



Intermittent sea ice transport from the Transpolar Drift shapes thickness variability in the northwestern Barents Sea

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Abstract. Sea ice thickness affects a wide range of processes in the Arctic, but remains poorly constrained by observations. This study focuses on the northwestern Barents Sea, an area where sea ice is highly variable and affected both by local processes and ice transport from the adjacent Central Arctic Ocean. Satellite-derived sea ice age and back-trajectories indicate that sea ice was transported from the Central Arctic Ocean into the northwestern Barents Sea during 7 of 15 ice seasons between 2009–2024. Three of these seasons (2019–2021) coincided with moored in situ sea ice draft observations in the area. In these seasons, the arrival of ice from the Central Arctic Ocean coincided with a local transition to thicker and more uniform ice – a seasonal evolution that could not be explained by local thermodynamic forcing alone. Satellite-derived sea ice thickness and modelled thermodynamic ice growth along back-trajectories indicate that the Central Arctic-origin ice grew along its pathway within the Transpolar Drift, and had acquired its thickness before entering the Barents Sea. While intermittent at the study area, an advection-driven shift to thicker and older ice between February and June occurs at the margin between the Barents Sea and the Nansen Basin in the 2011–2023 climatology. The driver appears to be a seasonal progression of the atmospheric pressure configuration over the Atlantic sector of the Arctic Ocean. Large-scale patterns of sea ice transport are a key control on the pronounced interannual variability of summer sea ice thickness in the region, with implications across the marine system.

1 Introduction

The northern Barents Sea (*nBS*), a seasonally sea ice-covered Arctic Ocean shelf sea region located between the Arctic and North Atlantic Oceans, is a rapidly changing environment by most measures. Over several decades of observations (from around 1980 to 2015–2020), the ocean and lower atmosphere have warmed (Isaksen et al., 2022; Gerland et al., 2023), ocean stratification and water mass composition have been significantly altered (Lind et al., 2018), and marine ecosystems (Eriksen et al., 2025) and ocean geochemistry (Ericson et al., 2023) have undergone pronounced shifts. These changes are all closely linked to changes in sea ice. During the same period, sea ice extent, duration and concentration have decreased (e.g. Parkinson, 2014; Onarheim and Årthun, 2017; Asbjørnsen et al., 2020; Sandven et al., 2025), and the ice has become thinner and younger

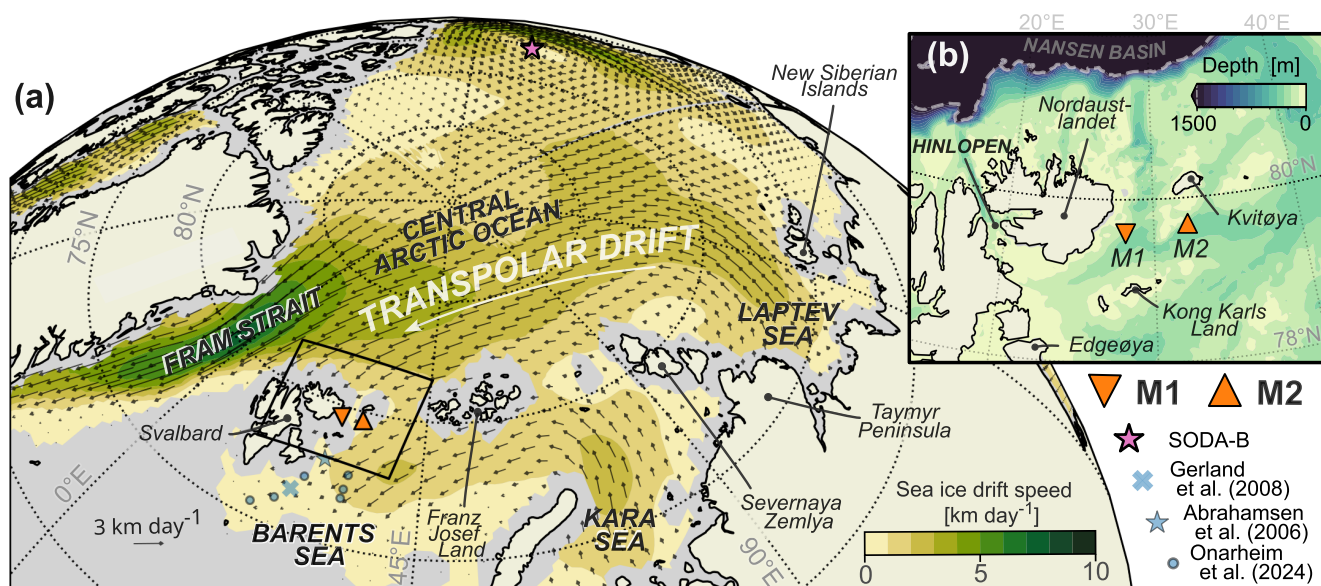


Figure 1. *a*: Mean sea ice drift from NSIDC PP during 2018–2021. Drift vector averages were computed as arithmetic means of the individual vector components, with instances of no drift included as zero. Quiver arrows show vectors subsampled every third grid point (75 km), and colour contours show the magnitude of the mean drift vectors. Also shown are the locations of the M1 and M2 moorings as well as other long-term sea ice thickness observations mentioned in the text. *b*: As in (a), but zoomed in to the study area and showing bottom depth. Displayed bathymetric data are from IBCAO-4 (Jakobsson et al., 2020).

(Gerland et al., 2008; King et al., 2017), although there has been no apparent thinning trend since 2016 (Onarheim et al., 2024). Sea ice changes have been most pronounced in late winter and spring (Onarheim et al., 2018); the 1979–2019 negative trend in winter sea ice area in the Barents Sea region exceeded that of any other ice-covered Arctic Ocean region (Fox-Kemper et al., 2021).

The sea ice state in the nBS is controlled by a range of processes. *Thermodynamic* forcing drives sea ice formation and melt; sea ice forms in the nBS in late autumn and winter, and largely melts in summer (Gerland et al., 2023), resulting in a characteristic, fresh upper ocean layer (Ellingsen et al., 2009; Smedsrud et al., 2013; Koenig et al., 2024). Thermodynamic forcing can act from below as well as from above, and warm Atlantic Water (AW) is a key driver of sea ice melt in adjacent regions (Barton et al., 2018; Duarte et al., 2020). AW-influenced water masses are occasionally found near the surface also in the nBS (Lundesgaard et al., 2022).

In addition, sea ice *dynamics*, including local motion and deformation as well as the large-scale advection of sea ice floes drifting between regions, plays a particularly significant role in the nBS. Substantial quantities of ice are advected between the nBS and regions to the north and east, and the nBS is located south of the main pathway of the *Transpolar Drift* (TPD), which transports ice across the Central Arctic Ocean (CAO) from the Siberian shelves toward the Fram Strait (Fig. 1a). Sea ice transport is in turn governed by large-scale atmospheric forcing and exerts a primary control on sea ice extent in the nBS and the



net freshwater budget of the region (Kwok et al., 2005; Koenigk et al., 2009; Lind et al., 2018; Aaboe et al., 2021; Koenig et al., 2024). Recent pan-Arctic analyses further show that dynamic processes constitute a first-order component of the winter sea-ice thickness budget. Dynamical thickening through convergence can be comparable in magnitude to thermodynamic growth, although it is partly offset by dynamical thinning associated with divergence and by subsequent ice growth in newly formed leads (von Albedyll et al., 2026). The relative importance of these processes varies strongly between regions and with the pre-existing ice thickness.

Sea ice *thickness* (*SIT*) at a given location is affected by both thermodynamics and dynamics; melt and growth from above or below modify the thickness, and local convergence can generate thick sea ice ridges. Advection can introduce ice of different origins: local *SIT* may not only reflect local conditions, but also the history of ice that has been advected from elsewhere. *SIT* is required to translate ice area into volume and governs mechanical properties of the ice cover (Timco and Weeks, 2010). It is also key to predicting ice persistence (Landy et al., 2022), contributes to freshwater budgets and ocean stratification (Ellingsen et al., 2009; Lind et al., 2018), and shapes the sea ice as a habitat for ice-associated organisms (e.g. Lange et al., 2017). Moreover, *SIT* is of practical importance for human activity; e.g., the International Maritime Organization's *Polar Code* (Deggim, 2018) classifies ice-going vessels in terms of *SIT* where they can safely operate. In the nBS region, navigation can be complicated by thick and strongly deformed sea ice, with moored observations showing substantial spatial and interannual variability in ridge frequency and keel depth (Hansen et al., 2023) and satellite observations indicating similarly strong variability in pressure-ridge characteristics (Fredensborg Hansen et al., 2024; Mchedlishvili et al., 2023b). Unusual sea ice extent and thickness around Hinlopen prevented salvage operations for the stranded *Northguider* trawler during the summer of 2019 (Løset et al., 2022). This illustrates that understanding *SIT* and the processes that govern it has both scientific and practical implications.

While sea ice concentration and extent are readily observable from remote sensing, *SIT* is more challenging to estimate and consequently a less well-constrained quantity, with the observational record of *SIT* rather sparse in the nBS, as in most ice-covered seas. In situ measurements are costly and logistically demanding, while remote sensing techniques still have clear limitations as they rely on accurate satellite observations of ice freeboard (typically on the order of a few to tens of cm) and auxiliary estimates of the snow load and ice density to scale freeboard to thickness (Landy et al., 2020). Strong temporal and spatial heterogeneity also presents considerable challenges for characterising nBS *SIT*.

Sea ice thickness in the nBS is complex and highly variable on a range of temporal and spatial scales, shaped by a variety of processes and ice floe histories. The longest and most consistent time series of ice thickness (Gerland et al., 2008), from coastal, landfast sea ice by the small island of Hopen (Fig. 1), showed annual maximum values ranging from <0.5 m to 2 m, with a 1966–2007 thinning trend of 0.11 m per decade, superimposed on considerable seasonal and interannual variability. In recent years, this thinning trend appears to have disappeared for drifting sea ice (Onarheim et al., 2024), although the covariance between fast ice and regional drift ice thickness is unclear. Abrahamsen et al. (2006) reported mean Feb–May draft of 2.6 m (1995) and 1.6 m (1996) based on data from moored upward looking sonar (*ULS*) located east of Edgeøya (Fig. 1). A later study (King et al., 2017) using helicopter-borne electromagnetic *SIT* surveys from 2003 and 2014 observed significantly thinner ice, with modal thickness in March ranging from 0.5 to 1.4 m. They attributed the difference between their measurements and Abrahamsen et al. (2006) to a reduction in multiyear ice (*MYI*), as well as to enhanced ridging and deformation near the coast

in the 1990s ULS record. A record of Barents Sea winter ice thickness compiled from consecutive satellite altimeters between 1994 and 2023 suggests a thickening trend for October, little change for November–January, and a significant thinning trend of around 0.1–0.2 m per decade for February–April (Bocquet et al., 2024). Collectively, these studies have substantially advanced our baseline understanding of SIT in the nBS, illustrating the range of processes driving spatiotemporal variability.

However, key questions remain about the origins of the sea ice, the representativeness of existing observations, and the underlying drivers of SIT variability. In this study, we focus on a region in the northwestern nBS, roughly 79° N–80° N, 27° E–35° E. Bordering the Svalbard archipelago to the west and the CAO to the north, the area is influenced by ocean inflows and sea ice imports from the north (Pavlov et al., 2004; Kwok et al., 2005; Lind et al., 2018; Lundesgaard et al., 2022; Aaboe et al., 2021). We analyse a combination of remote sensing products together with a novel set of moored sea ice draft observations to address the following questions:

- *How often is sea ice in the northwestern Barents Sea transported from the Central Arctic Ocean rather than formed locally?*
- *How does sea ice thickness in the region vary, and on which time scales?*
- *Can sea ice thickness at a fixed location in the region be explained by local conditions?*

The paper is structured as follows: We first use available remote sensing products to investigate the origin of sea ice in the study region over a 15-year period and more closely in the period covered by the in situ observations, late 2018 to late 2021. We use the findings to classify different source areas for the origin of sea ice. We then examine the observed sea ice draft, and examine whether different sources are reflected in the ice draft observations. Next we discuss drivers of the variability and how processes may vary in other Arctic regions and place the new observations in context with previous work from the Barents Sea. We conclude with the broader implications of large-scale sea ice advection for the Barents Sea system.

2 Data and methods

2.1 Remote sensing and atmospheric reanalysis products

Table 1 shows the various gridded, openly available datasets used to examine the large-scale sea ice and atmospheric context. Sea ice age was compared across three independent products in order to verify key signals discussed in the paper.

For time series analysis and comparison between in situ observations and gridded products, we extracted time series from the grid points nearest to each of the moorings. For the along-trajectory analysis, CryoSat-2 (CS2) SIT sea ice draft was spatially and temporally interpolated to the daily trajectory positions.



Table 1. Gridded sea ice and atmospheric products used in this study.

Variable	Product	Shorthand	Temporal res.
Sea ice drift	Polar Pathfinder Daily EASE-Grid Sea Ice Motion Vectors, v4, NSIDC-0116 (Tschudi et al., 2019b)	<i>NSIDC PP</i>	Daily
Sea ice concentration	Sea ice concentration from University of Bremen AMSR2, ASI algorithm (Spreen et al., 2008)	<i>UoB SIC</i>	Daily
Sea ice age	Arctic Sea Ice Age Climate Data Record, v2.1, monthly (Korosov and Edel, 2025), daily (Korosov, 2026)	<i>Korosov SIA</i>	Daily, monthly
Sea ice age	EASE-Grid Sea Ice Age, v4, NSIDC-0611 (Tschudi et al., 2019a)	<i>NSIDC SIA</i>	Weekly
Sea ice age (FYI/MYI)	Sea Ice Edge and Sea Ice Type Climate Data Records, v4.0 CDR (C3S, 2018)	<i>OSISAF SIA</i>	Daily
Sea ice thickness and draft	Year-round Arctic sea ice thickness from CryoSat-2 Baseline-E observations 2010–2025, V2 (Landy et al., 2026)	<i>CS2 SIT</i>	Biweekly
Snow depth	Snow depths derived from gridded ICESat-2 and CryoSat-2 observations 2018–2023 (Landy, 2024)	<i>KuLa</i>	Monthly
Snow depth	Lagrangian reanalysis-driven snow evolution scheme SnowModel-LG (SM-LG) (Liston et al., 2021)	<i>SM-LG</i>	Daily
Sea ice ridge spacing	Gridded pan-Arctic total neutral atmospheric 10-m drag coefficient estimates derived from ICESat-2 ATL07 sea ice height data (Version 2) (Mchedlishvili et al., 2023a)	<i>IS2 ridge</i>	Monthly
2-m air temperature, sea level pressure	ERA5 global reanalysis (Hersbach et al., 2020), daily (C3S, 2024), and monthly (C3S, 2019)	<i>ERA5</i>	Daily, monthly

2.2 Sea ice back-trajectories

100 To examine the origin of the ice at the mooring sites (see Sect. 2.3), we computed backwards particle trajectories using the Polar Pathfinder (NSIDC PP) drift product. Trajectories were integrated backward using a first-order Euler scheme with a daily time step:

$$\mathbf{x}_{i-1} = \mathbf{x}_i - \mathbf{u}_i \Delta t \quad (1)$$



where $\mathbf{x}_i$ is the particle coordinate at the i -th time index, $\Delta t = 1$ day is the time step, and $\mathbf{u}_i$ is the NSIDC PP drift velocity vector at time index i at the particle position $\mathbf{x}_i$. The method was compared with trajectories from Sumata et al. (2023) and found to be equivalent.

Ice drift velocity $\mathbf{u}_i$ was obtained by spatial interpolation from the four nearest non-land grid points using inverse-distance weighting. Among these four, grid points classified open water (defined by missing velocity values, corresponding to ice concentrations below 15 %) were excluded from the interpolation. Trajectories were extended backward iteratively using Eq. (1) until either *a*) the grid cell nearest to the particle location was outside the land mask but with no valid drift (indicating that the particle hit open water), *b*) the net displacement was negligible over three successive days (indicating that the particle stopped moving), or *c*) the trajectory intersected the coastline excluding Svalbard (indicating that the particle hit land). For the latter, the coastline was obtained from IBCAO-4 (Jakobsson et al., 2020) and smoothed to 2 km resolution.

Particles were allowed to intersect Svalbard coastlines since the mooring locations were located close to the coast, and the computed trajectories frequently intersected Kvitøya or Nordaustlandet. Sea ice concentration maps from the area typically show sea ice passing southward into the nBS very close to the coasts (e.g. Fig. A1). Along with past studies showing substantial northerly imports of ice in the area (e.g. Kwok et al., 2005; Pavlov et al., 2004; Aaboe et al., 2021), this renders it unlikely that a large fraction of the ice *originated* at these islands; we therefore allowed trajectories to intersect the Svalbard archipelago by excluding Svalbard from the coastline in step *c* above.

2.3 In situ moored sea ice and ocean observations

Two moorings were deployed in October 2018 in the nBS as part of the Nansen Legacy project (Fig. 1b). Mooring *M1* was located ~40 km east of the east coast of Nordaustlandet, south of the Kvitøya-Nordaustlandet gap and north of Kong Karls Land. *M2* was located south of Kvitøya, ~85 km east of *M1*. Both mooring sites were positioned in areas of sloping bathymetry, primarily to capture seasonal AW inflow from the north through Kvitøya Trough (*M1*) and Franz-Victoria Trough (*M2*). A detailed description of the moorings and the hydrographic regime between autumn 2018 and autumn 2020 can be found in Lundesgaard et al. (2022).

An upward-looking, five-beam, Nortek Signature 500 (*Sig500*) 500 kHz Acoustic Doppler Current Profiler was mounted in the top float of both moorings, at depths of ~19 m to ~32 m below the surface (Table 2). Four slanted beams were used to measure ice drift velocity, and a central, vertical beam was used to measure the distance from the transducer to the ice-ocean or air-ocean surface using an onboard leading-edge algorithm. This distance was in turn used to calculate the sea ice draft, i.e., the depth of the ice below the water surface. Ice draft was calculated based on the known depth of the transducer (calculated from an onboard pressure sensor), and corrected for instrument tilt (from an onboard tilt sensor), atmospheric pressure variations (using ERA5 sea level pressure), and varying sound speed in water (measured by an instrument directly below the *Sig500*). Biases in the initial draft estimate were further corrected such that the "ice draft" measured during open water periods was effectively zero over longer time scales, amounting to a constant correction per deployment (0.14 to 0.20 m) for the five different deployments as well as a smaller, time-varying correction.



In addition, we discarded a number of samples where scatterers close to the transducer resulted in very short distances. Such "false keels" were diagnosed based on comparison with distances derived from a maximum amplitude criterion from the same acoustic data in the onboard processing, reliably removing false keels, but likely at the cost of removing some true ridge keels.

140 Measurements were collected in ensembles of 48 samples at 15-minute intervals. Samples collected in open water were diagnosed using a quality criterion of the return signal from the four slanted beams, which proved a reliable indicator of sea ice presence or absence, comparing well with satellite-derived sea ice concentration (see Fig. 3a, f and Divine et al., 2025). The analysis presented here only includes samples classified as "ice", and only samples with draft ≥ 0.10 m. Probability density functions were computed based on all valid samples, with 0.1 m bins over the range 0.1 to 10 m. Associated modal draft is
 145 reported as the centre of the most populated bin, while median values were computed from unbinned samples.

Although the corrections and rejection criteria described above greatly increase the accuracy of the estimates, there are multiple sources of error. At very shallow drafts, it is difficult to separate thin ice and open water, so the shapes of distributions in the lowest bins should be interpreted with caution. Very thin ice during freeze-up is in principle not represented at all due to the rejection of samples below 10 cm. On the tail end of the draft distribution, the method used to remove false keels
 150 may introduce additional artifacts. Moreover, the open-water distance correction is inherently an approximation, and biases and errors on the order of >0.10 m are therefore to be expected. While all of the above should be taken into account when evaluating the results of the analysis, the dataset is internally consistent, and we maintain that it is well suited for the analysis of the seasonal evolution of sea ice draft focusing on distribution shapes and summary statistics. Further details of the data and processing can be found on the landing page of the dataset (Foss and Sundfjord, 2025) and in Divine et al. (2025).

155 In addition to sea ice draft, sea ice drift velocity was also measured by the instrument. The locally observed ice drift velocities generally show higher flow speeds and otherwise limited agreement with satellite-derived drift, although major episodes were often found both in the in situ and remote sensing observations, likely due to fundamental differences between these two datasets (Divine et al., 2025).

Ocean temperature and salinity were measured by an RBR Concerto Conductivity-Temperature-Depth instrument mounted
 160 directly below each Sig500 (Lundesgaard et al., 2022). These data were used to assess the state of the surface ocean as well as for sound speed corrections in the sea ice draft calculation.

In addition to the M1 and M2 moorings, this study compares the observations with sea ice draft data from a Sig500 deployed on the SODA-B mooring in the Beaufort Sea (75°28' N, 145°38' W) from October 2018 to September 2019. Details of these data have previously been published in Brenner et al. (2021).

165 **2.4 Estimates of thermodynamic growth**

To estimate sea ice thickness resulting from thermodynamic forcing in the absence of ice dynamics, we applied the widely used freezing-degree-day model by Lebedev (1938) that estimates thermodynamic ice growth from accumulated freezing degree days over the freezing period:



M1 (79°35' N, 28°05' E)

Dates	06.10.18 – 16.11.19	17.11.19 – 21.09.20
Depth	21 m	19 m

M2 (79°41' N, 32°19' E)

Dates	04.10.18 – 17.11.19	18.11.19 – 23.09.20	25.09.20 – 11.11.21
Depth	19 m	32 m	21 m

Table 2. Measurement dates and Sig500 instrument depths for M1 and M2 moorings.

$$h_{growth}(t) = 1.33 \times FDD^{0.58} \quad (2)$$

170 where $h_{growth}(t)$ is the accumulated ice thickness growth through the season (in cm), and FDD (in °C days) is:

$$FDD(t) = \sum_{t_0}^t \max(T_f - T_a, 0) \Delta t \quad (3)$$

175 where $T_f = -1.8^\circ \text{C}$ is the seawater freezing temperature, T_a is daily mean ERA5 2-m air temperature, and $\Delta t = 1$ day. The model was used to obtain reference estimates of thermodynamic growth *i*) locally (using local temperature at the mooring sites) and *ii*) along sea ice back-trajectories (using temperature sampled along the trajectories). For the trajectory calculations, the summation was initialised at the oldest valid point of each trajectory. For the local calculations, the start time of the integration was set to an approximate day of sea ice onset during each of the three seasons: 1 January 2019, 18 October 2019, and 13 December 2020, respectively.

To account for melting, thickness loss due to basal and surface heat flux was calculated as:

$$\Delta h_{melt} = \frac{Q_f \Delta t}{\rho_i L_f} \quad (4)$$

180 where Q_f is the sum of the prescribed monthly surface melt energy flux and basal ocean heat flux from the TPD (West et al., 2020, *North Pole* area). Both terms are energy fluxes (W m^{-2}): the surface term represents energy available for surface ablation, while the ocean heat flux represents energy supplied from the ocean to the ice base. We convert these energy fluxes to an ice-equivalent thickness loss using the latent heat of fusion. This provides a simple, observationally based melt parameterisation without requiring a full radiative calculation. Here, Δt is expressed in seconds, $\rho_i = 900 \text{ kg m}^{-3}$ is sea-ice density, and $L_f =$



185 335 kJ kg^{-1} is the latent heat of fusion, following Leppäranta (1993). At each daily time step, the FDD-based thickness was first expressed in metres and the corresponding surface and basal thickness losses were applied, with ice thickness constrained to remain non-negative. The surviving thickness was subsequently converted back to equivalent FDD before the next time step.

To assess forcing sensitivity, we repeated the FDD calculations with air temperature perturbed by $\pm 1^\circ\text{C}$, reflecting documented ERA5 biases over Arctic sea ice (Wang et al., 2019), and with the monthly ocean heat flux and surface melt energy
190 flux perturbed independently by ± 1 standard deviation reported by West et al. (2020). A combined conservative envelope was calculated using simultaneous warm/high-melt and cold/low-melt perturbations. Sensitivities were evaluated separately for trajectories ≤ 365 days and > 365 days.

Ice draft, d , was estimated from ice thickness, h , as

$$d = 0.92 \times h, \quad (5)$$

195 based on the modal late-winter first-year ice thickness and freeboard reported by Alexandrov et al. (2010).

3 Results and discussion

3.1 Origins of sea ice in the northwestern Barents Sea

We begin by examining the origins of sea ice in the study area, over a longer period (2009–2024) including the 3-year *study period* of moored ice and ocean observations (2019–2021). Sea-ice back-trajectories computed from the two mooring locations
200 (Fig. 2a) indicate a large spread in the origin of sea ice arriving during these 15 years. The majority of trajectories originate in the region between Svalbard and Franz Josef Land, in or directly north of the nBS. However, a smaller subset of trajectories originate much further east, with travel pathways extending north of 83°N , well into the Eurasian Basin of the CAO and along the path of the TPD.

There is substantial interannual and seasonal variability in the pathways, as shown by the time series of the maximum latitude
205 (Fig. 2b) and total travel duration (Fig. 2c) of sea ice arriving at the sites. In particular, the vast majority of the sea ice arriving in the 2011 and 2015 sea ice seasons¹ originated from the CAO, having travelled for several years along a path extending north of 86°N . On the other hand, during 8 of the 15 seasons (2010, 2012, 2013, 2016, 2018, 2022–2024), arriving sea ice was less than one year old and sourced within or near the nBS region. During a third set of 5 seasons (2014, 2017, and the study period of 2019–2021), the sea ice originated in the Barents region for the first part of the season, but was replaced by ice arriving from
210 north of 83°N in spring or summer.

The overall interannual variability is corroborated by satellite-derived sea ice age in the nBS; while methodologically different from the back-trajectory approach, age category concentrations from Korosov SIA in the study region confirm that standout years in terms of long and old trajectories correspond to years with significant presence of MYI in the study area (Fig. 2d). It should be noted that while the NSIDC PP product used to compute trajectories represents the drift of the oldest ice within
215 a parcel, the Korosov SIA product handles sea ice age more subtly by keeping track of concentrations of various ice ages.

¹For simplicity, we will denote each sea ice season by its end, i.e., the summer year.

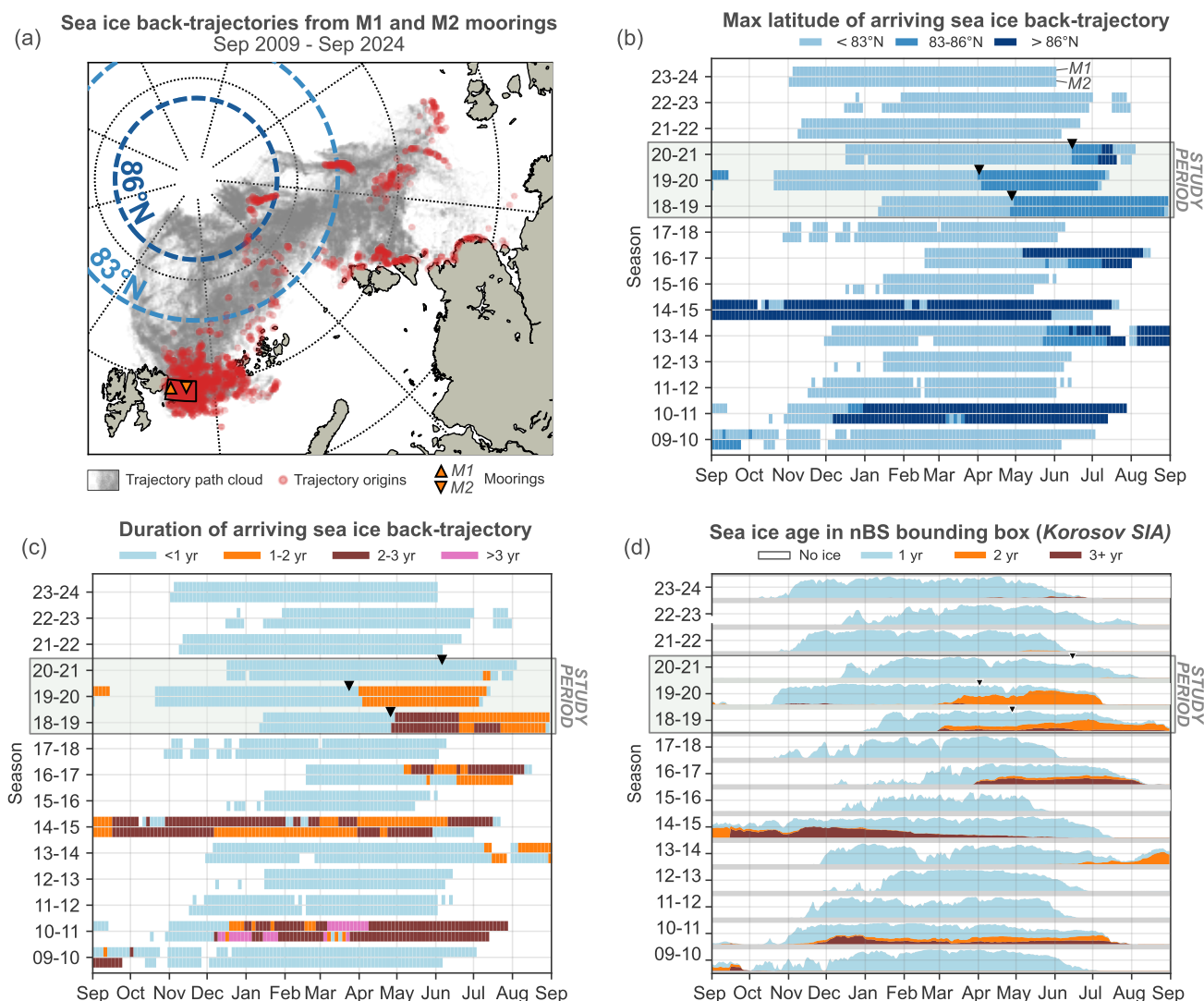


Figure 2. *a*: Computed sea ice back-trajectories arriving at the M1 and M2 locations between September 2009 and September 2024. *b*: Maximum latitude of trajectories arriving at M1 (upper bands) and M2 (lower bands). *c*: Travel time of trajectories arriving at M1 (upper bands) and M2 (lower bands). *d*: Sea ice age from the Korosov SIA product averaged within the bounding box shown in *a* (79° N–80° N, 27° E–35° E). Black triangles in *b* and *c* indicate the transition dates between origin regimes defined based on *b* (see text).

The latter may therefore provide a more realistic overall picture of the age distribution. For example, in the 2011 season, the back-trajectory analysis shows almost exclusively MYI after January. While the Korosov SIA confirms the presence of MYI in the area throughout this period, it also suggests a first-year ice (FYI) concentration above 50 % through much of the season. This illustrates an important note of caution about the interpretation of back-trajectories discussed throughout this paper; while long and remote back-trajectories may indicate ice arriving from the CAO, this ice likely exists together with younger ice that



Table 3. Transition dates from the *Barents-origin* to the *Central Arctic-origin* phase for each of the three sea ice seasons, taken as the mean of the M1 and M2 transition dates (see text).

Season	Transition date
2019	28 April 2019
2020	01 April 2020
2021	15 June 2021

has formed at the location of the trajectory along its route, including regionally or locally formed nBS first-year ice in most cases.

Broadly, the record indicates high interannual variability in sea ice age and origin in the nBS; adjacent years can be different from each other, and the influence of Central Arctic-origin versus regional sea ice is highly variable. We also see abrupt late-season transitions from one type of origin to another. This includes the years of the study period; the first two of which show a clear change from FYI formed locally to MYI arriving from the north in spring, also evident in the Korosov SIA. The 2021 season showed no MYI, but we also observe a late-season arrival of FYI originating in the CAO. The trajectory origins during these three seasons should be kept in mind as context for the study period (which was defined by data availability). In a longer perspective, the period represents a particular subset of three consecutive years of mixed Barents-origin and Central Arctic-origin sea ice – but also an interesting opportunity to examine whether the arrival of sea ice from the CAO can be observed in the *in situ* data records.

We classify the three ice seasons in the study period into two phases based on back-trajectory analysis: a *Barents-origin* phase and a *Central Arctic-origin* phase (Table 3). We define the transition between one phase and another as the *first arrival date of ice from north of 83° N* after the seasonal freeze-up (average between M1 and M2 arrival dates). The 83° N threshold separates trajectories originating in and directly north of the nBS from those extending into the Central Arctic Ocean and TPD region, often originating in the Laptev Sea (Fig. 2). Since trajectories generally fall into two distinct groups, the particular threshold value is not critical, although it does affect the exact dates of the transition. We apply a single break per season, so that late-season arrivals of *Barents-origin* ice (e.g., mid-July 2021) do not define an additional phase.

3.2 Direct observations of sea-ice draft in the 2019–2021 seasons

We move on to describe the *in situ* observations collected from the moorings during the 2019–2021 seasons (Fig. 3), and evaluate whether the measurements show any indication of a shift in ice characteristics between the Barents-origin and Central Arctic-origin phases defined in the previous section. The timing and duration of the sea ice season varied between the three years of the study period. Sea ice appeared near the start of January of 2019 and 2021, but the ice season of 2020 began as early as mid-October 2019. The appearance of sea ice generally coincided with the combination of below-freezing air temperatures (Fig. 3c, h) and near-freezing upper ocean temperatures (Fig. 3e, j), but in the run-up to both the 2019 and 2021 seasons, there was a period in autumn/early winter during which the surface remained ice-free despite below-freezing air temperatures. The

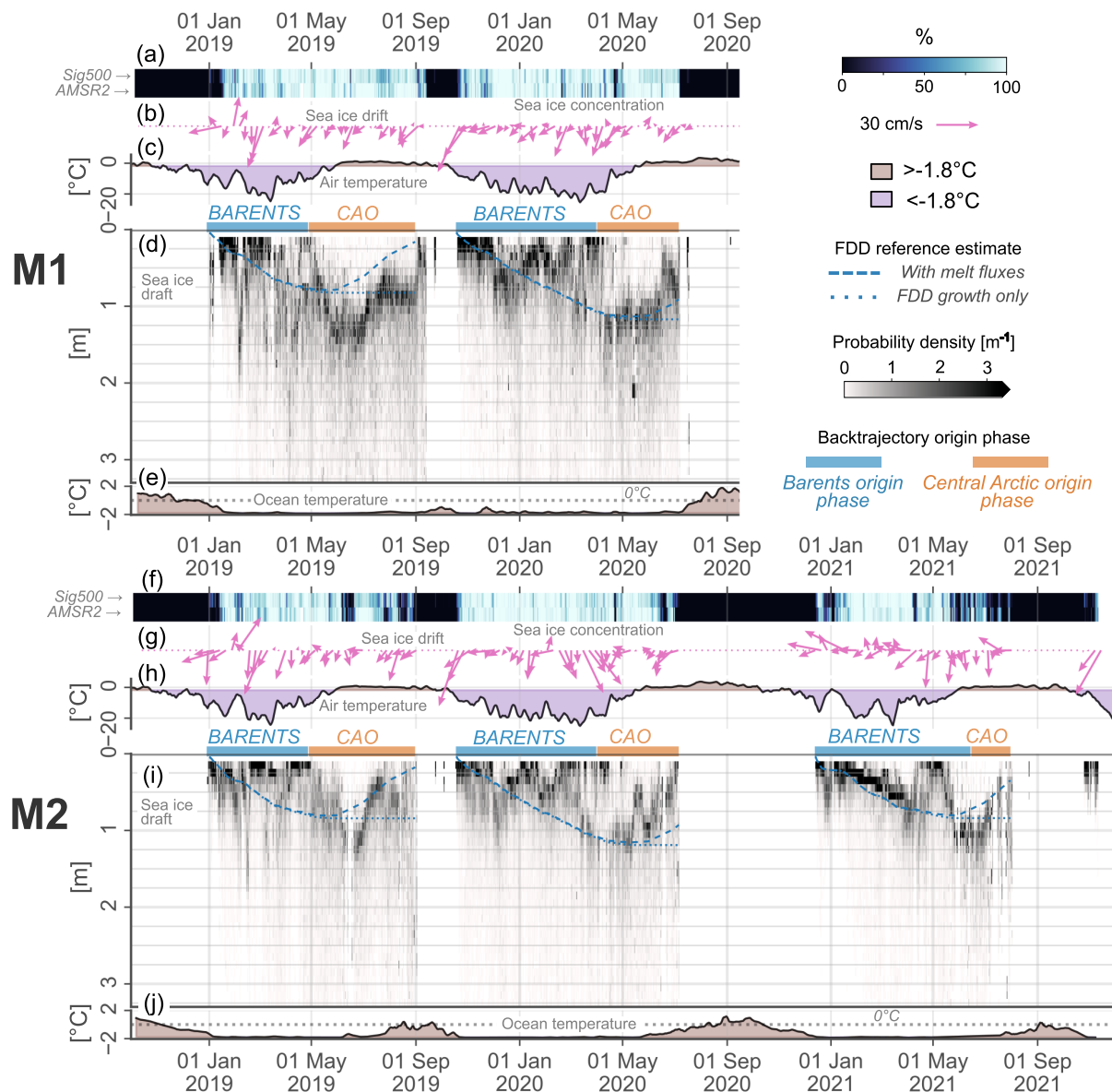


Figure 3. Composite time series from the M1 and M2 moorings. *a, f*: Daily sea ice concentration from Sig500 sea ice presence classification (upper) and from UoB AMSR2 (lower). *b, g*: Weekly averaged sea ice drift vectors measured by the Sig500s. *c, h*: Weekly mean air temperature at 2 m elevation from ERA5. *d, i*: Daily probability density functions (PDFs) of sea ice draft from the measurements of M1 and M2 moorings, zoomed in on the <3.5 m range. Blue lines show the local FDD reference estimate with (dashed) and without (dots) melt fluxes from West et al. (2020). *e, j*: Upper ocean Conservative Temperature from sensors mounted below the Sig500s (~1 m below the depths in Table 2). Blue and orange bars in *d, i* indicate the Barents-origin and Central Arctic-origin phases respectively, defined from the back-trajectory analysis (Table 3).



upper ocean mooring records show temperatures above freezing during both these periods, suggesting an extended period of heat loss from the ocean to the atmosphere before ice could form or persist in the area.

The sea ice season extended into summer during all three years, with relatively thick (~ 1 m draft) ice persisting into a period of upper ocean warming and above-freezing air temperatures (Fig. 3d, i). Ice draft and concentration decreased in summer, and the ocean became ice-free in early September 2019, early July 2020, and late July 2021, respectively. This suggests a summer ice environment where thinner ice had melted away while only thicker and more resilient ice floes remained, as opposed to the thinner but more consistent ice cover in winter. Snapshots of the sea ice concentration field from these periods (Fig. A1) show large, isolated floes moving southward toward the nBS northeast of Svalbard; such floes may persist for longer periods before disintegrating.

The observations show large subseasonal variations in ice draft (Fig. 3d, i). At several points, the record shows abrupt drops or increases in draft, most notably a high variance in early 2019 and 2020, and as a sudden month-long period of very thin (< 0.25 m) ice between periods of significantly thicker ice at M2 during summer 2021. Similarly, we observe occasional sudden, temporary drops in sea ice concentration to near ice-free conditions in several places of the record, notably at M2 during summer 2019. Rapid increases and decreases in sea ice draft are consistent with a highly dynamic ice pack; we will examine this in more detail in Sect. 3.4.

On seasonal time scales, a notable feature of the draft time series is a rather abrupt shift from thin or variable ice drafts in winter to ice with a distinguishable and comparably thicker and more consistent mode in spring into summer. The clearest shift occurred in spring 2020, where a relatively rapid transition from thin (< 0.5 m modal draft) to thicker (~ 1 m) ice was observed at both moorings (Fig. 3d, i) in March–April. A comparable but somewhat less pronounced shift was observed in May of 2019. The 2021 season differed somewhat, but we still observe a transition to a more distinct and thicker mode in summer, with a pronounced and sustained thicker mode appearing in late May.

The observed shifts to thicker ice in spring 2019 and 2020 are broadly consistent with the shift from Barents-origin to Central Arctic-origin sea ice found in the back-trajectory analysis. While it is difficult to define an exact transition point from the observations, the increases in draft occur close to the shifts in trajectory origins, although the in situ change arguably happens *after* the trajectory shift in 2019 and *before* in 2020. In 2021, there was less of a distinct binary seasonal structure in the sea ice draft, although summer observations in the Central Arctic-origin phase of 2021 were dominated by relatively thick ice well into summer, appearing a few weeks before the shift in trajectory origins.

Figure 4 shows ice draft histograms for both phases during each season, along with the back-trajectory paths and origins for each period. To exclude freeze-up, only the two months before and after the transition date are included. There is a clear separation between the two phases in the histogram shapes from 2019 and 2020. Barents-origin histograms are peaked at low draft values (< 0.5 m) with a long tail, suggesting a mixture of ice types including very thin ice. In contrast, the Central Arctic-origin distributions are narrower and more concentrated around a central peak near 1 m, indicating a more uniform, thicker ice type. While modal draft increases between phases for all years (by between 0.5 and 1.1 m), median drafts differ somewhat less (by between 0.30 and 0.62 m). The fraction of thin ice (< 0.5 m) also drops each year, from 27–58 % before the transition to 5–19 % after it. The relatively long tails of the distributions in the Barents-origin phases indicate that there was also substantial

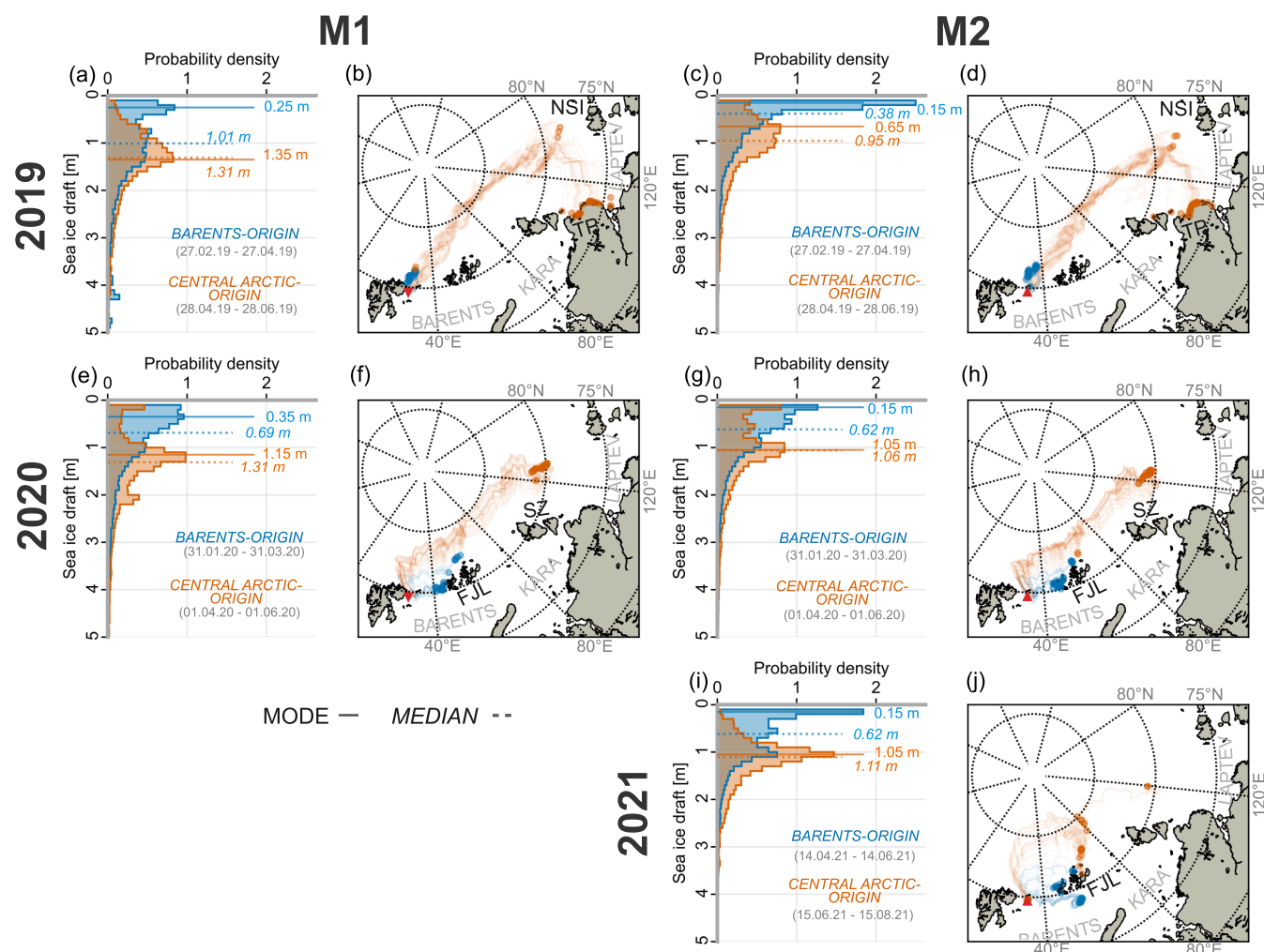


Figure 4. Sea ice draft distributions and back-trajectory origins for the two phases of each ice season. *Histograms:* probability density of sea ice draft during the two months preceding (blue, Barents-origin) and following (orange, Central Arctic-origin) the phase transition dates given in Table 3. Date ranges used for each period are shown in gray on each panel. Annotated horizontal lines mark the modal (solid) and median (dashed) draft; modes are given as bin centres for a bin width of 0.1 m. *Maps:* back-trajectory origins for the same two periods (circles, coloured as above), with trajectories shown as thin white lines and mooring locations as red triangles. *NSI:* New Siberian Islands, *TP:* Taymyr Peninsula, *SZ:* Severnaya Zemlya, *FJL:* Franz Josef Land.

thicker ice present before the shift. It should be noted that simply comparing averaging statistics between the two phases does mask short-term variability, but the overall impression together with the full time series in Fig. 3 supports the notion that there is an observed transition matching the shift in origin.

285 In 2019, the Central Arctic-origin phase back-trajectories largely extended into the Laptev Sea (Fig. 4b, d), with most of the trajectories originating either north of the New Siberian Islands or close to the eastern coast of the Taymyr Peninsula. In 2020,

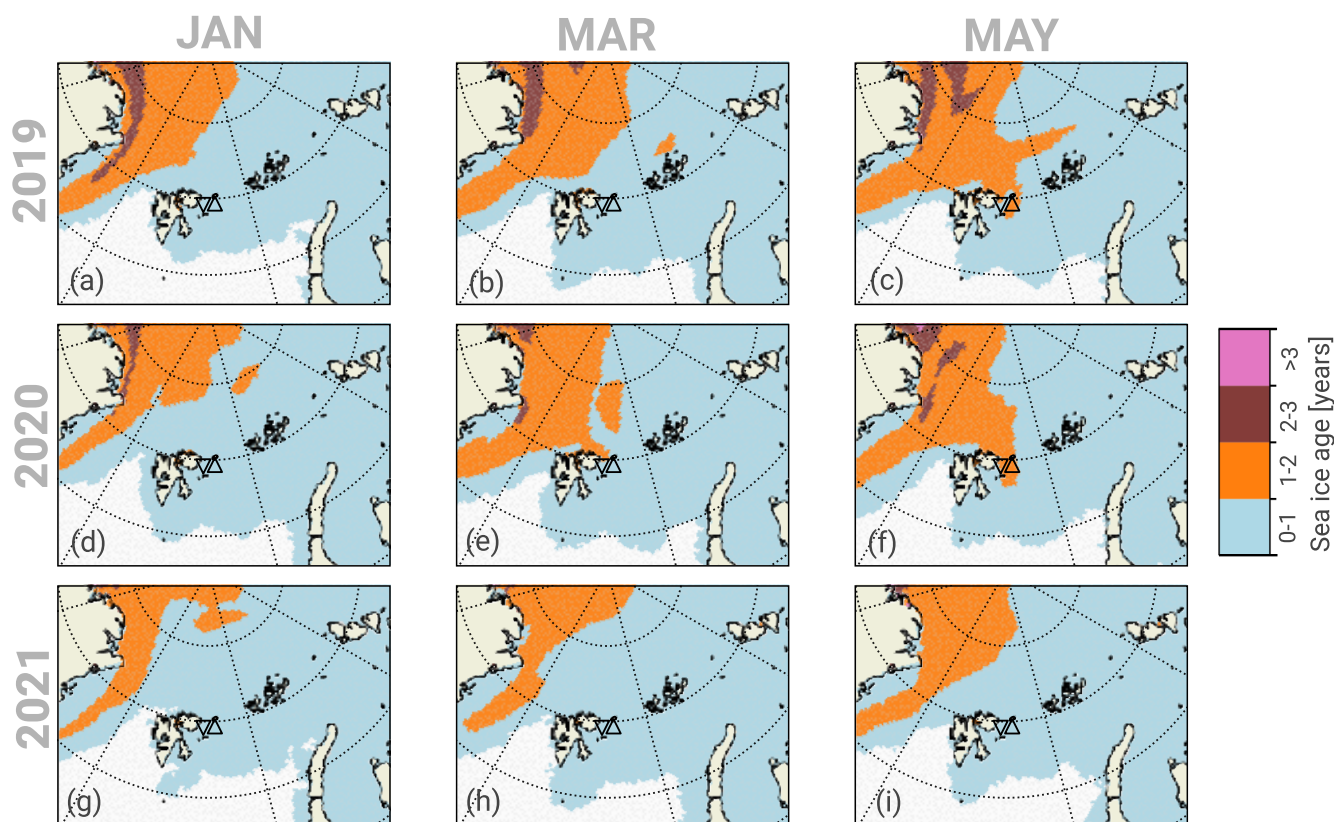


Figure 5. Monthly sea ice age from the Arctic Sea Ice Age Climate Data Record Version 2.1 (Korosov and Edel, 2025). The product tracks the concentration of sea ice of different age classes, and the colour shows the weighted average of sea ice age within each cell.

the majority of the Central Arctic-origin trajectories originated east of Severnaya Zemlya, near 120° E, with some trajectories to M2 from late March originating near the northeastern coast of Franz Josef Land (Fig. 4h). Ice arriving in the 2021 Central Arctic-origin season originated closer to the nBS, with starting points in the Nansen Basin north and east of Franz Josef Land between 45° E and 80° E, with some minor exceptions (Fig. 4j). The shape of the trajectories suggests that the ice arriving after the 2021 seasonal shift had travelled westward in the Nansen Basin along the general pathway of the TPD. In 2020 and 2021, the Central Arctic-origin trajectories entered the Barents Sea from the north and northwest and frequently through the Nordaustlandet-Kvitøya gap, while in 2019 the trajectories entered the Barents Sea from a more northeasterly direction.

Satellite-derived sea ice age (Fig. 5) corroborates the general pattern; a MYI belt located north of Svalbard in January advanced toward the Barents Sea in spring, resulting in MYI intrusions into the mooring area in 2019 and 2020, but not 2021. Two other, independent sea ice age products differ in the details, but confirm the general pattern of a seasonal southward movement of the MYI belt toward Svalbard (Figs. C1 and C2).



Compared to 2019 and 2020, 2021 stands out as a season with relatively modest influence of ice originating north of 83° N and nearly no MYI. Back-trajectories from 2021 differ somewhat from the preceding years in that the ice arriving from the Central Arctic does not seem to have formed as far east nor as far back in time. Instead, the sea ice arriving after 15 June 2021 appears to have been FYI formed predominantly near the coast of Franz Josef Land and north of the Kara Sea during the freeze-up period in late 2020 and early 2021. A clear seasonal shift is still observed; while ice arriving in winter and spring largely originated in the nBS, much of the summer ice arrived from the north after having travelled along a counterclockwise trajectory well into the Eurasian Basin, as far north as 85° N (Fig. 4j). Although the ice floes arriving in mid-summer 2021 are unlikely to be of multi-year ice origin, back-trajectories indicate a gradual increase in travel time through the season and a jump from ~150 to ~240 days around the transition date of 15 June 2021.

Broadly speaking, the observed end-of-season modal sea ice draft was comparable to the FDD-estimated values, although the observed modal draft did exceed the FDD estimate near the summer maxima of 2019 and 2021 (Fig. 3). More striking than the differences in absolute values are the differences in temporal characteristics. The FDD thickness was estimated for a single freeze onset date at the beginning of each year's growth season. So, while the FDD thickness by nature evolves smoothly and gradually through the season before flattening toward summer, the observed draft distributions exhibit a complex temporal structure with a much higher day-to-day variance, particularly during winter. The spread in the distributions during the early stage of the season was also quite wide, often lacking a distinct peak representing the typical level ice draft. Such variability indicates that ice with different histories, formation dates and degree of deformation, pass the moorings, despite floes all being sourced from the nBS.

Winter 2021 at M2 stands out as the one period where the observed ice draft distribution largely follows the gradual thickening curve of the FDD estimate (Fig. 3i). Between mid-January and mid-May 2021 the observed draft increased nearly linearly at a rate of ~0.6 cm day⁻¹. This period coincided with consistent easterly sea ice drift, whereas sea ice drift was predominantly oriented in the north-south direction during the two preceding winters (Fig. 3b, g). Moreover, satellite-derived estimates of ridge spacing show distinctly fewer ridges in the nBS in 2021 compared to 2019–2020 (Appendix D), indicating a weaker influence of sea ice dynamics in a year where we also observed the weakest northerly sea ice transport.

The separation of each sea ice season into one Barents-origin and one Central Arctic-origin phase is a simplification. The observations clearly show that the ice is typically composed of several ice types, consistent with the Korosov SIA product often showing a mixture of sea ice age classes (Fig. 2d). The 83° N criterion is a threshold on a continuum; especially in 2021, the trajectories themselves indicate more of a gradual transition in sea ice pathways, including a reversal to more Barents-origin ice in summer. While the exact transition dates depend on the cutoff criterion, and the transition is less clear in 2021, we maintain that the key finding is robust: there is a local shift to thicker and more consistent ice draft corresponding to a change in sea ice origin.

Following up this finding, we will examine *why* ice arriving from the Central Arctic is thicker. In the following section we will look at sea ice thickness and thermodynamic conditions along the back-trajectories to evaluate whether the growth history along sea ice pathways can explain the thickness of the ice arriving in the nBS.

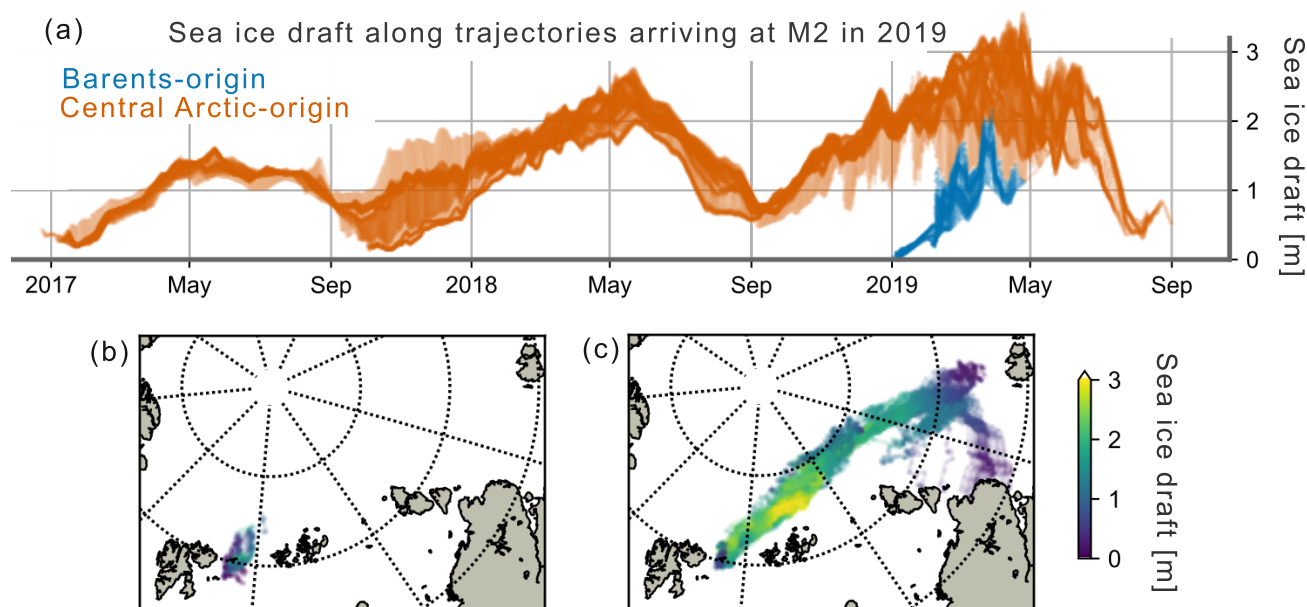


Figure 6. Sea ice draft from CS2 SIT along back-trajectories arriving at the M2 mooring during the 2019 season (biweekly, interpolated to the daily trajectory time step). *a*: Along-trajectory draft against time, with each line showing one trajectory and coloured by origin phase. Lines terminate on the arrival date. *b*, *c*: Maps of the same trajectories for the 2019 Barents-origin (*b*) and Central Arctic-origin (*c*) phases, with colour showing draft on a shared scale.

3.3 Sea ice thickness along trajectories

To investigate the thickness evolution of sea ice arriving at the study site, we sampled CS2 SIT along the 2019–2021 back-trajectories from the mooring sites. An example is shown for M2 in 2019 in Fig. 6; results were similar for M1 and 2020, with 2021 having a less clear pattern. Barents-origin sea ice had a relatively simple history of gradual thickening through 2019. In contrast, ice arriving in the Central Arctic-origin phase had undergone thickening and thinning through three successive seasonal cycles along its pathway from the Laptev Sea sector. The sampled CS2 fields suggest a strong seasonal cycle in ice transiting along the TPD. Estimated maximum thickness increased over successive winters and peaked in May–June, with autumn thickness frequently below 1 m. The thickest ice was observed in the months before the sea ice entered the nBS, in winter and spring 2019, where the draft along certain trajectories exceeded 3 m. Mapping the results spatially (Fig. 6b, c) shows that the thickest ice was found in late winter and early spring in the region north of Franz Josef Land. The analysis supports the notion that the thick ice observed at the mooring sites late in the season originated in the Central Arctic and acquired or retained much of its thickness in one or more freezing seasons *before* entering the nBS.

Similarly, the history of thermodynamic sea ice growth was examined by sampling ERA5 air temperature along the trajectories and evaluating the FDD model (Fig. 7b). Note that running the FDD model without prescribed basal and surface melt resulted in unrealistically large drafts (~ 2 m) for ice arriving from the Central Arctic (Fig. B1b). Including the monthly surface-

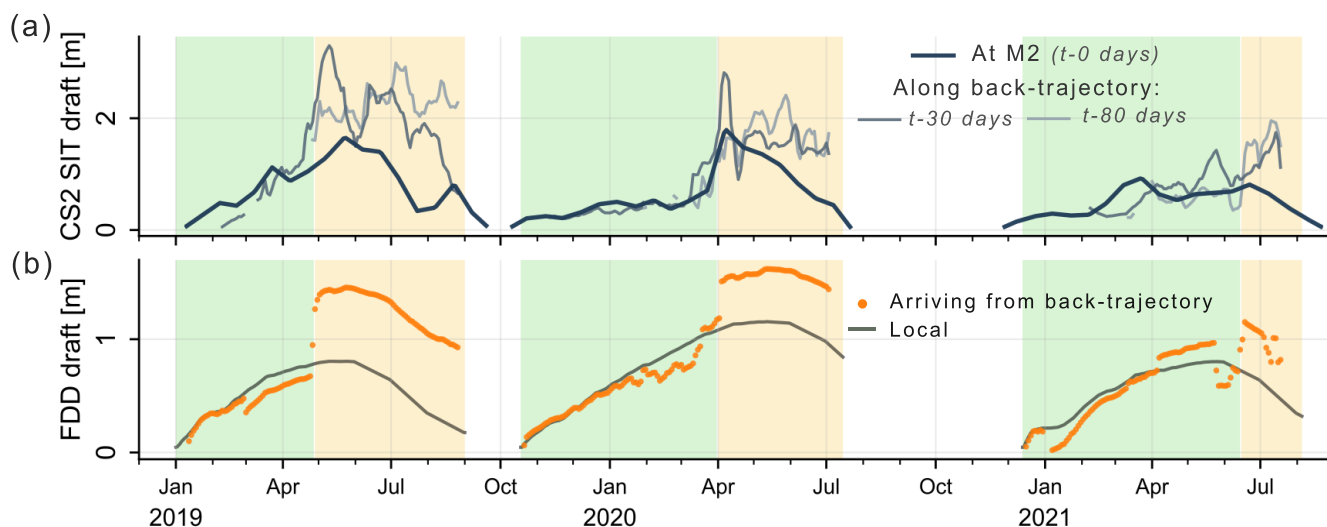


Figure 7. *a*: CS2 SIT draft on arrival, and 30 and 80 days upstream along the arriving back-trajectory. *b*: Ice draft based on FDD models with flux corrections from West et al. (2020), integrating ERA5 2-m temperature locally at the mooring site (gray lines) and along back-trajectories (orange dots). Shaded by origin phases. All at the M2 mooring.

and basal-melt fluxes from West et al. (2020) reduced the estimates on the order of 0.75 m (Appendix B1), but retained a clear difference in ice thickness between the two phases. Given the empirical multi-season extension of the FDD relationship and uncertainties in the prescribed melt and snow forcing, we interpret the model results primarily as indicators of the timing and character of thermodynamic evolution rather than as quantitative draft predictions. The time series of the draft of arriving ice exhibits a step at the seasonal transition between origin phases in 2019 and 2020, with a clear increase in modelled draft near the transition dates. No such discontinuity is present in the model thickness curves based on local air temperature alone (also shown in Fig. 7b). We infer that the local thermodynamic model fails to reproduce the observed transition because it does not account for the upstream history of the advected ice. Again, the picture is less clear in 2021, where FDD-modelled sea ice draft for ice arriving during the Central Arctic-origin phase is dominated by high variance but smaller amplitudes than the preceding years.

Figure 7a shows CS2 SIT when arriving at the M2 site ($t = 0$) as well as upstream along the ice trajectories at a time lag before arrival. Lagged and unlagged time series broadly agree in the Barents-origin phase, indicating a relatively young and uniform ice pack where growth was dominated by relatively slow seasonal thermodynamic growth. In the Central Arctic-origin phase, lagged thickness was consistently thicker than unlagged, indicating a recent loss of thickness. This is consistent with thinning of ice advected from the Central Arctic before it arrives in nBS, which can be linked to large ocean heat fluxes and ice melt over the Atlantic water inflow even in winter (e.g. Provost et al., 2017; Duarte et al., 2020). It should be noted that the large spread in upstream thickness, especially in the latter phase of the season, indicates that CS2 SIT is highly variable in this area in the melt season, with large uncertainties, and we have therefore made no attempt to quantify melt rates.



365 Snow on ice has an insulating effect, and can significantly limit thermodynamic ice growth. The FDD model does not represent snow explicitly, but implicitly corresponds to an effective snow depth of ~ 0.06 m for our specific conditions. Across non-summer (September–May) trajectory points, observed mean snow depth was 0.14 m for the KuLa snow-depth product and 0.16 m for SM-LG. This suggests that the FDD model might underestimate snow insulation and as a result overestimate thermodynamic growth. This bias could potentially result in an artificial difference between Barents- and Central Arctic-origin
 370 trajectories, which may have been exposed to quite different snow conditions. To test this, we repeated the along-trajectory growth calculations replacing FDD with a thermal resistance model including satellite-derived snow depth (Appendix B). This indeed reduced the thickness of ice arriving in the Central Arctic-origin phase, bringing it closer to the observed drafts (Fig. B2). A clear increase in modelled draft associated with the phase switch is observed irrespective of which model is used, however, suggesting that the transition itself does not depend on the treatment of snow.

375 While the along-trajectory analysis provides a coarse indication of underlying processes, several sources of uncertainty must be considered. Uncertainties include those associated with the back-trajectories themselves as they propagate into all the results integrating quantities along the pathways. Moreover, applying the basal- and surface-melt corrections to FDD has a large effect on accumulated sea ice drafts (Fig. B1), but it should be noted that the parameterisation is based on a regional average from the TPD area (West et al., 2020): This could underestimate basal melt of sea ice in areas with shallow Atlantic Water, particularly
 380 north of Svalbard, where substantially higher ocean-to-ice heat fluxes have been measured directly (Meyer et al., 2017; Provost et al., 2017; Peterson, 2018). Observation-constrained modelling and satellite-derived ice-loss estimates further indicate that such fluxes can produce rapid regional ice melt (Duarte et al., 2020).

Sensitivity tests (Appendix B) suggest that while short trajectories are relatively insensitive to perturbations in the prescribed fluxes, multiyear trajectories are highly sensitive to perturbations particularly in ocean heat flux.

385 Pan-Arctic Lagrangian simulations show that thermodynamic growth decreases as ice becomes thicker, whereas dynamical thickening becomes increasingly important for thicker ice (von Albedyll et al., 2026). Thus, the thickness of ice arriving in the nBS reflects not simply the cumulative atmospheric conditions along its trajectory, but an integrated history of thermodynamic growth and mechanical redistribution. Finally, the CS2 SIT product has its own uncertainties. Interpolating from relatively coarse temporal and spatial resolution (biweekly, 80×80 km) onto daily positions introduces errors, particularly in spatially
 390 heterogeneous coastal regions. Uncertainties in SIT retrieval are higher during the melt season and in the marginal ice zone. Nevertheless, the analysis consistently indicates that the thicker ice observed in the nBS in the Central Arctic-origin phase consisted of ice largely grown in the CAO, and subsequently *advected* into the study region.

3.4 Local and upstream controls on sea ice thickness

Both moorings were located relatively close to land, and the influence of the coasts is obvious at several points in the time
 395 series. Wind-driven polynyas forming in the wake of Kvitøya and Nordaustlandet islands resulted in sudden shifts to no or very thin ice. For example, a large (up to >100 km long) polynya which developed south of Kvitøya in May–June 2021 (Fig. A1b) frequently meandered across the M2 mooring site, explaining an extended period of open water or very thin ice drafts at M2. Conversely, during winds favourable to shoreward drift, we observed temporary "land-locking" of the ice as the



ice pack pushed towards the coast. For example, in March 2019, the M1 record shows near-zero sea ice drift at M1, including
 400 background tidal motion, and sea ice draft ~ 4 m over several days (Fig. A2), suggesting that a sea ice ridge was fixed in
 position above the mooring at this time. The ice state at a given time and location in the nBS is highly dependent on wind
 direction relative to the surrounding land masses. The region is also always proximal to the sea ice edge, which enables winds
 from certain directions to spread the ice into open water to the west, south or east – there is rarely a barrier to ice divergence
 toward the open ocean. This characteristic of the local ice dynamics differs from those of the CAO, and results in higher rates
 405 of convergence and divergence. As a result, sea ice thickening due to deformation significantly affects local SIT close to the
 Svalbard coast (Abrahamsen et al., 2006; Marchenko, 2022). It is generally challenging to disentangle these effects from those
 of thermodynamics and advection although, at seasonal scales, a remotely sensed ice volume budget shows net import to the BS
 (Heorton et al., 2025). Satellite-derived ridge spacing (Fig. D1) shows increasing ridge frequency from February to May each
 year – possibly due to a combination of ridges accumulating over time and the arrival of more deformed Central Arctic-origin
 410 ice.

Local thermodynamic growth alone cannot reproduce the observed evolution of sea ice draft at the study sites, including the
 shift to thicker ice in 2019 and 2020. This is in broad agreement with Ricker et al. (2021), who found that the Barents Sea had
 a higher influence of ice advection on winter ice volume change than any other Arctic Ocean marginal sea. Mallett et al. (2021)
 found higher interannual satellite-derived SIT variability in the Barents Sea compared to other marginal seas. This is likely
 415 related to the high year-to-year variability in regional ice conditions in the Barents Sea, reflecting strongly varying regional
 patterns of ice advection, which are mainly wind-driven and therefore less consistent between years than the annual cycle in
 air temperature.

The time series of 2010–2024 back-trajectories from the M1 and M2 moorings (Fig. 2) is dominated by high interannual
 variability; the late-season shift found in 2019–2021 does not seem to be a regular and predictable feature of the study site.
 420 However, the area between northern Svalbard, northern Franz Josef Land, and Severnaya Zemlya stands out as a region in the
 Eurasian Arctic Ocean (in fact in the entire Arctic Ocean; not shown) where the sea ice thickens significantly from February
 to June in the 2011–2023 climatology of the CS2 SIT dataset (Fig. 8a). The region north of Svalbard is also the only place
 within the broader TPD region where the MYI fraction tends to *increase* between February and June (Fig. 8b). The study area
 around the two moorings is near the southern edge of these regional anomalies. While the margin between the Barents Sea and
 425 the Eurasian Basin shows a consistent late-season thickening in part due to the arrival of MYI, the mooring sites appear to be
 located far enough south to only fall within the influence of this process some years (Fig. 2).

The seasonal increase in thickness and MYI fraction northeast of Svalbard suggests that an advective mechanism drives
 regularity in the region – which in turn implies a seasonally consistent atmospheric driver. Monthly mean sea level pressure
 from winter to summer over the Barents region during 2011–2023 (Fig. 8c–g) shows a clear seasonal progression, including
 430 a weakening and eastward displacement of the climatological low-pressure centre. From being centred near the canonical
 position of the Icelandic Low in the Nordic Seas in February, the regional pressure minimum reaches the Barents Sea in
 March, and continues moving eastward to reach Siberia in May. The associated geostrophic winds favour ice export through
 the Fram Strait in winter, and increasingly into the Barents Sea in spring.

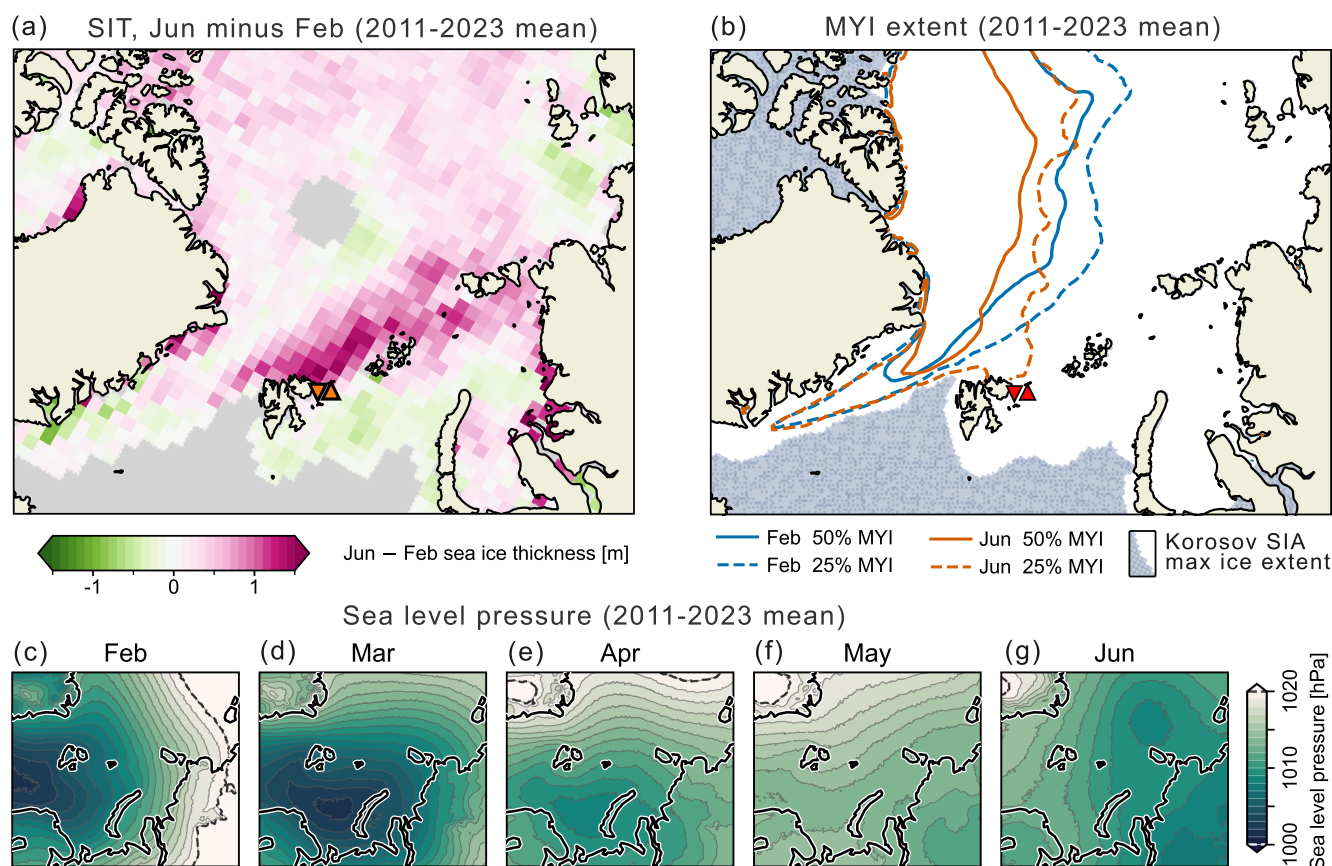


Figure 8. Climatological fields for 2011–2023. *a*: Mean sea ice thickness difference (22 June minus 21 February) from CS2 SIT. *b*: Average 50 % and 25 % MYI concentration in February (blue) and June (orange) contours from Korosov SIA. *c*–*g*: February to June monthly sea level pressure from ERA5. Based on 2011–2023 due to the availability of the CS2 SIT product.

A previous study (Pavlov et al., 2004) found that 1966–2000 mean northerly sea ice area flux into the nBS reached an annual peak in May, qualitatively consistent with this regional seasonality – although the sea ice environment in the nBS has changed substantially since that period. Together, these observations point toward a seasonal regularity in the wind-driven sea ice drift direction in the downstream regions of the TPD, even if the local expression at the mooring sites, at the fringe of the affected area, is more variable. If this regular shift in the direction of mean ice advection did not occur, it is unlikely that such late-season arrival of much thicker ice from the CAO would happen in any year.

All three years of the study exhibited late-season sea ice transport from the north (Fig. 2). During each year, a low pressure region developed in the Barents Sea, and subsequently evolved to a configuration where the geostrophic wind direction shifted from being predominantly easterly in February in the mooring region to northerly later in spring (Fig. E1). The timing corresponded roughly to the transition between Barents-origin and Central Arctic-origin phases of each year. This is consistent with

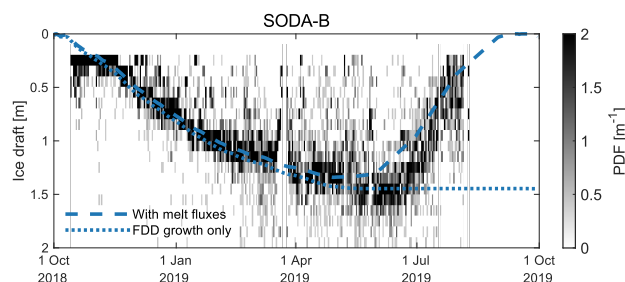


Figure 9. Daily histograms of sea ice draft from a Sig500 mounted on the SODA-B mooring deployed in the Beaufort Sea ($75^{\circ}28' \text{ N}$, $145^{\circ}38' \text{ W}$) as part of the SODA project. FDD curves based on local ERA-5 temperature shown in blue lines with (dashed) and without (dotted) Beaufort Sea melt fluxes based on West et al. (2020).

the atmospheric pressure configuration exerting a strong influence on the seasonal ice drift patterns in the region – and, as a result, on the local sea ice thickness distribution at the study site.

von Albedyll et al. (2022) found that the seasonal cycle of SIT within the TPD in the Eurasian Basin, observed during the MOSAiC drift, was largely governed by local thermodynamics. The MOSAiC observations represent a Lagrangian viewpoint, following a drifting, distributed observational network along the TPD. The observations presented here are fundamentally Eulerian and therefore show the end product of along-trajectory ice growth across ice from different origins; the abrupt shifts reflect the arrival of ice with a different history.

Sea ice draft observations from the Beaufort Sea, collected as part of the SODA project (Brenner et al., 2021), provide an interesting comparison with the M1 and M2 measurements. Collected during a period overlapping with the first year of this study, the record from the *SODA-B* mooring (shown in Fig. 9) is based on similar, moored instrumentation and directly comparable with the observations presented here. Comparing with Fig. 3d, i, the seasonal evolution at the Beaufort Sea site differed substantially from what we observed in the nBS, with a main mode evolving smoothly and monotonically from very thin new ice in October to thick ($\sim 1.5 \text{ m}$) ice in June, before decreasing rapidly in late summer. In comparison, the SIT records presented in this study are substantially more irregular on both seasonal and subseasonal time scales, generally dominated by rapid shifts rather than a smooth seasonal evolution. The contrasting characteristics of the time series from these two study areas indicate that SIT variability in distinct regions within the Arctic Marginal Ice Zone may be dominated by quite different processes. In particular, the Barents Sea sector of the Arctic marginal ice zone is exposed to strong and variable, synoptic wind forcing (e.g. Li et al., 2026). Wind-driven variability exerts a primary control on sea ice transport into the nBS from the north (Kwok et al., 2005; Efstathiou et al., 2022), and this study suggests that local SIT variability is also strongly influenced by wind-driven advection.

Several studies (Kwok et al., 2005; Lind et al., 2018; Efstathiou et al., 2022; Heorton et al., 2025) have emphasised the importance of sea ice imports in the Barents Sea region. At the same time, it is frequently highlighted that this is a region where ocean heat plays a direct role in the sea ice distribution, largely due to the presence of warm AW (Årthun et al., 2012; Docquier and Koenigk, 2021; Gerland et al., 2025). Studies from the nBS (Aaboe et al., 2021; Efstathiou et al., 2022) and the



area directly to the north (Lundesgaard et al., 2021) suggest that on interannual and shorter time scales, strong northerly ice advection exerts a primary control on sea ice extent. Strong advection events may effectively override the effects of a relatively warm ocean, at least from the perspective of maintaining sea ice cover during summer. In the northern reaches of the Barents Sea sector, the inflow of AW and the local ocean heat content reach a minimum in April–May (Renner et al., 2018). Sea ice floes arriving from the TPD in spring may therefore be less prone to melt from below, more likely to survive the journey into the nBS, and stay thicker for longer into early summer.

3.5 Comparison with previous studies

The nBS sea ice drafts observed in this study are consistent with previous work from the area, although comparisons between different times, regions, and methodologies are not always straightforward. In the vicinity of the M1 and M2 moorings, King et al. (2017) (their *north-east* domain) reported a modal thickness (total ice thickness including snow) on the order of 0.5 m in March 2014 from airborne electromagnetic surveys. They used back-trajectory analysis to identify this ice as first-year ice originating in the Franz Josef Land area, in line with the Barents-origin trajectories found for the same period in this study (Fig. 2). Their reported thickness is also in line with this study, where March was dominated by Barents-origin ice before the arrival of thicker and older ice. Modal March sea ice draft for the two moorings during the five deployments in this study ranged from 0.15 to 0.55 m.

Abrahamsen et al. (2006) reported monthly mean ice thicknesses as high as 4.5 m based on mooring data from 1994–1996 further south in the nBS (Fig. 1a). These figures are substantially higher than those reported here or by King et al. (2017), who attributed the difference to a combination of extreme coastal ridging at the older site and the reporting of mean rather than modal thickness. In addition, other studies including Gerland et al. (2008), Mallett et al. (2021) and Bocquet et al. (2024) indicate that the Barents Sea ice pack itself may have thinned substantially during the >20 years separating our studies. The satellite records used in the latter two studies only cover October to April, however, and therefore do not capture the summer period. Despite the discrepancy in reported ice thickness, we observe that the overall seasonal evolution reported by Abrahamsen et al. (2006), with a seasonal thickening toward a maximum in May–June, is broadly consistent with our findings.

More recently, Onarheim et al. (2024) used ULS data from a mooring array in the southern part of the nBS (Fig. 1a) to document a net increase in SIT between 2013 and 2022, mainly driven by local thermodynamic forcing. However, their 10-year dataset is intermittent and cannot reliably differentiate between short-term system variability and long-term climate trends. They emphasised that the ongoing long-term sea ice loss in the nBS may make SIT more sensitive to atmospheric and oceanic thermodynamic conditions. Hansen et al. (2023) reported a typical winter level sea ice thickness of ~0.6 m using the same dataset for the period 2013–2020. Our analysis suggests that the marginal sea ice regime described in these studies is much less influenced by MYI (Figs. 5 and 8b) and does not show the climatological February–June thickening seen further north (Fig. 8a). Since the southern parts of the nBS are more exclusively influenced by local thermodynamics as well as imports from the east, these long-term trends are most relevant to our study area during the Barents-origin phases.



500 3.6 Broader implications for the Barents Sea system

Since most aspects of the Barents Sea system are closely connected to sea ice (e.g., Reigstad et al., 2025), the episodic arrival of sea ice from the TPD region of the Arctic Ocean has potential implications for a range of processes in the nBS, from the physical environment to the marine ecosystem and human activity in the area.

Late-season northerly ice advection may act to prolong the sea ice season, providing a supply of thicker ice to replace thinner, locally-formed ice that melts early in summer (Fig. 6). Seasons in which ice arrives from the CAO tend to have sea ice cover later in the year (Fig. 2b), although we have not examined the underlying relationship in detail here. Landy et al. (2022) showed that summer SIT anomalies are a skillful predictor of late-summer and early-autumn sea ice extent in the Barents Sea.

The freshwater budget of the nBS is strongly influenced by sea ice processes, and arriving sea ice that melts locally is a major source of surface freshwater in the nBS. This contributes to the characteristic ocean stratification where a warmer deep or intermediate layer of modified AW is overlaid by a fresh and cold "Arctic" upper layer (Lind et al., 2018; Koenig et al., 2024). The observed freshwater content at end of summer in the nBS cannot be explained only by locally grown ice (Koenig et al., 2024), and the arrival of thicker ice carrying freshwater sourced in the CAO may meaningfully contribute to maintaining stratification. In particular, late-season arrival of thicker floes that survive longer will also act to distribute the freshwater supply into the summer season, potentially maintaining upper-ocean stratification later in the year and limiting upper ocean mixing (cf. Koenig et al., 2024). Sea ice (presence and especially the length of the ice season in spring) is also key in controlling the amount of light reaching the ocean in the nBS (Sandven et al., 2025).

The thickness and age of sea ice have direct and indirect effects on Arctic marine life. Sea ice floes host ice-specific ecosystems that differ between MYI and FYI (Campbell et al., 2022; Lange et al., 2017). Specifically in the region north of Svalbard, older ice arriving from the north may be important in maintaining or seeding specific algal communities (Olsen et al., 2017). The timing and length of the ice season have a significant impact on the seasonality (phenology) of Arctic marine ecosystem processes (e.g., Søreide et al., 2010); the date of ice retreat significantly affects summer biomass and vertical carbon fluxes in the nBS (cf. Kohlbach et al., 2023). Moreover, the distribution and migration patterns of several key species of fish, seabirds and marine mammals in the region are highly dependent on sea ice (Kovacs et al., 2011; Kuletz et al., 2024). For example, the ocean in the Svalbard-Franz Josef Land area is an important hunting and transit area for the pelagic subpopulation of polar bears in the Barents Sea region, and the extent and seasonality of sea ice in this area have direct effects on their distribution and life cycle (Mauritzen et al., 2003; Aars et al., 2017; Blanchet et al., 2020).

Sea ice and the meltwater-induced surface stratification have direct implications for air-sea exchange. The reduced sea ice coverage in the nBS has been shown to have increased the uptake of atmospheric CO₂ (Ericson et al., 2023). This in turn means that sea ice (itself and the meltwater it provides) plays an integral role in the ocean acidification state of surface waters in the nBS (e.g. Jones et al., 2023; Fransson et al., 2025), and suggests that sea ice transport could directly influence the local ocean carbon budget and surface water chemistry. Moreover, the exchange of momentum from the atmosphere to the ocean is strongly impacted by sea ice concentration and morphology (Haapala et al., 2026; Brenner et al., 2021), and the arrival of thicker sea ice floes could affect how surface wind forcing is transferred to the ocean below.



Lastly, transport-driven shifts to thicker ice directly impact options for navigation and human activity. The activity and mobility patterns of fishing and tourism vessels in Svalbard waters are strongly modulated by sea ice extent, and exhibit a strong seasonality mirroring that of the sea ice (Stocker et al., 2020). A prolonged sea ice season due to northerly ice advection can directly affect the duration of the seasons for tourism and fishing activity around Svalbard from year to year. Moreover, older and thicker sea ice transported from the north may pose challenges even for vessels that can comfortably navigate in thinner ice, particularly if compressed against land by winds or ocean currents. Similarly, large, thick ice floes would pose a significant challenge for any type of permanent infrastructure in ocean areas east or north of Svalbard. As the thickness of the locally-formed winter sea ice in the nBS continues to decline (Mallett et al., 2021; Bocquet et al., 2024), it may counter-intuitively reduce the obstruction for thicker ice transported from the north and present a hazard for activities around Svalbard for longer into the century than might be expected.

4 Conclusions

Sea ice in the Barents Sea is chiefly composed of young ice formed in the Barents and Kara Seas, but towards its northwestern margin, it is influenced by older ice entering from the Central Arctic Ocean. During the period 2009–2024, this influence was intermittent, with 7 out of 15 seasons having sea ice originating from the Transpolar Drift region (defined here as north of 83° N) arriving in the northwestern corner of the Barents Sea. Moored sea ice draft observations from three consecutive years (2019–2021), which were partially influenced by sea ice transport from the Central Arctic, show a transition in April–June toward thicker and more uniform ice, with a modal sea ice draft increase of 0.5 to 1.1 m.

The thicker ice originated in the Transpolar Drift region, and its thickness reflects the history of the sea ice during its path across the Eurasian Basin, in some cases over several consecutive seasons. Satellite-derived sea ice thickness sampled along back-trajectories indicates that the Central Arctic-origin ice was already thick before entering the northern Barents Sea, although it arrived considerably thinner than at its upstream maximum. A simple thermodynamic growth model forced by conditions along the same back-trajectories supports a transition to thicker ice at a similar time as the observations, while the same model forced by local conditions does not.

On a broader scale, the margin between the Barents Sea and the Nansen Basin displays a pattern of ice thickening and increasing presence of multiyear ice between February and June in the 2011–2023 climatology. This suggests a seasonal progression of large-scale sea ice drift patterns, in turn forced by regular seasonal evolution of regional atmospheric pressure patterns. The mooring sites are located at the southern margins of the affected area, likely explaining why they are affected by the arrival of Central Arctic-origin ice only during some years. Overall, this study shows that sea ice thickness in the region east and north of Svalbard is influenced by a complex combination of variable thermodynamic forcing, large-scale ice advection, and local coastal interactions. Combined, they produce high spatial and temporal variability. In contrast, comparable in situ observations from the Beaufort Sea show a far more regular and predictable seasonal evolution, highlighting large contrasts in the seasonal ice thickness evolution across the Arctic Ocean.



Sea ice arriving from the Transpolar Drift region of the Central Arctic Ocean is an important factor affecting the physical environment of the present-day Barents Sea, with downstream effects on sea ice thickness and persistence, ocean stratification, marine ecosystems, and human activity. Since the mechanism is so variable from year to year, we expect its broader effects on the Barents Sea system to be equally variable.

570 **5 Data availability**

The M1 and M2 mooring data are available from the Norwegian Polar Institute Data Centre: Foss and Sundfjord (2025) (Sig500 data) and Lundesgaard and Sundfjord (2022) (CTD data). SODA-B mooring data are available at <http://hdl.handle.net/1773/46919>. The various gridded products and associated data DOIs are listed in Table 1. UoB SIC data were downloaded from <https://data.seaice.uni-bremen.de/>.

575 *Author contributions.* ØF developed the original idea with input from MAG, SB, JL, AS and ES. AS planned and led the mooring campaign. ØF analysed the in situ observations with input from SB, and computed the back-trajectories with input from HS. JL analysed the along-trajectory CS2 SIT. ES carried out the thermodynamic modelling. SB and ES analysed the SODA mooring data. ØF, ES and JL analysed additional remote sensing and reanalysis products. SG and MAG advised on sea ice context. ØF wrote the initial draft, and all authors contributed to the manuscript.

580 *Competing interests.* Sebastian Gerland is a member of the editorial team of The Cryosphere.

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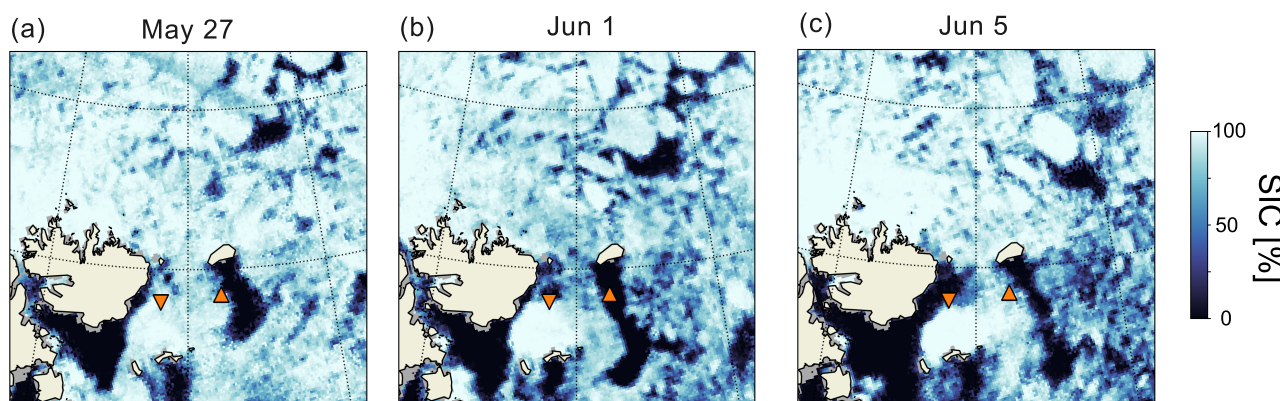


Figure A1. Snapshots of UoB AMSR2 daily sea ice concentration in the broader study area, 27 May to 5 June 2021. Showing persistent wind-driven polynyas in the lee of Kvitøya and Nordaustlandet, and large floes entering the area north of Svalbard. Orange triangles indicate mooring positions.

Appendix A: Examples of coastal influence on the sea ice cover at the mooring sites

The mooring sites were located close to land, and influenced by direct effects of coastal interaction. In particular, drops in sea ice concentration and thickness occurred when the mooring sat downstream of the coast in the dominant ice drift direction. Fig. A1 shows an example where an extensive polynya in the wake of Kvitøya fluctuates over the M2 mooring. In contrast, a sudden increase in sea ice draft to 4–5 m over a period of several days (Fig. A2a) occurred at M1 in March 2019 during a period of north-northeasterly winds (Fig. A2c). Simultaneous measurements of sea ice drift (Fig. A2b) show that during this period, sea ice motion at M1 ceased entirely, including the background tidal motion – indicating a stationary ice pack due to the coast locking in the ice. After a strong reversal of the winds around 19 March, sea ice motion recommenced and draft values were reduced again.

Appendix B: Sensitivity of the thermodynamic models

B1 Effect of melt fluxes on FDD estimates

Fig. B1 illustrates the effect of including parameterised melt on FDD estimates of thermodynamic sea ice growth. Fig. B1a shows the per-season FDD based on local air temperatures at M2 with (green) and without (blue) basal and surface melt fluxes from West et al. (2020) applied through Eq. (4). Including fluxes results in a summer thinning not parameterised by the FDD model alone.

Similarly, Fig. B1b shows the effect of including parameterised melt along multi-year trajectories from M2. Including melt results in a ~ 0.75 m reduction in sea ice draft of ice arriving at M2.

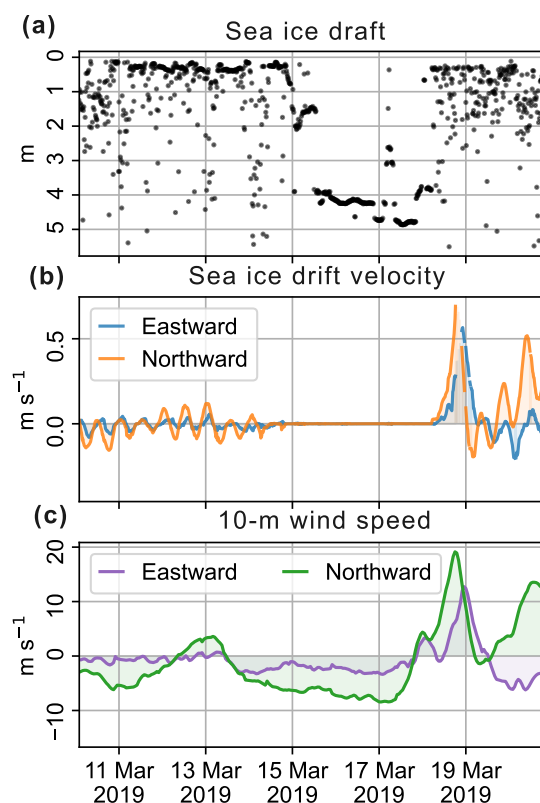


Figure A2. Land-locking event at M1, March 2019. *a*: Sea ice draft (per-ensemble medians). *b*: Sea ice drift velocity components. *c*: ERA5 10-m wind components at nearest grid point.

840 For trajectories ≤ 365 days, the combined forcing sensitivity of the FDD-derived thermodynamic draft was approximately -0.07 to $+0.03$ m. Air-temperature perturbations of $\pm 1^\circ\text{C}$ changed the derived draft by about ± 0.03 m, while perturbing ocean heat flux by ± 1 standard deviation produced changes of approximately -0.04 to $+0.01$ m; sensitivity to the surface melt energy flux was negligible. For trajectories > 365 days, the sensitivity increased substantially, with a combined range of approximately -0.56 to $+0.66$ m. This was dominated by ocean heat flux (-0.42 to $+0.32$ m) and surface melt energy flux
 845 (-0.16 to $+0.20$ m), while sensitivity to the $\pm 1^\circ\text{C}$ air-temperature perturbation remained comparatively small at approximately ± 0.08 m.

B2 Effects of snow: Comparison with a thermal-resistance model using gridded snow depth

As an alternative to the empirically-based FDD model, which does not account for variations in snow depth, we applied the thermal-resistance (*TR*) model (Adams et al., 1960; Salganik et al., 2021). The model estimates conductive heat flux through
 850 snow and ice as

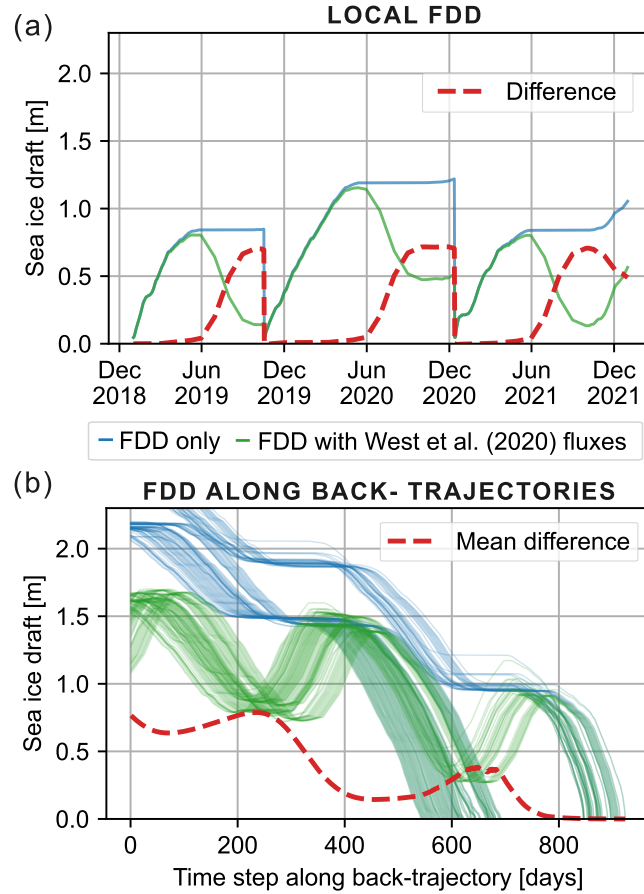


Figure B1. FDD-modelled draft with (green) and without (blue) the surface- and basal-melt fluxes of West et al. (2020). Red dashed line shows the difference (green minus blue). *a*: Locally at M2. *b*: Along all multiyear back-trajectories from M2.

$$R = \frac{h}{k_i} + \frac{h_s}{k_s} \quad (\text{B1})$$

$$Q_{atm} = \max\left(\frac{T_f - T_a}{R}, 0\right) \quad (\text{B2})$$

where h_s is snow thickness. Along the back-trajectories, we used a hybrid forcing, with KuLa snow depth used where available and SM-LG used otherwise. We use fixed effective conductivities of $k_i = 2.0 \text{ W m}^{-1} \text{ K}^{-1}$ for ice (Leppäranta, 1993) and $k_s = 0.25 \text{ W m}^{-1} \text{ K}^{-1}$ for snow (Macfarlane et al., 2023).

Ice growth is calculated as:

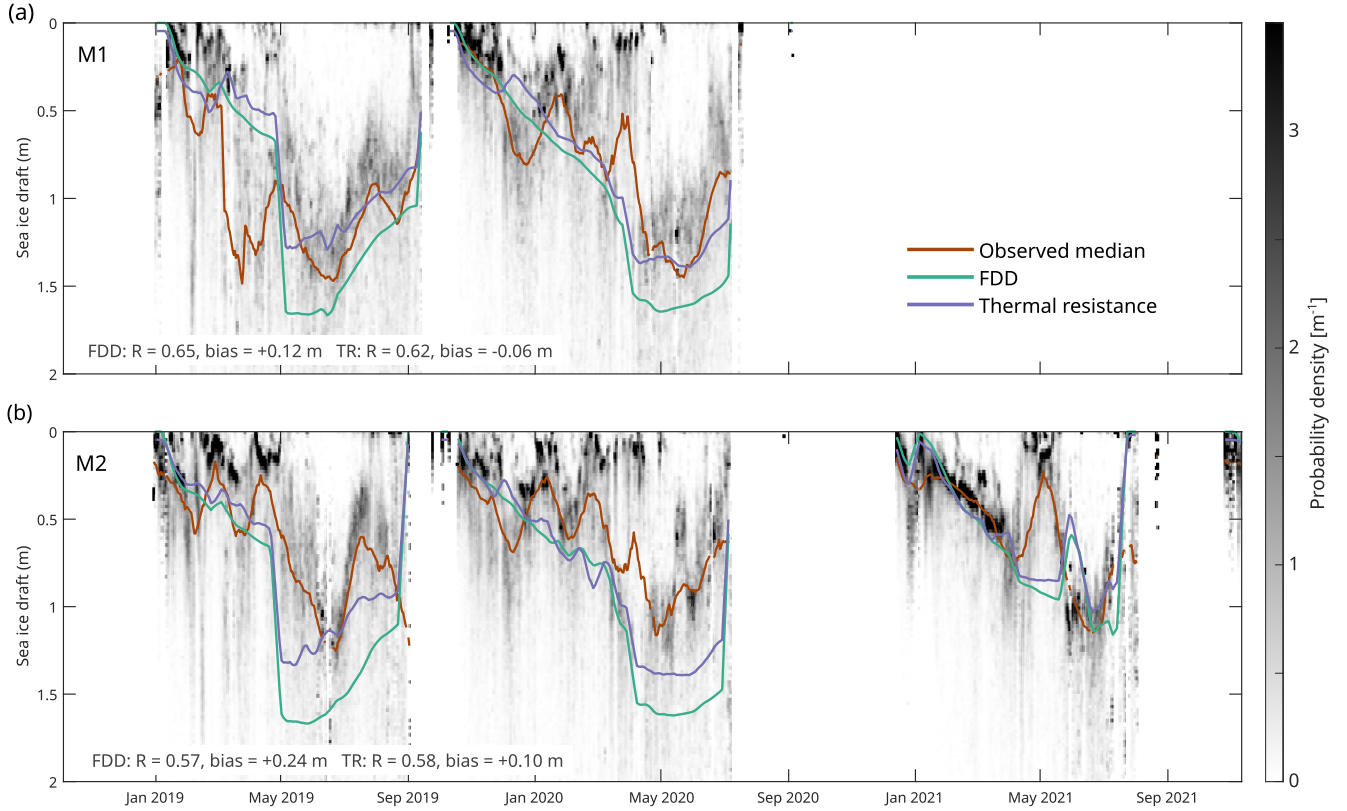


Figure B2. Observed and thermodynamically modelled sea-ice draft at moorings (a) M1 and (b) M2. Grayscale shading shows the daily probability density of observed draft. The orange line shows the smoothed observed median draft, while green and purple lines show back-trajectory draft estimates from the FDD and TR models, respectively.

$$\Delta h_{\text{growth}} = \frac{Q_{\text{atm}} \Delta t}{\rho_i L_f} \quad (\text{B3})$$

Ice thickness is updated as:

$$h(t + \Delta t) = \max(h(t) + \Delta h_{\text{growth}} - \Delta h_{\text{melt}}, 0) \quad (\text{B4})$$

860 The TR model was initialised with an ice thickness of $h_0 = 0.05$ m at the oldest valid trajectory point in the trajectory calculations and at the prescribed sea-ice onset date in the local calculations.

Fig. B2 shows the along-trajectory modelled sea ice draft arriving at the mooring sites using the FDD and TR models. The two align closely during the Barents-origin phase, but differ in the Central Arctic-origin phase, where FDD produces thicker ice. As a result, the overall model bias relative to observed median draft is reduced from +0.12 m to −0.06 m at M1 and

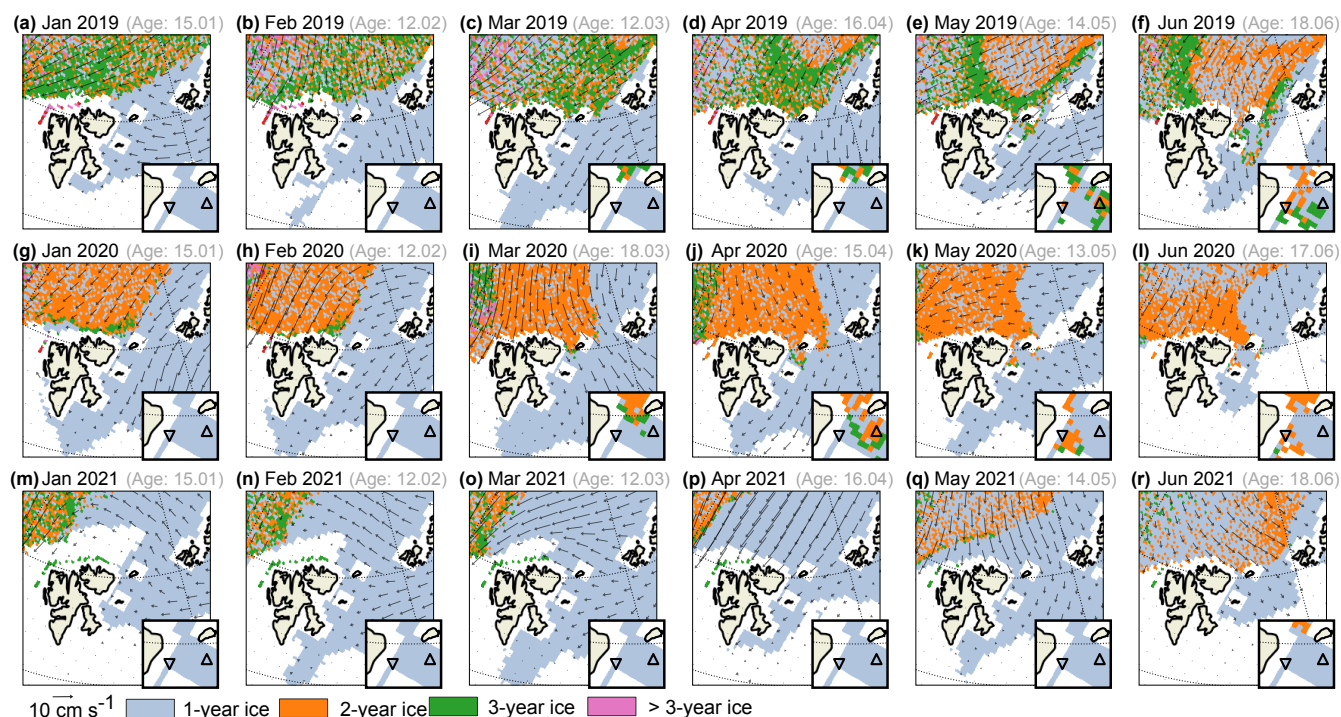


Figure C1. Maps of satellite-derived sea ice age (NSIDC SIA) and drift (NSIDC PP) for January through June during the three study years. Sea ice age was selected for the closest available time stamp to the 15th of each month (time stamp shown in gray). Sea ice drift is based on monthly mean of sea ice vectors (counting no drift as zero). Inset maps show a zoomed-in view of sea ice age around the mooring sites.

865 from +0.24 m to +0.10 m at M2. Meanwhile, correlation coefficients are nearly unchanged (0.65 and 0.57 for FDD, 0.62 and 0.58 for TR). Both moorings show a pronounced shift to thicker drafts associated with the switch from Barents- to Central Arctic-origin phase in 2019 and 2020.

Appendix C: Sea ice age from other products, 2019–2021

In addition to the Korosov SIA product (Fig. 5), we examined sea ice age in the study period in two additional independent
 870 satellite-derived products, NSIDC SIA and OSISAF SIA. The three products differ in the details, but all show the same general pattern: a MYI belt north of Svalbard migrating south and east from winter into spring and summer each year. NSIDC SIA (Fig. C1) shows MYI entering the study area in May 2019 and March 2020, broadly consistent with the later transition dates in Table 3, and no MYI entering in 2021. OSISAF SIA, available only for the two first seasons, shows a southward migration of the MYI belt in both years, reaching northern Svalbard earlier in 2020 than 2019. While directionally consistent with the other
 875 products, OSISAF SIA never shows MYI actually entering the study area.

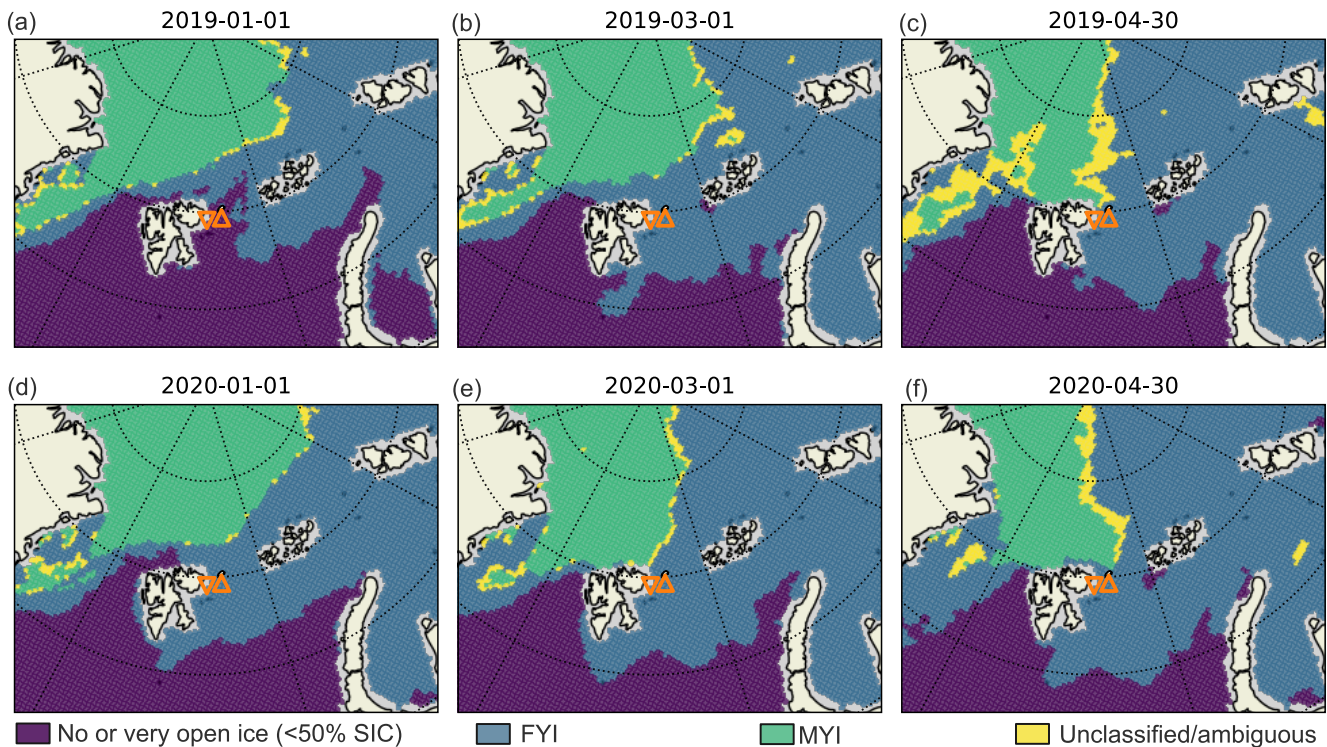


Figure C2. Sea ice age from OSISAF SIA through the winters of 2019 and 2020.

Appendix D: Sea ice ridges in the Barents Sea, 2019–2021

Fig. D1 shows ridge spacing obtained from the *IS2 ridge* product (Mchedlishvili et al., 2023a). Ridge spacing is smoothed using a 5×5 -cell moving median followed by a moving mean; only locations with at least five valid observations within the smoothing window are shown in the figure.

880 The figures show a general increase in ridge spacing moving southward from the CAO to the nBS. Within the nBS, a clear decrease in ridge spacing occurred from February to May each year. The year 2021 stands out as a year with fewer ridges relative to the two preceding years both in February and May.

Appendix E: Atmospheric forcing during the study period

885 Monthly mean SLP from the 2019–2021 study period (Fig. E1) followed the general eastward progression as seen in the 2011–2023 climatology (Fig. 8c–g). In all three years, a period of low pressure centred in the Barents Sea was followed by a pressure configuration consistent with northerly geostrophic winds (increasing pressure toward the west). This was observed in April 2019, March 2020, and May 2021, preceding the change to the Central Arctic-origin phase during the respective years.

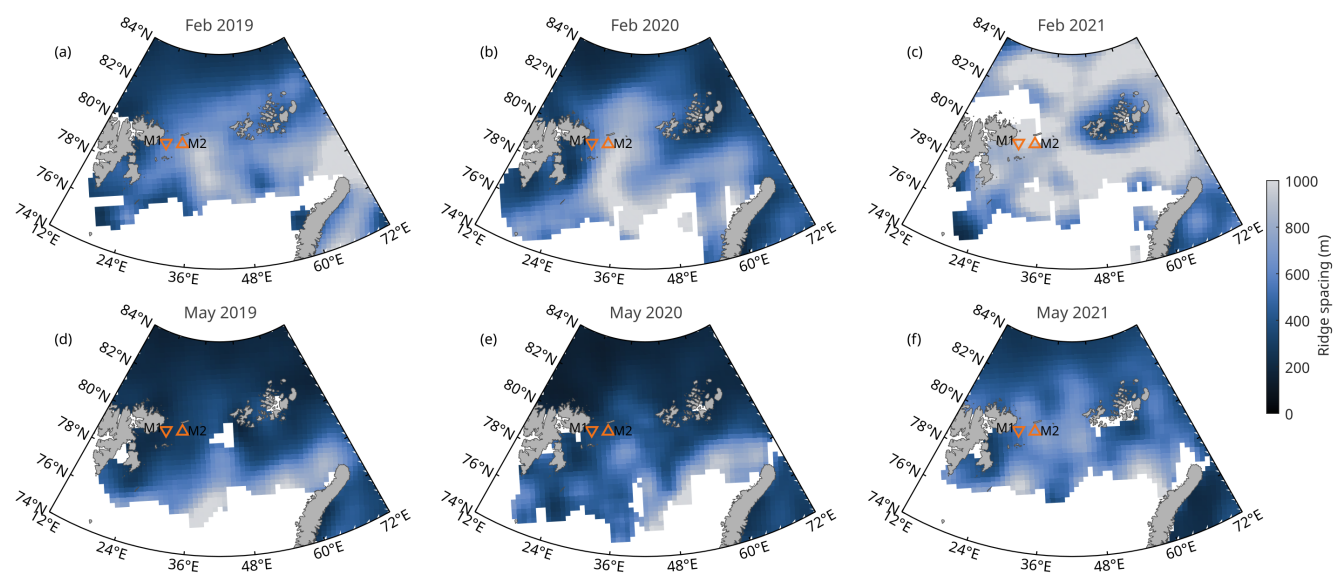


Figure D1. Spatial distribution of ridge spacing from *IS2* ridge in the northern Barents Sea in February (a–c) and May (d–f) of 2019–2021. Smaller ridge spacing indicates more frequent ridging. Orange triangles mark the M1 and M2 mooring locations.

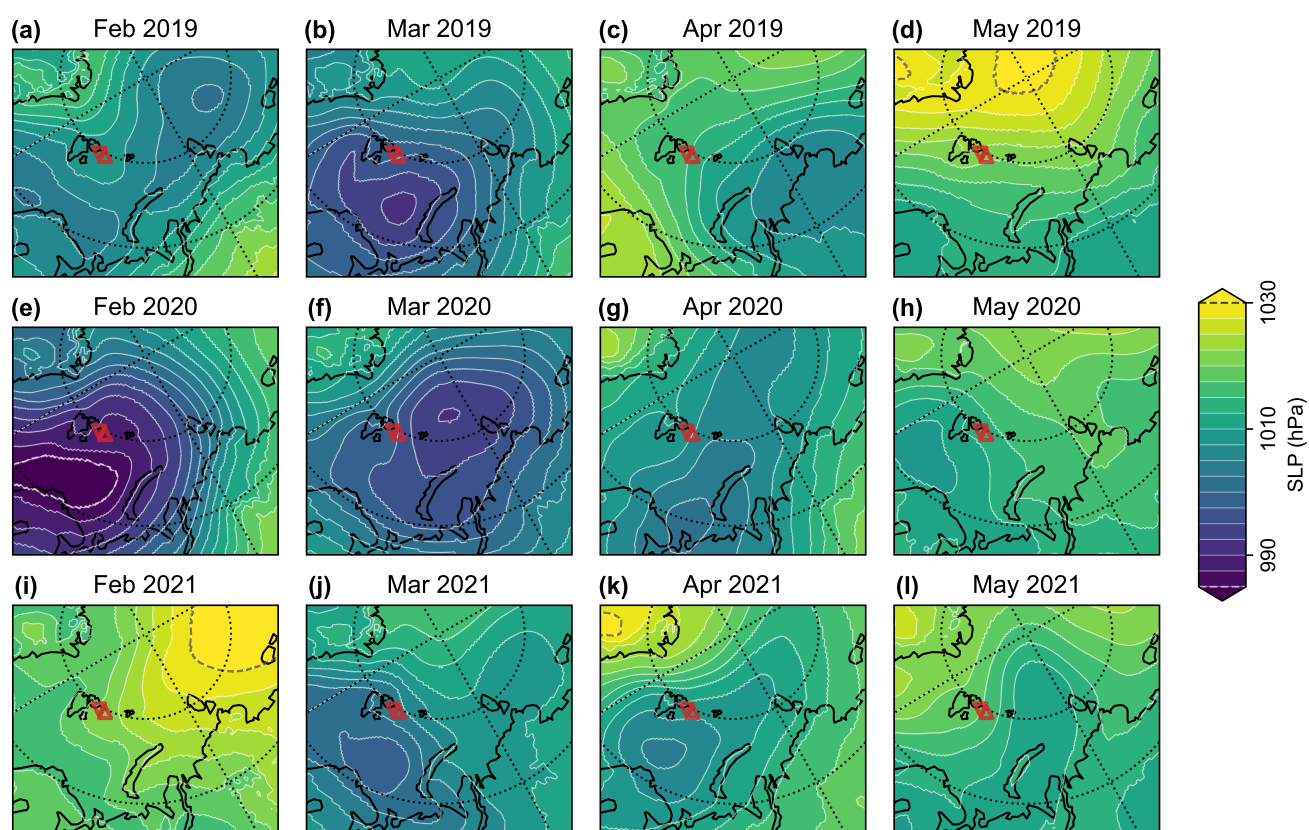


Figure E1. Monthly average sea level pressure from ERA5 for Feb–May during the study period. Mooring locations are shown as red triangles.