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Polar Amplification in the Earth's Three Poles Based on MODIS Land Surface Temperatures

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Abstract: Polar amplification appears in response to greenhouse gas forcing, which has become a focus of climate change research. However, polar amplification has not been systematically investigated over the Earth's three poles (the Arctic, Antarctica, and the Third Pole). An index of polar amplification is employed, and the annual and seasonal variations of land surface temperature over the Earth's three poles are examined using MODIS (Moderate Resolution Imaging Spectroradiometer) observations for the period 2001–2018. As expected, the warming of the Arctic is most conspicuous, followed by the Third Pole, and is weakest in Antarctica. Compared to the temperature changes for the global land region, positive polar amplification appears in the Arctic and the Third Pole on an annual scale, whereas Antarctic amplification disappears, with a negative amplification index of −0.72. The polar amplification for the Earth's three poles shows seasonal differences. Strong Arctic amplification appears in boreal spring and winter, with a surface warming rate of more than 3.40 times the global mean for land regions. In contrast, the amplification of the Third Pole is most conspicuous in boreal summer. The two poles located in the Northern Hemisphere have the weakest amplification in boreal autumn. Differently from the positive amplification for the Arctic and the Third Pole in all seasons, the faster variations in Antarctic temperature compared to the globe only appear in austral autumn and winter, and the amplification signal is negative in these seasons, with an amplification index of −1.68 and −2.73, respectively. In the austral winter, the strong negative amplification concentrates on West Antarctica and the coast of East Antarctica, with an absolute value of amplification index higher than 5 in general. Generally, the polar amplification is strongest in the Arctic except from June to August, and Antarctic amplification is the weakest among the Earth's three poles. The Earth's three poles are experiencing drastic changes, and the potential influence of climate change should receive attention.

Keywords: polar amplification; Earth's three poles; land surface temperature; MODIS

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1. Introduction

The Arctic, Antarctica, and the Third Pole have the largest amount of ice volumes on Earth, which are sensitive to global warming, and they are collectively referred to as the "three poles of the Earth" [1,2]. The global climate is in unprecedented warmth [3], and the Earth's three poles have experienced even more drastic changes; therefore, the Earth's three poles serve as indicators for global change [2].

Changes in the Earth's three poles have an important role in the climate system and are crucial for sea level rise, which is partly related to increases in surface temperature [4,5]. Arctic amplification can generally be observed in global climate models. However, the 27,000 temperature profiles measured in the lower troposphere over the Arctic Ocean did not reflect widespread surface warming for the period 1950–1990, and there was a significant cooling trend in the western Arctic Ocean in boreal autumn and winter [6]. Similarly, the analysis of measured data in the North Atlantic Arctic showed that there was a steady decline in all seasons from 1930 to 1987 [7]. In addition, the dataset from the International Arctic Buoy Programme/Polar Exchange at the Sea Surface (IABP/POLES) also reported winter cooling over the western Arctic Ocean for the period 1979–1997 [8]. During the first two decades of the 21st century, the warming rate of the Arctic was almost four times the global average rate, which is in response to the changes in greenhouse gases, aerosols, and other climate drivers [8–11]. However, the selection of the time period has a significant impact on the existence of Arctic amplification. For example, Arctic amplification often can be observed in multi-decadal variability, whereas the rate of changes in temperature over the Arctic and Northern Hemisphere in the 20th century was basically similar, and Arctic amplification disappeared when a more than 125-year record (1875–2001) was considered [10]. Nonetheless, the intensity of Arctic amplification will decrease with increasing radiative forcing in the future [12,13]. Moreover, the existence of Arctic amplification may have an impact on the mid-latitude weather and extreme climate events. For example, rapid warming over the Arctic can influence extreme precipitation in the Northern Hemisphere, which is related to a negative North Atlantic Oscillation and the increase in the duration of weather patterns [14]. On the whole, three potential dynamical pathways may link Arctic amplification to mid-latitude extreme events: changes in storm tracks, the jet stream, and planetary waves and their associated energy propagation [15]. However, a large amount of research suggests that only a weak link exists between Arctic amplification and mid-latitude extreme events, and the different perspectives may be associated with deficiencies in separating the effects of Arctic amplification from those of natural variability or background warming [16–18]. Similarly to the Arctic, the Third Pole has undergone rapid warming in recent years, and the warming trend is almost twice the global average, which has resulted in melting permafrost, retreating glaciers, and decreasing biodiversity [19–21]. The variations in temperature over the Third Pole also have an influence on extreme events. For example, Southwest China experienced an extremely wet spring in 2022, and the Tibetan Plateau's upper tropospheric warming is a major factor leading to the extreme event [22]. Differently from the large increase in temperature over the Arctic and the Third Pole, the variations in Antarctic temperature show regional differences and are sensitive to the selected time period. For the second half of the 20th century, the Antarctic Peninsula and West Antarctica displayed rapid warming, whereas the analysis of Antarctic meteorological data reflects a net cooling on the Antarctic continent in this period [23–26]. However, the spatial distribution of changes in Antarctic temperature has changed since the beginning of the 21st century. The strong warming signal has disappeared in the Antarctic Peninsula since the late 1990s, which is related to the strengthening of mid-latitude jets [27]. In addition, the warming sign dominated East Antarctica in the austral spring, and Antarctic amplification existed in the austral spring for the period 1979–2019 [28–30]. Generally, the Arctic and the Third Pole have experienced obvious warming, while Antarctic temperature decreased in the second half of the 20th century, and the variations have reversed in recent years. Based on the mechanism analyses, the warming in the land region of the Arctic and the Third Pole is influenced mainly by longwave radiation and surface albedo feedback, whereas the changes in longwave radiation and surface heat storage are important [2]. In addition, a study of the temperatures at 200 hPa over the Earth's three poles shows that the tropopause warming over the Third Pole enhances the poleward Brewer–Dobson circulation, particularly to Antarctica [1].

For the harsh environment in the Earth's three poles, measured data are relatively scarce. Satellite remote sensing data cover the world and can provide high spatial resolution data, which can serve as reliable data for the study of climate change. Although there have been many studies on temperature changes over the Arctic, Antarctica, and the Third Pole, comparative studies on polar amplification among the Earth's three poles are still very scarce. Polar amplification over the Earth's three poles based on MODIS (Moderate-resolution Imaging Spectroradiometer) land surface temperature observations is still in a blank state. Therefore, our goal in this study is to investigate changes in surface temperatures in the Earth's three poles and further quantify and compare the amplification among the Earth's three poles.

2. Materials and Methods

2.1. Data

In this study, global MODIS Terra monthly LST (land surface temperature) data with a spatial resolution of 0.05° × 0.05° for the period 2001 to 2018 from the datasets of the MODIS Level 3 data product MOD11C3v061 were employed. The dataset were synthesized by the NASA MODIS Data Working Group after a series of preprocessing steps, enabling a better understanding of the Earth as an interacting system [31].

ERA5 (ECMWF Reanalysis v5) is the latest generation of atmospheric reanalysis product released by the ECMWF (European Centre for Medium-Range Weather Forecasts); it provides atmospheric, land and oceanic climate variables covering the period from January 1940 to the present [32]. ERA5 is used for the improvement of observation operators and for model physics, as well as for core dynamics and data assimilation, and is considered to offer outstanding performance in the representation of temperature [33–35]. In the present study, we used surface temperature data with a spatial resolution of 0.25° × 0.25° for the period 2001 to 2018.

In addition, we used high-resolution gridded monthly air temperature observations from the CRU TS (Climatic Research Unit gridded Time Series) version 4.06 provided by the UK National Centre for Atmospheric Science (NCAS); these can be downloaded from the website https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.06/cruts.2205201912.v4.06/tmp/ (accessed on 25 March 2023). The CRU TS dataset provides monthly observations for all land areas of the world except Antarctica, with a horizontal resolution of 0.50° × 0.50°.

2.2. Study Areas

The locations of the three poles are shown in Figure 1. For the purposes of this study, the Arctic refers to the region with a latitude higher than 60°N, Antarctica refers to the Antarctic ice sheet, and the Third Pole denotes the area of High-Mountain Asia with an average elevation above 4000 m [12]. Because the dataset MOD11C3v061 only contains land surface temperatures, the analysis of polar amplification based on MODIS was carried out only for land regions at the Earth's three poles.

2.3. Methods

The F-test was used to estimate the significance of temperature trends, with significance at the 95% confidence level. Trends were not labeled with a p-value when they failed to pass the significance test.

In previous studies, two methods have been commonly used for calculating polar amplification indexes: (1) the ratio of trends in Arctic/Antarctica temperature to corresponding trends in the Northern Hemisphere/Southern Hemisphere or globally; (2) linking Arctic/Antarctica and Northern Hemisphere/Southern Hemisphere temperature anomalies via the regression relationship $T_{\mathrm{Arctic/Antarctica}} = a_0 + a_1 \times T_{\mathrm{Northern\ Hemisphere/Southern\ Hemisphere/globe}} + \varepsilon$, which avoids extreme values when the denominator is close to zero, and where $T_{\mathrm{Arctic/Antarctica}}$ and $T_{\mathrm{Northern\ Hemisphere/Southern\ Hemisphere/globe}}$ represent temperature anomalies over these regions during the same period [36–38]. In this study, the research object was the Earth's three poles; therefore, because the Arctic and the Third Pole are located in the Northern Hemisphere and Antarctica is located in the Southern Hemisphere, the trend in global temperature change was used as the reference object for calculating polar amplification indexes.

There is no obvious difference between the polar amplification indexes obtained using the two calculation methods. The annual polar amplification index for the Third Pole is found to be 1.50 using the first method, and 1.33 using the second method. In this study, we define the polar amplification index as the ratio between the value of the LST linear trend over the Earth's three poles and the linear trend for the globe. A specific example may be stated as follows: the annual warming rates over the Third Pole and the globe are

0.29 °C per decade and 0.19 °C per decade, respectively; the annual polar amplification index is therefore the ratio of 0.29 to 0.19, and so has a value of 1.50.

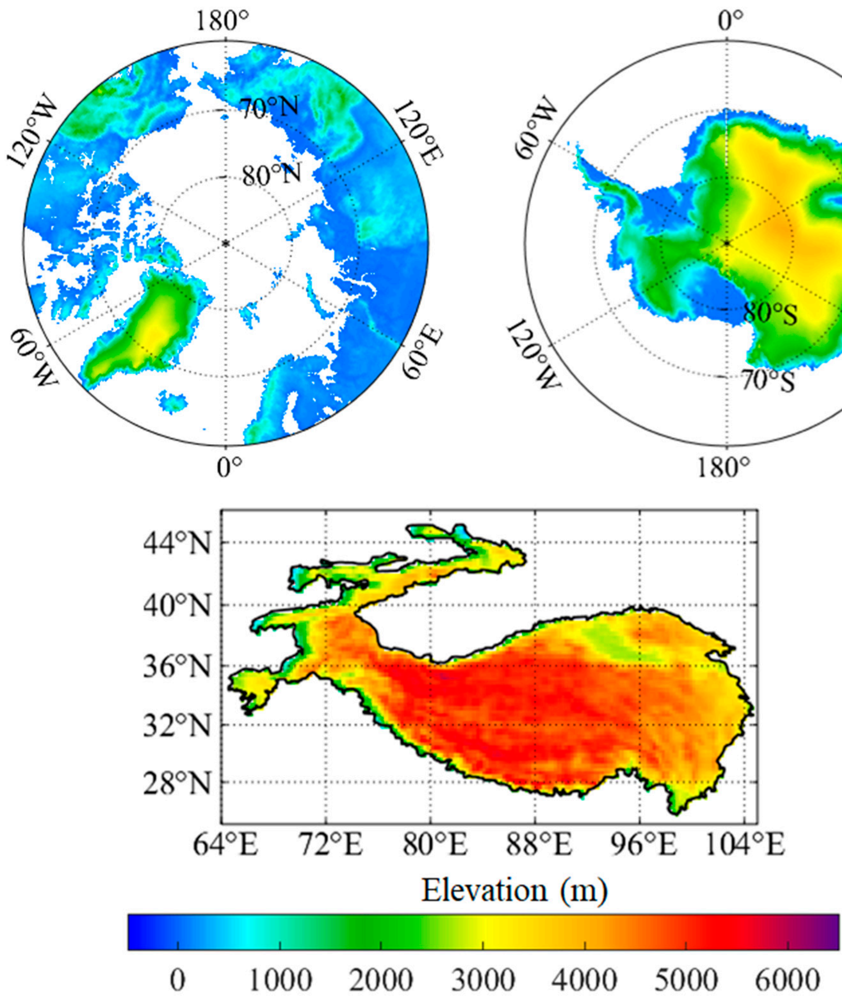

Figure 1. Maps of the Earth's three poles.

3. Results

3.1. Performance of MODIS Observations in Representing Land Surface Temperature at the Earth's Three Poles

Firstly, we analyzed the performance of MODIS observations in representing surface temperature at the Earth's three poles. Because the CRU gridded observations do not currently include temperatures over Antarctica, we used the CRU TS dataset to evaluate the performance of MODIS LST for the Arctic and the Third Pole only. On an annual scale, MODIS observations are highly correlated with CRU TS in the Arctic, with a correlation coefficient of 0.95 ($p < 0.05$). This high correlation can be detected in all seasons, with the strongest signal appearing in boreal spring, when the correlation coefficient is as high as 0.98 ($p < 0.05$). Compared with CRU observations, MODIS LST always shows cold bias in the Arctic; the lowest bias (−0.10 °C) appears in boreal summer, and the bias is relatively obvious in cold seasons. In the case of the Third Pole, the correlation coefficient between MODIS LST and CRU is as high as 0.75 (boreal autumn), and the MODIS observations show a warm bias on all annual and seasonal scales, with the highest warm bias of 1.95 °C in boreal autumn. In previous research, we analyzed the performance of MODIS LST in Antarctica using measured data from 128 stations. We found that the monthly correlation coefficient between MODIS and observations was higher than 0.90 at 104 stations, and that the bias was lower than 4.0 °C in general [30].

Overall, we can state that MODIS LST observations do reflect changes in temperature over the Earth's three poles. Although some deviations are inevitable, results based on MODIS observations are credible.

3.2. Trends in Temperatures over the Earth's Three Poles

Figure 2 shows spatially averaged time series of annual and seasonal mean anomalies in LST (relative to their 2001–2018 means) over the Earth's three poles for the period 2001–2018. On an annual scale, the Arctic and the Third Pole exhibit an increasing tendency, with warming rates of 0.59 °C per decade ($p < 0.05$) and 0.29 °C per decade, respectively. On the other hand, the warming signal is absent in Antarctica, which exhibits a cooling trend of −0.14 °C per decade. The annual anomalies in temperature over the Earth's three poles show positive correlations with global changes, with correlation coefficients of 0.73 ($p < 0.05$), 0.37 and 0.50 ($p < 0.05$), respectively. As expected, the Arctic shows the strongest variations among the Earth's three poles in all seasons, with warming rates of 0.82 °C per decade ($p < 0.05$), 0.27 °C per decade, 0.36 °C per decade and 0.90 °C per decade ($p < 0.05$) in MAM (March–May), JJA (June–August), SON (September–November) and DJF (December–February), respectively. In contrast, Antarctica displays a warming trend only in SON, the austral spring, when there is a strong correlation with global temperature anomalies, with a correlation coefficient of 0.76 ($p < 0.05$). In the case of the Third Pole, a warming tendency can be observed for all seasons, with seasonal differences similar to those in the Arctic, so that strong warming occurs in MAM and DJF, and weak warming signals appear in JJA and SON.

To display changes in temperature over the Earth's three poles in more detail, Figure 3 illustrates the distribution of trends in annual temperature over the Arctic, Antarctica and the Third Pole. Clearly, a warming trend can be observed for most land regions in the Arctic, and a high center of warming appears in the 30°E to 120°E sector, where the warming rate is more than 1.00 °C per decade. However, the area of Greenland with a latitude below 80°N displays a conspicuous cooling tendency of more than −0.80 °C per decade. One previous study noted that temperatures over coastal Greenland increased at an accelerating rate during 2013–2017 [39], suggesting that the cooling in 2001–2018 is likely related to the time period selected, rather than indicative of a stable and continuous trend. On an annual scale, a warming signal dominates the Third Pole in general, with a high degree of change evident in the region near the Tanggula Mountains. In contrast to the situation in the Arctic and the Third Pole, the variations in temperature over Antarctica are inhomogeneous. West Antarctica and the Antarctic Peninsula display a cooling trend, and this phenomenon also appears in areas of East Antarctica between 60°E and 150°E with latitude below 80°S. In Antarctica, the warming trend is concentrated on the interior of East Antarctica; a strong signal may also be identified in the area between Dronning Maud Land and Coats Land.

As a whole, the Arctic shows the strongest warming, followed by the Third Pole, while Antarctica exhibits the weakest variations and even a cooling trend.

3.3. Comparison of Amplification at the Earth's Three Poles

Table 1 summarizes the amplification indexes for land regions at the Earth's three poles. Compared with changes in global mean temperature, the Arctic and the Third Pole show stronger warming on an annual scale, with corresponding amplification indexes of 3.09 and 1.50, respectively. Analyses of observations and climate reanalysis have shown that Arctic amplification peaked sometime in the early 21st century, and that this was related to a reduction in ice–albedo feedback induced by a decreased rate of sea ice reduction and reduced incidence of shallow, stably stratified atmospheric boundary layers, accompanied by thinning and fragmentation of sea ice [40]. The amplification at the Third Pole may be partially attributed to ice–albedo feedback. During the period 2001–2019, yearly albedo and the extent of snow cover both exhibited obvious decreases [41]; this could have induced an increase in surface shortwave radiation which subsequently caused the surface warming in the Third Pole. In contrast with the annual amplification at the Arctic and the Third Pole, the rate of change in Antarctic temperature was lower than that of the global land region mean, and Antarctic amplification was negative.

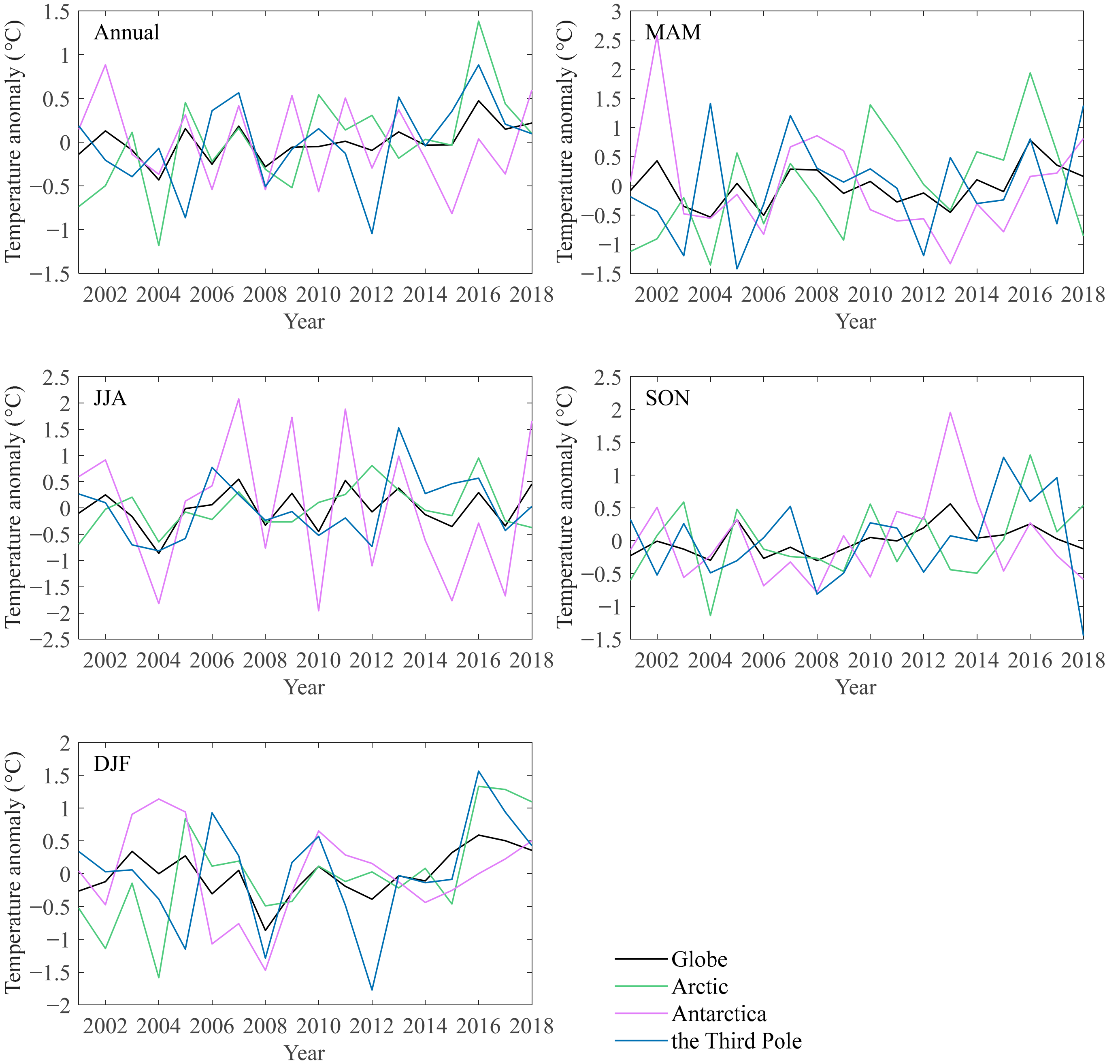

Figure 2. Annual and seasonal mean surface air temperature anomalies for the globe, the Arctic, Antarctica, and the Third Pole during 2001–2018.

Table 1. Amplification indexes the Arctic, Antarctica and the Third Pole, based on global means for land regions.

	Annual	MAM	JJA	SON	DJF
Arctic	3.09	3.98	2.15	2.02	3.44
Antarctica	−0.72	−1.68	−2.73	0.97	−0.15
Third Pole	1.50	1.71	2.19	1.01	1.30

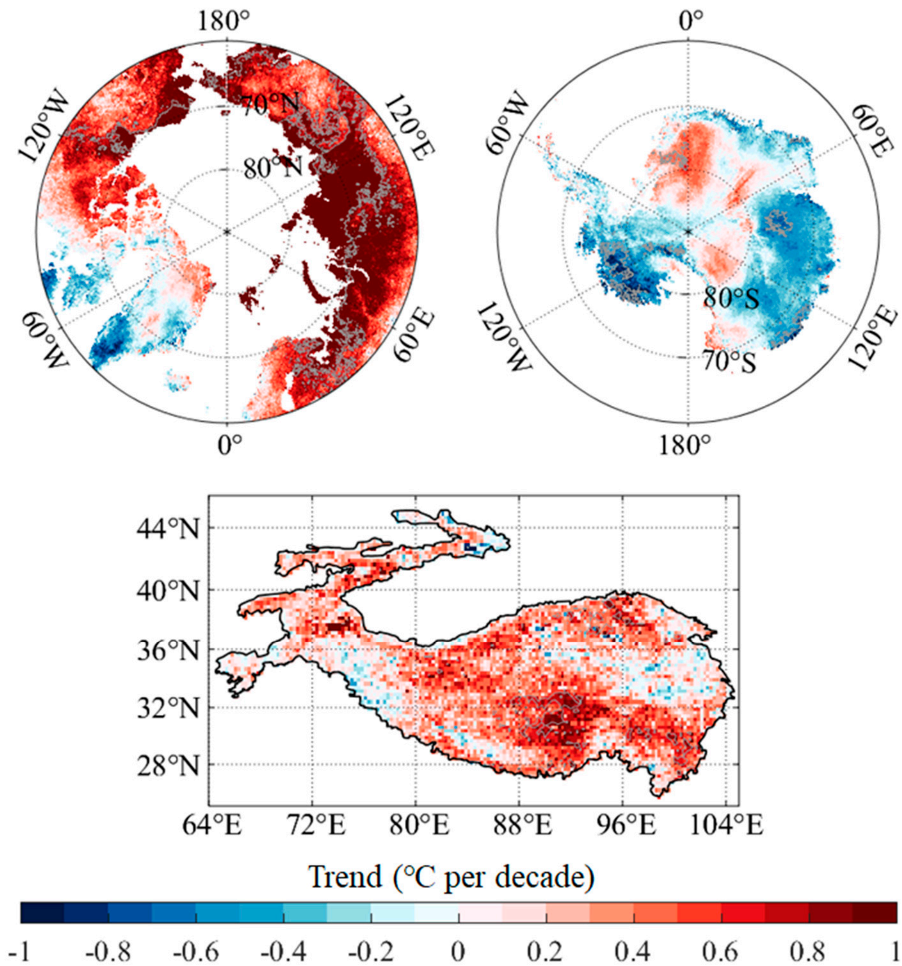

Figure 3. Spatial patterns of trends in annual temperatures over the Arctic, Antarctica, and the Third Pole during 2001–2018. The green lines outline areas with trends that are significant at the 95% confidence level.

As expected, the amplification at the Earth's three poles is characterized by seasonal differences. The strongest Arctic amplification can be observed in MAM and DJF, with amplification indexes of 3.98 and 3.44, respectively, and the weakest signal appears in SON. Even at its weakest, the rate of change in Arctic temperature is more than twice the corresponding rate for global land as a whole. Using surface energy budget analysis, researchers have found that changes in clear-sky downward longwave radiation make the greatest contribution to the obvious Arctic amplification in boreal winter [42]. In addition, the Arctic Ocean stores anomalous heat generated by sea ice loss in boreal summer; this heat is released back into the atmosphere in boreal autumn and winter, and the Arctic Ocean-mediated seasonal energy transfer plays an important role in strong Arctic amplification during the cold season [43]. As the other pole of the Earth, the magnitude of the Antarctic amplification index is apparently weaker than that for Arctic amplification. A positive Antarctic amplification index appears only in austral spring, and the warming rate for Antarctica is slightly lower than that of the global land region mean. In SON, i.e., austral spring, the warming signals are concentrated on East Antarctica; this finding is closely related to changes in the Southern Annular Mode [29,44]. In MAM, the austral autumn, and JJA, the austral winter, obvious negative Antarctic amplification can be observed, with amplification indexes of -1.68 and -2.73, respectively. On the whole, there is a strong asymmetry between the Antarctic and Arctic amplifications from the perspective of changes in surface temperature during the period 2001–2018. The asymmetry has been attributed to such phenomena as surface albedo feedback, more efficient ocean heat uptake in the Southern Ocean, and Antarctic ozone depletion [45,46]. Moreover, the height of the Antarctic surface induces north–south asymmetry in the zonal mean top of the atmosphere radiation budget, which also influences the weaker Antarctic amplification relative to Arctic amplification [47]. In common with Arctic amplification, the amplification at the Third Pole can be detected for all seasons, but with seasonal differences that differ from those of the Arctic amplification. In the case of the Third Pole, amplification is most conspicuous in JJA, with an amplification index of 2.19. This is the season when Arctic amplification is weakest, and the obvious amplification at the Third Pole at this time of year may be related to radiative and dynamical heating that is itself related to significant stratospheric ozone depletion [48]. In SON, rates of change in temperature over the Third Pole are basically consistent with those over global land as a whole. Overall, the weakest positive amplification at the Earth's three poles occurs in SON.

Generally, the amplification at the Earth's three poles appears most pronounced in MAM and JJA. However, there is variation in the intensity of amplification across the three poles: Arctic amplification is greatest, followed by Third Pole amplification, and Antarctic amplification is weakest.

Spatial patterns of amplification indexes for the Arctic, Antarctica and the Third Pole on an annual scale are shown in Figure 4. Clearly, in the case of the Arctic, these patterns are similar to those for temperature changes (Figure 3).

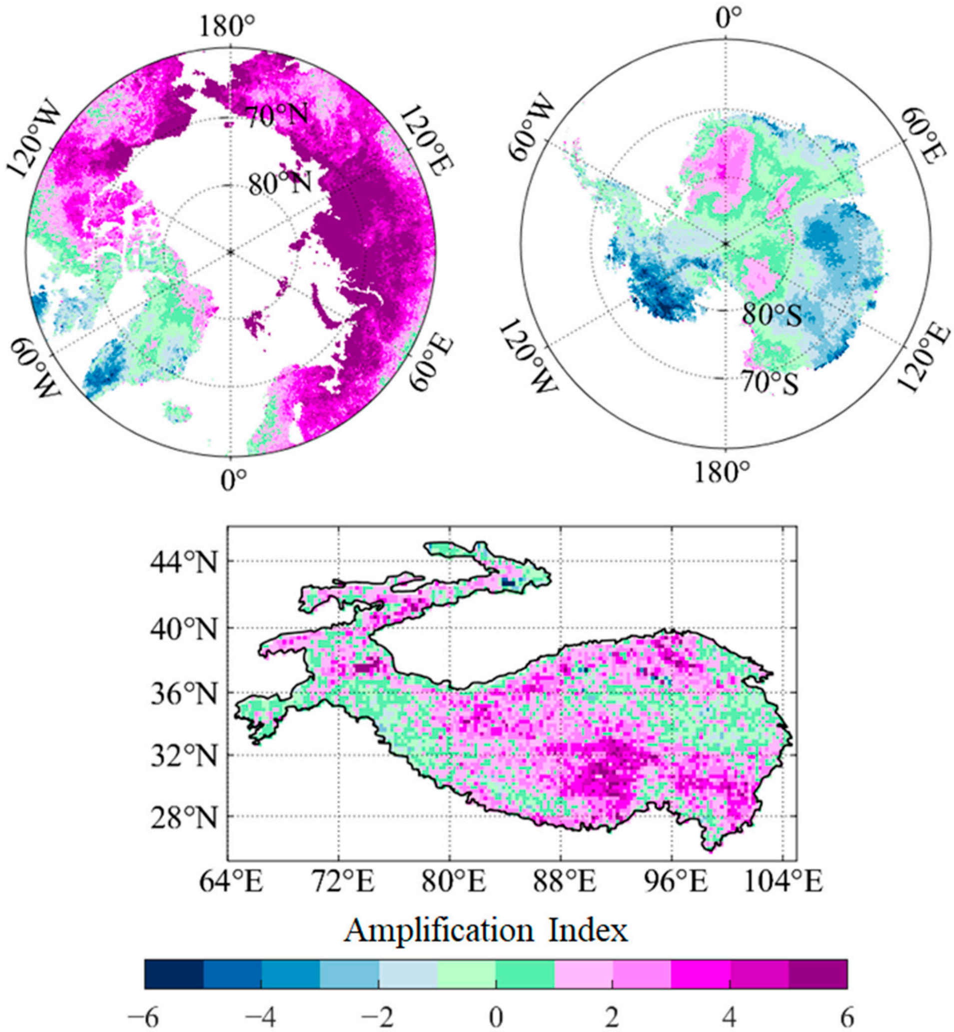

Figure 4. Spatial patterns of annual amplification indexes for the Arctic, Antarctica and the Third Pole.

Compared with the changes in the global land region mean, strong amplification, i.e., an amplification index higher than 4, is evident in land regions in the sector from

30°E to 120°E and 75°N to 85°N. Human activities are the primary driving factor for the warming in this region [49], and so this result indicates that strong amplification is related to the anthropogenically driven trend. However, the area of Greenland between 70°N and 80°N fails to show any amplification signal, and there is obvious negative amplification in southern Greenland. Generally, the most terrestrial region of the Arctic shows stronger variations relative to the global land region mean. In contrast to the widespread positive amplification in the Arctic, only a small portion of Antarctica shows positive amplification, mainly in the area between Dronning Maud Land and Coats Land. Negative amplification can also be observed in West Antarctica and East Antarctica, from 60°E to 150°E at latitudes below 80°S. The negative amplification in West Antarctica for the period 2001–2018 is contrary to the situation prior to 2000, which was characterized by rapid surface warming at a rate of about three times the global mean [50]. Such changes may have been the result of enhanced cold southerly winds related to cyclonic conditions over the Amundsen Sea region and a blocking high in the Drake Passage and northern Antarctic Peninsula; in addition, the role of atmospheric internal variability cannot be ignored [50,51]. In common with Arctic amplification and Antarctic amplification, the distribution of amplification indexes over the Third Pole is characterized by regional differences. An amplification signal with an index generally lower than 4 appears in the northern Tibetan Plateau, extending to the Hengduan Mountains; in contrast, the region near the Qilian Mountains shows weaker warming, compared with the global mean.

Variations in temperature during June–August (boreal summer, austral winter) and December–February (boreal winter, austral summer) are a particular focus of climate research. Spatial patterns of temperature trends and amplification indexes over the Earth's three poles in JJA and DJF are shown in Figures 5 and 6.

In JJA, most areas of the Arctic and the Third Pole display increases in temperature, while the opposite is true for Antarctica. Corresponding to the strong amplification in JJA, with an absolute value of amplification index higher than 2.15 (Table 1), amplification is obviously widespread over the Earth's three poles. In the Arctic, strong warming occurs in the region of Canada from 60°E to 90°E, and warming signals can also be observed in most regions of Russia. Corresponding to the strong warming, positive amplification is evident in these Arctic regions, with amplification index values higher than 2. In addition, the area of Greenland with latitude below 70°N shows a warming trend and positive amplification. Cooling in the east coast of Greenland also appears in observational data. In boreal summer, the Greenland measurement stations Ittoqqortoormiit (70.48°N, 21.95°W) and Danmarkshavn (76.77°N, 18.67°W) both experienced a cooling trend in the period 1991–2011 [52]. The slowing down of summer temperature warming in Greenland is related to the reduction in short-wave solar radiation induced by an increase in total cloud cover, which has been driven by a more durable positive summer North Atlantic Oscillation on a decadal scale [53]. In contrast to the general positive amplification over the Arctic, in the Antarctic, warming and positive amplification only appear in the Antarctic Peninsula and in the 60°E to 120°E sector at latitudes above 80°S. Consistent with obvious cooling, the negative amplification over West Antarctica and the coastal area of East Antarctica is especially noteworthy, with an absolute amplification index value greater than 6. In JJA, the most conspicuous variations, involving a warming rate higher than 1.0 °C per decade, are concentrated on the northern Tibetan Plateau and corresponding strong amplification occurs simultaneously, with a surface warming rate four times higher than the global land region mean.

In DJF, the spatial patterns of temperature trends and amplification indexes over the Earth's three poles are different to those in JJA. Clearly, warming over the Arctic is stronger in winter than in JJA, and the greatest variations can be observed in the 30°E to 180 °E sector. Correspondingly, the most pronounced amplification appears in this region, with amplification index values generally higher than 5. In boreal winter, the Arctic Ocean releases heat to the atmosphere, and the amount of heat released obviously increased in 1979–2018 [54]. The increase was widespread over the northern Barents Sea, and this may have been connected with strong amplification in the adjacent land areas during winter. In contrast to the strong warming and amplification in DJF in the Arctic, the variations over Antarctica are inhomogeneous, and positive amplification signals appear mainly in the area extending from the West Antarctic to the Antarctic Peninsula, as well as the 20°E to 30°W sector with a latitude lower than 80°S; in these areas, the amplification index is lower than 2. Generally, the temperature over the Third Pole shows an increasing trend in winter, whereas the distribution of the amplification index is inhomogeneous. The change in temperature over the region between Nyainqêntanglha Shanmai and the Hengduan Mountains is generally faster than that of the global land region mean, and this phenomenon also commonly occurs in the region with longitude between 64°E and 74°E and latitude between 32°N and 42°N.

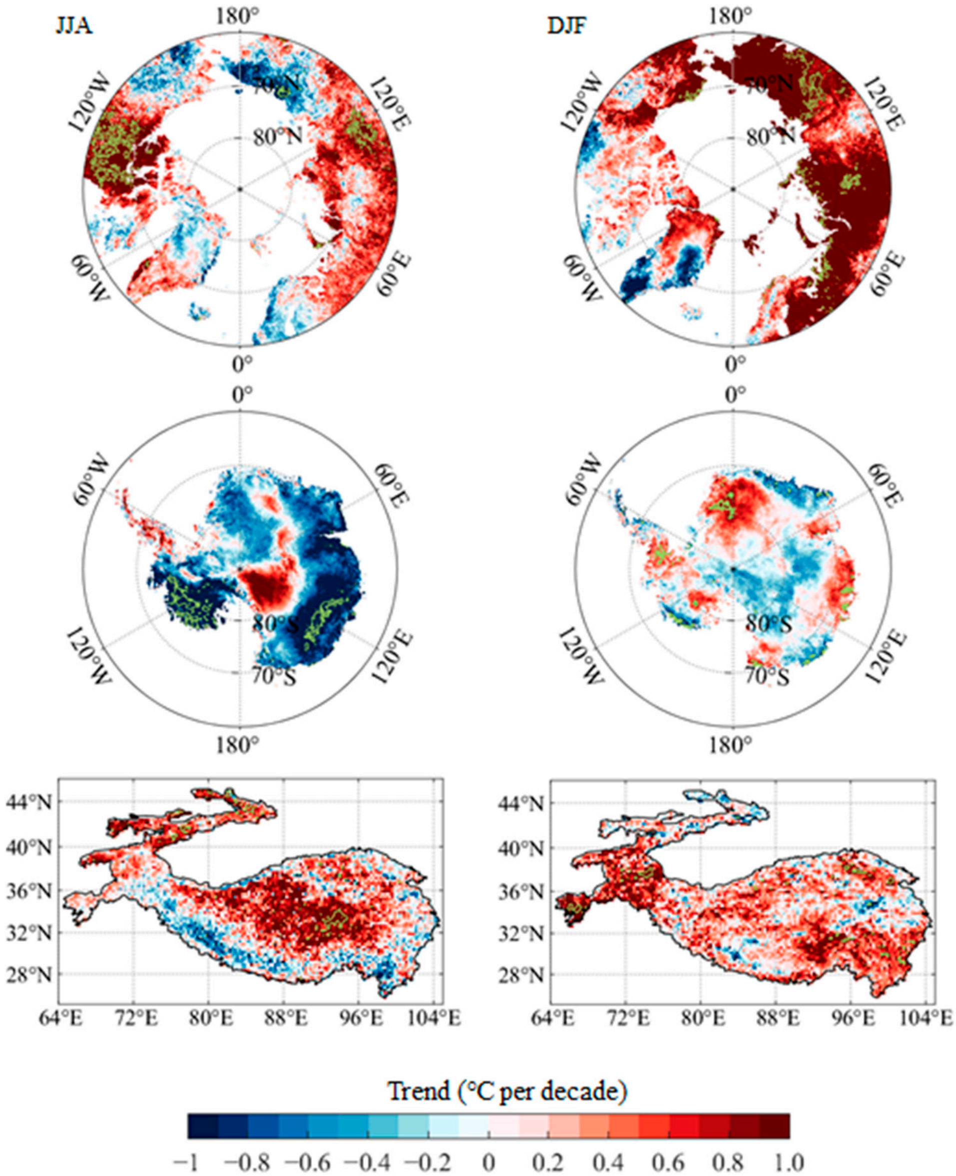

Figure 5. Spatial patterns of temperature trends for the Arctic, Antarctica and the Third Pole in JJA and DJF. The green lines outline areas with trends that are significant at the 95% confidence level.

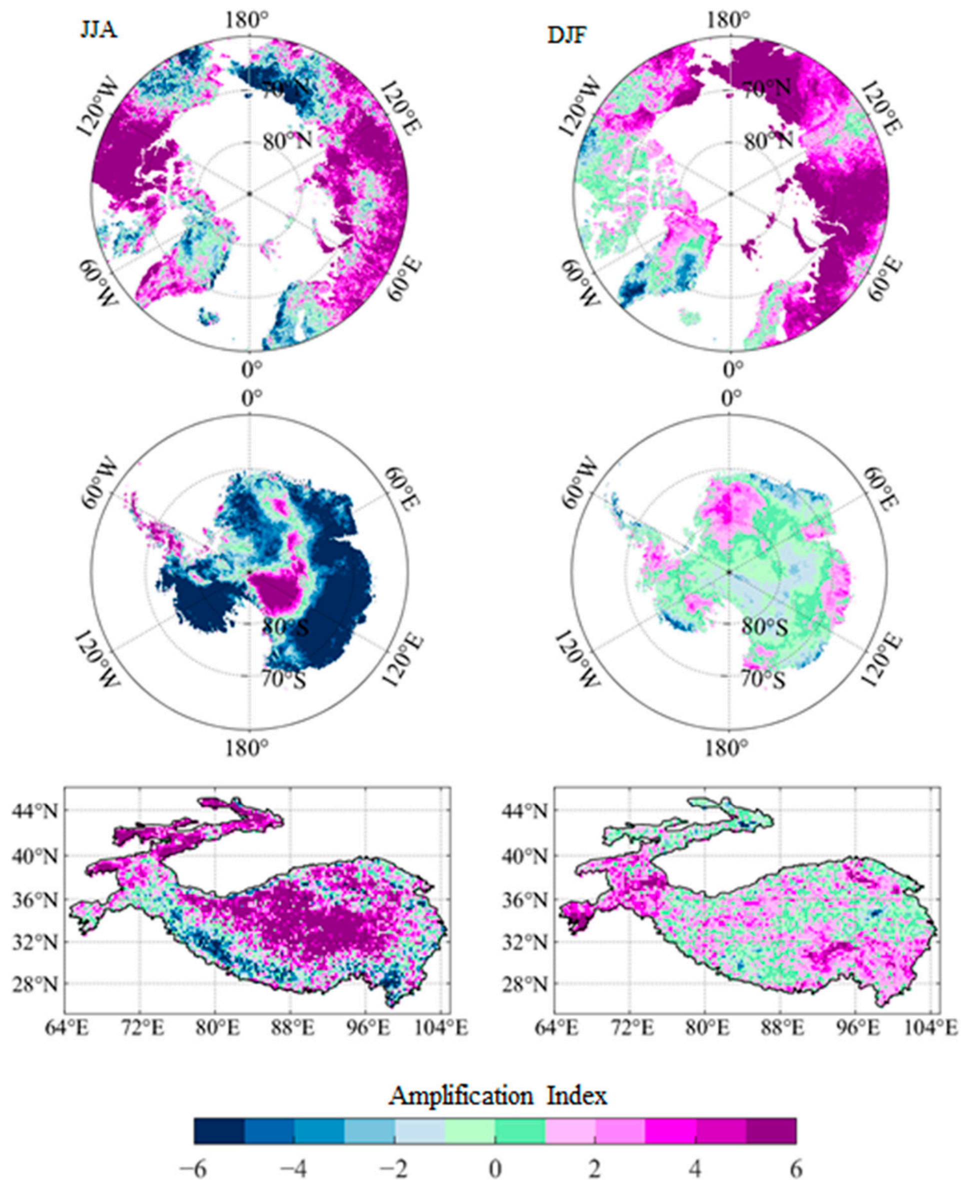

Figure 6. Spatial patterns of amplification indexes for the Arctic, Antarctica and the Third Pole in JJA and DJF.

Figure 7 displays annual amplification indexes for the Earth's three poles with differing start years and interval lengths. Generally, Arctic amplification is absent for the periods 2005–2014, 2005–2015, and 2006–2014, but is present in the other periods, with the most conspicuous signal for the period 2001–2014. In contrast, the existence of the Antarctic amplification is not stable, and an amplification index higher than 1 can only be observed for periods where 2001/2002 is the starting year and 2017 is the ending year. For the Third Pole, variations in temperature are greater than those of the global mean in most time periods, and the amplification index is generally lower than 2. Although the intensity of polar amplification varies across different time periods, the Arctic amplification is most conspicuous, followed by the Third Pole, and it is weakest overall for Antarctic amplification.

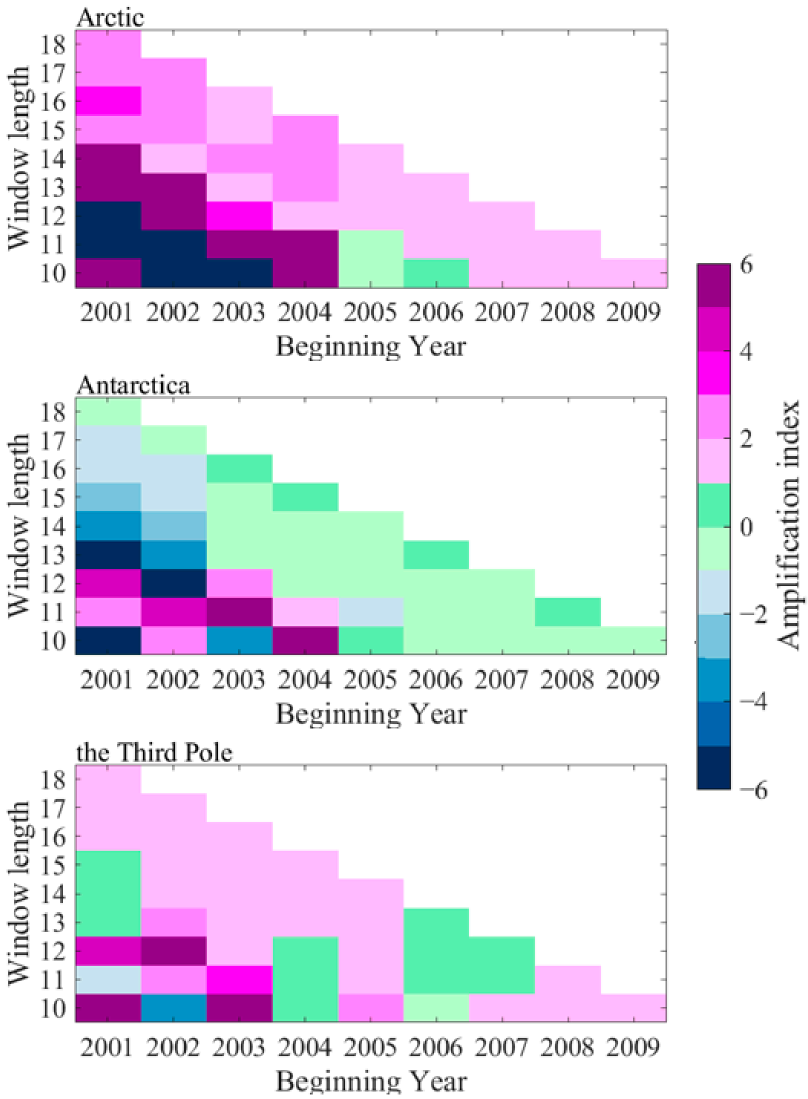

Figure 7. Annual amplification indexes with different start years and interval lengths for the Arctic, Antarctica and the Third Pole.

4. Discussion

For the period 2001–2018, MODIS LST shows dramatic changes over the Earth's three poles. When these are compared with variations in temperature over land across the entire globe, the phenomenon of polar amplification is revealed in the Arctic and at the Third Pole, whereas Antarctic amplification only appears in cold seasons in the Southern Hemisphere. However, polar amplification in Antarctica does appear on all annual and seasonal scales, when compared with temperature changes over the entire Southern Hemisphere land region, so that the rate of variation in Antarctic temperature exceeds 1.27 times that for the Southern Hemisphere in austral summer [30]. The choice of a hemispherical or global scale as a reference has a significant impact on the identification of polar amplification, and especially affects the judgment of whether Antarctic amplification exists. Moreover, most parts of the world are covered by ocean, and only land regions are considered in this study. Using the latest-generation reanalysis data product, ERA5, polar amplification indexes were compared with variations in temperature over the whole globe, including both land and ocean. We found that, on an annual scale, the amplification indexes for the Arctic, Antarctica and the Third Pole are 3.04, 0.67, and 1.26, respectively. Amplification at the Earth's three poles also shows seasonal differences. The intensity in the Arctic is strongest in boreal winter, with an amplification index of 3.93, and is weakest in boreal summer, with a corresponding index of 1.18. In contrast, the most conspicuous amplification at the Third Pole occurs in boreal summer, with an amplification index of 2.41. Antarctic amplification can be identified in JJA, the austral winter, and SON, the austral spring. Therefore, although there may be some differences in results based on different datasets, amplification is evident both in the Arctic and at the Third Pole, whereas Antarctic amplification is evident only in certain seasons.

The mechanisms of polar amplification are complex, and there is no consensus on the dominant factors involved [55]. Local conditions and the poleward transport of heat and moisture are two factors that are commonly thought to contribute to Arctic amplification; however, the interaction between them makes it difficult to separate their respective contributions [56–59]. Surface albedo feedback, cloud feedback, and water vapor and radiative flux feedback are also known to act on amplification at the Third Pole [2,60,61]. In recent years, most areas in the Third Pole have experienced significant warming. This increase may induce more snow to melt, with a resulting decline in local albedo which could lead to an increase in absorbed solar shortwave radiation [55]. In boreal spring, the mean air temperatures are near freezing point, and changes in surface albedo feedback related to the melting of snow play an important role in amplification at the Third Pole. Total and low-level cloud cover both show an increasing trend in boreal summers, and this can induce the cooling of temperature, even when changes in surface albedo are small [20]. Therefore, surface albedo feedback and cloud feedback are not regarded as factors contributing to the obvious amplification over the Third Pole in boreal summer. In addition, changes in land use and values of total ozone also contribute to the warming over the Third Pole [55,62]. In the future, amplification is expected to exist at the Earth's three poles, with the intensity of Arctic amplification being stronger than that of the Antarctica [12]. By quantifying the contributions made to warming by different feedback mechanisms, it has been found that the asymmetry between Arctic amplification and Antarctic amplification is mainly caused by the lapse rate feedback, followed by the albedo and Planck feedback [63].

The mechanisms that underlie temperature changes at the Earth's three poles are still unclear, and there has been relatively little research linking the three poles together. In order to better understand the potential impact of how changes in global climate might affect the Earth's three poles in particular, the correlations between temperature changes at the three poles of the Earth should be explored in future work, through a combination of climate model simulation and the analysis of multi-source data.

5. Conclusions

In this study, we provide an evaluation of temperature changes in the Arctic, Antarctica and the Third Pole, based on the MODIS land surface temperature dataset for the period 2001–2018; we further explore polar amplification at the Earth's three poles.

Among the Earth's three poles, the Arctic shows the strongest warming, with an annual trend approaching 0.60 °C per decade. The Third Pole ranks second, with Antarctica displaying the weakest warming, and even a cooling trend. In addition, variations in temperature over the Earth's three poles show seasonal differences. The warming over the Arctic is most conspicuous in DJF, the boreal winter (0.90 °C per decade), and is weakest in JJA, the boreal summer (0.27 °C per decade). The increase over the Third Pole is greatest in cold seasons, when the warming rate is higher than 0.30 °C per decade; the weakest warming appears in SON, the boreal autumn (0.18 °C per decade). In contrast to the situation in the Arctic and the Third Pole, increases in mean Antarctic temperature appear only in SON, the austral spring (0.17 °C per decade).

Compared to the changes in global mean temperature for land regions only, the polar amplification in the Arctic and at the Third Pole can be detected on an annual scale, and the amplification signal is always positive. In contrast, annual Antarctic amplification cannot be observed and shows a negative amplification index of −0.72.

The amplification at the Earth's three poles shows seasonal differences. The Arctic and the Third Pole show positive amplification in all seasons, whereas the Antarctic amplification index is positive only in SON, the austral spring, a season characterized by a warming rate that is slightly lower than that for the global land region. The strong Arctic amplification can be observed in boreal spring (MAM) and winter (DJF), with corresponding amplification indexes of 3.98 and 3.44, respectively, and is weakest in boreal autumn (SON). Similarly, the amplification at the Third Pole is also weakest in boreal autumn, and the amplification index is only 1.01. However, the greatest polar amplification at the Third Pole appears in boreal summer (JJA), in contrast to the situation for Arctic amplification. Antarctic amplification occurs in austral autumn (MAM) and winter (JJA), although these signals are negative, with amplification indexes of −1.68 and −2.73, respectively. Generally, the Earth's three poles show polar amplification in MAM and JJA, with the stronger signal appearing in JJA when the absolute value of amplification index is higher than 2.00. As expected, among the Earth's three poles, Arctic amplification is the most obvious, with an amplification index higher than 2.02 in boreal spring (SON); the Third Pole ranks second, and Antarctic amplification is the weakest of all, appearing only in austral cold seasons.

In addition, regional differences can be observed in the spatial patterns of the amplification indexes for the Earth's three poles. On an annual scale, in the Arctic, the most obvious amplification appears in the eastern Arctic, and this feature also appears in JJA and DJF. Negative Antarctic amplification is strong in West Antarctica and the East Antarctic coast in JJA, while amplification is not evident in DJF in most regions. At the Third Pole, amplification is widespread over the northern Tibetan Plateau, but this signal is absent in DJF. In conclusion, among the Earth's three poles at different time periods, the intensity of amplification is most conspicuous in the Arctic.

In this study, we sought to assess and compare polar amplification at the Earth's three poles using MODIS land surface temperature data. We found that polar amplification is characterized by regional and seasonal differences, as well as asymmetries with respect to amplification intensity. However, the mechanisms underlying these asymmetries are not yet clear. In order to better understand the role played in climate change by polar amplification, it is necessary to further study the driving factors involved in changes in temperature over the Earth's three poles.

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