Atmospheric and Oceanic Science Letters xxx (xxxx) xxx

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Atmospheric and Oceanic Science Letters

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Perspective

Arctic sea-ice extent: No record minimum in 2023 or recent years

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ARTICLE INFO

Keywords:
Sea ice
Arctic
Minimum ice
Climate

ABSTRACT

Arctic sea-ice extent reaches its minimum each year in September. On 11 September 2023 the minimum was 4.969 million square kilometers (mill.km^2). This was not a record low, which occurred in 2012, when the minimum was 4.175 mill.km^2, 0.794 mill.km^2 less than the minimum in 2023. However, the ice extent had decreased by 0.432 mill.km^2 compared with 2022. Nevertheless, the summer melting in 2023 was remarkably less than expected when considering the strong heat waves in the atmosphere and ocean, with record temperatures set around the world. In general, there is a high correlation between the long-term decrease in sea-ice extent and the increasing CO_2 in the atmosphere, where the increase of CO_2 in recent decades explains about 80% of the decrease in sea ice in September, while the remainder is caused by natural variability.

1. Introduction

Since November 1978, the sea ice in the Arctic has been observed on a daily basis with satellite-borne microwave sensors, which have the ability to see through darkness and clouds. Many algorithms from different countries have been produced to retrieve the sea-ice extent (SIE) and sea-ice area (SIA) from these microwave data. For example, Ivanova et al. (2014) compared 11 different algorithms, and differences of up to 1 million square kilometers (mill.km^2) daily were found, but the long-term trends were the same. Several centers are using these daily microwave data and different algorithms to produce sea ice information on their web pages in near real time—for example, the Nansen Center in Bergen, Norway (https://iceobs.nersc.no/), which uses the Norwegian-developed algorithm NORSEX (Svendsen et al., 1983). This algorithm was validated with aircraft radiometric measurements to be ± 3% for the total ice concentration and ± 10% for the multiyear concentration under a no-melting condition. Other ice information systems include the EuroGoos Arctic Roos System (https://arctic.eurogoos.eu/), which shows ice information from six European centers including the Nansen Center and the National Snow and Ice Data Center in the USA (https://nsidc.org/).

The sea ice in the Arctic, which is sensitive to both anthropogenic and natural variability, is one of the most important climate indicators in the Northern Hemisphere, especially the melting of the summer ice, which reaches a minimum in September (Fig. 1). Despite the different daily values for the SIE from the different ice information centers, the trends in September are the same, showing that the SIE has decreased by 8.99%/10 yr, or about 40%, since 1979 (Fig. 1). The SIA, which is less than the extent, has decreased by about 45% (https://iceobs.nersc.no/). Because the multiyear ice is defined as the ice that has survived the summer melt, this implies that about 45% of the multiyear ice is lost with a significant decrease in thickness (Kwok, 2018; Babb et al., 2023).

In this regard, the interannual variability of the September SIE minimum in recent years, with a focus on 2023, will be discussed in this paper, as well as some brief comments on the future of this minimum in the coming years.

2. September minimum of SIE

Despite heat waves in the atmosphere and ocean, the Arctic summer ice in September has stood up quite well and has not reached a new record minimum in recent years. In 2023, the SIE reached its minimum of 4.969 mill.km^2 on 11 September, according to Nansen Center's Ice Information System (https://iceobs.nersc.no/). This is 0.432 mill.km^2 less than the minimum in 2022 of 5.401 mill.km^2, but 0.794 mill.km^2 more than the minimum record in 2012, which was 4.175 mill.km^2. Fig. 1 shows the September monthly mean for each year

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https://doi.org/10.1016/j.aosl.2024.100499

Available online xxx

Please cite this article as: O.M. Johannessen and T.I. Olaussen, Arctic sea-ice extent: No record minimum in 2023 or recent years, Atmospheric and Oceanic Science Letters, https://doi.org/10.1016/j.aosl.2024.100499

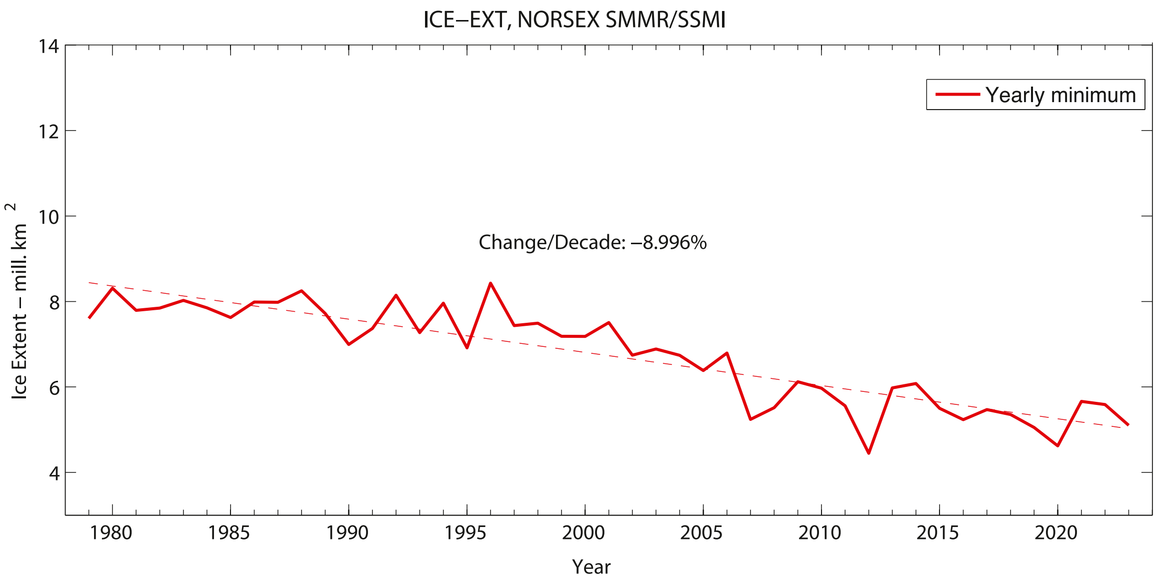

Fig. 1. Minimum SIE in September in the period 1979–2023 in million km^2 (source: https://iceobs.nersc.no/). The solid line indicates the individual values; the dotted line indicates the linear trend.

in the period 1979–2023, where the dotted red line is the trend indicating the anthropogenic impact (IPCC, 2021) and the solid line the actual values. The variability of these values around the trend line indicates the natural variability. The 2012 record minimum stands out clearly from the anthropogenic impact (trend line) and was caused by a strong storm that entered the central Arctic in early August 2012, breaking up the summer ice and resulting in the record low value (Parkinson and Comiso, 2013).

Since this record minimum, the summer minimum has recovered and has varied less around the trend line (Fig. 1), with both positive and negative residual values, indicating less influence from natural variability compared to 2012.

Fig. 2 depicts the sea-ice cover in the Arctic on 15 September 2023, four days after the minimum, where the ice extent had increased to 5.022 mill.km^2. It shows that the Northern Sea Route along the coast of Russia was ice-free, but ship traffic through it by non-Russian ships has ceased due to sanctions. Several of the routes through the Northwest Passage were also free of ice, but the traffic here is strongly regulated by the Canadian Government. Furthermore, there is reduced ice in the Beaufort Gyre north of Alaska and no ice around Svalbard and along the Greenland coast apart from the northern region.

The daily curves for the ice extent from 2007 up to the end of November 2023 (Fig. 3) show the variability of the SIE including the annual minimum in September. The red curve represents 2023, where the minimum in September is between the black curve of 2022, and the purple curve of 2012, the total minimum record. Note the strong increase of the SIE in 2023 after the minimum reaching the same level as in 2021 (orange curve), indicating a colder Arctic in the beginning of the freeze-up period than during previous years.

In general, the decreasing September mean SIE is highly correlated with the increasing CO_2 concentration in the atmosphere, with the R^2 varying between 0.81–0.84 (Johannessen, 2011; Johannessen and Shalina, 2023) and 0.89 (with total CO_2 emissions (Stroeve and Notz, 2018)). In a recent paper, Johannessen and Shalina (2023) showed that about 81% of the September minimum could be explained by the September CO_2 in the atmosphere in the period 1979–2022, and the remainder by natural variability, which, for example, is caused by the North Atlantic/Arctic Oscillation, the Pacific Decadal Oscillation, the Atlantic Multidecadal Oscillation, the Transpolar current and the outflow of ice from the Fram Strait between Svalbard and Greenland—as reviewed by Johannessen et al. (2020)—and the Arctic Dipole and the Atlantification of the Arctic Ocean (Polyakov et al., 2023).

Using the regression equation from Johannessen and Shalina (2023) for the monthly mean in September, SIE $= -16.10 \times \ln(CO_2/CO_{2r}) + 8.40 = 4.70$ mill.km^2, where $CO_2 = 419$ ppm is the mean for September 2023, and 333 ppm for September for the reference year 1979 (https://gml.noaa.gov/), the difference between the predicted monthly CO_2-driven melt of 4.70 mill.km^2 and the larger mean observed melt for September of 5.28 mill.km^2 is 0.58 mill.km^2, indicating that the natural variability accounts for about 11% of the observed mean value in September 2023. However, at present, it is not clear which of the natural processes mentioned above caused this.

3. The future of summer ice

The future of the summer ice is uncertain. The global climate models predict different times for a summer ice-free Arctic Ocean, varying between 2030 and 2100—see a brief review about these different model results by Johannessen and Shalina (2023). Therefore, they need to be improved. In addition, they are forced with different CO_2 scenarios, the Shared Socioeconomic Pathways (SSPs) (Gidden et al., 2019). It is also uncertain which of these scenarios will be correct in the future.

In contrast to the scattered results from the global model predictions for the SIE up to 2100, Johannessen and Shalina (2023) hypothesized that the summer ice in the Arctic will not disappear, i.e., no tipping point, if a major reduction in the CO_2 concentration in the atmosphere can be reached. They based their hypothesis on a simple statistical analysis for the period 1979–2022, where for September they correlated the ice extent with the CO_2 in the atmosphere—actually, the $\ln(CO_2/CO_{2r=\text{reference 1979}})$, since this is the empirical law for long-wave radiation back to space from the surface of the Earth (Myhr et al., 1998). Of course, this is a statistical relationship based on past data

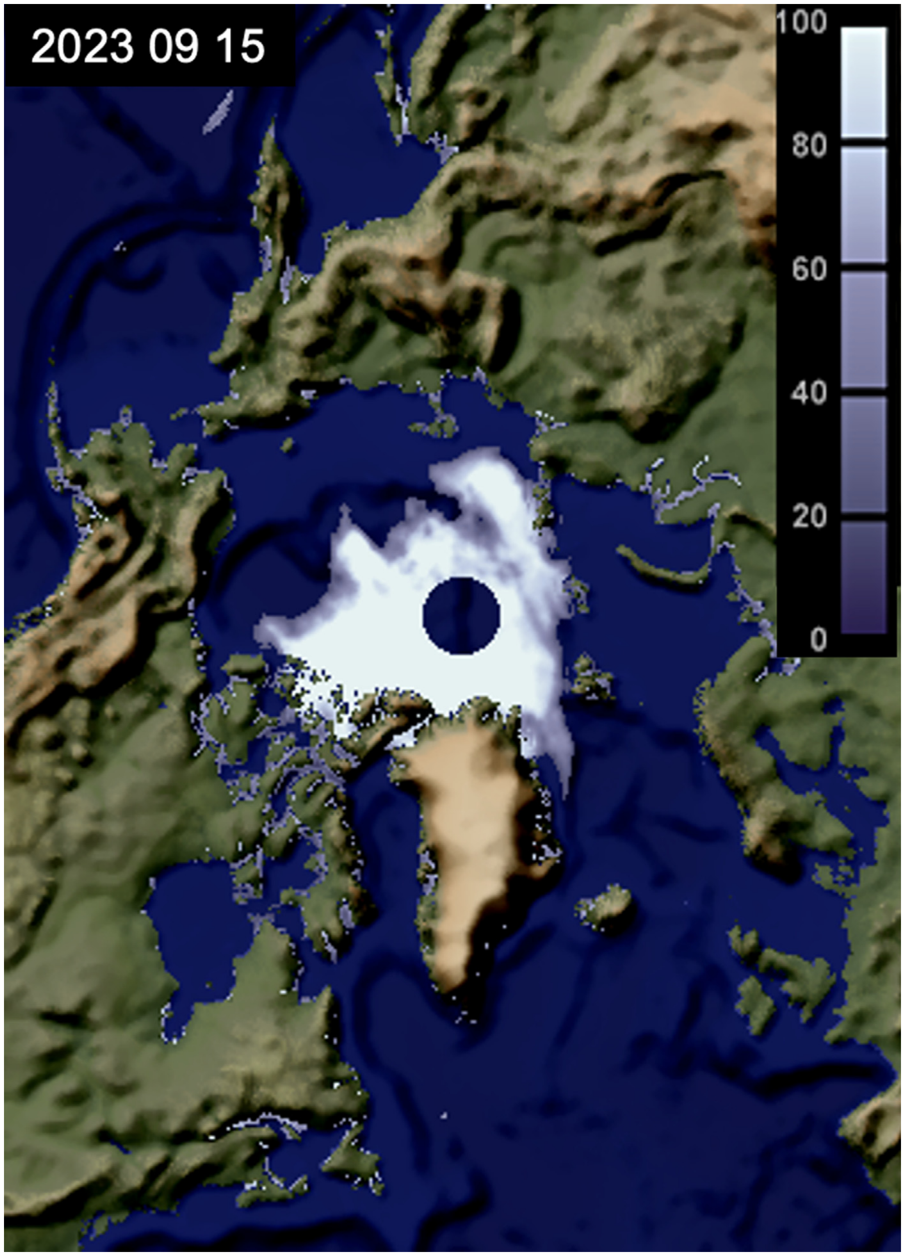

Fig. 2. Arctic sea-ice concentration on 15 September 2023, four days after the minimum on 11 September. The concentration (%) is marked on the right. Source: https://iceobs.nersc.no/.

from 1979 to 2022; therefore, it is conservative and hopefully represents a worst-case scenario for the future. As mentioned above, the increase in CO_2 in the atmosphere could explain about 80% (R^2) of the decline in the SIE in September, with the remainder explained by natural variability as mentioned above. Solving the regression equation gave an ice-free Arctic Ocean if the CO_2 concentration reached 563 ± 17.5 parts per million (ppm). This is far above the Paris Agreement, which is 450 ppm in 2060 and 425 ppm in 2100 (IPCC, 2021, Table SPM.1).

The CO_2 concentration in the atmosphere in September 2023 was 419 ppm and the yearly global average increase since 2010 has been 2.4 ppm per year (https://gml.noaa.gov/). If this yearly increase continues, the Paris Agreement will already be reached in about 16 years, at around 2040, 20 years before 450 ppm in 2060. This demonstrates how urgent it is to drastically reduce the CO_2 concentration in the atmosphere.

As mentioned, the calculations by Johannessen and Shalina (2023) show that the Arctic will be ice-free if the CO_2 concentration in the atmosphere reaches 563 ppm, which is a conservative estimate. If the yearly increase continues as of today, 2.4 ppm yr^{-1}, the Arctic will be ice-free in September 60 years from now, i.e., around 2080—again, a worst-case situation. This is one of the many examples that a major reduction in CO_2 concentrations in the atmosphere is urgently required in parallel with strong implementation of renewable energy and very importantly a major reduction in the per capita consumption, at least in the industrialized world.

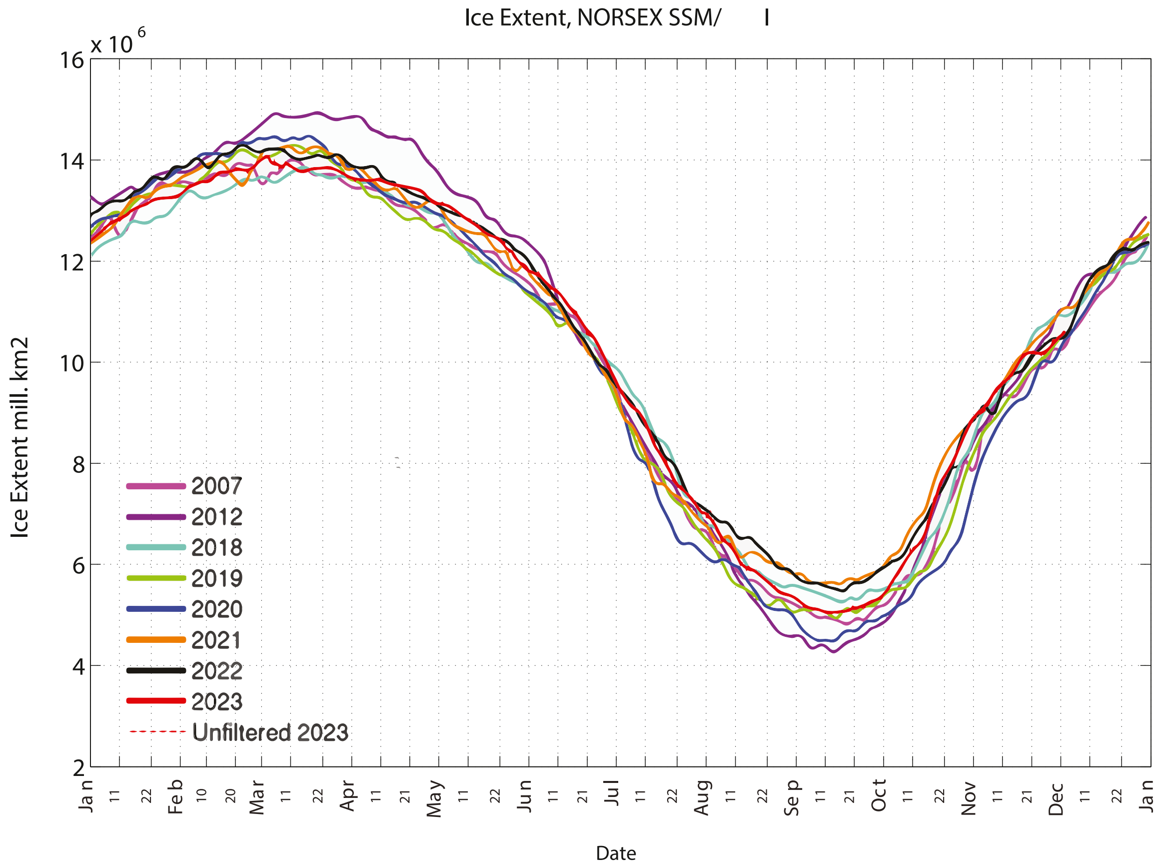

Fig. 3. Variability of daily Arctic SIE from 2007 to the end of November 2023, in mill.km^2. The color coding for the different years is in the lower left. Source: https://iceobs.nersc.no/.

4. Conclusion

The minimum summer ice extent for 2023 was reached on 11 September, but was not a record minimum, which occurred in 2012. The summer ice stood up remarkably well despite heat waves in the atmosphere and the ocean in different parts of the world, but not in the Arctic. The SIE followed more the decline caused by the yearly increase of CO_2 in the atmosphere, which could explain most of the decline, while only 11 % was caused by natural variability in September 2023, but of course this can change from year to year. After the minimum on 11 September, the SIE increased very rapidly compared with previous years, indicating a colder Arctic in the beginning of the freeze-up period than in previous years.

The future of the sea ice is uncertain, with some global models predicting that the Arctic will already be ice-free in September from 2030, while other models indicate later this century, suggesting that models should be improved. A simple statistical correlation between the SIE decline and the increasing CO_2 in the atmosphere suggests that the Arctic Ocean could be ice-free in September if the CO_2 in the atmosphere reaches about 560 ppm, which is much higher than the Paris Agreement of 450 ppm in 2060 and 425 ppm in 2100. Therefore, if this agreement can be reached or a major reduction in CO_2 in the atmosphere can be reached, no tipping point for the sea ice in the Arctic Ocean will occur.

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