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Driving mechanisms of an extreme winter sea-ice breakup event in the Beaufort Sea

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ABSTRACT

The thick multi-year sea ice that once covered large parts of the Arctic Ocean is being replaced by thinner and weaker first-year ice, making it increasingly vulnerable to breakup by storms. Here we use a sea ice model to investigate the driving mechanisms behind a large sea-ice breakup event in the Beaufort Sea in response to a series of storms during February–March 2013. These simulations are the first to successfully reproduce the timing, location and propagation of sea-ice leads associated with storm-induced breakup. We found that rheology in the sea-ice model and horizontal resolution in the atmospheric model are both crucial in accurately simulating such breakup events. The sensitivity of the breakup to the initial sea-ice thickness indicates that large breakup events will become more frequent as Arctic sea ice continues to thin. Here we show that large breakup events during winter have a significant impact on ice growth through enhanced air-sea fluxes in open leads, and enhanced drift speeds which increase the export of old, thick ice out of the Beaufort Sea. Overall, this results in a thinner and weaker ice cover that may precondition earlier breakup in spring and accelerate sea-ice loss.

Introduction

Arctic sea ice is thinning¹ as the area covered by thick multi-year ice (MYI) is decreasing² and is being replaced by thinner first-year ice (FYI) which is more mobile and less dynamically stable^{3,4}. This makes the ice cover more vulnerable to extreme storm events that break up the sea ice. In the Beaufort Sea in particular, the loss of MYI may contribute to the earlier onset of the melt season seen in recent years (arriving earlier by 5–7 days per decade)⁵. In addition, the frequency and intensity of Arctic storms has increased^{6,7}, which has been linked to the reduced sea-ice extent in recent years^{8,9}. In particular, wintertime cyclone activity in the Atlantic sector of the Arctic Ocean has increased by 6 events per decade during the period 1979–2015¹⁰, while an increase of the number of cyclones entering the Beaufort Sea for the period 1948–2002 has been observed⁶. Climate model projections suggest that this trend will likely continue into the mid-21st century^{11,12}. Intuitively, both strong winds and the thinning of sea ice are candidates as contributors to driving extreme sea-ice breakup events, but their relative importance and the implications for polar climate has not yet been established.

When sea ice breaks up it exposes the underlying warmer ocean within narrow, linear openings in the ice cover known as leads. This has important consequences for air-sea exchange, ocean eddies generation and dynamics, sea ice production and Arctic Ocean properties in general^{13–15}, especially during the winter months when heat fluxes over sea ice are generally small¹⁶. In addition, breakup in winter weakens the ice cover and could precondition the minimum ice extent in summer and thus create a positive feedback to Arctic amplification^{17,18}. Therefore, extreme breakup events are of crucial interest for understanding the seasonal and long-term evolution of Arctic sea ice, which in turn affects weather, ecosystems and local communities in polar regions and beyond^{19,20}.

Several studies have investigated the impact of storms on Arctic sea ice cover^{14,21,22}. However, when it comes to modelling individual breakup events, and accurately reproducing the spatial distribution of sea-ice leads, there have been few successful attempts^{22,23} and breakup events are not well captured in current sea-ice and climate models²⁴. This presents a critical gap in our understanding of atmosphere-ocean-ice interaction processes and limits the credibility of future projections of climate in polar and sub-polar regions²⁵. This paper is the first step towards filling this gap by presenting high-resolution simulations using the next-generation sea-ice model — neXtSIM^{23,26,27} — focusing on a large breakup event that occurred in the Beaufort Sea during February–March 2013. This event, which was captured by the Visible Infrared Imaging Radiometer Suite (VIIRS) of the

37 Suomi NPP satellite²⁸, coincided with a high-pressure system centred over the northwest Beaufort Sea (Fig. 1a) that drove
38 the strong winds and fractured the ice cover. The objective of this study is to identify the key factors driving such wintertime
39 sea-ice breakup events and provide a first estimate of the consequences of these events for the Arctic sea ice volume budget.

40 Simulating the 2013 sea-ice breakup event

41 We simulated the breakup event using the neXtSIM model in a stand-alone configuration, in the present case forced by the
42 ERA5 atmospheric reanalysis downscaled using the polar-optimized version of the Weather Research and Forecasting model
43 (Polar-WRF) to a horizontal resolution of 10 km (i.e. WRF10; see "Methods" for details). Snapshots of observed and simulated
44 leads during the breakup event are shown in Fig. 1b and c for February 18, February 23 and March 1. The satellite observations²⁹
45 show that a fracture was already present by mid-February at Point Barrow in the western Beaufort Sea within an area covered
46 by FYI (Fig. 1b). Over the next few days, large pieces of ice started to break off and be transported towards the Chukchi Sea.
47 On February 23 an extensive arch-shaped fracture about 1000 km long and ~4 km wide had formed, extending across nearly
48 the entire Beaufort Sea, with secondary fractures on the leeward side. By the end of February the fracturing had expanded
49 towards Banks Island in the east, at which point the ice cover was broken up and consisted of a myriad of free-drifting plates
50 and floes. The simulated lead distribution and propagation shows remarkably good agreement with the observations (Fig. 1c),
51 with leads appearing as regions of low sea ice concentration in the otherwise dense pack ice. In particular, the model captures
52 the characteristic arch-shaped wave of fractures, first opening close to Point Barrow in mid-February and then propagating
53 progressively east towards Banks Island.

54 The ability of the model to reproduce the observed breakup pattern depends strongly on accurately capturing the location
55 and propagation of strong winds. The storm-passage and the associated ice drift is shown in Fig. 2a and b, along a transect
56 running perpendicular to the primary fracture propagation in the Beaufort Sea. By comparing the direction of wind vectors
57 (Fig. 2a) relative to the lead propagation direction, we find that the fractures form as a consequence of failure under shear
58 stress associated with winds blowing parallel to the Alaskan coast in a southwesterly direction, i.e. away from Banks Island,
59 whereby ice breaks approximately tangentially to the coast³⁰. Once the wind speed exceeds a critical value (about 10 m s^{-1})
60 the internal stresses in the ice pack become such that the ice starts to fracture in a step-like manner matching the timing of the
61 storm-passage (Fig. 2b). This critical threshold likely depends on multiple factors including ice thickness and concentration,
62 wind direction and sea-ice floe size distribution^{3,31}.

63 Another important factor in getting the right characteristics of the breakup is the new brittle-like rheology formulation (here
64 the Brittle Bingham-Maxwell – BBM³²) employed in the neXtSIM simulations. In particular, the arch-shaped deformation (in
65 response to accumulating sea ice damage) and threshold mechanics seen in both observations and the simulation is a behaviour
66 that is characteristic of the brittle nature of sea-ice mechanics^{27,33}. In comparison, this is not adequately resolved in traditional
67 elastic-viscous-plastic (EVP) or modified EVP (m-EVP) models, which typically require being run with a horizontal resolution
68 of about 1 km — between one and two orders of magnitude higher than what used in the latest CMIP6 climate models — in
69 order to represent sea-ice deformation features at smaller scales^{22,24}. This can be seen from the neXtSIM simulations performed
70 using the EVP and m-EVP rheologies instead of the BBM (see Supplementary Figure 1). Both EVP and m-EVP simulate a
71 much smoother ice velocity field and does not capture the fracture propagation as obtained with the BBM.

72 Impact of atmospheric resolution on sea ice breakup

73 Accurate representation of wind forcing plays a key role in modelling sea ice deformation, but this forcing depends on the
74 atmospheric model and the resolution of the model. Regional atmospheric properties, such as storm dynamics and horizontal
75 gradients are generally more skilfully reproduced at higher resolution³⁴. To test how the simulated breakup is affected by the
76 resolution of the atmospheric forcing we performed additional experiments with different resolutions of the Polar-WRF model
77 (10, 20, 40 and 80 km). Despite relatively modest differences in the location and amplitude of maximum winds for the different
78 simulations (Supplementary Figure 2 and 3), we obtain major differences in the simulated breakup pattern. In Fig. 2c the
79 propagation of leads in the Beaufort Sea is visualised by looking at the 5-cm s^{-1} ice velocity contour, which tracks the eastward
80 movement of the primary fracture. This is compared to the observed leads from satellite (see "Methods"). Both simulations
81 forced by the 10-km and 20-km resolution winds show the very characteristic progressive wave of fractures from Point Barrow
82 to Banks Island which matches the timing of the observed sequence of lead openings quite well, although slightly faster than
83 observed. Whereas for the simulations forced by low-resolution winds (40- and 80-km), the ice immediately breaks much
84 further east closer to Banks Island instead of showing an eastward propagation of fractures as seen in the higher resolution runs,
85 and in the observations.

86 The improved breakup pattern can be attributed primarily to the difference in the simulated winds in the Beaufort Sea at
87 high and low resolutions. In particular, the propagation of the storm is better constrained at higher resolution (10- and 20-km),
88 the gradients in the wind field are sharper, and high wind speeds are more localized, particularly along the coast and at Point

Barrow where it creates strong local shear stresses on the ice (Supplementary Figure 2). In comparison, at lower resolution (40– and 80–km) stronger winds, exceeding 10 m s^{-1} , extend further east into the central Beaufort Sea at the start of the breakup event and the storm-passage happens less gradually. Note that this difference is not purely due to the resolution of the wind field, but is related to how the atmospheric dynamics behave at these higher resolutions. The importance of capturing the proper atmospheric dynamics related to the storm was further demonstrated by running a simulation forced by the global ERA5 reanalysis at 31–km resolution³⁵ and another simulation where we coarse-grained WRF10 to the WRF80 grid (not shown). Here we found that the ERA5 simulations performed similarly to the WRF80 despite the higher resolution of the ERA5 forcing (Supplementary Figure 3), whereas the WRF10 coarsened to the WRF80 resolution performed similarly to the WRF10 simulations. This suggests that not only the resolution, but also the quality/tuning of the atmospheric model (e.g. improved parameterisations optimised for polar regions) is an important factor for simulating ice deformation³⁶.

Thinning sea ice accelerates storm-induced breakup

Following the minimum extent in 2012, the ice cover in the Beaufort Sea was exceptionally thin and weak in winter 2013³⁷, which may have preconditioned the breakup. Indeed, and as suggested by P. Rampal and collaborators³, long-term sea-ice thinning could be expected to weaken the ice cover further and increase deformation rates. To test how the initial ice conditions affect the breakup, we first reduced the ice thickness at the start of the breakup by 50% ($0.5 \cdot \text{SIT}$; Fig. 3). Next, we consider what happens if the ice was thicker by increasing the initial thickness distribution by 50% ($1.5 \cdot \text{SIT}$) and 100% ($2.0 \cdot \text{SIT}$). The average thickness in the Beaufort Sea for the three scenarios is 0.69 m, 2.01 m and 2.75 m respectively (compared to 1.37 m in the control experiment). Thus, for $0.5 \cdot \text{SIT}$ the winter ice cover mostly consists of thin FYI which is projected to occur before the end of 2100 by CMIP6 models (Supplementary Figure S4). The remaining two cases reflect sea ice conditions prior to the 2000's when the ice in the Beaufort Sea was considerably thicker (more than 2 m based on submarine measurements over the period 1975–2000³⁸).

When the ice is thinner it breaks up more easily and becomes more mobile, while for thicker ice the threshold for initiating breakup is higher. This is because thicker ice cover has a higher mechanical strength compared to thin ice, limiting its fragmentation, which both control the overall ice mobility³. This relationship between thickness and mobility is reflected in the ratio between ice drift and wind speeds (Fig. 3a), which increases with thinner ice, consistent with observations showing that in areas covered by FYI, the ratio is relatively large³⁹. As a result, the ice cover is more damaged when the ice is thin ($\text{SIT} \cdot 0.5$), with more leads (lead fraction increases by $\sim 3\%$), while for thicker ice ($\text{SIT} \cdot 1.5$ and $\text{SIT} \cdot 2.0$) stronger winds ($> 14 \text{ m s}^{-1}$) are required to break up the ice and there is a large reduction in the drift speed to wind speed ratio. The start of the breakup also occurs progressively later with increasing thickness (Fig. 3b), a direct consequence and illustration of thicker ice being more resistant to breakups. On February 21 for $1.5 \cdot \text{SIT}$ and around March 1 for $2.0 \cdot \text{SIT}$. The location where the ice initially breaks also shifts from Point Barrow closer to Banks Island, which is where the winds are strongest. The fact that the breakup still occurs even if the ice is significantly thicker and stronger implies that storm dynamics did play a dominant role in the 2013 breakup event and that similar events likely occurred in the past too. Indeed, estimates of lead occurrence in the Beaufort Sea over the last 20 winters from 1993 to 2013 show that breakup events also took place several decades ago when the ice was significantly thicker³⁰.

Local impact on ice thickness and volume

Opening of sea-ice leads exposes the relatively warm ocean to the cold atmosphere above, resulting in stronger heat and moisture transfer from the ocean to the atmosphere. Locally, heat fluxes upwards of 300 W m^{-2} are found in open leads in neXtSIM (Supplementary Figure 5), similar to those found from observations¹⁶. The enhanced ocean heat loss promotes new ice growth within the leads thereby affecting the ice thickness distribution in the Beaufort Sea (Fig. 4a). During the breakup the median thickness increases from 1.29 m to 1.45 m (16 cm), corresponding to a net increase of 113 km^3 in ice volume (Fig. 4b and Supplementary Table 1).

Changes in ice volume occur due to ice growth (thermodynamics) and ice advection (dynamics). First, we consider the thermodynamic growth in response to the sea ice breakup. The storm happened in mid-winter at a time when the ice cover is growing thicker. Thus, to isolate the storm-induced growth from the ice thickening in “normal” conditions, we estimated the growth for the leads and pack ice separately (see “Methods”), as shown in Fig. 4b. The total thermodynamic ice growth (leads + pack ice) in the Beaufort Sea from February 13 to March 13 is 346 km^3 . This corresponds to an average growth of 25.5 cm over the whole Beaufort Sea, and is dominated by ice growth in the pack ice which contributes about 80% (279.2 km^3) of the total growth. Thus, the ice formed in leads contributes with a $\sim 20\%$ increase (67 km^3) to the local ice volume. This gives an average growth rate of $\sim 20 \text{ cm day}^{-1}$ within leads (Supplementary Figure 6), which for instance is comparable to growth rates observed in open water due to supercooling⁴⁰.

Next, to fully understand the impact of the breakup on the sea ice mass budget we examine the ice transport in the Beaufort region (Fig. 4c). As the ice cover becomes more fractured and mobile, more ice is also transported out of the Beaufort Sea as a consequence of the strong (westerly) winds and enhanced drift speeds shown in Fig. 3a. During the storm passage there is a net ice export of 240 km³, implying that more than 2/3 of the ice formed by thermodynamic processes is transported out of the region. Overall, the increased volume export dominates over the thermodynamic growth thereby contributing to decreasing ice volume locally (Fig. 4b). This indicates that extreme winter breakup events may have a negative impact on the regional sea ice mass balance, resulting in less ice altogether compared to years without any breakup. We find that, in the initial stage of the breakup, it is predominantly FYI (<1.6 m thick) located in the central- and southwestern Beaufort basin that is being exported westward into the Chukchi Sea (see inset in Fig. 4a). When the fractures reaches Banks Island on March 1 it mobilises the thicker, older ice (>1.6 m) which is subsequently transported to the Canadian Basin. This pattern is largely consistent with the climatological mean ice flow in the Beaufort Sea, following the anticyclonic motion of the Beaufort Gyre⁴¹. Towards the end of the breakup the ice flux decreases associated with a reversal of the winds to the southeast (Fig. 2a) driving enhanced transport of MYI located in north of Greenland into the Beaufort Sea where it replenishes the dynamic ice loss, but also becomes more vulnerable to summer melt⁴².

Challenges simulating extreme breakup events

Our findings show that we are able to successfully capture the main features of the 2013 breakup, and highlight the importance of the atmospheric forcing and sea-ice conditions as key components in preconditioning and triggering the event. When it comes to the long-term impacts of the breakup there are some notable limitations of the current study. In particular, the lack of atmospheric and oceanic feedbacks has potential implications for air-sea interactions and their wider impacts on Arctic sea ice. Opening of sea-ice leads has considerable influence on the atmospheric boundary layer (ABL)⁴³. For example, the emission of oceanic heat within leads warms the ABL (near-surface temperature increases by more than 20°C over simulated leads; not shown) which could increase the convective potential of the storm, driving further breakup and enhancing ice production. On the other hand, low-level clouds are often found over leads^{14,28} further increasing the downward long-wave radiation which reduces surface heat loss and inhibits thermodynamic ice growth. Similarly, the presence of snow on ice, resulting from enhanced precipitation during storms, can significantly slow-down the thermodynamic growth process¹⁴, which would cause us to overestimate the ice growth associated with the breakup.

Storm-induced changes in the sea-ice state, e.g. from enhanced ridging or reduced concentration, will influence the atmosphere-ice momentum transfer⁴⁴, but this is not captured when using a constant atmospheric drag coefficient. At the ice-ocean interface the opening of leads can trigger eddy generation through increased buoyancy flux which in turn affects large-scale ice dynamics and drift¹³. The increase in drift speeds promotes significant increase in ocean mixing and drives enhanced bottom melt by mixing up warmer water from below^{14,21}. As most of these processes and feedbacks occur in areas of high deformation rates (shear or convergence) only models that properly capture small scale sea-ice dynamics can be used to study these processes. In this respect, a model like neXtSIM, which includes a brittle rheological framework based on damage propagation to simulate sea-ice dynamics, is a much more appropriate candidate^{23,27,32}. Furthermore, they also occur on small spatial and temporal scales, thus highlighting the need for developing sub-grid scale parameterisations if such processes are to be included in global climate models.

Potential implications for Arctic sea-ice loss

There are two main competing effects when it comes to the impact of sea-ice breakup events on the Arctic sea ice mass balance. Opening of leads in winter increases ice production and therefore we could expect such events to have a positive impact on the Arctic volume budget. On the other hand, ice breakup increases the mean drift speed of the ice pack and with this there is a tendency towards stronger volume export out of the Arctic⁴. The seasonality, i.e. the time of year when the breakup occurs, is also important. Whereas breakup in winter results in enhanced ice growth, lead opening in summer, however, accelerates sea ice thinning by decreasing the albedo and allowing more shortwave absorption by the ocean³.

We cannot directly assess the impact of winter leads on the wider Arctic sea ice at seasonal time-scales or longer due to the absence of potentially important feedbacks detailed above, and the relatively short time frame considered here. However, recent findings suggest that the downstream effects of sea-ice breakup in winter can lead to an overall reduction in Arctic sea ice in the long term. Arctic winter storms may precondition the ice cover for a faster summer melt by promoting enhanced lateral melt rates in deformed sea ice¹⁴. Similarly, more leads in winter may affect the evolution of Arctic sea ice throughout the melt season, as the thinner and weaker sea ice in refrozen leads is more vulnerable to atmospheric forcing (e.g., cyclones entering the Arctic in summer)¹⁷. This can lead to earlier breakup and increase the lead fraction in summer which accelerates the ice-albedo feedback and further loss of Arctic sea ice¹⁸. To put this into perspective, however, the Arctic sea ice volume

actually increased in 2013 after the anomalously low melting in the summer⁴⁵, implying that other factors (like atmospheric variability) are important for controlling year-to-year variations in the Arctic sea ice mass budget.

We have shown that the effect of storm-induced breakups is likely to become more pronounced in the future, as the ice pack transitions toward younger, thinner sea ice. Even if the frequency and intensity of Arctic storms remains unchanged, the thinning of sea ice alone will lead to more severe and frequent breakup events. However, the frequency of extreme cyclones entering the Arctic is also likely to increase in the future¹⁰ which will only increase the importance of cyclones on the sea ice mass budget. As sea ice in the Beaufort Sea continues to thin², it becomes more vulnerable to storm-induced breakup during winter months and could accelerate the loss of MYI currently residing in the Central Arctic. These findings highlight that winter breakup events may lead to a faster reduction in Arctic sea ice volume than currently projected by coupled climate models⁴⁶.

Methods

Description of the neXtSIM sea-ice model

Here we use the stand-alone-version of the sea-ice model neXtSIM to study the 2013 breakup event in the Beaufort Sea. NeXtSIM is a finite-element sea-ice model that uses a moving Lagrangian mesh^{26,27,32,47}. The dynamical core of neXtSIM is a rheology with a brittle behaviour, whereby the ice in individual mesh triangles can “fail” if they experience too high a stress — then their internal stress drops towards zero and the applied stress must be supported by neighbouring triangles that may then fail as well. This behaviour leads to a cascade in damage and manifests in the production of linear kinematic features like cracks and leads. Such models are ideal for simulating breakup events like the one we are targeting in the 2013 winter.

The latest version of neXtSIM uses the BBM sea-ice rheology³², which mainly differs from previous versions of the rheology in the way it prevents excessive convergence — in the case of BBM, it uses a Bingham friction element that is independent of the damage parameter to do this, while previous versions used ice pressure terms in the sea-ice momentum balance. The simulation domain that we use covers the central Arctic and has a spatial resolution of about 10 km (approximate distance between nodes of the moving triangular mesh).

Atmospheric and oceanic forcing

The sea ice model receives daily-averaged ocean forcing fields (30-m-currents, surface temperature and salinity, and mixed layer depth) from the TOPAZ4 reanalysis for the sea ice and ocean⁴⁸. For the atmosphere, we use hourly atmospheric forcing fields (10-m-winds, rainfall, snowfall, surface temperature, pressure, and specific humidity) from the polar-optimized version of the Weather Research and Forecasting model version 3.9.1 (Polar-WRF)³⁶. The Polar-WRF atmospheric model is based on the standard WRF model, but has been optimized for polar applications by implementing a specification of sea-ice thickness and snow depth over sea ice. The vertical grid encompasses 60 hybrid model levels with a grid spacing of about 8-10 hPa in the lowest 3 levels. The value of the atmospheric drag coefficient is 0.0016 and is spatially uniform throughout the domain. WRF is configured following the Antarctic Mesoscale Prediction System. Both the oceanic and atmospheric forcing variables are interpolated temporally and spatially onto the model grid at run time using a linear and bilinear interpolation method, respectively.

The WRF output is a dynamical downscaling of the European Centre for Medium Range Weather Forecasts (ECMWF) operational analyses. The analyses provide the initial and 6-hourly boundary conditions of the WRF simulations. Further, the model interior is nudged towards the ECMWF analyses at scales larger than approx. 650 km. We tested four different horizontal resolutions of the Polar-WRF downscaling (10, 20, 40 and 80 km) to investigate the role of atmospheric resolution on simulating the 2013 breakup event. These are referred to as WRF10, WRF20, WRF40 and WRF80. In addition, to test the impact of using a polar-specific atmospheric model we performed a model run with the standard global reanalysis from ERA5 with a horizontal resolution of 31 km (Supplementary Figure 3).

Initial conditions

All the neXtSIM simulations are initialised with sea-ice fields from CS2-SMOS⁴⁹ and are integrated from February 13 to March 13, 2013 covering the storm passage. The rationale for choosing this relatively short time period, is that we wish to focus primarily on the dynamics of the breakup. To address the long-term impacts will require running longer simulations ideally in a coupled framework over multiple years, which is beyond the current scope of this study. Instead we focus on the immediate impacts of the breakup event (i.e. on new ice growth, changes in ice drift, and ocean-atmosphere heat fluxes).

To explore how the breakup is affected by the initial sea-ice thickness conditions, we consider three cases: initial ice thickness (on February 13) is reduced uniformly by 50% (0.5*SIT), and two cases where ice thickness is increased by 50% (1.5*SIT) and 100% (2.0*SIT) respectively (see Supplementary Figure 4). Note that the atmospheric forcing (i.e. wind strength etc.) is the same for all these experiments (WRF10).

Comparison to satellite observations

To evaluate the simulated sea ice deformation and lead formation in neXtSIM, we take advantage of the lead detection product based on Moderate Resolution Imaging Spectroradiometer (MODIS) thermal infrared imagery²⁹. This product provides daily wintertime Pan-Arctic categorical lead maps at 1-km resolution including lead class, artefacts, sea ice, clouds, open water and land mask, covering the period 2003–2015. The 2013 breakup event is clearly visible in the MODIS data (Fig. 1b) as long linear features within the Beaufort Sea ice pack. We compare the simulated lead propagation to the MODIS data in Fig. 2c by downsampling the high-resolution ArcLeads product (1 km) onto the neXtSIM grid. Grid-cells classified as open water (i.e. leads) are then plotted as black horizontal lines along the transect.

Estimating storm-induced ice growth

From the sea-ice model we obtain the thermodynamic growth rate (in m s^{-1}) at each model time-step for three ice thickness categories: *new ice* (ice formed in open water due to supercooling), *young ice* (ice thinner than ~ 25 cm) and *old ice* (ice thicker than ~ 25 cm). Generally, it is assumed that the growth in leads consists of frazil ice growth in open water and young ice formation, whereas the growth of old ice typically occurs in the pack ice. The total cumulative volume growth is then calculated for each of these categories by multiplying the growth in meters by the grid cell area and summing each cell in the Beaufort Sea region. Note that the dynamic thickening (e.g. due to ridging) is not considered in the growth estimates, but could be considerable within leads⁵⁰.

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Author contributions statement

J.W.R designed the experiments, carried out the neXtSIM simulations, analysed the model outputs, made all the figures (except Supplementary Figure 4e which was done by R.D.) and wrote the paper. E.O., R.D. and P.R. helped in developing this study that is based on the original idea of P.R., and participated in constructive discussions that helped improve the paper. C.S. performed the simulations of the Polar WRF model. T.W. helped set up the neXtSIM experiments, and contributed to writing and discussions. All authors reviewed the manuscript.

Figure 1. Extreme breakup of the Beaufort Sea winter ice cover (a) Schematic map of the Arctic Ocean with the observed winter sea-ice thickness from CS2-SMOS in colors and the ice flow field from neXtSIM on February 23 shown by arrows. Solid, grey lines represents mean sea-level pressure from ERA5. (b) Daily categorical lead map based on satellite data (MODIS)²⁹, where blue colors corresponds to sea ice leads. (c) Simulated lead fraction (in %) using the 10-km Polar-WRF downscaling ("WRF10") as the atmospheric forcing. The lead fraction is calculated as the combined fraction of open-water and sea ice thinner than ~ 25 cm in each grid cell (1-sic + sic_thin). Both the observed and simulated sea-ice leads are shown on February 18, February 23 and March 1 in the Beaufort Sea during the 2013 breakup event. ERA5 data in **a** were obtained from the [Copernicus Climate Change Service Climate Data Store](#). A time-lapse of the simulated and observed breakup event can be found in the Supplementary Movie 1 and 2.

Figure 2. Time series of simulated winds and ice drift in the Beaufort Sea during the breakup event. (a) wind speed and direction (red arrows), (b) sea-ice velocity, (c) sea-ice lead propagation simulated with different atmospheric resolutions (coloured lines) indicated by the 5-cm s^{-1} ice velocity contour. Detected sea-ice leads based on the ArcLeads product are shown by black lines²⁹. All variables are calculated along a transect running from the western Beaufort Sea (close to Point Barrow) to Banks Island in the east. The inset in **b** indicates its geographical position. Black lines in **a** and **b** represent the 10-m s^{-1} wind-speed and 5-cm s^{-1} ice velocity, respectively. Vectors in **a** shows the average wind speed along the transect, with the direction relative to the transect.

Figure 3. Relationship between sea ice thickness and extreme breakup events. (a) Time series of mean ice velocities averaged over the Beaufort Sea and maximum winds (grey dashed line) in the direction along-transect (inset in Fig. 2b). (b) Average lead fraction (as a % of the total Beaufort Sea area). Here, a grid cell is considered a lead when the combined concentration of open-water and thin ice (less than ~ 25 cm) is larger than 5%. Otherwise it is considered pack ice. The area of the Beaufort Sea region is indicated in the inset in Fig. 4a.

Figure 4. Impact of storm-induced sea-ice breakup on ice growth and ice export. (a) Histograms of the normalised sea-ice thickness in the Beaufort Sea region before (blue) and after (orange) the breakup event. (b) The cumulative ice volume growth in the Beaufort Sea calculated for three different ice categories: new ice (ice formed in open-water; blue line), young ice (orange line) and old ice (green line). See "Methods" for specific details. The dashed grey line represents the change in Beaufort ice volume (ΔSIV) relative to the start of the simulation, and is the combination of dynamic and thermodynamic process, i.e. ice import/export and ice growth. (c) Time series of sea-ice volume flux (in km³), where positive values corresponds to an export of ice out of the Beaufort Sea. The total flux is split into contributions from newly formed ice (SIT < 1 m), FYI (1 < SIT < 1.6 m) and MYI (SIT > 1.6 m). All the data are based on the WRF10 experiment. The inset in a outlines the Beaufort Sea area with coloured contours showing the initial sea-ice thickness (on February 13) corresponding to the thickness classes used in c.

Supplementary Files

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