on the shore than on the Antarctic plateau). These findings permit to assess a spatial pattern but not a trend over time. In fact, the relationship between albedo, oceanic basins and continentality points to heterogeneous patterns among the basins and an increasing variability from the inner continent to the shore. In general, our albedo values are: i) slightly lower than the typical range of "snow on the plateau" (0.80-0.90, Dalrymple & *alii*, 1966; Dolgina & *alii*, 1976; Gardiner & Shanklin, 1989); ii) in agreement with field data from Hells Gate, Neumayer, Concordia and Reeves Névé stations (0.58-0.82, Pirazzini, 2004); iii) slightly lower than values of 0.80-0.85 found by Grenfell & *alii* (1994) at Scott South Pole and Vostok stations. However, for some glaciers the albedo reaches values equal or lower than blue ice (0.56-0.69 according to King & Turner, 1997; Bintanja, 1999; Reijmer & *alii*, 2001; Hui & *alii*, 2014).

In future research, the results obtained by means of GLASS products should be compared with other remote-sensing albedo datasets (e.g. MOD10A1, CLARA-A2, bearing in mind that MOD10A1 needs cloud filtering and CLARA-A2 has a much coarser resolution). This would allow to i) ensure the reliability of GLASS; ii) increase the period of observations, from the 1980s up to the present, and investigate longer-term trends in Antarctic albedo, iii) assess the impact of albedo variations on the energy budget at the local and global scale.

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