Rapid Sea Ice Changes in the Future Barents Sea

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Abstract. Winter Observed and future winter Arctic sea ice loss is strongest in the Barents Sea. The anthropogenic However, the anthropogenic signal of the sea ice decline is superimposed by pronounced internal variability that represents a large source of uncertainty in future climate projections. A notable manifestation of internal variability are periods of rapid ice loss or growth rapid ice change events (RICEs) that greatly exceed the anthropogenic trend. These rapid ice change events RICEs are associated with large displacements of the sea ice edge which could potentially have both local and remote impacts on the climate system. In this study we accordingly present the first investigation of the frequency and drivers of these rapid ice change events RICEs in the future Barents Sea, using multi-member ensemble simulations from CMIP5 and CMIP6. A majority of rapid sea ice changes are RICEs are triggered by trends in ocean heat transport or surface heat fluxes. Rapid ice change events are Ice loss events are associated with increasing trends in ocean heat transport and decreasing trends in surface heat loss. RICEs are a common feature of the future Barents Sea until the region becomes close to ice free. As their evolution over time is closely tied to the average sea ice conditions, rapid ice changes in the Barents Sea may serve as a precursor for future changes in adjacent seas.

1 Introduction

The Arctic is the region of most intense warmingon the planet, a region of amplified warming, with temperatures increasing twice as fast as the global average, i.e., an Arctic amplification of climate change (Cohen et al., 2020). (Serreze et al., 2009; England et al., 2 . The strong temperature increase is accompanied by a decline in sea ice thickness (Kwok, 2018) and extent (Onarheim et al., 2018) (Onarheim et al., 2018; Meredith et al., 2019) in all regions and all seasons. Future climate simulations project the strong sea ice decline to continue, leading to seasonally ice-free conditions in the Arctic as early as the middle of the 21st century (Notz and SIMIP Community, 2020; Årthun et al., 2021)(Notz and SIMIP Community, 2020; Årthun et al., 2021; Bonan et al., 2021b) . However, future Arctic sea ice loss and the projected timing of ice-free conditions display a substantial spread across different models (Jahn et al., 2016). This large uncertainty results from model structure and emission scenario, but also internal climate variability (Swart et al., 2015; Bonan et al., 2021b). Understanding internal variability (Swart et al., 2015; Bonan et al., 2021a) . Understanding the causes and impacts of internal variability in Arctic sea ice is therefore important to predict for predicting future sea ice change under anthropogenic warming.

Whereas Arctic summer ice loss has largely occured occurred in the central Arctic, winter ice loss has so far been confined to the outer shelf seas. The Barents Sea (Fig. 1) is the area of most intense winter sea ice area (SIA) loss, being and is on track towards experiencing year-round ice-free conditions sometime in the second half of the 21st century (Onarheim and Årthun, 2017). A large part of the recent winter sea ice loss in the Barents Sea can be related to internal variability that is particularly strong in this region ~~(England et al., 2019; Årthun et al., 2019; Bonan et al., 2021b). On the sub-decadal timescale this variability is~~ (England et al., 2019; Årthun et al., 2019; Bonan et al., 2021a). Internal variability is also manifested in multi-year episodes of pronounced ice growth or ice loss that greatly exceed the long-term trend. These events of rapid ~~ice changes~~ changes in sea ice cover are important to understand as they are characterized by substantial movements of the sea ice edge that have potential implications for ~~e.g.,~~ marine ecosystems (Fossheim et al., 2015; Sandø et al., 2021), shipping routes (Melia et al., 2016), and terrestrial climate ~~(Lawrence et al., 2008).~~ (Lawrence et al., 2008; Zhang et al., 2018). Rapid ice loss events have been investigated for pan-Arctic summer sea ice ~~(Holland et al., 2006; Auclair and Tremblay, 2018).~~ (Holland et al., 2006; Auclair and Tremblay, 2018)And although there have been several studies conducted on interannual winter sea ice variability in the Barents Sea ~~(Kwok, 2009; Schlichtholz, 2011; Årthun et al., 2012; Nakanowatari et al., 2014; Skagseth et al., 2~~ (Kwok, 2009; Schlichtholz, 2011; Årthun et al., 2012; Nakanowatari et al., 2014; Liu et al., 2022), a detailed investigation of rapid ~~ice change events~~ sea ice changes is lacking.

In this study we ~~accordingly~~ present the first investigation of rapid ice change events (RICEs) in the Barents Sea using large ensemble climate model simulations. We first quantify the probability of ~~rapid ice change events~~ RICEs in present and future climates, demonstrating that strong ~~–~~ – more than 7 times the observed ice decline ~~–~~ – multi-year sea ice trends are a common feature of the Barents Sea until it becomes close to ice-free~~, leading to substantial displacements of the sea ice edge on rather short timescales.~~ . The drivers of these ~~rapid sea ice changes~~ RICEs are thereafter investigated. Our analysis is largely based on a large ensemble simulation from the Community Earth System Model version 1, but the sensitivity of our results to model differences and future emission scenarios is also assessed using CMIP6 models.

2 Data and Methods

The main part of this analysis is based on future simulations from the Community Earth System Model Version 1 (CESM1; Hurrell et al., 2013), a fully coupled climate model that has a horizontal resolution of approximately 1° in all model components. We make use of two sets of ~~experiments~~ simulations from the model. The large ensemble ~~simulation~~ experiment (CESM-LE; Kay et al., 2015) consists of 40 members and covers the period from 1920-2100 based on historical greenhouse gas emissions until 2005 (Lamarque et al., 2010) and the RCP8.5 (Moss et al., 2010) thereafter. The other experiment applies an external greenhouse gas forcing that limits global warming to $2\,^\circ$C (CESM-2C; Sanderson et al., 2017). This experiment consists of 11 members over the period 2006-2100. The model setup is identical to the CESM-LE with the external forcing as the only difference. ~~The setups~~ To test the robustness of our results, we additionaly investigate RICEs in five CMIP6 climate models that have 10 or more ensemble members (Table 1), using both a high (SSP585) and a low (SSP126) warming scenario (O'Neill et al., 2017).

The CESM-LE has been used in several previous studies to investigate Arctic sea ice conditions and has been found to compare well to observations (Auclair and Tremblay, 2018; Labe et al., 2018; England et al., 2019; Årthun et al., 2019; Dörr et al., 2021)

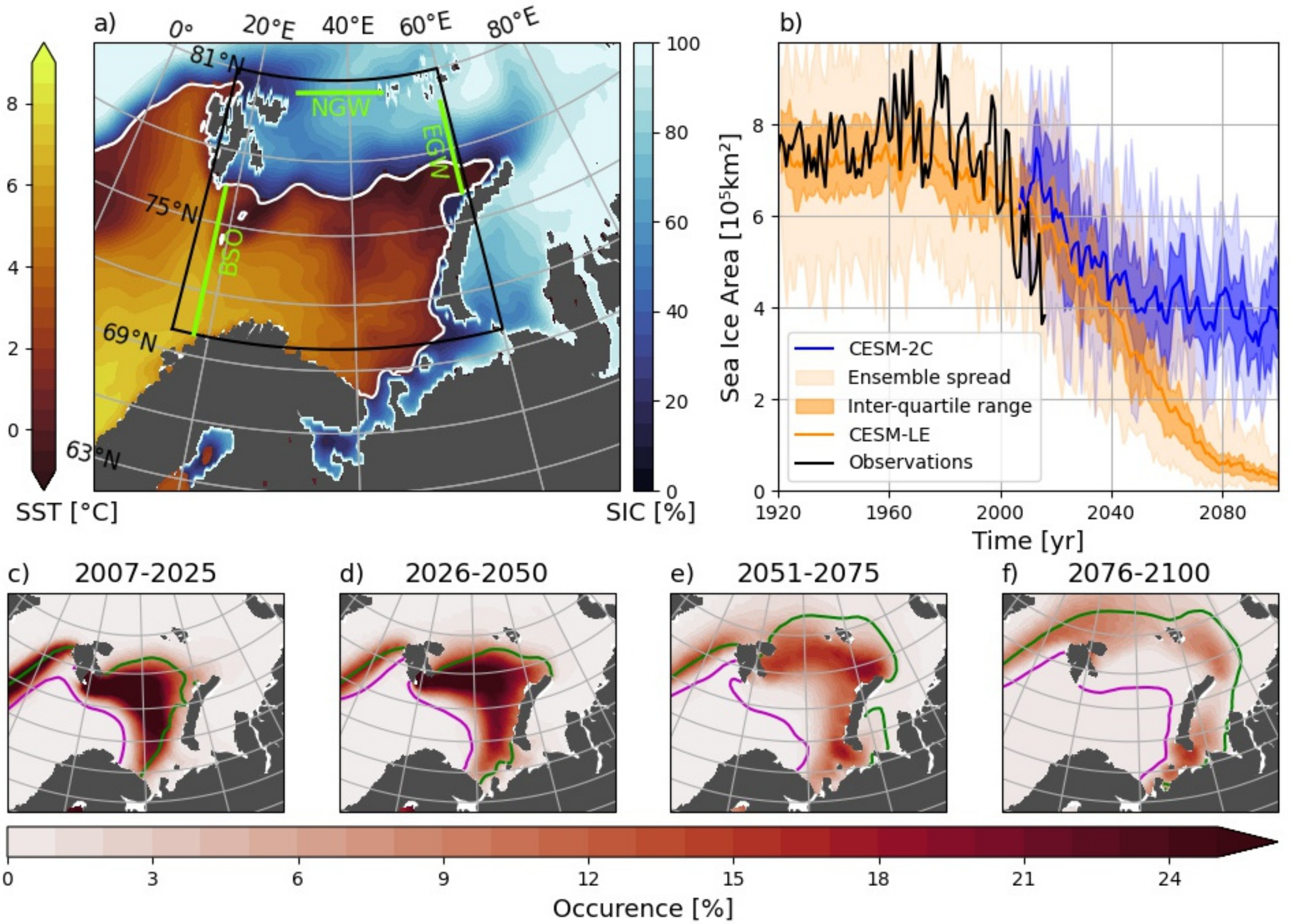

Figure 1. a) Observed winter (November-April) mean sea ice concentration (SIC; Walsh et al., 2017) and sea surface temperature (SST; Hersbach et al., 2019) in the Barents Sea (black box) between 2013 and 2017. Note the two different colorbars. The white line indicates the mean location of the winter sea ice edge (15 %-SIC). b) Winter sea ice area in the Barents Sea from observations, the CESM-LE and CESM-2C. c) - f) Occurrence of strong 5-year trends in SIC (≥ 8 %/yr) during different time periods of the CESM-LE simulations. The coloured lines indicate the southernmost (magenta) and northernmost (green) location of the ice edge during the respective time periods.

. The model slightly overestimates the sea ice cover in the Barents Sea as a result of lower simulated ocean temperatures than observed (Park et al., 2014). However, the observations (Walsh et al., 2017) fall within the ensemble spread (Fig. 1b). The model also has a realistic representation of sea ice transport into the Barents Sea (Lind et al., 2018) not shown; [see][]Lind2018. The sensitivity of simulated Barents Sea ice extent to interannual variations in Barents Sea opening ocean heat transport is also consistent with observations (Årthun et al., 2019).

Using multi-member ensemble experiments allows for a detailed investigation of internal variability. The setup of the individual simulations ~~differ~~ differs only in slightly perturbed initial atmospheric conditions. ~~All~~ Since the external forcing is the same for each simulation, the differences between the ~~members~~ individual simulations are thus solely a result of ~~internal~~ internally-generated variability (Deser et al., 2020). ~~This allows us to split the variables into a common part (~~The externally-forced contribution of sea ice change is thus defined as the ensemble mean ~~) representing external forcing, and an individual part representing internal variability. In our analysis~~ change (either from the 40 members of the CESM-LE or each CMIP6 model). To isolate the internal variability, we subtract the ensemble mean from each ensemble member~~to focus on~~ . Choosing CMIP6 models with minimum 10 ensemble members represents a trade-off between robustly separating internal and external variability and the number of available models (Milinski et al., 2020). All analysis in this paper concerns internal variability.

As the Barents Sea is practically ice-free in summer, our analysis is based on winter means (November-April). To assess ~~rapid ice changes~~ RICEs we first calculate linear ~~trends of Barents Sea ice area~~ 5-year-trends of sea ice area over the Barents Sea (15-60 ° E, 70-81 ° N; Fig. 1). We note that our results do not qualitatively change if we consider sea ice volume or sea ice extent instead. RICEs were then defined as linear trends that exceed ~~a threshold of 7.7*10^4 km^{2}yr^{-1} over at least five years. This corresponds to~~ two standard deviations of the distribution of 5-year trends in CESM-LE between 2007 and ~~2025 (Fig. 2a), and~~ 2025. This is equivalent to 7 times the ~~observational~~ observed ice decline over the satellite era ~~(11.0*10^3 km^{2}yr^{-1} for 1979-2017, based on Walsh et al., 2017)~~ (1979-2017; Walsh et al., 2017). Our results are not sensitive to the exact choice of this threshold ~~.~~ (e.g., 1-2.5 standard deviations). We apply the same threshold to CESM-2C and the CMIP6-models to enable direct comparison. ~~Trends in~~ To assess potential drivers of RICEs, we investigate ocean heat transport~~via the Barents Sea Opening (BSO)~~, sea ice area transport~~between Franz Josef Land and Novaya Zemlya (eastern gateway)and between Svalbard and Franz Josef Land (northern gateway) , net~~ , and surface heat fluxes. First, we calculate the trend for each of these variables during the duration of each RICE. We then identify the number of RICEs where one or several of the variables have a trend that exceeds one standard deviation. The relative importance of the investigated drivers does not change if we rather use a different threshold (1-3 standard deviations). Our method thus identifies a fraction (in %) of RICEs related to each driver, similar to the approach by (Auclair and Tremblay, 2018). Additionally, we look at the spatial distribution of surface heat fluxes, sea level pressure and surface air temperature ~~have then been calculated over the duration of the events to assess their relationship to the RICEs.~~ during RICEs. Ocean heat transport ~~across~~ (OHT) across the Barents Sea Opening (BSO; Fig 1a) is calculated as

$$OHT_{BSO} = \int_{S_{BSO}} \rho c_p F dS, \qquad (1)$$

~~with~~ where ρ and c_p are the density and specific heat capacity of water, ~~and F the advective heat flux~~ respectively, and F is the advection of temperature per unit volume (model variable UET). Ocean heat transport through individual sections (such as the BSO) must be calculated relative to a reference temperature, which is in principle arbitrary (Schauer and Beszczynska-Möller, 2009) . In CESM, UET is calculated~~in the model~~ , using a reference temperature of 0 ° ~~C.~~ C. We have explored other reference temperatures (-2 ° C, 2 ° C) and found that the magnitude of present and future ocean heat transport trends and their link to RICEs are not sensitive to this. Sea ice area transport between Franz Josef Land and Novaya Zemlya (eastern gateway; EGW; Fig. 1a) and between Svalbard and Franz Josef Land (northern gateway; NGW; Fig. 1a) is calculated as the product of sea ice

Table 1. CMIP6 models used in the study

Model	Ensemble Members	Reference
ACCESS-ESM1-5	10	Ziehn et al. (2020)
CanESM5	10	Swart et al. (2019)
EC-Earth3	15	Döscher et al. (2021)
MIROC6	20	Tatebe et al. (2019)
MPI-ESM1-2-LR	10	Mauritsen et al. (2019)

concentration and ice drift velocity, integrated over the ~~eastern and northern~~ two gateways. Sections are defined in alignment with the native grid of the model. ~~The results are not sensitive to their exact definition.~~

~~The CESM-LE has been used in several previous studies to investigate Arctic sea ice conditions and has been found to perform well (Auclair and Tremblay, 2018; Labe et al., 2018; England et al., 2019; Årthun et al., 2019; Dörr et al., 2021). The model slightly overestimates the sea ice cover in the Barents Sea as a result of lower simulated ocean temperatures than observed (Park et al., 2014). However, the observations (Walsh et al., 2017) fall within the ensemble spread (Fig. 1b). The sensitivity of simulated Barents Sea ice extent to interannual variations in BSO heat transport is furthermore consistent with observations (Årthun et al., 2019). The model simulates ice import from the Kara Sea via the eastern gateway and variable ice transport across the northern gateway (not shown), both of which is in good agreement with observations (Lind et al., 2018). To test the robustness of our results, we additionaly investigate RICEs in five CMIP6 climate models that have 10 or more ensemble members (Table 1), using both a high (SSP585) and a low (SSP126) warming scenario (O'Neill et al., 2017).~~

3 ~~Barents~~ Sea Ice Loss and Variability in the Barents Sea

Observed winter SIA in the Barents Sea has experienced an accelerating decline in the late 20th and early 21st century, resulting in a minimum SIA in 2017 which was ~~only~~ approximately half of the 20th century mean (Fig. 1b). Future ~~simulations under the assumption of the~~ projections under the RCP8.5 ~~climate~~ emissions scenario project a continuation of this decline ~~towards~~ and an entirely ice-free Barents Sea by the end of this century (Fig. 1b; Onarheim and Årthun, 2017). The observed ice decline is, however, overlaid by large interannual to decadal fluctuations, indicative of strong internal variability. In the CESM simulations, this internal variability is expressed as an ensemble spread in SIA of approximately $\pm 30\,\%$. The magnitude of the internal variability in CESM-LE remains quite constant over time until SIA becomes very low ~~in CESM-LE~~ (Fig. 1b). In CESM-2C, where SIA stabilises after 2050, the ensemble spread remains unchanged. The strength of internal variability can clearly be seen in the location of the southernmost and northernmost ice edges across the different ensemble members in CESM-LE (Fig. 1c-f). Although both shift northwards during the simulation, they encompass a large area of possible locations. For example, for 2076-2100 (Fig. 1f) the ensemble spread includes an ice edge close to its present location but also one that has retreated past the boundaries of the Barents Sea.

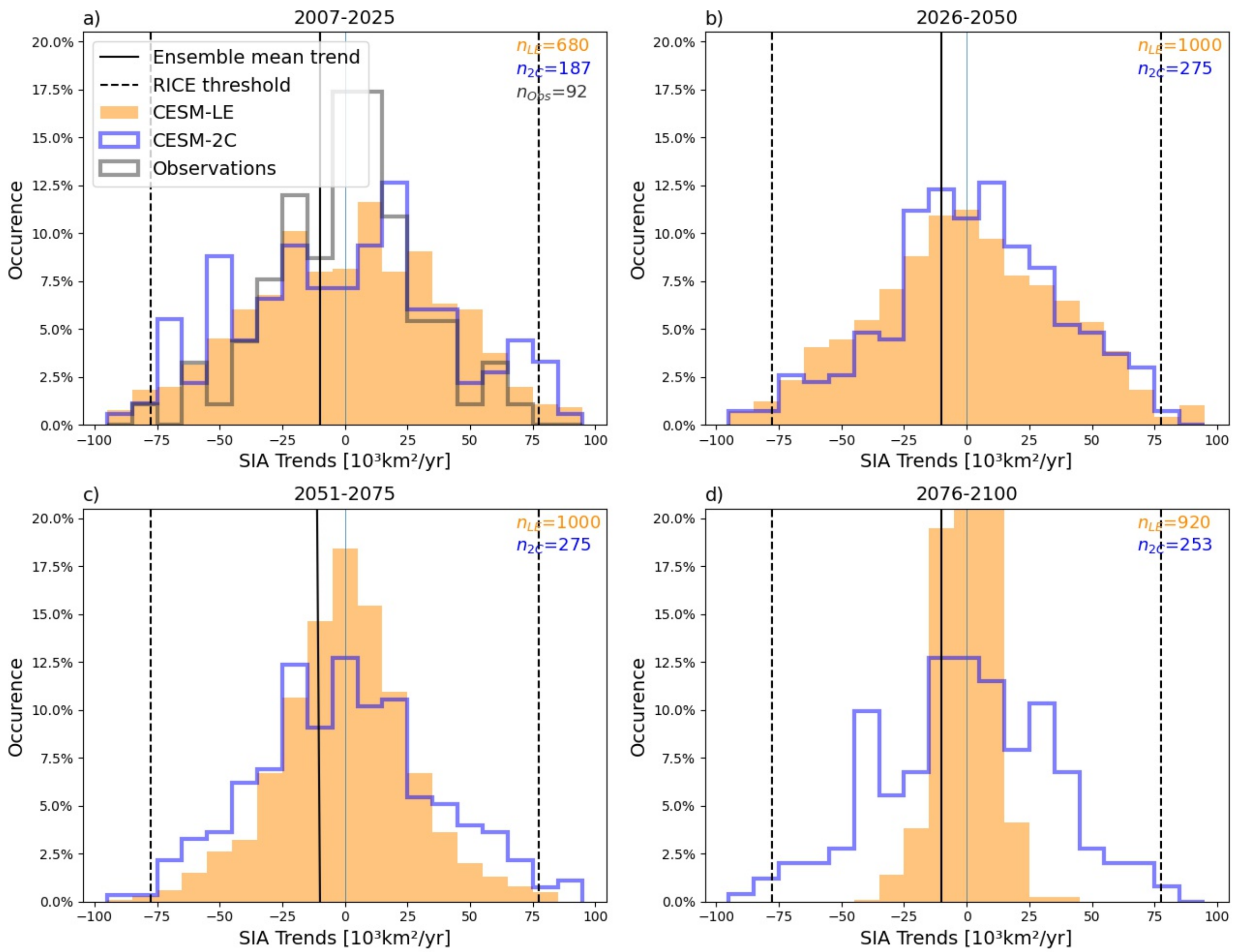

Figure 2. Histograms of internally-driven 5-year trends 5-year-trends of SIA sea ice area (deviations from the ensemble meanSIA) during different time periods in the 21st century for the CESM-LE and CESM-2C. The black solid line indicates the maximum 30-year ensemble mean externally-forced ice decline in CESM-LE ($10.0*10^4$ km^2 yr^{-1} for defined as the maximum 30-year trend in ensemble mean SIA, 2031-2060), the dashed lines indicate the threshold for RICEs. The sample size (number of trends) of the histograms is indicated in the top-right corner. A 4th-order polynom polynomial has been removed from observations (Walsh et al., 2017) prior to calculating trends to represent the externally-forced signal (following Bonan et al., 2021a).

4 Rapid Sea Ice Changes in CESM1

To quantify the occurrence of rapid ice change events in the Barents Sea, distributions of 5-year SIA-trends are presented in Fig. 2 for the CESM-LE and CESM-2C for different periods. The distribution of observed trends after 1920 SIA-trends based on observations is shown for comparison, and is similar to both, the historical simulations of CESM-LE (not shown) and the

~~future simulations~~ seen to be similar to simulated trends between 2007 and 2025 (Fig. 2a). Until 2050 CESM-LE and CESM-2C show similar distributions with many trends being much stronger than the ~~anthropogenic (ensemble mean)~~ externally-forced ice decline (~~indicated by the~~ solid black line ~~).~~ in Fig. 2). In CESM-2C, the distributions in the second half of the 21st century remain ~~quite~~ similar to the previous time periods, as the average SIA remains rather constant during this time (Fig. 1b). In CESM-LE, however, the distribution becomes more confined towards smaller trends between 2051 and 2075, and even more so ~~between~~ for 2076-2100~~, as the Barents Sea approaches ice-free conditions.~~

~~The~~ . This absence of strong sea ice trends toward the end of the century can be understood by looking at the spatial distribution of strong ~~5-year trends in CESM-LE (≥ 8% SIC/yr; the patterns are not sensitive to the exact choice of this threshold) is shown in Fig. 1c-f~~trends in sea ice concentration ($\geq 8\,\%\,\mathrm{yr}^{-1}$) in CESM-LE. It is seen that as the sea ice cover gradually retreats toward the end of the century, the area where large trends occur ~~is shifting towards the~~ accordingly shifts towards the northern and eastern boundaries of the Barents Sea ~~in the north and the east.By~~ (Fig. 1c-f). At the end of the century~~(2076-2100) this area has moved out of the boundaries of the Barents Sea as it is defined in this study, which results in the absence of strong SIA trends in~~ , strong sea ice trends are predominantly found outside the Barents Sea ~~during that time~~ (Fig. ~~2d).~~ 1f), implying that a more variable winter sea ice cover in the Kara Sea and central Arctic Ocean can be expected in the future.

In the following, we will focus on the tails of the distributions, i.e., RICEs, as these trends lead to the strongest changes in Barents Sea ice conditions. In CESM-LE we find 31 ice growth and 44 ice loss events between 2006 and 2100, and in CESM-2C we find 13 ice growth and 19 ice loss events that exceed our definition of a rapid ice change event~~(Section 2; vertical dashed lines in Fig. 2)~~. This corresponds to an average of ~~2~~ two RICEs per ensemble member in CESM-LE and ~~3~~ three in CESM-2C.

The RICEs are associated with a large displacement of the ice edge, with ice loss (growth) events leading to a northward (southward) movement of the ice edge of ~~up to 900 kilometres~~ approximately 400-700 km depending on emission scenario (Fig. 3~~). Ice loss events are on average related to asomewhat larger displacement than ice growth events, and the displacement also increases over time as sea ice retreats into the northeastern part of the Barents Sea (see the numbers given in~~ a) and time period (Fig. 4). Two example cases from CESM-LE are depicted in Fig. 3. During an ice growth event in the second half of the 21st century (2059-2063), the ice edge is pushed 678~~km southwards from close-to-average sea ice conditions into the south-western part of the Barents Sea~~ km southwestwards, resulting in a present-day location (Fig. 3b). The example ice loss event in the early 21st century ~~results in~~ (2018-2022) demonstrates a rapid northward retreat of the ice edge (Fig. 3c). These examples emphasize the severity of RICEs as they can initiate a shift from average ice conditions to an ~~unusually~~ anomalous northward or southward location of the ice edge in only a few years. All ice growth events in CESM-LE, even those after 2050, result in an ice edge location very close to or even south of the present-day average (represented by the ensemble mean ice edge between 2007-2025).

4.1 Forcing of Rapid Ice Change Events

To understand and possibly predict ~~these~~ RICEs and their impacts, it is essential to identify the underlying mechanisms. ~~We thus calculate the corresponding trend for potential drivers during each event, and assume those whose trend exceeds the threshold~~

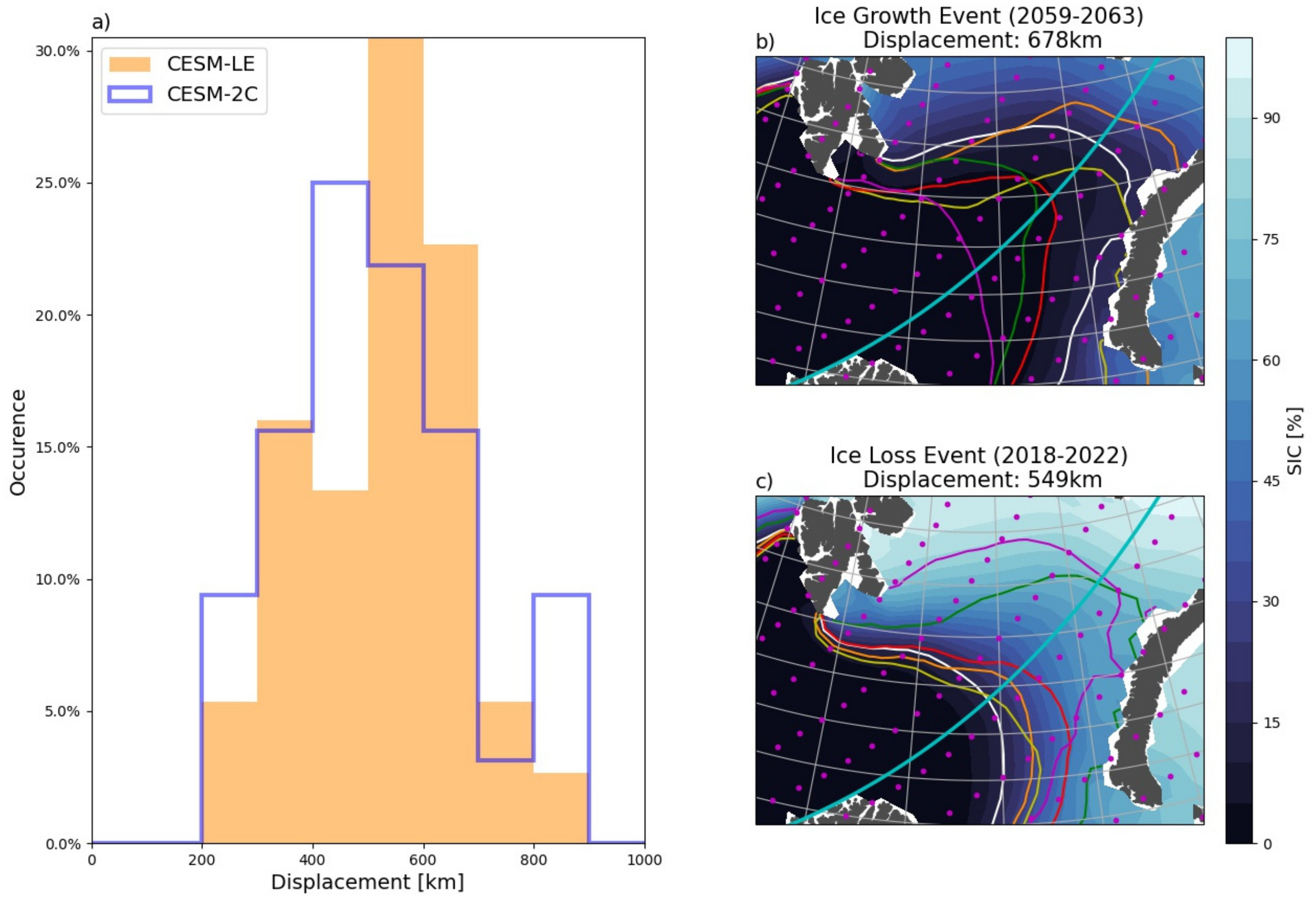

Figure 3. a) Distribution of ice edge displacement during RICEs in CESM-LE and CESM-2C. The displacement is calculated along the cyan line in panels b and c. b), c) Ice edge evolution during an example ice growth and ice loss event. Shading indicates the ensemble mean SIC during the respective time frame and the white line the ensemble mean ice edge (15 %-SIC). The coloured lines indicate the ice edge (15 %-SIC) during the RICEs in the order orange (first year), yellow, red, green, magenta (last year).

~~of one standard deviation to be related to that event. The relative importance of the investigated drivers is not sensitive to the exact choice of this threshold. Also note that as RICEs can be related to anomalous trends in more than one driver, ratios can add up to more than 100%.~~ There are no significant differences between ice growth and ice loss events, and the forcing is therefore evaluated for ice growth and ice loss events combined. There are also no systematic changes in the relative importance of the drivers during the simulations, suggesting that the forcing of RICEs are unaffected by the mean sea ice state. Numbers are presented for CESM-LE, but the relative importance of the different drivers is similar for CESM-2C (Fig. 4). Based on previous literature we consider three main drivers:

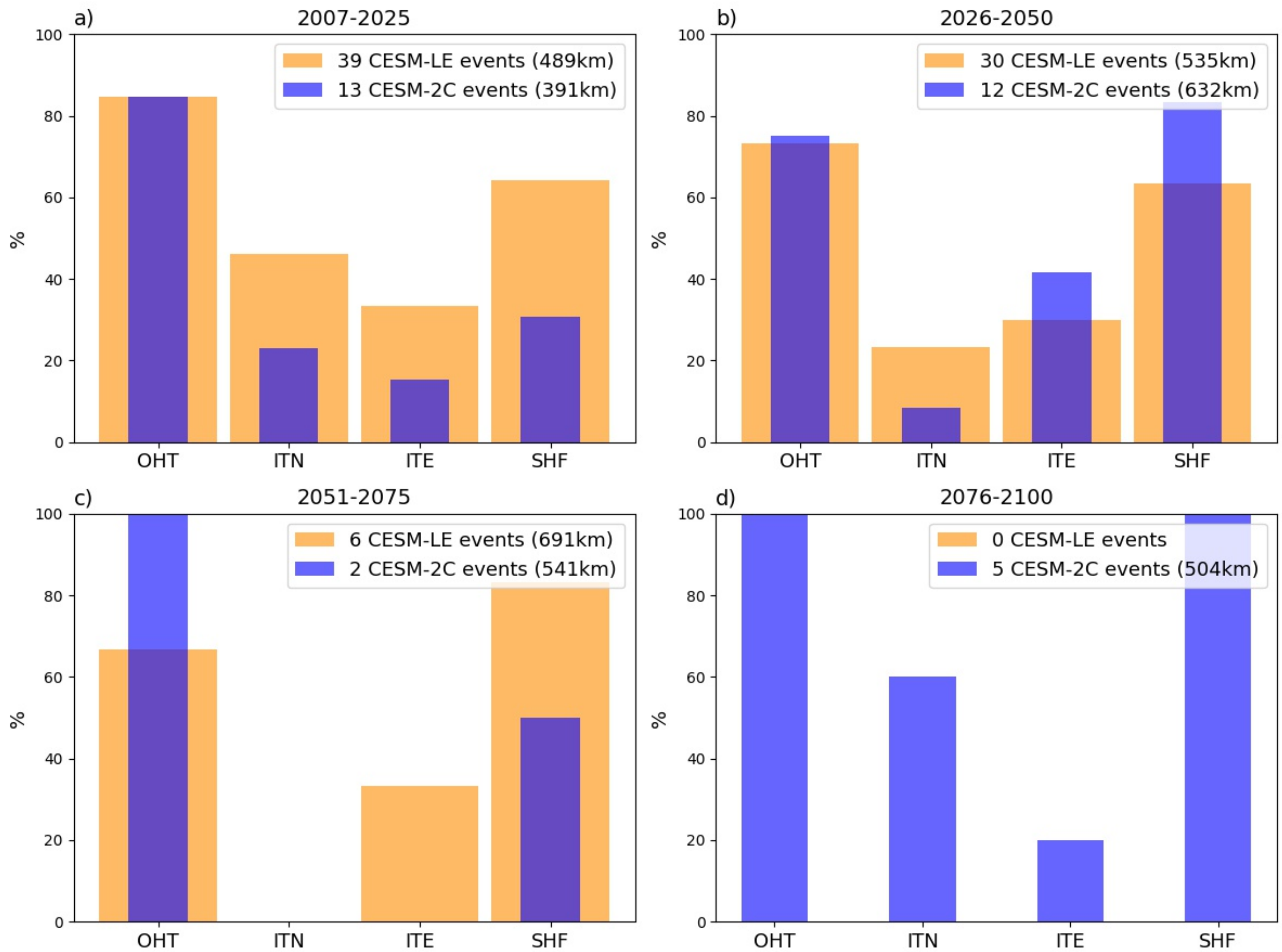

Figure 4. The fraction of RICEs that show a simultaneous trend in the respective forcing parameter of more than one standard deviation. The drivers are BSO ocean heat transport (OHT), ice transport through the northern (ITN) and eastern gateway (ITE) and surface heat flux (SHF) in the southwestern Barents Sea (Figure 5c). Note that as RICEs can be related to anomalous trends in more than one driver, ratios can add up to more than 100 %. The average movement of the sea ice edge during RICEs is provided in the legend.

The fraction of RICEs that show a simultaneous trend in the respective forcing parameter of more than one standard deviation. The drivers are BSO ocean heat transport (OHT), ice transport through the northern (ITN) and eastern gateway (ITE) and surface heat flux (SHF) in the southwestern Barents Sea (Figure 5c).

Ocean heat transport: Previous studies

- **Ocean heat transport (OHT):** Previous studies have found a strong influence of BSO ocean heat transport through the Barents Sea Opening on sea ice variability, with stronger (weaker) heat import leading to less (more) sea ice

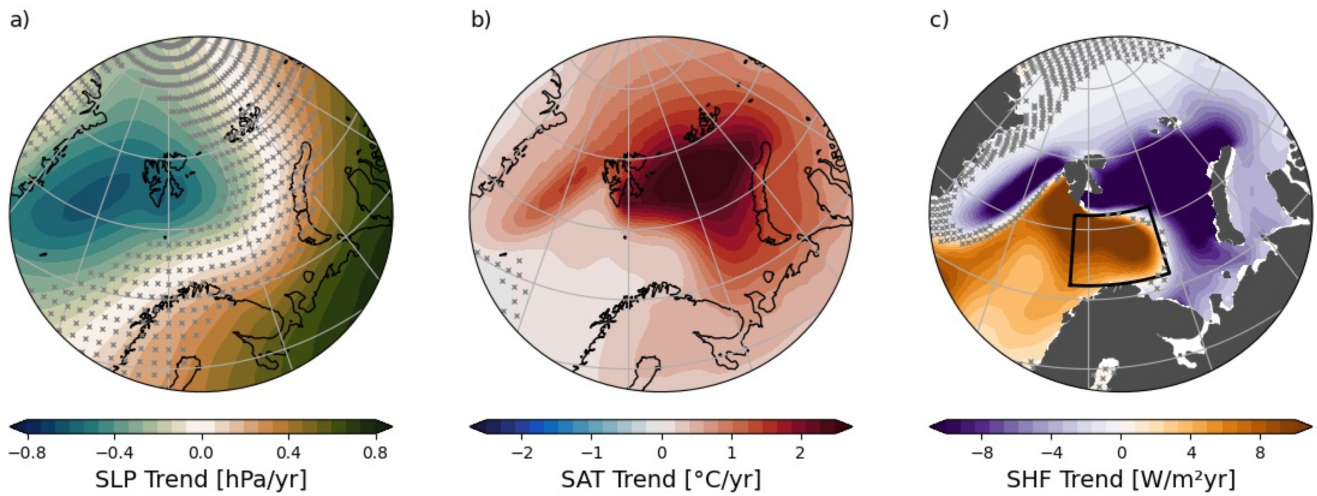

Figure 5. Linear trend of a) sea level pressure (SLP), b) surface air temperature (SAT) and c) surface heat flux (SHF) anomalies during ice loss events, averaged over all events. Ocean heat loss is defined as negative, meaning that positive (negative) anomalies refer to less (more) heat loss. The black box indicates the area for averaging SHF to assess its influence on RICEs. Crosses indicate areas where the trend is not statistically significant at the 95 % confidence level.

(Schlichtholz, 2011; Årthun et al., 2012; Docquier et al., 2021). ~~We~~ In line with these findings, we find ocean heat transport to be the most dominant driver of rapid ice changes. 79~~% (84%)~~ % of all RICEs in CESM-LE ~~(CESM-2C)~~ exhibit a simultaneous trend in ~~OHT~~ ocean heat transport that exceeds one standard deviation (Fig. 4). For ~~5-year-trends~~ 5-year ocean heat transport trends the standard deviation ~~in OHT~~ is 5.8 ~~(5.2) TWyr^{-1}~~ TW yr^{-1}. In comparison, the ~~OHT increase~~ increase in ocean heat transport needed to induce the observed sea ice loss in the Barents Sea since 1979 is approximately 1~~TW yr^{-1} (Li et al., 2017).~~ TW yr^{-1} (Li et al., 2017).

~~*Sea ice transport:*~~

– **Sea ice transport (ITN; ITE):** An increase (decrease) in ice import can be associated with a growing (decreasing) sea ice cover, both via direct import and influences on local ice formation via stratification changes (Kwok, 2009; Lind et al., 2018). This is the case in 33 % and 32~~% (22% and 25%)~~ % of the events for the northern and eastern gateway~~in CESM-LE (CESM-2C)~~, respectively (Fig. 4). The threshold of one standard deviation is ~~$7.4*10^4$ $(8.8*10^4)$~~ $7.4 \cdot 10^4$ km^2~~yr^{-2}~~ yr^{-2} for the northern and ~~$4.3*10^4$ $(5.2*10^4)$~~ $4.3 \cdot 10^4$ km^2~~yr^{-2}~~ yr^{-2} for the eastern gateway. This ~~would mean~~ implies that even the strong increase in ~~ice import between Svalbard and Franz-Josef-Land that observations show~~ observed ice import through the nothern gateway between 1999 and 2003 ~~($6.5*10^4$ km^2 yr^{-2} ; Kwok, 2009) would be slightly~~ ($6.5 \cdot 10^4$ km^2 yr^{-2}; Kwok, 2009) would be too small to be considered relevant for triggering a RICE.

~~*Surface heat fluxes:*~~

– **Surface heat fluxes (SHF):** Changes in atmospheric circulation and associated heat and moisture transport can also influence the sea ice cover (Woods and Caballero, 2016; Boisvert et al., 2016)(Woods and Caballero, 2016; Liu et al., 2022) . In support of this, our results show a negative trend in sea level pressure over the Fram Strait during ice loss events (Fig. 5a) , associated with which corresponds to strengthening westerly winds over BSO the Barents Sea Opening and southerly winds over the central and northern Barents Sea. As a result, surface air temperatures increase in the northern Barents Sea (Fig. 5b) during ice loss. Warmer westerly winds also lead to reduced ocean heat loss in the ice-free southern Barents Sea, whereas more heat is lost in the northern Barents Sea as a result of more open ocean area (Fig. 5c Skagseth et al., 2020)(Fig. 5c; Skagseth et al., 2020). Considering surface heat fluxes in the permanently ice-free southwestern Barents Sea (16-38 °E; 71-76 °N) as a fingerprint of atmospheric forcing of ocean temperature and, hence, sea ice (Schlichtholz and Houssais, 2011), we find 65% (62%) % of the RICEs to be associated with anomalous trends in SHF in CESM-LE (CESM-2C); surface heat fluxes; decreasing (increasing) ocean heat loss corresponding to SIA decline (increase).

Although the different drivers have been assessed and quantified individually, they are to some extent interconnected. For example, ice loss events are associated with an anomalous atmospheric circulation (Fig. 5a) that will influence both ocean heat transport (Herbaut et al., 2015), surface heat fluxes (Skagseth et al., 2020), and sea ice area transport (Kwok, 2009). 51 % of the RICEs exhibit significant trends in both, OHT and SHF, ocean heat transport and surface heat fluxes, emphasizing their interconnection. Most of the variability in OHT on interannual to decadal timescales is a result of varying volume transport which is highly influenced by atmospheric circulation patterns (Muilwijk et al., 2018; Årthun et al., 2019). A detailed analysis of these relationships is not presented here. However, removing (by regression) the linear signal associated with OHT ocean heat transport from time series of regional winds over the Barents Sea suggests that atmospheric circulation (wind) anomalies are mainly affecting the sea ice cover through changes in BSO ocean heat transport, consistent with the findings of e.g. Lien et al. (2017). In general, we find that the relative importance of the different drivers varies somewhat during the simulations, but no systematic change is seen (Fig. 4) . Differences between

The above analysis identifies the fraction of RICEs that are associated with individual drivers. We have also investigated whether the magnitude of individual RICEs relates to the strength of the corresponding trends in any of the drivers (or their linear combination) but find no significant relationships. We note that a clear relationship exists in CESM-LE and CESM-2C are also small and show no consistency, suggesting that the forcing of RICEs remains unaffected by the underlying ice conditions. between trends (5-30 years) in sea ice area and ocean heat transport if all trends are considered and not just those associated with RICEs (Årthun et al., 2019; Dörr et al., 2021). Our results thus suggest that the occurrence of RICEs can possibly be predicted, but not their magnitude, although more sophisticated approaches (e.g., extreme event attribution; Philip et al., 2020) should be explored with respect to the latter.

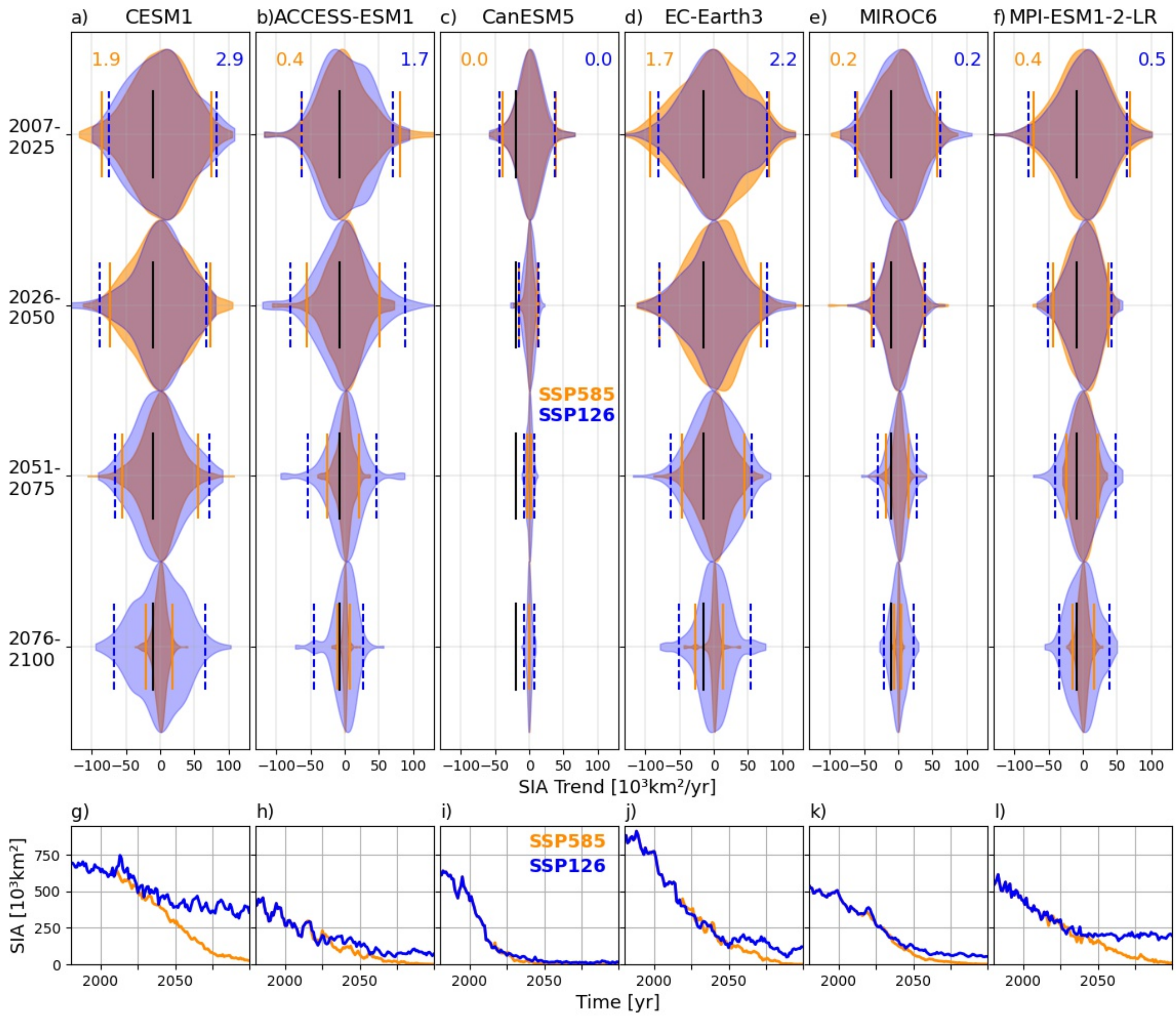

Figure 6. Violin plots showing the distribution of 5-year trends of SIA during different episodes of the 21st century in different model simulations. The orange and blue vertical lines indicate the 95-percentile for SSP585 and SSP126, respectively. The black vertical lines indicate the ~~strongest 30-year~~ externally-forced ice decline ~~in~~ (strongest 30-year trend of the ensemble mean) of the respective SSP585 ~~simulation~~experiment. The ~~numbers indicate the average SIC in the Barents Sea in~~ number of RICEs per ensemble member for the SSP585 (left) and SSP126 (right) experiment ~~for each model during~~ is indicated in the ~~respective time periods~~top panels. The bottom panels show the ensemble mean SIA in the different simulations. For CESM the colors indicate the CESM-LE (RCP8.5; orange) and the CESM-2C (blue).

5 Rapid Sea Ice Changes in CMIP6 models

The occurrence of rapid sea ice changes is further studied in a suite of CMIP6 models. Figure 6 shows the distribution of 5-year trends from the CMIP6 models under two emission scenarios. Most models show a distribution of trends that is fairly similar to, yet slightly narrower than the CESM. An exception is CanESM5 that simulates much weaker trends than the other models, likely as a result of the low average SIA in this model after 2030 (Fig. 6). During the 21st century SIA decreases in all model simulations and the distributions become more confined to weaker trends. Although the models agree on this general behaviour, the future changes in trends differ as a result of the different rates of SIA decline in each model. ~~Trends simulated in the SSP126 experiments~~ After 2050, simulated trends are generally stronger ~~compared to the~~ in the low-warming SSP126 simulations than in the high-warming SSP585 ~~experiments after 2050~~simulations, consistent with a larger SIA ~~.~~ in the former. Only the MPI-ESM1-2-LR simulates a stabilisation of the SIA in the Barents Sea under a low-emission scenario (in agreement with CESM-2C), whereas the other CMIP6 models show practically ice-free conditions at the end of the 21st century even under SSP126 (see also Årthun et al., 2021).

The different mean states in the models are also reflected in the number of RICEs (provided in the top panels in Fig. 6). The CMIP6 model that simulates the largest average SIA in the Barents Sea, EC-Earth3, also simulates most RICEs per ensemble member~~(1.6/2.2 in the SSP585/SSP126-simulation) using the same criterion of 7.7_*10^4 km^2 yr^{-1} (7 times the observational ice loss)~~. However, this model exhibits a very strong ~~anthropogenic~~ externally-forced (ensemble-mean) ice decline (~~represented by the maximum 30-year ensemble mean SIA trend of -15.2*10^3 km^2 yr^{-1} in SSP585 between 1993 and 2022;~~ Fig. 6j), which leads to RICEs in EC-Earth3 being weaker relative to the externally-forced ice loss than in CESM. In contrast, RICEs in ACCESS ESM1 ~~(0.4/1.7 in SSP585/SSP126)~~ are much stronger than the externally-forced ice loss (Fig. 6b,h)~~which is rather small (-7.4*10^3 km^2 yr^{-1} between 1981 and 2010 under SSP585).~~ . RICEs can also be found in MPI-ESM ~~(0.4/0.5)~~ and MIROC6 ~~(0.2/0.2)~~ that simulate average ice loss similar to the CESM-LE~~(-8.3 (1987-2016) and -9.8*10^3 km^2 yr^{-1} (2016-2045) in SSP585).~~ . Only CanESM simulates no RICEs whatsoever in either experiment. This model is characterised by a very strong externally-forced ice loss (~~-18.8*10^3 km^2 yr^{-1} between 1993 and 2022),~~ Fig. 6i), resulting in ice-free conditions as early as 2025. CanESM5 is also the model with the weakest internal variability, evident from the very narrow distribution of sea ice trends (Fig. 6c; also manifested in a narrow ensemble spread in SIA). The weak internal variability in this model has also been noted in other studies (Bonnet et al., 2021). ~~In general, we find that models with stronger internal variability produce more RICEs.~~ We thus conclude that although the CESM seems to represent an upper bound for RICEs in the Barents Sea, they generally occur also in other CMIP6 models. Model differences in the occurrence of RICEs are closely related to average sea ice conditions and the strength of internal variability.

6 Discussion and Conclusion

The Barents Sea is the ~~area~~ region of most intense winter sea ice loss and future projections show a continued decline towards ice-free conditions by the end of this century (Fig. 1; Onarheim and Årthun, 2017). ~~Internal variability in~~ Internal variability of the climate system leads to large interannual and decadal fluctuations that are superimposed on this long-term trend (England et al., 2019). A visible manifestation of these internally-driven fluctuations is the occurrence of large, abrupt changes in the sea ice cover. These rapid ice change events (RICEs) are several times stronger than the externally-forced ice loss and can hence lead to an acceleration, pausing or reverse of the ice decline. In this study we present the first investigation of RICEs in the Barents Sea. We use outputs from two ensemble simulations from experiments from the CESM and multi-member CMIP6 simulations models to investigate the future evolution of winter sea ice variability in the Barents Sea under different emission scenarios. Although CESM simulates the largest number of RICEs, possibly representing an upper bound for their occurence, RICEs are also found at similar rates in most other models. The occurence of RICEs is directly related to average sea ice conditions and hence to future emissions.

Rapid ice loss events RICEs have previously been studied in future climate simulations for the pan-Arctic in summer. Holland et al. (2006) and Auclair and Tremblay (2018) find most of those pan-Arctic events to be associated with anomalies in ocean heat transport which is consistent with our results for the Barents Sea. In addition to OHT ocean heat transport we also investigate the influence of other parametres variables and find a substantial contribution from surface heat fluxes andice transport. This is , to a smaller extent sea ice area transport. Our findings are thus largely consistent with the results from studies focusing on interannual variability in the Barents Sea (Kwok, 2009; Schlichtholz, 2011; Årthun et al., 2012; Nakanowatari et al., 2014; Skagseth et al., 2020). We emphasize that this is not a priori granted, and note that distinct mechanisms have been identified for interannual variability and long-term trends in ocean heat transport into the Barents Sea (Wang et al., 2019). Venegas and Mysak (2000) also found different dominant mechanisms of sea ice variability in the Barents Sea for different time scales. We find no systematic change of the underlying drivers over time, between the emission scenarios or between ice growth and loss events. From this we infer that the underlying processes of driving rapid ice changes in the Barents Sea remain unaffected by global warming and the retreating sea ice.

In this study we have shown the importance of rapid ice changes in the Barents Sea. RICEs are especially important due to the substantial movements of the ice edge, which, as the border between ice-covered and open ocean, is of large importance for climate (e.g., Zhang et al., 2018) and ecosystem processes (e.g., Fossheim et al., 2015). Identifying the leading drivers of RICEs is therefore crucial for understanding and predicting such events and their associated broad impacts. When the Barents Sea approaches ice-free conditions, the area experiencing rapid sea ice changes will retreat past the boundaries of the Barents Sea into the central Arctic and the Kara Sea, a visible footprint of the future Atlantification of the Arctic Ocean (Fig. 1f; Dörr et al., 2021; Shu et al., 2021). change associated with future Atlantification (Fig. 1f; Dörr et al., 2021; Shu et al., 2021) . Our results could therefore provide important insight into future sea ice variability in other Arctic seas. in other parts of the Arctic.

Data availability. All data in this study are publicly available. Output from CESM is available via the Earth System Grid: https://www.earthsystemgrid.org. CMIP6 data are available from the Earth System Grid Federation (ESGF) (e.g., https://esgf-node.llnl.gov/search/cmip6). Observed Arctic SICs are available from https://nsidc.org/data/G10010 (Walsh et al., 2019).

SST from ERA5 is available through the Copernicus Climate Change Service: https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.f17050d7 (Hersbach et al., 2019).

Author contributions. MÅ conceived the study. OR performed the analysis, produced the figures, and wrote the paper. MÅ and JD contributed to improving the manuscript. All authors contributed to the methods design, results analysis and manuscript reviewing

Competing interests. The authors declare no conflict of interests

Acknowledgements. This study was funded by the Research Council of Norway project Nansen Legacy (Grant 276730), and the Trond Mohn Foundation (Grant BFS2018TMT01). We thank D. B. Bonan, L.H. Smedsrud and A.B. Sandø for input and suggestions.

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