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Arctic Amplification

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Abstract

Rapid warming of the Arctic has profound impacts on the Earth's climate system and the well-being of humans. The Arctic has been warming at a rate up to four times faster than the global average over the last forty-five years, primarily as a consequence of sea ice melt exposing the darker Arctic Ocean to incoming shortwave solar radiation. This warming has led to accelerated melting of the Greenland Ice Sheet, a significant increase in lightning and peatland wildfires, increased disruptions to wildlife, increased permafrost thaw, and a slowdown of the Atlantic Meridional Overturning Circulation. There has also been emerging evidence of sea ice melt on changing weather patterns and wintertime cold air outbreaks across North America and Europe. Besides the sea ice-albedo feedback, other mechanisms responsible for this warming include temperature feedbacks such as the Planck and Lapse-rate feedbacks, changes in atmospheric oceanic heat and moisture transport to the Arctic, and reductions in air pollution in Europe and Asia. Higher amplification ratios in recent research can be attributed to incorporating satellite observations in the Arctic and using the latitudinal boundaries for the Arctic Circle (areas poleward of 66.5°N). Some research suggests that a potential slowdown in anthropogenic global warming between 1998 and 2012 may also have a role. Despite improvements in climate models, they still have a difficult time simulating Arctic amplification, especially as it relates to sea ice melt and the associated warming. This paper will examine the various mechanisms driving Arctic Amplification, its associated impacts, and prospects for the future in climate modeling of this phenomenon.

Introduction

The Arctic region has seen a dramatic warming relative to the rest of the world over the last several decades as the planet continues to warm from increasing atmospheric greenhouse gases from the burning of fossil fuels, agricultural expansion, land-use and land-cover changes, and tropical deforestation. This phenomenon is commonly referred to as Arctic Amplification (AA). Recent research has indicated that the Arctic has warmed nearly four times faster than the rest of the planet since 1979[1]. This warming is considerably higher than what previous studies have quantified. This is primarily due to using multiple observational datasets and comparing them with simulated climate models, dissimilar to previous works. The authors of that study determined that this was an extremely rare occurrence in the climate model simulations, leading the authors to conclude that the four-fold warming ratio is either an extremely unlikely event or the climate models systematically tend to underestimate the amplification.

There have been copious amounts of studies in recent years trying to advance the understanding of the underlying mechanisms driving this occurrence and its associated impacts. Past studies have primarily focused on the sea ice-albedo feedback as the predominant driver of AA. The loss of sea ice due to Anthropogenic Global Warming (AGW) reduces the albedo of the surface, allowing for increased absorption of solar radiation. In turn, this drives further warming of the Arctic and intensifies sea ice loss even more, creating a destabilizing positive feedback loop that has led to the rapid warming of the Arctic. Since the late 1970s, when satellite-based measurements of Arctic sea ice began, Arctic sea ice extent has declined in all months and all regions. Between 1979 and 2021, sea ice cover at the annual September minimum extent shrank by 13 percent per decade relative to the 1981-2010 average. In addition to the declining sea ice extent, there has been a significant decrease in thick multiyear sea ice, with thin, young sea ice making up 95 percent of the total ice pack[2]. These changes in sea ice extent and thickness have been altering heat fluxes between the ocean and the atmosphere. Besides sea ice, other complex processes are also driving AA. These include local feedbacks and changes in atmospheric and oceanic heat and moisture transport to the Arctic. Additionally, reduced air pollution in Europe, along with possible reductions of Asian aerosols in the future, may help amplify future arctic warming. A study published by Ono et al. in 2022 suggests that future arctic warming is stronger in a low-emission scenario and weaker in a high-emission scenario. Higher emissions will lead to ice-free summers in the Arctic, removing ice-albedo feedback. In a low-emission scenario, ice continues to exist in the summer, thus continuing the ice-albedo feedback. This would be a climate change mitigation side effect[3].

With regards to impacts, previous literature has looked at the impacts AA is having on the thawing of Arctic permafrost, increased melting of the Greenland Ice Sheet (GrIS), the slowdown of the Atlantic Meridional Overturning Circulation (AMOC), and disruptions to ecosystems. There has also been an ongoing debate within the scientific community regarding arctic amplification altering atmospheric circulation patterns, which may or may not be impacting the intensity and frequency of extreme weather events[4]. Thawing of the permafrost is significant because of its potential to release carbon dioxide and methane into the atmosphere, driving further warming of the planet. Permafrost thaw can also have serious implications for ecosystems, hydrological systems, and infrastructure integrity[5]. Prior to 2019, there had been no globally consistent assessment of permafrost temperature change compiled. Only recently have studies been conducted to evaluate temperature change across permafrost regions. Widespread disturbances are also occurring in the Arctic as sea ice melts and air and ocean temperatures rise, including increased ocean traffic, seabird die-offs, and increased precipitation. Other effects of a warming Arctic include tundra greening, early snowmelt, open water at the North Pole, intense Greenland ice sheet melting, Pacific Arctic storms, and changes in lake ice[6].

Published research has also begun to look at changes in the AMOC as global warming accelerates. The AMOC is an important oceanic circulation in the Atlantic Ocean driven by salinity and sea surface temperature. It helps to regulate nutrients and the global climate. Recent studies have shown that this circulation may have begun to slow down due to Arctic sea ice loss and injections of freshwater into the North Atlantic from Greenland Ice Sheet melt. In addition to the AMOC, there have been an increasing number of studies analyzing changes in global atmospheric circulation patterns as declines in sea ice loss in the Arctic alter oceanic and atmospheric heat fluxes. There remains a high amount of uncertainty in terms of conclusions as to how extreme weather events will change in intensity and frequency as the Arctic warms. However, recent research has begun to show that even though winters are becoming more mild, severe winter weather continues to exist, with some regions experiencing more frequent heavy snowfall events. Cohen et al. state that it should be expected to see wide ranges in results in Arctic warming and extreme winter weather, as there are numerous different approaches to tackling this issue and the complexity of Arctic-midlatitude connections.

Evidence

Between 1979 and 2021, the minimum Arctic sea ice extent observed in September decreased by 13% per decade compared to the 1981-2010 long-term mean (Figure 1). Multiyear sea ice, thick sea ice that persists through the summer months, has declined by more than 86% since 1985. At the maximum sea ice extent in March 2020, multiyear sea ice accounted for 2% of the total sea ice, with thinner first-year sea ice making up 70% (Figure 2)[7]. This is concerning because the younger, thinner ice is more vulnerable to melting during the summer months, which leads to an increase in absorbed solar radiation as the lower albedo ocean surface becomes uncovered. Arctic temperatures have warmed at least 0.5°C per decade over the period 1979 to 2021 with the greatest warming observed in the Eurasian sector of the Arctic (Figure 3). The highest temperature trends in the Eurasian sector exceeded 1 – 1.25°C of warming. Figure 3C illustrates local amplification, which shows how fast a region is warming compared to the rest of the world. Values greater than one signify regions that are warming faster than the global average, while values less than one signify regions that are warming slower than the global average. The majority of the Arctic has seen a warming at least three to four times faster than the global average, with maximum values exceeding six to seven times as fast as the global average. Declining sea ice during the winter along with changes in atmospheric circulation have been the principal drivers behind this amplification.

Mechanisms

The main drivers of Arctic Amplification are still undergoing scientific study. Some of the currently proposed mechanisms include sea-ice loss and the associated albedo feedback, water vapor and cloud feedbacks, lapse-rate feedback, and changes in atmospheric and oceanic moisture and heat transport to the Arctic (Figure 4). Temperature and sea ice-related feedbacks are particularly important for Arctic Amplification, as those feedbacks are more positive in higher latitudes than in lower latitudes. Changes in heat and moisture transport are tightly coupled with local feedbacks and their contributions, therefore, should not be considered in isolation[8]. The climate state plays an important role in changes in the strength of Arctic Amplification and has implications for past and future climate change. Prevedi et al. states the importance of Arctic Amplification being a prominent feature in the paleoclimatic record, present-day observations, and model projections of future change, citing numerous studies. It is also important to note that Arctic Amplification is present in climate models even without changes in sea ice. Pithan et al. argues that the largest contribution to AA comes from temperature feedbacks with the sea ice-albedo feedback being a second main contributor. This was determined by analyzing climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) to quantify the contributions of various feedbacks[9]. In cases in which AA occurs without the sea ice-albedo feedback, feedbacks acting on terrestrial longwave radiation were the primary driver. Another important driver of AA is the water vapor feedback in which temperatures rise in response to increased water vapor in the air as temperatures rise from human emissions of carbon dioxide and methane. The cloud feedback, another contributor to AA, involves changes in the effect of clouds on the Earth's radiative balance, including the reflection of incoming solar radiation and increased downwelling of outgoing longwave radiation from the Earth's surface. Arctic clouds reduce wintertime cooling of the surface and summertime surface heating with a net effect of a warming of the surface. Arctic clouds are important because their presence or lack thereof has a large impact on sea ice growth and the melting of snow and ice in Arctic regions. Satellite observations over the past two decades have shown significant increases in Arctic cloudiness, which result in changes to the surface energy budget. Global climate models, even the more recent ones, have simulated polar clouds poorly. Part of that difficulty is due to the function of cloud fraction, height, thickness, and water content on the overall cloud radiative forcing. Many of these models also fail to properly capture the correct phase of the annual cloud cycle in the Arctic[10].

Arctic Precipitation

Arctic Amplification is expected to intensify the hydrological cycle throughout the remainder of the twenty-first century as greenhouse gas emissions continue to rise, contributing to rising air temperatures and sea ice loss in the Arctic. Evaporation increases as global temperatures rise, increasing the ability of the atmosphere to carry moisture. Evaporation also increases as sea ice melt continues to expose larger sections of the Arctic Ocean and as poleward moisture transport increases. Precipitation in the Arctic could increase by 30% to 60% by 2100, according to literature cited in McCrystall et al.'s paper on climate model projections of Arctic precipitation[11]. Additionally, there is also an expectation that the Arctic will transition from a snow-dominated to a rain-dominated precipitation regime, with that transition already underway in the Atlantic sector of the Arctic. These changes in precipitation types and amounts will likely have notable impacts on the Greenland Ice Sheet, Arctic sea-ice extent and thickness, permafrost, and the flora, fauna, and linked social-ecological systems.

Permafrost

Permafrost, any ground that is frozen for at least two consecutive years, has the potential to amplify anthropogenic global warming as permafrost begins to melt in response to rising global temperatures. Organic material begins to decompose once permafrost thaws, releasing planet-warming carbon dioxide and methane gases into the atmosphere, further accelerating global warming. The thawing of permafrost can also destabilize landscapes, resulting in ground subsidence, slope instability, rock glacier acceleration, and changes to hydrological processes[12]. Infrastructure built upon thawing permafrost could collapse as the ground gives way underneath the foundations of buildings, homes, and other infrastructure. A rapid increase in lightning in the Arctic since 2018 poses an additional threat to peatlands in the Arctic. Areas poleward of 80°N saw approximately 7,300 lightning strikes in 2021, with the previous nine years having a combined total of about half of the observed strikes in 2021[13]. Increasing thunderstorm frequency as Arctic evaporation increases from declining sea ice has led to an increase in peatland wildfires. These fires release carbon dioxide and methane into the atmosphere, further amplifying warming.

Ecosystems

Melting sea ice along with changes in global atmospheric circulation are negatively impacting polar bears and narwhals in the Arctic. Sea ice extent and thickness have both decreased and the freeze-up of open water during the fall is getting later as sea surface temperatures increase. Sea ice melt is starting 3-9 days earlier per decade relative to the 1979-2014 normals with sea ice freezing starting 3-9 days later per decade relative to the normal. In addition to sea ice declines and delayed freezing, major sea ice loss is also increasing the distance that both species have to travel. Polar bears primarily hunt on the ice surface while narwhals hunt at extreme depths below. Major sea ice loss causes an energy imbalance for polar bears from the effects of reduced caloric intake and increased energy expenditure. Narwhals, on the other hand, face a higher risk of ice entrapment due to the unreliability of breathing holes[14]. Another threat to polar bears and narwhals is the increased presence of humans and killer whales, an additional consequence of declining sea ice. As of 2019, four polar bear subpopulations have experienced declines with five stable populations, and two increasing populations. Subpopulations in 8 regions are currently data-deficient (Figure 5)[15].

Atlantic Meridional Overturning Circulation

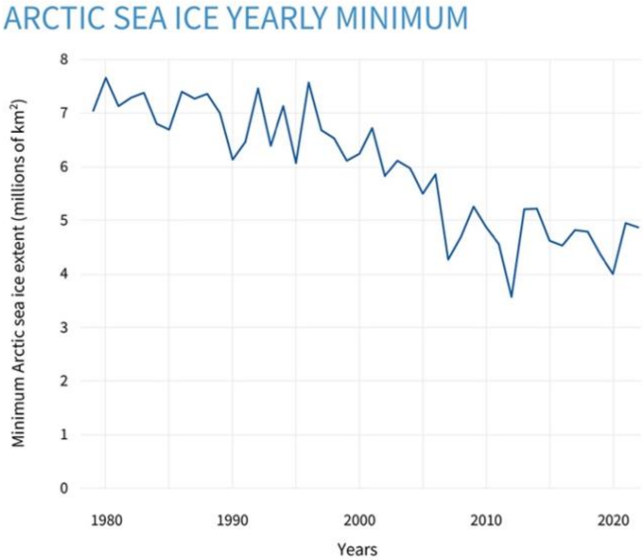
Another aspect of a rapidly warming Arctic is the slowdown of a significant oceanic circulation known as the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is a system of ocean currents that transports warm salty water from the tropical Atlantic northward to the Arctic Ocean with cooler fresher water sinking as it returns back towards the equator (Figure 6)[65]. It is an important climate regulator for regions such as Europe, by providing mild ocean temperatures, and additionally influences the climate of other regions. This system is driven by differences in sea surface temperatures and salinity. Increasing atmospheric carbon dioxide by the burning of fossil fuels and other anthropogenic sources is projected to weaken this overturning circulation. Warming and freshening of the sea surface in the subpolar North Atlantic caused by oceanic warming and freshwater runoff from the Greenland Ice Sheet leads to ocean stratification, limiting deep water formation, and thus weakening the AMOC. One research article argues that there is a dominant role of Arctic and subpolar forcing over ocean dynamics in controlling the strength of the circulation. Enhanced Arctic warming has a larger role in future changes in the AMOC's strength than changes at lower latitudes[17]. It should be noted that this is for larger increases in carbon dioxide, particularly exceeding 570 ppm. Under RCP 4.5 pathway with moderate emissions increases, atmospheric carbon dioxide concentrations could reach that level prior to 2100 (Figure 7)[18]. Recent studies have shown that the AMOC has slowed down by 15% since the mid-1900s. A slowdown of the AMOC may result in cooling of the Northern Hemisphere, decreased precipitation in the Northern Hemisphere midlatitudes, large changes in precipitation in the tropics, and a strengthening of the North Atlantic storm track. Impacts in Europe include changes in summertime and wintertime precipitation. An altered atmospheric circulation may locally increase wintertime precipitation in Europe as there would be more winter storms and a strengthened winter storm track. Uncertainty remains as to how much the AMOC will weaken as global warming intensifies.

More studies will be needed to get a better understanding of future changes in the AMOC. Even though a complete shutdown of the AMOC is unlikely to occur by 2100, the potential consequences of a shutdown necessitate continued studies into the behavior of the AMOC, its drivers, and past changes in this overturning circulation on global climate. This would be a low-probability–high-impact event[19].

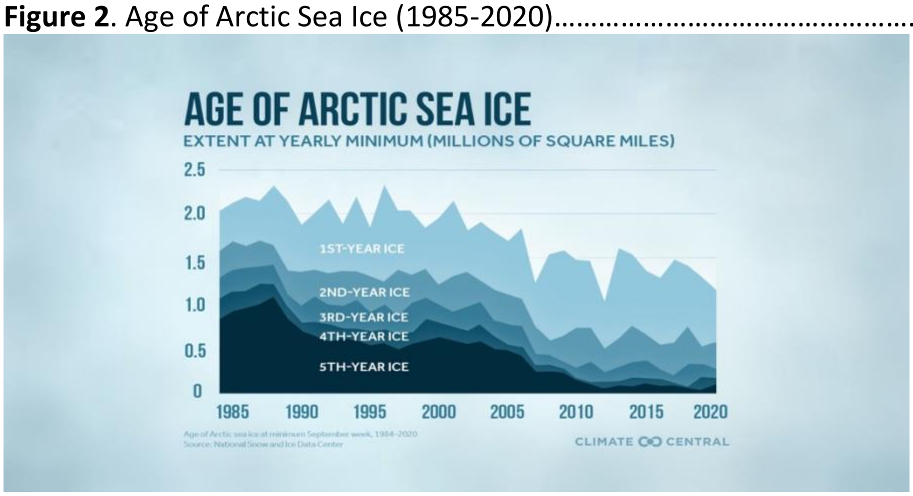
Conclusion

The scientific community has gotten a better understanding of the drivers of Arctic Amplification and its associated impacts over the last decade as the understanding of climate feedbacks improved, comparisons were made between observations and climate simulations, and biases within climate models were identified. There remains a large amount of uncertainty, which is not unexpected, with future changes in the magnitude of Arctic Amplification and in impacts such as changing Arctic precipitation regimes, declining Arctic polar bear and narwhal populations, alterations in global weather patterns, and a slowdown of the Atlantic Meridional Overturning Circulation. Numerous projects have or will start to look at some of the biggest questions related to these issues to help improve global climate models' projections of future change in the Arctic as the Earth continues to warm from rising greenhouse gas concentrations. Recent research has already indicated that the Arctic has warmed up to 4 times faster than the global average, with Arctic precipitation regimes beginning to shift from a snow-dominated regime to a rain-dominated regime in portions of the Arctic during the summer months. Scientists are also more confident in other mechanisms driving Arctic Amplification besides sea ice melt and the resultant albedo decline, such as changes in atmospheric and oceanic heat and moisture transport to the Arctic, temperature feedbacks, water vapor and cloud feedbacks, lapse-rate feedback, and reductions in air pollution in Europe and Asia. Arctic Amplification has occurred in the past with or without changes in sea ice extent, albeit that mechanism significantly increases Arctic Amplification. Reductions in greenhouse gas emissions in the future could lead to a higher magnitude of Arctic Amplification as sea ice continues to exist in the summer past 2040. Finally, permafrost thaw can intensify global warming and cause infrastructure collapse by releasing ancient carbon back into the atmosphere and causing ground subsidence.

Figures

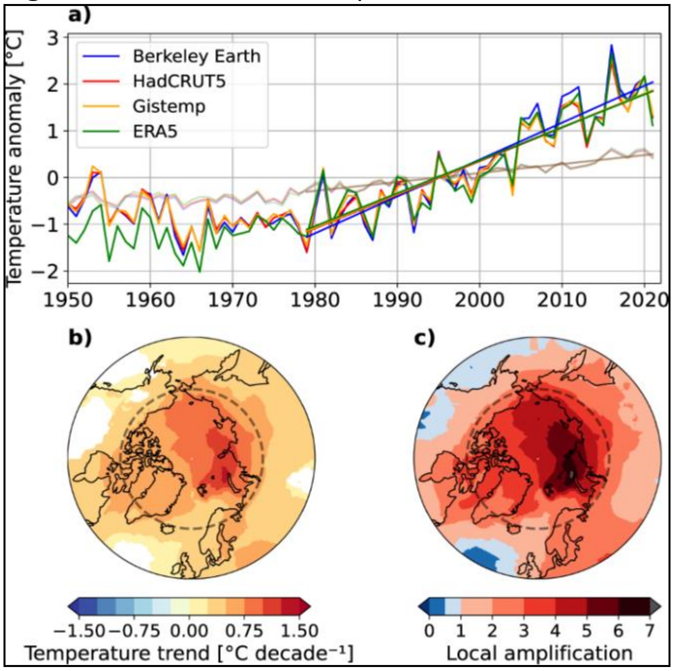


Adapted from NOAA.gov from data by the National Snow and Ice Data Center (NSIDC). Satellite observations of Arctic sea ice during the minimum sea ice extent in September between 1979-2022.



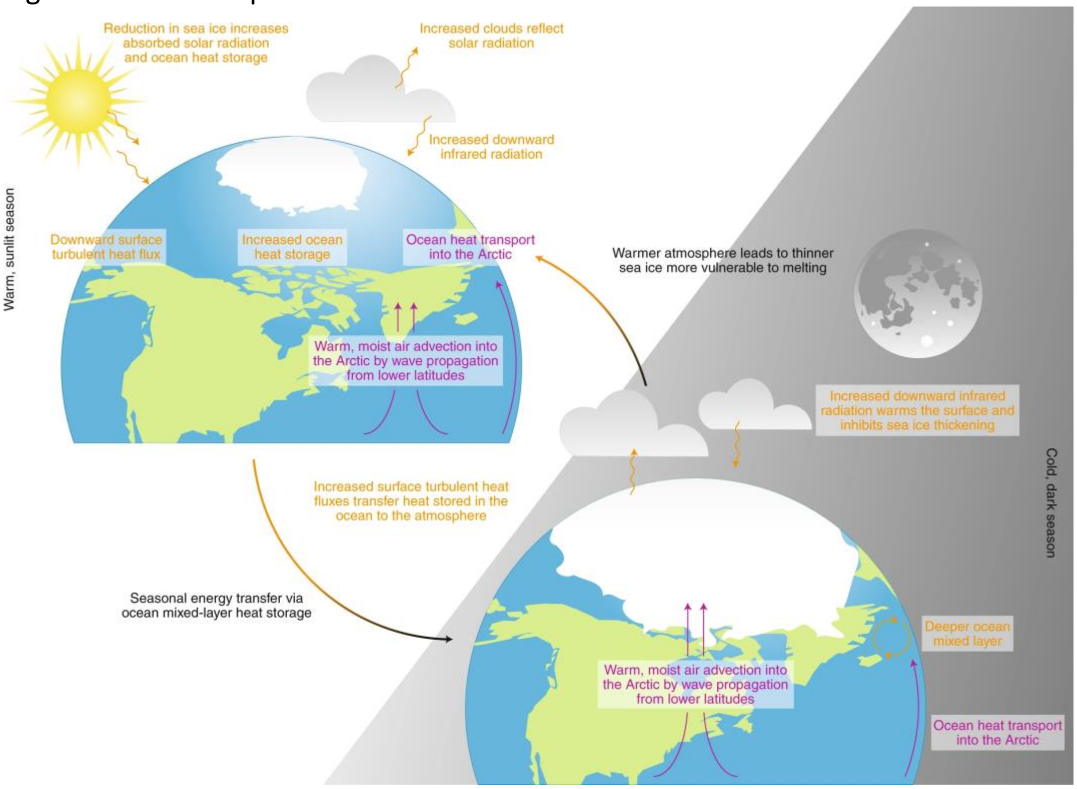
Climate Central age of arctic sea ice at the yearly minimum extent. Thick, multiyear sea ice has significantly decreased in the Arctic since 1985, with first-year sea ice making up the majority of the total ice pack.

Figure 3. Annual mean temperature evolution in the Arctic……………………………………………………**4**



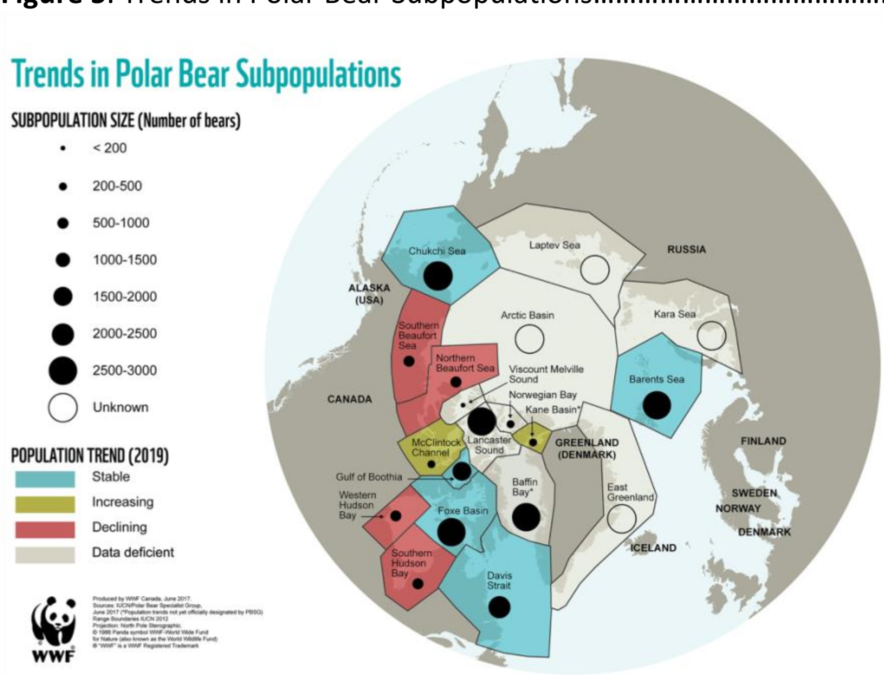
Adapted from Rantanen et al., 2022 under Creative Commons Attribution 4.0 International License. **a)** Annual mean temperature anomalies in the Arctic (66.5°–90°N) (dark colours) and globally (light colours) during 1950–2021 derived from the various observational datasets. Temperature anomalies have been calculated relative to the standard 30-year period of 1981–2010. Shown are also the linear temperature trends for 1979–2021. **b)** Annual mean temperature trends for the period 1979–2021, derived from the average of the observational datasets. Areas without a statistically significant change are masked out. **c)** Local amplification ratio calculated for the period 1979–2021, derived from the average of the observational datasets. The dashed line in (**b**) and (**c**) depicts the Arctic Circle (66.5°N latitude).

Figure 4. Arctic Amplification Mechanisms……………………………………………………………………………………**4**

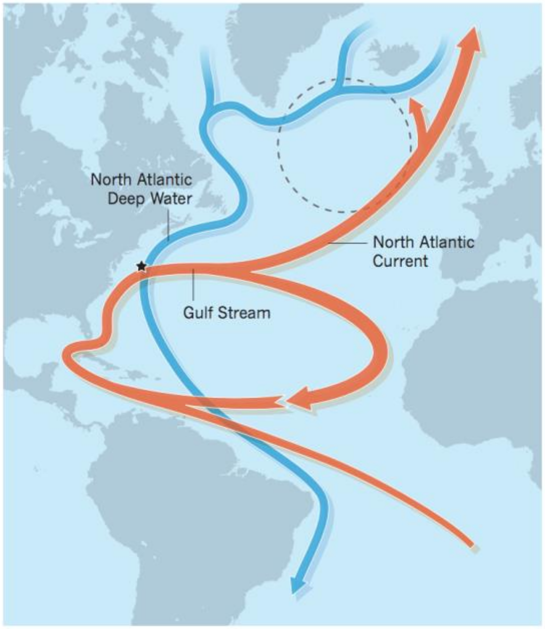


Adapted from Cohen et al. 2019. Depicts local (orange) and remote (purple) forcings that drive Arctic Amplification.

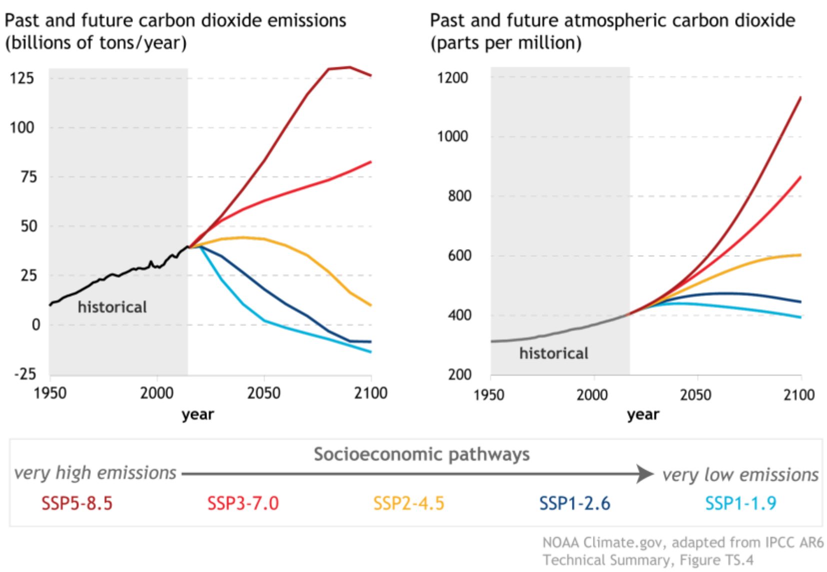
Figure 5. Trends in Polar Bear Subpopulations……………………………………………………………………………**6**



Produced by WWF Canada in June 2017 with data from the IUCN Polar Bear Specialist Group. Shows subpopulation trends in Polar Bears as of 2019 with stable, increasing, declining, and data-deficient subpopulations.



Adapted from Praetorius, M., 2018, *Nature*.



Adapted from NOAA Climate.gov. Plausible future socioeconomic pathways for annual carbon dioxide emissions (left) and the resulting atmospheric carbon dioxide concentrations (right) through the end of the century. A *shared socioeconomic pathway* is an internally consistent set of assumptions about future population growth, global and regional economic activity, and technological advances. Models use these pathways to project a range of possible future carbon dioxide emissions; for simplicity, the image only shows the only the mean value. NOAA Climate.gov graphic adapted from figure TS.4 in the IPCC Sixth Assessment Report Technical Summary.

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