Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL104657

Key Points:

- Cyclones can significantly impact the sea ice in the Atlantic Arctic in all months of the year, but with strong spatiotemporal variations
- Impacts are stronger in the cold season than in summer due to variations in cyclone intensity and traversed sea ice conditions
- Significant changes emerged throughout the year, recently strongest in the Barents Sea in autumn due to a reduced mean ice concentration

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Aue, L., & Rinke, A. (2023). Cyclone impacts on sea ice concentration in the Atlantic Arctic ocean: Annual cycle and recent changes. *Geophysical Research Letters*, *50*, e2023GL104657. https://doi.org/10.1029/2023GL104657

Received 22 MAY 2023
Accepted 25 AUG 2023

Cyclone Impacts on Sea Ice Concentration in the Atlantic Arctic Ocean: Annual Cycle and Recent Changes

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Abstract We quantify sea ice concentration (SIC) changes related to synoptic cyclones separately for each month of the year in the Greenland, Barents and Kara Seas for 1979–2018. We find that these SIC changes can be statistically significant throughout the year. However, their strength varies from region to region and month to month, and their sign strongly depends on the considered time scale (before/during vs. after cyclone passages). Our results show that the annual cycle of cyclone impacts on SIC is related to varying cyclone intensity and traversed sea ice conditions. We further show that significant changes in these cyclone impacts have manifested in the last 40 years, with the strongest changes occurring in October and November. For these months, SIC decreases before/during cyclones have more than doubled in magnitude in the Barents and Kara Seas, while SIC increases following cyclones have weakened (intensified) in the Barents Sea (Kara Sea).

Plain Language Summary We study how the sea ice cover in the Arctic Ocean changes due to the passage of low-pressure systems (cyclones). Our study covers all years between 1979 and 2018 and each individual month of the year. Our results show that the passage of cyclones can affect the sea ice year around, but the strength and the sign (less or more sea ice concentration due to cyclones) of this impact varies strongly. These variations in cyclone impacts throughout the year are related to variations in the strength of the cyclones and changes in the state of the sea ice cover (e.g., thinner vs. thicker ice). We further show that the cyclone impact on the Arctic sea ice has changed during the last 40 years. These changes are strongest in autumn, particularly in October and November. In these months, the strength of the destructive cyclone impacts on sea ice has more than doubled in some regions of the Arctic compared to previous times. In some regions, however, also the strength of ice preserving cyclone impacts (more sea ice due to cyclones) has intensified recently.

1. Introduction

Over the last decades, surface temperatures in the Arctic have been rising rapidly, associated with pronounced environmental changes such as a strong sea ice decline (IPCC, 2021). These changes potentially have implications for various climate interaction processes; one of these is the strong coupling between synoptic scale cyclones and sea ice (Crawford et al., 2022; Valkonen et al., 2021).

It has been shown that synoptic cyclones can exert significant impacts on the Arctic sea ice (recently, Aue et al., 2022; Clancy et al., 2022; Finocchio et al., 2022; Schreiber & Serreze, 2020), including both dynamically caused sea ice changes via enhanced ice drift and deformation as well as thermodynamic sea ice changes associated with the advection of warm-moist/cold-dry air (Aue et al., 2023; Clancy et al., 2022). Additionally, there is evidence on enhanced basal melting of sea ice due to up-mixing of relatively warm ocean water following some (extreme) summer cyclones (Stern et al., 2020; Tian et al., 2022; J. Zhang et al., 2013). It is, however, still an open research question how the interplay of these mechanisms and thus the resulting cyclone impact on sea ice concentration (SIC) might change under the changing conditions in the Arctic.

For example, the Arctic sea ice is getting thinner (Kwok, 2018; Meier & Stroeve, 2022) and more mobile (Spreen et al., 2011). This facilitates for example the occurrence of break-up events under strong wind conditions (Rheinlænder et al., 2022) and could lead to a future intensification of cyclone impacts on sea ice. The Arctic sea ice retreat and related changes in ocean-atmosphere heat fluxes in winter can potentially also impact the atmosphere by favoring local cyclonic circulation conditions (Heukamp et al., 2023) and intensified winter storms (Crawford et al., 2022), creating possible feedback loops involving cyclones and sea ice.

A better understanding of how cyclone impacts on sea ice are affected by these "new Arctic" conditions can help to improve short-term sea ice forecasts during cyclone events. Such forecasts are important for Arctic navigation, particularly during hazardous weather conditions (Inoue, 2021), and will presumably gain further importance in future due to increasing shipping activities in the Arctic (Cao et al., 2022). Additionally, this understanding can feed into an improved representation of cyclone-sea ice interactions in climate models (Valkonen et al., 2023) and potentially contribute to more accurate predictions on the future Arctic sea ice cover, since cyclones drive a substantial part of regional SIC variability (e.g., Schreiber & Serreze, 2020).

Recent studies provided first insights into ongoing changes in cyclone impacts on sea ice. Aue et al. (2022) found an intensification of SIC changes during and following cyclone passages in the Barents Sea in winter, while Schreiber and Serreze (2020) found that anomalous SIC increases following cyclones in summer and autumn have generally weakened in the Arctic. Considering a monthly time scale in summer, Finocchio et al. (2022) revealed that cyclone impacts on sea ice are different for June (slow down of seasonal sea ice loss) and August (acceleration of seasonal sea ice loss), and that particularly the cyclone-related sea ice decreasing effects in August have intensified recently. Their results highlight the importance to study the cyclone impacts on sea ice on monthly instead of only seasonally averaged time scales. However, no study has investigated this throughout the whole year on a monthly basis yet. Thus, a comprehensive view on the complete annual cycle of cyclone impacts on sea ice combined with an analysis of trends over the last four decades during the ongoing warming of the Arctic is missing.

Given the rapidly changing Arctic environment, addressing this knowledge gap to improve understanding on (changing) cyclone impacts on sea ice is urgent. Thus, we present the first quantification of (a) the impacts of synoptic cyclones on Arctic SIC separately for each month of the year and (b) their changes during the period from 1979 to 2018. We further relate both the annual cycle and recent changes of cyclone impacts to varying relevant background conditions, namely mean sea ice thickness (SIT), SIC, air temperature, as well as cyclone intensity. We focus on the Atlantic Arctic ocean (covering the Greenland, Barents, and Kara Seas, hereafter GBKS; Figure 1), as this is the Arctic hot spot region with largest warming and sea ice reduction in recent decades (Isaksen et al., 2022; Rieke et al., 2023).

2. Data and Methods

Following Aue et al. (2022), cyclone impacts on SIC are calculated as follows: (a) The Akperov et al. (2020) cyclone tracking algorithm is applied to the ERA5 reanalysis at 0.25° horizontal resolution to obtain 6-hourly cyclone positions and characteristics, (b) cyclone and non-cyclone-days are separated at each grid-cell depending on whether it was or was not situated within the outermost closed isobar of a cyclone (for a least one, 6-hourly timestep), (c) at each grid-cell, the SIC change is calculated over a few days associated with each cyclone occurrence (before/during cyclone: day −3 to day 0; following cyclone: day 0 to day 5; overall effect: day −3 to day 5), (d) this result is averaged for all cyclone occurrences and compared to the non-cyclone-days SIC change reference. We utilize daily SIC data from ERA5 (based on HadISST2 and OSI SAF satellite data; Hersbach et al., 2020), which have been shown to be suitable for the purpose of our study (Aue et al., 2022) as the SIC response to cyclones agrees with the one derived from passive microwave data (Schreiber & Serreze, 2020). To assess the background state, we further analyze 2 m air temperature (based on ERA5) as well as SIT. The latter is taken from Ocean ReAnalysis System 5 (ORAS5) ensemble means (available until 2018; Zuo et al., 2019), which have been shown to be suitable to assess the general background state and long-term changes in the Atlantic Arctic ocean (e.g., Shu et al., 2021; Tietsche et al., 2018) and provide complete coverage both in space and time (in contrast to satellite-derived SIT).

We analyze cyclone impacts on SIC for all individual months for 1979–2018, and quantify their recent changes with two approaches: First, we calculate 11-year running means of domain averaged cyclone impacts on SIC within the analysis period. Statistical significance is reported on 95% confidence level utilizing the students *t*-test; 11-year periods with a mean sea ice extent in the domain below 50% of its value for 1979–1999 are excluded to ensure a certain consistency of the averaged ice-covered area and an adequate sample size. In addition, trends of these means are assessed based on Theil-Sen's Slope Estimator and a Mann-Kendall test for statistical significance (on 95% confidence level) utilizing the “pymannkendall” python package (Hussain & Mahmud, 2019). Second, we divide the analysis period into two parts, which are in the following referred to as “old Arctic” (1979–1999) and “new Arctic” (2000–2018), and conduct a composite analysis for both.

3. Changes in Cyclones and Traversed Sea Ice

Before analyzing cyclone impacts on SIC in the study domain of the GBKS, we provide context on the background conditions that control them. Specifically, we analyze the seasonally averaged cyclone occurrence frequency and

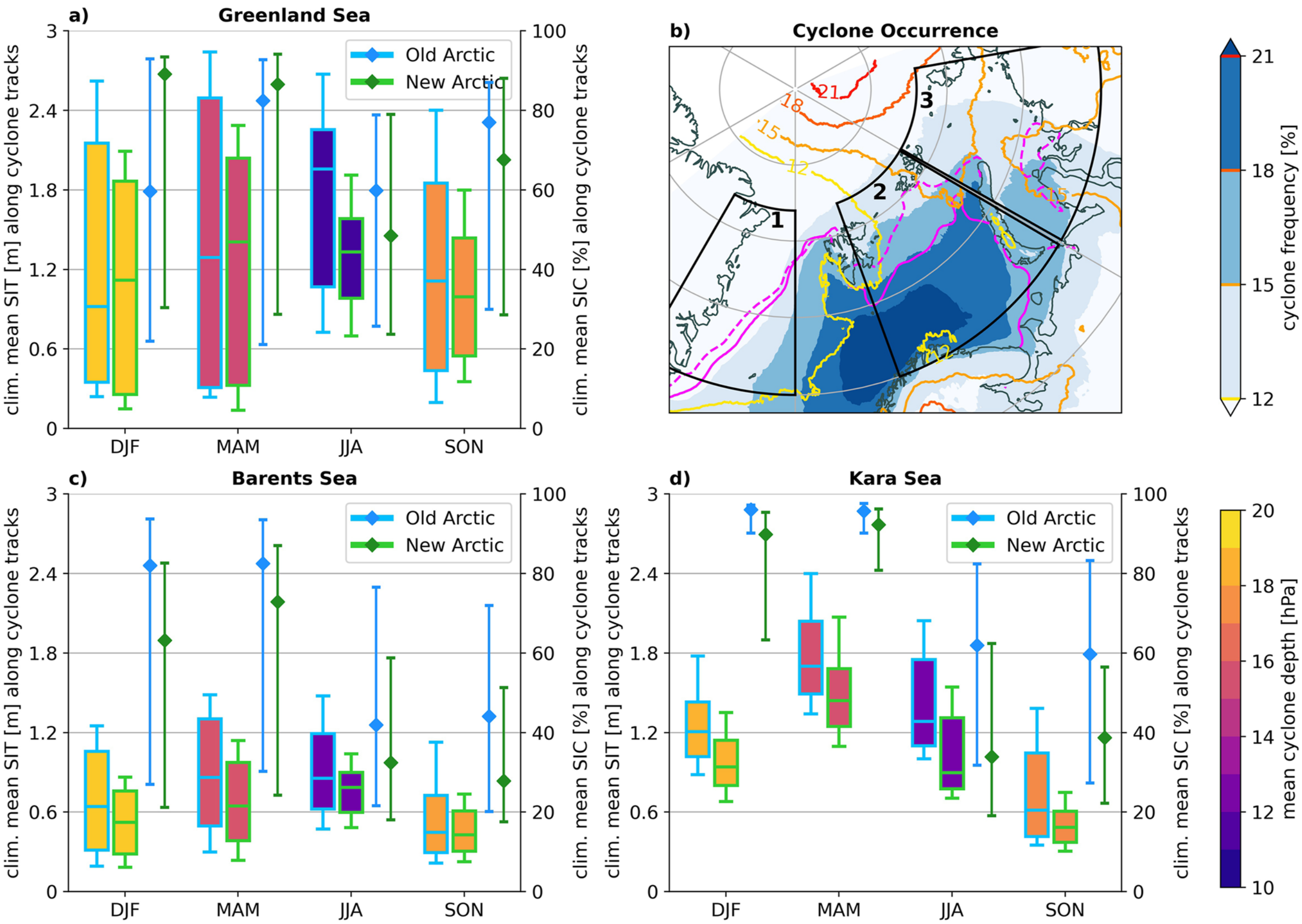

Figure 1. Box-Whisker-Plots of mean sea ice thickness (with boxes) and sea ice concentration (no boxes) along cyclone tracks for the Greenland Sea (a, domain 1), Barents Sea (c, domain 2) and Kara Sea (d, domain 3) for 1979–1999 (blue) and 2000–2018 (green). Extend of boxes (whiskers) indicates 25th/75th (10th/90th) percentile, line/marker indicates median. Color of boxes indicates mean cyclone depth. Subfigure (b) shows the cyclone frequency for winter (DJF, blue colors) and summer (JJA, colored contour lines) and the mean position of the 15% SIC-contour for winter (summer) as solid (dashed) magenta line, as well as domains for the box-plots.

cyclone depth as well as the mean SIC and SIT conditions along the cyclone tracks for the old and new Arctic (Figure 1).

Generally, maxima in cyclone occurrence frequency (Figure 1b) are found in the Norwegian/southern Barents Sea (in the central Arctic) in winter (summer) related to the prevailing North Atlantic storm track (frontal zone), which is a well known feature (pioneered by Serreze, 1995). We further demonstrate that the pronounced annual cycle of mean cyclone depth (i.e., intensity) being twice as high in winter (ca. 20 hPa) as in summer (ca. 10 hPa) is the same in all three regions (Figures 1a,1c, and 1d). Additionally, the sea ice conditions over which the cyclones pass show distinct regional and seasonal characteristics.

Cyclones move over the thinnest ice in the Barents Sea, compared to the other two regions (Figures 1a,1c, and 1d). That makes the Barents Sea potentially more susceptible to the cyclones' forcing than the other regions. The median SIT along cyclone tracks in the Kara and Greenland Seas is generally higher in all seasons, compared to the Barents Sea. But, in the Greenland Sea, the SIT distribution ranges widely, particularly in winter and spring, which is in accordance with the observed broad (and bimodal) SIT distribution of sea ice that is exported through the Fram Strait (e.g., Sumata et al., 2023). High (low) SIC values underneath cyclones are found in winter-spring (summer-autumn) in the Barents and Kara Seas, while in the Greenland Sea, the seasonal cycles of both SIC and SIT are less pronounced and comparatively low SIC values are mainly found in summer. In the Kara Sea, the 10th percentile of SIC underneath cyclones is approx. 90% in winter and spring in the old Arctic, indicating a closed ice cover for almost all cyclone passages.

Importantly, our results do not show significant changes in mean cyclone depth (Figure 1) between the old and new Arctic neither for any season nor any region. However, we show that the sea ice conditions along cyclone tracks have changed throughout the year. In the new Arctic, cyclones pass over sea ice of much lower thickness and concentration, compared to the old Arctic (except for the Greenland Sea in winter-spring, see below; Figures 1a, 1c, and 1d). In the Barents Sea, the largest SIC (SIT) reduction along the cyclone tracks occurs in autumn-winter (spring), while in the Kara Sea, this is shifted to summer-autumn (summer), respectively. Our analysis shows evidence that changes in sea ice conditions (rather than in cyclone characteristics) can be expected to be mostly responsible for a changed cyclone impact—a hypothesis which was raised earlier by Aue et al. (2022) and will be discussed further in the next sections.

In the Greenland Sea, a striking result is that both the cyclone track related median SIT and SIC for winter and spring are higher in the new Arctic than in the old Arctic (Figure 1a), which is in contrast to all other domains and seasons. For the SIC, also the 10th and 90th percentile are increased, indicating a shift of the whole SIC distribution toward higher SIC, while for SIT, the shift is de facto limited to the median value.

4. Cyclone Impacts on SIC

Figure 2 shows the changes of cyclone impacts on SIC (based on 11-year running means; see Section 2) as regional averages for the Greenland, Barents and Kara Seas, separately for each month and for different daily time scales (days before/during and following cyclone passages as well as both time scales combined). Our results are insensitive to the length of the running mean and can also be found for a shorter window length (Figure S1 in Supporting Information S1). Further, our results clearly demonstrate that the separation of cyclone-related SIC decreases and increases by the time scale, that is, the time considering before/during and after cyclone passages (Aue et al., 2022), is valid throughout the complete annual cycle (Figure 2). In the following Section 4.1 we assess the annual cycle of cyclone impacts under old Arctic conditions, while recent changes toward the new Arctic are discussed afterward in Section 4.2.

4.1. Annual Cycle in the Old Arctic

At the beginning of the year (January to May), a significant decrease in SIC of up to 4% is found before/during cyclones in the Greenland and Barents Seas (Figures 2a and 2d). The magnitude of this SIC decrease before/during cyclones is decreasing toward summer, and in July-August, no significant impact is found anymore. This demonstrates that cyclone-related summer SIC changes are much less relevant in the GBKS than in the Laptev and East Siberian Seas and in the Amerasian Arctic Ocean (Finocchio et al., 2022; Schreiber & Serreze, 2020). These findings are consistent with the generally decreased cyclone depth in summer compared to winter and the higher median SIT underneath cyclones in the Greenland Sea in summer (Figure 1; see Section 3), which can hamper the cyclones' ability to impact the ice. The SIC impacts following cyclones show a similar seasonal behavior as those during cyclones with insignificant impacts in summer (Figures 2b and 2e). The SIC increase following cyclones in winter-spring is regionally different, strong in the Barents Sea, but absent or weak in the Greenland Sea (significantly only in March, May, and occasionally in January).

The annual cycle of cyclone impacts on SIC in the Kara Sea exhibits some differences to the other two regions (Figures 2g–2i). In winter and spring, SIC decreases before/during cyclones are much weaker and are only significant in April-May. This is in accordance with the extraordinarily high SIC in the Kara Sea in winter-spring and the high SIT in spring (Figure 1). Significant SIC increases following cyclones are found for all months (except August), but are not as strong as in the Barents Sea (Figure 2e vs. Figure 2h).

Cyclone impacts on SIC are generally more intense in autumn than in the preceding summer months in all three regions. In the Barents Sea, cyclone impacts both before/during and following cyclones are strong throughout September-November (Figures 2d and 2e), while in the Kara Sea, particularly the October stands out (Figures 2g and 2h). These findings are consistent with results from Section 3, SIC and particularly SIT along cyclone tracks are lowest in autumn (Figure 1), so that cyclones can act effectively on the ice cover. At the same time, the mean cyclone depth returns to higher intensity in this season.

4.2. Changes in the New Arctic

Figure 2 further highlights that cyclone impacts on SIC have been subject to significant changes over the past 40 years (slope of linear trends can be found in Figure S2 in Supporting Information S1). Those are regionally

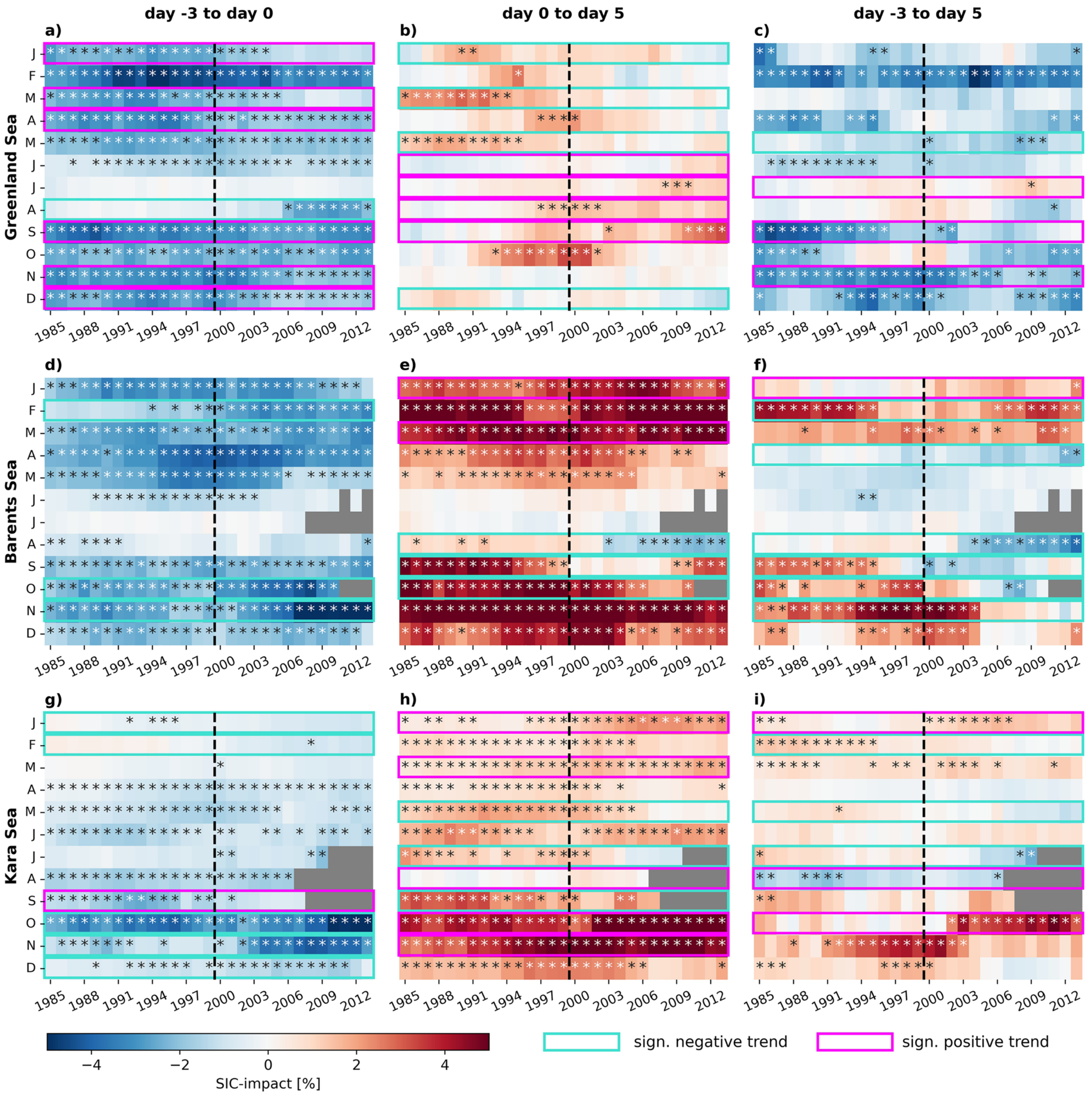

Figure 2. 11-year running means of anomalous sea ice concentration (SIC) changes associated with cyclone passages (SIC-impact in %) in the Greenland (a–c), Barents (d–f) and Kara Seas (g–i) for each month. Stars indicate statistical significance, magenta (turquoise) boxes indicate significant positive (negative) trends of these changes. Black dashed line separates old and new Arctic time period. Gray colored time steps are excluded due to a too low sea ice extent in the region. All statistical significance is at the 95% level.

different, depend on the considered time scale (before/during and after the cyclone passage), and show intra-seasonal (month to month) differences.

Between January and April, cyclone impacts on SIC exhibit opposing trends in the Greenland Sea and the Barents-Kara Seas. In the Greenland Sea, decreases in SIC before/during cyclones have weakened (significantly in January, March, April; Figure 2a), while they have intensified in the Barents and Kara Seas (significantly in January, February; Figures 2d and 2g). Similarly, also the SIC increasing effects following cyclones have intensified in the Barents and Kara Seas (significantly in January, March; Figures 2e and 2h), while they have weakened (for the same months) in the Greenland Sea (Figure 2b). These findings agree with results from Section 3: In the Greenland Sea, the traversed mean SIT and particularly SIC have increased in the new Arctic in winter and spring, presumably making the ice cover more resistant against the cyclones' forcing. In contrast, SIC and SIT have decreased in the Barents and Kara Seas in the new Arctic, thus favoring the sea ice impact of cyclones.

In summer, the changes in August point to interesting regional differences. In the Barents Sea, SIC changes following cyclones shift from slightly positive (SIC increase after cyclone passage) to significantly negative (SIC decrease) (Figure 2e). This results in significant negative cyclone impacts on SIC on the overall time scale starting around the year 2000. Differently, the Greenland Sea experiences a positive trend in SIC increase following cyclones, which offsets a strengthening of the decrease in SIC before/during cyclones (emerges around 2005). Accordingly, no significant trend is found in the overall cyclone impact on SIC (Figure 2c).

In autumn, strong changes in the cyclone impacts on SIC occur in the whole study domain of the GBKS, but they differ among the regions and months. In the Greenland Sea, the SIC decrease before/during cyclones is consistently weakened (significantly in September, November; Figure 2a), which determines the overall weakened cyclone-related SIC decrease (Figure 2c). In contrast, the Barents Sea experiences an intensification of the SIC decreasing effects before/during cyclones (significantly in October, November), but the SIC increase following cyclones is weakened (significantly in September, October) (Figures 2d and 2e). Consequently, the overall cyclone impact on SIC shifts from increasing SIC in the old Arctic to neutral/slightly decreasing SIC in the new Arctic (significantly between September and November; Figure 2f). In the Kara Sea, the trends in the cyclone impact on SIC are not uniform among the autumn months. While in September both the SIC decrease before/during and the SIC increase following cyclones have weakened, they have both intensified in October and November (Figures 2g and 2h). Still, the overall change in the impact of cyclones is different for October and November (Figure 2i). In October, the intensified SIC increase following cyclones outweighs the intensified SIC decreases before/during cyclones, resulting in a significant overall cyclone-related SIC increase. Again, a step change appears around the year 2000. In November, both effects are of similar strength (Figure S2 in Supporting Information S1), but the intensification of the SIC increase after cyclones emerges earlier in time than the occurrence of the significant SIC decrease before/during cyclones. Thus, a significant overall increase in SIC due to cyclones started to appear around the year 1990, but then disappeared around the year 2000 due to the cancellation of both intensification effects.

As indicated above, autumn is a season of interesting contrasting regional differences in the recent changes of cyclone impacts on SIC. Therefore, we have selected the 2 months of October and November for a composite analysis to elucidate in the following Section 4.3 the regional changes between the old and new Arctic in more detail. Reasons for the month selection include the following features: The strongest trend (ca. −1% per decade) before/during cyclone passages is found in November in the Barents and Kara Seas. For the days following cyclones, the strongest trend (+1.83% per decade) occurs in October in the Kara Sea. The overall cyclone impact shows in October a regional difference between the Barents and Kara Seas (negative trend in the Barents Sea vs. positive trend in the Kara Sea).

4.3. Regional Changes in Autumn

Cyclone impacts on SIC in October and November consist of a decrease (increase) in SIC before/during (after) the cyclone passage in the entire GBKS (Figures 3a and 3b), which is consistent with our previous region-averaged analysis (Figure 2). Considering the overall impact from day −3 to day 5 (Figure 3c), a significant decrease in SIC is found along the Greenland Sea ice edge and around Svalbard, while a significant increase is found at the ice edge in the central Barents and southern Kara Seas as well as in the northern Kara Sea.

Strong changes between the old and new Arctic in October (Figures 3d–3f) are found for the 5 days following cyclone passages (Figure 3e), which is consistent with the strong trends on this time scale (Figure S2 in Supporting Information S1). Here, SIC increasing impacts of cyclones have weakened in a broad region extending from Svalbard into the Kara Sea north and east of Novaya Zemlya, but newly emerge in the northern Kara Sea, west of Severnaya Zemlya, where cyclones previously did not have an impact on SIC. These differences determine the overall impact of cyclones on sea ice (Figure 3f). Contrary, the changes in overall cyclone impacts in November (Figure 3i) are dominated by a strong intensification of SIC decreases before/during cyclones (Figure 3g), which extend across almost the complete ice-covered parts of the Barents and Kara Seas. After cyclone passages, SIC

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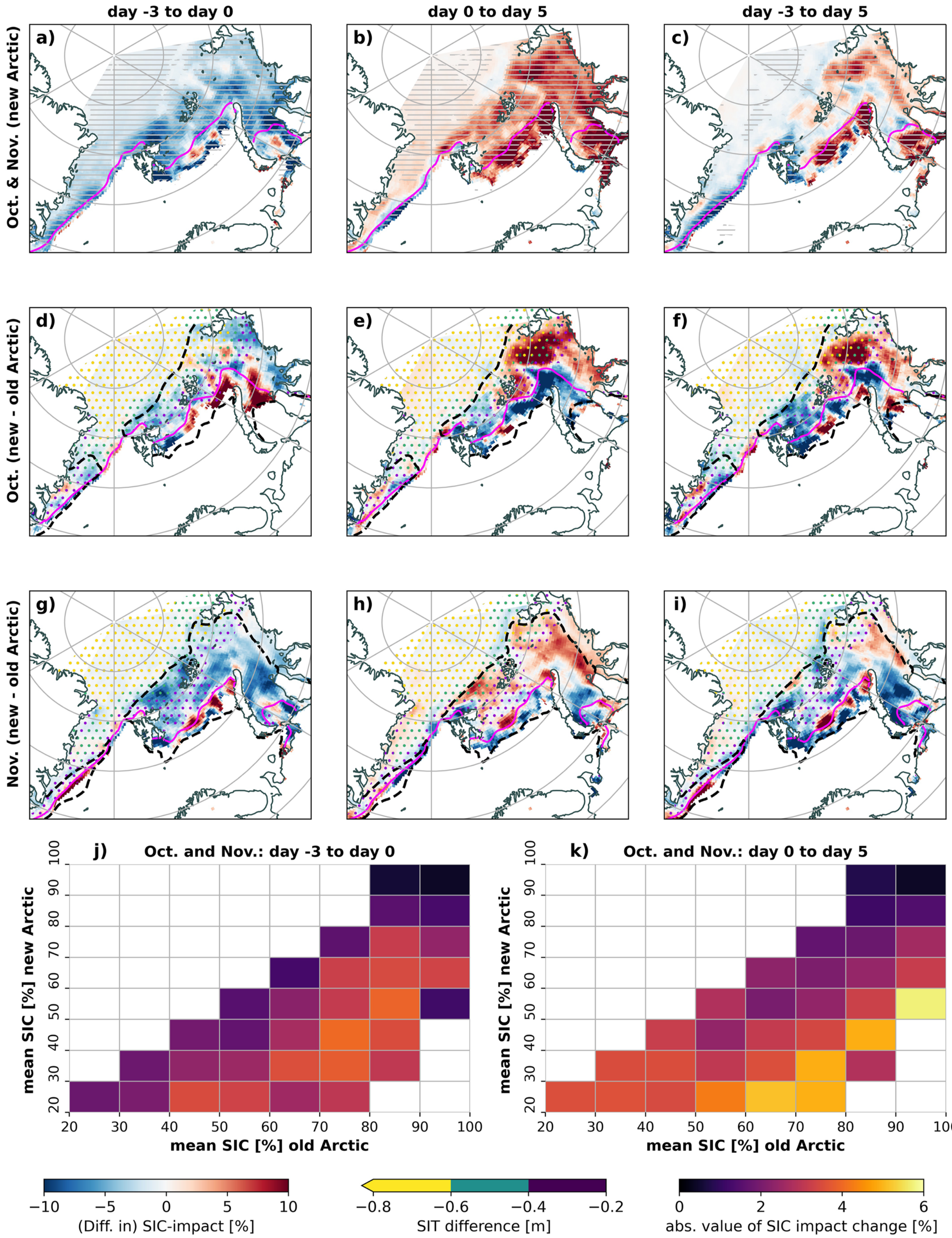

Figure 3. Subplots (a–c) show cyclone impacts on sea ice concentration (SIC) for different daily time scales averaged for October and November 2000–2018. Hatches indicate statistical significance on 95%-level. Subplots (d–i) show difference (2000–2018 minus 1979–1999) in cyclone impacts on SIC (blue-red colors) and sea ice thickness (colored dots) for October (d–f) and November (g–i). Black dashed line indicates grid-cells with at least 10% SIC decline. Solid magenta line in (a–i) shows 15% SIC contour for 2000–2018. Subplots (j–k) show absolute values of changes in cyclone impacts on SIC (2000–2018 minus 1979–1999) for different SIC bins.

increases become more intense in the northeastern Kara Sea and west of Franz-Josef-Land and less intense close to the ice edge (Figure 3h).

The vast majority of these changed cyclone impacts between the new and old Arctic occurs in regions with a decline in mean SIC between both time periods (Figures 3d–3i). In contrast, regions with simultaneous intensified cyclone impacts and comparatively strong SIT decline, as for example, found in October and west of Severnaya Zemlya, are more limited. To follow-up on this, we group changes in cyclone impacts between the old and new Arctic across all grid-cells in the study domain (and for October and November combined) by the respective mean SIC and SIT in both periods (Figures 3j, and 3k, Figure S3 in Supporting Information S1).

Our results clearly demonstrate that the absolute values of changes in the SIC decreases before/during cyclones (Figure 3j) are higher, wherever SIC is declined in the new Arctic. This relationship is not equally clear for SIT (Figure S3 in Supporting Information S1), confirming that particularly the decline in mean SIC (which results in a more mobile ice cover; e.g., Spreen et al., 2011) is the primary driver of amplified destructive cyclone impacts on SIC. This finding is in accordance with the linear (exponential) relation between ice strength and SIT (SIC) (ice strength parameterization of Hibler, 1979).

For the days following cyclones, the relation between decreased mean SIC and intensified SIC changes is even stronger than before/during cyclones, but only for grid-cells with medium-high SIC (above 50%) in the old Arctic (Figure 3k). Presumably, the decline in mean SIC enhances the potential for sea ice growth, when the ocean is exposed to cold air temperatures after the cyclone passage (e.g., Aue et al., 2023). However, for grid-cells that already had a rather low SIC (below 50%) in the old Arctic, the change of cyclone impacts does not really depend on mean SIC changes anymore. This indicates that the weakening of previously existing SIC increases following cyclones in the old Arctic, which occurs at grid-cells close to the ice edge (see e.g., blue colors in Figure 3e), seems to be driven differently, namely by thermodynamic processes.

To substantiate this, we compare the mean 2 m air temperature between old and new Arctic for October and November (Figure S4 in Supporting Information S1). This reveals that the mean position of the −1.8°C isotherm (freezing point of sea water) is significantly displaced northwards in the new Arctic in the Barents (and southern Kara) Sea, particularly in October. This suggests that, close to the ice edge, a rise in mean air temperature hampers a thermodynamic recovery of the ice cover after it has been damaged by strong winds during a cyclone passage. This mechanism could thus explain the weakened SIC increase following cyclones and the less pronounced relation between SIC changes (following cyclones) and the mean SIC in grid-cells close to the ice edge.

5. Conclusions

Our analysis of cyclone impacts on SIC in the Greenland, Barents and Kara Seas revealed statistically significant impacts for all months of the year. Those (a) are subject to strong variability in space (region to region) and time (before/during vs. after cyclone passages, month to month), and (b) exhibit a distinct seasonal cycle (stronger impacts in the cold season, but weaker in summer) associated with variations in cyclone intensity and sea ice conditions (SIC and SIT) underneath the cyclone tracks. We further reveal year-round, statistically significant changes in cyclone impacts on SIC during the last four decades, which are magnitude-wise strongest in autumn. The pronounced spatiotemporal variability is striking and should be considered in future research on trends in cyclone impacts on sea ice, for example, focusing on different regions or exploiting model projections. For the Barents and Kara Seas in October and November, we relate an intensification of SIC decreases during cyclone passages to a preceding decrease in mean SIC. Notably, however, the thermodynamic SIC increasing effects following cyclones intensify only in sufficiently cold regions, resulting in opposing trends of overall cyclone impacts on SIC in the Barents Sea (negative trend) and the Kara Sea (positive trend) in October.

Our finding that changes in ice conditions (rather than cyclone intensity changes) are responsible for intensified cyclone impacts is consistent with studies, which attribute an observed acceleration of ice drift speed mainly to ice thinning (rather than to wind speed increase) (Spreen et al., 2011; F. Zhang et al., 2022). An ongoing shift in cyclone impacts on SIC in the Barents Sea from overall SIC-increasing toward overall SIC-decreasing in summer/autumn emphasizes that cyclone-sea ice feedbacks are important for future changes of the Arctic sea ice and that it is crucial to capture them correctly in model simulations. To assess cyclone impacts on smaller scale sea ice deformation characteristics such as leads, which cannot be covered by ERA5, future research exploiting sea ice data at high horizontal resolution would be beneficial.

Data Availability Statement

We used reanalysis data from the fifth generation ECMWF reanalysis for the global climate and weather (ERA5). ERA5 data is available through the Copernicus Climate Change Service Climate Data Store (Hersbach et al., 2023) via: https://doi.org/10.24381/cds.adbb2d47. We further used ocean reanalysis data from the Ocean ReAnalysis System 5 (ORAS5) from the ECMWF. ORAS5 data is available through the Integrated Climate Data Center—ICDC at University of Hamburg (Zuo et al., 2019) via: https://www.cen.uni-hamburg.de/icdc/data/ocean/easy-init-ocean/ecmwf-oras5.html.

Acknowledgments

We acknowledge the funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) project 268020496 TRR 172, within the Transregional Collaborative Research Center "ArctiC Amplification: Climate Relevant Atmospheric and SurfaCe Processes, and Feedback Mechanisms (AC)3." AR further acknowledges the funding by the European Union's Horizon 2020 research and innovation framework programme under Grant agreement no. 101003590 (PolarRES project). We thank Mirseid Akperov for providing the cyclone tracking data. We further thank Petteri Uotila, Dörthe Handorf and Sofie Tiedeck for their feedback on earlier manuscript versions. Open Access funding enabled and organized by Projekt DEAL.

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