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Polar climate change: a multidisciplinary assessment

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ABSTRACT

The rapid environmental changes in polar regions have been attracting considerable political, public, and scientific attention in recent years. The polar amplification is recognized as a robust feature of the climate system in response to carbon dioxide (CO_2) forcing, resulting in sea ice loss, ice sheet melting, and methane release from permafrost thawing. From a physical perspective, this paper examines the polar amplification and sea ice changes for past and future scenarios using satellite, reanalysis, and climate model datasets. From an interdisciplinary perspective, we discuss the potential environmental, socioeconomic, and political effects associated with these changes. The observational data showed enhanced warming and rapid changes in sea ice cover in polar regions. Under the largest future CO_2 forcing, climate simulations indicate an unprecedented rise in air temperature and fast sea ice loss, even in low emission scenarios. This results in a number of physical, environmental, and social-economic effects that need to be carefully considered. Polar climate change, however, offers new opportunities, including the local increase in fisheries and the opening of new navigation routes, which substantially impact the world economy. At the same time, it also implies critical environmental consequences associated with many socioeconomic and ecological risks, such as migration or extinction of populations and species; sea level rise; an increase in frequency and intensity of extreme weather in mid-latitudes; and infrastructure damage from permafrost thawing. Even with the advances and improvements in climate modeling in recent decades, the exact nature of these nonlinear interactions is still in debate.

Keywords: Arctic; Antarctica; climate models; sea ice; polar amplification

Mudanças climáticas nos polos: uma avaliação multidisciplinar

Resumo

Nos últimos anos, as rápidas mudanças ambientais nas regiões polares têm atraído considerável atenção política, pública e científica. A amplificação polar é uma característica importante do sistema climático, em resposta ao forçamento do dióxido de carbono (CO_2), que resulta na perda de marinho, derretimento do manto de gelo e liberação de metano através do derretimento do solo congelado. De uma perspectiva física, este artigo utiliza dados de satélite, reanálise e modelos climáticos para analisar a amplificação polar e mudança de gelo marinho no tempo passado, presente e cenários futuros. De uma perspectiva interdisciplinar, discutimos quais os potenciais efeitos ambientais, socioeconômicos e políticos associados a essas mudanças. Os resultados, a partir de dados observados, mostraram aumento do aquecimento e mudanças rápidas na cobertura de gelo marinho nas regiões polares. As simulações climáticas mostraram um aumento sem precedentes na temperatura do ar e uma rápida perda de gelo marinho em resposta ao aumento de CO_2, mesmo em cenários de baixa emissão. Isso resulta em uma série de efeitos físicos, ambientais e socioeconômicos que precisam ser cuidadosamente considerados. As mudanças climáticas nas regiões polares, no entanto, oferecem novas oportunidades incluindo o aumento local da pesca e abertura de novas rotas de navegação, que impactam substancialmente a economia mundial. Ao mesmo tempo, observam-se consequências ambientais críticas associadas à riscos socioeconômicos e ecológicos, como migração e extinção de espécies, aumento do nível do mar, aumento na intensidade e frequência de eventos extremos em médias latitudes, e danos a infraestrutura causados pelo derretimento do solo congelado. Mesmo com os avanços e melhorias na modelagem climática nas últimas décadas, a natureza exata dessas interações não lineares ainda está em debate.

Palavras-chave: Ártico; Antárctica; modelos climáticos; gelo marinho; amplificação polar

Introduction

One of the most visible signs of ongoing global climate change is the fast change in polar regions, mainly characterized by enhanced warming and rapid ice loss. Polar regions are critical to regulating the Earth's temperature and providing essential ecosystem services to local and global communities. (Serreze and Barry, 2011; Post et al., 2013; Meredith et al., 2019). The rapid changes in the polar regions have drawn attention and concern around the world, especially considering ongoing climate change and its potential to affect weather and climate regionally and globally in multiple ways (Meredith et al., 2019)

The polar region's warming has been almost twice as fast as the globe as a whole in recent decades, particularly in the Arctic and Antarctic Peninsula regions. This phenomenon is known as the Polar Amplification (PA) and is related to many nonlinear and complex coupled ocean-atmosphere processes with effects beyond high latitudes (Smith et al., 2019; Casagrande et al., 2021). Although numerous studies have investigated the Arctic PA over the last three decades, the Antarctic PA is still poorly understood (Salzmann et al., 2017; Casagrande et al., 2020; Wang et al., 2021; Previdi et al., 2021).

The scientific community, through important international reports from panels such as the Intergovernmental Panel on Climate Change (IPCC) and an expressive number of scientific publications, has warned about polar climate change's impacts on a wide range of environmental and socioeconomic activities, including tourism, fishing productivity, resource exploration, navigation, and some geopolitical issues. (Vavrus, 2018; Coumou, 2018; Meredith et al., 2019; England et al., 2020; Box et al., 2022). Coordinated scientific efforts to better understand high latitude changes have been carried out by organizations such as SCAR (Scientific Committee on Antarctic Research), YPI (International Polar Year), ACCESS (Arctic Climate Change Economy and Society), ISMIP (Ice Sheet Model Intercomparison Project) and SIMIP (Sea-Ice Model Intercomparison Project), endorsed by the Coupled Model Intercomparison Project (CMIP), scientific basis of IPCC.

The Arctic experiences one of the most drastic and severe climate changes on Earth (Figure 1). The Arctic is warming at an alarming rate, about 2 to 4 times faster than the rest of the world, and the sea ice has been decreasing on average by about 11% per decade over the past four decades (Stroeve, 2018; Smith et al., 2019; Meredith et al., 2019; Matveeva et al., 2020; Casagrande et al., 2021). The annual average surface air temperature (SAT) for 2022 was 0.76°C higher than in 1991–2020. In fact, including 2022, the 15 warmest years observed in the Arctic have all occurred since 2005(Blunden et al., 2023). The Arctic climate emergency is associated with continental ice melting and the release of methane (CH4) and carbon dioxide (CO_2) from permafrost thawing (Smith et al., 2019; Meredith et al., 2019; Pedrivi et al., 2021; Schuur et al., 2022).

The Arctic´s environmental changes are linked to a cascading series of effects, including ocean warming, sea level rise, increasing risks of mid-latitude weather extreme events, species extinction and migration, increasing opportunities for resource exploration and tourism, and geopolitical tensions (Box et al., 2022; Constable et al., 2022). The changes have affected all sectors of society, impacting approximately 4 million Arctic inhabitants, including 400,000 indigenous people (Johannsdottir and Cook, 2019; Huntington et al., 2022).

Antarctica has also undergone systematic and progressive climate change over the last few decades. The effect of rising air temperatures on the Antarctic continent may result in instability and melting of the ice sheet, causing ice shelves to collapse and accelerating global sea level rise (DeConto et al., 2016; DeConto et al., 2021). In this regard, it is worth noting that the Antarctic ice sheet stores close to 70% of all freshwater on the planet. If we consider both poles, the Antarctic's and Greenland's ice sheets hold enough fresh water to rise approximately 58 m and 7 m, respectively, if completely melted (Marzeion et al., 2019; Oppenheimer et al., 2019; Magnan et al., 2022). In March 2022, East Antarctica experienced a remarkable and unprecedented large-scale heat wave. In Concordia station (Antarctic Plateau), the thermometers recorded a SAT maximum of -11.5 °C, contrasting with the climatological normal of -50 °C (i.e., SAT record-breaking increase of 38.5 °C) (state of climate, 2023). Antarctic sea ice reached its lowest extent in the 45-year satellite record in February 2023 and has continued to decline since then. This recent decline has raised concerns about whether it is a brief anomaly or an early sign of a long-term trend and a potential tipping point indication (Ludescher et al., 2019; Lui et al., 2023; NSCID, 2023). Antarctica has no permanent settlements. However, many nations conduct field research and operate stations on a seasonal basis (Dodds et al., 2017). According to the Council of Managers of National Antarctic Programs (COMNAP) and the Antarctic Treaty System (ATS) data, there are currently 76 active research stations in Antarctica during the summer, hosting approximately 5,500 people.

Our hypothesis suggests that the impacts of climate change on polar regions are complex and uncertain with a widw range of potential socioeconomic evironmental, and political implications both locally and globally.In this paper, we use observational data (satellite and reanalysis) and climate models (CMIP6) to investigate the past, present, and future of PA, sea ice changes, and their associations with mid-latitude extreme weather events. We also discuss the socioeconomic, environmental, and geopolitical implications of polar climate change.

The paper is organized as follows: Section 2 provides a description of the observational data, the climate models, and the numerical designs used in this work. In Section 3, we investigate the past, present, and future of interhemispheric PA, sea ice changes, and their mid-latitude effects on extreme weather events. Section 4 discusses the socioeconomic, environmental, and political implications of polar climate change. A summary of the results and the conclusions are presented in Section 5.

Material and Methods

Climate data

The monthly SAT data used are atmospheric reanalysis obtained from the European Center for Medium-Range Weather Forecasts Reanalysis 5 (ECMWF ERA5, Hersbach et al., 2020) for the period of 1980-2020. The data is used in order to evaluate the observed interhemispheric PA. The sea ice concentration (SIC) and sea ice extent (SIE) data used here are satellite data obtained from the Scanning Multichannel Microwave Radiometer (SSMR) onboard the Nimbus-7 satellite and from the Special Sensor Microwave/Imager SSM/I onboard the Defense Meteorological Satellite Program's (DMSP). Both satellite datasets are monthly means refering to the period 1979 to 2022 and are available at the National Snow & Ice Data Center (NSIDC, 2023) (Fetterer et al., 2017). The SIE is the sum of the areas of pixels covered by ice, where each pixel is at least 15% ice covered.

The CMIP6 data were used here to estimate the interhemispheric PA and the sea ice changes as responses to the atmospheric CO_2 increase by the end of the 21st century. The numerical experiments used here were the historical experiments. These experiments aim to simulate the past and present time of the Earth System. Future climate projections are simulated through the Shared Socioeconomic Pathway experiments. In this case, we consider that the radiative forcing value (directly correlated to the atmospheric CO_2 concentration) in the year 2100, relative to pre-industrial values, is 8.5 $W.m^{-2}$ (equivalent to a concentration of 1200 ppm CO_2). This scenario, known as the SSP5-8.5, simulates the Earth System at very high levels of fossil fuel use, representing the highest emissions of a "no-policy" baseline scenario of any developed in the SSP process (O'Neill et al., 2016; Kriegler et al., 2017; O'Neill et al., 2017).

The following CMIP6 models were used in this study:

ACCESS-CM2, ACCESS-ESM1-5, AWI-CM-1-1-MR, BCC-CSM2-MR, CAMS-CSM2-MR, CESM2-WACCM, CESM2, CMCC-CM2-SR5, CNRM-CM6-1-HR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, EC-Earth3-Veg, EC-Earth3, FGOALS-g3, GFDL-CM4, GFDL-ESM4, HadGEM3-GC31-LL, IITM-ESM, INM-CM4-8, INM-CM5-0, IPSL-CM6A-LR, KACE-1-0-G, KIOST-ESM, MIROC-ES2L, MIROC6, MPI-ESM1-2-HR, MPI-ESM1-2-LR, MRI-ESM2-0, NESM3, NorESM2-LM, TaiESM1, UKEESM1-0-LL. The data are available in the ESGF platforms (https://esgf.llnl.gov/) and in the IPCC Atlas (https://interactive-atlas.ipcc.ch/).

Results

Polar climate change: current climate and future scenarios

Interhemispheric PA mean state climate

In the late 19th century, Svante Arrhenius (Arrhenius, 1896) proposed that changes in the atmospheric CO_2 concentration could modify the near-surface air temperature (SAT), and that this change would be stronger at high latitudes. This seems to be the first formal consideration related to the PA concept. Currently, PA is recognized as a phenomenon where external radiative forcing produces a larger change in air temperature at high latitudes compared to the mean (global) air temperature change. PA is considered a robust feature and an indicator of global climate change (Previdi et al., 2021).

Figure 1 shows the Arctic and Antarctic PA, represented by the enhanced SAT at high latitudes compared to the rest of the globe. The phenomenon is more evident in the cold season (boreal winter for the Arctic and boreal summer for Antarctica). During the last two decades, the Arctic region has warmed more than twice as fast as the global average (Figure 1). The highest Arctic PA values (more than 3.5 ºC warmer than the global mean) occur in the cold season (Figure 1a) and are found in the Kara and Barents seas, regions that are recognized as important nursery and feeding areas for commercial fish stocks such as herring, cod, and capelin (Ellingsen et al., 2008). Dai et al. (2019) suggested that strong PA is expected to occur in regions with significant sea ice loss. According to the authors, sea ice melt is mandatory for causing a large Arctic PA because, in the newly opened (ice-free) waters, the increase in outgoing longwave radiation and heat fluxes amplifies the atmospheric warming, whereas all other (dynamical and thermodynamical) processes linked to the melting sea ice contribute only indirectly to the PA.

According to Casagrande et al. (2021), the ocean-atmosphere-sea ice physical processes involved in PA are complex, and conclusive answers on how they work are lacking and still under debate. The "albedo-sea ice" and the "lapse rate" feedback mechanisms are often described as the main contributors to the Arctic PA. However, other mechanisms, such as changes in the poleward heat transport by the atmosphere and the ocean, temperature feedbacks (Planck response and lapse rate feedback), and longwave feedback associated with polar clouds and water vapor are also suggested to contribute (Hwang et al., 2011; Pithan and Mauritsen, 2014; Goose et al., 2018; Ono et al., 2022).

In comparison to the Arctic, the high latitudes of the southern hemisphere are warming at a lower rate (Figure 1e). That warming, nevertheless, cannot be disregarded since it há s the potential to affect the oceanic and atmospheric global circulations and to contribute to the sea level rise due to the ice sheet melting and the sea water thermosteric effect (Meredith et al., 2019; DeConto et al., 2021). The observed SAT trend in the Antarctic Peninsula, Bellinghausen Sea and Weddell Sea regions (Pine Island Sea and parts of Central Western Antarctica) in the austral winter - JJA (austral summer - DJF) season is close to 1.5 ºC (1.6 ºC) per decade (Figure 1b,a). In Antarctic continent, the PA is enhanced in Austral Spring (Figure 1d). Bromwich et al. (2013), suggest that Central Western Antarctica is among the most rapidly warming regions on the planet. According to the authors, the region has probably warmed since the 1950s, but the magnitude, seasonality, trend, and spatial variability of this warming are still a subject of debate, mainly due to the substantial gaps in the datasets.

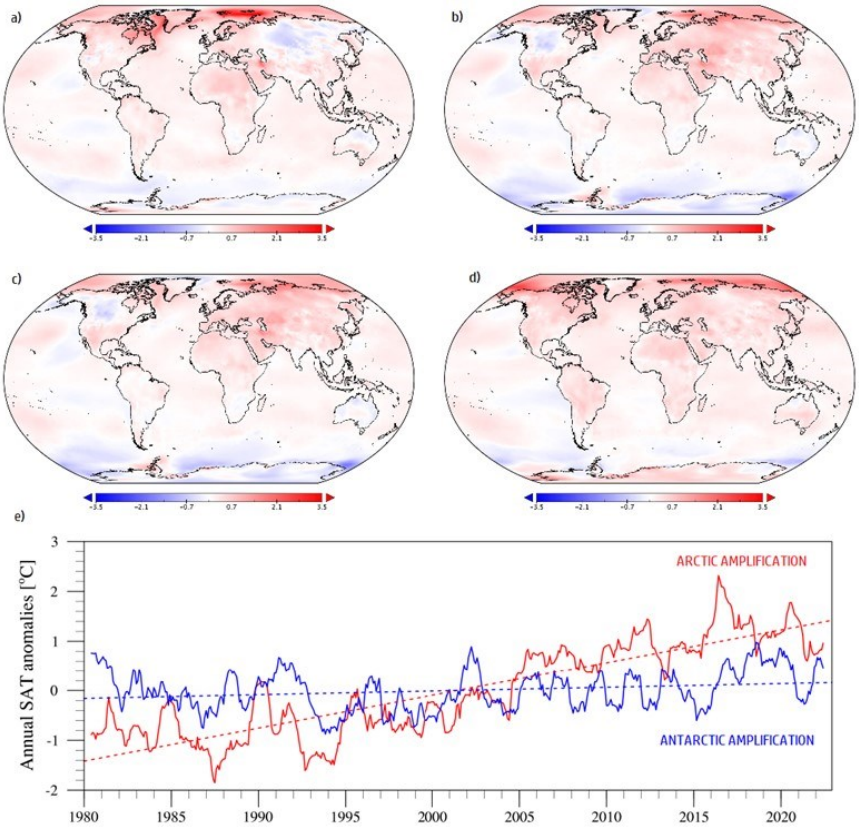

Figure 1. Near-surface air temperature trend average (◦C per decade), average in (a) DJF (December-January-February); (b) MAM (March-April-May); (c) JJA (June-July-August); (d) SON (September-October-November), and (e) annual SAT anomalies, estimated from ERA5 Reanalysis for the period 1980-2022.

Polar amplification in the future scenarios

In this session, we investigate the response of polar regions to an increase in atmospheric CO_2 concentrations simulated by 33 climate models from CMIP6. Figures 2 and 3 exhibit enhanced SAT warming at high latitudes compared to the rest of the globe for the winter and summer seasons. The peak of Arctic (Antarctica) warming, representing the PA, is during the boreal winter - DJF (austral winter - JJA) period. This PA is not symmetric (Figure 2, 3)being more evident in the Arctic region. However, it is clear that the Antarctic PA cannot be neglected, particularly in the Bellinghausen, Amundsen, and Weddell seas and on the Antarctic Peninsula, where the simulated PA exhibits the highest values around Antarctica (more than 7 ^{o}C higher than the global mean (Figure 2b). Under the largest future CO_2 forcing imposed by the SSP5-85 scenario, the central Arctic presents the highest SAT warming in months from January to March (boreal winter), with SAT increases being close to 20 ^{o}C (Figure 2, 3).

In continental, high-latitude areas of the northern hemisphere (north of Russia and Canada) PA values are as high as 10 oC. Here it is important to consider the effect of the CH4 and CO2 releases through the thawing of permafrost on accelerating the PA that imposes important effects on the local ecosystems and infrastructure (Schaefer et al., 2014; Turetsky et al., 2020). The Antarctic region and its surroundings present, during the austral winter (Figure 2c) and spring (Figure 2b), a warming that exceeds the simulated warming at all other latitudes of the southern hemisphere. The Antarctic PA is more pronounced in western Antarctica (Bellingshausen and Amundsen seas) and in parts of eastern Antarctica (Weddell Sea and Antarctic Peninsula).

The simulated Antarctic PA increase is close to 8 oC in the Bellingshausen and Amundsen seas and about 9 oC in the Weddell Sea region during the austral winter (Figure 2b). According to Casagrande et al. (2022) and in agreement with Figure 5, these areas will be the most vulnerable to the expected sea ice loss of the forthcoming decades (Figure 5). The Antarctic PA could lead to more frequent and intense ice sheet melting episodes in the West Antarctic Ice Sheet (WAIS), a region already recognized as an important contributor to sea level rise (Bromwich et al., 2013). The Antarctic PA effect on the Southern Ocean will probably cause significant changes in the sea ice, resulting in important changes in the marine ecosystem and in the global atmospheric circulation (Purich and England, 2019). In this respect, our findings are in full agreement with previous studies using climate models (Smith et al., 2019; Cai et al., 2021; Eayrs et al., 2021; Casagrande et al., 2021). The PA phenomenon, measured as the warming excess with respect to lower latitudes, occurs if the magnitude of the zonal or meridional mean SAT change in the poles exceeds the tropical SAT mean change in response to climate forcing and on time scales greater than the annual cycle. According to Casagrande et al. (2021), recognizing the physically coupled ocean-atmosphere-sea ice processes underlying the PA is essential for providing confidence and also for constraining model projections of Arctic and Antarctic climate change.

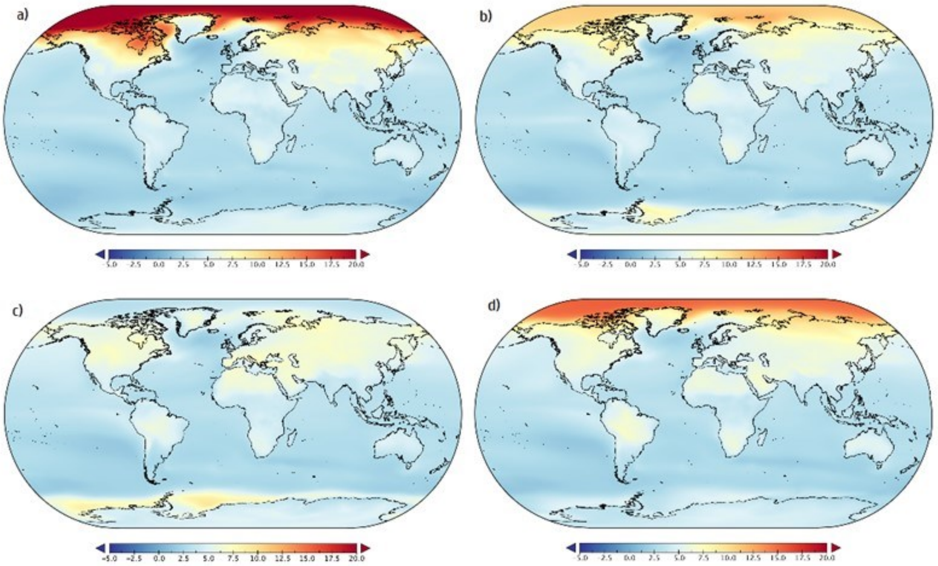

Figure 2. Near surface air temperature changes for the period 2081-2100 in future scenario simulations related to 1995–2014 in CMIP6 historical simulations in (a) DJF (December-January-February); (b) MAM (March-April-May); (c) JJA (June-July-August); (d) SON (September-October-November).

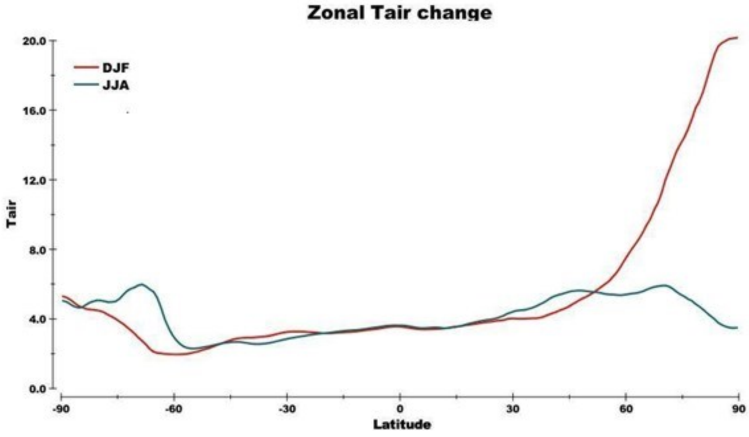

Figure 3. CMIP6 - Zonal mean of the SAT change (°C) for the period 2081-2100 relative to the 1995-2014 period in (a) boreal winter (December-January-February) and (b) boreal summer (June-July-August)

In continental, high-latitude areas of the northern hemisphere (north of Russia and Canada) PA values are as high as 10 oC. Here it is important to consider the effect of the CH4 and CO2 releases through the thawing of permafrost on accelerating the PA that imposes important effects on the local ecosystems and infrastructure (Schaefer et al., 2014; Turetsky et al., 2020). The Antarctic region and its surroundings present, during the austral winter (Figure 2c) and spring (Figure 2b), a warming that exceeds the simulated warming at all other latitudes of the southern hemisphere. The Antarctic PA is more pronounced in western Antarctica (Bellingshausen and Amundsen seas) and in parts of eastern Antarctica (Weddell Sea and Antarctic Peninsula).

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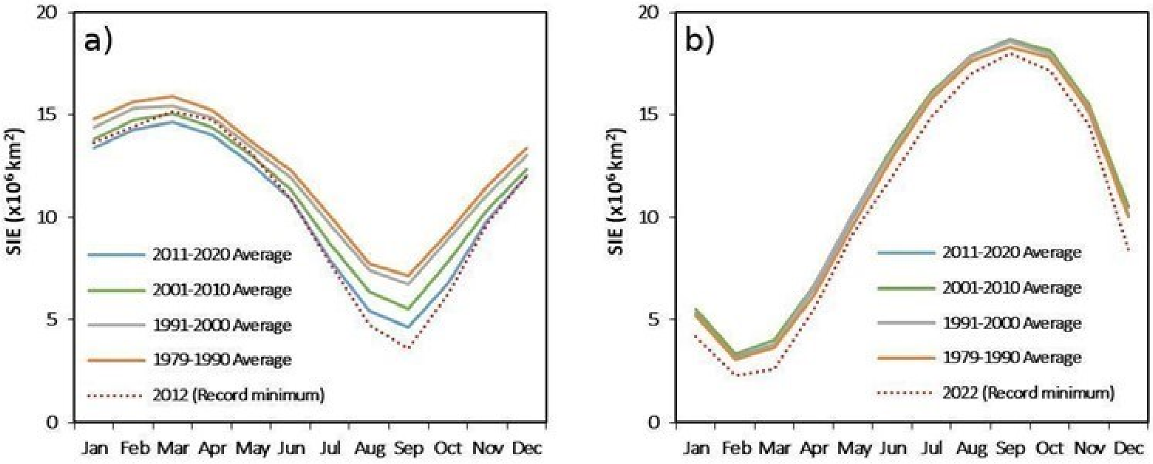

Figure 4. (a) Arctic and (b) Antarctic SIE seasonal cycles from NSCID satellite data (in millions of Km^2) . Decennial SIE average from 1979-1990 (orange line), 1991-2000 (gray line), 2001-2010 (green line), 2011-2020 (light blue line), minimum record (dashed line).

Sea ice future scenario

Here we evaluate the sea ice concentration (SIC) changes under the global warming targets specified by the Paris Agreement (+1.5, 2, and 3 °C global warming). These scenario targets were chosen due to their global political and environmental relevance. Figure 5 shows the September and February SIC climatology of 1980–2014 and the simulated SIC when the ensemble mean models reach a threshold of +1.5 °C, 2.0 °C, and 3.0 °C global warming. The representative months of September and February were chosen because they commonly represent the time when the Arctic and Antarctica, respectively, reach their annual minimum in sea ice concentration, area and extent. The future scenarios point to a rapid decline of both the Arctic and Antarctic SIC over the coming century for all global warming thresholds envised by the Paris Agreement (Figure 5). The observed Arctic (Antarctic) SIC climatology in September (February) was close to 7.5 x 106 km2 (2 x 106 km2). Under the global warming threshold of +1.5 oC (2 oC), the Arctic SIE in September was 5.8 x 106 km2 (4.6 x 106 km2). Under the global warming threshold of +1.5 oC (2 oC), the Arctic SIE decrease is approximately 24% (39%), relative to present-day SIC climatology. In scenarios of 3 °C global warming, the Arctic SIE was approximately 1.9 x 106 km2, which is equivalent to a decrease of 74.6% relative to historical climatological values (Figure 5). These findings are in agreement with Sigmond et al. (2018) and Casagrande et al. (2021). According to England et al. (2020), the combined Arctic and Antarctic sea ice losses will account for 20-30% of the projected tropical warming and precipitation increase under a high CO2 emission scenario. Additionally, it is critical to recall that sea ice affects marine ecosystems in a variety of ways, for instance: (i) sea ice provides habitat for a variety of polar species, including seals, penguins, and krill, which rely on sea ice for breeding, feeding, and resting; (ii) sea ice supports a complex food web, with algae growing on its surface and serving as a critical food source for zooplankton and other animals (Arrigo, 2014; Constable et al., 2022)

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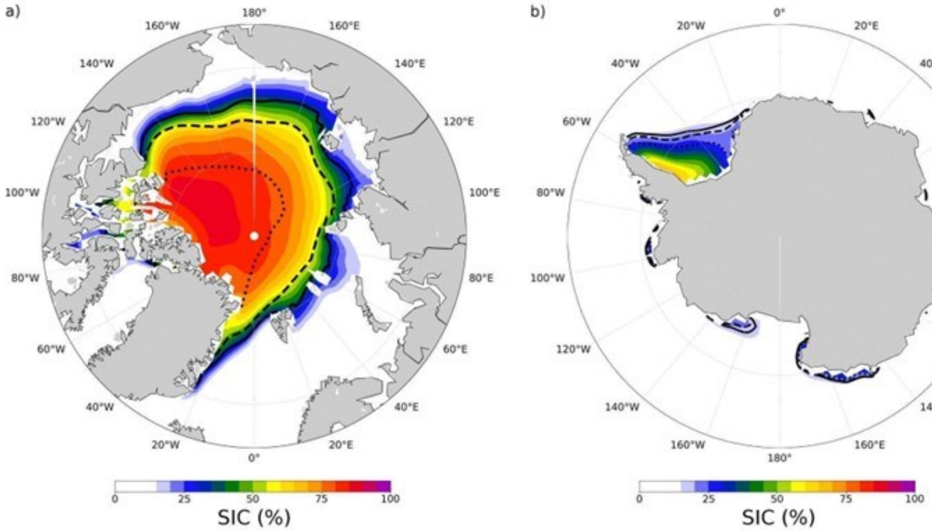

Figure 5. (a) Arctic SIC climatology of September (1980-2014) from satellite observations (shaded colors). (b) Antarctic SIC climatology of February (1980-2014) from satellite observations (shaded color); both months represent the minimum SIC months for the northern and southern hemispheres, respectively. The black solid lines, black dashed lines, and black dotted lines refer to the SIC average under each global warming threshold of the Paris Agreement: +1.5 ºC, 2.0 °C, and 3.0 °C, respectively.

Polar climate change and its influence on mid-latitude weather and climate

The accelerated polar warming and the ice changes impose profound impacts on mid-latitude weather and climate, which pose potential high-impact risks for society. The Arctic climate change forces an impact, still subject to active debate, in an observed increase in frequency and intensity of mid-latitude extreme weather events in the northern hemisphere (Barnes, 2013; Vihma, 2017; Overland et al., 2021).

The Arctic PA and sea ice and snow cover are associated with a weakened equator-to-pole thermal gradient and a weakening of the mid-latitude circulation caused by global warming (Coumou et al., 2018). According to Cohen et al. (2014), the impacts of the Arctic PA on northern hemisphere mid-latitude weather includes changes in the storm tracks, in the upper atmosphere jet stream, in planetary waves and their associated energy propagation.

The effects of Arctic warming on mid-latitude extreme weather events, however, are known to vary both seasonally and spatially. According to

Coumou et al. (2018), in summer, the Arctic PA could lead to more persistent hot-dry extremes in the mid-latitudes. The major evidence proposed by the authors to explain the influence of Arctic PA on mid-latitude summer circulation is related to the following phenomena related to global warming: (i) weakened storm tracks; (ii) shifted jet stream; and (iii) amplified quasi-stationary waves. In winter, the Arctic PA is also associated with extreme cold winters in heavily populated regions across parts of Eurasia and North America (Overland et al., 2020; Cohen et al., 2021). Overland et al. (2020), for example, investigated the effect of Arctic climate changes during February-March 2018 “Beast from the East" cold air winter event that dramatically affected parts of Europe and north-central North America.

The results indicated that the 2018 cold air winter event was significantly influenced by the delay of sea ice formation during early winter in the Barents and Chukchi seas and by a weakening of the stratospheric polar vortex with a sudden stratospheric warming. The Antarctic climate change also plays an important role in the global ocean and atmospheric circulation, as well as the mean state of the southern hemisphere (Hu et al., 2022). Saurral et al. (2014) investigated the changes in precipitation and river discharge in southeastern South America as a response to regional changes in Austral SIC concentration. According to the authors, the Antarctic SIC anomalies in the Weddell Sea in September were linked to dry (wet) conditions over northeastern Argentina and Uruguay (eastern Brazil) and associated with changes in river discharges in the study regions. Changes in Antarctic PA and SIC may result in near surface air temperature and precipitation changes in southern hemisphere mid-latitudes, affecting extensive agriculture regions in South America, thus causing productivity and economic losses. Moreover, it may have the potential to affect consumers, particularly in low-latitude regions, resulting in higher food prices (Meredith et al., 2019; Constable et al., 2022).

Using climate simulations, Zhu et al. (2023) investigated the changes in extreme precipitation and temperatures over the southern, extratropical continents in response to the Antarctic sea ice loss by the end of the 21st century. According to the authors, although the projected Antarctic sea ice shrinking will contribute to a decrease in cold extremes over most regions, it will probably cause an opposite effect over the southern continents. Furthermore, the intensity and frequency of the wet extremes are expected to increase over South America and Antarctica.

Interdisciplinary aspects

There is a complex interplay between the physical, environmental, social, and political dynamics of polar regions. These interactions take place across a wide range of spatio-temporal scales and have a substantial impact on local communities and the availability of natural resources like fish, oil, and gas stocks. These issues promote a great deal of worldwide interest. Many environmental, socioeconomic, and geopolitical changes are expected as a result of high latitude climate change. Figure 6 illustrates some of these changes or effects. The following physical processes are the the primary evidence of climate change in polar regions: the PA (Smith et al., 2019; Previdi et al., 2021), the ocean warming (Cheng et al., 2022), the sea ice loss (Notz and Stroeve, 2018; Eayrs et al., 2021), the permafrost thawing (Patton et al., 2019), the ice sheet melting (Golledge, 2019), the sea level rise (Golledge, 2020; Slater et al., 2020), the ocean acidification (Hansel et al., 2020), the water cycle changes (Vihma et al., 2016), the ocean and atmosphere circulation changes (Coumou et al., 2018; Zhang et al., 2020; Li et al., 2021), the changes in the biogeochemical cycle (Lannuzel et al., 2020), the coastal erosion (Nielsen et al., 2022) and the increase in heat waves (Dobricic et al., 2020), among others. Among the environmental or ecological consequences of climate change in high latitudes, especially in the northern hemisphere, we can include changes in the food web (Marsh and Mueter, 2020; Pecuchet et al., 2020), migration and extinction of species (Chambault et al., 2022), the presence and increase of invasive species (Chan et al., 2019) and the risk of oil spill accidents (Johannsdottir and Cook, 2019). The economic impacts include short-term advantages for commercial fisheries (Hansel et al., 2020; Marsh and Mueter, 2020), new Arctic routes reducing the distance between Europe and Asia (Liu and Kronbak, 2010; Ng et al., 2018); expansion of coastal and marine tourism (Shijin et al., 2020), expansion of natural resources exploration (Gautier et al., 2009; Petrick et al., 2017) and loss and damage to infrastructure due to permafrost thawing (Hjort et al., 2018). The main social implications associated with climate change in high latitudes are related to human health (Huntington et al., 2022; Lebel et al., 2022), food security (ICC, 2015; Huntington et al., 2022), vulnerability, perception, and adaptation of human populations (Ford et al., 2015).

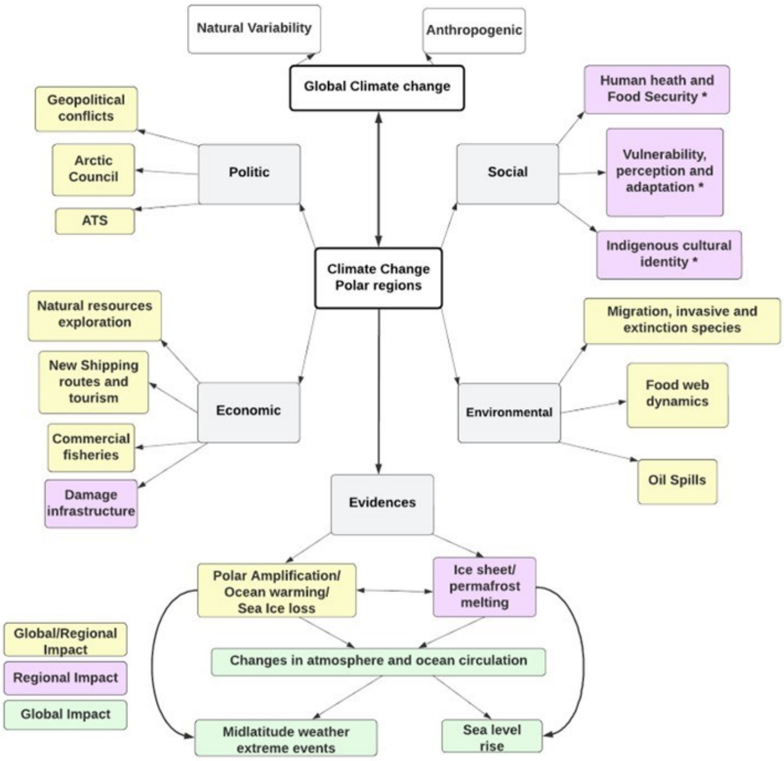

Figure 6. Multidisciplinary scheme of the potential environmental, socioeconomical, and political effects of high latitude climate change. (*) denotes processes restricted to the Arctic region

The PA, the abrupt sea ice decline and other evidence described in Section 3.1 are considered to be the primary causes of high latitude environmental changes with significant impacts on the local, regional, and global economies, as well as social and political implications (Figure 6). Future projections from climate models (Figures 2,5) have shown that SAT will continue to increase and summer sea ice will rapidly decrease for both the Arctic and Antarctica, even in a low emission scenario (Notz and SIMIP Community, 2020; Ono et al., 2022).

The potential socioeconomic and political implications of climate change in high latitudes include impacts on fish and shellfish, and fishery-dependent communities through a complex set of interconnected processes (Hollowed et al., 2013).

According to the authors, Arctic climate change will impact ecosystem productivity and habitat quantity and quality; habitat of marine fish and shellfish species, including effects on community species composition and spatial distributions; fisheries and community dependency; and food security. Marsh et al. (2020) suggested that climate change has considerable impacts on commercial fisheries by altering various levels of the Arctic food web, ranging from seaweed species to the main fish traded worldwide, such as salmon and polar cod. As the Arctic Ocean warms and the sea ice melts, new fishing grounds will become available, with a likely increase in fishing activities, mainly in northern Norway, making the sector more economically attractive. Additionally, rising ocean temperatures may carry some invasive marine species and, as a consequence, lead to predation on native species and habitat destruction (De Rivera et al., 2007; Falk-Petersen et al., 2011; Troell et al., 2017; Crépin et al., 2017). Hansel et al. (2020) argue that near-term climate change will benefit the Arctic cod fishery as long as the water temperatures stay below the optimum for cod reproduction. The authors report, however, that under projected ocean warming and acidification, this commercially important fishery in the Barents Sea may be at risk of collapse by 2100, even with the best adaptation effort in terms of reduced fishing intensity. Since warming oceans are expected, adaptive fisheries management is essential. In the Arctic, ocean warming and sea ice loss have resulted in population declines of several species of fish, birds, and marine mammals, including polar bears (Bestley et al., 2020; Constable et al., 2022). Chambault et al. (2022) investigated the shifts in the distribution of three Arctic cetaceans (whales) as a response to the projected Arctic Ocean warming. According to the authors, the long-term predictions suggested northward shifts in the distribution of 243 km (121 km) in summer (winter) to confront environmental changes imposed by climate change. At the same time, the current summer habitats of these whales will decline by about 25 %, although an expansion of about 3% into new winter areas is likely. Nevertheless, the comparison between gains and losses raises serious concerns about the ability of these polar species to deal with the disappearance of their traditionally colder habitat (Chambault et al., 2022). Climate change is also affecting all levels of the marine food web in Antarctica. The pelagic food web is dominated by the Antarctic krill (Euphasia superba) and its predators (Laffoley and Baxter, 2016).

The impacts on Antarctic ecosystems will likely vary regionally for different communities and species. According to Laffoley and Baxter (2016), krill productivity is expected to decline with ocean warming and its vast cascading effects. Coastal communities and sub-Antarctic islands, in particular range-restricted endemic communities, will likely be negatively affected. Simultaneously, ecosystem services in the Southern Ocean will likely increase with changes in fisheries (Rogers et al., 2020). Laffoley and Baxter (2016) proposed the following implications of the Antarctic sea ice loss: a reduced breeding areas for emperor penguins; a decrease in sea ice dependent predators (Adelie penguins and crabeater seals, for example) in ice-free areas; increased access to fisheries in the Southern Ocean and the decline of Antarctic krill population. In the Arctic, new commercial activities in the ocean will likely impact marine resources by increasing environmental pressure, air pollution, and the risk of shipping incidents such as oil spills (Law et al., 2017; Johannsdottir and Cook, 2019). Aside from increasing fishing activity, the sea ice change allows for easier access to the Arctic Ocean and should have an impact on the extraction of nonrenewable natural resources such as gas and petroleum, with significant implications for the global economy. According to Gautier et al. (2009), it is estimated that a significant part of the world's undiscovered oil (13%) and natural gas (30%) resources are under the Arctic Ocean seabed, making the region increasingly attractive for natural resource extraction. Still, European oil and gas importers wish to reduce their reliance on conventional suppliers from Russia, the Middle East, or Africa, which are perceived by western countries as having some geopolitical constraints (Petrick et al., 2017), particularly after Russia's military operation in Ukraine. On the other hand, the Paris Agreement and international climate protection goals put into question the Arctic's natural resource exploration, requiring a closer examination of how, where, and under what conditions, in the future, additional offshore oil and gas production is desirable.

The observed Arctic sea ice loss is projected to continue in the future (Figure 5), opening up new shipping routes with potentially global economic and geopolitical implications (Ng et al., 2018). The great interest in the new Transpolar Route (which crosses the central Arctic in summer) and the Northern Sea Route (NSR) stems from the fact that these routes offer a shorter transit between Asia and Europe, potentially reducing the time and cost of travel (Liu and Kronbak 2010; Yumashev et al., 2017). Shipping over the Arctic Ocean via the NSR might reduce the sailing distance from Asia to Europe by about 40%, compared to the conventional route via the Suez Canal. Nevertheless, it does not correspond to 40% in cost savings due to a variety of factors, such as higher building costs for ice-classed ships, the development of modern infrastructure, navigation risks, the need for extra icebreaker services, and robust meteorological and oceanographic forecasting support (Liu and Kronbak, 2010).

According to Yumashev et al. (2017), around 5% of the world's trade could be shipped through the NSR in the Arctic throughout the year, increasing profits for many European and East Asian countries. The impressive polar landscapes (sea ice, ice sheet, ice shelf, polar night and day, aurora, tundra, and animal life), the strong cultural authenticity, the severe and cold climate, and the unique ecosystem have emerged as a top tourist destination, attracting adventurers and nature enthusiasts from around the world (Shijin et al., 2020). In Antarctica, from 1992 to 2018, an average of nearly 2,000 new tourists were added each year, and the annual average number of visitors increased by 27% (IAATO, 1992–2019; Shijin et al., 2020). According to the International Association of Antarctica Tour Operators (IAATO), about 74,000 tourists visited Antarctica in the 2019–2020 season, a 32% increase from the previous year. During this summer (2022–2023) a total of 106,000 tourists visited Antarctica, setting up a new record (Cordero et al., 2022; Constable et al., 2022). As a direct consequence of the human presence in Antarctica, the black carbon (BC) footprint has increased in recent decades. The levels of BC content in snow near research stations and popular shore tourist-landing sites are significantly higher than levels measured elsewhere on the continent (Cordero et al., 2022). In the Arctic region (including Canada, Russia, Iceland, Norway, Sweden, Finland, Alaska, and the continental United States), the number of tourists is also rapidly growing. According to Shijin et al. (2020), the number of visitors to these regions reached 66.37 million in 2017, representing a 3.71 million annual increase with respect to 1995 numbers. Despite potential short-term economic benefits for Arctic nations and some businesses, there is a significant global price associated with climate change. According to Whiteman et al. (2013), in the absence of mitigation, the release of methane from melting permafrost in the East Siberian Sea has an estimated average cost of US$ 60 trillion, which is comparable to the global economy in 2012, which was about US$ 70 trillion. To quantify these methane leak effects on the global economy, the authors used a numerical model called PAGE09. The model calculates the climate change impacts as well as the mitigation and adaptation costs. It considers the changes in mean sea level caused by Antarctic and Greenland ice sheets melting, as well as the methane emissions from permafrost melting. The findings of Whiteman et al. (2013) suggest that the poorest economies of Africa, Asia, and South America would be the most affected, summing up 80% of the economic consequences of climate change. On a regional scale, thawing permafrost poses a serious risk to the structural integrity of buildings, roads, pipelines, trains, and electrical lines. Hjort et al. (2022) report that up to 80% of the buildings in some Russian cities and 30% of roads on the Qinghai-Tibet Plateau have already experienced substantial infrastructure damage. The authors suggested that infrastructure costs associated with permafrost degradation could rise by US$10 billion through the second half of the 21st century. Climate change in polar regions also has a wide range of impacts on society (Huntington et al., 2022). Among the most significant societal effects are human health and food security, which are particularly important to Arctic human settlements and communities. Unlike the vast majority of the world's population, who usually form their opinions on climate change from newspapers, television, the internet, or even scientific articles, the awareness of Arctic native peoples is the result of practical, individual, or collective life experiences (Wildcat 2014; Meredith et al., 2019). According to Wildcat (2014), awareness of climate change is greater among indigenous peoples when compared to most United States citizens, for example. Indigenous peoples are particularly exposed and sensitive to the effects of climate change due to their livelihoods based on local resources and the vulnerability of their homes. Indigenous peoples, despite their cultural diversity, share long histories of dealing with adverse conditions and environmental changes. However, the rapid pace of climate change and its impacts raise concerns about adaptive capacity and sustainability. Warm winters and the Arctic sea ice loss influence key aspects of Indigenous Peoples' perceptions of vulnerability, resilience, risks, and opportunities associated with climate change. These perceptions vary regionally, but a common feature is that climate change magnifies the social and political challenges (Ford et al., 2015; Meredith et al., 2019; Constable et al., 2022).

Indigenous traditional livelihoods are dependent on local resources and activities, such as hunting, fishing, and herding. They are also essential parts of an indigenous cultural identity. Climate change and its environmental impacts strongly influence the health and availability of terrestrial and marine resources for food production. For instance, Crépin et al. (2017), report that the sea ice retreat will threaten all ice-dependent seal species and could make seal hunting unsustainable, thus affecting the economic self-sufficiency, empowerment, and cultural identity of some indigenous communities, in particular the Inuit, who live in remote settlements in the Arctic and subarctic regions of North America, Greenland, Russia, and Alaska. Indigenous communities recognize the invasion of new species moving into Arctic waters as both a new economic opportunity and a potential threat. Thus, the effects of climate change raise concerns about indigenous peoples' adaptive capacity and sustainability.

Air pollution also represents an important threat to the health and well-being of indigenous peoples. In addition, extreme events associated with climate change, such as strong winds, have the potential to harm food production activities (fishing, for example). Studies indicate amplified negative impacts of climate change on mental health among those most dependent on the environment for livelihoods and those facing socioeconomic inequalities (Cunsolo et al., 2014; Minor et al., 2019).

Indigenous and local knowledge were included in the latest IPCC report. In addition to the scientific bases proposed by the last Assessment Report (AR6), indigenous authors led the assessment of the impacts, adaptation, and governance of climate change for indigenous peoples, which is a great advance compared to the previous IPCC report and represents an important step towards indigenous self-determination in processes of international assessment (Hill et al., 2020).

The present human interest in oil, natural gas, fishing, and shipping is high and will likely remain high following the potential increase in demand from other locations. This interest poses significant challenges for management and governance, particularly at the international level, in terms of reducing risks to people and the environment. Arctic governance is shared among multiple stakeholders, including indigenous peoples, Arctic states (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States), non-Arctic states that organize themselves in various international organizations, legal regimes, international agreements and possess strategic aspirations (Nerc, 2015; Dodds and Woodward, 2021).

The Arctic is ruled by international agreements through the Rovaniemi Declaration on the Protection of the Arctic Environment (1991), the Nuuk Declaration (1993), the 1982 United Nations Convention on the Law of the Sea, the United Nations Convention on the Law of the Sea (Paasivirta, 2015; Nicol and Heininen, 2022), the Arctic Environmental Protection Strategy (Heininen, 2020), the Arctic Council (Graczyk and Koivurova, 2015; Council, 2021), and the Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic (Council, 2011; Takey, 2013).

These agreements aim to promote Arctic cooperation, sustainable development, and environmental protection. The Arctic Council is the primary intergovernmental forum for Arctic governance, bringing together the eight Arctic states, Arctic indigenous communities, and other Arctic inhabitants with the objective of addressing common concerns and developing policies and recommendations on Arctic issues. The Council has six working groups focusing on different areas, including the environment, sustainable development, monitoring, conservation, prevention, and protection of the Arctic marine environment (Graczyk and Koivurova, 2015; Bary et al., 2020).

The governance of the Arctic faces numerous challenges apart from climate change: resource exploration, geo-political tensions, maritime governance, and the protection of indigenous rights and cultural heritage. As the region continues to undergo significant changes, effective governance will be critical to ensuring the sustainability and resilience of Arctic communities and ecosystems. According to Forbis and Hayhoe (2018), Arctic governance is critical to properly address the climate policy targets. The authors suggest that linking climate science to resource economics via its unique governance structure is the best way to preserve and protect the Arctic environment and to influence international energy and climate policy. Antarctica, on the other hand, is poorly occupied with permanent settlements and with no indigenous inhabitants. It is one of the world's most preserved and environmentally sensitive habitats, home to a variety of threatened species and rich in mineral resources. With ever-increasing human activities such as scientific surveys and tourism and external threats like climate change, effective protection of the Antarctic environment has become even more urgent. The international laws, governed and controlled by the International Antarctic Treaty System (ATS), have helped to shape the legal and policy frameworks for marine resources and environmental protection in Antarctica (Nicol and Heininen, 2022; Vince et al., 2022; Warner, 2022).

The Protocol on Environmental Protection to the Antarctic Treaty, signed in Madrid in 1991 (and coming into force in 1998), is the international agreement that establishes the framework for comprehensive protection of the Antarctic environment and designates Antarctica as a “natural reserve, devoted to peace and science” (ATS, 2023). In 2048, the main instrument of ATS’s environmental protection could be called upon to review and that can broaden the debate on changing Antarctica’s resource-exploitation regime. Many states may take the opportunity to review the issue of mining, for example, and to take other measures for environmental protection (Press, 2022; Vince, 2022).

The regulation of resource use and the prohibition of militarization in the Antarctic territory and waters have effectively reduced the geopolitical competition in the region to the present days. As part of the ATS, the Madrid Protocol imposed a moratorium on resource exploitation that guarantees the environmental protection of the Antarctic and sub-Antarctic regions (Nicol and Heininen, 2022). The ATS committees for decision-making are the Commission for the Conservation of Marine Living Resources (CCAMLR) and the Antarctic Treaty Consultative Meeting (ATCM). In addition, there is the Committee for Environmental Protection (CEP), the United Nations Convention on the Law of the Sea (UNCLOS), and the Scientific Committee on Antarctic Research (SCAR - Nicol and Heininen, 2022; Vince et al., 2022). According to Nicol and Heininen (2022), the current geopolitical framework of both the Arctic and Antarctica faces a new strategic challenge: climate change and environmental deterioration. A new global understanding of human security, for example, shapes new strategic assessments of national interest in this unusual scenario, which is existential in nature and related to environmental change. Hence, modifications to the geopolitical framing of events are important when studying geopolitics in the Arctic and Antarctica, and they determine the extent to which, in the future, there will be such a thing as "polar geopolitics".

Conclusions

This paper offers a multidisciplinary overview of polar climate change and its effects by using satellite, reanalysis and climate model simulations datasets to study the PA phenomenon and associated sea ice changes in the past and present, as well as in future climate change scenarios. Our results showed that polar regions are more sensitive to climate change than any other region on the planet. During the last two decades, the Arctic region has warmed at a pace two to three times faster than the rest of the globe, with enhanced Arctic PA occurring in the cold season, albeit varying spatially in the northern hemisphere (Figure 1). The highest Arctic PA occurs in Kara and the Barents Seas (more than 3.5 oC warmer than the global average). These regions are recognized as important nursery and feeding areas for commercial fisheries of herring, cod, and capelin species, among others (Ellingsen et al., 2008).

Polar climate change is occurring faster than previously predicted and is unprecedented in recent history. This is particularly true for the Arctic as a whole and for western Antarctica (Figs. 1-5). Polar warming and sea ice loss are expected to accelerate over the coming decades as a response to CO2 forcing, even under low-emission climate change scenarios (Figure 5). Our results are in agreement with Ono et al. (2022) and Smith et al. (2019).

The Antarctic PA and the fast sea ice decrease over the last years have drawn a lot of attention, especially through the free press. This reflects a reversal from the long-term positive trend on the SIE to a negative trend towards a SIE minimum, suggesting that the Antarctic sea ice may enter a new regime with possible effects on midlatitude weather extremes, the marine food chain and wildlife population, and sea level rise (Liu et al., 2023). In terms of SIC, our results are in agreement with Meredith et al. (2019), showing that the Antarctic SIC is projected to rapidly decline over the coming century under all Paris Agreement global warming thresholds (Figure 5).

As a result of the pronounced changes in the polar environment, numerous physical, ecological, and social processes are approaching an irreversible level of change that can last hundreds of years, if not millennia, with the potential to affect billions of people (Meredith et al., 2019; Constable et al., 2022). It is clear that the polar regions are facing significant environmental changes, and climate change is one of the most pressing issues. We also discussed here the challenges and opportunities arising from climate change in the polar regions, particularly with respect to fishing activity and the opening of new navigation routes that have a significant impact on the global economy (Figure 6). The unprecedented environmental transformations of the polar regions have profound implications for biodiversity, mid latitude weather patterns, sea level rise, the global economy, indigenous peoples, human health and food security, along with all other geopolitical issues. Climate change opportunities in the Arctic are primarily associated with new commercial activities in the Arctic Ocean that have already increased local tourism and fisheries.

Even though the precise pathways by which climate change affects society in polar regions are being debated, a scientific consensus is emerging that these regions pose potential high-impact risks to society. A better understanding of climate modeling is definitely required in order to reduce model uncertainties and provide better climate scenarios for decision-makers and society as a whole.

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