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# Arctic amplification metrics and their relation to regional warming

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# Arctic amplification metrics and their relation to regional warming

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Bachelor thesis, 15 credits, in **Physical Geography and Ecosystem Analysis**

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## Abstract

Arctic amplification (AA) is defined as the enhanced warming of the surface temperatures in the Arctic region relative to the globe or Northern Hemisphere (NH) in response to external forcings. It is a prominent feature of the climate system. Various metrics have been used in studies to quantify AA, and this introduces a challenge when comparing studies due the differences in AA magnitudes. This study aims to compare these different metrics and investigate their relation to the regional surface temperature changes in the NH. Furthermore, the difference between metrics used to quantify the amplification of the Arctic region (60° - 90°N) were investigated along with their variations through time. A brief review of the processes causing AA is done, including both local and remote influences that may affect AA. A moving window of 11-years was applied to the surface air temperature (SAT) anomalies to reduce interannual variability. The regional SAT changes that contribute to the variations in the AA metrics were further investigated by correlating the AA metrics with the SAT in the NH (0 °- 90°N). The results show how temperature changes in the Arctic and NH varied through time from the years 1950-2021. This study also shows new results for the state of AA until 2021. Metrics using the ratio of the linear trends ($A_2$), ratio of SAT variations ($A_3$), and regression between the Arctic and NH SAT anomalies ($A_4$) show similar variations in time, with a prominent increase and subsequent decrease of AA between 2000-2010. These metrics also show similar variations in time for the later years where there is a slight increase of Arctic Amplification Index (AAI) until 2016. The ratio of SAT anomalies between the Arctic and NH ($A_0$) shows an overall similar temporal pattern as the previous three metrics but with smaller magnitude in the variations. The difference between the SAT anomalies between the Arctic and NH ($A_1$) does not clearly show enhanced AA around 2003, but rather reflect a steady increase over time. Furthermore, defining AA as the ratio of SAT anomalies between the Arctic and NH sometimes leads to extreme values in the AA index which are found in metrics $A_0$ and $A_2$. The correlations show that $A_0$ and $A_1$ show similar correlations with SAT anomalies, with positive correlations in the North Atlantic Ocean, over a large part of Asia and on the western side of the North Pacific Ocean and along the western coast of North America. $A_2$, $A_3$, and $A_4$ on the other hand show positive correlations over most of the NH, except for a patch of negative correlations in the North Pacific Ocean. This study provides data for the recent magnitude of AA using the different metrics, and some insight on the driving SAT changes in the NH on the AA.

# Contents

# 1 Introduction

Arctic amplification (AA) is defined as the increased response of the Arctic's surface air temperature (SAT) to external forcings relative to the global average. AA is seen in paleoclimatic records (Cronin et al., 2017; Nicolle et al., 2018), instrumental observations (Wang et al., 2021), and in climate models simulations (Holland & Landrum, 2021; Overland, 2009). This induced warming has both local and large-scale impacts, both for the environment from the observed decrease in Arctic sea ice extent, (Q. Cai et al., 2021), the highly debated topic of the effect of AA on midlatitude weather extremes (Barnes, 2013; Francis & Vavrus, 2015), and socioeconomic impacts on both within and beyond the Arctic.

The Arctic region varies in definition for each study, ranging from north of 60°N to 75°N. Moreover, the overall amplification is calculated either relative to the globe or to the Northern Hemisphere (NH) and differ in whether annual or seasonal data is used (Hind et al., 2016). Alongside these differences when studying Arctic amplification, a problem arises when the AA is quantified using a ratio of the Arctic and NH anomalies. Namely, by using the ratio of surface air temperature anomalies of the Arctic and NH, the denominator (NH anomalies) can approach zero which leads to extreme values for AA (Fang et al., 2022; Hind et al., 2016; Taylor et al., 2022). This metric is the most common method for the quantification of AA in many studies and can introduce erroneous values. Several metrics have been used in the past decade and the resulting magnitudes of AA vary greatly from study to study (Johannessen et al., 2016). Owing to a lack of a standardized metric, it is challenging to compare results from AA studies. Moreover, a recent study by Fang et al. (2022) show how the Arctic amplification index (AAI), the resulting measure of AA, has varied from 1.21 to 2.12 in the past millennia which demonstrates that the amplified temperatures in the Arctic are an inherent feature of the climate system. Most studies have not quantified how AA has varied over time, but instead calculate an overall index for the timeseries (Chylek et al., 2009). Chylek et al. (2009) further explains how AA is not a constant but varies through multi-decadal timescales.

A feature of global warming is the uneven spread of the temperature changes, even within the Arctic. In other words, some parts of the Arctic have been found to warm at a faster rate than the rest of the Arctic (Taylor et al., 2022). The regional differences and the unequal spread of AA should be further investigated to produce regional targets, as an alternative to global targets as the Arctic is more sensitive to greenhouse gas forcings. One of the next steps to improve the knowledge on AA is a standard, well-defined metric that could make it easier to reach consensus about the magnitude of the warming, making it easier to compare studies. Furthermore it is also important to highlight the regional distribution of the SAT differences within the Arctic (Taylor et al., 2022). Therefore, the aim of this study is to quantify AA using the different metrics that have been used in previous literatures (Bekryaev et al., 2010; Crook et al., 2011; Francis & Vavrus, 2015; Johannessen et al., 2016; Kobashi et al., 2013) and discuss what they may reflect and their advantages/disadvantages to aid future studies about AA. Moreover, the relation between the NH surface air temperatures and the different metrics will be investigated to examine the regional variation and the possible driving force of AA. The aim of this study is to compare the magnitude of the different metrics and relate this to regional temperature differences. Since these metrics may reflect different processes in the Arctic (e.g. different magnitude or different behaviour of the AAI), they may provide insight on remote and local processes affecting AA.

## 1.1 Study aim & research questions

The aim of this study is to quantify Arctic amplification according to the different metrics used in previous studies and to investigate the regional temperature changes in the Arctic and the NH and how they contribute to the different metrics. This aim is divided into further research questions enumerated below.

1. How does AA vary with each metric quantified? What are the similarities and differences in magnitude with each metric? How do they vary through time?
2. What are the shortcomings and advantages of using the different metrics?
3. What is their relation to temperature changes in the NH?

# 2 Background

This section will provide some contextual knowledge surrounding the Arctic amplification topic such as defining the Arctic region, various metrics used in previous studies, a brief review of the mechanisms known to cause AA, and how AA has evolved through time based on the current literature available.

## 2.1 Defining Arctic amplification

There are several factors to consider when studying Arctic amplification. Different definitions of the Arctic region have been used in various studies, such as demonstrated by Hind et al. (2016) where the boundary for the Arctic ranges from 60°N to 75°N. This choice could be related to the resolution of the data being used, but it is rare that a justification is stated as to why this boundary was chosen. Another factor to consider in the definition of the amplification is whether to use annual or seasonal data. AA has a strong seasonality where it manifests the strongest in the autumn and winter months (Serreze & Francis, 2006). Additionally, the choice of the region for comparison can also vary. The temperature differences can either be relative to the NH, or the globe. This is important because studies often do not justify their choices for choosing the region of what the AA is relative to, and what is referred to as higher latitudes (the Arctic) as referred to above. Moreover, the choice of looking at AA in near surface temperatures or the entire atmospheric column also matter to consider when looking at AA. This is relevant to the matter since despite AA manifesting the strongest in surface air temperatures, it is also related to changes in the atmospheric column which will be explained further in subsection *2.3 Processes affecting Arctic amplification.* Moreover, analysing temperature records from observations in the Arctic show that this amplification is not constant but varies in time on a multidecadal time-scale (Chylek et al., 2009). Therefore, the time period used can affect the strength of AA. Interannual variability, which is strong in the Arctic, can mask the effects of climate processes occurring on a decadal to multi-decadal scale. This is further complicated by the ongoing global warming induced by greenhouse gas forcings. A recent study by Fang et al., (2022) on a millennial timescale shows that the greenhouse gas forcing is suggested to have weakened AA. This further highlights the knowledge gap within AA science. Overall, there are several factors to consider before analysing the amplification of the Arctic. It is important to be aware of these limitations when comparing studies and have a justification as to why certain factors are chosen based on which processes are being studied.

## 2.2 Arctic amplification metrics

The commonly used metric for AA is a ratio of anomalies estimator, which has been proven to show extreme values for the Arctic amplification index (AAI) when denominator values are close to 0, as proven by previous studies investigating this metric such as that done by Hind et al. (2016). Since then, studies such as Bekryaev et al. (2010), Kobashi et al. (2013), Francis and Vavrus (2015), and Johannessen et al. (2016) have used alternate ways to measure this amplification (Table 1). This was further investigated by Davy et al. (2018), where they calculated these aforementioned metrics using different datasets available. Their results highlight the current problem, where these different metrics vary in magnitude, and vary in time. For studying the periods of rapid Arctic warming one may use a metric based upon the rate of warming in the Arctic (Davy et al 2018). Metrics based on anomalies can be subject to high chances of variability in monthly scales or longer due to the large natural variability of the Arctic SAT. Another metric is to use the ratio of the linear trends of Arctic and NH SAT anomalies (Johannessen et al 2016). With this method there is no high temporal variability, so it can be used to assess the Arctic on longer time scales. However, this could be disadvantageous since linear trends can be sensitive to outlier data points, close to the beginning or the end of the timeseries. Moreover, when considering the trends, we need to account for the uncertainty in both linear regressions.

Using the interannual variability as done by Kobashi et al. (2013), the ratio of the standard deviations of the SAT of the regions are used to measure AA. This metric shows the larger SAT variation in the Arctic relative to lower latitudes, which could reflect the radiative feedbacks (Davy et al., 2018). Lastly, a method by Bekryaev et al. (2010) is using the slope of the ordinary least squares of the temperatures in the Arctic on to NH temperatures. This metric links the temperatures of the Arctic and the NH without the resulting extreme values when using a ratio. This value for the AAI thus depends on the rate of the change of the independent (NH temperature anomalies, $T_{NH}$) and dependent (Arctic temperature anomalies $T_{arc}$) of the regression (Fang et al., 2022). This is shown in the equation below (eq 1), where $T_{Arc}$ is the SAT anomalies of the Arctic, the ordinary least squares determine the parameters $a_0$, $a_1$, and ε, where $a_1$ is the AAI.

$$(1)\, T_{Arc} = a_0 + a_1 * T_{NH} + \varepsilon$$

These metrics are summarized in Table 1.

**Table 1**. The different metrics that quantify AA according to various studies investigating AA in the past decade. This metric IDs will be used to refer to the metric within this study.

| *Metric ID* | **Description** | **Used by** |
|---|---|---|
| $A_0$ | Ratio of the Arctic and NH SAT<br>$\frac{Arctic\ SAT\ anomalies}{NH\ SAT\ anomalies}$ | (Crook et al., 2011) |
| $A_1$ | Difference between the NH and Arctic SAT<br>*Arctic SAT anomalies – NH SAT anomalies* | (Francis & Vavrus, 2015) |
| $A_2$ | Ratio of the linear trends of the Arctic and NH<br>$\frac{SAT\ 11-year\ linear\ trend\ in\ Arctic}{SAT\ 11-year\ linear\ trend\ in\ NH}$ | (Johannessen et al., 2016) |
| $A_3$ | Ratio of interannual variability of the Arctic and NH<br>$\frac{11-year\ standard\ deviation\ of\ the\ Arctic\ SAT}{11-year\ standard\ deviation\ of\ the\ NH\ SAT\ anomalies}$ | (Kobashi et al., 2013) |
| $A_4$ | Coefficient of the linear regression between the Arctic and NH | (Bekryaev et al., 2010) |

## 2.3 Processes affecting arctic amplification

The mechanisms known for causing AA will be discussed in the section below to provide context to the study. These mechanisms include both local feedbacks and remote influences known to cause AA. These processes are climate forcing, climate feedbacks, changes in poleward energy transport, and the coupling of these processes.

### 2.3.1 Climate forcing

Climate forcing is defined as the change in external drivers of global temperature changes, such as the increase of $CO_2$ concentrations. Lower latitudes respond differently to $CO_2$ radiative forcing, the response to the climate forcing is largest at the top of the atmosphere, and this decrease towards the poles (lowest response to top of the atmosphere at higher latitudes). In contrast, the doubling of $CO_2$ and its induced radiative forcing at the surface is greater in the poles relative to lower latitudes (Previdi et al., 2021). This difference in the spatial pattern of $CO_2$ radiative forcing at the top of the atmosphere and at the surface results in a strong latitudinal gradient in atmospheric radiative forcing. This pattern of atmospheric radiative forcing has implications on the poleward energy transport which will be discussed in a later subsection. In other words, $CO_2$ forcing has different impacts on AA depending on the perspective. From the top of the atmospheric and the atmospheric column budget, the radiative forcing by $CO_2$ counteracts AA by heating the tropics. At the surface, however, $CO_2$ radiative forcing contributes to AA by heating the Arctic (Previdi et al., 2021). Climate forcing causing AA also encompasses changes in solar irradiance, aerosols, methane, and land use/land cover changes. However, climate forcing alone is not sufficient to explain AA, and various feedback mechanisms are also relevant to discuss. These will be explained in the next subsections.

### 2.3.2 Climate feedbacks

Climate feedbacks known to affect AA are temperature feedbacks, surface albedo feedback, and cloud & water vapor feedback.

#### *2.3.2.1 Temperature feedbacks*

Temperature feedbacks in the Arctic are one of the known main contributors to AA. Simulations by Pithan & Mauritsen (2014) demonstrate AA despite the absence of surface albedo feedbacks, highlighting the importance of temperature feedbacks to the overall enhanced warming in the Arctic. Temperature feedbacks are commonly divided into two mechanisms, the Planck response and lapse rate feedback.

The Planck response is a mechanism that acts to stabilize the climate by restoring the temperature equilibrium through increasing the overall outgoing long wave radiation that the Earth emits (Brown et al., 2016). Therefore, the surface and tropospheric warming is balanced by this increase in outgoing longwave radiation and thus opposes the positive climate forcing, particularly in the tropics. In the Arctic, however, the Planck response is weaker owing to generally colder temperatures. This follows the Stefan-Boltzmann law where a given surface warming at colder temperatures produces a weaker increase in emitted longwave radiation causing a less-negative feedback in the Arctic than in the tropics (Hahn et al., 2021).

The lapse-rate feedback contributes to AA due to the bottom-heavy structure of the warming in higher latitudes. The stable stratification in the Arctic accounts for this type of warming. Looking at the rest of the globe, changes in the tropospheric lapse rate are characterised by a reduction in the rate of temperature decrease with height, since the upper troposphere warms more than the lower troposphere and surface as mentioned in section *2.3.1 Climate forcing*. This change in the temperature profile leads to a larger increase of outgoing longwave radiation, which creates a negative feedback response on surface warming. However, the Arctic experiences the opposite since the troposphere warms less than the lower troposphere and the surface. The surface warming contribution arises because a larger increase in surface temperature is needed over the colder Arctic to balance a given increase in downward energy flux.

#### *2.3.2.2 Surface albedo feedbacks*

In all the seasons except for the summer, the Arctic Sea ice insulates the warmer ocean column from the colder temperatures in the atmosphere. A reduction of this sea ice cover will result in a warmer atmosphere, owing to the exposure of the darker surface of the ocean and the resulting increase in absorption due to lower surface albedo in the summer months. This reduction of sea ice leads to the increase of sensible heat in the mixed layer (the top 20 m of the surface) (Serreze & Barry, 2011). Aside from the warming caused by the reduction of the sea ice cover, this also decreases the surface albedo, increasing the amount of shortwave radiation absorbed by the darker surface. Surface albedo is a well-established cause of AA and has been shown to contribute to AA in models and observations (Boeke & Taylor, 2018; Dai et al., 2019; Screen & Simmonds, 2010). Most studies generally find that surface albedo feedbacks are the largest local Arctic feedback (Taylor et al., 2022).

Pithan and Mauritsen (2014) argue that their simulations find that surface-albedo feedbacks make the second largest contribution to AA, after temperature feedbacks. Since surface albedo is related to the seasonality of the Arctic, AA itself is usually absent in the summer and strongest in winter and fall. This is related to the heat storage within the Arctic Ocean. The ocean acts as a heat storage in late spring and summer and is followed by a consequent loss of heat from the ocean to the atmosphere in the fall and winter. With a warming climate, the amplitude of this seasonal cycle is expected to increase, which implies greater ocean heat uptake in spring and summer and an eventual greater ocean heat loss in fall and winter as a direct result of the loss of Arctic sea ice (Previdi et al., 2021).

Over land, the warming induced by greenhouse gas forcing leads to an earlier melt of snow (therefore an early summer in the Arctic lands). This leads to an earlier exposure of the dark and snow free surface, resulting in more solar radiation being absorbed. As a response to this, the warmer surface emits more longwave radiation which leads to higher air temperatures with stronger longwave radiation flux back to the surface (Serreze & Barry 2011).

#### *2.3.2.3 Cloud and water vapor feedbacks*

Climate model projections and analyses of observed cloud changes in the recent decades predict that the Arctic will become cloudier in a warmer climate, mainly caused by an increase in low clouds in fall and winter. The increase in arctic low clouds in fall and winter are a direct response to sea ice loss (Previdi et al 2021). This loss acts to enhance the moisture available in the region. Sea ice loss impacts on Arctic cloud cover during summer show no significant effects. Since low cloud cover formation are associated in the fall and winter seasons, the radiative effects occur in longer wave radiation. But once again, the radiative effects differ between the top of the atmosphere and on the surface. For this study, the focus is placed on the effects on the surface. These low cloud formations enhance the emissivity of the Arctic's lower troposphere and the surface downwelling longwave radiation. The resulting increase in downwelling longwave radiation enhances the surface warming and sea ice melt. However, cloud feedbacks have a high uncertainty and studies are divided between the overall effect of cloud feedback on AA, and how this will change in the future (Previdi et al., 2021).

### 2.3.3 Changes in poleward energy heat transport

The remote influences on AA are debated despite there being a large number of studies in the past decade (Taylor et al., 2022). Remote influences are defined as both the warming that occurs due to non-Arctic changes such as changes in meridional heat transport, and the local feedbacks they induce. These non-Arctic changes are quantified in several studies to contribute up to 60-85% of the overall Arctic warming (Previdi et al., 2021). Studies such as these indicate that non-Arctic forcing that increase non-Arctic temperatures contribute to the increase in Arctic temperatures (Taylor et al., 2022). Moreover, these in turn could amplify local feedback processes that may account for half or more of the overall AA.

#### *2.3.3.1 Atmospheric transport*

Poleward energy transport (PET) is the transport of energy in the form of moisture transport and dry static energy transport from midlatitudes to the poles. Changes in PET are related to the heating anomalies outside the Arctic which can influence the Arctic climate. Several studies have highlighted the importance of heating anomalies in NH midlatitudes and the potential roles they may play in AA (Previdi et al., 2021). Moreover, a study by Yang et al. (2010) shows that about 25% of the cooling trend observed in the later part of the $20^{th}$ century can be related to the decreasing poleward energy transport into the Arctic, and 50% of the recent decadal warming trend was due to increasing PET. These changes were reflected in the troposphere and associated with the changing intensity of the polar meridional circulation cell. This is also supported by Graversen et al. (2008), further highlighting that the surface albedo feedback is absent in the winter months where AA manifests the strongest. These studies investigate the tropospheric manifestations of PET, which then affects the surface temperatures. It is important to note, however, that these heating anomalies in both the midlatitudes and the tropics have different preferred teleconnection pathways to the Arctic, implying that they may have a regional dependence (Previdi et al., 2021).

#### *2.3.3.2 Oceanic transport*

Energy transport through oceanic circulations is known to affect Arctic temperature and sea ice, and thus may influence AA. Observations show enhanced ocean heat transports into the Arctic through the Fram Strait and Barents Sea in recent years. Models generally simulate a decrease in oceanic PET at NH midlatitudes, and increases in oceanic PET into the Arctic, and marine sediments off Western Svalbard show increased oceanic PET into the Arctic in the recent decades (Previdi et al., 2021).

A decrease in oceanic PET at NH midlatitudes is mainly due to a weakening of the Atlantic meridional overturning circulation with climate warming (Previdi et al., 2021). However, the cause of the increase in Arctic PET is less certain. Several studies find a high correlation between the Atlantic multi-decadal oscillation and Arctic temperature changes (Chylek et al., 2009; Fang et al., 2022), which suggests that the Atlantic thermohaline circulation is coupled with changes in the Arctic temperature on a multi-decadal time scale. Serreze & Barry (2011) highlight the link between the strength of the thermohaline circulation and Atlantic multi-decadal oscillation, which transports warm waters poleward. Currently, a positive phase of

Atlantic meridional overturn is occurring, in contrast to the negative (cooling) phase after 1940-1970 (Ting et al., 2009).

Enhanced ocean heat transports as seen in observations into the Arctic are through the Fram Strait and Barents Sea it the recent years (Taylor et al., 2022). It is highly debated whether the increased ocean heat transport contributes to Arctic warming or if this is not correlated at all to the Arctic warming. This mismatch is however due to difference of the latitudes chosen where the ocean heat transport is focused, since ocean heat transport increases poleward of 60°N and are positively correlated with AA (Taylor et al., 2022)

Another long-term oceanic process theorized to be related to the warming Arctic is the Pacific decadal oscillation. Screen and Francis (2016) findings show that sea-ice loss in the wintertime AA has a dependence on the phase of the Pacific decadal oscillation. This is supported by a similar study by Svendsen et al. (2018), where the Pacific surface changes were shown to weaken the polar vortex which leads to adiabatic heating of the Arctic surface. They furthermore conclude that the recent shift to a positive Pacific decadal oscillation predicts an intensified warming in the decades to come.

#### 2.3.4 Coupling between mechanisms

The feedbacks and changes in energy transport that affect AA are dependent on the state of the climate system itself, and this means that changes in the state of the climate will lead to changes in the strength of AA (Previdi et al., 2021). This is further demonstrated by Q. Cai et al. (2021) showing that AA is driven not only by a single factor but instead is driven by the internal variability of the climate itself, with coupled effects of the current global warming. This is further emphasized by Hwang et al. (2011), since local feedbacks affect temperature gradients. Therefore, the coupling between energy transports and Arctic feedbacks cannot be ignored when studying AA. The difference of Arctic surface types (e.g., sea ice, ocean, and land) governs the features of the spatial structure and the seasonality of AA. The surface-specific characteristics such as the albedo, surface turbulent fluxes, vertical and horizontal heat transport, and specific heat capacity control the impact of each surface transport (Taylor et al., 2022). The observed temperature changes imply that regions with the largest loss of sea ice are particularly warming the fastest. Coupled Model Intercomparison Project Phase 6 (CMIP6) model projections show that the magnitude and the seasonality of the warming is affected by the surface type such as sea ice retreat (Q. Cai et al., 2021).

## 2.4 Previous studies

Since the beginning of the 20th century, there are two major warming events that have been identified in the Earth's climate system. The warming in the early 20th century was strongest in the Arctic and attributed to natural climate variations, but the modern warming period is observed in all latitudes (Yamanouchi, 2011). Firstly, the warming in the 1920s and 1940s was strongest in the Arctic, and the recent ongoing observed warming that has started in the 1980s is observed on a global scale. Periods of cooling (negative anomalies relative to the climatology) have also been observed in 1960s and 1970s between these warming events

(Johannessen et al 2016). What was previously known is that AA manifests the strongest in the winter and autumn, but AA values have become positive in all the seasons (Francis & Vavrus 2015). Arctic warming was also observed to have become stronger and present in all seasons compared to the warming in the 1930s and 40s. The results from Davy et al. (2018) on the quantification of AA show that the magnitude of AA in 2006 is the highest since their datasets start in 1901. In contrast, the late 1980s increase of SAT in spring was as strong in winter and in autumn (Bekryaev et al 2010). Fracis & Vavrus (2015) define the period from 1995 to 2013 as the AA era.

There is an inherent difficulty in identifying the trends and strong long-term fluctuations in the Arctic, which makes the quantitative analysis of the contribution of the trends versus multidecadal variability difficult (Serreze & Barry, 2011; Taylor et al., 2022). However, studies suggest that the previous warming was a result of the natural climate variability, while the recent emergence of surface air temperature changes are attributed to anthropogenic forcing (Chen et al., 2018).

# 3 Methodology

ERA5 reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) was used for computation of the metrics. Two reanalysis datasets were used, namely ERA5 1979-present and ERA5 back extension 1950-1978. These two datasets were merged to create the timeseries 1950-2021. The data covers a global extent with a resolution of 0.25° x 0.25°. 2 meter SAT were chosen since AA manifests strongest at the surface (Manabe & Wetherald, 1975). Moreover, the ERA5 dataset has been found to reflect Arctic temperature changes well (Z. Cai et al., 2021).

Annual averages were calculated averaging monthly values weighted by the number of days in each month. Furthermore, weighted spatial averages were calculated accounting for the areal differences between higher and lower latitudes. To quantify Arctic amplification, the warming rates in the Arctic and the NH were compared as this study focuses on temperature changes within the NH. The region constraining the Arctic for this study is north of 60°N up to 90°N. The NH is regions within the northern part of the equator to the poles (0°N- 90 °N).

To calculate anomalies, the period 1951-1980 was used as the climatological reference period due to this being the beginning of the timeseries. This climatology was then deducted from the annual averages, producing the temperature anomalies needed for the calculation of the different metrics. 11-year moving windows were used to reduce the natural variability which produces noise that is characteristic of the Arctic region. An 11-year moving window was chosen since a larger moving window will shorten the timeseries substantially. A moving window is essential to observe the emergence of the signal of AA from the noise of natural variability.

For the first metric ($A_0$), which is the ratio between the SAT anomalies of the Arctic and NH, the 11-year moving averages were taken for the data from years 1982-2021. The ratio was then calculated from these SAT values. The second metric ($A_1$) which is the difference between the SAT anomalies of the Arctic and the NH was calculated by subtracting the 11-year moving average of the Arctic from the NH values. The third metric ($A_2$) was calculated by first calculating the 11-year linear trends of both the NH and Arctic SAT anomalies, and by masking out the insignificant trends ($p>0.1$) from the NH region. The ratio of these linear trends was then calculated. The fourth metric ($A_3$) was calculated by taking the standard deviation of the NH and Arctic SAT in 11-year moving windows, resulting in the standard deviation values for the NH and the Arctic. The ratios of these standard deviation were then calculated to obtain the Arctic amplification index. Lastly, the fifth metric ($A_4$) was quantified by calculating the coefficient of the linear regression between the NH and the Arctic in 11-year windows (Bekryaev et al., 2010).

Finally, the correlation between the different AAI and the detrended SAT at each grid point in the NH were calculated to produce correlation maps. The SAT anomalies of the entire NH were detrended to remove the common effects of external factors in the dataset These maps show the correlation values in the NH ranging from 1 to -1. Positive correlations mean that as the SAT increase, the AAI increase along with it, while a negative correlation means that as one variable increases, the other decreases along with it.

# 4 Results

The results are presented below in the order of the calculated SAT anomalies, the metrics, and finally the correlation maps for each metric calculated.

## 4.1 SAT anomalies

The SAT anomalies in the NH and Arctic region using the climatological reference period (1951-1980) (Fig 1a.) show that Arctic SAT anomalies show greater variation than NH SAT anomalies owing to the multidecadal variation and interannual processes occurring within the Arctic. However, a key feature of this figure is the generally higher magnitude of SAT Arctic anomalies relative to the NH. Closer to the climatology, NH values approach 0, and negative values for the Arctic are also observed. Fig 1b shows the resulting 11-year averages calculated from the SAT anomalies to highlight the long-term variability. A characteristic of the SAT anomalies shown in the graph is the steeper increase of the Arctic SAT anomalies of up to approximate 2.5 C in 2016 relative to the NH with 0.5 for the same year. This shows the rapid increase of the Arctic surface air temperatures. Fig 1c shows the interannual variability of the Arctic & NH SAT calculated as the standard deviation in an 11-year moving window. This graph shows the overall higher variability of the Arctic, with peak values around 2000.

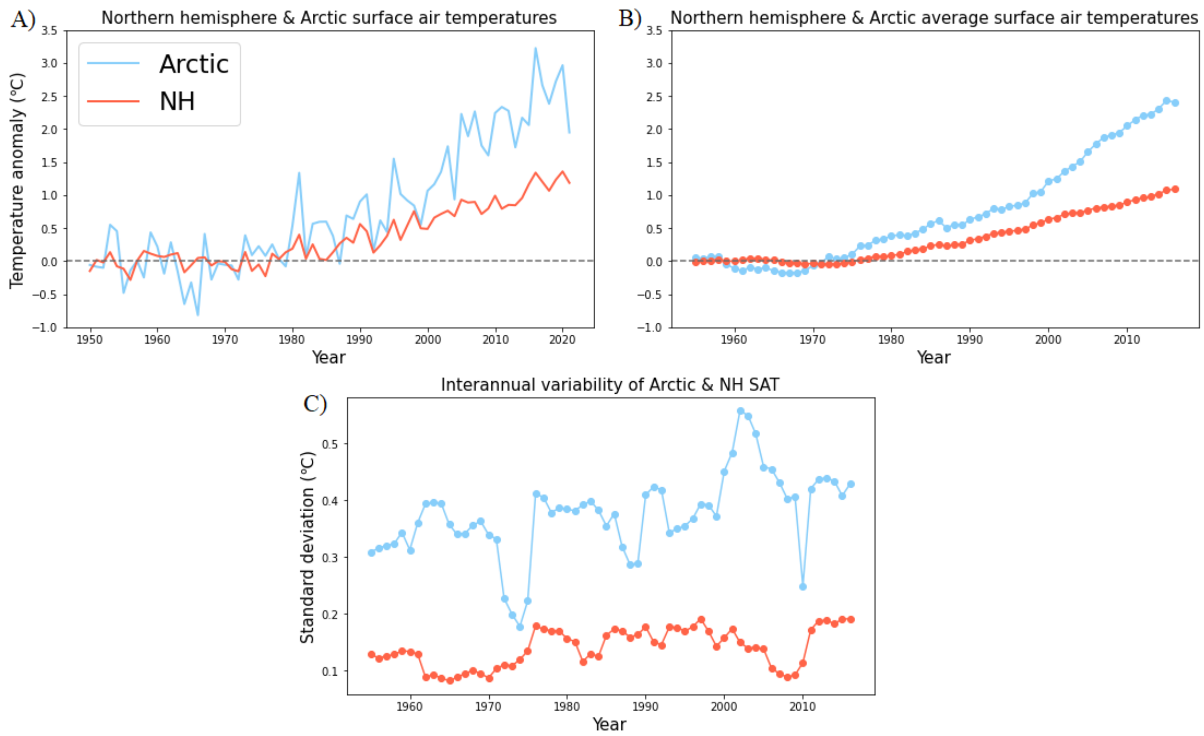



Figure 1. A) The Arctic and NH SAT anomalies for the years 1950-2020 relative to the climatology 1951-1980. Figure B) shows the calculated 11-year moving average of the NH and the Arctic., and C) shows the interannual variability of the Arctic with an 11-year running window.

The calculated anomalies below show the surface air temperature anomalies for the year 2020 (Fig 3). From this figure, we can see that the values for SAT anomalies are greatest along the Barents and Kara Sea region, where sea ice melt are occurring at a rapid pace (Screen & Francis, 2016). There is also a cooling region in the North Atlantic.

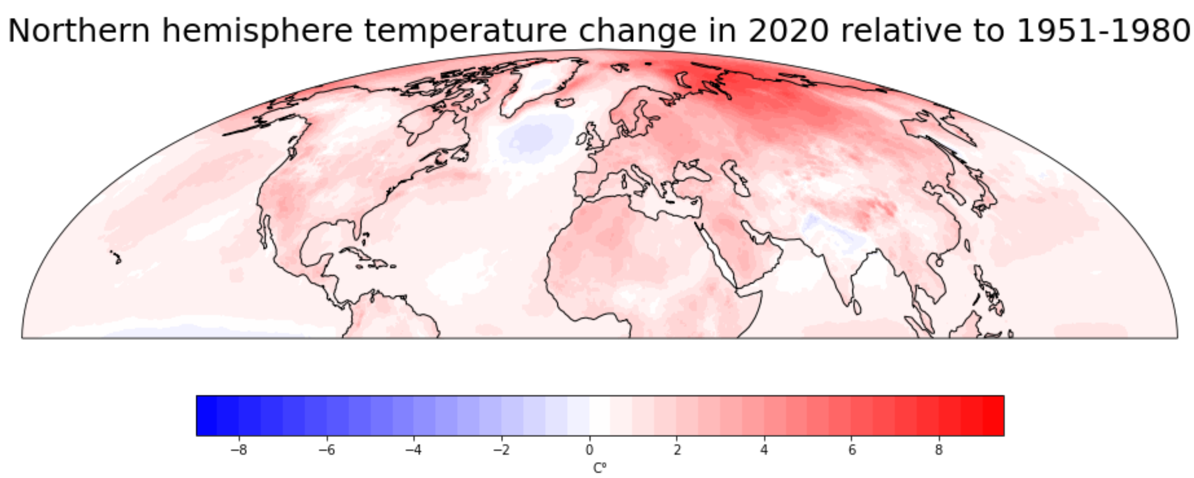



**Figure 3.** The calculated SAT anomalies in the NH from the ERA5 reanalysis data for the year 2020 relative to 1951-1980. The darker blue colours show regions with negative anomalies, and red colours show an increase in anomalies.

## 4.2 Metrics

Figure 4 shows all the metrics for AA quantified. The years within the climatology of all the metrics were masked out because metrics $A_0$ and $A_2$ show extreme values close to the climatology due to their definition, as NH SAT anomalies are naturally close to zero closer to the climatology. However, they provide an insight to the differences in the metrics and the possible unreliability of using earlier years to analyse AA.

$A_0$ and $A_1$ show a relatively steady measure of AA. $A_0$ shows extreme values for AA closer to the climatology where the NH value were approaching zero and was thus masked out. Similar results were observed in $A_2$ where high values for AA were observed closer to the beginning of the time series where the climatology also starts. The number of data points for $A_2$ was therefore greatly reduced by masking out of the AA values when the trends are insignificant. Generally, the magnitude of AA for the three metrics $A_2$, $A_3$, and $A_4$ show a common increase in the beginning of the 21$^{st}$ century, a decrease from 2004, and a subsequent slight increase after 2012. $A_2$ shows the largest peak in the early 2000s and shows the greatest magnitude for measuring AA of up to 7.5 times greater than the NH. The $A_3$ and $A_4$ curves look similar, with a rise in around the 1980s, and decrease thereafter. Moreover, they show similar peaks in the years 2000-2004, which can also be observed in $A_2$. A common period of increase and decrease in AAI is observed in both metrics $A_3$ and $A_4$ in years between 1988 and 1992. A following dip for both metrics are also observed after 1992. Furthermore, $A_2$ and $A_4$ show a decline in around 2005, while in $A_3$ this decline is delayed until 2008. Overall, these metrics ($A_2$, $A_3$, and $A_4$) seem to agree with those years to manifest the highest AA period according to the ERA5 dataset. The magnitude of AA differs per metrics, as well as their variation through the time series.

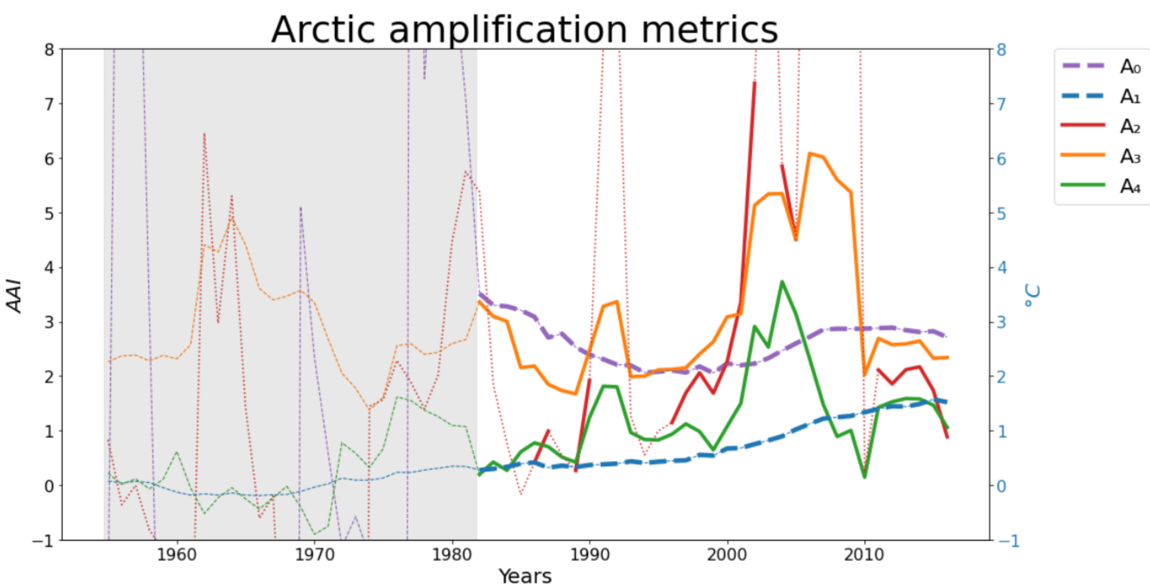



**Figure 4**. The metrics to quantify AA, with $A_0$ as the ratio of the SAT anomalies of the Arctic and NH in purple, $A_1$ as the difference between the SAT anomalies of the Arctic and NH with units of

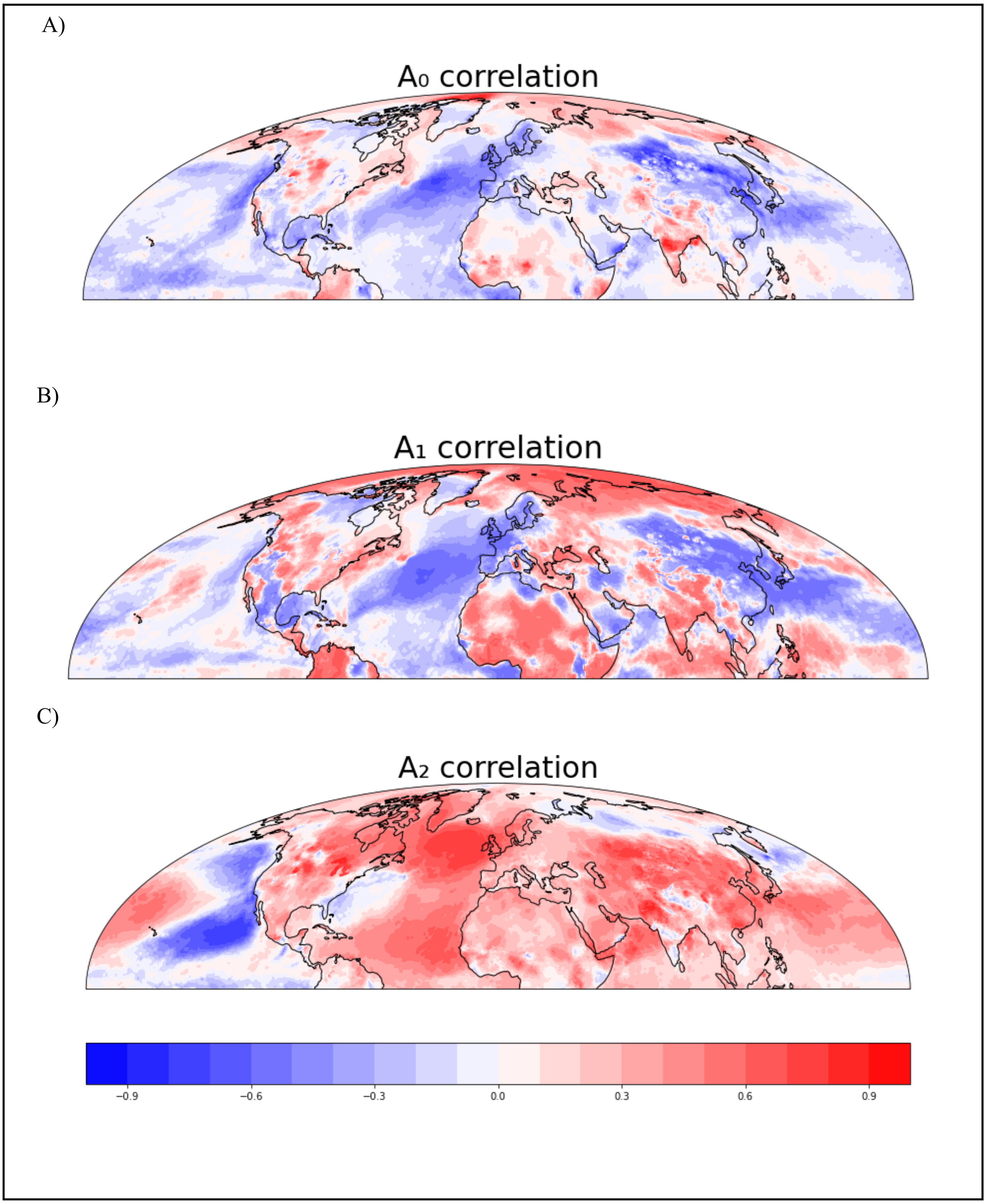
degrees C shown in blue and units in the right y axis. $A_2$ is the ratio of the significant (p>0.1) 11-year linear trends of the Arctic and NH shown in red. In a lighter shade of red, the insignificant linear trends are shown. The bold red line is the actual measurement of the $A_2$ metric including only significant NH linear trends. $A_3$ is the ratio of the interannual variability of the Arctic and NH SAT anomalies in the colour orange. Lastly, $A_4$ as the coefficient of the linear trends between the Arctic and the NH in green. The shaded region in the timeseries is the years that are within the climatology. The climatology 1951-1980 is shown with a light grey mask, showing the high values of AA for $A_0$ and $A_2$.

$A_4$ has an observed decline in the years after 2008, with AAI values closer to 1 and almost 0. Overall, the metrics show different AAI magnitudes. Similar patterns are seen in the AAI curves between $A_2$, $A_3$, and $A_4$, while $A_0$ shows a relatively small variations I the AAI with values between 3.5 – 2 times greater than that of NH. $A_1$ shows a steady increase through time with a value of 1.5 ° C more than the NH by 2010. The results show poor agreement in the years within the climatology between metric $A_3$ and $A_4$ which otherwise show relatively the same pattern after the mid-1980s. There are also notably very high values for AA for $A_0$ and $A_2$ which is indicated using thinner lines. Metrics $A_2$, $A_3$, and $A_4$ show that the years within the start of the 21st century (between 2000 – 2005) show the highest values for AA considering the earlier shaded region which are the years within the climatology 1951-1980.

## 4.3 Correlation

In Fig 5, the correlations between the SAT anomalies in the entire NH and the Arctic amplification indices are shown to have different values. Starting with $A_0$, the areas with high negative correlation are found in the Asian continent, along with the Pacific Ocean. The North American west coast also shows a high negative correlation with this metric. Another notable feature is the high negative correlation in the north Atlantic Ocean. Areas with high positive correlation are northern Greenland, and some sparse areas in midlatitudes US, and India. The entire Arctic region has some positive correlation to the $A_0$ index (Fig 5a). Overall, $A_0$ which is a ratio of the SAT anomalies show high correlations within the Arctic, and some parts of the midlatitude and tropics. Negative correlations are mostly found in lower latitudes, but some regions within the Arctic correlate negatively to this metric, such as Greenland, North America, and parts of Scandinavia. Similarly, $A_1$ reflect the same spatial pattern as A0. This is apparent in the ocean where negative correlations are observed, especially in the north of the Atlantic Ocean. Similarly, a high negative correlation between the amplification for these metrics are seen in the Asian continent. However, it is notable that $A_1$ showed the most substantial difference of the correlation results after detrending the SAT anomalies.

Artic amplification metrics and the regional correlation in the NH



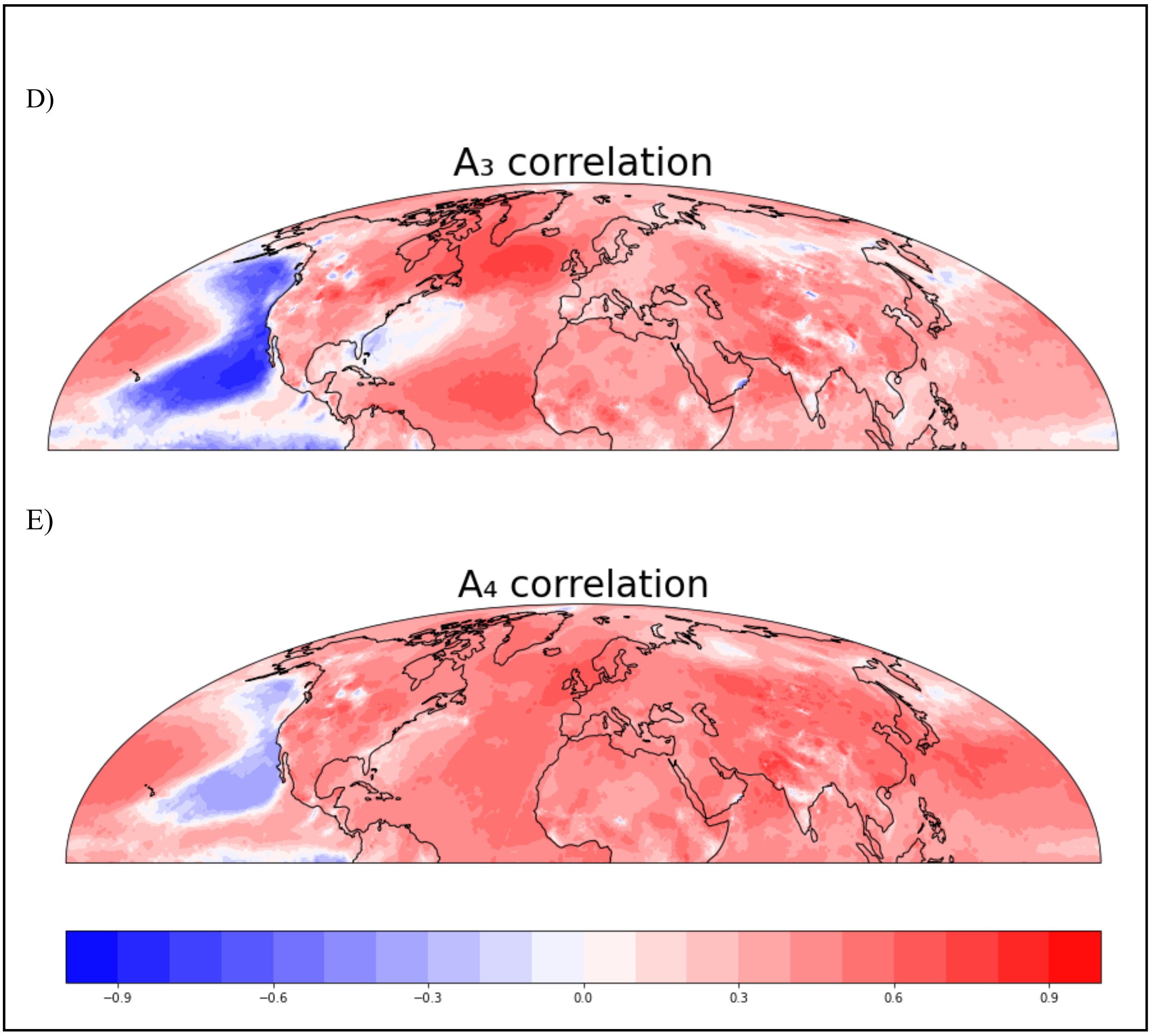



**Figure 5.** The correlation between the Arctic amplification indices a) $A_0$, b) $A_1$, c) $A_2$, d) $A_3$, and e) $A_4$ and the 11-year SAT anomalies for the time series in the NH for the years 1982-2016.

$A_2$ correlations as seen in Fig 5c show high positive correlation values in particularly the Atlantic Ocean, parts of the middle of the USA, parts of the Pacific Ocean, and in the Asian continent. Values of positive correlation dominate the entire NH. There is a noticeable patch of strong negative correlation in the North Pacific Ocean, and some patches of weaker negative correlations in the North-eastern Eurasian continent, stretching out to the Northwestern Pacific region.

The correlations of metric $A_3$ as seen on Figure 5d show high positive correlations in the north and south Atlantic Ocean. High negative values are observed in the Pacific Ocean. $A_4$ (Fig 5e) shows similar patterns, but less pronounced than that of $A_3$. The same region of high negative correlation values is observed in the Pacific Ocean, and positive correlations in the eastern Pacific Ocean. $A_2$, $A_3$, and $A_4$ exhibit approximately similar spatial correlation patterns.

# 5 Discussion

There are several factors that affect the total magnitude of AA that were explored in this study. Firstly, the choice of climatology affected the results of the ratio calculations. The problem arose in the metric $A_0$ as a ratio when the NH values were close to zero in the climatology in the beginning of the dataset. The earlier years of 1951-1980 show an overall disagreement with the metrics that otherwise showed similar patterns in the later years ($A_3$ and $A_4$).

The extreme values for the AAI were also observed in $A_2$. Hence, masking out ratios with insignificant linear trends in $A_2$ resulted in a slight improvement of the metric but created large gaps in the timeseries. However, the p value chosen is also relevant to the results of $A_2$ since choosing a lower significant ($p<0.05$) would result in a smaller number of data points for the index. A longer time series would be more useful in the future if $A_2$ is to be used. Hind et al. (2016) came to similar conclusions, advising against this metric. Their results show a significant value from the mid-1980s to the present, which is not observed in the ERA5 dataset metrics calculation and in the timeseries itself. At no point in the time series was AA less or equal to 1, which means that in this study AA was present for all the years in the timeseries. This was not the case for $A_4$, where values of AAI $\leq 1$ are observed for the years 1955 to around 1975. The 1970s also show negative values of AA, which has been observed in other studies as well (Johannessen et al., 2016).

As Chylek et al. (2009) emphasized in their study that the nature of AA is not a constant value but instead varies in time on a multi-decadal time scale, which is reflected more in metrics $A_3$ and $A_4$ and lesser so in $A_1$, $A_2$, and $A_0$. The application of the 11-year window reduced the number of data points but was necessary to reduce the natural variability and to investigate atmospheric processes that are related to AA that vary naturally with the climate and have a long overturning period (Atlantic meridional overturning circulation, Pacific decadal oscillation). When choosing a metric, the timescale should be considered and adjusted to which process is being examined. For example, processes that occur in a shorter timespan than the chosen window length (11-year) cannot be examined. Moreover, most studies use a longer time window of 21-years and 31-years. This study was limited due to the ERA5 reanalysis data covering a shorter duration, creating a shorter time series of 16 years in total when using a 31-year window, for example.

Similarities between the indices are observed in metrics $A_2$, $A_3$, and $A_4$. However, they show different magnitudes for the AAI. For example, the highest AAI that was found for $A_2$ and $A_4$ is in the years between 2000 and 2005 but differ in magnitude of up to 7.5 for $A_2$, and around 3.5 for $A_4$. The highest value for $A_3$ is found in the years after 2005. This overall implies that they may reflect similar processes.

Looking at the correlation results, $A_0$ shows a pattern of negative correlation in the oceans, as in the Asian region. This could imply a coupling between oceanic-transport processes from the oceans to the Arctic, where the correlations are positive. The negative correlation in the ocean implies an inverse relationship between the two temperatures, since as the ocean temperatures in the oceans decrease, the Arctic temperatures at the same time increases. This observed positive phase of the Atlantic multi-decadal oscillation which brings warm waters poleward is currently at a positive state since the 1980s (Ting et al., 2009), and these values do not agree with the results shown for this metric if one was to relate this to the assumed coupling between the Atlantic sea surface temperatures and Arctic surface air temperatures. However, this relationship is not known to be linear, since as mentioned in Previdi et al. (2021) in their study to review AA mechanisms, these oceanic connections are coupled to local Arctic feedbacks and work to enhance the warming from a larger scale to a local scale.

The similarities between A0 and A1 imply that they may reflect the same SAT that drive AA. In general, $A_1$ is a difference between the SAT anomalies and therefore has a unit of °C. It is therefore not directly comparable to the other metrics which are nondimensional indices. This proves to be disadvantageous when using this to quantify AA since the units are different. Despite this, $A_0$ and $A_1$ share a common pattern and could be advantageous when looking at the overall warming in the Arctic. The uneven contribution of the Arctic to the overall value of AA is also observed more in these metrics, since the Arctic is shown to not correlate uniformly to the metrics unlike that of $A_2$, $A_3$, and $A_4$.

The high correlation in $A_2$ in the North Atlantic can give an insight to the coupling of this region to the AA. Interestingly, the Arctic region does not show strong correlations to this index, despite positive correlations being present. This could imply that this metric may be useful to analyse non-local feedback contributions to AA. This could also be due to an error within the calculations since $A_2$ had gaps in the timeseries due to the lesser significant AA values.

The $A_3$ correlations show a strong correlation in the Atlantic region as well. The Pacific Ocean negative correlations are also strongest in this metric. This could be due to the nature of $A_3$ which uses the interannual variation of both the NH and the Arctic. The $A_4$ correlations show a similar pattern to $A_3$ in terms of their regional distribution (for example, negative correlation in the Pacific, and positive correlation in the Atlantic region, but also in the rest of the NH). However, both the positive and negative correlations are less than that of $A_3$.

Separating the random noise of performing a spatial correlation analysis, a reoccurring region showing either no correlation or a high to low negative correlation in most of the metrics is the Pacific Ocean sector. This could be evidence in support of the theorized coupling between the Pacific and the local processes occurring within the Arctic, and their relation to the ongoing Arctic response to global warming. Taking this to the next step, the $A_3$ metric shows the greatest negative correlation to this region. It can be suggested that this metric can be used to investigate the multi-decadal processes in the Arctic using a longer time series, and possibly the remote connections and influences. Modelling studies by Docquier et al. (2021) show that the enhanced melting of the sea ice is induced by temperature changes in the North Pacific, even more than the North Atlantic. Praetorius et al. (2018) also come to similar conclusions, where latent heat transports into the Arctic from the Pacific result in more clouds that insulate the radiation within the Arctic.

In a broader perspective, proxy records reflecting Arctic amplification by Fang et al. (2022) show that AA has been decreasing in connection to greenhouse gas emissions, and the decrease in AA in the last millennia shows how we need to investigate these processes and produce established metrics to fully understand AA, how it varies on multi-decadal timescales, and the effects of the anthropogenic greenhouse gas forcing.

Moreover, as mentioned in the previous subsections, AA manifests the strongest in the surface temperatures of the Arctic. However, several ways to see the effects of AA can also be found when analysing tropospheric temperatures, or the entire atmospheric column. Looking at different pressure heights as well may be useful to assess the underlying processes of AA, especially changes in poleward energy transport to compliment this study. This is supported by Screen et al., (2012) as they conclude that remote influences explain the majority of the observed warming higher in the atmospheric column.

# 6 Conclusion

Arctic amplification (AA) metrics reflect different processes and features of AA. Metrics $A_0$ (the ratio of the SAT anomalies of the Arctic and NH) and $A_1$ (the difference between the Arctic and NH SAT anomalies) show a relatively steady magnitude of AA through time and seem to reflect similar patterns in their regional variation, showing high correlation within the Arctic. $A_2$, $A_3$, and $A_4$ show a varying magnitude of AA through time and reflect similar patterns regionally and remotely. For studying the strength of the driving force of surface air temperatures within the Arctic and their contribution to the overall index, $A_0$ and $A_1$ could provide an insight to these. Moreover, if the overall magnitude of the warming is to be studied, these metrics can be used as well since $A_1$ shows a steady increase in °C through time, while $A_0$ shows a constant AAI. It is important to be mindful of the extreme values near the climatology which yields unrealistic magnitudes for AA. Using $A_2$ could be disadvantageous, since insignificant NH trends must be removed to avoid division with smaller trends, which resulted in large gaps in the timeseries.

This study highlights the need for well-established metrics and justification to choosing which one to describe AA depending on the processes being investigated. The changing Arctic has been gaining attention in the past decade both within the scientific community and the public. The choice of climatology affects the metrics, and the choice of the definition of the regions. While the choice of the boundaries of the Arctic was proven to not affect the study overall such as that in Davy et al. (2018), perhaps choosing to include the Arctic in the NH (0°N - 90°N) or not (NH is 0°N - 60°N) could also affect the magnitude of AA since the variations within the Arctic are included in the measurement itself. Owing to the strong seasonality of the Arctic, quantifying the metrics for the different seasons may add insight to the magnitude of the warming and the regional relations. If this topic is further studied, using the seasonal data should be investigated as well to compliment the current results, showing the seasonal pattern of both the local and remote processes causing AA.

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