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Long-Term Variability of Surface Albedo and Its Correlation with Climatic Variables over Antarctica

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Abstract: The cryosphere is an essential part of the earth system for understanding climate change. Components of the cryosphere, such as ice sheets and sea ice, are generally decreasing over time. However, previous studies have indicated differing trends between the Antarctic and the Arctic. The South Pole also shows internal differences in trends. These phenomena indicate the importance of continuous observation of the Polar Regions. Albedo is a main indicator for analyzing Antarctic climate change and is an important variable with regard to the radiation budget because it can provide positive feedback on polar warming and is related to net radiation and atmospheric heating in the mainly snow- and ice-covered Antarctic. Therefore, in this study, we analyzed long-term temporal and spatial variability of albedo and investigated the interrelationships between albedo and climatic variables over Antarctica. We used broadband surface albedo data from the Satellite Application Facility on Climate Monitoring and data for several climatic variables such as temperature and Antarctic oscillation index (AAO) during the period of 1983 to 2009. Time series analysis and correlation analysis were performed through linear regression using albedo and climatic variables. The results of this research indicated that albedo shows two trends, west trend and an east trend, over Antarctica. Most of the western side of Antarctica showed a negative trend of albedo (about -0.0007 to -0.0015 year^{-1}), but the other side showed a positive trend (about 0.0006 year^{-1}). In addition, albedo and surface temperature had a negative correlation, but this relationship was weaker in west Antarctica than in east Antarctica. The correlation between albedo and AAO revealed different relationships in the two regions; west Antarctica had a negative correlation and east Antarctica showed a positive correlation. In addition, the correlation between albedo and AAO was weaker in the west. This suggests that the eastern area is influenced by the atmosphere, but that the western area is influenced more strongly by other factors.

Keywords: Antarctica; ice sheet albedo; Antarctic oscillation index; in situ temperature

1. Introduction

Recently, the Polar Regions have provided remarkable examples of rapid environmental change [1]. In addition, these regions are important areas for climate change. The Antarctic and Arctic have direct effects on climate change despite their isolation from human settlements [2]. Antarctic climatic conditions are directly linked to ice sheet dynamics and environmental changes at the global scale [2]. The Antarctic cryosphere has experienced increasing trends in the rates of loss of sea ice and ice shelves due to warming [3]. The Intergovernmental Panel on Climate Change (IPCC) confirmed that the Antarctic ice sheet has been losing mass during the last two decades. The average rate of ice sheet loss in Antarctica likely increased by about 30 Gt·year^{-1} from 1992 to 2001 and by about 147 Gt·year^{-1} from 2002 to 2011 [3]. These losses have occurred mainly in the northern Antarctic Peninsula and in the Amundsen Sea sector of west Antarctica. The extent of sea ice over Antarctica showed strong regional differences between the years 1979 and 2012 [3]. Previous studies based on satellite surface air temperature data revealed trends of increasing temperature [4,5]. Furthermore, the number of days with an average daily temperature greater than zero has increased during the last 50 years [6,7]. However, recent studies have indicated the occurrence of an "Antarctic paradox", with more cooling and increasing sea ice extent over Antarctica despite global warming, and these studies indicate that the rates of sea-ice cover and ice mass variation have different trends across the Antarctic region [1,8]. Antarctic sea-ice coverage can be considered to exhibit two separate trends, a decreasing trend of ice cover in the Bellingshausen Sea and an increasing trend in the western Ross Sea [1]. In addition, Rignot indicated variability in the trends of ice mass [8]. Antarctica shows differing trends such that the Bellingshausen Sea and Amundsen Sea lose mass while the Ross Sea and Weddell Sea gain mass. In other words, the extent to which the glaciers of Antarctica have begun to melt varies by region. Furthermore, in the case of station surface temperature, 11 stations have shown a warming trend in annual surface temperature, but seven stations have shown a cooling trend [7]. Specifically, temperature appears to exhibit different regional trends in the maritime regions and continental regions of Antarctica.

Thus, understanding the changes over the entire Antarctic cryosphere is important in climate study. Perovich et al. [9] mentioned that ice–albedo feedback plays a key role in the amplification of climate change in Polar Regions [9]. Albedo of a surface is the ratio of the amount of energy reflected and the amount of energy absorbed by that surface. Ice–albedo feedback from ice and snow is one of the most important factors in climate change observed in Antarctica because almost the entire South Pole region is covered by snow or ice, which has high albedo and reflects most of the incoming solar energy. As the snow/ice surface begins to melt, the albedo is lowered; hence, more radiation can be absorbed, which increases the temperature, causes more melting, and in turn lowers the albedo further. This warming feedback for Antarctica is accelerating [10]. In this feedback, the change of albedo is a next-step response after the change of snow, and vice versa. Albedo is an important factor affecting the energy budget and climate change due to radiation budget is an important factor of variation on energy budget [11]. Albedo of sea ice and ice sheets is one of the most important factors affecting the radiation budget in Polar Regions. Additionally, the net solar radiation absorption and the energy balance at the terrestrial surface are controlled by the surface albedo [12], and variability of albedo determines the characteristic energy balance in climate models. In the case of Arctic, Foley [13] stated that energy budget increased 2.5 MJ·m^{-2} in one year based on albedo data.

Recently, the cryosphere has received much attention because of its connection to climate change [14,15]. Databases pertaining to surface albedo, an indicator of cryosphere variability, especially high-quality data for long-term periods, such as 30 years (generation of climate), are currently insufficient. As a result, there have been fewer climate analysis studies on albedo over Polar Regions than studies that examined other climatic factors. Laine [16] performed an analysis of the change of the regional albedo of ice sheets and sea ice in Antarctica from 1981 to 2000 using Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder data. However, most studies have focused on the Arctic, and there have been few studies pertaining to the spatial trend of albedo, such as those of Laine [17], Stroeve [18], and Istomina et al. [19]. Overall, albedo variability is an indicator for analyzing the long-term climate change of Antarctica. Therefore, it is necessary to analyze the amount of long-term change of albedo.

Previous studies have shown that: (a) variations of albedo and temperature have a strong relationship in high-latitude areas [10,13]; (b) albedo can represent the difference, by its value range, between sea-ice types, such as first-year ice, multi-year ice, and nilas ice [20,21]; (c) sea-ice concentration has a strong correlation with the El Niño Southern Oscillation and sea-ice albedo [11,22]; and (d) the South Pole region has shown a consistent trend of increasing temperature [4,7]. However, these previous studies have some shortcomings, such as insufficient data for quantitative analysis of climatic change and variability of albedo and climate over the Antarctic. In addition, we need to analyze numerous climatic factors to reveal the environmental variation in Antarctica.

The purpose of this study is to analyze environmental changes based on quantifying the long-term variability of glacier albedo over Antarctica. To understand the variation of albedo, we analyzed long-term glacier albedo and its relationship with climate variables. To achieve this goal, we used satellite albedo data during summer, considering the characteristics of the Antarctic, calculated the rate of change per year of albedo, and performed time series analysis and correlation analysis.

2. Scope of the Study and Data

The study area covers Antarctica, from about 65°S to 90°S and 180°E to 180°W, and the temporal scope of the study is 28 years (1982 to 2009).

2.1. Albedo

The Satellite Application Facility on Climate Monitoring (CM SAF) in EUMETSAT provides surface albedo as a part of one of its products (CLARA-A1, edition 1), which includes the CM SAF clouds and albedo and radiation datasets obtained from AVHRR data over a period of 28 years (1982–2009). The albedo data of CLARA-A1 were obtained by several AVHRRs of the National Oceanic and Atmospheric Administration (NOAA). Generally, albedo based on satellite observation does not represent blue-sky albedo, which is the real representation of albedo, but rather black-sky albedo and white-sky albedo, which assume extreme atmospheric conditions. Black-sky albedo assumes completely directional solar irradiance, similar to dark sky, whereas white-sky albedo assumes a completely diffuse condition of illumination [23]. We selected black-sky albedo, which is a broadband albedo obtained by using a mathematical method within the wavelength range of 0.25–2.5 μm by AVHRR, due to a Global Climate Observing System report that indicated that the use of black-sky surface albedo is desirable for forecasting climate change [24]. According to the CM SAF validation report [25], the RMSEs of estimated albedo are 0.173 at Neumayer station (70.65°S, 8.25°W) and 0.188 at Syowa station (69°S, 39.59°E) over Antarctica, respectively. Recently, several studies used the CLARA A1 surface albedo data [26–28]. In this study, we selected monthly mean data of albedo to match the temporal resolution of the in situ temperature data during 1982 to 2009.

2.2. In Situ Temperature

Surface temperature is an important factor in climate change, and it is also closely related to albedo, the main variable of this study. Therefore, we also collected and analyzed temperature data. We used surface temperature data that were observed at stations across Antarctica provided by the Reference Antarctic Data for Environmental Research (READER). These data include monthly mean results of station data as near-surface temperature data. We used data from three sites located in the study area (Faraday/Vernadsky, Casey, and Dumont d'Urville), which had no missing data. The latitude and longitude coordinates of the stations are 65.4°S, 64.4°W (Faraday Vernadsky), 66.3°S, 110.5°E (Casey), and 66.7°S, 140.0°E (Dumont d'Urville). READER data were also used for research of long-term climate change over Antarctica by Turner [7]. The temperature data from READER can be downloaded via the web (http://www.antarctica.ac.uk/met/READER/data.html).

2.3. Antarctic Oscillation

The Antarctic Oscillation (AAO) is a seesaw phenomenon between middle and high latitudes in the Southern Hemisphere [29]. AAO affects the variation of sea ice, sea surface temperature, and surface temperature over Antarctica [30]. The NOAA Climate Prediction Center (CPC) provides monthly AAO index data. The NOAA CPC explains that these data are calculated from the monthly

700-hPa height anomalies poleward of 20°S latitude using an empirical orthogonal function (EOF). These data are normalized according to standard deviation using the base period from 1979 to 2000 to set the principle time series [31]. AAO data are calculated for the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset, and the seasonal cycle is removed using the monthly mean height field. These data were used for researching the relationship between AAO and rainfall over the Korean Peninsula by Choi [31]. In the case of a positive index value, the polar vortex is stronger than the mean pressure pattern. In the opposite case, the vortex is weaker than the pressure pattern. Using the characteristics of the index, it is possible to monitor atmospheric circulation in Antarctica [30]. In this study, we used monthly AAO data from 1982 to 2009, which can be downloaded from the NOAA CPC homepage at http://www.cpc.noaa.gov/.

3. Results

3.1. Spatial Trend and Classification of Albedo over Antarctica

To observe albedo, solar radiation is indispensable. This being so, the collection of albedo data in Antarctica is possible only in the summer because of the polar night during the winter months. For this reason, we set the study period as the summer (November–February) of each year. In general, maximum sea-ice extent in Antarctica is observed in September, whereas minimum extent occurs in February. Therefore, we divided the study periods into two terms, albedo average for November–December and albedo average for January–February, to reflect the seasonal characteristics of Antarctica.

We calculated the annual rate of change of albedo for each period by simple linear regression analysis, pixel-by-pixel, using time as the independent variable and albedo data as the dependent variable. Figure 1 illustrates the distribution of the change of albedo mean per year for each pixel in three portions of the summer study period (whole period, November–December, and January–February) over Antarctica. We divided the result into 11 parts using intervals of 0.04 to obtain a deeper understanding of the trend around the South Pole. The blue shading represents a positive trend of albedo change, and the red shading represents a negative trend. The spatial distribution of the rate of albedo change represents a different trend in West Antarctica (WA) than in East Antarctica (EA) during the whole period and the January–February period (Figure 1a). This pattern is similar to the surface temperature trend in a previous study by Turner [7]. Additionally, Comiso indicated a cooling trend on the plateau of EA for 1987 to 1998, but observed a remarkable warming trend in WA [4,6,7,32,33]. In this study, we analyzed the time series of albedo over Antarctica during the two parts of the study period: albedo means in November–December and January–February. The variation of the albedo average was 0.0002 year^{-1} in November–December and 0.0003 year^{-1} in January–February over the entire continent. It is apparent that albedo is increasing steadily over Antarctica. Figure 1b,c shows the albedo changes per year in the study area for the two periods (November–December average and January–February average). Both WA and EA show greater variation for January–February mean than for November–December mean per year. In general, Antarctica receives more solar radiation during the middle of summer, and thus there is more heating of the surface. Additionally, the state of snow and ice is in flux because greater melting of snow and ice occurs in the middle of summer. Although almost all of WA shows a negative trend, the Bellingshausen/Amundsen Sea regions show a positive trend in November–December.

We thus classified Antarctica into three regions according to the variation of albedo (Figure 1d). EA shows an increase in the variability of albedo change per year in all study periods. We refer to this region as Section 3 (Figure 1d, blue section). On the other hand, we divided WA into two regions because the area shows two variabilities for albedo mean in November–December. We defined Section 1 by its decreasing rate of change of albedo during all periods (Figure 1d, red section), and Section 2 according to its increasing rate of change of albedo for the period November–December (Figure 1d, yellow section). Section 1 is adjacent to Ross Sea and Weddell Sea, which have huge ice shelves.

Previous studies have shown a positive trend in coverage and season length of sea ice in the Ross Sea and Weddell Sea regions (adjacent to Section 1) [1,34]. Both Sections 2 and 3 include areas of ice sheet, but the Bellingshausen/Amundsen Sea is adjacent to Section 1 and the Indian Ocean and Pacific Ocean are adjacent to Section 3.

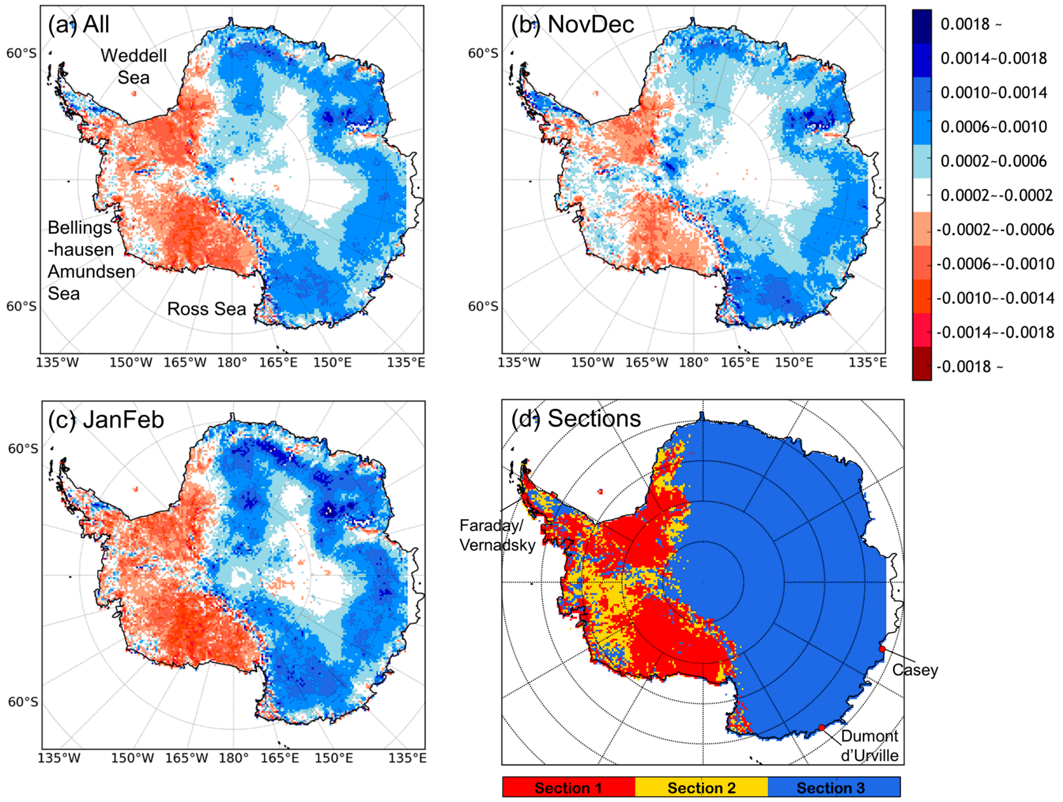

Figure 1. Spatial distribution of the change of albedo per year from 1983 to 2009 by pixel over Antarctica, and albedo variability values are divided into 11 levels with intervals of 0.0004. Blue shading indicates a positive trend of albedo mean in each of the periods and red shading indicates a negative trend. (**a**) Albedo mean for the whole period; (**b**) albedo mean for November–December; and (**c**) albedo mean for January–February; (**d**) Classification of Antarctica from change of albedo per year. Red color is Section 1, in which the rate of change of albedo decreased for all of the study period; yellow is Section 2, where the rate of change decreased in January–February but increased in November–December; and blue is Section 3, where the rate of change of albedo increased for the entire study period. Red dots indicate locations of stations.

3.2. Homogeneity Test of Each Section

Each section was subjected to homogeneity testing because they suitably reflect the temporal and spatial characteristics of albedo. Thus, for this testing, we set out to analyze the standard deviation during the study period for each section and to analyze the EOF for each of the study periods. We computed the standard deviation (SD) of albedo for each of the sections to ascertain the albedo variability of each. Figure 2 illustrates the SD; the upper figure shows the period of November–December and the lower one shows the period of January–February. The orange line represents Section 1, the blue line is for Section 2, and the black line is for Section 3. The vertical range of the lines of each color indicates SD, which reveals the extent of the uncertainty. In the case of Section 1, the SD of January–February is greater than the other deviations. However, as shown in the graph, all of the sections show a few standard deviations within the range of albedo values (0–1). The distribution of the albedo is relatively constant for each section.

We also performed EOF analysis to understand the principal signal of Antarctic variation in albedo. The results of the EOF analysis indicate a simplification of the spatial-temporal data of albedo by the transformation. These results represent the principal components of surface albedo in the study area, and the components indicate the influence of the variation on surface albedo. We compared the distribution pattern between the results of EOF and albedo trend each sections; if trend of albedo each sections represent similar to the EOF patterns, the sections are homogeneous considering the temporal-spatial pattern of albedo during the study periods. Figure 3 shows EOF-1 of the albedo in each of the periods: November–December in Figure 2a and January–February in Figure 2b. The first EOF eigenvalues are 0.78 (15.12%) and 1.11 (15.59%), respectively. These values explain the extent of albedo variation. Overall, the distribution of EOF-1 is similar to that of the change of albedo per year, which was calculated by simple linear regression, during the same period (Figure 1b,c). Opposite trends are shown between WA and EA. In summary, the major component as EOF-1 is similar to the pattern of change of albedo per year, which is described individually for each component. From the results of EOF, each section appears similar to Figure 1d, reflecting a principle signal of Antarctic variation, and these area distributions are homogeneous.

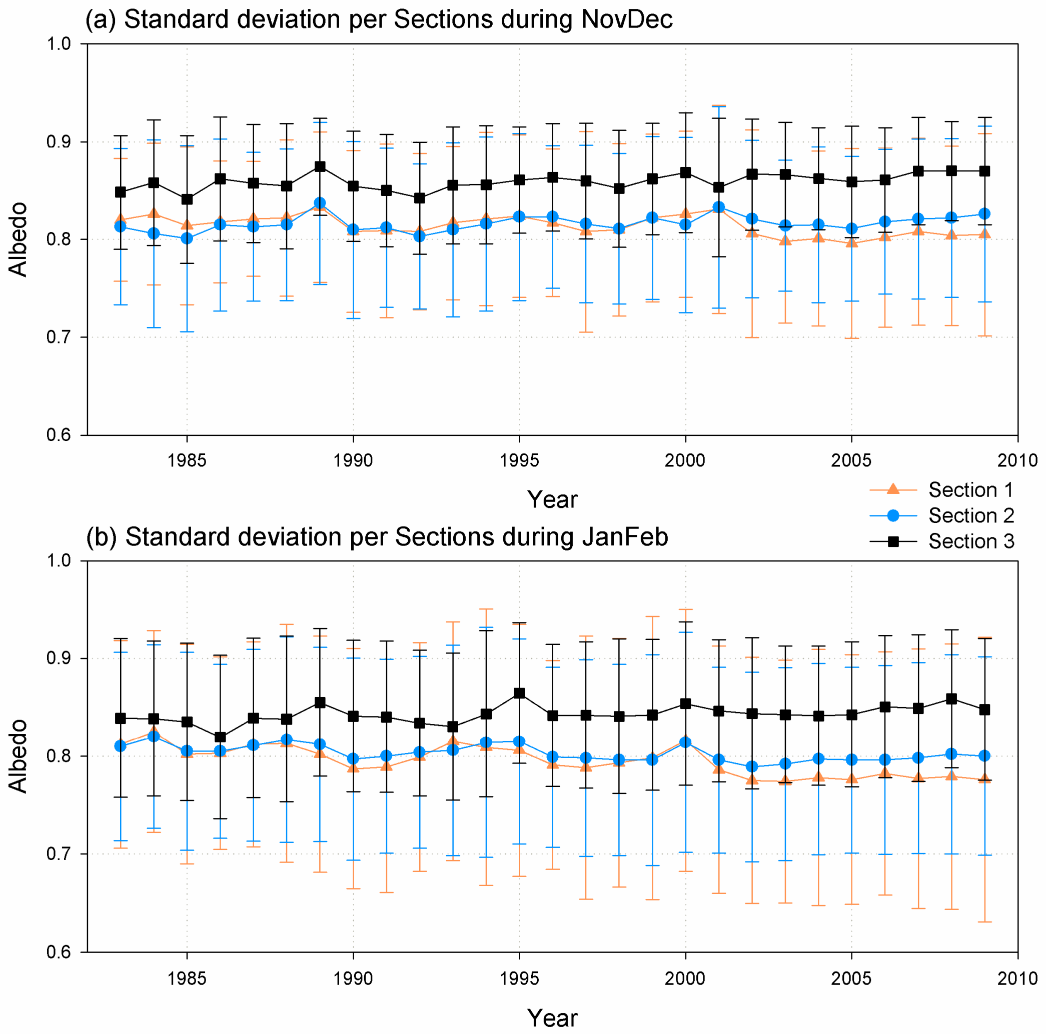

Figure 2. Distribution of standard deviation on albedo time series for each section (orange is Section 1, blue is Section 2, and black is Section 3), where vertical lines indicate the standard deviation in each section: (**a**) November–December; and (**b**) January–February.

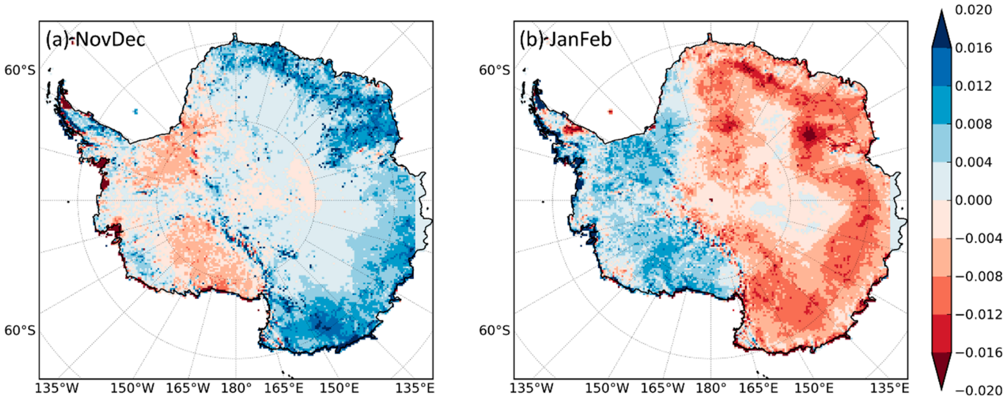

Figure 3. EOF-1 results of 2-month-average 1983–2009 albedo data: (**a**) November–December period; and (**b**) January–February period shown as change of albedo per year for each study period.

3.3. Time Series Analysis

We calculated the change of albedo per year for each of the three sections (1, 2, and 3) using simple linear regression analysis. Time is an independent variable and albedo is a dependent variable. In Section 3, both the January–February average trend and the November–December average trend were 0.0006 year^{-1}. In contrast, Section 1 shows negative trends, −0.0007 year^{-1} and −0.0015 year^{-1}, for both periods, respectively, and Section 2 shows two different trends, a positive average trend of 0.0004 year^{-1} for November–December and a negative average trend of −0.0007 year^{-1} for January–February. The periods of January–February and November–December have the same trend in Sections 1 and 3, but have two different trends (positive and negative) in Section 2. During our analysis, we focused on Sections 1 and 3, for which there were no missing surface temperature observation data during the study period, and the period of January–February, during which the surface would experience stronger solar heating.

Figure 4 shows time series of average albedo, in situ surface temperature, and AAO for each of the sections during January–February (Figure 4a shows Section 1 and Figure 4b shows Section 3). In Section 1, albedo shows a negative trend with a change of albedo per year of −0.0015, average value of 0.79, and standard deviation of 0.01. In situ temperature (Faraday/Vernadsky) shows a positive trend with a change of albedo per year of 0.0002 ± 0.66 °C·year^{-1} and a time series average temperature of 1.15 °C. This change rate value is very small compared with the result of a previous study that obtained a rate of 0.036 ± 0.088 °C·year^{-1} for the period of 1971 to 2000 [7]. Thus, albedo and surface temperature show opposite patterns with opposite peaks in Section 1. However, the trends appear relatively weak but still opposite after 2000. Table 1 shows this opposite trend between albedo and temperature changes is weak over Arctic [10] and Antarctic Section 1. Temperature change trends over both regions appear a similar negative pattern, while albedo change over Antarctic Section 1 shows a stronger negative trend than that over Arctic due to the impact of vegetation and changes in sea ice near each area. It clearly represents that albedo has a negative relationship with temperature in Antarctic Section 1 and Arctic.

Table 1. Comparison of variation of albedo and temperature between Arctic tundra (Chapin et al. [10]) and Antarctica (this study).

	Albedo	Temperature
Arctic tundra *	−0.0002	0.0500
Antarctica **	−0.0023	0.0560

* Data for variability of albedo and temperature in Arctic tundra are from a previous study [10]. Tundra data are based on AVHRR pathfinder data (Albedo: surface broadband albedo; Temperature: surface skin temperature).
** Section 1 after 2000 in this study.

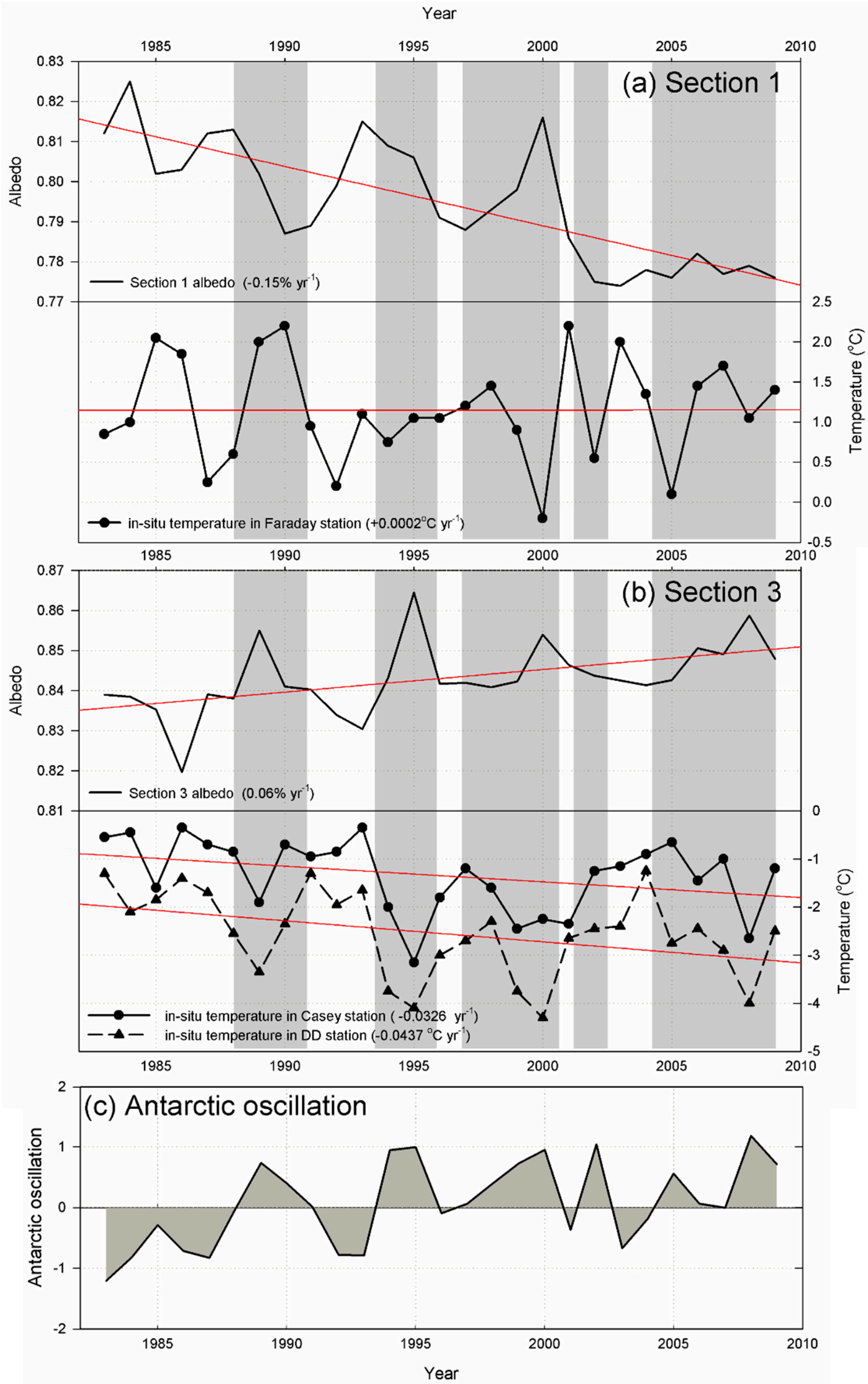

Figure 4. Time series of albedo and climatic variables (temperature and Antarctic oscillation) comparing the same period in Sections 1 and 3. Black line is time series and red line is trend of each variable (from the top: albedo, in situ temperature). (**a**) Section 1 (from the top: albedo and Faraday/Vernadsky station); (**b**) Section 3 (from the top: albedo, Casey station shown by dotted line, Dumont d'Urville shown by a triangle line); and (**c**) Antarctic oscillation.

In Section 3, the albedo trend during the study period is positive at 0.0006 year^{-1}, the time series average albedo is 0.84, and the standard deviation is 0.008. However, the January–February average in situ temperature from the same period at both the Casey and the Dumont d'Urville stations shows a cooling trend in Section 3. The trend at the Casey station is -0.033 ± 0.75 °C·year^{-1}, and the average temperature of the study period is -1.35 °C. At the Dumont d'Urville station, the trend is -0.044 ± 0.88 °C·year^{-1} and the average temperature of the study period is -2.5 °C. The time series trends for Section 3 reveal opposite patterns for albedo and surface temperature. Section 3 (similar to EA) shows a higher average albedo than Section 1 due to the difference of ice sheet thickness. In general, albedo values are higher when ice is thicker [20,21]; the ice in EA is thicker than the ice in WA. In the case of in situ temperature, Section 3 shows cooling compared with Section 1, as reported in a previous study [7]. AAO shows a positive trend per year of 0.0444 same as albedo trend in Section 3. The shaded parts in Figure 4 indicate the periods of positive AAO, when there is generally a strong polar vortex and a decrease in pressure and temperature. Section 3 also shows a general correlation: the AAO annual time series has the same peak point as the albedo, and AAO has a symmetric pattern with the surface temperature at the Casey and Dumont d'Urville stations when AAO is positive. However, Section 1 has a different pattern of slightly rising temperature and decreasing albedo when AAO is positive.

3.4. Correlation Analysis with Climatic Variables

Table 2 shows correlation coefficients between albedo and climatic variables during January–February from 1983 to 2009. The albedo time series was compared with the surface temperature of the Faraday/Vernadsky station, and the resulting correlation coefficient for Section 1 is -0.30. This value indicates a low negative correlation, although the time series patterns indicate that albedo and surface temperature had symmetric patterns until 2001 (Figure 4). For the period, the correlation coefficient between albedo and the Faraday/Vernadsky station temperature is -0.4. In addition, we used the same steps to perform the analysis for Section 3. The albedo time series was compared with the surface temperature of the Casey and Dumont d'Urville stations. The results of the correlation analysis yielded a correlation coefficient of -0.74. Both Sections 1 and 3 had a negative relationship between temperature and albedo. In other words, albedo increases while temperature decreases, or vice versa; this result provides albedo–temperature feedback. In addition, the average albedo data of January–February were compared with AAO in the west and east sections, separately.

In Section 1, this component showed a low correlation with albedo with a correlation coefficient between AAO and albedo of -0.30. In the case of Section 3, the correlation between albedo and AAO was 0.68. The AAO index provides information about the atmospheric circulation in Antarctica. In general, when AAO is positive, a strong polar vortex exists, cold air remains in Antarctica, and cooling occurs. This phenomenon contributes to a decrease in temperature and increase in albedo. Section 3 showed a high correlation between albedo and AAO compared with that in Section 1. We can infer the relationship between atmospheric pressure and variability of albedo by observing the results. In addition, the snowfall trend was positive in EA (akin to Section 3) during 1982 to 2002 [35]. Its trend affected the albedo time series because snow is the contributing factor that has the highest albedo value. However, Section 1 showed a negative correlation with this phenomenon, which means that this section had an abnormal mechanism with AAO. This may have been due to WA (similar to Section 1) having higher variation on the ice sheet than EA [36]. Additionally, the factor of circumpolar deep water is involved, which is melting ice beneath the grounding line of WA [37]. The albedo trend of Section 1 may have a relatively low correlation with other climatic variables (such as temperature and AAO.

Table 2. Correlation coefficient between albedo and climatic variables at each section.

	Albedo (Section 1)	**Albedo (Section 3)**
In situ temperature	-0.30 (Faraday/Vernadsky)	-0.74 (Casey) -0.74 (Dumont d'Urville)
AAO	-0.30	0.68

4. Summary and Discussion

The key results of this study are as follows: (a) long-term variability of albedo has different trends in different regions (positive in EA, but negative in most of WA); (b) the patterns of albedo and in situ surface temperature are opposite; and (c) in Section 3 (EA), there was a strong positive correlation between albedo and AAO.

Although the overall variation of albedo involved an increase of 0.0002 year^{-1}, albedo variability showed polarization of negative and positive trends over Antarctica from 1983 to 2009. Section 3 (covering EA) showed a positive trend. In contrast, the whole of WA showed a negative trend, except for a part that showed a positive trend for November–December. On the basis of these results, we classified Antarctica into three sections (1, 2 and 3) and then analyzed time series trends of albedo and climatic variables for each section. In Section 1, albedo had a negative trend of −0.0015 and surface temperature had a small positive trend of 0.0002 °C·year^{-1} (at Faraday/Vernadsky station). In Section 3, albedo had a positive trend of 0.0006 year^{-1} and surface temperature had negative trends of −0.033 °C·year^{-1} and −0.044 °C·year^{-1} at the Casey and Dumont d'Urville stations, respectively; AAO had a positive trend of 0.0444 year^{-1}. There was a symmetric pattern between albedo and surface temperature during the study period. However, this pattern was partly abolished in Section 1 after 2000. The regional polarization of albedo trend between west and east increased over time. The same regional trend also appeared in the case of surface temperature. The local in situ temperature trend was positive at the Faraday/Vernadsky station, but negative at the Casey and Dument d'Urville stations. These differences are representative of in situ temperature results from previous studies [4,7]. Thus, in situ temperature increases when albedo decreases and vice versa, which can be explained by evidence of the ice and albedo mechanism from observed data over Antarctica. In addition, adjacent Antarctic ocean sectors appear to show an Antarctic paradox. Previous studies have confirmed that sea-ice extent (or sea-ice cover, ice mass balance) has a positive trend at the Pacific Ocean, Weddell Sea, and Ross Sea, but a negative trend at the Bellingshausen/Amundsen Sea [1,8,32]. The results of this study and those of previous studies indicate that Antarctica has regional marine and continental trends. This study represents an Antarctic continental paradox according to albedo, which is one of the Essential Climate Variables, and these results are connected to the oceanic paradox in Antarctica reported in previous studies [1,8].

5. Conclusions

There was a need to reveal factors that appear in the regional trend over Antarctica. Therefore, a correlation analysis was performed between albedo and climatic factors to investigate the causes of the different albedo trends. In Section 3 (EA), most of the variables showed strong correlations. These results provide evidence of an interrelationship between surface albedo and climatic variables in Section 3. Antarctica had a positive phase of AAO trend through the study period, which shows that when there is a strong polar vortex, the whole of the South Pole exhibits a cooling trend. The obtained results, in conjunction with those of previous studies, indicate that snowfall and ice mass are increasing in EA [34]. On the other hand, Section 1 showed a relatively low correlation. However, Pine Island Bay in the Amundsen Sea near WA is affected by circumpolar deep water, which causes melting of the Pine Island Glacier ice shelf beneath the grounding line [37].

Generally, Antarctic environmental change appears to be more static than changes in the North Pole region. Overall, the climatic change pattern over all of Antarctica appears to be similar to the EA variation pattern. For this reason, Antarctic variability is strongly influenced by EA. However, Antarctica has a regional paradox between its west and east. Therefore, we derived quantitative results of long-term environmental variability over Antarctica using albedo, which is an indicator of change in the cryosphere, by region. These results can be used as basic data in the prediction of climate change at the South Pole. The variability of each area was also observed using albedo and climatic variables. The study was carried out with regional differentiation to obtain an improved understanding of Antarctic climate change. Next, we will perform more in depth analysis of various climatic factors, such as sea-ice extent and wind with albedo in the future.

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