Displacement of the South Pole from 2006 to 2021: Role of sea ice and Antarctic surface temperature

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Abstract

The effect of global warming on the southern polar regions necessitates careful monitoring of glacier deformations and their movements, as well as an understanding of atmospheric physics. For this purpose, the yearly movements of UNAVCO stations-South Pole Station (AMU2) (winter-summer) and other stations in the South Pole region have been observed in this paper for about a fifteen-year period (2006–2021). In addition, the area differences of the Antarctic continent due to seasonal changes (winter-summer) between 1980 and 2021 were investigated in this study. Moreover, the height values of the stations on the Antarctic continent were observed seasonally. The subglacial lakes in the Antarctic continent cause the differences in the height values as a result of the seasonal changes. A decrease in sea ice of 0.91 million km^2 for the winter season and 0.55 million km^2 for the summer season during a 41-year period has been determined for four sectors of the Antarctic continent. The temperature changes on the Antarctic continent in the summer and winter seasons (2005–2022) were also evaluated in this paper. Air temperature increases was apparent especially in the Antarctic Peninsula, East Antarctic and West Antarctic coasts. The Weddell Sea and the Amundsen Sea regions have had the most sea ice loss, each with 1.24 million km^2. On the other hand, it can be observed that the East Antarctic sector has expanded by 0.32 million km^2.

Key words: Antarctica, South Pole, GNSS, Satellite images

List of symbols and abbreviations: GNSS – Global Navigation Satellite System, PPP – Precise Point Positioning, AMU2 – Amundsen-Scott South Pole Station Antarctica, UNAVCO – University NAVSTAR Consortium, RINEX – Receiver INdependent EXchange, CSRS – Canadian Spatial Reference System Precise Point Positioning

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Introduction

The South Pole is one of the two sites where the Earth's axis of rotation touches its surface, known as the Geographic Pole or Terrestrial Pole. Verity's south geographic pole is found close to Amundsen-Scott Pole Station. Amundsen-Scott Pole Station of the US (AMU2) was established in 1956. The position of AMU2 has to be calculated every year because it moves about 10 meters every year. Numerous indicators at

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AMU2 indicate the motion of the real geographic pole throughout time (National Geographic Society 2020[8]). A lot of studies have been performed on the Antarctic continent (computation of the area and motion of this continent) in last decades (Bouin and Vigny 2000, Dietrich et al. 2004, Donnellan and Luyendyk 2004, Dietrich and Rülke 2008, Argus et al. 2014, Ghavri et al. 2015, Adhikari and Ivins 2016, DeConto and Pollard 2016, Gardner et al. 2018, Rudolph et al. 2018, Shepherd et al. 2018, 2019; Holland et al. 2019, Li et al. 2019, Parkinson 2019, Gonzales 2019[2]). The usability of GNSS and PPP in such studies is supported by various studies (Dietrich et al. 2004, Dietrich and Rülke 2008, Ruotoistenmäki and Lehtimäki 2009, Zanutta et al. 2017, Andrei et al. 2018, Li et al. 2019, Erol et al. 2020).

The thermohaline cycle that transfers warm water to the ocean's deeper layers may provide an explanation for the difference between the Antarctic and the Arctic region. Rapid sea ice melting is observed in the Arctic and in Amundsen and Bellingshausen (Jacobs and Camiso 1997, Kwok and Comiso 2002). Despite this, land ice is stabilized by ice sheets, which are vulnerable to warmer seas. There have been a number of ice shelf collapses along the eastern Antarctic Peninsula coast in recent decades. This increase is far more than what scientists had anticipated and is almost as big as the 5°F rise in the nearby Antarctic Peninsula, the area of the planet that is warming the quickest. Warmer seawater melts the glaciers from below. It changes the winds so the currents bring warmer water to the fringes of Antarctica (Spence et al. 2017). This "buttressing" of ice has been thought to be the main reason why glaciers are melting on the West Antarctic Ice Sheet, but it has also been observed on the East Antarctic Ice Sheet (Pritchard et al. 2012, Hur et al. 2021). Future projections of ice loss depend upon the speed of temperature change mitigation and area unit uncertainty. Some regions are already melting, and once a certain level of warming is reached, these regions could start melting much more quickly and permanently (Adhikari and Ivins 2016, Gardner et al. 2018, Rudolph et al. 2018, Holland et al. 2019, Lemonick 2012[4], National Geographic Society 2020[8]).

In this paper, the displacements (winter-summer) originating from AMU2 and other UNAVCO stations in the Antarctic region were investigated. Data from UNAVCO stations (AMU2 and other stations) from 2006 to 2021 were used (Table 1). Receiver Independence Exchange (RINEX) observation data for 18 stations was obtained from the UNAVCO server[10]. Analyses were carried out with CSRS-PPP (Canadian Spatial Reference System-Precise Point Positioning[5]) software and time series data of UNAVCO stations. The deformations that are monitored in the GNSS position time series may depend on the geological structure of the crust and its thermal variations caused by global warming, especially in Antarctica. For this reason, the study deals with the Antarctic continent with the displacements obtained by GNSS station observations. The melting of glaciers due to global climate change exerts force on the geological structure and causes local movements in the Earth's crust. Oceans absorb 90% of the Earth's warmth, and this fact affects the melting of marine glaciers, which are mostly located near the poles. Glacial melting has contributed to rising sea levels and affects the height of the GNSS stations. The coordinate differences were used to compute the overall displacements. In addition, the area differences of the Antarctic continent due to seasonal changes between 1980 and 2021 were computed. This study also looked at how the Antarctic continent's summer and winter temperatures changed from 2005 to 2022.

Material and Methods

Study area

The area is dominated by the Antarctic Ice Sheet. It's the world's greatest glacier. When winter weather is at its maximum, this ice cap may reach far beyond the continent's borders. Due to the Antarctic Peninsula's being in a hot spot of regional climate warming, the effects of the seasonal changes were evaluated in the area covered by selected GNSS stations. In the selection of GNSS stations, attention was paid to the fact that the stations were homogeneously distributed and located on the lakes of the Antarctic continent (Schöder et al. 2019, Stammerjohn and Smith 1997, Stewart et al. 2019, Ruotoistenmaki and Lehtimaki 2009).

Station	Northing (m)	Easting (m)	Elevation (m)
AMU2 (South Pole)	1999940.304	1999897.069	2820.224
BENN	1741921.093	1481463.088	1416.372
DUMG	-11457.471	3687682.342	-1.628
THRO	3065792.285	1425676.212	1058.179
VL01	68268.687	2350181.781	596.894
VL30	-73690.39	2652831.595	1491.515
JNSN	2766518.131	270074.666	1373.916
GMEZ	2658822.062	324356.388	1420.195
MCAR	761092.955	1109870.131	964.883
PHIG	645116.904	2311556.214	3126.155
CAS1	1064140.538	4500447.853	22.486
DAV1	2501237.175	4352605.635	44.446
PALM	3244825.884	-558061.878	30.967
ROB4	616350.944	2418008.953	41.633
MAW1	3147875.787	4240321.617	59.149
THUR	1742918.377	62845.192	212.808
VESL	4048946.827	1898291.964	862.353
SYOG	3815834.874	3501321.618	50.014

Table 1. Location of UNAVCO stations (UPS-South).

Dataset processing

CSRS-PPP modernization includes PPP with ambiguity resolution (PPP-AR) for data collected on or after January 1, 2018. Data collected prior to this date will continue to be processed with the IGS final products without ambiguity. Beginning Friday, March 26, 2021, the CSRS-PPP service will automatically decimate high-rate static datasets to a data rate of 30 seconds. This will affect dual-frequency, static data sets containing both code and phase data for which at least 75% of the expected 30 second intervals are available. For all other data sets, there will be no impact. Automatically decimating high-rate data sets in static mode has benefits for the CSRS-PPP service as well as the user. These include significantly reducing the processing time for each submission, allowing users to receive their results faster while also reducing the amount of computing resources required. In static mode, processing data at rates higher than 30 seconds does not improve the accuracy of the solution. In fact, for short data sets, it can actually reduce the accuracy. This is because CSRS-PPP uses precise GNSS clock products at a 30 second rate. Ambiguity resolution (PPP-AR) offers significant benefits for users by transforming ambiguous carrier-phase observations into precise ranges. As a result, centimeter-level accuracies can be obtained more rapidly. Furthermore, due to satellite geometry, resolving carrier-phase ambiguities results in improved estimates for the longitude (east) component. CSRS-PPP version 3 now includes an ambiguity status plot. The plot indicates, for all satellites at each epoch, the status of the estimated parameters (Olive: float ambiguity, Cyan: datum ambiguity, Green: fixed ambiguity, Red: new ambiguity). CSRS-PPP uses precise satellite orbit, clock, and bias corrections derived from a global network of receivers to determine accurate user positions. This strategy differs from other online positioning services based on differential positioning, *i.e.*, using nearby base stations. CSRS-PPP enables up to millimeter level accuracy for long observation sessions (24+ hours) in static mode, but an accuracy of a few centimeters can typically be achieved in an hour. On August 16, 2018, a new version of the software supporting CSRS-PPP was launched. This software replacement was the first step in the CSRS-PPP modernization plan, which includes PPP with ambiguity resolution (PPP-AR), faster convergence using external ionospheric information, and processing of multi-GNSS observations (CSRS-PPP 2022).

Many geodetic and geodynamic modeling studies employ the Global Navigation Satellite Systems (GNSS) approach because of its high accuracy, low cost, and three-dimensional (3D) location in a global coordinate system. For this study, the data of 18 UNAVCO stations in the Antarctic region was used. The displacements of AMU2 and other UNAVCO stations in this study were calculated by using the time series generated from yearly (2000–2021 winter-summer) solutions (*see* Figs. 1 and 2).

The 24 hours of RINEX files at 30 second intervals were acquired from the IGS server for this fifteen-year period. In this study, the CSRS-PPP service provides a static method, and the obtained accuracy is between 4 mm and 15 mm for horizontal and vertical components in this study. As a result of the GNSS observations, it was observed that the horizontal displacement values of AMU2 were not equal at other stations. During the period (2020–2021), it was determined that the movement that occurred at the AMU2 station was in the north-west direction (Figs. 1 and 2). The average displacement movements of the AMU2 and other stations were computed annually as a result of the evaluation of the surveys conducted during the 15-year measurement period. Time series belonging to AMU2 and other stations are presented in Fig. 2a, Fig. 3, and Fig. 4 for the horizontal and vertical directions (Northing (X) and Easting (Y), height (H) values). In order to make displacement effects clearly noticeable in the time series, these data were analyzed from January 1 of 2006 to January 1, 2021. During the same period, it was determined that the movement that occurred at the other stations was in the north-west direction (Fig. 2a). When the results of the stations (static processing by using the CSRS-PPP software) are compared with each other, the horizontal displacements of the stations are separately determined by these tests, which differ from a few centimeters to about 50 cm between 2000 and 2021 (Fig. 2a). The vertical displacement values for 18 UNAVCO stations are about 5-8 cm between 2000 and 2021 (Fig. 2a).

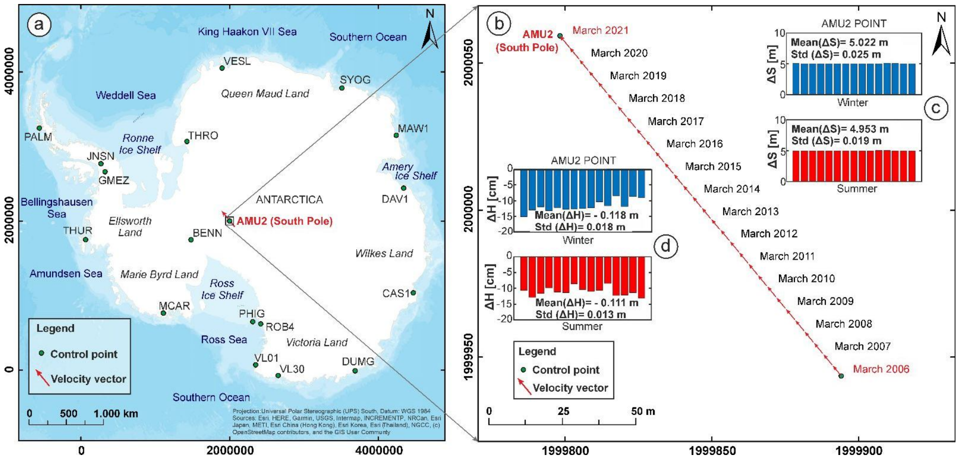

Fig. 1. a) Location of control stations (UPS-South), b) velocity vectors, c) distance and d) height differences of South Pole, AMU2 station (2006-2021 winter-summer).

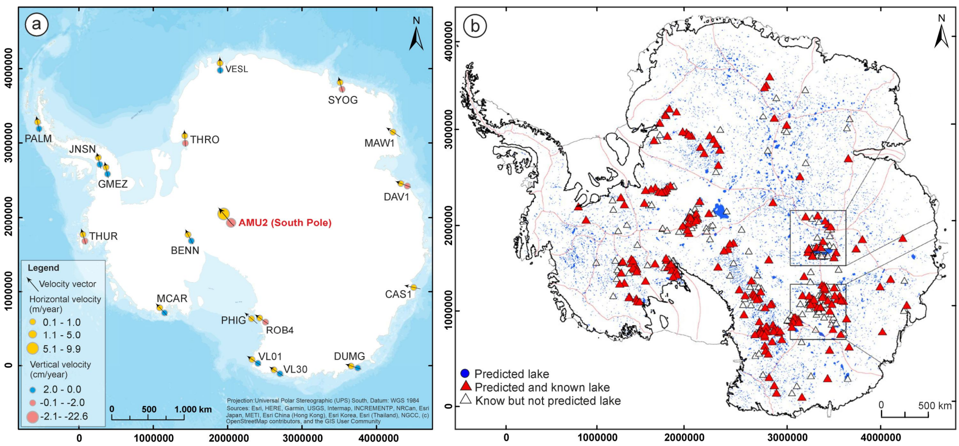

Fig. 2. a) Horizontal and vertical velocity of Antarctica (2006–2021) and b) the locations of all lakes included in the current inventory (Goeller et al. 2016, Stearns et al. 2008).

For monitoring Antarctic lakes in the field, satellite imagery is used. In our study, the Sentinel-2 (European Space Agency), was used. It provides global coverage of the Earth's surface every five days and can detect features as small as ten metres. Subglacial lakes in Antarctica are mainly studied for three scientific reasons: First, subglacial lakes are one of the most unique and extreme habitats on Earth. Second, sediments existing at the base of subglacial lakes may contain high-resolution records of ice-sheet history. The steady flow of *dirty ice* across a subglacial lake combined with low melting rates at the ice/lake interface of ~1 mm a^{-1} results in a very low sedimentation rate. Since subglacial lakes may be millions of years old, sediment layers in the order of tens or hundreds of meters could have accumulated at the lake bottom. The third reason is the most relevant one for this study: subglacial lakes are an important component of the widespread hydraulic system beneath the Antarctic Ice Sheet. They are known to interact with the overlying ice and considerably affect the ice dynamics. So far, 379 lakes have been identified beneath the Antarctic Ice Sheet using satellite altimetry, airborne RES, or seismic investigations. For the following comparison, the listed geographic positions of the observed lakes are interpreted as the central lake positions because an estimate of their outline only exists for seven lakes, while no length is given for 131 lakes. For all predicted lakes, the outlines are determined and expanded by a buffer zone of 5 km, which is thought to compensate for the uncertainties originating from the 5 km grid resolution. A predicted subglacial lake is considered to successfully match an observed subglacial lake if the central position of the observed lake is situated inside the expanded outlines of the predicted lake (Goeller et al. 2016, Stearns et al. 2008).

The most consistent means of investigating the global sea ice cover is by satellite passive microwave sensors, as these are independent of illumination and cloud cover. The Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) and the Defence Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSMI) provide information on the global sea ice cover from 1978 to present. This dataset contains gridded daily surface melt data for Antarctica estimated from passive microwave observations from the Scanning Microwave Multichannel Radiometer (SMMR), the Special Sensor Microwave/Imager (SSM/I), and the Special Sensor Microwave Imager Sounder (SSMIS) spaceborne sensors and covering the 1978–2017 period. The Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR), which was in operation between 1978 and 1987; the F8 Special Sensor Microwave Imagers (SSMI), which were in operation between 1987 and 1991; the F11 SSMI between 1991 and 1995; and the F13 SSMI between 1995 and 2006 (Parkinson and Cavalieri 2008). When operating with sensors that have various frequencies, footprint dimensions, ascending node durations, and calibrations, the challenge of creating a long-term, continuous time series of sea ice extent and regions is important. Since the Nimbus 7 SMMR, overlap time has been used to reduce differences by matching each successive sensor with the previous sensor. In this study sea ice data were obtained from the NASA Earth Observatory[7] archive and The Physical Oceanography Distributed Active Archive Center[9]. Sea ice data was digitized and converted to vector data using ArcGIS 10.3 software. Also, surface areas were obtained from vector data. Figures 5 and 6 show maps of mean sea ice extent in September (austral winter) and March (austral summer) during a 41-year period (decennium: 1980, 1990, 2000, 2010, and 2020–21) (NASA 2021[6]); Shepherd et al. 2018, 2019).

Results and Discussion

The height displacement of Antarctic continent and Lakes

Figure 2a shows the height values of the UNAVCO stations on the Antarctic continent. The results suggest that the regions with small lakes on the Antarctic continent cause great changes in height values. At some stations, the height differences are large, such as PALM (+ 18 cm at 5 years), BENN (+ 7 cm at 7 years), ROB4 (-3 cm at 15 years), DAV1 (-6 cm at 25 years), THRO (-4 cm at 5 years) and AMU2 (-350 cm at 15 years) (*see* Fig. 3, and 4). The station with the highest elevation change rate was the THRO station. The reason for this situation is that the THRO station was located in the region that covers the small lakes on the Antarctic continent. In addition, the THRO station is located near the Weddell Sea and is affected by the ocean's lower warm water currents (Lemenkova 2021). The PHIG station was located near the Ross Sea in West Antarctica. The height change at this station was calculated as +6 cm. During the summer, the Ross Sea quickly soaks up heat from the sun, and it is clear that this source of heat is affecting the melting in the glacier cavity. The Ross Sea melt rates are predicted to rise in the future due to climate change, which is predicted to lead to less sea ice and warmer ocean surface temperatures (Stewart et al. 2019, Gonzales 2019, DeConto and Pollard 2016). It is understood that the reason for the height increase at the PHIG station is the melting and evaporation in the Ross Sea. It is predicted that the height changes at the AMU2 and BENN stations are caused by the small lakes in these regions (Fig. 2b) (Goeller et al. 2016, Stearns et al. 2008). Station DAV1 was located in East Antarctica. As the atmosphere warms, more moisture is carried into the Polar Regions, resulting in a significant increase in East Antarctic snowfall in the twenty-first century. The general trend shows that a warming climate within the hemisphere would transport additional moisture to the continent, causing the ice sheets in the interior to grow, whereas parturition events on the coast can cause these areas to shrink. For the whole of the Antarctic Ice Sheet, this process is projected to contribute between 0 and 70 mm to sea level fall. The PALM station was on the Antarctic Peninsula. The height change at this station was computed as +18 cm. There is a well-documented record of ice-shelf collapse on the northerly peninsula, which seems to be linked to the regional warming that has occurred in recent decades (Church et al. 2013, Holland et al. 2019, Lemonick 2012[4], Schröder et al. 2019, Zwally et al. 2008).

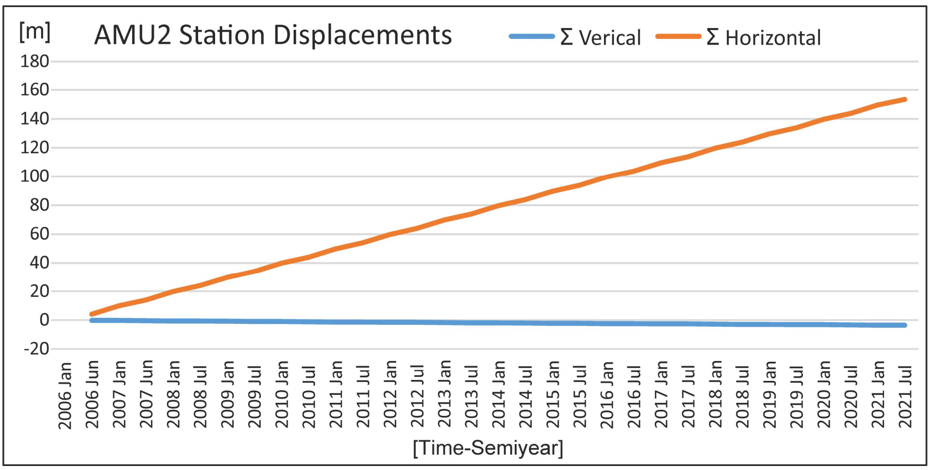

Fig. 3. Horizontal and vertical displacement graphic of AMU2 (South Pole) station (2006 –2021).

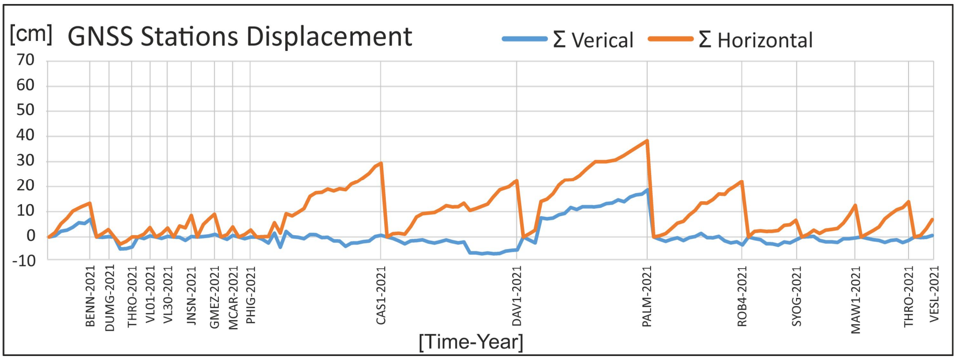

Fig. 4. Horizontal and vertical displacement graphic of GNSS stations in Antarctica continent.

Sea ice change values of the Antarctic continent (Summer-Winter, 1980–2021)

In this study, the (1980–2021) 41-year time series was expanded and investigated the variations in Antarctic sea ice and trends seen throughout the period (Parkinson 2019, Zwally et al. 2002). The focus of this research is on the differences between the previous 41-year time-series data findings and results. The time series maps were created using a collection of microwave sensor data from a sequence of Defense Meteorological Satellite Program missions. Microwaves from the Earth's surface are picked up by the sensors. The response of microwave to sea ice and the open ocean is different, which is used to map ice sheet densities (Gardner et al. 2018, Holland et al. 2019, Parkinson 2019).

As can be seen in Fig. 5, it is clearly understood that the most affected areas of the Antarctic continent between 1980 and 2020 were the Weddell Sea and Ross Sea during winter season (Table 2).

In Fig. 6, it is understood that the most affected areas of the Antarctic continent during the summer season between 1980 and 2021 were the Weddell Sea, Ross Sea, and Amundsen Sea (Table 3). The Antarctic Peninsula and West Antarctica, the regions that first experience the summer season, stand out as the regions where the warming is experienced the most. In the Antarctica, sea ice expands significantly throughout the winter but almost disappears during the summer. Antarctic sea ice melts every summer, keeping the earth's energy balance mostly unchanged (Lemonick 2012, Shepherd et al. 2018, 2019).

Mean seasonal sea ice extents and regions for the Antarctica as a whole from 1980 to 2021, as well as for each of the four Antarctic sectors, are presented (Tables 2 and 3). They are the Weddell Sea, the Amundsen Sea, the Ross Sea, and the East Antarctic Section of the Indian Ocean. On average, maximum ice cover appears in September during a 41-year period, with minimum ice cover appearing in March. Ice extents have varied in September from a peak of 19.22 million km^2 in 2010 to a low of 17.94 million km^2 in 2018 over the past 41 years (decennium records) (*see* Table 2). Figures 7 and 8 show seasonal sea ice cover changes in 41-year data for four sectors and the Antarctic overall. The most noticeable thing about Figs. 7 and 8 is how the ice cover changes in each of the four sectors at different times of year.

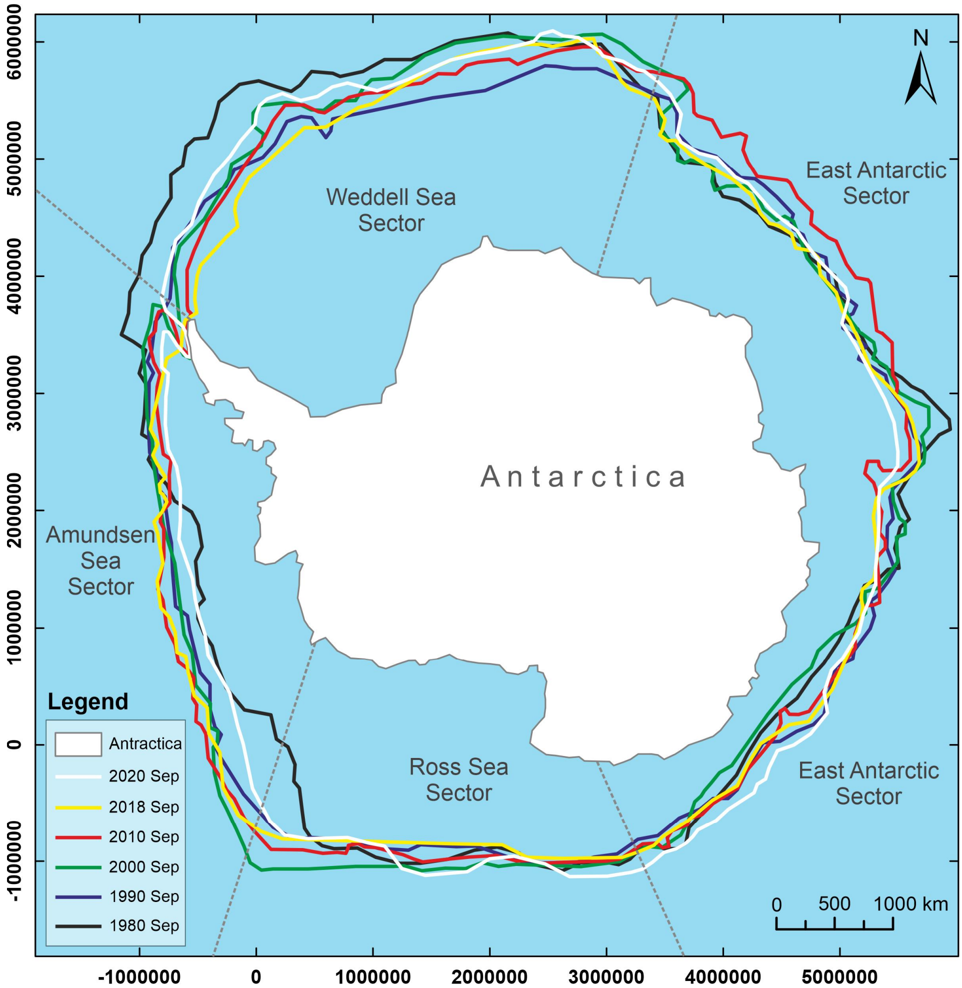

Fig. 5. Sea ice change map of the Antarctica for the winter season (1980–2020) (NASA 2021[6]).

Date	Surface (km^2)	Sea Ice Change (million km^2) – Winter				
		Weddell Sea	Amundsen Sea	Ross Sea	East Antarctic	TOTAL
1980 Sep	19.14	-	-	-	-	-
1990 Sep	18.48	-1.81	+0.88	-0.27	+0.54	-0.66
2000 Sep	19.12	+0.81	+0.05	+0.48	-0.70	+0.64
2010 Sep	19.22	-0.51	+0.03	-0.35	+0.93	+0.10
2018 Sep	17.94	-0.27	-0.09	-0.17	-0.75	-1.28
2020 Sep	18.23	+0.54	-0.82	+0.27	+0.30	+0.29
1980 Sep - 2020 Sep		-1.24	+0.05	-0.04	+0.32	-0.91

Table 2. Sea ice change in the Antarctica for the winter season (1980–2020).

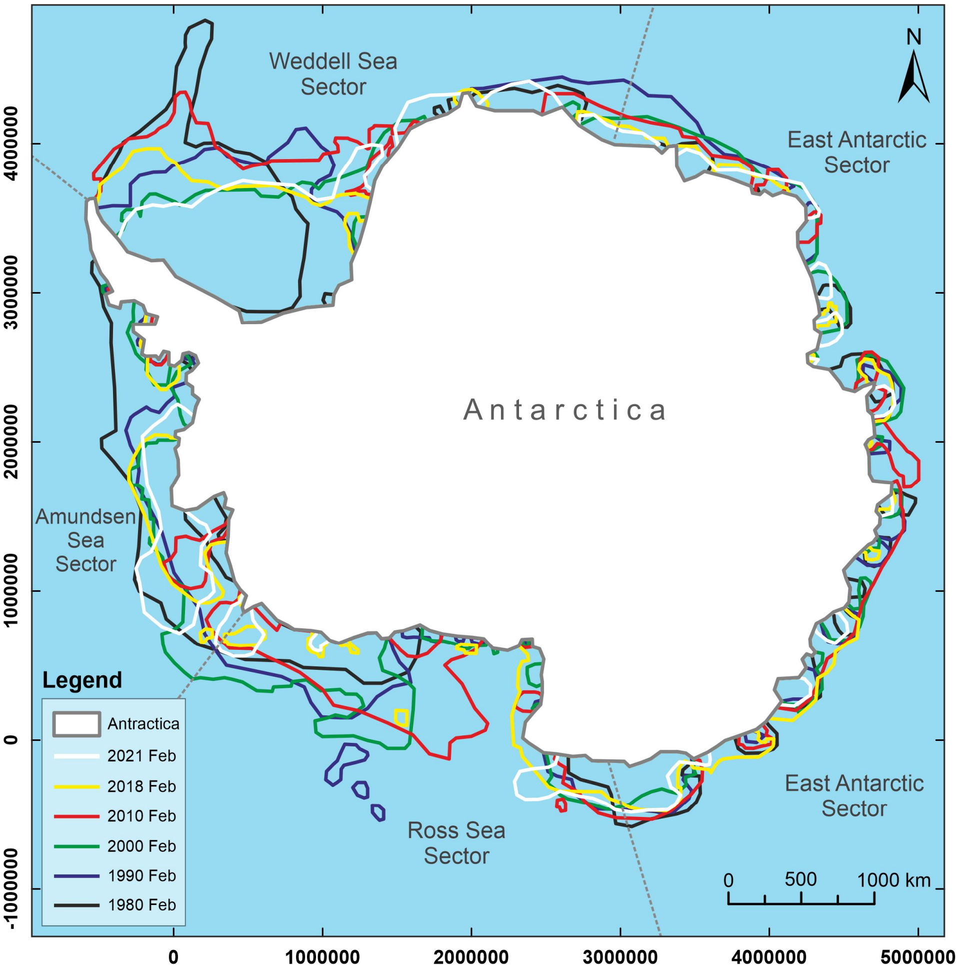

Fig. 6. Sea ice change map of the Antarctica for the summer season (1980–2021) (NASA 2021[6]).

Year	Surface (km^2)	Sea Ice Change (million km^2) - Summer				
		Weddell Sea	Amundsen Sea	Ross Sea	East Antarctic	TOTAL
1980 March	2.81	-	-	-	-	-
1990 March	3.00	+0.03	-0.38	+0.23	+0.32	+0.19
2000 March	2.89	-0.16	+0.19	+0.04	-0.18	-0.11
2010 March	3.22	+0.62	-0.64	+0.23	+0.11	+0.33
2018 March	2.32	-0.52	+0.20	-0.37	-0.22	-0.90
2021 March	2.26	-0.02	+0.09	-0.18	+0.05	-0.06
1980 March - 2021 March		-0.05	-0.54	-0.04	+0.08	-0.55

Table 3. Sea ice change of in the Antarctica for the summer season (1980–2021).

There is usually less sea ice during summer in the Amundsen Sea and Ross Sea, which are in the west of Antarctica. However, the amount of ice along the coast of the East Antarctica has not changed much (Fig. 7). During the winter season, sea ice tends to decrease in the Amundsen Sea. On the other hand, total ice cover change in East Antarctica shows an increasing trend over a 41-year period. However, ice cover tends to decrease for 41 years in other regions (Fig. 8). A lower declining trend has been observed in the Ross Sea and Eastern Antarctic from 1980 to the present. When the whole continent is evaluated, glacier loss is seen for summer and winter seasons between 1980 and 2021; *see* Tables 2 and 3. As shown in Tables 2 and 3, and Figs. 7 and 8, Antarctic glacier losses are faster in the summer season than in the winter season.

The Weddell Sea region has the largest sea ice concentration in the Antarctica. The seasonal cycle of ice cover follows the same phasing as the Antarctic total, with the lowest ice cover in March and the highest ice cover in September. The majority of the existing sea ice cover in March is located east of the Antarctica (Parkinson 2019). For the 41-year cycle, the maximum Weddell Sea ice cover loss is 1.81 million km^2 from September 1980 to September 1990. The total Weddell Sea ice cover loss is 1.24 million km^2 from September 1980 to September 2020 (Table 2). The winter season trend of the Weddell Sea is stable on the minus side of the graphic for a 41-year period (Fig. 9). The summer season trend of the Weddell Sea is stable and its decadal ice cover changes are fluctuating.

The Weddell Sea and the Amundsen Sea regions both have considerable share of multi-year ice. The area covered by it is known for its thick, impenetrable icepack, which has allowed ships to be stuck for months during the winter (Zwally et al. 2002). The level of multiyear ice fell tremendously over the summers of 1989 – 1994, with the other characterization as the result of an opposite climatic trend (Jacobs and Comiso 1997, Stammerjohn and Smith 1997, Lemonick 2012[4]). The Amundsen Seas region is presently experiencing a variance trend that is negative seasonally. It also negatively affects the trend of total ice cover. The maximum Amundsen Sea ice cover loss is 0.82 million km^2 from September 2018 to September 2020 in winter and 0.64 million km^2 from March 2000 to March 2010 in summer for the 41-year cycle. The total Amundsen Sea ice cover loss is 0.54 million km^2 from March 1980 to March 2021 (Table 3). The summer season trend of the Amundsen Sea is to decrease for a 41-year period. Its ice cover changes are influenced by decadal summer seasons. The winter season trend of the Amundsen Sea is stable until 2018, and then it tends to decrease.

The Ross Sea region has less total sea ice cover and approximately the same interdecadal fluctuation as the Weddell Sea region. This is especially obvious when the summer minimum ice extents are recorded. The Ross Sea has a more noticeable minimum in March and a greater fall and winter maximal level than the Antarctic total decadal cycle. For the 41-year cycle, the maximum Ross Sea ice cover loss is 0.37 million km^2 from March 2010 to March 2018. The Ross Sea's last 41 years of ice cover loss was 0.04 million km^2 from September 1980 to September 2020 (Table 3). The summer season trend of the Ross Sea is to decrease for a 41-year period.

The average ice cover cycle of the East Antarctica has a winter high in September and a summer low in March, much like the other sectors. The East Antarctica has substantially less ice than the Weddell Sea, with the peak September maximum sea ice cover in September 2010. The maximum ice cover loss of the East Antarctica was 0.75 million km^2 from September 2010 to September 2018. On the other hand, the ice sheet decreased in 1990 and then followed a parallel trend to 2021 in the winter season in the Weddell Sea. The total ice cover yield of the East Antarctica is 0.32 million km^2 from September 1980 to September 2020 (Table 3).

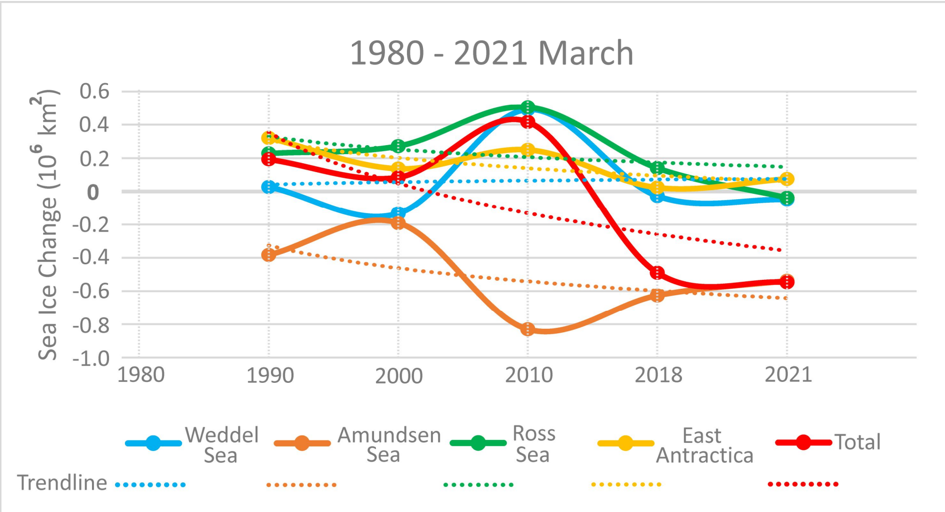

Fig. 7. Sea ice change and polynomial trend line graphic of the Antarctica for the summer season (1980–2021).

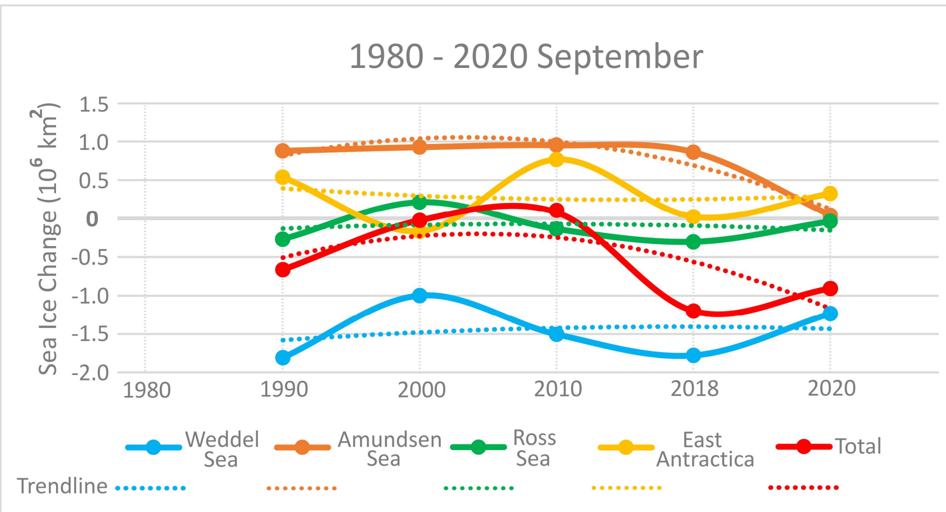

Fig. 8. Sea ice change and polynomial trend line graphic of the Antarctica for the winter season (1980–2020).

There is a variability in Antarctic Sea ice from different places across the continent. The extent of sea ice in the eastern Ross Sea has grown somewhat, whereas it has decreased in the seas surrounding the Antarctic Peninsula. The ice cover change of the Amundsen Sea sector and Antarctic total is negative, and the graphs seem to show a downward trend in the summer season for the past few years. This downward trend in the winter season is the same as in the summer season. The ice cover of the Weddell Sea and the Ross Sea has decreased since 1980, and their trends are similar in winter and summer seasons. The ice loss in the Weddell Sea is particularly high and adversely affects the total amount of ice for the winter season. The Amundsen Sea has a great decrease in volume and reduces the total ice surface. East Antarctica and the Ross Sea are in parallel trends in their summer and winter periods. Since 1980, there has been a small decrease in the Ross Sea ice surface and an increase in the East Antarctica.

Previous research showed a relationship between El Niño Southern Oscillation (ENSO) and the decrease of sea ice in the Amundsen Sea region (Kwok and Comiso 2002). They discovered an important correlation between sea ice loss and all four phases of the negative Southern Oscillation Index (SOI) from 1982 to 1998. The gradient, which has been shown to be on the rise in the Antarctic Peninsula, was shown to be closely associated with sea ice extent in the region.

In this study, the melting of the Antarctic ice cover was investigated seasonally and found to be hazardous for a 41-year period. As a result, it was determined that there was a decrease in glaciation for both winter and summer periods. It is apparent that the losses in the Amundsen Sea are effective in the reduction of total ice cover for the summer season in the Antarctica. In the winter season 1990, the decrease in the Weddell Sea could not be compensated for and it was in a horizontal trend. Also, for the winter season, the decreasing trend in the Amundsen Sea after 2018 accelerated the total glacial loss trend. If global warming is not controlled, it is difficult to prevent glacier loss.

West Antarctica is exposed to warm ocean currents due to its location in a large bowl that descends below sea level. However, the East Antarctica ice sheet is thought to be more stable since it occupies the chilly South Pole and the majority of it is located on land, which protects it from the ocean's warmth. Warming ocean waters are destroying glaciers similar to the Thwaites and Pine Island glaciers of West Antarctica (Lazzara 2011[3], Fox 2019, 2020[1]; Adhikari and Ivins 2016, Spence et al. 2017). It has long been believed that the West Antarctic Ice Sheet, whose base is below sea level, is the most susceptible to collapse. On the other hand, the East Antarctic Ice Sheet is thought to be relatively safe from heat and water because it is cold and its base is mostly higher than sea level. The ice surface is eroded by several centimeters each year by constant dry winds. Based on the glaciers that have broken away from the Antarctic continent so far, it is clear that warm water currents and rising ocean temperatures in the Antarctic Peninsula, Weddell Sea, and Ross Sea regions will continue to cause glacier breaks in the coming years (Lazzara 2011[3], Fox 2019, 2020[1]; Adhikari and Ivins 2016, Spence et al. 2017).

The temperature changes of Antarctic continent (2005–2022)

In the Antarctic continent, especially in the northwest part called the Antarctic Peninsula, the temperature increase from September 2005 to September 2021 was higher than in other regions. This temperature increase also occurs in parts of the West and East Antarctic in September 2018 and September 2020 (Weather in Antarctica 2022[11]). In addition, the temperature increase in the East Antarctic section, especially in the coastal regions, is shown in Figs. 9 and 10 (September 2021 and March 2022).

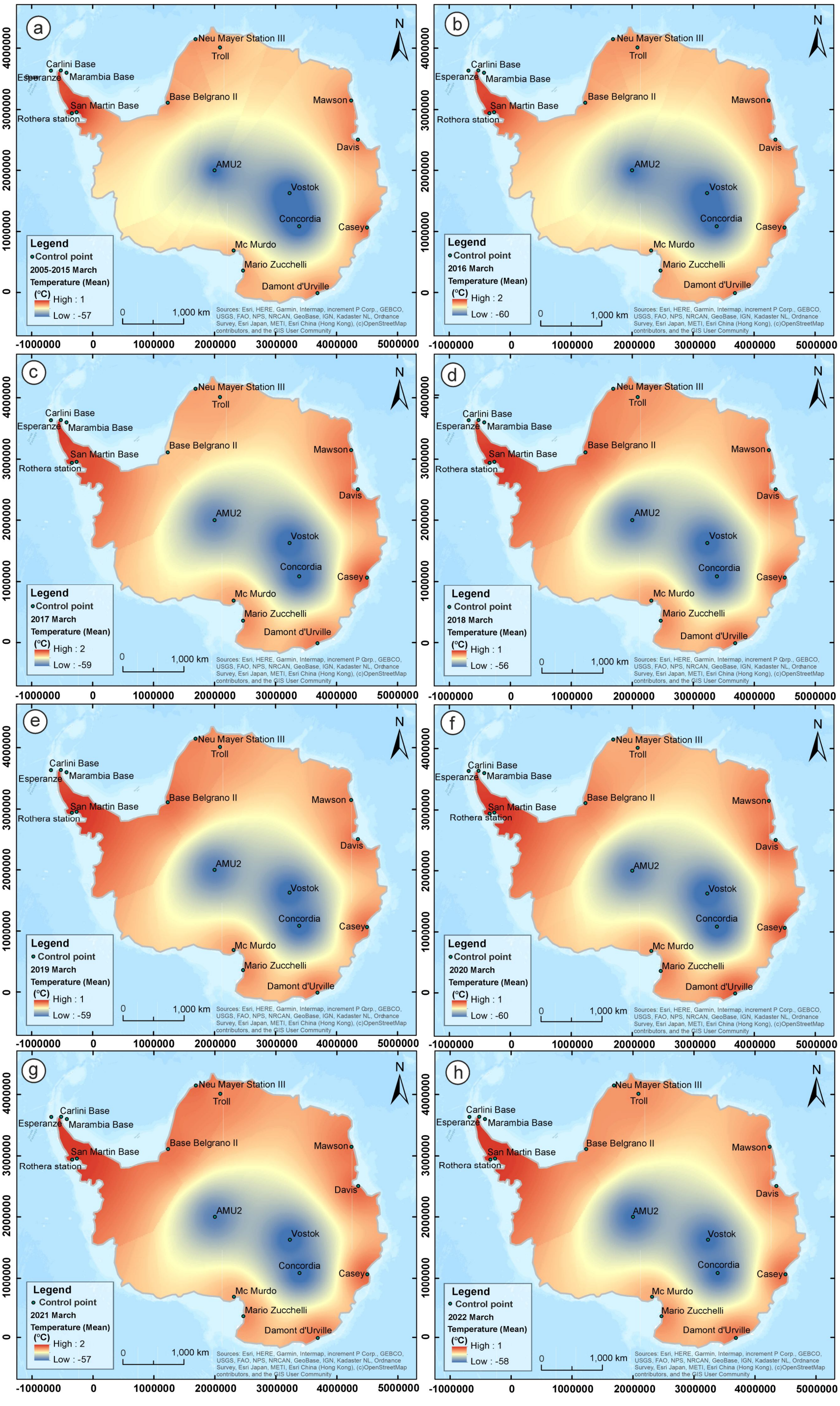

Fig. 9. Average temperature maps of the Antarctica continent in March (2005–2022): a) 2005–2015, b) 2016, c) 2017, d) 2018, e) 2019, f) 2020, g) 2021 h) 2022 (Weather in Antarctica 2022[11]).

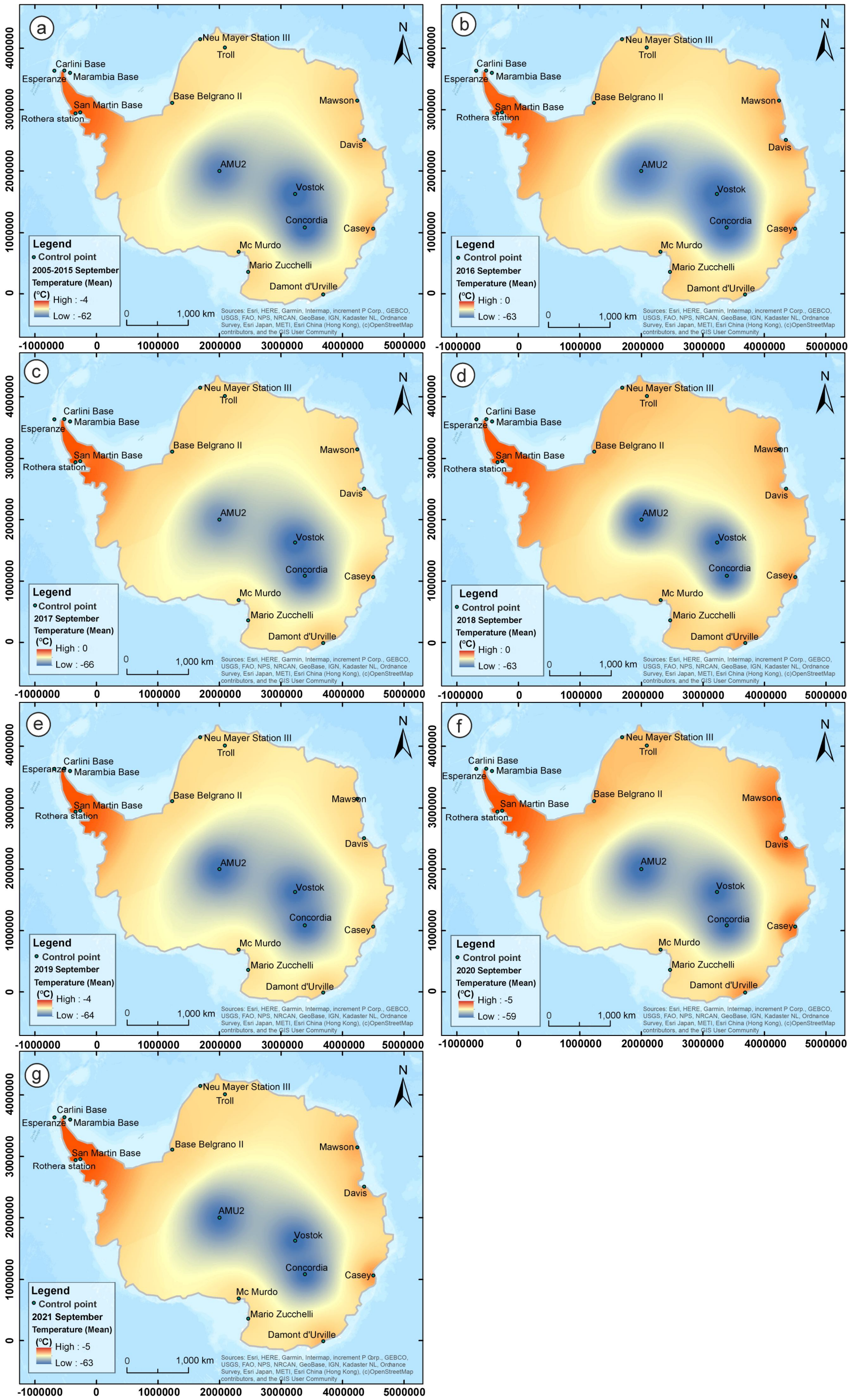

Fig. 10. Average temperature maps of the Antarctica in September (2005–2021): a) 2005–2015, b) 2016, c) 2017, d) 2018, e) 2019, f) 2020, g) 2021 (Weather in Antarctica 2022[11]).

No big changes in temperature have been seen at AMU2, Vostok, and Concordia stations in September for many years.

When temperatures rise and warm water currents move through the ocean, they can cause cracks in glaciers in the Antarctic Peninsula, Ross Sea, and Weddell Sea regions in West Antarctica. On the other hand, the situation in the East Antarctic Region is at greater risk of melting.

Conclusions

This study uses data from the South Pole station and other stations derived from UNAVCO in the Antarctic region. The yearly coordinate time series from 2000 to 2021 was used to estimate horizontal direction shifts with an accuracy of less than 1 cm.

The results obtained from 3D displacement estimation are listed below:

- At the AMU2 station in Antarctica, the horizontal displacement in the north-west direction was found to be 5.022 m in the winter and 4.953 m in the summer.
- Between 2000 and 2021, horizontal movements of about 210 m were seen at the AMU2 station, which is in the middle of the Antarctic continent.
- At the AMU2 station, the vertical movement caused by the displacement was found to be about 0.118 m in the winter and 0.108 m in the summer.

It has been calculated that the displacement movement at the other stations on the Antarctic continent is in the north-west direction and reaches an average value of 2.5 cm annually.

On the temperature maps of the Antarctic continent, temperature increases have occurred, especially in the West Antarctic, Antarctic Peninsula, and East Antarctic coasts. In addition, the lakes on the Antarctic continent cause changes in height values as a result of seasonal changes.

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