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Key Points:

- Cyclones cause an anomalous sea ice concentration (SIC) decrease in the Greenland Sea and an anomalous increase in the Barents Sea in winter
- Intense cyclones combined with locally low to medium SIC leads to the strongest impacts on sea ice
- Cyclone impacts on sea ice have intensified under "New Arctic" conditions, particularly during the last decade in the Barents Sea

Supporting Information:

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

Correspondence to:

L. Aue,
lars.aue@awi.de

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New Insights Into Cyclone Impacts on Sea Ice in the Atlantic Sector of the Arctic Ocean in Winter

Lars Aue[1], Timo Vihma[2], Petteri Uotila[3], and Annette Rinke[1]

[1]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Potsdam, Germany, [2]Finnish Meteorological Institute, Meteorological Research, Helsinki, Finland, [3]Institute for Atmospheric and Earth System Research, University of Helsinki, Helsinki, Finland

Abstract Based on the ERA5 reanalysis, we report on statistically significant impacts of transient cyclones on sea ice concentration (SIC) in the Atlantic sector of the Arctic Ocean in winter under "New Arctic" conditions (2000–2020). This includes a pattern of reduced SIC prior to and during cyclones for the whole study domain, while a regional difference between increased SIC in the Barents Sea and reduced SIC in the Greenland Sea is found as the net effect from 3 days prior to 5 days after the cyclone passage. Generally, locally low to medium SIC conditions combined with intense cyclones drive highest SIC changes. There are indications that both thermodynamic and dynamic effects contribute to the SIC changes, but a detailed quantification is required in future research. We provide evidence that cyclone impacts on SIC have amplified compared to the "Old Arctic" (1979–1999), particularly in the Barents Sea.

Plain Language Summary We analyze how storms impact the sea ice cover in the Atlantic part of the Arctic Ocean in winter. To capture the current state of the Arctic, we focus on the last two decades (2000–2020). A few days prior to the arrival of a storm at a certain location, the sea ice concentration (SIC) at that location starts to decrease and is reduced most during the day of the storm. After the storm has passed over, the SIC increases again, but only for the Barents Sea, not for the Greenland Sea, where the sea ice remains reduced for at least 1 week. Generally, the impact of storms on sea ice is strongest during intense events and at locations with a broken sea ice cover. During the storm events, the ice cover is modified by different mechanisms, by wind driven ice movement and deformation, as well as by changes in the surface heating, which affect ice growth and melt. Comparing the impact of storms on sea ice for the last two decades with results for a previous period (1979–1999) shows that the impact of storms got stronger recently, particularly in the Barents Sea.

1. Introduction

Cyclones are important drivers of heat and moisture transport from lower latitudes into the polar regions; they account for nearly three-quarters of the average annual moisture transport into the Arctic (Fearon et al., 2021). The direct thermodynamic impacts of intrusions of warm and moist air in winter are increased downward fluxes of longwave radiation and sensible heat at the snow/ice surface, accompanied by a reduction in sea ice concentration (SIC) (Woods & Caballero, 2016). It has been shown that anomalous warming and moistening triggered by extreme cyclone events can result in near-melting conditions in winter in the Arctic, turn the normally negative surface energy budget (SEB) into a positive one, and thus promote ice melt or reduced ice growth (Boisvert et al., 2016; Moore, 2016; Rinke et al., 2017). But cyclone impacts on Arctic sea ice in winter are not limited to thermodynamics. Cyclone-related wind anomalies lead to a shift of the ice edge position and thus locally reduce or increase the sea ice extent dynamically (Boisvert et al., 2016; Schreiber & Serreze, 2020). Furthermore, ice deformation during storms can promote ice drift divergence and subsequent lead formation and new ice growth as well as ice drift convergence, closing of leads, and formation of pressure ridges (Itkin et al., 2017).

Due to these various dynamic and thermodynamic impacts, cyclones are an important driver of Arctic sea ice variability, which plays a key role in the Arctic climate system. Apart from that, the ice edge position and the local SIC are important factors for the marine ecosystem and short-term predictions of both are also crucial for navigation in the Arctic Ocean and its marginal seas. With the climate warming and associated reductions in sea ice thickness and concentration (IPCC, 2021), Arctic navigation is hereby expected to increase in the future (Cao et al., 2022). All this makes it important to understand the impact of cyclones on sea ice. Thereby, the focus of

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our study is on the Atlantic sector of the Arctic Ocean in winter. This is motivated by (a) the dominance of the North Atlantic storm track, in particular in winter, and (b) the strong SIC variability and sea ice decline over the last winters in the Atlantic sector.

Cyclone impacts on Arctic sea ice in winter are rarely studied in a statistical manner. Recently, Schreiber and Serreze (2020) analyzed the temporal change in local SIC 4 days after cyclone events (compared to a non-cyclone reference) and found an overall increase in SIC. Their results are to some extent in contradiction with previous findings from case studies (Boisvert et al., 2016; Graham et al., 2019), which reported about cyclones' destructive effects on the sea ice cover in winter. Another recent study emphasized that the SIC change depends on whether considering the warm sector to the east of the cyclone or the cold sector to the west (Clancy et al., 2022). Additionally, these few existing statistical studies are limited to the day of the cyclone event itself or to a fixed time frame of a few days following the cyclone. However, this approach bears the risk that the results are influenced by the choice of the specific time frame. Accordingly, Schreiber and Serreze (2020) pointed out that analyzing short-term cyclone impacts on sea ice on varying timescales (of i.e., different number of days before/after each cyclone) is a possible path to more robust results.

The first objective of our study is to quantify the cyclone impacts on SIC in the Arctic in winter, considering the following new aspects: (a) temporal variability on time scales up to a week before/after the occurrence of each cyclone, (b) detailed regional differences between the Greenland, Barents and Kara Seas, and (c) the case conditions, that is, dependency on cyclone intensity and state of the local ice cover. The second objective is to explore if the impacts have changed over the past four decades and if a signature of the "New Arctic" conditions has emerged.

2. Data and Methods

2.1. Database and Cyclone Identification

The analysis is based on the ERA5 reanalysis (Hersbach et al., 2020), with a 0.25° horizontal resolution, and focused on winter (December–February) of the last two decades from 2000 to 2020. We have chosen this comparatively short investigation period to focus our analysis on cyclone impacts on SIC under the "New Arctic" conditions. Those are characterized by a strong sea ice decline and increased cyclone intensity over the last 20 years (Valkonen et al., 2021). However, we also compare our findings to results from 1979 to 1999, the first two decades of the ERA5 coverage, representing the "Old Arctic."

The 6-hourly ERA5 data of mean sea level pressure (MSLP) are used as input for a cyclone detection and tracking algorithm (Akperov et al., 2020). The algorithm determines cyclones by identifying local minima in MSLP, that are surrounded by closed isobars. In addition to the cyclone position and pressure, the tracking algorithm provides the geographical coordinates of the outermost closed isobar for each 6-hourly time step in the lifetime of a cyclone. We define all grid-cells that are enclosed by this outermost isobar as being located within the cyclone area and thus create a binary cyclone occurrence data set matching the spatial resolution of the ERA5 horizontal grid. We use the cyclone depth as a measure of cyclone intensity. Hereby, the cyclone depth is determined as the difference between the pressure in the cyclone geometric center and the outermost closed isobar. Following Akperov et al. (2020), we define intense cyclones as those with a cyclone depth of more than 20 hPa, a threshold roughly corresponding to the 90th percentile of cyclone depth distribution. The results are insensitive to the choice of this threshold.

2.2. Quantification of Cyclone Impacts on SIC

We use SIC data from ERA5, which is based on satellite data (HadISST2 and OSI SAF; Hersbach et al., 2020). Our basic concept to quantify cyclone impacts on sea ice follows Schreiber and Serreze (2020) and is based on statistics of SIC on grid-cell level for two groups of samples: days with cyclone presence at a grid-cell for at least one out of four 6-hourly time steps, and days without any cyclone presence at the grid-cell. To capture all short-term impacts on sea ice that are associated with a cyclone traveling across a certain location, we do not limit our analysis to the day of the cyclone event itself, but evaluate the temporal evolution of SIC prior to, during and following each cyclone passage. For this purpose, each cyclone sample consists of a SIC time series of several days, starting from 3 days prior to the day of the first arrival of the cyclone at a grid-cell and extending to 7 days

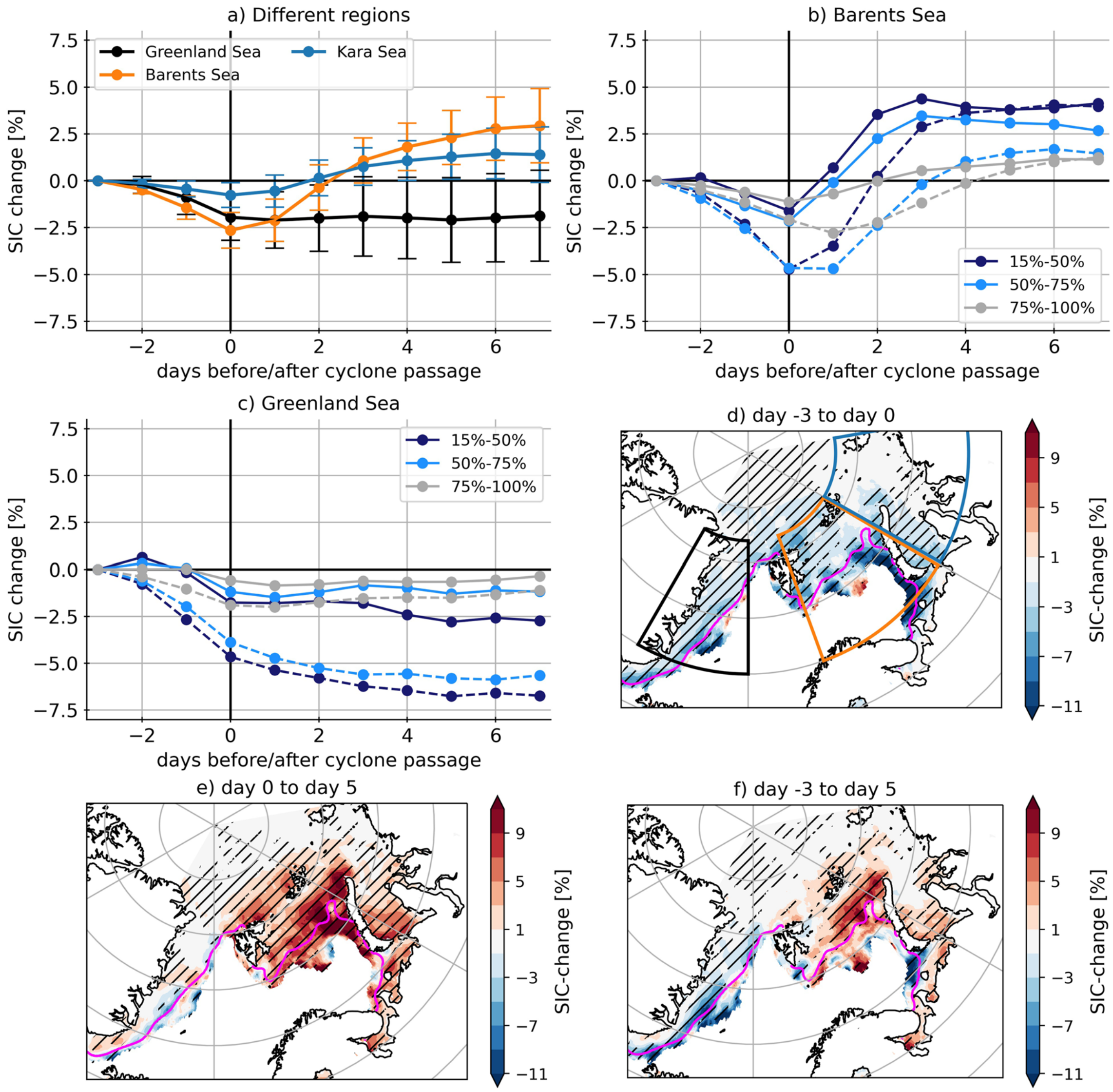

Figure 1. Difference in sea ice concentration (SIC) change (%) over a few days between the cyclone samples and the non-cyclone reference, averaged for different sub-domains of the Arctic Ocean (a) and for different classes of SIC and cyclone depth (dashed/solid lines represent intense/non-intense cyclones) in the Barents Sea (b) and Greenland Sea (c). Error bars in (a) indicate standard deviation of cyclone impacts for individual years in 2000–2020. (d–f): SIC change at grid-cell level averaged over three different time periods. Shading indicates significance at 95% level and pink line shows the position of the ice edge. The sub-domains used in (a–c) are displayed in (d).

after the cyclone passage. Corresponding SIC time series for the non-cyclone samples are calculated. Averaging all non-cyclone samples at a grid-cell results in a non-cyclone reference that we subtract from the cyclone samples at the same grid-cell. Hereby, we calculate the non-cyclone reference separately for December, January, and February, and choose the appropriate reference for each cyclone sample, since the temporal evolution of SIC due to the seasonal cycle can change significantly between the individual months. Eventually, we obtain a multi-day time series at each grid-cell that represents the difference in temporal evolution of SIC between cyclone and non-cyclone samples.

To evaluate both the temporal and spatial variability of cyclone impacts on SIC, we analyze (a) time series of spatial averages over the Greenland Sea (70°N–82°N, 30°W–00°E), Barents Sea (70°N–82°N, 20°E–60°E) and Kara Sea (70°N–82°N, 60°E–100°E; Figure 1d) as well as (b) composites on grid-cell level for different time frames. Statistical significance (reported at 95% level) is calculated using the Students *t*-test.

To initially discuss thermodynamic and dynamic aspects of SIC changes, we calculate the SEB (positive values indicate energy gain of surface) as the sum of net radiation and turbulent heat fluxes and apply a metric called cross-ice-edge wind, similar to the one recently introduced by Finocchio et al. (2020). Hereby we calculate the angle between the local ice edge (defined as grid-cells with SIC between 15% and 40%) and a zonally oriented line, and apply a coordinate transformation to the zonal and meridional wind speed. The SEB and wind analyses are again based on the 6-hourly ERA5 data.

3. Cyclone Impacts on SIC

3.1. Effects of Different Time Scales and Regions

Our analysis reveals that the impact of cyclones on SIC strongly depends on the analyzed time scale and selected sub-region of the Arctic Ocean (Figure 1a). Generally, at the day of the first arrival of a cyclone at a location (day 0), SIC is lower than in the non-cyclone reference for all regions due to the dominant eastern flank effects (warm sector, southern wind pushes the ice edge northwards). This decrease of SIC in the cyclone samples starts already up to 2 days prior to the cyclone arrival, which fits to findings of Woods and Caballero (2016). Starting with day 3 after the cyclone event, an increase in SIC is found for the Barents and the Kara Seas, with the increase being more pronounced in the Barents Sea. This post-cyclone response agrees with the increase in SIC after 4 days as discussed by Schreiber and Serreze (2020), which they explain primarily due to thermodynamic effects (stronger ice growth during cyclone conditions).

In contrast, no such increase in SIC appears in the Greenland Sea, where the cyclone related decrease in SIC lasts consistently for a week. This results in an interesting pattern with respect to the overall impact of cyclones on SIC 1 week after the cyclone passage. On this time scale, the strongest changes in SIC occur in the Greenland and Barents Seas, but are of opposing sign. The magnitude of the overall SIC change at days 5–7 is about 2.5% for both marginal seas, increasing in the Barents Sea and decreasing in the Greenland Sea. This also means that the changes in SIC from day 0 to days 5–7 are small in the Greenland Sea, while they are large (5%) averaged over the Barents Sea. These results suggest that cyclones make an impact on SIC via different mechanisms in both regions (Section 3.4).

SIC changes are generally less pronounced in the Kara Sea, indicating that cyclones are not an important source of SIC variability in this part of the Arctic Ocean. This is understandable because winter SIC is generally higher in the Kara Sea than in the Barents and Greenland Seas (e.g., Dörr et al., 2021), making the ice cover less susceptible to the impact of cyclones, in addition to the constraint by the Novaya Zemlya island and the coast. Figure 1a further shows that generally the SIC reduction prior and during the cyclone covers only 2 days, while the change in SIC after the cyclone passage persists longer. This indicates that the processes acting to restore the SIC changes are slower than those driving the SIC reduction during the arrival of the cyclone, and was previously discussed for the impact of moisture intrusions in the Barents Sea in winter (Woods & Caballero, 2016).

3.2. Effects of SIC Conditions and Cyclone Depth

The impact of an individual cyclone can vary from event to event, depending on the local sea ice conditions at the time of the passage. Therefore, we investigated the sensitivity of the cyclone impact on SIC to the local SIC at the grid-cell that was passed over (Figures 1b and 1c, solid lines). For this purpose, we created three subsets of grid-cells within the cyclone area for each cyclone case containing grid-cells with SIC from 15%–50% (low SIC), 50%–75% (medium SIC) and 75%–100% (high SIC).

Our analysis indicates that the strongest overall cyclone impacts on SIC (after 1 week) occur close to the ice edge at grid-cells with comparatively low SIC in both the Greenland and Barents Seas. This supports the hypothesis raised earlier (e.g., by Schreiber & Serreze, 2020) that regions with high SIC are more resistant to cyclone related changes in winter. Partly, this might also be related to the fact that cyclones likely weaken as they move into the denser pack ice and get cut off from their open ocean energy source. To further follow-up on the importance of cyclone intensity, we analyze cyclone impacts separately for intense and non-intense cyclones overall three types of SIC conditions.

Generally, the SIC decrease during the cyclone (day 0) is amplified for intense cyclones compared to non-intense cyclones (Figures 1b and 1c, dashed vs. solid lines). Furthermore, this amplification is considerably stronger for low and medium SIC conditions than for high SIC conditions, indicating that especially the combination of low to medium SIC and intense cyclones leads to the highest SIC changes during a cyclone passage. For the Greenland Sea, this is also found 7 days after the cyclone passage. In contrast, no difference with respect to cyclone depth is found at day 7 in the Barents Sea, at least for low and high SIC conditions. Surprisingly however, for medium SIC conditions, the SIC increase is weaker for intense cyclones. The reason for this could be that such conditions, including the upper ocean stratification, provide enough air-to-sea momentum to drive oceanic upwelling and associated upward heat fluxes (Manucharyan & Thompson, 2017).

To our knowledge, the effects of different cyclone strength on SIC in winter have not been studied before, but it was recently hypothesized that the effects of intense cyclones are more rapid (Schreiber & Serreze, 2020). Our results partly verify this. Intense cyclones show a stronger rate of decrease in SIC prior to and during the cyclone passage, compared to non-intense cyclone effects, but after the cyclone, changes are similar.

3.3. Spatial Variability of SIC Response to Cyclones

To investigate the spatial variability of cyclone impacts on SIC in more detail, Figures 1d–1f shows the analysis for three time periods, which are chosen based on results of Figure 1a. These capture the SIC decrease taking place prior to and during the cyclone, the SIC increase after the cyclone passage as well as the overall effect on the local sea ice cover.

For our entire study domain it becomes clear that the cyclone-related decrease and increase in SIC can be separated by the chosen timescales. In other words, SIC generally decreases prior to and during the arrival of the cyclone (day −3 to day 0; Figure 1d) and increases after the cyclone passage (day 0 to day 5; Figure 1e) in all grid-cells. Both the obtained spatial pattern and the magnitude of the post-cyclone increase in SIC for day 0 to day 5 supports the finding of the 4-day changes of Schreiber and Serreze (2020). Additionally, the spatial patterns confirm that the results for the sub-regions (Figures 1a–1c) are robust and not a consequence of inappropriate spatial averaging.

For both the pre-cyclone decrease and post-cyclone increase of SIC, the strongest changes are of the order of approximately 10% and are found in the Barents Sea, west of Novaja Zemlya. With respect to the overall impact of cyclones on SIC (day −3 to day 5), a significant decrease in SIC occurs in the Greenland Sea and in the south-eastern Barents Sea, while a significant increase in SIC appears in the northern Barents Sea (Figure 1f).

3.4. Relation to Near-Surface Wind and Surface Energy Budget

To investigate the physical processes responsible for the detected cyclone impact on SIC, we compare the SEB and wind conditions for the cyclone samples to the non-cyclone reference (Figure 2). For the wind conditions, we calculate the cross-ice-edge-wind speed (Section 2.2) to evaluate how the position of the ice edge might change during the cyclone passage, following Finocchio et al. (2020).

Generally, the spatial patterns of SEB and wind speed agree with the spatial changes in SIC (Figures 1d–1f). Prior to and during the cyclone arrival (Figures 2a and 2b) an increase in SEB (i.e., less net energy loss from the surface) in combination with increased on-ice wind speed is found close to the ice edge in the Greenland Sea and southeastern Barents Sea, as well as (south)west of Svalbard. This can contribute to a decreased SIC (Figure 1d), because (a) the ice edge gets pushed toward the coast, resulting in more ice-free grid-cells, and (b) although leads formed by the ice drift divergence rapidly refreeze in winter, the SEB change related to the advection of warm, moist air on the front side of the cyclone slows down the growth of this new thin ice, making it more liable to deformation when the ice drift converges.

After the cyclone passage (Figures 2c and 2d), increased off-ice wind speed in combination with cold, dry air on the backside of the cyclone and a more negative SEB contribute to an increased SIC in the northern Barents Sea (Figure 1e). In the southern Barents and Greenland Seas, however, no such signal is detected. The combination of these dynamic and thermodynamic mechanisms, previously discussed for sea ice growth and variability in winter (Boisvert et al., 2016; Cai et al., 2020; Graham et al., 2019; Hegyi & Taylor, 2017; Park et al., 2015; Schreiber & Serreze, 2020), results in the clear regional difference with respect to the overall time scale (Figure 1f; Figure S1 in Supporting Information S1).

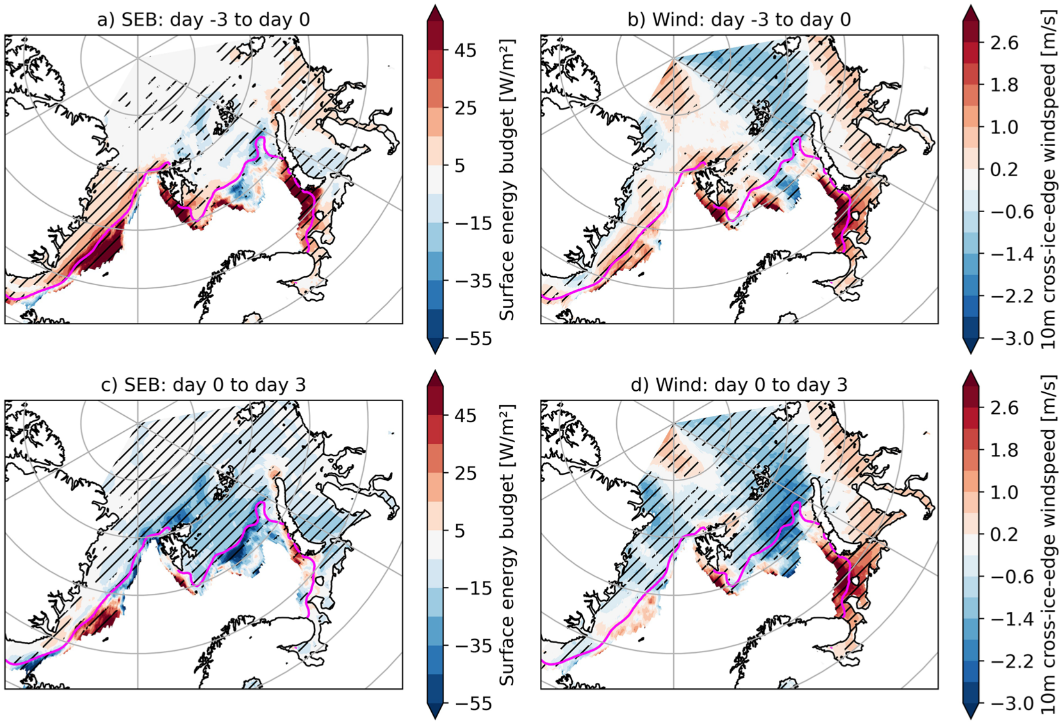

Figure 2. Difference in surface energy budget (left) and cross-ice-edge wind speed (right) between the cyclone samples and the non-cyclone reference, averaged for 3 days before the cyclone (a, b) and 3 days after the cyclone (c, d). Shading indicates significance at 95% level. Pink line indicates the position of the ice edge.

The changes in SEB and wind speed fit to the front (warm sector) and backside (cold sector) effects of cyclones traveling along the main winter cyclone track from the North Atlantic into the Barents Sea toward the Kara Sea (Figure S2 in Supporting Information S1). For those, increased on-ice airflow is expected for the Greenland Sea, because the grid-cells are affected by (south)westward winds, before the cyclone leaves the Greenland Sea to enter the Barents Sea. The latter region is, however, affected by both the (northward) on-ice winds located in front (east) of the cyclone and the (southward) off-ice winds located behind (west of) the cyclone.

Statistical differences in regional cyclone properties—another possible explanation for our findings—cannot explain the regionally different sea ice impact in the Greenland and the Barents Seas. The number of cyclone passages and the mean cyclone intensity are similar for both regions (Figure S2 in Supporting Information S1). However, variations in cyclone properties likely contribute to the interannual variability of cyclone impacts on sea ice (error bars in Figure 1a). In this regard, also variations in large-scale atmospheric circulation and sea ice cover might play an important role.

4. Signature of "New Arctic" Conditions

The "New Arctic" conditions, here represented by the period 2000–2020, are characterized by a reduced and thinner sea ice cover. In winter, the Barents Sea is the region with the largest ice retreat; it contributes to about one quarter of the observed Arctic sea ice loss in winter (Docquier et al., 2020). The northward shifted ice edge compared to the "Old Arctic" (here represented by the period 1979–1999) is shown in Figures 3a and 3b.

Recently, the question has emerged if cyclone effects on SIC in winter have changed under these changing ice state conditions (Schreiber & Serreze, 2020; Valkonen et al., 2021). Indeed, we find significant differences in the overall cyclone impact (day −3 to day 5) between both periods (Figure 3a). The cyclone related increase in SIC in the northeastern Barents Sea is significantly stronger (up to 5%) for the recent two decades than in the past. Also, the cyclone related decrease in SIC in the southeastern Barents Sea is amplified. These intensified effects in the Barents Sea are associated with a decrease in mean SIC and an associated shift of the mean position of the ice edge (Figure 3b).This indicates that local SIC conditions are a key factor for the changed impact of cyclones

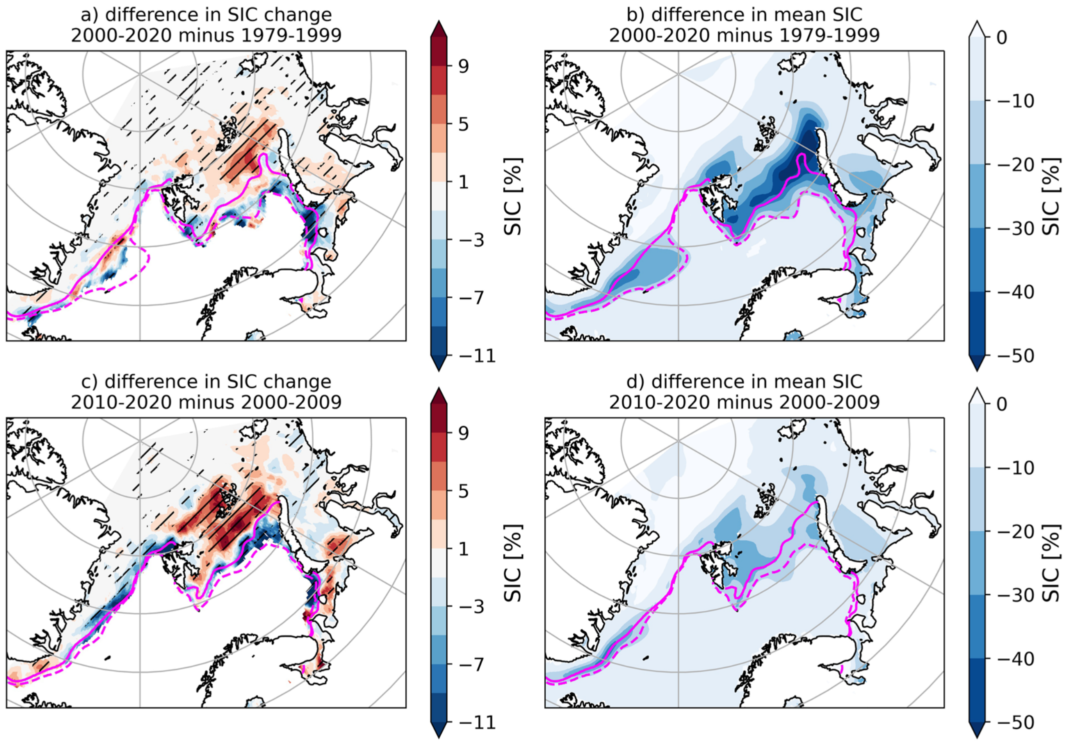

Figure 3. Difference in cyclone impact on sea ice concentration (SIC) (left), defined as 8-day SIC change (day −3 to day 5) between the cyclone samples and the non-cyclone reference, and difference in mean SIC (right) between "Old Arctic" and "New Arctic" conditions (a, b) as well as between the two decades within the "New Arctic" period (2000–2009 vs. 2010–2020, c, d). Shading indicates significance at 95% level, whereas changes in mean SIC (b, d) are significant at all grid points and therefore not shaded. Solid (dashed) pink line shows the position of the ice edge for the newer (older) time period.

on sea ice and is in accordance with our previous findings (Section 3.2; Figures 1b and 1c). In addition, it can be assumed that also the decreasing ice thickness promotes increased cyclone impacts because a thinner ice cover is more susceptible to atmospheric and oceanic forcings (Rampal et al., 2009; Rheinlænder et al., 2022; Zhang et al., 2012).

Potentially, and as we have discussed in Section 3.2, changes in cyclone characteristics might have contributed to the intensified effect on SIC. However, estimates of trends in (deep) cyclone occurrence and intensity over the past four decades are uncertain. While some studies discuss an increase of cyclone depth and the occurrence of deep cyclones in winter (Zahn et al., 2018), others do not find significant changes (Vessey et al., 2020) or report on positive and negative trends depending on the period (Valkonen et al., 2021). Based on our calculations using the ERA5 reanalysis, we find a slight but non-significant decrease in the occurrence of intense cyclones in the study domain (not shown). This indicates that changes in sea ice conditions are a more likely explanation for the amplified cyclone impacts than changes in cyclone characteristics.

Still, the "New Arctic" undergoes a rapid climate change, including an accelerated warming in the most recent decade (IPCC, 2021). Hence, we compare the cyclone impact on SIC between 2010 and 2020 with that during 2000–2009 (Figures 3c and 3d; Figure S3 in Supporting Information S1). Our results show a further significant intensification of the cyclone-related impact on SIC in the Barents Sea in the most recent decade. This change is even stronger than the difference between the "Old Arctic" and "New Arctic" (1979–1999 vs. 2000–2020; Figure 3a). At the same time, the recent decrease in mean SIC is less strong than for 1979–1999 compared to 2000–2020, which could be expected because of the shorter period. Nevertheless, the fact that a stronger intensification of the cyclone impact on SIC is found for a smaller difference in mean SIC might indicate that the SIC in the Barents Sea has reached a critically low value during the last decade, making the ice cover significantly more susceptible to the passage of cyclones than in previous times. This hypothesis is supported by the strong intensification of cyclone impacts on the sea ice cover which we found when grid-cells SIC transfers from the 75%–100% category to the lower categories (Figure 1b).

5. Conclusions

We provide new insights into the cyclone impacts on SIC in the Atlantic sector of the Arctic Ocean in winter. Overall, we show that this impact strongly depends on the considered time scale, region, cyclone intensity and local sea ice conditions, and we provide a quantitative assessment of those effects.

In conclusion, a cyclone related SIC increase in the Barents Sea and a SIC decrease in the Greenland Sea were found, both reaching values of up to 10% 1 week after the cyclone for individual grid-cells. The regionally averaged impact varies between 1%–6% for both regions, depending on cyclone intensity and local sea ice conditions. This seems to be a rather small effect on first glance, however, given the fact that the sea ice in, for example, the northern Barents Sea is affected by approximately 15–20 cyclones each winter (Figure S2 in Supporting Information S1), these SIC impacts easily sum up and form a significant contribution to the overall SIC variability in this region. This effect obviously depends to some extent on the number, timing and properties of cyclones when they approach and move over a certain location. Further, in winter even a change in SIC by a few percent generates a large impact on SEB, and subsequently on near-surface air temperatures (Lüpkes et al., 2008). In the course of our analysis we further point out that the cyclone impacts have amplified recently, associated with the declining SIC in the Arctic. However, the quantification and detailed understanding of the thermodynamic and dynamic processes that drive the cyclone-induced regional and temporal SIC changes is a remaining research task, which is further complicated by feedbacks from SIC to the atmosphere, including the wind speed (Jakobson et al., 2019). Regional coupled model experiments should be beneficial in this regard with the approach to first study individual winter events before starting a statistical analysis.

Data Availability Statement

ERA5 data are available on the Copernicus Climate Change Service Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form).

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