Arctic Sea Ice in a Warming World

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Abstract: In the past few decades the Arctic has been warming faster than the global average, a phenomenon known as Arctic Amplification. At present, there is an ongoing discussion among the scientific community on how to quantify the magnitude of this phenomenon and what the causes of it might be. The aim of this study is to investigate the evolution of Arctic sea ice in the past few decades and its link with global and regional temperatures and to quantify Arctic Amplification. For that purpose, observational data, as well as a general circulation model, have been used.

I. INTRODUCTION

It is a fact that the Arctic ["ARC"] is warming faster than the global mean ["GLOB"]. The recent study carried out by Rantanen et al., 2022, showed that the global average surface air temperature ["TAS"] is increasing at a rate of $0.19\,°C$ per decade, while the Arctic TAS is rising $0.73\,°C$ per decade. This phenomenon, known as Arctic Amplification ["AA"], is likely to have several consequences in a mid-term future. It is thought that it will reduce the meridional temperature gradient, weakening zonal winds in the mid-upper troposphere. As a result, it has been suggested that the mid-latitude circulation might become wavier, which would bring a decrease in winter temperature variability, changing both the weather and the climate in these latitudes [5].

There are several mechanisms that are known to contribute to AA (Dai et al., 2019, and Rantanen et al., 2022), but there is a bit of uncertainty about the magnitude of each one. This study is focused on the effect of sea ice loss on AA, which is believed to be of great importance [10]. Due to global warming induced by greenhouse gases, a noticeable portion of Arctic sea ice has melted and dark water regions have opened their way, increasing the sunlight radiation absorption by the Arctic ocean - and, thus, the water temperature - because of a significantly lower albedo. A warmer ocean, in turn, favours the melting of more sea ice. This feedback, known as the sea ice-albedo feedback, contributes to the faster warming of the Arctic and the globe, as a lower proportion of the solar radiation is reflected [12].

There are remarkable discrepancies among previous findings on AA, which might be driven by the fact that there is not full agreement on the definition of the Arctic region and Arctic Amplification, on the period chosen, and even on the data used. Richter-Menge and Druckenmiller (2020) found that the Arctic TAS is increasing more than twice faster than the global TAS, using observational data starting in the mid-1980s. Jansen et al., 2020, reached the same conclusion studying the period 1979-2018, affirming that in some particular Arctic areas this rate is noticeably intensified. Moreover, some other works have come up with more pessimistic outcomes. For instance, the 2021 recent Arctic Monitoring and Assessment Programme (AMAP) report found that the Arctic region is warming three times faster than the global average, using data from the period 1971-2019. Lastly, Rantanen et al., 2022, found that the Arctic region is warming almost four times faster than the global average when studying the period 1979-2021.

II. DATA AND METHODOLOGY

A. Data

The temperature data come from the European Centre for Medium-Range Weather Forecasts reanalysis version 5 (ERA5) [7]. It provides global two-meter temperature monthly means with a spatial resolution of 0.5° x 0.5° from January 1950 up to date. However, it has been interpolated into a 2.5° x 2.5° grid to be computally more efficient.

The sea ice data are from the Met Office Hadley Centre version 1 (HadISST1) [9], which provides global sea ice concentration monthly means from January 1870 until the present with a spatial resolution of 1.0° x 1.0°. Historically, the measures were in situ, but from October 1978 onwards passive microwave satellites have been used for sea ice concentration observations.

Additionally, the climate model IPSL-CM6A-LR [3] from the Coupled Model Intercomparison Project Phase 6 (CMIP 6) [6] has been used. It provides historical simulations up to 2014 and future projections spanning from 2015 to 2100, both with a spatial resolution of 2.5° x 1.3°. For this study the members r1i1p1f1, r2i1p1f1, r3i1p1f1, r4i1p1f1, r6i1p1f1, and r14i1p1f1 have been considered.

Two different scenarios, known as "Shared Socioeconomic Pathways" (SSPs), have been used for the future projections. Each of these take into account a different evolution of some socioeconomic factors, such as population, socioeconomic growth, education, urbanisation, and the rate of technological development [11]. On one hand, we consider ssp126 (called "Sustainability - Taking the Green Road"), supposing that some action is taken and a more sustainable path is followed and, on the other hand, ssp585 (named "Fossil-fueled development - Taking the Highway"), assuming that there is a rapid technological progress and development of human capital, exploiting abundant fossil fuel resources [11].

B. Methodology

First and foremost, it is important to decide the period to be selected for the research. It has conveniently been chosen the period covered from 1979 until 2020 for two main reasons. Firstly, it is the most relevant period regarding anthropogenic climate change [10] and, secondly, the reanalysis products have been by far more reliable since 1979 because from this year onwards satellites have been used for observational purposes [9].

In order to analyse the data, the programming language Python has been employed. Let the function of the linear fit be

$$y = ax + b. \tag{1}$$

The parameters a (slope) and b (intercept) have been computed through the `scipy.stats.linregress` function from the `scipy.stats` package (SciPy library of Python). Given the observational data as an input, this function calculates the linear regression through the least squares method, and returns its slope, intercept, Pearson correlation coefficient, p-value of the Wald test, and standard error of both the slope and the intercept.

Furthermore, to evaluate the statistical significance of the trends, the one-tailed t-student test has been used. It makes the hypothesis (known as the null hypothesis) that there is no correlation between the two variables and evaluates whether this hypothesis is satisfied with a given probability (confidence level). If the null hypothesis is not satisfied, then the trend is statistically significant. In order to carry out this test, first of all the t coefficient has to be calculated using the `scipy.stats.t` function from the `scipy.stats` package as well. The inputs of this function are the confidence level and the number of degrees of freedom, and it returns the value of t.

Then, the minimum Pearson correlation coefficient for the null hypothesis not to be satisfied (i.e. for the trend to be statistically significant) can be calculated using the t value, according to

$$r = \sqrt{\frac{t^2}{t^2 + N - 1}}, \tag{2}$$

where N is the number of observations (i.e. 42 years). In this case, the number of degrees of freedom is $N - 1$.

If the Pearson correlation coefficient of the trend is equal or higher than the one computed from these relations, it can be firmly stated that the trend is statistically significant. For the analysis of this research results, it has been chosen a confidence level of 95%.

While there are multiple ways of defining the Arctic, such as the geographical definition (the region above the $66° \, 34'$ parallel, the *Arctic Circle*) or a delimitation based on vegetation, the one chosen for this work is the area encircled by $60° \, N - 90° \, N$. To quantify the AA, the definition from Rantanen et al., 2022, has been applied. It is *the ratio of Arctic warming to the global-mean warming*:

$$AA = \frac{dT/dt_A}{dT/dt_G}, \tag{3}$$

where dT/dt_A and dT/dt_G are the slopes of linear trends of the time series of Arctic and global temperatures, respectively.

III. RESULTS

One can find in the bibliography that the annual sea ice concentration ["SIC"] minimum is typically during the month of September [12]. This is because most of the sea ice melting occurs during the summer season. As a consequence, September is the month with the largest variability, which is why this September sea ice data have been chosen to present the results in this work. This statement is reinforced by Fig. 1, which displays the monthly mean sea ice concentration values for the period of interest and the standard deviation of the mean. Furthermore, the maximum of SIC, with its smallest variability, is usually in the month of March because during the winter temperatures rarely become high enough for the sea ice melting to take place.

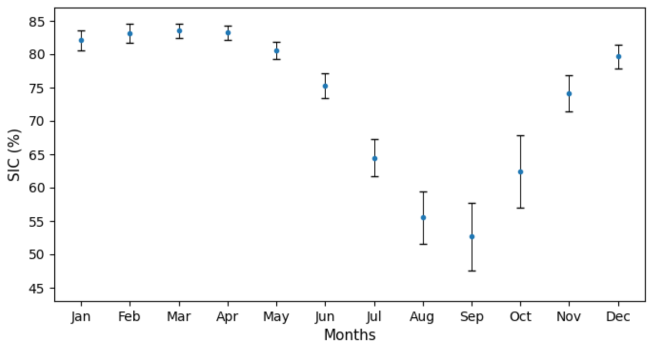

FIG. 1: Annual SIC cycle with the monthly average and the standard deviation values computed for the period 1979-2020.

Furthermore, the spatial climatology of September SIC from 1979 until 2020 is presented in Fig. 2. The central region of the Arctic is mainly covered with a SIC greater than a 90 % and, the closer we are from the coast, the lower the SIC becomes. It can be seen that the sea ice reached the Russian shore in September 1979, whereas in September 2020 water regions have opened their way, allowing the navigation from Alaska to Scandinavia.

TAS and SIC time evolution are shown in Fig. 3. Fig. 3a illustrates the annual global and Arctic temperature anomalies respect to the climatology of 1979-2020. The Arctic TAS trend (0.61 ± 0.12 $°C/decade$) is more than three times greater than the global TAS trend (0.18 ± 0.03 $°C/decade$). In spite of using a different

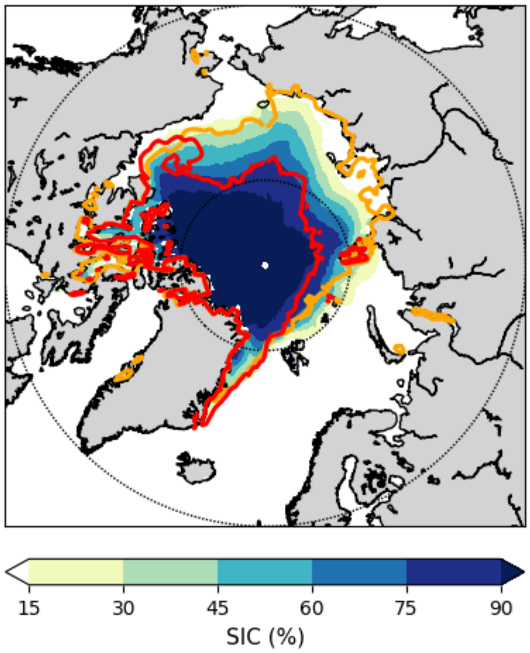

FIG. 2: Arctic sea ice climatology of September over the period 1979-2020. Contour lines indicate the sea ice fraction of 15% in September 1979 (orange) and 2020 (red).

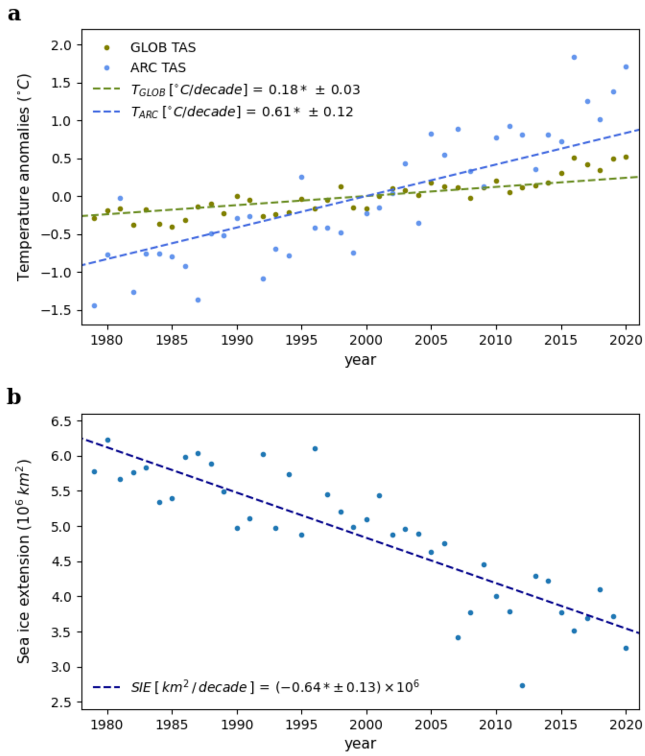

FIG. 3: Time evolution of global and Arctic temperature anomalies (a), and Arctic September sea ice concentration time evolution (b). Linear fits are shown in dashed lines. Asterisk (*) indicates that trend is statistically significant at 95% using a t-student test.

observational data set, these findings are consistent with Rantanen et al., 2022. It should be remarked that the value for the Arctic TAS trend would have been even more compatible if we had defined the Arctic in a more restrictive way; for instance, delimiting the Arctic with higher latitudes.

The sea ice extension ["SIE"] is defined as the area covered with a SIC of at least 15% [13]. Fig. 3b displays the sea ice extension time evolution during the month of September (minimum extension) over the period 1979-2020. A noticeable decline in the Arctic sea ice extension can be observed ($0.64 \pm 0.13 \times 10^6\ km^2/decade$). There is a significant drop-off in 2012. This coincides with the monthly averaged historical Arctic SIC minimum ever recorded [12][13], being approximately a 44% less than in 1980. In regards to previous studies, when using data from the National Snow and Ice Data Center (NSIDC) the trend is $-0.87 \times 10^6\ km^2/decade$, while the data from the Ocean and Sea Ice Satellite Application Facility (OSI-SAF) lead to a trend of $-0.93 \times 10^6\ km^2/decade$ (Barber et al., 2017), both for the period 1979-2015. Furthermore, Serreze et al., 2018, obtained a decline in SIE of $-0.83 \times 10^6\ km^2/decade$ (1979-2017). The discrepancies between these results and the trend from Fig. 3b can be mainly attributed to a different definition of the Arctic region, but it is still consistent with our findings.

Spatial trends of annual TAS are shown in Fig 4a. It can be easily noted that there are almost no regions with negative trends, which means that the temperature has risen in all the represented area. Particularly, in the Barents and Kara Seas the temperature has increased noticeably faster than its surroundings, even surpassing the trend of $1.5\ °C/decade$. Moreover, September SIC local trends are displayed in Fig. 4b. The areas where the sea ice has decreased faster, hitting the rate of $-0.9 \times 10^6\ km^2/decade$ between the East Siberian Sea and the Beaufort Sea, coincide with the areas where temperature has increased more rapidly. This fact reveals the tight relation between AA and sea ice decline. Lastly, local AA, which is the magnitude defined as Arctic Amplification according to Eq. (3) for each grid point, is represented in Fig. 4c. Local AA values greater than one entail a faster warming than the global average. Consequently, almost the whole represented region is warming at a greater pace than the global average; and, the regions that are not, do not display statistically significant trends. In addition, some areas are warming more than eight times faster than the global average. All of these results are consistent with Rantanen et al., 2022 (see their Fig. 1b and 1c), and Jansen et al., 2020 (see their Fig. 1a and 1b).

In Fig. 5a the Arctic annual temperature anomalies are represented as a function of the global temperature anomalies from 1979 to 2020. In this figure a quantification of AA has been made. In accordance with Eq. (3), AA is the slope of the linear regression, with a value

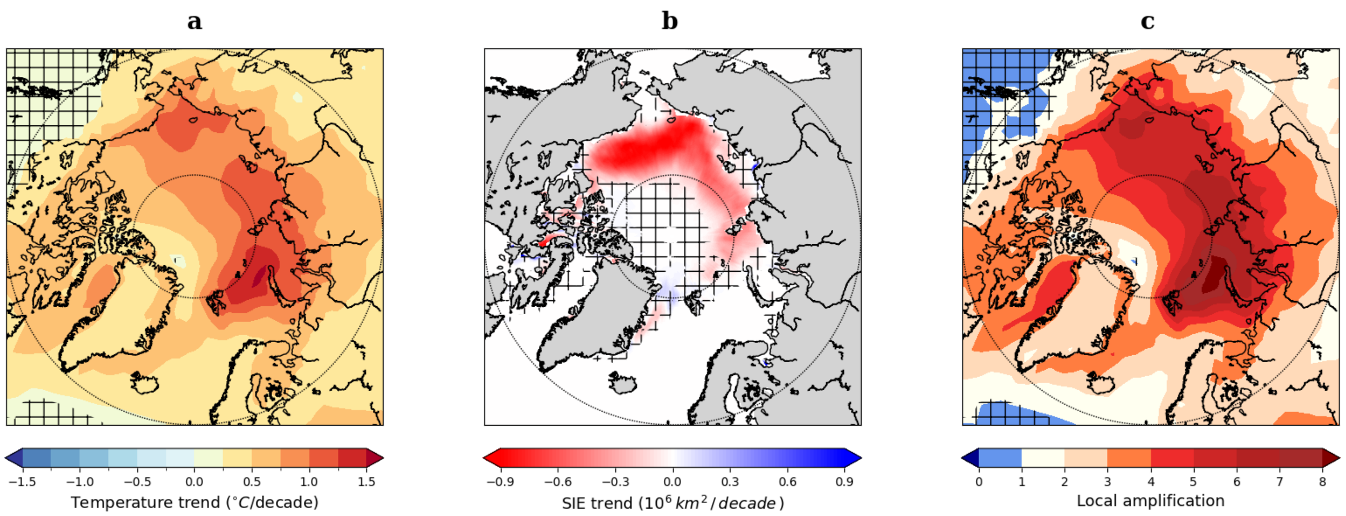

FIG. 4: Spatial trends of annual local temperatures (a), September sea ice extension trends (b), and local amplification (from Eq. 3) (c) over the period 1979-2020. The outer circle indicates the $60^{\circ}N$ parallel, which encloses the defined Arctic region. Hatched areas are not statistically significant using a t-student test.

of $AA = 3.2 \pm 0.5$. That is, the Arctic is warming 3.2 times faster than the average global warming. This value is compatible with Rantanen et al., 2022, who stated that the definition of the Arctic as the area of latitudes greater than $60^{\circ}N$ yields to a ratio of 3.2 for Arctic Amplification.

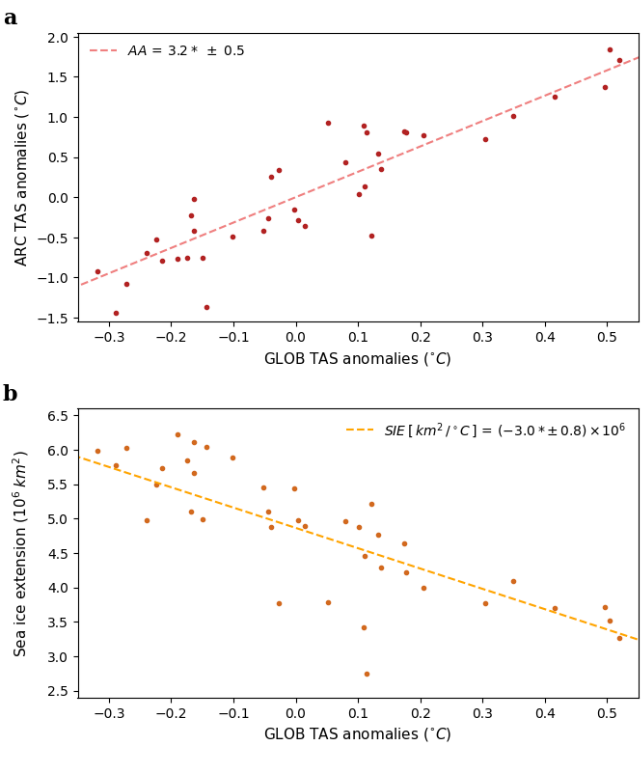

FIG. 5: Arctic annual mean temperature anomalies (a) and Arctic September mean sea ice extent (b) as a function of global annual mean temperature anomalies. Linear fits are shown in dashed lines. Asterisk (*) indicates that trend is statistically significant at 95% using a t-student test.

In addition, Fig. 5b displays the Arctic SIE as a function of the global temperature anomalies for every year within the period of interest. It shows how fast Arctic sea ice has decreased due to the global temperature increase. And the slope of the linear regression leads to a rate of $-3.0 \pm 0.8 \times 10^6\ km^2/^{\circ}C$. Indeed, for every degree of global temperature increase, the sea ice concentration has been reduced by roughly three million square km.

The last part of this study includes future projections with the two different scenarios mentioned in section II A. Fig. 6a illustrates how global temperature will evolve until 2100 in each scenario, according to the data from the model used. The historical data using the same model for the period 1979-2014 are also represented, with the observational data. The same representation has been made in Fig. 6b, but for the Arctic temperature. In both cases, regionally and globally, IPSL-CM6A-LR model exhibits an underestimation of annual temperatures of approximately 2 $^{\circ}C$. It should be remarked that observational data is not inside the error range of the historical simulations computed with the model.

According to ssp126 scenario, the global average temperature will reach 15.0 $^{\circ}C$ by 2050 and 15.1 $^{\circ}C$ by 2100, while the Arctic temperatures in 2050 and 2100 will be -4.0 $^{\circ}C$ and -3.0 $^{\circ}C$, respectively. Conversely, the ssp585 scenario predicts a steeper increase of temperature, 15.8 $^{\circ}C$ in 2050 and 19.6 $^{\circ}C$ in 2100. And, regarding the Arctic temperatures, -2.3 $^{\circ}C$ in 2050 and 5.5 $^{\circ}C$ in 2100.

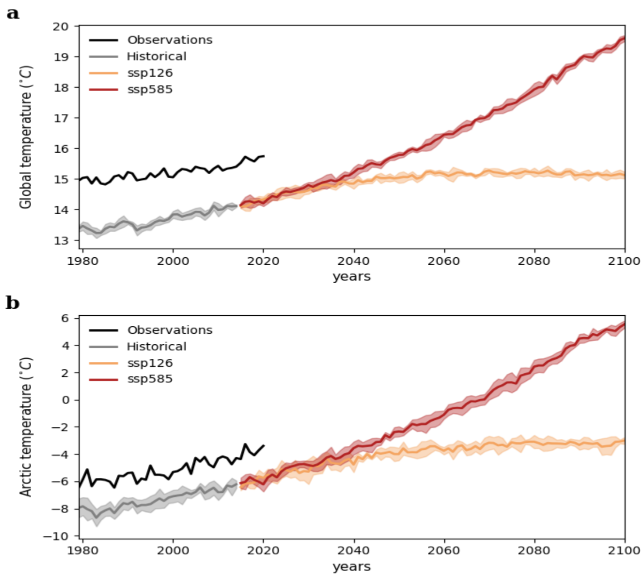

FIG. 6: Global (a) and Arctic (b) temperatures from observational data (black; 1979-2020), and from IPSL-CM6A-LR model historical simulations (grey; 1979-2014) and future projections (ssp126 in organge and ssp585 in red; 2014-2100). The solid lines are the ensemble means of the six members considered, and the shading represents the spread, computed as the standard deviation.

IV. CONCLUSIONS

In this work the Arctic sea ice evolution has been studied, examining its connection with local and global temperature increases over the last few decades. Furthermore, we have simulated global and Arctic temperature future projections using a climate model in the case of two possible scenarios. The highlights are the following:

- The global temperature is increasing at a rate of $0.18 \pm 0.03\ °C/decade$, while the Arctic temperature is rising more than three times faster, at a rate of $0.61 \pm 0.12\ °C/decade$.
- The sea ice extension is decreasing at a rate of $-0.64 \pm 0.13 \times 10^6\ km^2/decade$.
- The confined areas where the temperature is rising more rapidly are the regions that have a greater sea ice loss rate.
- The quantification of Arctic Amplification has yield a ratio of 3.2 degrees of Arctic temperature increase for each global temperature degree increased.
- The model historical simulations are underestimated, since observational data is not within the delimited area of the error shading. Two scenarios have been considered for future projections: ssp126 foresees a temperature of 15.1 $°C$ for the global average and -3.0 $°C$ for the Arctic by 2100, and ssp585 predicts a temperature of 19.6 $°C$ for the global average and 5.5 $°C$ for the Arctic by 2100.

Acknowledgments

A very special thank to my advisor, María Santolaria, for her guidance and support throughout the whole process to achieve this work. I would also like to thank my family and friends for their unconditional support.

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