https://doi.org/10.5194/egusphere-2026-3855
Preprint. Discussion started: 27 July 2026

Review article: Arctic polynyas in a changing climate

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Abstract. The Arctic is the fastest changing region in the world. Its atmosphere is warming 3-4 times the global average; the ocean is warming through increased advection of heat from the Atlantic and Pacific; the sea ice cover is disappearing, thinning, and becoming more mobile. The interactions between ocean, ice and atmosphere are also evolving. These changes are manifest in polynyas, openings in the sea ice that are crucial for exchanges of heat, moisture, momentum and gases between ocean and atmosphere, but also for ecosystems, Indigenous communities, and navigation. We here review how polynyas and their impact on the climate system have changed throughout the satellite record, focussing on the last twenty years. The trend is of fewer but larger polynyas that open for longer, unless they depend on ice arches (in which case they are shorter-lived). Many regions have switched from "latent heat" polynyas, only driven by dynamics, to "hybrid", where the heat from ocean or atmosphere matters. Consistent with that switch and with an overall warming and wetting of the atmosphere, moisture fluxes from polynyas in winter seem to be decreasing despite an increase in polynya area. How this will impact the low altitude clouds, generated by polynyas and that help maintain polynyas, has not been studied. Similarly, sea ice production in polynyas is decreasing at the pan-Arctic scale. In the ocean's Eurasian basin, process studies suggest a conflict between this switch to hybrid polynyas (suppressing dense water formation) and Atlantification (favouring it). In the Amerasian basin, where upwelling of warm water is necessary for dense water formation, this should be enhanced, but it also facilitates the inflow of warm water into the Greenland glacial fjords. In all components of the climate system, large uncertainties remain because of the lack of direct observations and the lack of continuous time series in the atmosphere, ice, and ocean.

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1 Introduction: The changing Arctic

Polynyas are recurrent openings in the sea ice, caused predominantly by strong winds but also preconditioned by thin ice, warm air, or warm upwelling of oceanic waters (see section 2). As polynyas provide a window of light into the ice-covered ocean, a breathing hole, and are often associated with vertical upwelling of nutrients, they are ecosystem hotspots (Karnovsky et al., 2007; Moore et al., 2023) and have thus long been used as a food source for Indigenous communities and as hunting ground by whalers (e.g. Hastrup et al., 2018). Polynyas were identified early on as crucial for submarine surfacing in winter (Lyon, 1961) and for Arctic navigation, notably through the northwest and northeast passages, but also for researchers to reach their area of interest faster (e.g. Rabe et al., 2022). That is, polynyas have long played a crucial socio-economic role for humans in the Arctic. Changes in polynyas in response to changes to the wider Arctic climate system are therefore of relevance to all. The topic of this review is however limited to their crucial role for the climate system. The last review of Arctic polynyas is now two decades old (Smith Jr and Barber, 2007) and this paper provides an update in the context of a rapidly changing Arctic.

The atmosphere: The Arctic atmosphere has changed dramatically over the last decades in response to anthropogenic greenhouse gas emissions (Masson-Delmotte et al., 2021). Through a process known as "polar amplification", the Arctic atmosphere has been warming faster than anywhere else in the world, nearly three to four times as fast as the global average (Rantanen et al., 2022). Polar amplification had first been identified in climate models (Manabe and Wetherald, 1975; Manabe and Stouffer, 1980), with Holland and Bitz (2003) finding an upper limit of 4.5 times the global average, but we had to wait until Serreze et al. (2009) for it to be established as an observed feature of the Arctic.

Recent thermodynamical changes in the Arctic atmosphere are not limited to the warming of surface air temperature. Boisvert et al. (2018) report that the total amount of precipitation has not changed significantly over 2000-2016, but with warmer air the rain-to-snow ratio has increased, with rainfall increasing between 1 and 6 mm/ year depending on the reanalysis product. Similarly, the onset of rain-on-snow events has shifted early by 4 to 6 days per decade (Dou et al., 2021). The authors of both studies acknowledge that owing to the extreme scarcity of in-situ meteorological observations over the Arctic Ocean region, such estimates have to rely on uncertain reanalyses (see Boisvert et al., 2018, for a quantification of the uncertainty and intercomparison of the reanalysis products).

Extreme temperature and precipitation events are also becoming more intense and more frequent in the Arctic, as recently reviewed by Zhang et al. (2025). The probability of extreme daily temperature in winter, i.e. winter heatwaves, has increased from 8% pre-2000 to 28% since (Zhang et al., 2025), and their magnitude has been increasing twice as fast as that of the mean temperature (Moore, 2016). The duration of these warm events (T2m > -10°C) has also been increasing, by 4 days per decade (Graham et al., 2017). Poleward moist air intrusions — such as atmospheric rivers, which transport extreme moisture (and heat) toward the Arctic — have also increased in frequency, nearly doubling during December and January from 1990 to 2012 (Woods and Caballero, 2016).

The atmospheric dynamics have also been changing over the last two decades. Of relevance to polynyas, i.e., the opening of sea ice, more extra tropical cyclones formed in the North Atlantic and North Pacific reach the Arctic during the shoulder seasons, and more cyclones are forming locally in the Arctic in summer (Li et al., 2026) and in winter (Valkonen et al., 2021).

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Year-round, the frequency and magnitude of extreme monthly winds has slightly increased (Stegall and Zhang, 2012; Zhang et al., 2025). To our knowledge, there is no study on trends in extreme wind events in the Arctic; however, as pointed out in the review by Zhang et al. (2025), publications on this topic are near-absent before 2000, but have been proliferating over the last decade (e.g. Moore et al., 2018; Mallett et al., 2021; Rheinlænder et al., 2022; Blanchard-Wrigglesworth et al., 2022), suggesting a recent increase in extreme winds during winter.

The ocean: Human-induced climate change also affects the ocean. The Arctic Ocean receives water both from the Atlantic, through Fram Strait and the Barents Sea Opening, and from the Pacific through Bering Strait (Fig. 1). All inflows have been warming up and remaining warm further into the Arctic, through a process jointly known as the "borealization" of the Arctic (Polyakov et al., 2020). On the Atlantic side, the "Atlantification" of the Barents Sea sector was first identified by Årthun et al. (2012), who referred to the situation where a prolonged excess heat inflow through the Barents Sea Opening may overcompensate winter ice production over an increasing area in the Barents Sea. An increasing trend in the heat transport through the Barents Sea Opening since the 1980s of +20 TW, corresponding to about a third of the mean state value and equivalent of 0.9°C, was reported in the same paper (Årthun et al., 2012). The Barents Sea, which already received two thirds of the Atlantic inflow oceanic heat (Skagseth et al., 2008), dissipated this extra heat primarily through ice melting (Smedsrud et al., 2022). There are however indications that the Barents Sea "cooling machine" has now reached its limit and cannot dissipate more (Gerland et al., 2023), although others argue that the cooling has simply shifted northward (Shu et al., 2021). This warming signal appeared to be a starting point of the long-lasting general warming trend in the Atlantic Water layer in the Nansen Basin (e.g. Polyakov et al., 2005, 2020; McPherson et al., 2026), interrupted by intermittent cooling events (Polyakov et al., 2011; McPherson et al., 2026). Basing on the results of Ivanov et al. (2016) obtained for the western Nansen Basin, Atlantification has been defined since Polyakov et al. (2017) as an ability of efficient delivery of Atlantic Water heat to the sea ice under conditions of weak stratification. This is of high relevance for the topic of this paper since this upward heat flux may produce polynyas through ice melting in areas where this did not normally happen in the past, under conditions of thick consolidated ice. In the western Eurasian Basin, where the Atlantic Water is in close proximity to the ice cover in winter (Meyer et al., 2017; Ivanov et al., 2018) ice thinning (detectable by satellite measurements, see section 3) has been reported in the mid-winter along the Atlantic Water pathway since 2007 (Ivanov et al., 2012; Renner et al., 2018). Meanwhile in the Pacific sector, Woodgate et al. (2012) detected a significant heat content increase between 2001 and 2011 at moorings through the Bering Strait; by 2019, this had resulted in warming of the summer oceanic inflow of 2°C, and 4°C for the winter inflow (Woodgate and Peralta-Ferriz, 2021). This warmer winter inflow has also freshened and become buoyant enough that it now lays right under the sea ice, instead of under the summer inflow waters (Woodgate and Peralta-Ferriz, 2021).

The warm Atlantic and Pacific waters are only relevant for polynyas and the sea ice if/where they can reach the surface and sea ice. Globally, the top surface layer is usually well mixed. In most of the Arctic however, sea ice still is protected by a persistent cold and fresh layer that can extend to 200-300 m depth (Timmermans and Marshall, 2020); we here use its generic name of "halocline layer" but acknowledge that it has many other denominations in the literature. The Arctic halocline effectively stratifies the ocean and prevents the warmer Atlantic Water or Pacific Water from melting sea ice. In the Eurasian basin, where the halocline is naturally thinner, Atlantification has already reduced it (Polyakov et al., 2025). Direct

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observations have shown low ice concentration and mixed layers deepening to 500 m north of Svalbard in winter 2012/2013 (Pérez-Hernández et al., 2019) and in winter 2013-2014 (Ivanov and Repina, 2019). These deepened mixed layers are consistent with Ivanov et al. (2018) that found that, under conditions of depleted ice cover in the western Nansen Basin, enhanced vertical thermohaline convection delivers additional heat from the Atlantic Water layer to the upper mixed layer, contributing to an accelerated sea ice melt and/or impeding local ice formation. In contrast in the Amerasian basin, where the halocline has always been thicker, it has been further freshening and thickening over the last decade (Solomon et al., 2021), consistent with sea ice melt and the re-routing of Siberian river discharge (see review by Timmermans and Toole, 2023).

Small scale ocean dynamics are hard to monitor through the sea ice, but Armitage et al. (2017) nonetheless reported a strengthening in geostrophic currents from the late 2000s. They link their largest observations in the Amerasian basin to a concurrent intensification of the Beaufort Gyre, the large scale convergent loop that traps freshwater and sea ice in the Amerasian basin (Fig. 1). Timmermans and Toole (2023) has since reported a stabilisation of the Beaufort Gyre. The Transpolar Drift, the large scale conveyor that carries sea ice and surface waters from the Siberian shelf to Fram Strait through the central Arctic (Fig. 1), also seems to have been accelerating and/or changing its location (e.g. Krumpen et al., 2021). Our knowledge of ocean currents in the Arctic is however extremely limited due to the presence of sea ice and logistical constraints; these results cannot easily be put in a long time perspective.

Sea ice: The combined changes in the ocean and atmosphere obviously result in changes in the cryosphere, with the loss of summer Arctic sea ice having become one of the starkest symbols of ongoing climate change. Since satellite observations began in 1979, summer sea ice extent has been declining at around 13% per decade (Notz and Stroeve, 2016; Meier and Stroeve, 2022), and winter at 3% per decade (Stroeve and Notz, 2018). This decline is strongest on the Eurasian shallow regions: Over the last decade the sea ice cover has increasingly become seasonal over the Barents Sea and Russian continental shelf (Onarheim et al., 2018). Besides, the rate of change is accelerating, with all of the 10 record low maxima and minima sea ice extents taking place since 2006 (Serreze and Meier, 2019), and for both seasons, 7 of these 10 are since 2015 (NSIDC, 2025a, b). In particular, landfast ice and ice bridges/arches are disappearing, breaking up early or not forming at all (Vincent, 2019; Kirillov et al., 2022; Jensen et al., 2023). The melt season has also become longer: Melting starts earlier — in the marginal seas the melt onset occurs 10-20 days earlier each decade —, while the autumn freeze-up is delayed — up to a month later each decade in the Chukchi Sea (Meier and Stroeve, 2022). In the Laptev Sea the duration of the ice-free season in 2010s – 2020s increased to 1.5 - 2 months (Polyakov et al., 2025).

Sea ice has also thinned substantially, by 1.5–2.0 m since the early 1980s at the pan-Arctic scale (Kwok, 2018). It has also become younger, i.e., survives fewer summers before melting or being flushed out of the Arctic through Fram Strait, Nares Strait or the Canadian Arctic Archipelago, with first-year ice now dominating the Arctic ice cover (Tschudi et al., 2020). By definition, the reduction of the sea ice cover means that there is less area available for polynya formation, but this thinner sea ice is more prone to breaking and melting.

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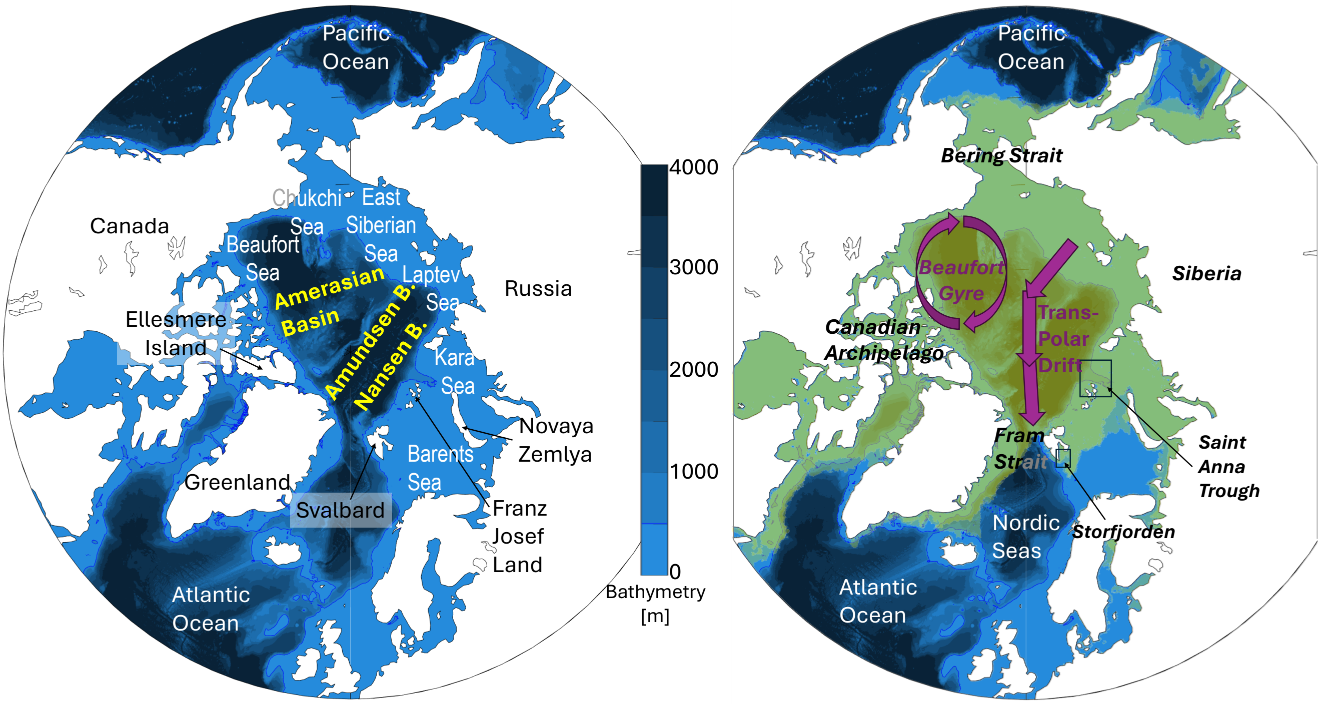

Figure 1. Places and features named in this manuscript; for readability, the coordinates are purposely omitted and shown on the next figure. Blue background is the GEBCO 2025 bathymetry (GEBCO Compilation Group, 2025); anything shallower than 500 m (palest shade of blue and indigo contour) is the continental shelf. In the manuscript, the Amundsen Basin and Nansen Basin are occasionally grouped together and referred to as the "Eurasian Basin". On the right panel, green shadings are the daily sea ice maximum in 2005 (12 March) vs sea ice maximum in 2025 (22 March) from Spreen et al. (2008); the few areas with less ice in 2025 than in 2005 are more transparent, e.g. in the Barents Sea.

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Sea ice temperature is another variable that shows a rapid increase. Until recently, large uncertainties and dataset discontinuities prevented a reliable estimate in the Arctic. As a result, Masson-Delmotte et al. (2021) reports no trend in Arctic sea ice temperature. However, through reprocessing and bias correction of combined satellite-based datasets, Kolbe et al. (2025) found a significant Arctic sea ice surface warming of 1.11°C per decade since 1982.

Besides, this thinner and warmer sea ice at lower concentrations seems to be more mobile. On the one hand, sea ice drift speeds have accelerated (Tschudi et al., 2020), and there is anecdotal evidence that overall the Transpolar drift is accelerating as well (Krumpen et al., 2021). The age of the sea ice leaving the Arctic through Fram Strait has also been decreasing, with second/third year ice now dominating the export (Yang et al., 2023). This acceleration is consistent with model results that suggest a maximum momentum transfer from the wind at sea ice concentrations of 80-90% (Martin et al., 2014; Muilwijk et al., 2024). On the other hand, Krumpen et al. (2025) found that the first year ice, which now is the norm in the Arctic, is smoother with fewer pressure ridges than the older ice was, i.e. harder to move by the wind. The net effect on polynyas, which primarily open in now-seasonal sea ice areas, has yet to be established.

Given all these changes to the processes that can impact polynya formation and maintenance in the Arctic, we argue that a new Arctic polynya review is timely. We first summarise what a polynya is, focussing on when, where and why it opens (section 2). A specific section is dedicated to the current methods to observe polynyas, primarily through satellites (section 3). We then review the observed changes to polynya activity in the Arctic, including the emergence of polynyas in summer (section 4). Finally, we give an overview of Arctic polynyas' effects on the climate system, in the Arctic and globally, and how these have been reported to have changed (section 5). We conclude with a summary of the positive and negative feedback that impact polynyas, extrapolate on their future, and list the remaining limitations as well as provide recommendations for future programs, both observational and modelling. We acknowledge that a lot more could be written about Arctic polynyas, such as polynyas in the paleorecord, or impacts of polynyas on biogeochemistry and/or ecosystems. We here however limit our work to the physical climate system as detected in the observational satellite-based records.

2 What a polynya is

"Polynya" is the Russian word for an opening in the sea ice. The World Meteorological Organisation defines polynyas more specifically as "any non-linear shaped opening enclosed in ice", adding that "polynyas may contain brash ice and/or be covered with new ice, nilas or young ice" (World Meteorological Organization, 2014). According to this definition, the only difference between a lead and a polynya is their shape. The current absolute reference when it comes to polynyas is the book "Polynyas, Windows to the World" edited by Smith Jr and Barber (2007). In its first chapter, Barber and Massom (2007) further distinguish between leads and polynyas based on their timescales, with polynyas being mostly open for weeks to months, potentially with occasional closed day, whereas leads are synoptic scale, short-lived. In the second chapter, because of these different timescales, Williams et al. (2007) add that polynyas are recurrent, somewhat predictable, whereas individual leads are not, only their overall statistics are predictable.

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Polynyas tend to be further divided into categories based on their formation mechanism. For example Morales Maqueda et al. (2004) divided them into:

- Latent heat polynyas, which open in response to dynamics forcing, in general divergent winds. They tend to open by the coast or next to an obstacle (for example grounded landfast ice edge), and are therefore often called coastal polynyas. They are (or as we will show, were) the norm in the Arctic.
- Sensible heat polynyas, which in contrast open in response to thermodynamic forcings, in general melting of the ice from under by upwelled warm water. They tend to open away from the coast and are therefore often called open-ocean polynyas. Note that there are no sensible heat-only polynyas in the Arctic.
- Hybrid polynyas open as a result of both dynamics and thermodynamics, with in general thermodynamics preconditioning the region by thinning the ice and dynamics being the trigger for the opening.

In the Arctic, most polynyas are coastal latent heat polynyas (Morales Maqueda et al., 2004), with the exception of the North Water polynya between Greenland and the Canadian Arctic Archipelago which has long been known to be a hybrid (Kozo, 1991; Barber et al., 2001), and Whalers Bay north of Svalbard (Ivanov et al., 2012; Tetzlaff et al., 2014). In response to the strong climate-change induced warming of the Arctic, this may be currently changing. A recent study of the surface fluxes before Arctic polynyas open found that nearly half of them are now exhibiting signatures typical of hybrid polynyas (Wong et al., 2026). This transition will be the topic of section 4.

A related categorisation is provided by Williams et al. (2007) for the Arctic polynyas: mechanically-forced polynyas vs convectively-forced polynyas, where the latter are further split into free convection (from brine rejection) vs forced convection (from tides). Barber and Massom (2007) instead used the three categories “ice bridge”, “land bridge” and “ocean strait” polynyas for the Arctic, which highlights the absence of open-ocean polynyas in the Arctic, but as we detail in this review is no longer relevant for the changing Arctic.

The first records of polynyas were based on the historical observations by whalers and explorers. Augmented by early-era satellite remote sensing, Smith Jr and Barber (2007) provided a map and statistics of 61 active polynyas in the Arctic. These polynyas are small, with January open water area ranging from 2 km^2 to of 7000 km^2. It remains unresolved if their size is actually underestimated. Returning to the WMO definition of polynyas we note that polynyas can be open water or covered with thin ice (Morales Maqueda et al., 2004; Tamura and Ohshima, 2011). Thin ice detection presents a challenge to satellite remote sensing methods, as we review in the next section.

Here we show the polynya distribution at the onset of the satellite record (Fig. 2, left) for Arctic polynyas. As we review in section 4, previously small polynyas are now merging into larger areas (Fig. 2, right).

3 How polynyas are observed from space: Linking grid cell values to sea ice on the ground

Direct observations of polynyas are rare and limited to qualitative observations. These can be systematic such as the Soviet Sever Operation with regular flights (Zakharov, 1966) or the ship-borne observations of Ice Watch/ASSIST (Arctic Ship-based

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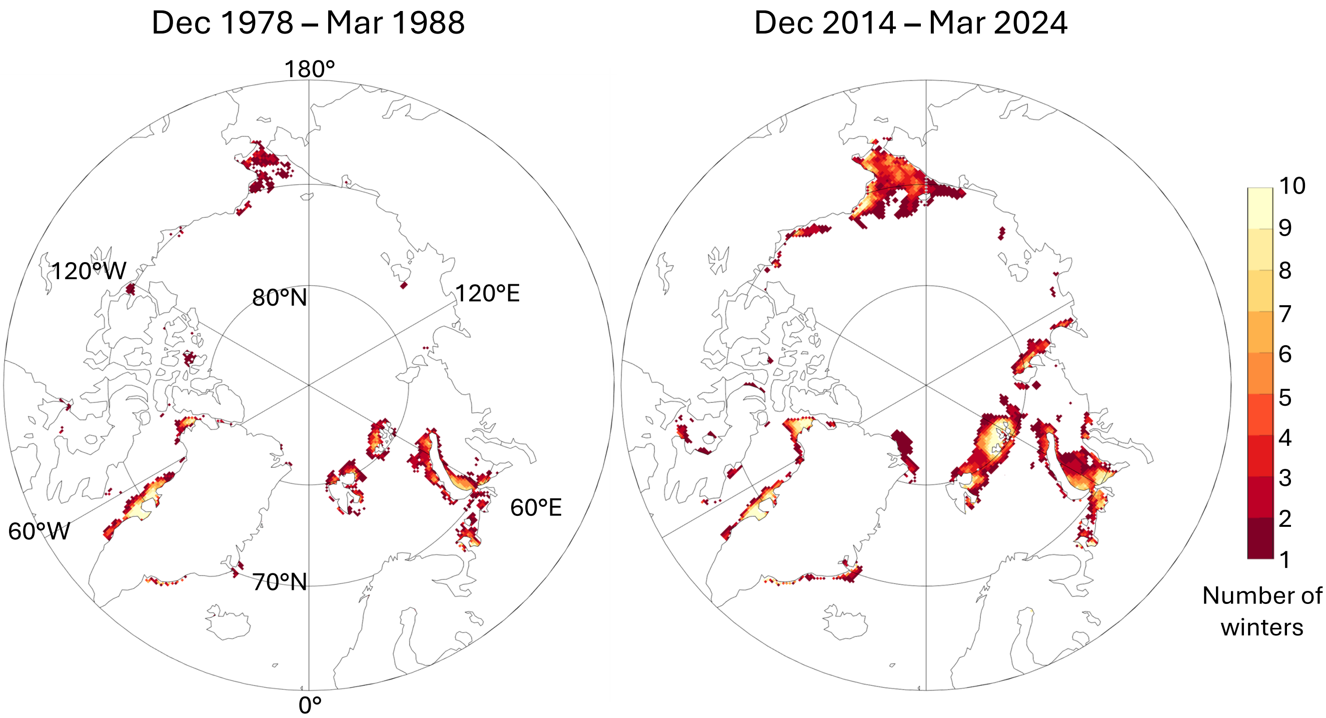

Figure 2. Fewer but larger polynyas over the satellite record: For each pixel, how many winters (out of 10) did a polynya open there at least once per winter over the first 10 vs last 10 years. Computed using the SMMR sea ice concentration masks of Wong et al. (2026), where winter is 1st December till 31st March. See their publication for a discussion on contamination by the marginal ice zone, e.g. around Bering Strait.

Sea-Ice Standardization, more information at https://climate-cryosphere.org/ice-watch-assist). Polynyas can also be detected indirectly through their consequences on the climate system (see also section 5):

- by radiosondes or flight campaigns dedicated to boundary layer dynamics, clouds, and/or aerosols (e.g. Raddatz et al., 2011; Tetzlaff et al., 2015);
- by ice-tethered oceanographic instruments impacted by changes of sea ice drift or thickness, or airborne sea ice thickness surveys (e.g. Kirillov et al., 2013; von Albedyll et al., 2021);
- or by oceanographic moorings and even water mass tracers, detecting polynyas' impacts on the water column (e.g. Dmitrenko et al., 2005; Bauch et al., 2012).

These observational studies can only cover local scales. In order to create a Pan-Arctic polynya inventory, Smith Jr and Barber (2007) instead used Inuit knowledge, historical recordings such as whaling logs, and satellite observations. Hereafter, we focus on the latter, the space-borne observations of Arctic polynyas.

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Polynya detection from space primarily relies on either of two proxy variables derived from satellite sensors: sea ice concentration or thickness. We here review their limitations, including their sensitivity thresholds (e.g. how thick sea ice must be to be detectable), along with their spatial and temporal resolution, which will impact their ability to resolve the seasonal and regional variability of polynya events. Table 1 gives an overview of the different satellite detection methods and examples of satellites/satellite sensors.

Early studies of Arctic polynyas using satellite observations (Martin and Cavalieri, 1989; Bareiss and Goergen, 2005; Alfultis and Martin, 1987; Cavalieri and Martin, 1994) rely on sea ice concentration derived from passive microwave data at about 19 and 37 GHz — data that are unaffected by darkness during polar night or cloud conditions during polar day. These data are available as climate data record Arctic-wide on a daily basis since October 1978 (Meier et al., 2021; Lavergne et al., 2019). One main limitation of this sea ice concentration data is its coarse spatial resolution ($\sim$25 km) compared to typical polynya dimensions (can be O(1 km)). Additionally, the signal at these frequencies is not sensitive to thin ice (above$\sim$2.5 mm, as noted by Grenfell and Comiso, 1986), resulting in polynyas — often covered by such thin ice layers — being incorrectly classified as closed sea ice.

To detect polynyas regardless of whether they are really open waters or have a thin-ice cover, sea ice thickness retrievals have been used in more recent studies: Taking the advantage of a higher microwave frequency available since the SSM/I satellite series (near 90 GHz), algorithms retrieving thin (15 cm to $\sim$25 cm) ice thickness information for polynya detection were developed by Markus and Burns (1995) (classifying the surface in different thickness classes), Martin et al. (2004), Tamura and Ohshima (2011), and Iwamoto et al. (2014). These approaches to derive sea ice thickness (classes), which has the added advantage of a finer spatial resolution ($\sim$5 km), have been used in many studies dedicated to Arctic polynyas (e.g. Kern et al., 2005; Kern, 2008; Martin et al., 2005; Willmes et al., 2011; Ohshima et al., 2016, 2020; Kawaguchi et al., 2011; Wong et al., 2026). The resolution is still coarse enough to introduce significant uncertainty in ice cover estimates due to the conflation of water, thin ice, and thick ice signals at polynya edges (e.g. Willmes et al., 2010). Since most Arctic polynyas are coastal polynyas, land contamination and/or the presence of fast ice introduce additional uncertainties. These frequencies are also more sensitive to water vapour presence in the atmosphere (Spreen et al., 2025).

A higher spatial resolution of 1 km for thin sea ice thickness distributions ($\leq$20 cm) can be derived from thermal infrared ice-surface temperatures (e.g., from the MODIS sensor available since 2000) to identify polynyas through their fluxes to the atmosphere (see section 5.2): this method however needs to account for cloud-induced data gaps (Adams et al., 2013; Preußer et al., 2016). It is instead more common to use thin ice products based on passive microwave observations observations at L-band (1.4 GHz), which are available since 2009 (Kaleschke et al., 2012; Huntemann et al., 2014), have a higher detection limit ($\leq$50 cm) than the previously mentioned products, are not affected by clouds, but come at a coarser spatial resolution (original resolution of $\sim$30 km). They have been used to study Arctic polynyas (Ludwig et al., 2019), including for pan-Arctic polynya mapping (Wong et al., 2026), but are only available in winter months.

Other, more rarely used, methods to observe polynyas are worth mentioning here. Optical data (used, e.g., by Shen et al., 2021; Ito, 1985) come at a spatial resolution on the order of meters, but their use is hindered by clouds and polar night. In the polar night, one could in theory use moonlit (gibbous/full moon) scenes (Foster and Hall, 1991) or near-infrared (lunar)

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reflectance data to observe polynyas, albeit at the slightly lower resolution of hundreds of meters (Miller et al., 2013). Sea ice information derived from Synthetic Aperture Radar (SAR), which is not limited by cloud and daylight constraints, offers high resolution (tens of meters) and serves as an effective tool for studying polynyas as done by Dokken et al. (2002); Ren et al. (2022); Drucker et al. (2003); von Albedyll et al. (2021). However, to this date, it still suffers from challenges in distinguishing surface classes from backscatter signatures (e.g. Aldenhoff et al., 2018) and a relatively poor spatial and temporal coverage with no guaranteed Arctic-wide coverage (Ludwig et al., 2019). Even harder to interpret in terms of polynya area are (coarse-resolution) scatterometer data ($\sim$25 km) as the backscatter signal is strongly influenced by the cm-scale surface roughness, which is ambiguous in a polynya (Hollands and Dierking, 2016): the open ocean surface can be rough or smooth, ice can be smooth or deformed (rafted), bare or covered with frost flowers, etc. Note that altimeter data such as CryoSat-2 (Ricker et al., 2017) and ICESat2 (Petty et al., 2020) are limited to thick ice, less sensitive to thin ice ($<\sim$0.3 m to 0.5 m), also struggle with surface characterization (Quartly et al., 2019), and can therefore not be used efficiently to detect polynyas from sea ice thickness.

Ultimately, the majority of approaches to detect polynyas are sensitive to the sea ice concentration threshold chosen, or thresholds used to discriminate between thick and thin ice. These thresholds need to be carefully chosen and adapted to the products' spatial resolution and limitations to provide robust polynya areas and counts; see Wong et al. (2026) for an overview of thresholds used in the Arctic polynya literature and the consequences of varying these. Although for Antarctic polynyas, Landrum et al. (2026) provides an even more detailed analysis of the sensitivity of coastal polynya estimations to the settings of the detection method. Regardless of the method, automatic detection of polynyas using sea ice concentration, thickness, or fluxes faces the challenge of answering whether potential polynyas really lie within the sea ice cover and are not part of the marginal ice zone/open ocean (e.g. Ohshima et al., 2016; Nakata and Ohshima, 2022; Wong et al., 2026).

As example, we consider the February 2018 North Greenland polynya (Fig. 3), which is also discussed at the end of section 4. Several different polynya proxies were used to study the event: a high ($\sim$6 km) and a low (25 km)-resolution passive microwave sea ice concentration dataset (Moore et al., 2018), a merged passive microwave - thermal infrared (1 km)-resolution sea ice concentration dataset (Ludwig et al., 2019), thin ice thickness based on thermal infrared ice-surface temperature data at 2 km resolution (Preußer et al., 2019) and SAR data (von Albedyll et al., 2021), with the latter allowing the study of the polynya at 50 m resolution. And although it occurred during polar night, it can be observed by a low-light visible/near infrared day-night band at $\sim$750 m (Fig. 3, and Fig. 1a in Lee et al., 2023). Differences in the minimum sea ice concentration among the datasets for the area of interest during the polynya event are evident, reflecting their varying resolutions and sensitivities to sea ice thickness. But the different observational techniques also complement each other, as the longer time span of the coarse-resolution dataset, for example, allows a climatological perspective while the high-resolution SAR data enables a detailed case study, whereas sea ice thickness from thermal infrared data and the sea ice drift derived from microwave backscatter data can help to explain the evolution and ice production of the polynya.

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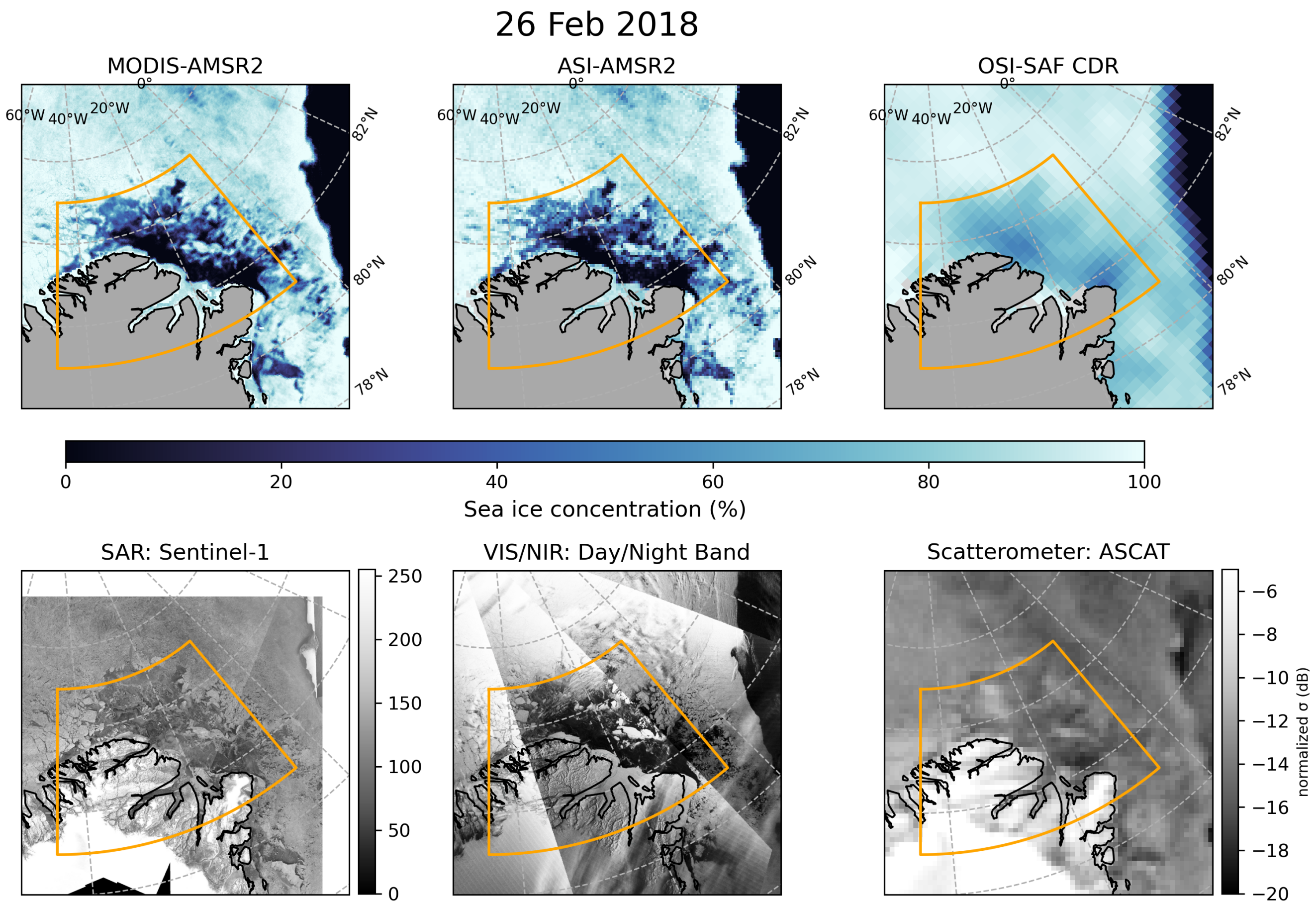

Figure 3. The day of maximum extent (according to Ludwig et al., 2019) of the North Greenland polynya in 2018 as seen (or not) by different satellites/ satellite products: upper row from left to right: 1 km MODIS/AMSR2-based (passive microwave + infrared) sea ice concentration data, 5 km AMSR2 sea ice concentration data, 25 km Climate Data Record OSI–450-a1 sea ice concentration data ; second row from left to right: Synthetic Aperture Radar data (Sentinel-1A/B daily mosaics, units are greyscale values), VIIRS Day/Night Band (visible and near infrared), and normalised radar backscatter (ASCAT).

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Table 1. Comparison of satellite remote sensing methods for polynya observation. Temporal resolution is given for the Arctic-wide coverage.

Sensor	**Retrieved variable**	**Spatial Resolution**	**Temporal Resolution**	**Detection Limits**	**Available Time Period**	**Satellites/Sensors**
L-Band PMW	SIT	∼30 km	daily	thin SIT up to 50 cm, only winter	2009 (SMOS)/ 2015 (SMAP)–today	SMOS, SMAP, *CIMR*
PMW (19 GHz and 37 GHz)	SIC	∼25 km	daily	ice up to a few mm	1978 (SMMR)–today	SMMR, AMSR-E, AMSR-2, *CIMR*
PMW near 90 GHz	SIC	∼5 km	daily	thin SIT up to ∼10 cm	2002 (AMSR-E)–today	AMSR-E, AMSR-2, *CIMR*
PMW near 90 GHz	SIT	∼5 km	daily	thin SIT up to 15 cm to ∼25 cm	1987 (SSM/I)–today	SSM/I, AMSR-E, AMSR-2, *CIMR*
Scatterometer (K-band)	surface type	∼25 km	daily	detecting ice classes	1999 (QuikSCAT)–today	QuikSCAT, ASCAT
Thermal IR (8 µm to 12 µm)	SIT	∼1 km	daily	only in cloud-free conditions, thin SIT up to 20 cm	1979 (AVHRR) / 2000 (MODIS)–today	AVHRR, MODIS, VIIRS, Sentinel-2, many visual satellites
SAR (1 GHz to 8 GHz)	surface type	∼30 m (C-band)	weekly	detecting ice classes, temporal/spatial coverage	1991 (ERS-1)–today	ERS-1, ERS-2, ASAR, Sentinel-1, RCM, many other SAR satellites
Altimeter (lidar/ radar)	SIT	Meters (lidar) 5 km to ∼15 km	monthly	sparse spatial and temporal coverage, high uncertainty for thin ice	2003 (ICESat) – today	ICESat, CryoSAT-2, ICESat-2, Sentinel-3, *CRISTAL*
Visible + near IR (0.4 µm to 0.7 µm)	surface type	Meters	daily (summer)	daylight-only, only in cloud-free conditions	1972 (Landsat)–today	Landsat, MODIS, Sentinel-2, many other visual satellites

Note: PMW = Passive Microwave; IR = Infrared; SAR = Synthetic Aperture Radar; SIC = sea ice concentration; SIT = sea ice thickness. Start of the time periods depends on specific satellite mission (given in brackets), in many cases successor instruments are flown until today. Satellite missions and Sensor names are abbreviations, but are used as full names in the community and their explanation is thus not given. Future missions are given in *italic*. Near-infrared/low-light data is also available for moonlit scenes (e.g. Day/Night Band).

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4 Trends in Arctic polynya area and/or duration in the observational record

Over the last 20 years, anthropogenic climate change has become so strong in the Arctic that distinguishing signal to noise has become possible, albeit still with large interannual variability. Over the same time period, remarkable advances in sea ice observations (see previous section), notably reduced inaccuracies and increased in spatial and temporal resolutions, have allowed researchers to move away from the question of "Can we monitor Arctic polynyas?" (e.g. Martin et al., 2004) to that of "Are Arctic polynyas changing in response to climate change?". As we detail below, in all regions, the answer is a resounding "yes, they are". Note however that a direct comparison of the results of the studies listed below is complicated by their different region- and diagnostic definitions, even though they tend to use similar names to refer to them. All trends quoted below are significant at least at 95% unless stated otherwise.

Eurasian Arctic: Starting with Svalbard, Tetzlaff et al. (2014) reported that in the so-called "Whaler's Bay polynya", north of the archipelago, the length of the polynya more than doubled over their study period (1992-2014), from less than 200 km until 1998 to more than 400 km half of the winter season since 2012. Short-lived (approximately 10 days) extreme extents, where the open water area reached all the way to the eastern slope of Saint Anna Trough, were observed in 2016 (Ivanov and Repina, 2018). South of the island, in Storfjorden, the polynya areas published by Preußer et al. (2015b) yield a significant trend of +324 km^2/year over their study period (2002-2014), which is also a doubling. A similar trend of +240 km^2/year was found by Kern (2008) in the Kara Sea, over 1979-2003. In the Laptev Sea, Bareiss and Goergen (2005) report a shortening of the polynya duration over 1979-2002 from 21 days switching to 13 days since 1990s, associated with an increase in the polynya area (no trend value given). Willmes et al. (2011) also found a shift in the early 1990s in the Laptev Sea, this time in the seasonality of polynyas with an increase in polynya area in early and late winters but a decrease over January-February over 1979-2008. Although they do not give a trend value, they further highlight a shift in the size classes of the polynyas towards larger polynyas ($> 5000\ \mathrm{km}^2$). Focussing on the more recent period of 1997-2023, Timofeeva et al. (2025) also indicate an increase in the Laptev Sea polynya area in the early winter, and give increasing trends in the year-round polynya area of +986 km^2/year and +271 km^2/year for stable (50% of the winter) and stationary (75% of the winter), respectively. In summary, in the Eurasian Arctic, polynyas open earlier, are sometimes shorter-lived, but expand over larger areas.

Amerasian Arctic: Similar to the Eurasian Arctic, Moore and Pickart (2012) report a more than doubling of the area of the so-called "Wrangel Island polynya" in the Chukchi Sea over 1979-2011. The setting is more complicated in the Beaufort Sea, where Jewell et al. (2026) did not find any trend over their study period 2003-2025, but rather exceptionally large polynyas (> 400 km length, or more than double the norm) that extend over the continental shelf break becoming more common since 2015, in response to warm water upwelling and exceptional wind forcing. Polynyas are even more complex in the Canadian Arctic Archipelago (CAA), where they often require the formation of an ice arch. Although we were unable to find peer-reviewed trends in the CAA polynya area, Vincent (2023) provides trends regarding the ice arch of Lancaster Sound over 1979-2022, noting a linear move of 115 km to the west (significant at 90%), a formation 26 days later (also at 90%), which was most pronounced until 2000, and a collapse 22 days earlier (99%). The authors had conducted a similar study on the ice arches around the North Water polynya (Vincent, 2019) and found a decreasing duration trend of -2.1 days/year over 1979-2019, with

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the northern arch forming 0.8 days/year later and collapsing 1.1 days/year earlier. They further note the emergence of "an era of ice arch anomalies" since 2007, there have been a number of years where a southern arch did not form, including the winters of 2018/2019 and 2021/2022 (Moore et al., 2021, 2023). In parallel, Preußer et al. (2015a) report a steady increase in polynya area since the mid-1990s, resulting in a doubling of polynya area during their study period 1979-2015, while Ren et al. (2022) who focussed on the recent period 2006-2019 found no significant trend in the polynya area. To summarise, the North Water polynya, for which ice arches contribute to its formation, is now open for shorter duration, but with a larger area, especially so until 2000s. In summer however, and for the North East Water polynya (which does not depend on ice arches), Bennett et al. (2024) finds opposite results: over 1980-2022, the polynya duration has extended by 3 weeks, opening mid- instead of late-June and closing early October instead of mid-September. No area trends were reported.

New polynyas: Around Greenland, new polynyas have been opening recently. In May 2020 in the "Last Ice Area" north of Ellesmere Island, i.e. north of the North Water polynya location, a polynya opened for the first time in response to anomalous divergent winds (Moore et al., 2021). The thinning of sea ice in the region was also hypothesized to contribute to its formation. The same year, a second unprecedented polynya opened north/east of Greenland on 2nd May, allowing the participants of the international MOSAiC expedition to take opportunistic measurements in the polynya when they passed through in July (Rabe et al., 2022). The development of polynyas in this region may suggest that the Last Ice Area, forecast to be the last region in the Arctic to lose its permanent ice cover (Moore et al., 2019), may not be as stable as previously thought. Even more surprising, in winter, Moore et al. (2018) reported the "first occurrence" of a polynya at the approximate location of the North East Water polynya but in winter, in February 2018 (see Fig. 3), in response to a sudden stratospheric warming event that brought strong warm southerly winds over the region. Lee et al. (2023) have since shown that this opening had occurred three times previously, in December 1986, February 2011 and February 2017, but note that the 2018 event was unprecedented in both magnitude and duration.

Pan-Arctic trends: At the pan-Arctic level, assessments focussed first on ice production rather than the polynya area. Tamura and Ohshima (2011) reported a significant decrease in ice production over 1992 - 2007 in all regions, except in the Chukchi Sea and North Water polynya where they increased. Iwamoto et al. (2014) then found the opposite results over 2002 - 2011, and note a shift of sea ice production towards the higher latitude regions of the Amerasian sector after 2007. The change of sign of the trends between these two studies is consistent with the other studies listed above, that often highlight a shift in the early 2000s. Consistent with the higher ice production of Iwamoto et al. (2014), Preußer et al. (2016) find overall increases in polynya area over 2002-2015 but points out that many regions are dominated by interannual variability. At the pan-Arctic scale over 2002-2011, even when comparing the different retrieval methods of the previous studies, Preußer et al. (2019) find consistent polynya area trends of +7200 to +7500 km^2/year. Wong et al. (2026) find a similar pan-Arctic polynya area trend of +7100 km^2/year over 1979-2024, which Heuzé and Wong (2025), using the same dataset, significantly correlated with the pan-Arctic sea ice area/extent to argue that the less sea ice, the larger the polynyas. However, when Wong et al. (2026) split their study period before/after 2002, the trend increases to +11 000 km^2/year until 2002 but is no longer significant afterwards. They find a similar temporal effect in all sub-regions, which they suspect is caused by inconsistent trends in the wind along with increased sea ice variability.

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To summarise, over the last twenty years, polynya area has been increasing at the pan-Arctic scale and in individual regions. Regions where polynya formation depends on the establishment of an ice bridge have seen shorter polynya seasons, and there is a risk that these polynyas may not open anymore, or open in response to different processes. In all other regions, polynya season is extending, and new polynyas are even emerging in regions that used to be permanently ice-covered. The overall decrease in ice thickness and increased ice mobility are facilitating polynya opening, although inconsistent trends in the wind are for now resulting in large interannual and inter-regional variability. Nonetheless, with larger polynyas over a size-limited continental shelf, Arctic "coastal" polynyas are now extending into the open ocean in the Beaufort Sea (Jewell et al., 2026), and may do the same in the Eurasian Arctic soon (Wong et al., 2026). This would modify the polynyas' role in the climate system, which we now describe.

5 The role of Arctic polynyas in the climate system

In the Arctic, polynyas primarily open in response to divergent wind. This means that the air is cold, much colder than the newly-exposed ocean surface, resulting in large heat (and moisture) fluxes to the atmosphere. In subsection 5.1, we review the literature on these fluxes and their impact, along with their trends over the last 20 years. Since both air and ocean are cold, sea ice forms as soon as the polynya opens, and the last 20 years have seen large developments in the retrieval of sea ice production values via the heat fluxes to the atmosphere; we review these, along with trends in ice production in polynyas, in subsection 5.2. Finally, sea ice production has a large impact on the ocean via brine rejection; likewise, we review recent findings and reported trends on the importance of polynyas for the water column in subsection 5.3. Although beyond the scope of this review, we acknowledge that the impact of polynyas extend beyond the climate system. Polynyas may notably act as carbon sink, since they increase the ocean surface's solubility locally (cold and salty water) while potentially enhancing the biological pump through nutrient upwelling and light availability (Miller and DiTullio, 2007). Polynyas in fact play a crucial role for the entire food web beyond just phytoplankton bloom (see chapters 8 to 12 in Smith Jr and Barber, 2007).

5.1 Atmosphere: Moisture fluxes and cloud feedback

The Arctic atmosphere both impacts and is impacted by Arctic polynyas. As already described in section 4, even though many Arctic polynyas seem to have become hybrid, their primary trigger still is the wind. To the best of our knowledge, no observational study has reported trends in wind speeds in the Arctic; modelling studies however consistently report such an ongoing / projected increase (Ruosteenoja et al., 2019; Vavrus and Alkama, 2022; Muilwijk et al., 2024). It is worth acknowledging that observations above Arctic polynyas are few because it is an extremely challenging environment, even worse than in the ocean where one could, in theory, deploy moorings at the right location during the summer season. As a result, this section builds on timely flight campaigns above polynyas, satellite data, but also studies above leads, notably during the year-long Surface Heat Budget of the Arctic Ocean (SHEBA, Perovich et al., 1999) and Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC, Shupe et al., 2022) drift campaigns.

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Observations do show an increase in extratropical cyclones from the North Atlantic and North Pacific reaching the Arctic in winter, and even a strengthening of cyclones formed in the Arctic during the shoulder seasons (Li et al., 2026). Although these authors relate the large-scale changes in wind to the large-scale Arctic sea ice loss, observational studies explicitly linking the opening of a polynya to changes in the wind speed or direction (and therefore feedback on the polynya) are lacking. In the Arctic, the closest result comes from aircraft campaigns above leads, which found no significant increase in wind speed after their opening (Tetzlaff et al., 2015). What has been observed instead are changes to the entire atmospheric boundary layer.

As reviewed in Minnett and Key (2007), while a latent heat polynya is open, the atmosphere loses energy through sea ice formation (since the ocean is at freezing temperature already), which keeps the atmosphere directly above the polynya colder than the exposed ocean and results in high turbulent fluxes into the boundary layer. In the Chukchi Sea in March 1974, in response to leads, some of which had been artificially opened by the researchers, Andreas et al. (1979) reported a very unstable boundary layer, with sensible heat fluxes of up to 400 W m^{-2} and latent heat fluxes of 130 W m^{-2}. At the same location but in response to a polynya in January - June 2008, Raddatz et al. (2011) reported instead that the boundary layer was weakly stable until 350 m, with an inversion until 1000 m. Their measured heat fluxes were more than twice lower (15–185 W m^{-2}), and their latent heat flux one to two orders of magnitude smaller (0.7–8.8 W m^{-2} in winter), caused by moisture fluxes of 0.001–0.013 mm h^{-1}. This is consistent with aircraft measurements north of Fram Strait in March 2013 (Tetzlaff et al., 2015) of near-surface sensible heat fluxes ranging 15 to 180 W m^{-2}. They also report near-surface temperature and humidity increases of 3.2°C and 0.2 g kg^{-1}, respectively, caused by entrainment in response to the high-humidity plume generated by the polynya. Such high-humidity convective plume had previously been observed to reach up to 1000 m height (Minnett and Key, 2007). In the 2013 observations, the plume not only impacted the entire boundary layer but even penetrated the capping inversion (Tetzlaff et al., 2015). Through satellite observations over the North Water polynya during 2003-2009, Boisvert et al. (2012) showed that in general, moisture flux and polynya area are positively related, but pointed out that the moisture flux also depends on the air temperature and moisture, and the wind speed. They notably point out that when that hybrid polynya is in its latent heat phase (opening thanks to high winds, with limited upwelling), it is theoretically possible to form a small polynya with a large moisture flux. It would rather seem that the opposite is currently happening: more polynyas are switching to hybrid/sensible heat (see section 4), and overall the Arctic atmosphere is warmer and wetter (Boisvert et al., 2023), so despite larger polynya areas (Wong et al., 2026) moisture fluxes are significantly decreasing in winter (over 2003-2011, December: -3.94 × 10^{13} kg per year; January -4.04 × 10^{13} kg per year; February -2.40 × 10^{13} kg per year, Boisvert et al., 2013).

Regardless of the type of polynya that generated it, if the high-humidity plume is advected over sea ice, it decouples from the polynya and becomes a mixed-phase cloud (Zulauf and Krueger, 2003). Even if it is not advected, it seeds cloud formation (Key et al., 2004). In fact, in a series of campaigns and ice drift camps in the Chukchi Sea polynya, North Water polynya and North East Water polynya, Key et al. (2004) found that 70 to 85% of daylight measurements were cloudy. In the North Water polynya, through satellite observations over 2006-2010, low-cloud cover was reported to be 10–33% larger over the polynya than over the nearby sea ice, and the cloud liquid water content was up to 400% larger over the polynya (Monroe et al., 2021). Besides, polynyas are a source of aerosols, year-round: in spring and summer, through enhanced biological activity; in autumn, through the ammonium-producing decay of that now-dead biological activity; and in winter, from the strong winds blowing

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over the polynya, especially if frost flowers are present (Kurosaki et al., 2025). This combined effect of clouds and aerosols, along with changes to the surface albedo by opening the ice, mean that polynyas modify the radiative budget locally. The cloud radiative forcing tends to be positive above a polynya, meaning that clouds enhance ice melt (Minnett and Key, 2007). Over the North Water polynya, over 2006-2010, Monroe et al. (2021) report a cloud radiative effect at the surface 18 W m^{-2} larger over the polynya than over the nearby ice. Cloud cover over the Arctic has been increasing since 1930s (Chernokulsky and Esau, 2019); in particular, high altitude stratiform clouds have been decreasing, whereas convective clouds and, since the 1990s, low level clouds, have both been increasing (Chernokulsky and Esau, 2019). The authors do find a correlation with the overall sea ice decline, but to the best of our knowledge, no study has linked trends in cloudiness to changes in polynyas, either as a cause of consequence.

Finally, we could not find any study linking precipitation and polynyas. Likewise, although in the Southern Ocean literature large (sensible heat) polynyas have been suggested to impact the large-scale atmospheric circulation (e.g. Gordon et al., 2007), we could find no such study for the Arctic.

5.2 Sea ice: Production of thin ice and frazil ice

In latent heat polynyas, the wind opens the sea ice. The ocean surface immediately freezes over, but this new ice keeps being exported by the wind. Therefore, such polynyas have been nicknamed “ice factories” (e.g. Smith Jr and Barber, 2007, and references therein). The impacts of this sea ice production, and its associated brine rejection, on the ocean are discussed in details in section 5.3. However, obtaining in situ estimates of this sea ice production (hereafter “SIP”) within Arctic polynyas is not straightforward because of the severe observational conditions and limited accessibility.

To estimate SIP on regional scales, satellite microwave radiometer data, which are available globally regardless of darkness or cloud cover, have proven particularly useful (e.g. Cavalieri and Martin, 1994). In the SMMR data with a spatial resolution of 25 km × 25 km (see section 3), polynyas are represented as areas of low ice concentration. However, under typical winter conditions in the Arctic Ocean, open water in coastal polynyas freezes very rapidly. Thus, most of the polynya area in winter is covered with thin ice, except within a narrow zone adjacent to the coast, typically within about 1 km. With 25 km resolution microwave radiometer data, the open-water fraction within a coastal polynya is usually too small to be resolved; hence coastal polynyas should be identified as areas of thin ice rather than areas of low ice concentration.

To overcome this problem, Martin et al. (2004) introduced the concept of thermal ice thickness and developed a method to estimate physically reasonable heat fluxes, which can be converted into sea ice production, from satellite microwave radiometer data. Thermal ice thickness is defined as the thickness at which the calculated total heat flux would be realized if the ice thickness were uniform within the satellite footprint (e.g. Drucker et al., 2003; Martin et al., 2004; Tamura and Ohshima, 2011). In thin-ice regions, surface heat-budget calculations using thermal ice thickness can, in principle, estimate heat loss and thus sea ice production even when various ice thicknesses and open water coexist non-uniformly within the footprint (Kashiwase et al., 2019). Once thermal ice thickness is obtained from satellite microwave data, the surface heat loss can be estimated under the assumption that the sum of radiative and turbulent fluxes at the ice surface is balanced by conductive heat flux through the ice. Assuming that all heat loss at the surface contributes to freezing, the heat loss corresponds directly to sea

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ice production. Using this method and assumptions, Tamura and Ohshima (2011) produced the first estimate of SIP in polynyas at the pan-Arctic scale, with values of up to 20 m per year per 25 x 25 km grid cell in the North Water polynya. They also found negative trends in SIP in most major polynyas over 1992 - 2007, summing up to -462 km^3 over the 15 years. They also highlighted the large interannual variability in SIP, which they found to be most correlated to the polynya extent (and not really to the atmospheric conditions).

On the other hand, mappings of sea ice production have also been derived from higher-resolution MODIS infrared data (see section 3) using surface heat-budget calculations (Preußer et al., 2015a, b, 2016). Direct comparison between the sea ice production datasets derived from AMSR-E (Iwamoto et al., 2014) and MODIS showed generally good agreement (Preußer et al., 2019), suggesting high reliability for both methods. These SIP estimation methods have also been combined with other techniques and sensors in various studies. For example, Willmes et al. (2011) combined a SSM/I-derived polynya detection (see section 3) with MODIS-derived ice-thickness estimates to calculate sea ice production in the Laptev Sea over 1979-2008; their mean value and interannual variability were 55 ± 13 km^3, which is about one third of that estimated by Tamura and Ohshima (2011) using the lower-resolution SSM/I data (152 ± 43 km^3) and about 70% of that estimated by Iwamoto et al. (2014) using the finer-resolution AMSR data (77 ± 19 km^3); they also found no significant trend. Ren et al. (2022) further combined high-resolution SAR data with MODIS and AMSR data to investigate sea ice production and ice dynamics in the North Water polynya over 2006-2019; likewise, their mean value is a third of that of Tamura and Ohshima (2011), although their interannual variability is nearly twice as large (144 ± 103 km^3 compared to 353 ± 69), and they found no significant trend.

Accurate estimation of ice production requires not only spatial extent but also reliable sea ice thickness (SIT) measurements and tracking of newly formed ice as it advects away from the source region. Satellite-derived SIT from passive microwave sensors such as SMOS and SMAP has therefore been increasingly used to constrain thin-ice thickness and associated production rates (Tietsche et al., 2018; Landy et al., 2017; Mchedlishvili et al., 2022). At smaller scales, airborne electromagnetic induction surveys provide high-resolution thickness data and have been successfully applied in polynya environments (von Albedyll et al., 2021; Willmes et al., 2010). However, these observations are often spatially and temporally sparse, and interpretation is complicated by the preferential deformation and redistribution of thin ice within both polynyas and leads, which introduces additional uncertainty in derived production estimates.

It should be noted that regardless of the sensor used, ice production calculated with these methods can be overestimated if there is significant upward oceanic heat flux from below. Therefore, these mappings should be regarded as upper-bound estimates of sea ice production. This limitation becomes particularly important in hybrid polynyas, where upward oceanic heat flux can substantially reduce actual ice production (see section 5.3). As discussed in section 4, recent studies suggest that up to half of the Arctic polynya regions now exhibit characteristics consistent with hybrid latent–sensible systems, but for most polynyas, their areas are also larger (Wong et al., 2026). How, then, are polynya area and SIP related? Using the most updated datasets of Arctic polynya area (Wong et al., 2026) and sea ice production (Nakata and Ohshima, 2022), Fig. 4 compares the time series of annual integrated values for each Arctic sector since 2002. Year-to-year variability shows a generally good correspondence between polynya area and SIP in most regions (see R value at the top of each panel and in Appendix Table

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A1), indicating that larger polynyas tend to produce more sea ice on interannual timescales. The largest correlations are found in the North Water polynya (NOW), Laptev and East Siberian seas, where R values exceeding 0.8 mean that the polynya area alone explains more than two thirds of the variability in sea ice production. In contrast, the long-term trends exhibit markedly different behaviour. While polynya area shows increasing trends in most regions (dashed orange lines on Fig. 4), SIP tends to exhibit decreasing trends, although the magnitude and significance vary regionally (significant at 90% only around Svalbard, -53 m/year, and NEW, -34 m/year, dashed blue lines). This contrast is particularly evident in the Arctic-wide integrated values, where the two variables exhibit statistically significant trends of opposite sign (+1234 km^2/year in area but -161 m/year in SIP). Several mechanisms may contribute to this apparent discrepancy. First, atmospheric warming may promote larger and more persistent openings in the sea ice cover while simultaneously reducing net thermodynamic ice growth through warmer air temperatures. Second, continued thinning of pack ice may facilitate mechanical opening and a larger extent of polynya, while the expanded polynya area, extending into deeper regions, may become increasingly affected by enhanced oceanic heat flux from below (see Fig. 4). In addition, enhanced oceanic heat fluxes associated with ongoing Atlantification and the overall transition to hybrid polynyas might also contribute to the contrasting trend features in some regions. However, the relative importance of these processes likely differs among regions and remains to be quantified.

In general, sea ice production in polynyas is about half as large in the Arctic Ocean than in the Southern Ocean, mainly because the Arctic Ocean is surrounded by continents, which strongly suppress large-scale divergent ice motion (Ohshima et al., 2016). This large hemispheric contrast is mainly explained by the less frequent occurrence of active frazil ice and thin-ice areas in the Arctic Ocean due to the lower occurrence of strong wind events, in contrast to the katabatic wind over the Antarctic coastal polynyas (Nakata and Ohshima, 2022). Indeed, most sea ice production occurs within thin-ice areas where thermal ice thickness is less than approximately 0.2 m. Thin-ice areas are broadly classified into two ice types: active frazil ice, which consists of mixtures of frazil/pancake ice and open water formed under turbulent conditions, and thin solid ice, which is a relatively uniform thin-ice region formed under calmer conditions. Frazil ice production has been increasingly recognized as an important process in coastal polynyas: Underwater frazil ice formation prevents the formation of heat-insulating surface-cover ice, thereby enabling efficient ice production in a polynya (Ohshima et al., 2022). Further, when frazil ice reaches the seafloor or comes into contact with resuspended sediments, it can incorporate sediments including micronutrients such as iron (Eicken et al., 2005; Dethleff and Kuhlmann, 2009; Ito et al., 2019). These sediments or micronutrients are then transported by drifting ice floes and released upon melting, potentially stimulating phytoplankton blooms (Krumpen et al., 2019). Besides, seasonal atmospheric conditions further modulate ice growth: precipitation is typically maximised in autumn and early winter, followed by relatively dry conditions during the coldest months, reducing snow accumulation and thereby increasing conductive heat loss through the ice, which enhances thermodynamic growth rates in the thinnest ice that has shallow snow cover (Itkin et al., 2023).

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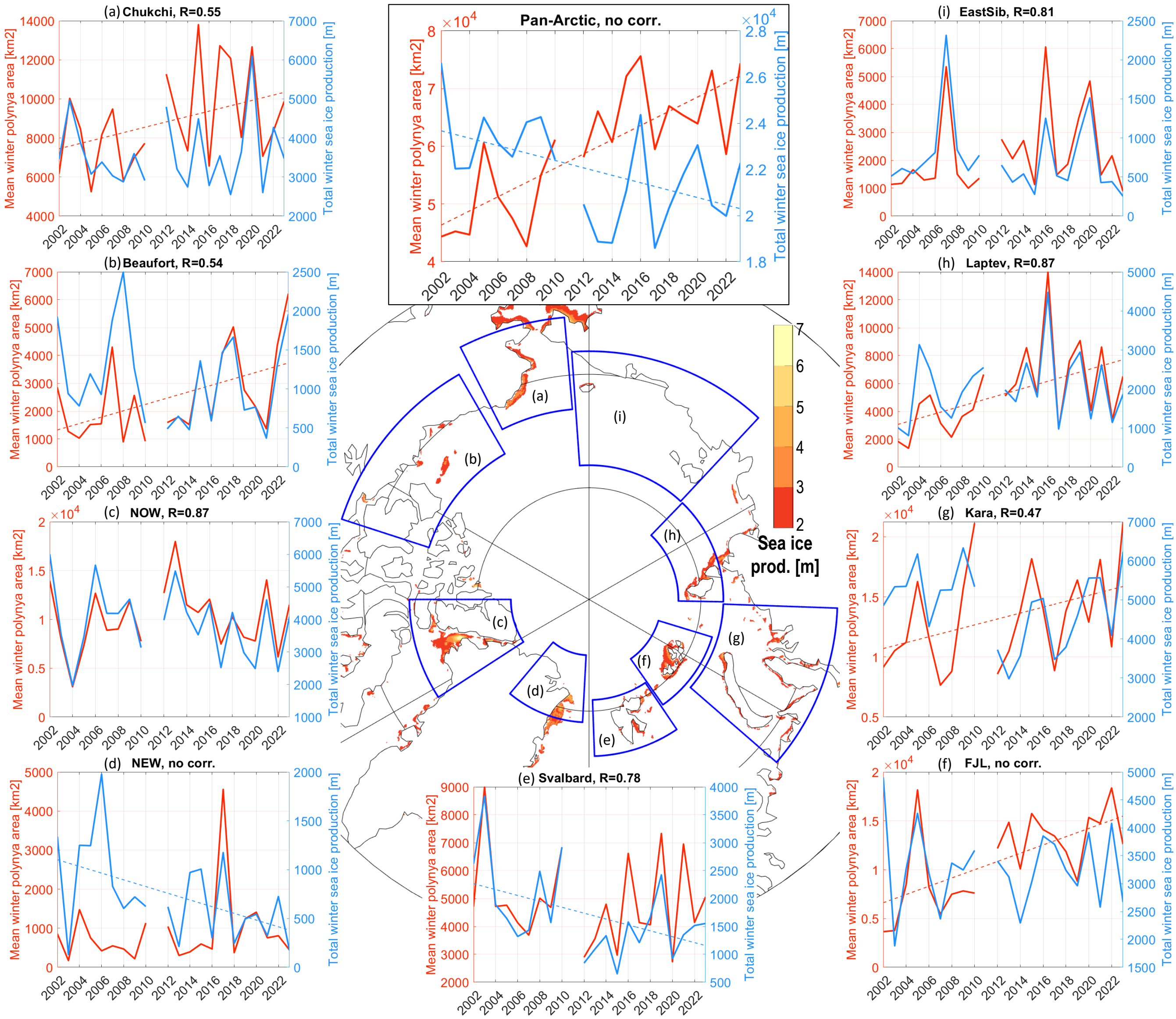

Figure 4. Map: Yearly mean winter cumulative sea ice production in meters for each pixel, using AMSRE (2002-2010) and AMSR2 (2012-2024). Calculation of sea ice production is based on Nakata and Ohshima (2022), where, for AMSR2, brightness temperatures are first converted to AMSR-E equivalents using the AMSR2/AMSR-E intercalibration correction provided by JAXA (e.g. Ohshima et al., 2020) and sea ice production is then estimated using the AMSR-E algorithm. Dark blue contours are the regions of the distinct panels, using the same definition as e.g. Wong et al. (2026). Panels: for the nine individual regions and for their pan-Arctic sum, in orange, time series of the winter mean daily polynya area, in km^2 (using the AMSRE/AMSR2-derived polynya masks of Wong et al., 2026). If the polynya area has a significant trend (at 90%), regression line is shown in dashed orange. In blue, time series of the winter cumulative sea ice production, in m; likewise, if it has a significant trend, regression line is shown in dashed blue. Panel titles indicate whether yearly polynya area and sea ice production are significantly correlated at the 90% confidence level and, if significant, the correlation coefficient (R). Values also given in Appendix Table A1. Note the different time period and sensor compared to Fig. 2.

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5.3 Ocean: Halocline maintainance and dense water formation

Around most of the Arctic Ocean, where a sharp halocline underlies a relatively fresh upper mixed layer (Timmermans and Marshall, 2020), winter polynyas on shallow Arctic shelves are the key producers of salty (dense) water with the potential to descend along the sloping seabed, thus ventilating the water column of the deep ocean (Ivanov et al., 2004). Knowledge of this process is not new: Nansen and Waters (1906), based on indirect observational evidence, postulated that dense water, originating over the shallow western shelf of Novaya Zemlya in the Barents Sea as a result of freezing and associated brine ejection, was able to descend (cascade) due to gravitational forcing along the sloping seabed, eventually reaching the depth where its density is equal to that of the density of ambient water. However, whether this process is critically important for the maintenance of a cold halocline (e.g. Aagaard et al., 1981; Cavalieri and Martin, 1994), the cooling of the Atlantic Water layer (e.g. Ivanov and Golovin, 2007; Ivanov et al., 2015) and the replenishment of deep waters (Rudels, 1986; Martin and Cavalieri, 1989, e.g.) has been a matter of debates since the earliest Arctic oceanography expeditions.

The crucial role of polynyas for the halocline was mostly unchallenged until the 2010s, despite Woodgate et al. (2005), using hydrographic observations along with nutrients and dissolved gases in the Chukchi Sea, having shown that polynyas hardly contributed to ventilating the halocline there. Using primitive equation models, Dethleff (2010) even calculated that the Laptev Sea polynyas alone contributed 23% of the pan-Arctic ventilation of the halocline, and warned the reader that this was most likely an underestimation. Bauch et al. (2011) were first to show at the pan-Arctic scale, using tracers, that polynyas may rather play an indirect role: They found that river water sinks to the bottom of the shelf in the Laptev and Kara seas thanks to sea ice formation in polynyas. Dmitrenko et al. (2010), using mooring observations, and Bauch et al. (2012), using tracers, both showed that the presence/absence of river water the preceding summer (linked to the wind) even pre-conditioned the region for its own sinking. Furthermore, Dmitrenko et al. (2012) demonstrated that by having a polynya opened, tides could have a large effect on the halocline. Besides, polynyas often open next to landfast ice, which both in observations (Kirillov et al., 2013) and in models (Itkin et al., 2015) have been shown to be crucial to control the depth reached by waters mixed from the surface, and therefore the halocline stability at the pan-Arctic scale. As a negative Arctic Oscillation (AO) phase leads to increased sea ice convergence in the Siberian Arctic, which in turn favours sea ice grounding and promotes the development of large fast ice extent (Selyuzhenok et al., 2023), this might explain the apparent link between AO and halocline stability (Polyakov et al., 2018).

Some research even suggests that polynyas are irrelevant for the halocline. Dmitrenko et al. (2011) and Dmitrenko et al. (2012) based on hydrography and water tracer data, and numerical modelling of the broader region, suggest that the halocline water should be formed by modification of the Atlantic Water in the Fram Strait and Barents/Kara Sea, and that the increased salinity of the halocline layer originates from sea ice formation in those marginal ice zones and not in the polynya (as evidenced by a 5-year lag). Besides, Krumpen et al. (2011) found that polynyas could not make water sink to the bottom of the Laptev shelf; this sinking is done by wind- and tidally driven mixing. Others go further and highlight that polynyas open in response to the process that matters, usually wind, but do not contribute significantly (e.g. in northeast Greenland, Dmitrenko et al., 2015a).

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In that region, the halocline is primarily modified by other water masses, the presence of glaciers, even geothermal heating on the shallow shelf, and only to a small extent by the presence of polynyas (Dmitrenko et al., 2023).

In summary, over the last two decades, the literature has moved from declaring that polynyas are the most important process for maintaining the cold halocline at the pan-Arctic level, to just being one process among many, with an importance that depends on the region (Oglethorpe et al., 2026) and on compounding interactions with the other processes (wind, river plume, tides etc). This is not linked to trends or a regime shift in polynyas, but rather to a better understanding thanks to more, more complex observations.

Regarding dense water formation in polynyas, logistical constraints, geopolitics, and an overall focus on the polynyas that the theory says can lead to dense water cascades (e.g. based on the shelf slope or ambient water salinity), mean that we still lack a pan-Arctic understanding of the process, its frequency, and extent. The location of sites in the Arctic Ocean where, according to direct observations, dense water cascaded downslope at least once in the observational record, was first summarised in Ivanov et al. (2004) and later rectified through modelling in Luneva et al. (2020). These locations do not necessarily coincide with polynyas, since dense water sometimes passes hundreds of kilometres from the source area before reaching the continental slope (Shapiro et al., 2003). These pan-Arctic studies estimate the downslope volumetric flux provided by cascading of dense water to 0.05 - 0.08 Sv per 100 km of Arctic shelf break (Ivanov et al., 2004) or 1.3 Sv cascading to the deep Arctic (Luneva et al., 2020). In their model, Luneva et al. (2020) further found an increasing trend in dense water fluxes of 0.0175 Sv/year in response to the retreat of sea ice.

Using observations only to conduct a trend analysis has so far been impossible. Even the best-observed overflow of the Storfjorden polynya in the south of Svalbard (which does not directly contribute to Arctic dense water ventilation), regularly monitored because comparatively easier to reach, only has a series of individual deployments rather than long-term time series. We nonetheless know that its very saline (over 35.4 g/kg) dense water plume, 30 m thick and 15 km wide, takes 12 to 18 days to reach the sill depth (Skogseth et al., 2008), and can be detected at a depth of 2000 m at the continental slope of Svalbard (Quadfasel et al., 1988). Although the dense water outflow has been estimated from individual deployments (0.078 Sv in 1990-1991, Schauer (1995); 0.06 Sv in 2001, Fer et al. (2003); 0.03 in 2003 - 2007, Geyer et al. (2009); 0.04 Sv in 2016-2017, Vivier et al. (2024)), no trend analysis has been performed, authors reporting instead individual episodes (Skogseth et al., 2013). Geyer et al. (2009) further demonstrated an interannual variability of 0.01 Sv and a seasonal variability of 0.05 Sv, depending on the atmospheric forcing. Recent studies do highlight changes in response to the Atlantification of the Arctic: Vivier et al. (2024) find that dense water formation in Storfjorden is not impeded by the Atlantification, and might even be favoured by that inflow of saline waters that destabilise the water column, a result also found in neighbouring Isfjorden which has shifted in the last two decades to an “Atlantic type fjord" with no sea ice and inflow of Atlantic Water, which de-stratifies the water column and produces the densest water (Skogseth et al., 2020). The outcome is a dense plume about 1°C above the pre-2005 values due to the entrainment of these warmer waters (Vivier et al., 2024).

Observations are even more sparse in the rest of the Eurasian Arctic. In the Kara Sea, Ivanov and Golovin (2007) reported dense water plumes observed down to 400 m at the continental slope in 1984-1985, with an estimated cascading of 0.02 Sv which cooled the Atlantic Water layer (also in 2007, as modelled in Ivanov et al., 2015). Dmitrenko et al. (2015b) could only

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reports indirect evidence of such a plume at the bottom of Saint Anna Trough in 2009-2010 as their mooring had no deep salinity sensor. Although the simple models of Dethleff (2010) found that the Laptev Sea polynyas contributed 30% of the dense waters of the Arctic, these and the polynyas in the East Siberian Sea have never been systematically explored since their shelves were deemed too shallow to change properties in the deep Arctic basins, which was confirmed by Dmitrenko et al. (2005) and Kirillov et al. (2013). Janout et al. (2017) nonetheless point out the importance of Laptev polynyas to modify the dense waters advected from upstream on the Eurasian shelves, and using reanalysis data over 1993-2018, Janout et al. (2020) argue that the shift from a permanent to seasonal sea ice cover on the Eurasian shelves could result in an increased role of polynyas for dense water formation, through an increased preconditioning by the wind on stratification. Besides, the polynya-induced entrainment of brine has been observed to lead to warm pulses at the bottom of the Laptev shelf, with potential consequences for the subsea permafrost stored there (Janout et al., 2016).

In the Amerasian basin, the dynamics of dense water formation are different: instead of a direct conduit between the polynya and the deep basins, polynyas rather facilitate the upwelling of warms waters which are modified by interaction with brine-enriched polynya waters or the atmosphere, and only then sink. The observational record is likewise not a long time series but made of distinct sets of deployments that show episodes of dense water formation in the Chukchi Sea in 2009 (Hirano et al., 2016), 2011 (Pickart et al., 2016), and occasionally over 2010-2015 (Ladd et al., 2016); in the Beaufort Sea in 2009-2011 (Jackson et al., 2015); and in the North Water polynya in 1997-1998 (Melling et al., 2001). Two main results emerged nonetheless:

- From 10 years of mooring deployment in the hybrid Chukchi Sea polynya, Hirano et al. (2022) showed that dense water formation took place only when the polynya was in its "latent heat phase".
- Polynyas around Greenland do not contribute to deep ventilation, as the dense water remains in the fjords (Rysgaard et al., 2020), but the formation of polynya-induced dense water facilitates the inflow of warm waters into the glacial fjords (Dmitrenko et al., 2015a; Huhn et al., 2021).

To summarise, there are still too few observations to infer any ongoing trend in dense water formation resulting from polynyas. The future in the context of the Atlantification of the Arctic is unclear: Half of the polynya regions, especially in the Eurasian Arctic, have become hybrid polynyas (Wong et al., 2026), which should lead to reduced dense water formation (Hirano et al., 2022), but by reducing stratification Atlantification is currently enhancing dense water formation (Vivier et al., 2024). On the Amerasian side where upwelling of warm water is a pre-requisite for dense water formation, an eventual Atlantification should enhance dense water formation, but with the downside of enhancing the inflow of warm water toward the Greenland glacier fronts (Dmitrenko et al., 2015a).

6 The future of Arctic polynyas

The review book on polynyas by Smith Jr and Barber (2007) concluded with a brief outlook of the future of polynyas in the Arctic, incorrectly projecting a northward migration of polynya locations and a reduction in the size of the polynyas depending

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on ice arches, but correctly predicting that these ice-arch dependent polynyas would become shorter lived. From this review we conducted here, we can instead highlight a series of positive feedback loops that can explain why Arctic polynyas have been becoming larger, which are summarised on Fig. 5:

- Polynyas are larger and stay open for longer (section 4). They release more heat (and moisture) to the atmosphere. This increases the low cloud cover, which melts the sea ice further, increasing the polynya size and event duration (section 5.1). Besides, low cloud cover in general is increasing in the Arctic and expected to continue increasing in response to pan-Arctic sea ice loss (Chernokulsky and Esau, 2019), so this loop may be enhanced.

- Many polynyas have switched from latent-heat only to hybrid (section 4), i.e. are increasingly opening or preconditioned by thermodynamics forcing instead of requiring dynamics only. The outcome is that polynyas open more readily, earlier in the autumn and stay open later in the spring, thus keeping the region preconditioned for future openings. At the pan-Arctic scale, the thermodynamics forcing is enhanced both in the atmosphere (polar amplification, winter heat waves) and in the ocean (borealisation). The dynamics may also have accelerated, with stronger winds, more storms reaching the Arctic (Li et al., 2026), and potentially faster ocean currents (Armitage et al., 2017). All these contribute to an overall thinner, more mobile ice, easier to open. In addition, polynyas that open in autumn and remain open in spring are more vulnerable to rain and rain-on-snow events, which have both increased and also changed their seasonality (Boisvert et al., 2018). To summarise, this loop may be enhanced.

- Hybrid polynyas do not form as much sea ice as latent-heat only ones; in fact, at the pan-Arctic scale and in different regions, sea ice production has been decreasing despite increased polynya area and longer polynya seasons (section 5.2). This further reinforces the previous feedback loop.

There are, however, potential negative feedback loops as well:

- The Arctic atmosphere is warmer, with an increased frequency of extreme heat and/or moist events in winter notably. This reduces the heat (and moisture) fluxes from the ocean to the atmosphere during a polynya event, therefore potentially reducing the formation of the low altitude clouds that enhance polynya activity.

- Polynyas in the Canadian Arctic Archipelago, including the very large and productive North Water polynya between Canada and Greenland, depend on the formation of ice arches to be established. At the pan-Arctic scale, many polynyas form next to landfast ice. Both ice arches/bridges and landfast ice are disappearing in the Arctic; these polynyas are opening for shorter periods (section 4). As air and ocean keep warming, it is not unusual that ice arches do not form at all (Vincent, 2019). This loop is expected to be enhanced. Even so, there is evidence that the North Water polynya may remain stable in the absence of the nearby ice arch as long as the winds in the region remain strong enough to advect ice away (Moore et al., 2023).

- As more areas of the Arctic are ice free in summer, and winter ice production in polynyas is decreasing, many of the regions where polynyas usually open are now covered with first-year ice, smoother than the older ice. This smoother

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ice is harder to move by the winds (Krumpen et al., 2025), which might mean fewer polynya openings despite stronger dynamics forcing on preconditioned, thinner ice.

– Reduced sea ice production means reduced brine rejection, which could be interpreted as reduced deep convection and/or upwelling of warm subsurface water. However, as long as polynyas are open in winter at times when the atmosphere is colder than the ocean, thermal convection can occur (Ivanov et al., 2016), which may be the cause of the recently observed deep mixed layers north of Svalbard (Pérez-Hernández et al., 2019). How deeper mixing and Atlantification will interact, and the net effect on polynyas, is highly uncertain.

The positive and negative feedback loops will most likely have different respective impacts depending on the time horizon considered. In particular, although the Arctic is likely to be ice-free in summer by 2050 (Jahn et al., 2024), and the conditions are in place for it to be ice-free for a day at any time now (Heuzé and Jahn, 2024), it should not be ice-free in winter before we reach 4-5°C of global warming (Jahn et al., 2024). That is, we will continue to have sea ice in which to open polynyas. Unfortunately, we cannot use global coupled "CMIP" models to verify which process will dominate future polynya openings, nor the timing of any potential shift. Heuzé et al. (2026) showed that not only do Arctic polynyas in the latest generation of such models (CMIP6) have wrong characteristics (too large and not opening often enough or at the right location), they are also all sensible heat-only polynyas, i.e., open through the wrong process. Instead of CMIP6 models, here we provide our expert assessment (summarised on Fig. 5b). Although we disagreed on which process dominated, reflective of our various specialties, we were unanimous in expecting polynyas to continue growing, increasingly switch to hybrid / sensible heat polynyas, and stay open longer in response to warmer air, thinner ice, and/or Atlantification. An acceleration, or even a regime shift, may occur when polynyas outgrow the shelf break and open over the deep Eurasian basins, where they would become even more vulnerable to the combined effect of weakened halocline and stronger Atlantification. We were also unanimous that extreme events are a very large source of uncertainty.

As summarised in the introduction, climate change is increasing the number, magnitude, and frequency of these extreme events in the Arctic. However, to date, barely any study has investigated the link between extreme events and Arctic polynyas. The exception is the emergence of polynyas in the "Last Ice Area" north of Greenland over the last decade (section 4), both in summer and winter, whose opening has been linked to anomalous winds (Moore et al., 2018, 2021). A future review should consider the impact of heat waves (including marine), storms, atmospheric rivers, precipitation, not only on polynya opening but also on polynya maintenance or closing, and reciprocally how polynyas impact these extreme events. Another large but crucial unknown is the link between polynyas and carbon storage. In many authors' introduction, including this team, one can read that polynyas should in theory act as carbon sinks, since latent heat polynyas result in a high solubility (cold and salty) at the surface and polynyas in general are associated with enhanced biological activity (Miller and DiTullio, 2007). This was admittedly not the topic of this review, but to the best of our knowledge, no one has verified these assumptions, nor has investigated how the switch from latent-heat only to hybrid polynyas will impact the carbon budget. Beyond the carbon budget, larger polynyas, open for longer both earlier in the autumn and later in spring, and increasingly in response to thermodynamics, should have large impact on the entire food web, from phytoplankton blooming earlier (too early?) to Indigenous communities

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having to hunt from thinner, not-yet consolidated ice. Polynya changes might also facilitate navigation and exploitation of the Arctic year-round, thus increasing the risk of catastrophic oil spills or other pollutions, further damaging the fragile Arctic ecosystem. The only way to minimise this risk is to reduce our uncertainties regarding polynya predictions and projections.

Reducing uncertainties obviously requires improving models used for these projections. Our recommendations overlap with those of the Antarctic coastal polynya review of Golledge et al. (2025): a higher resolution is needed for all subgrid scale processes (from clouds to ocean eddies), but also simply to represent the smaller polynyas. Instead of ice sheet dynamics, the freshwater forcing from rivers and the representation of river plumes is also crucial for polynyas on the Siberian shelf (section 5.3). In the Arctic, the assessment of polynyas in the latest generation of climate models (Heuzé et al., 2026) concluded with a similar wish for higher resolution, citing also the complex Arctic geometry as well as the resolution's impact on wind strength, and wishing for a better representation of landfast ice. They however pointed out that most model biases impacting Arctic polynyas are imported from upstream (e.g. a too warm but too deep Atlantic Water) or are caused by the sea ice model. The recent in-depth review by Haapala et al. (2026) points out that the main source of biases in sea models is that many parameters in these models are incorrectly assumed constant. Of relevance to polynyas, they notably recommend prioritising a better representation of sea ice itself, notably thickness distribution and fracturing, as these directly impact the representation of heat and moisture fluxes through the ice as well as ocean mixing. Haapala et al. (2026) also recommend moving away from bulk formulations for momentum transfer from atmosphere to ocean via sea ice, accounting instead for the above- and below-surface sea ice topography and roughness.

Many of these model improvements, however, require a better understanding of the processes leading to polynya formation and maintenance, and therefore long, high-resolution (since polynyas are intermittent features) observational programs. As we reviewed in section 5.3, most polynya observations in the ocean rely on short-lived, semi opportunistic deployments. Maintaining long mooring deployments in the Chukchi Sea (Hirano et al., 2022) and over the Siberian shelf break (Pnyushkov and Polyakov, 2022) should be an international priority. Moorings do not send data in real time but rather need recovery cruises, and are therefore susceptible to everything from extreme events to funding cuts or even national waters becoming off-limit. A complementary solution is the widespread deployment of autonomous sensors, notably Argo floats or even the so-called BGC-Argo (Bittig et al., 2019) to simultaneously address physics and biogeochemistry questions. In addition, many on-ice or ocean autonomous sensors can be equipped with weather stations, which addresses the extreme paucity of near-surface atmospheric data. Away from the surface, we expect atmosphere studies to continue relying primarily on satellite data, which also require continuity. Finally, since polynyas are complex atmosphere - ice - ocean processes, we would like to see process studies dedicated to studying polynyas, most likely based on drift missions in order to reach the polynya location in winter. The recent completion of the Tara Polaris station (Ardyna et al., 2026) along with the upcoming International Polar Year in 2032-2033 would be perfect opportunities for the international community.

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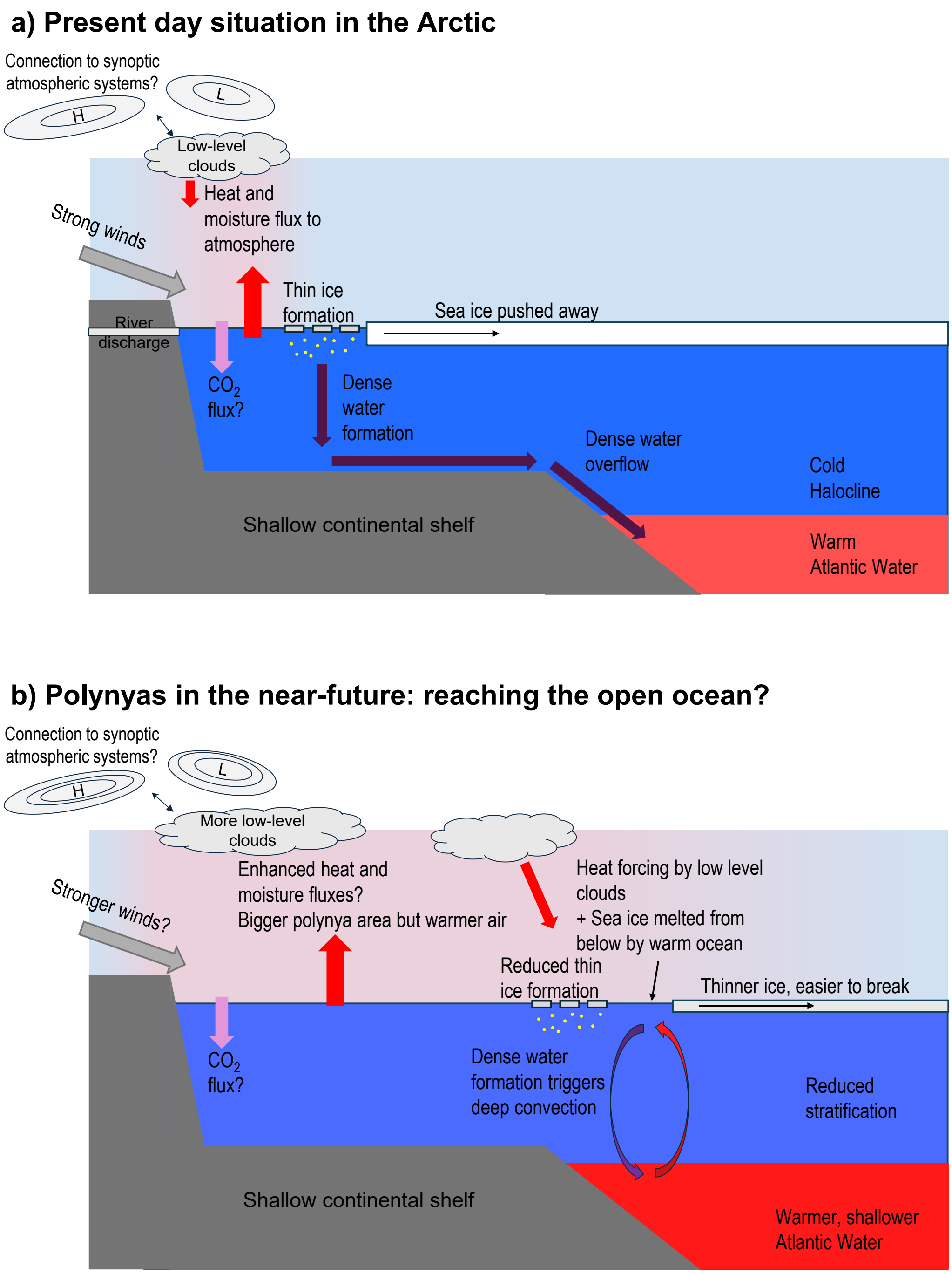

Figure 5. [This figure will be improved by a graphics designer after the first round of reviews] Schematic representation of a) present-day polynyas and their interaction with the climate system, and b) one possible future.

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Data availability. The bathymetry data used for Fig. 1, produced by GEBCO Compilation Group (2025), are publicly available at https://www.gebco.net/ (last accessed 17 February 2026). The sea ice data used for Fig. 1, produced by Spreen et al. (2008), are publicly available at https://seaice.uni-bremen.de/seaice-concentration/amsre-amsr2/ (last accessed 17 February 2026). The polynya masks produced by Wong et al. (2026) used for Fig. 2 are publicly available on PANGAEA as Wong and Heuzé (2025), at https://doi.org/10.1594/PANGAEA.987383 (last accessed 4 May 2026). The merged MODIS-AMSR2 sea ice concentration data used in Fig. 3, produced by **?**Ludwig et al. (2020), are publicly available at https://data.seaice.uni-bremen.de/modis_amsr2 (last accessed June 3, 2026). The AMSR2 sea ice concentration data used in Fig. 3, produced by Spreen et al. (2008), are publicly available at https://data.seaice.uni-bremen.de/amsr2/ (last accessed June 3, 2026). The EUMETSAT OSI SAF sea ice concentration climate data record (v3.1, 2025) used in Fig. 3, produced by EUMETSAT OSI SAF (2025), are publicly available at https://osi-saf.eumetsat.int/products/osi-450-a1 (last accessed June 3, 2026). The Sentinel-1 scenes used in Fig. 3, produced by the Copernicus program, are publicly available provided by Roberto Saldo, DTU Space and Technical University of Denmark, via http://north.seaice.dk/2018/02/26 (last accessed June 24, 2026). The Nighttime Imagery (Day/Night Band) layer used in Fig. 3 from the VIIRS instrument aboard the joint NASA/NOAA Suomi National Polar orbiting Partnership (Suomi NPP) satellite, produced by (VIIRS Calibration Support Team (VCST), 2025), is publicly available at https://worldview.earthdata.nasa.gov/ (last accessed June 3, 2026). The ASCAT radar backscatter data used in Fig. 3, produced by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), are publicly available at https://user.eumetsat.int/catalogue/EO:EUM:DAT:METOP:ASCSZF1B (last accessed June 3, 2026). The polynya masks produced by Wong et al. (2026) used for Fig. 4 are currently in the process of being archived on PANGAEA (https://pangaea.de/); when the process is complete, the data will be publicly available there. The sea ice production time series produced by Nakata and Ohshima (2022) used for Fig. 4 are in the process of being archived on Arctic Data archive System (https://ads.nipr.ac.jp/data/search/list/1) provided by the National Institute of Polar Research, Japan; when the process is complete, the data will be publicly available there.

Table A1. Values shown on Fig. 4: Annual mean and interannual standard deviation and, if significant at 90% ('-' otherwise), linear trend, in polynya area (left) and sea ice production (right) over 2002 - 2024, at the pan-Arctic level (top) and for each region (rows). Last column is the correlation between the annual time series of polynya area and SIP, if significant at 90% ('-' otherwise).

	Area		SIP		Correlation
	Mean [km^2]	Trend [km^2/year]	Mean [m]	Trend [m/year]	
Pan-Arctic	59371 ± 10133	1234	21966 ± 2004	-161	-
Chukchi	8903 ± 2386	138	3643 ± 893	-	0.55
Beaufort	2536 ± 1481	115	1146 ± 568	-	0.54
NOW	10142 ± 3220	-	3900 ± 1036	-	0.87
NEW	879 ± 902	-	731 ± 451	-34	-
Svalbard	4895 ± 1572	-	1686 ± 736	-53	0.78
FJL	11081 ± 4294	423	3307 ± 686	-	-
Kara	13301 ± 4008	246	4800 ± 934	-	0.47
Laptev	5407 ± 2918	221	2030 ± 848	-	0.87
East Sib	2228 ± 1461	-	722 ± 456	-	0.81

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Author contributions. C.H. came up with the original idea and led the work. All authors contributed to designing the study, writing the text, and reviewing it.

Competing interests. The authors declare no conflict of interest.

Acknowledgements. C.H. is funded through the Swedish National Space Agency project "MAPS", grant number 2022-00149. K.I.O. is funded through Grants-in-Aid for Scientific Research (25H00002) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. V.I.'s contribution was funded by the Russian Science Foundation, grant 24-17-00041.

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