

# Sea Ice Meltwater in the Beaufort Gyre: A Comprehensive Analysis Using Sea Surface Salinity Data from SMOS

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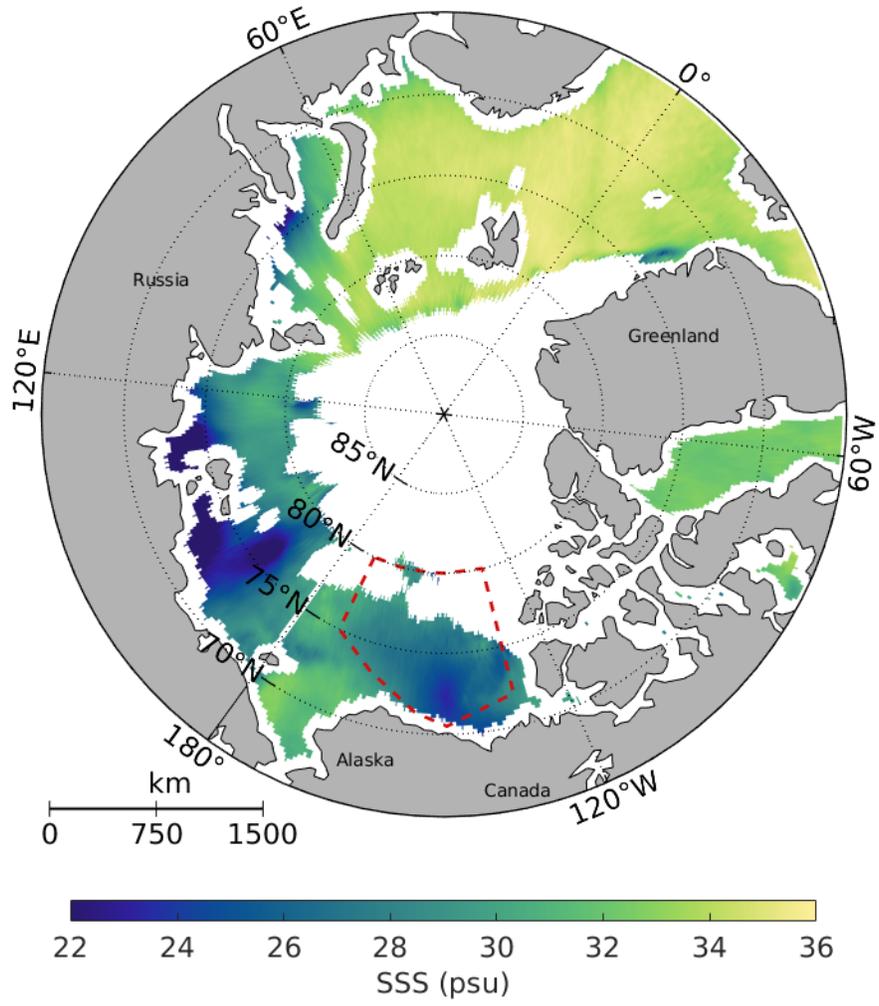
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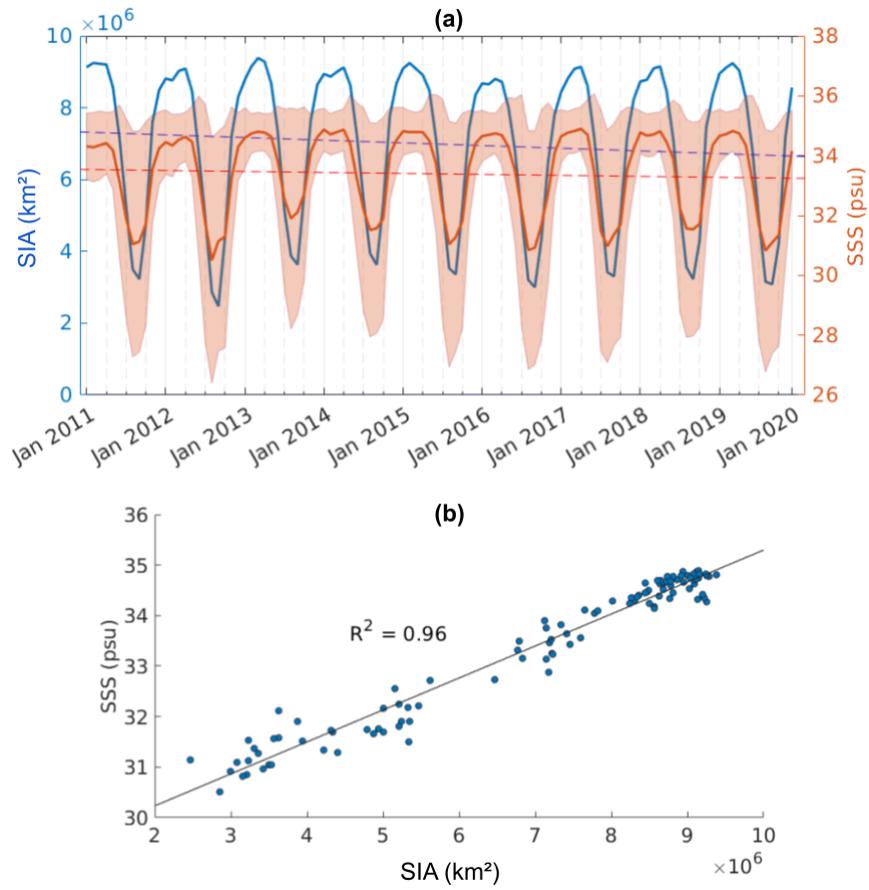
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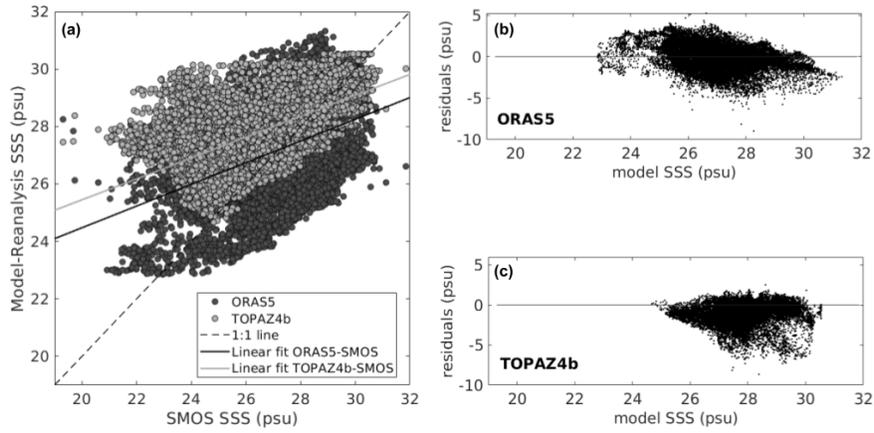
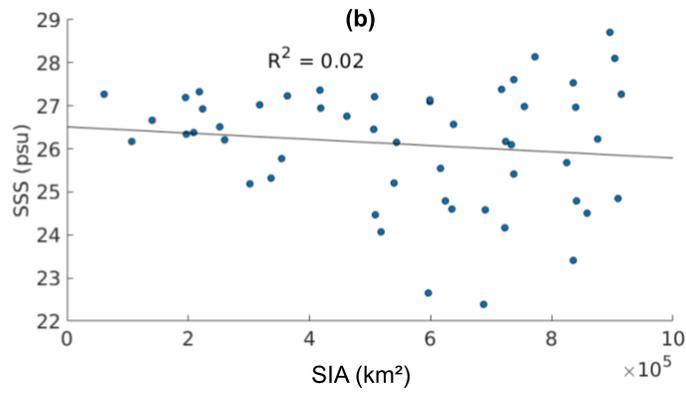
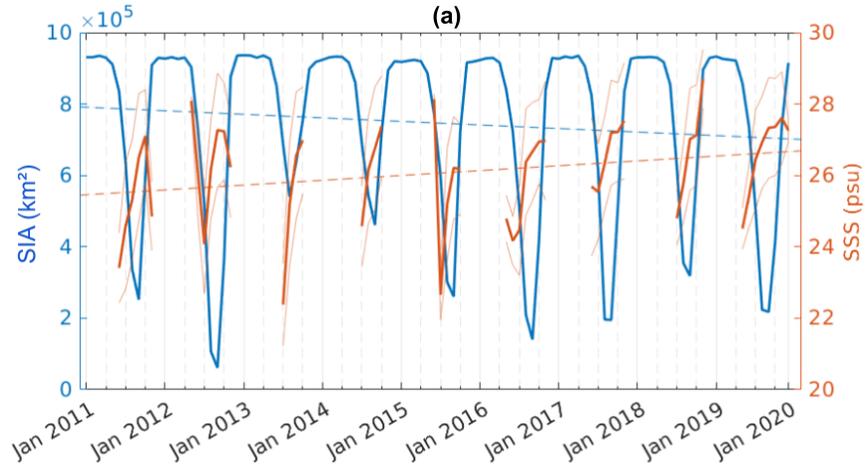
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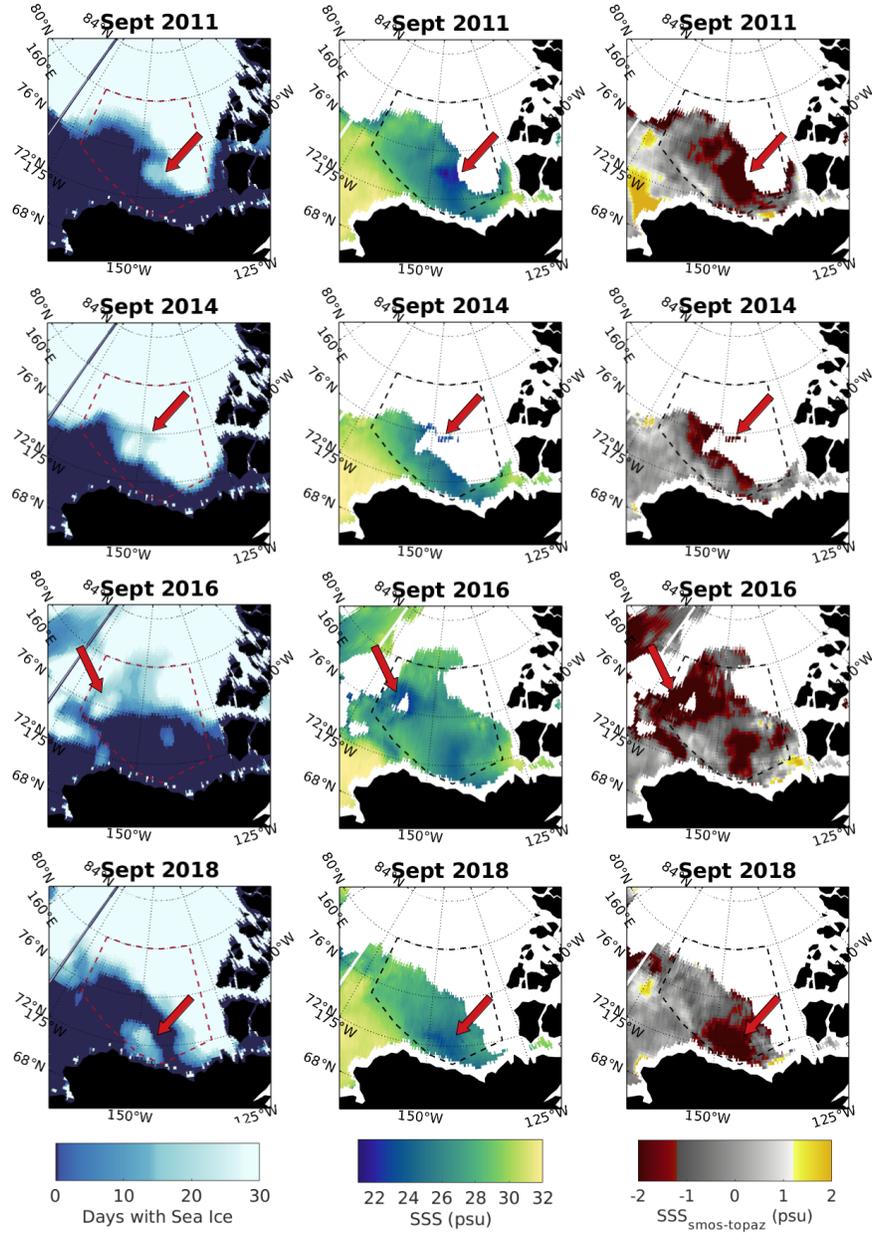
## Abstract

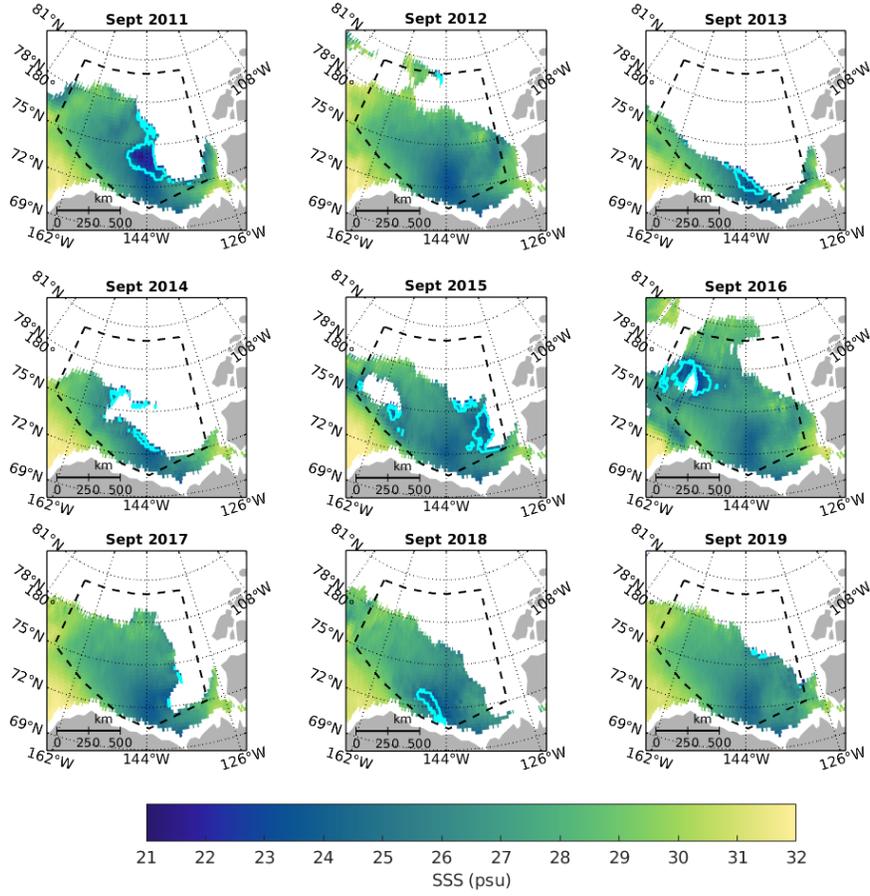
Arctic sea ice is retreating, thinning, and exhibiting increased mobility. In the Beaufort Gyre (BG), liquid freshwater content (FWC) has increased by 40% in the last two decades, with sea ice melting being a primary contributor. This study utilizes satellite observations of sea surface salinity (SSS) and sea ice concentration, along with model-based sea ice thickness from 2011 to 2019. The aim is to investigate the sea ice-SSS relationship at different scales in the Arctic and understand the sea-ice meltwater dynamics in the BG. Our findings reveal a strong synchrony and positive correlation between sea ice area and SSS in the Arctic Ocean. In September, when the BG exhibits the largest ice-free ocean surface, a noticeable release of freshwater from sea ice melting occurs, a phenomenon not accurately reproduced by the models. The SMOS (Soil Moisture and Ocean Salinity) mission proves valuable in detecting meltwater lenses (MWL) originating from sea ice melting. These MWLs exhibit mean SSS ranging from 19 psu at the beginning of sea ice retreat to 25 psu before sea ice formation. Wind-driven anticyclonic eddies can trap MWLs, preserving the freshest SSS imprints on the sea surface for up to 10 days. Furthermore, events of sea surface salinification following sea ice formation suggest that SMOS SSS might be capturing information on brine rejection. The daily evolution of sea ice-SSS within the MWLs demonstrates a tight correlation between both variables after sea ice melting and just before sea ice formation, indicating a transient period in between.

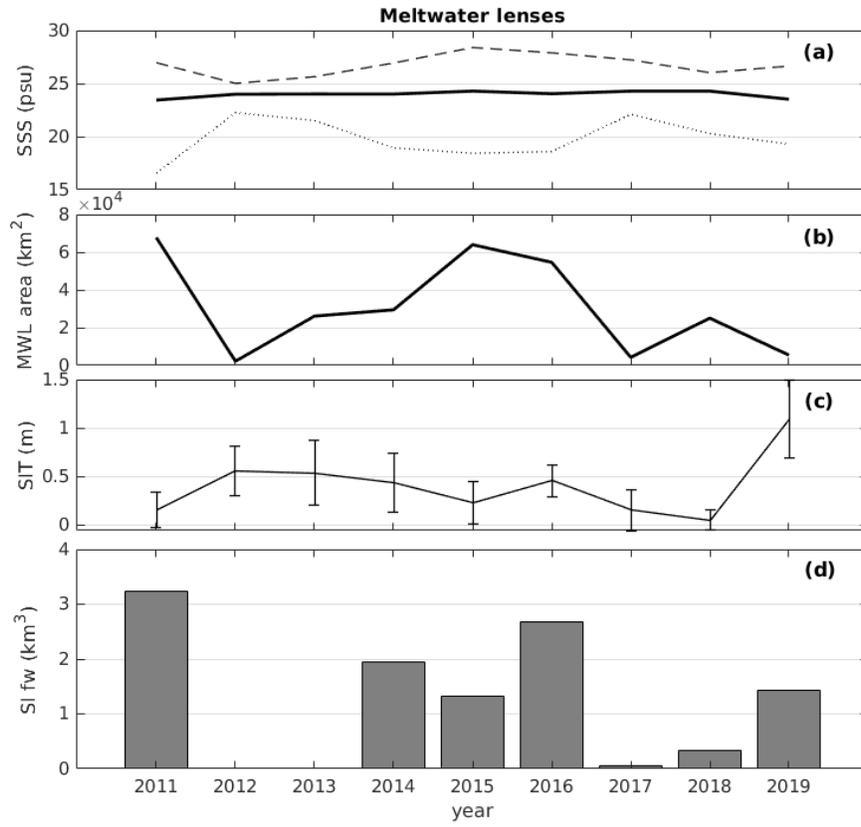


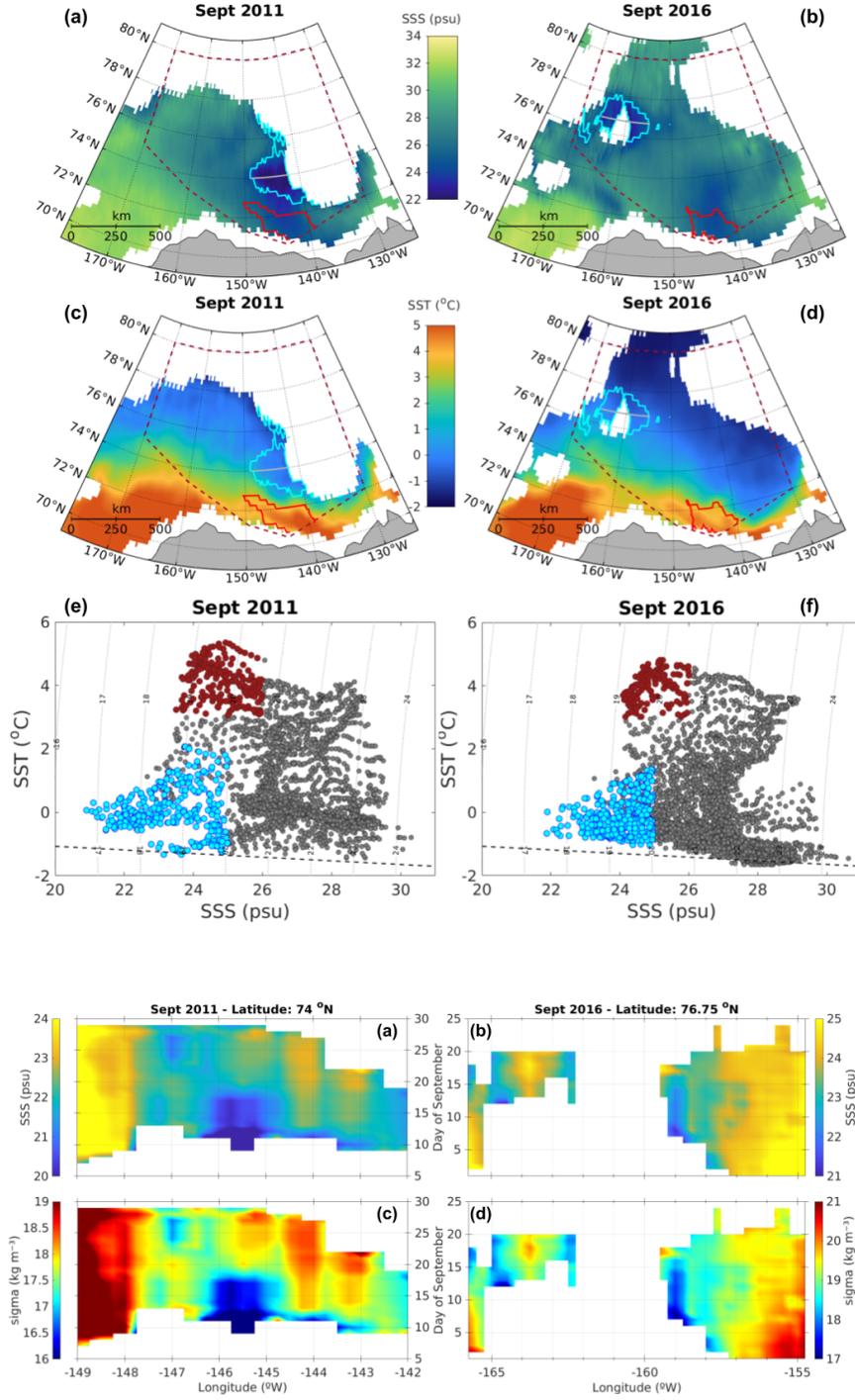


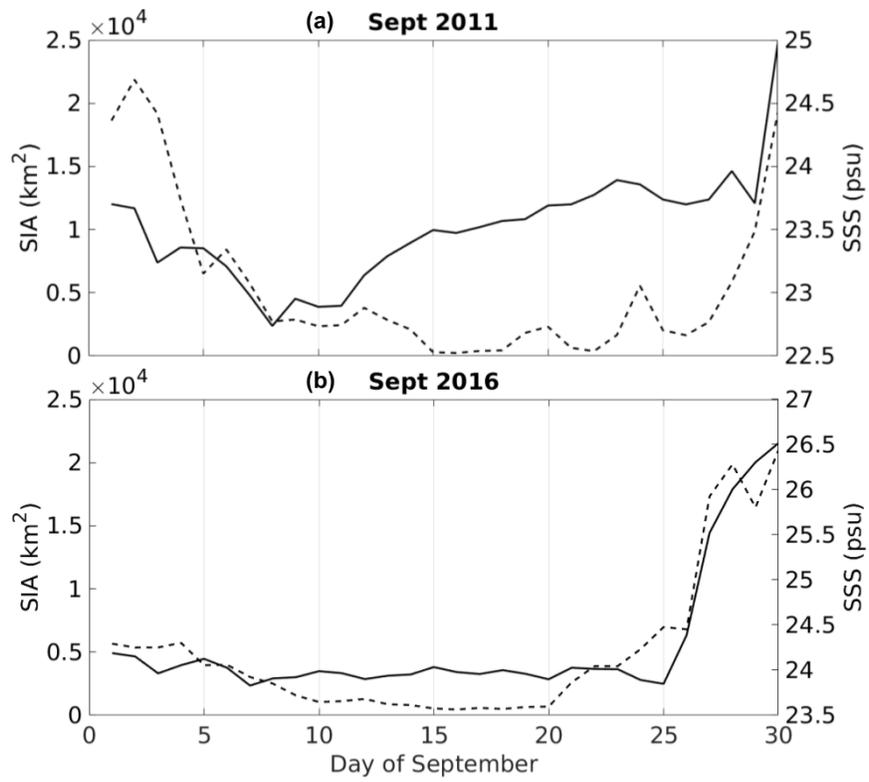
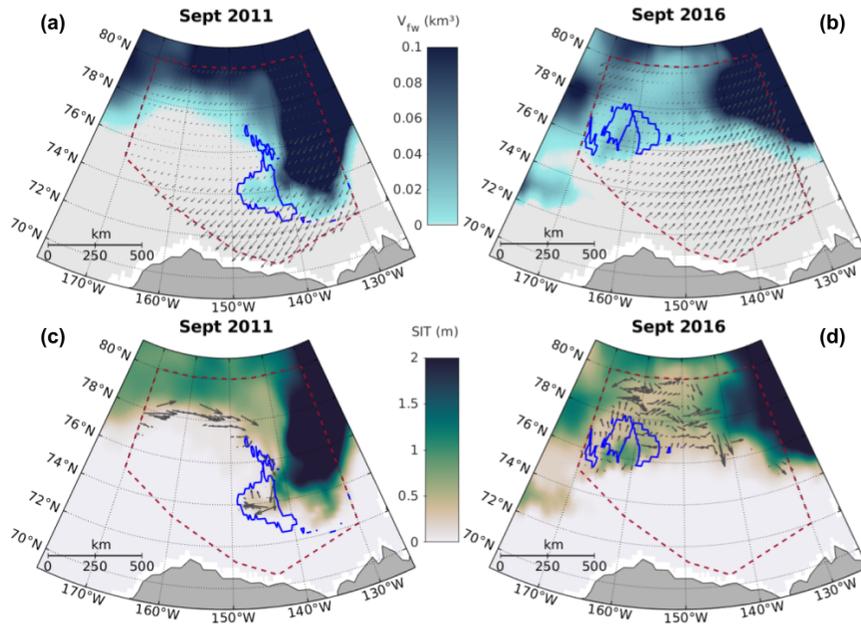


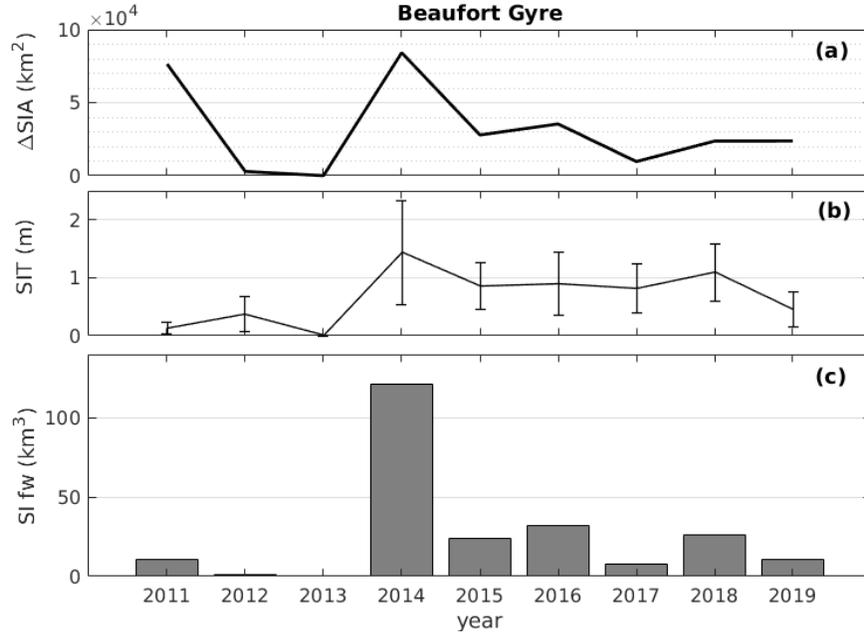












1                   **Sea Ice Meltwater in the Beaufort Gyre: A**  
2                   **Comprehensive Analysis Using Sea Surface Salinity**  
3                   **Data from SMOS**

4                   **Eva De Andrés<sup>1,2</sup>, Marta Umbert<sup>2</sup>, María Sánchez-Urrea<sup>2</sup>, Verónica**  
5                   **González-Gambau<sup>2</sup>, Estrella Olmedo<sup>2</sup>, Carolina Gabarró<sup>2</sup>, and Pedro**  
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9                   **Key Points:**

- 10                   • SMOS sea surface salinity is a key tool for detecting freshening events induced by  
11                   sea ice meltwater.
- 12                   • Sea ice cover and sea surface salinity are tightly coupled and positively correlated.
- 13                   • The ocean imprint ( $\sim 19$  psu) of sea ice melt events that persist for up to 10 days  
14                   are detected.

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**Abstract**

Arctic sea ice is retreating, thinning, and exhibiting increased mobility. In the Beaufort Gyre (BG), liquid freshwater content (FWC) has increased by 40% in the last two decades, with sea ice melting being a primary contributor. This study utilizes satellite observations of sea surface salinity (SSS) and sea ice concentration, along with model-based sea ice thickness from 2011 to 2019. The aim is to investigate the sea ice-SSS relationship at different scales in the Arctic and understand the sea-ice meltwater dynamics in the BG. Our findings reveal a strong synchrony and positive correlation between sea ice area and SSS in the Arctic Ocean. In September, when the BG exhibits the largest ice-free ocean surface, a noticeable release of freshwater from sea ice melting occurs, a phenomenon not accurately reproduced by the models. The SMOS (Soil Moisture and Ocean Salinity) mission proves valuable in detecting meltwater lenses (MWL) originating from sea ice melting. These MWLs exhibit mean SSS ranging from 19 psu at the beginning of sea ice retreat to 25 psu before sea ice formation. Wind-driven anticyclonic eddies can trap MWLs, preserving the freshest SSS imprints on the sea surface for up to 10 days. Furthermore, events of sea surface salinification following sea ice formation suggest that SMOS SSS might be capturing information on brine rejection. The daily evolution of sea ice-SSS within the MWLs demonstrates a tight correlation between both variables after sea ice melting and just before sea ice formation, indicating a transient period in between.

**Plain Language Summary**

The Arctic sea ice is changing. It's becoming younger, thinner, and more mobile. In the Beaufort Gyre (BG), the amount of liquid freshwater has increased by 40% over the last two decades, mainly due to melting sea ice. This study, using satellite data and models, explores how sea ice and sea surface salinity (SSS) are connected in the Arctic. It focuses on the BG to understand how melting sea ice contributes to freshwater. Results show a strong link between the area covered by sea ice and SSS in the Arctic Ocean. In September, when the BG has the most open water, there's a noticeable release of freshwater from melting sea ice that is not accurately represented by the models. The SMOS mission is useful in detecting areas of melted ice (MWL) characterized by low salinity and temperature. These MWLs can be trapped by ocean currents, keeping the freshest patterns for up to 10 days. The data also hints at brine rejection events after sea ice forms. Daily changes in sea ice and SSS within MWLs show a clear connection after ice melts and just before it forms again, suggesting a transitional period in between.

**1 Introduction**

The Arctic has warmed nearly four times faster than the globe since 1979 (Rantanen et al., 2022), experiencing a reduction in sea ice extent, thinning of the ice cover, warming and freshening of the Arctic Ocean, increased mixing and enhanced interactions within the ocean-ice-atmosphere system (Solomon et al., 2021).

Arctic freshwater originates from sea ice melting, glacial runoff, Arctic rivers, and precipitation (snowfall and rainfall) (Timmermans & Toole, 2023). This freshwater is retained within the upper layer, situated above the halocline and the Atlantic layer. The halocline serves as a crucial barrier, segregating Atlantic water heat from the surface and overlying sea ice (Polyakov et al., 2017). In the Pacific sector of the Arctic, the halocline is primarily influenced by Pacific Waters, which is a significant source of both heat and freshwater for the Arctic Ocean (Shimada et al., 2005). This influx occurs through the Bering Strait, playing a key role in the summer retreat of sea ice, particularly in the Beaufort Gyre (BG) (Shimada et al., 2001; Zhang, Lindsay, et al., 2008; Zhang, Steele, & Woodgate, 2008).

63 The BG is a key driver of Arctic Ocean salinity changes, as it is the largest reser-  
64 voir of liquid freshwater content (FWC) in the Arctic Ocean, storing an average of 21,800  
65 km<sup>3</sup> of FWC between 2003 and 2018 (Proshutinsky et al., 2019). Climate studies have  
66 recently focused on the BG freshening due to its capacity to eventually release substan-  
67 tial volumes of freshwater into the Arctic Ocean (Haine et al., 2015; Carmack et al., 2016),  
68 which is known to increase with future climate change (Jahn & Laiho, 2020). The fresh-  
69 water may be transported to the subpolar North Atlantic through eddies or gyre spin-  
70 down mechanisms, driving salinity and density decrease (Dickson et al., 1988; Belkin et  
71 al., 1998). As the subpolar North Atlantic is an important region for deep-water forma-  
72 tion, such freshening could impact the strength of the Atlantic Meridional Overturning  
73 Circulation (AMOC)(Jahn & Holland, 2013; Yang et al., 2016; Wang, Wekerle, Danilov,  
74 Wang, & Jung, 2018; Holliday et al., 2020; Zhang et al., 2021; Haine et al., 2023) and  
75 have broader global effects (Rahmstorf et al., 2015).

76 Sustained by the anticyclonic winds of the climatological Beaufort Sea High (Serreze  
77 & Barrett, 2011; Timmermans & Marshall, 2020), the upper-ocean circulation within the  
78 BG drives Ekman convergence and deepening of the halocline (Proshutinsky et al., 2002).  
79 Observations of hydrographic data and satellite-derived sea surface height measurements  
80 have revealed a substantial freshening of the Beaufort Gyre since the mid-1990s (Proshutinsky  
81 et al., 2009; Rabe et al., 2011; Giles et al., 2012; Krishfield et al., 2014). Notably, there  
82 has been a 40% increase in FWC during 2003-2018 compared to the previous climatol-  
83 ogy (Proshutinsky et al., 2019). These changes have been attributed to a combination  
84 of an anticyclonic atmospheric circulation, increased surface anticyclonic stress result-  
85 ing from retreated sea ice cover, direct contributions from sea ice melt, and wind-driven  
86 redirection of low salinity flows from the Mackenzie River (Proshutinsky et al., 2019; Giles  
87 et al., 2012; Wang, Wekerle, Danilov, Wang, & Jung, 2018; Armitage et al., 2020; John-  
88 son et al., 2018).

89 Recent research has pointed out the important role that sea ice transport exerts  
90 in redistributing freshwater into and out of the BG (Cornish et al., 2023). The ocean sur-  
91 face freshening induced by sea ice melting has been shown to restrict the momentum trans-  
92 fer from the atmosphere to the ocean, thereby enhancing near-surface stratification of  
93 the upper ocean (Supply et al., 2022). However, the impact of sea ice retreat on fresh-  
94 water dynamics and the broader climate system remains poorly constrained, being an  
95 active area of current scientific research.

96 Traditional estimation of the Arctic Ocean’s FWC using in situ measurements faces  
97 challenges of limited spatiotemporal sampling and high costs. In recent decades satel-  
98 lite data, in situ observations, and model reanalysis outputs have been integrated not  
99 only for FWC estimations (e.g. Fournier et al. (2020); Solomon et al. (2021); Umbert  
100 et al. (2023)) but also for improved analysis of sea ice decline and river discharge impact  
101 on the Arctic Ocean (Kilic et al., 2018), as well as in detecting a punctual meltwater lens  
102 (MWL) induced by sea ice melting (Supply et al., 2022).

103 The Soil Moisture and Ocean Salinity (SMOS) is a satellite mission from the Eu-  
104 ropean Space Agency to measure the sea surface salinity (SSS) of the ocean. SMOS pro-  
105 vides daily full coverage in polar regions, with an effective spatial resolution of  $\sim 50$  km  
106 in ice-free areas (Martínez et al., 2022). Despite lower sensitivity in polar oceans due to  
107 low sea surface temperatures (SST), recent advances in retrieval algorithms have led to  
108 tailored Arctic products (Martínez et al., 2022), facilitating the integration of SSS data  
109 into Arctic studies (e.g. Fournier et al. (2019); Hall et al. (2021); Umbert et al. (2021,  
110 2023)).

111 Our study explores the relationship between sea ice cover and SSS across various  
112 scales in the Arctic and quantifies the volume of freshwater released from sea ice melt-  
113 ing in the BG by integrating satellite data and reanalysis outputs. In addressing poten-  
114 tial solutions for filling spatiotemporal gaps in satellite data, we assess and compare the

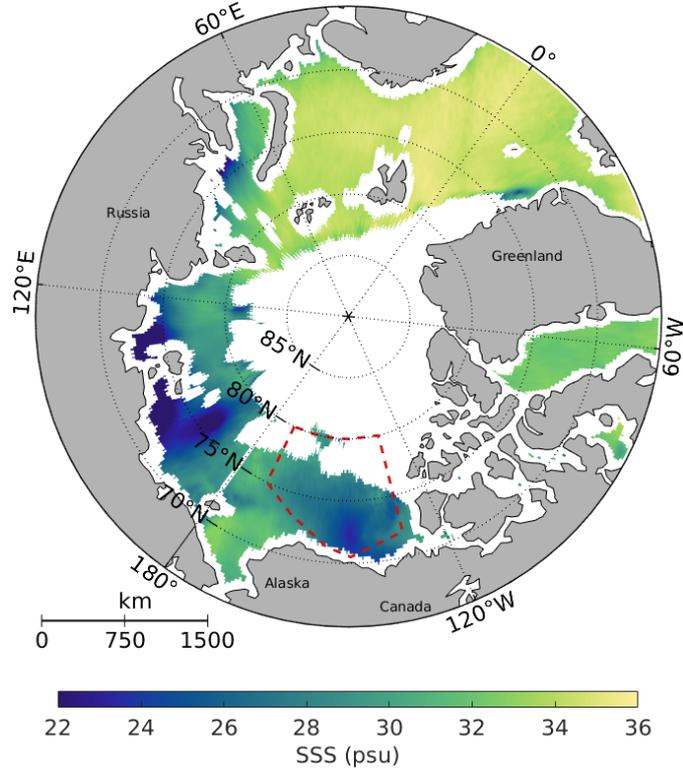


Figure 1: SMOS sea surface salinity over the Arctic ocean ( $>65^{\circ}\text{N}$ ) in September 2012. The Beaufort Gyre region is delimited by the dashed red polygon.

115 accuracy of two reanalysis SSS outputs in regions significantly impacted by sea ice melt-  
 116 ing against SMOS SSS. Leveraging the capabilities of SMOS SSS, we localize and mon-  
 117 itor the extent of MWLs induced by sea ice melting every September from 2011 to 2019,  
 118 compute the volume of freshwater released within these MWLs and characterize their  
 119 SST-SSS and density imprints. The impact of distinct atmospheric regimes on the daily  
 120 evolution of MWL properties is analyzed and discussed. To close our study, the sea ice-  
 121 SSS relationship is revisited at the local MWL scale.

## 122 2 Data

123 Our study spans from 2011 to 2019. Different data sets from both remote sensors  
 124 and reanalysis outputs are used and analyzed over the Arctic north of  $65^{\circ}\text{N}$  and the BG  
 125 area proposed in Proshutinsky et al. (2019) (Fig.1). All the data used in this study refer  
 126 to the sea surface level, meaning that they are spatially 2D variables, which do not  
 127 include the vertical component. All data sets were spatially regridded onto the same reg-  
 128 ular latitude-longitude mesh grid of  $0.25^{\circ}$  horizontal resolution.

### 129 2.1 Satellite observations: Sea Surface Salinity, Sea Ice Concentration 130 and Sea Surface Temperature

131 We use the SMOS SSS v3.1 Arctic product from the Barcelona Expert Center (BEC)  
 132 (Martínez et al., 2022), a specially tailored product for the Arctic Ocean with improved  
 133 effective spatial resolution that permits better monitoring of the mesoscale structures  
 134 larger than 50 km. The salinity maps used in this analysis are generated on a daily ba-

135 sis, using a 9-day running mean, in an Equal-Area Scalable Earth grid (EASE 2.0) (Brodzik  
 136 et al., 2012)) of 25 km horizontal spatial resolution from 2011 to 2019. Note that SMOS  
 137 only retrieves SSS within free-of-ice ocean areas.

138 The Ocean and Sea Ice Satellite Application Facility (OSISAF) from the European  
 139 Organization for the Exploitation of Meteorological Satellites (EUMETSAT) provides  
 140 sea ice concentration (SIC) data computed from atmospherically corrected SSMIS (Spe-  
 141 cial Sensor Microwave Imager Sounder) brightness temperatures, using a combination  
 142 of state-of-the-art algorithms. The product series has been operational since 2005. The  
 143 SIC data used in this work is the version OSI-450 until 2016 (Lavergne et al., 2019; EU-  
 144 METSAT Ocean and Sea Ice Satellite Application Facility, Darmstadt, Germany, 2017)  
 145 and OSI-430-b from 2016 onwards (EUMETSAT Ocean and Sea Ice Satellite Applica-  
 146 tion Facility, Darmstadt, Germany, 2019), which both provide daily-averaged fractional  
 147 ice cover in percentage, on an EASE 2.0 grid of 25 km horizontal resolution over a Global  
 148 Lambert azimuthal projection.

149 We use the satellite-derived dataset of daily SST from OSTIA (Operational Sea  
 150 Surface Temperature and Sea Ice Analysis) at a horizontal resolution of 0.05 degrees, which  
 151 translates to about 3 km at latitude 70°N (Good et al., 2020)). OSTIA uses satellite data  
 152 provided by the GHRSSST (Group for High Resolution Sea Surface Temperature) together  
 153 with in situ observations to determine the sea surface temperature. OSTIA SST is ob-  
 154 tained blending both infrared and microwave radiometers such as the Advanced Very High-  
 155 Resolution Radiometer (AVHRR) on NOAA satellites and the Moderate Resolution Imag-  
 156 ing Spectroradiometer (MODIS) on NASA’s Aqua and Terra satellites.

## 157 **2.2 Ocean Reanalysis: Sea Surface Salinity, Sea Ice Thickness, Wind Stress,** 158 **and Sea Ice Velocity**

159 ORAS5 (Ocean Reanalysis System 5) provides monthly mean global ocean and sea-  
 160 ice reanalysis data from the ECMWF (European Centre for Medium-Range Weather Fore-  
 161 casts) OCEAN5 (ocean analysis-reanalysis system). OCEAN5 uses the NEMO (Nucleus  
 162 for European Modelling of the Ocean) ocean model and assimilates sub-surface temper-  
 163 ature and salinity, satellite sea-ice concentration, and sea-level anomalies. ORAS5 is forced  
 164 by atmospheric reanalysis and constrained by observational data of SST, SSS, SIC, global-  
 165 mean-sea-level trends, and climatological variations of the ocean mass. The ocean model  
 166 is projected on a tripolar grid, and has an eddy-permitting horizontal resolution of 0.25°  
 167 and 75 vertical levels with near-surface resolution of 1 m. In this work, we used the con-  
 168 solidated (2011-2014) and operational (2015-2019) ORAS5 sea ice thickness (SIT), SST,  
 169 wind stress, and sea ice velocity.

170 TOPAZ reanalysis product is released by the Arctic Monitoring and Forecasting  
 171 Center of CMEMS (Copernicus Marine Service). The data sets of its latest version, TOPAZ4b,  
 172 are used in this study. TOPAZ4b uses the Hybrid Coordinate Ocean Model (HYCOM)  
 173 coupled to a sea ice model, which includes ice thermodynamics and elastic-viscous-plastic  
 174 rheology. The TOPAZ4b native grid is built on a Polar stereographic North projection.  
 175 It covers the Arctic and North Atlantic Oceans and has horizontal spatial resolution be-  
 176 tween 11 km at the North Pole and 16 km at the southernmost grid cells. It is composed  
 177 of 40 hybrid (z-isopycnal) vertical levels, with resolution varying from 1 m at the sur-  
 178 face to 1500 m at the deepest level. TOPAZ4b weekly assimilates observations, includ-  
 179 ing along-track Sea Level (SL) anomalies from satellite altimeters, SST from OSTIA, in  
 180 situ temperature and salinity from hydrographic cruises and moorings, OSISAF SIC, Cryosat-  
 181 SMOS SIT and SMOS SSS v3.1 from BEC. TOPAZ4b provides yearly, monthly, and daily  
 182 outputs at all depths. We used the monthly-averaged SSS in our study.

### 183 3 Methods

#### 184 3.1 Computation of Sea Ice Area

185 To get a general view of how salinity at the ocean surface behaves under sea ice  
 186 melting/formation, horizontally-averaged monthly means of SSS and SIC were calculated  
 187 over both the Arctic and the BG (see both regions in Fig.1). From SIC, we computed  
 188 the sea ice area (SIA), which is defined in Lavergne et al. (2023) as "the total ocean area  
 189 covered by any amount of ice (no SIC threshold applied, and the SIC value weights the  
 190 grid cell area)". Therefore,

$$SIA = \sum_{i=1}^N \alpha_i a_i, \quad (1)$$

191 where  $N$  is the number of grid cells inside the given region,  $\alpha_i$  represents the grid-cell  
 192 fraction covered by sea ice (SIC/100), and  $a_i$  is the grid-cell area, estimated with the Cli-  
 193 mate Data Toolbox for Matlab (Greene et al., 2019), assuming Equatorial and Polar ra-  
 194 dius of 6378.1 and 6356.8 km, respectively. Note that SIE (sea ice extent) is considered  
 195 a more reliable index for monitoring sea ice evolution in time, however, we have focused  
 196 on SIA, because it is the variable needed to ultimately compute the freshwater released  
 197 from sea ice melting (see Eqn. 2). We then analyzed the time evolution of the SSS and  
 198 SIA variables and evaluated their synchrony and relationship through correlation tests.

#### 199 3.2 Evaluation of Reanalysis Performance

200 SSS monthly means of ORAS5 and TOPAZ4b were compared with monthly means  
 201 of SMOS SSS to analyze the goodness of each reanalysis performance. Cell-to-cell dif-  
 202 ferences between remotely sensed observations and model-based outputs of SSS data sets  
 203 were calculated within the BG region to search for recurrent mismatch regions over the  
 204 time period.

#### 205 3.3 Estimation of Freshwater Release from Sea Ice Melting

206 The volume of freshwater ( $V_{fw}$ ) released into the ocean from sea ice melting within  
 207 a given region can be estimated by:

$$V_{fw} = \sum_{i=1}^N \alpha_i a_i h_i \frac{\rho_{ice}}{\rho_{fw}}, \quad (2)$$

208 where  $N$  refers to the number of grid cells inside the region,  $\alpha$  represents the grid-cell  
 209 SIC/100,  $a_i$  is the grid-cell area, and  $h$  is the melted sea ice thickness. For the sea ice  
 210 density,  $\rho_{ice}$ , and freshwater density,  $\rho_{fw}$ , we took the values of  $900 \text{ kg m}^{-3}$  (Timco &  
 211 Frederking, 1996) and  $1000 \text{ kg m}^{-3}$  (Tanaka et al., 2001), respectively. We calculated  
 212 the September budget of  $V_{fw}$  released over the BG region. To achieve this, we defined  
 213 September 1 as the starting point and the day of maximum sea ice retreat as the end-  
 214 point. Subsequently, we compared and quantified the contribution of September's sea  
 215 ice melting to the in situ FWC reported by Proshutinsky et al. (2019).

#### 216 3.4 Localization and Characterization of Meltwater Lenses

217 We analyzed the formation of MWLs every September during our study period (2011-  
 218 2019), because the ocean surface in the BG has the lowest sea ice cover in September.  
 219 As sea surface freshening would be expected after sea ice melting, we computed the num-  
 220 ber of days that each grid cell was covered by sea ice, considering OSISAF SIC > 10%  
 221 as a threshold. Using the number of iced days in each grid cell, we were able to identify  
 222 potential areas influenced by sea ice melting. For each grid cell to be considered as part  
 223 of a MWL, we applied two criteria: 1) the number of days covered by sea ice (SIC > 10%)  
 224 must range between 2 to 29 days, i.e. during September at least two days have been ice

covered; and 2) monthly mean values of SSS must be less or equal than 25 psu to ensure the presence of sea-ice meltwaters (Supply et al., 2022). Once the MWLs were delimited, we calculated their area, seawater properties, and the volume of freshwater released from sea ice melting (see Section 3.3). We also evaluated the SSS-SST properties of two large MWLs detected in September 2011 and 2016, as well as the daily SSS and density evolution over a MWL-crossing transect with constant latitude. We analyzed the wind stress and sea ice velocity patterns to search for drivers on the sea surface freshening during sea ice melting and sea surface salinification when sea ice forms.

### 3.5 Freezing temperature of Seawater

As MWLs form as a result of sea ice melting, it is anticipated that the SST within MWLs might closely approximate the freezing point, particularly during the initial stages of sea ice melting. The freezing temperature of seawater can be conceptually represented as a linear function influenced by both salinity and pressure (Holland & Jenkins, 1999):

$$T_f = \beta S + \kappa + \lambda P, \quad (3)$$

where  $\beta = -5.73 \times 10^{-2} \text{ }^\circ\text{C/psu}$  and  $\lambda = -7.61 \times 10^{-2} \text{ }^\circ\text{C/MPa}$  are the proportionality constants for salinity ( $S$ ) and pressure ( $P$ ), and  $\kappa = 8.32 \times 10^{-2} \text{ }^\circ\text{C}$  is the intercept. For this computation, and given the small variability range in comparison with the other two variables, we assumed the standard atmospheric pressure of 0.1 MPa at the SL.

## 4 Results and Discussion

### 4.1 Sea Ice Area and Sea Surface Salinity Relationship

The SIA north of  $65^\circ\text{N}$  (Fig. 2a) is annually cyclic, reaching its maximum extent in March and its minimum in September, with a decreasing trend of  $-6.2 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$  during the study period. In our estimations, maxima SIA varies from  $\sim 8.5$  to  $9.5 \times 10^6 \text{ km}^2$ , and minima varies from  $\sim 3$  to  $4 \times 10^6 \text{ km}^2$ . Since our study area is confined to latitudes above  $65^\circ\text{N}$ , substantial portions of the ocean susceptible to winter sea ice coverage -including the Okhotsk and Bering seas, the Gulf of Alaska, Hudson Bay, and the Labrador Sea- are not included in our estimations. Consequently, our maximum SIA estimates fall below those reported for the entire Northern Hemisphere (Lavergne et al., 2023). However, our minimum estimates align well with the reported SIA index (Lavergne et al., 2023), as sea ice coverage during summer is restricted to very high latitudes. The record low SIA, occurring in 2012 has been recently attributed to a La Niña-driven sea surface warming of the Arctic Pacific sector (Jeong et al., 2022) and is coincident with the anomalously warm stagnant air that contributed to the record-high melt over the Greenland Ice Sheet (GrIS) in 2012 (Nghiem et al., 2012). The monthly average SSS within the observable Arctic region (Fig. 2a) shows a strong synchrony and an identical annual cycle with the sea ice cover. Monthly means of horizontally-averaged SSS vary from  $\sim 31$  psu in September, marking the conclusion of the melt season, to  $\sim 35$  psu in March, coinciding with peak sea ice coverage. As observed for SIA, the record-low SSS recorded during the study period, approximately 30 psu, took place in September 2012, likely attributable to the increased freshwater released from sea ice and GrIS melting (Tedesco et al., 2013). The saltiest September occurred in 2013, with SSS of around 32 psu, aligning with the highest SIA observed in September throughout the study period. The SSS time series show a negligible decreasing trend of  $-0.003 \text{ psu yr}^{-1}$ . While the observable ocean for SMOS SSS retrieval fluctuates in tandem with sea ice cover, both SIA and SSS exhibit a strong correlation (Fig. 2b). A possible explanation of such a good fitting between both variables ( $R^2 = 0.96$ ) is that the observed sea surface is smaller and southern when sea ice cover expands, leaving only the saltier surface waters of the Norwegian and Barents Seas to be measurable from SMOS. On the other hand, a larger ocean surface is measurable when sea ice retreats, and the fresher SSS retrieved could reveal the

274 potential capability of SMOS in detecting the sea ice melt footprint, as it has been re-  
 275 cently reported in Supply et al. (2022).

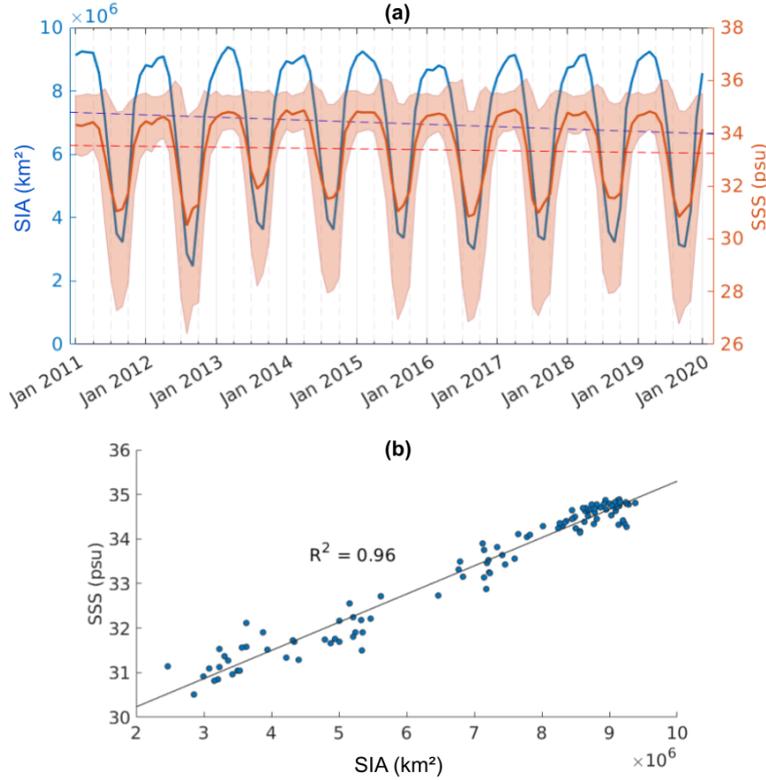


Figure 2: a) Time series of Arctic ( $>65^{\circ}\text{N}$ ) monthly means of sea ice area (solid blue line) and sea surface salinity (solid orange line). The shadow area shows the standard deviation of SSS and the dashed lines are the linear trends of SIA (blue) and SSS (orange) over the study period. b) Correlation between sea ice cover and SSS.

276 The SSS and SIA time evolution at the BG scale is shown in Fig. 3. As described  
 277 above for the Arctic, SIA in the BG also follows a seasonal pattern, accounting for around  
 278 a tenth of the Arctic SIA. The BG is entirely covered by sea ice (SIA around  $9 \times 10^5$   
 279  $\text{km}^2$ ) from November to May throughout the entire study period, leading to data gaps  
 280 in SMOS SSS. Minimum SIA takes place in September and ranges from less than  $10^5$   
 281  $\text{km}^2$  in 2012 to approximately  $5.5 \times 10^5 \text{ km}^2$  in 2013. Monthly means of SSS from June  
 282 to October do not exhibit a clear pattern, varying from 23 to 29 psu. Relative to 2011,  
 283 the annual mean SIA values have retreated around 1% in the BG and 0.7% in the Arctic  
 284 up to 2019. The lowest SIA record of 2012 is contributing to flattening the decreasing  
 285 trend observed in both the Arctic and the BG from 2011 to 2019 (Figs. 2a and 3a).  
 286 Regarding the SSS trends, having 2012 as the freshest SSS year at the beginning of the  
 287 time series may attenuate the observed decline in Arctic SSS and enhance the upward  
 288 trend in the BG SSS. Moreover, the positive trends observed in the BG for the SSS are  
 289 also contributing to relax the slope of the SSS negative trend observed in the Arctic.

290 Examining the SSS-SIA relationship in the BG (Fig. 3b), we observe that, in general,  
 291 a decreasing trend in SIA ( $-0.8 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ ) does not result in fresher sea  
 292 surface waters; instead, it leads to a salinification trend of  $0.01 \text{ psu yr}^{-1}$  (Fig. 3a). Hence,  
 293 it seems that the sea ice retreat in the BG may not necessarily be accompanied by sea  
 294 surface freshening. Nonetheless, we suspect that the sea surface conditions in the BG,

295 observable by SMOS SSS from June to October, experience distinct regimes depending  
 296 on the phase of the melting season. We propose that during the early stages of the melt  
 297 season (June-July), sea ice melting induces sea surface freshening, while sea ice forma-  
 298 tion results in sea surface salinification in the late season (September-October)(see Fig.  
 299 S1). However, in the middle of the melt season, a transient period is expected, where SIA  
 300 and SSS may not be tightly synchronized due to other processes (apart from sea ice melt-  
 301 ing/formation) exerting a more significant influence on sea surface properties. As described  
 302 in Section 1, the BG is a dynamically complex region, with sea ice distribution highly  
 303 dependent on atmospheric forcing (Asplin et al., 2009; Petty et al., 2016; Wang, Wek-  
 304 erle, Danilov, Koldunov, et al., 2018) and sea surface properties subjected to inflow rates  
 305 of Pacific waters through the Bering Strait (Hu et al., 2019; Timmermans & Toole, 2023),  
 306 which in turn vary periodically with ENSO (Jeong et al., 2022). These and other fac-  
 307 tors, such as cloud cover, rain/snow fall, riverine inflows, ocean mesoscale eddies, upwellings,  
 308 or brine rejection might play a non-negligible role on the sea surface properties and the  
 309 sea ice distribution in the BG (Timmermans & Toole, 2023). Moreover, different free-  
 310 of-ice regions of the BG become observable each year, likely resulting in capturing dif-  
 311 ferent water masses (e.g. from sea ice melting, the Alaskan Coastal Waters or the Macken-  
 312 zie River influence).

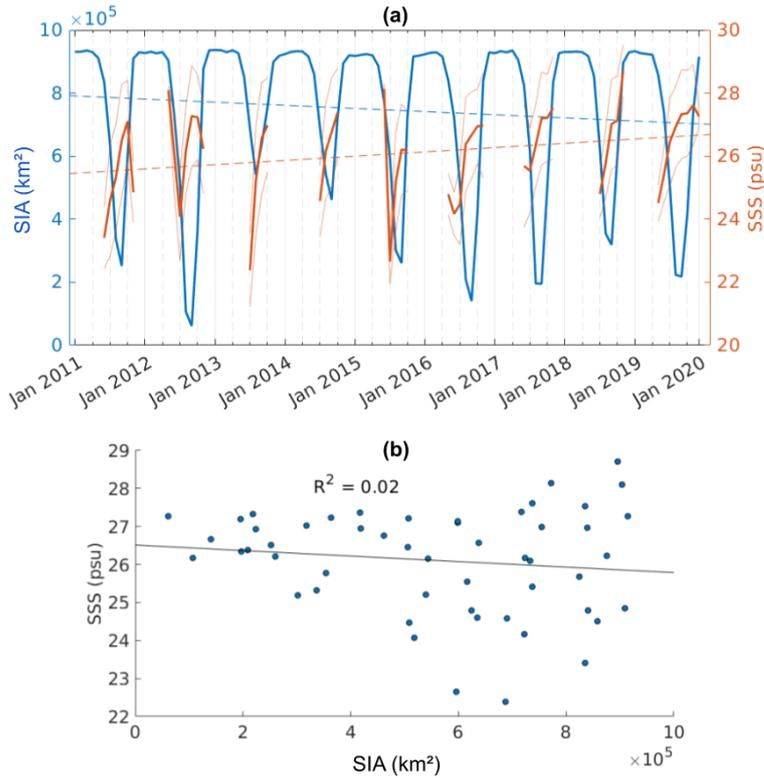


Figure 3: a) Time series of BG's monthly means of sea ice area (solid blue line) and sea surface salinity (solid orange line). The light orange lines shows the standard deviation of SSS and the dashed lines are the linear trends of SIA (blue) and SSS (orange) over the study period. b) Correlation between SIA and SSS in the BG.

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## 4.2 Reanalysis Performance vs. Remote Observations in the BG

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Model reanalysis outputs can serve to fill the spatial and temporal gaps in remote observations, extending their applicability even to ocean properties beneath the ice. They are very useful to get a more comprehensive picture of the sea ice-SSS relationship. September is the month with the lowest sea ice cover in the BG region (Fig. 3a), so a larger number of satellite SSS observations can be retrieved. Therefore, for all Septembers from 2011 to 2019, we first compare the SSS retrieved from SMOS against that solved by two model reanalysis: TOPAZ4b, which assimilates SMOS SSS data (Xie et al., 2023), and ORAS5, which has been reported as the best SSS performer in the BG (Hall et al., 2021).

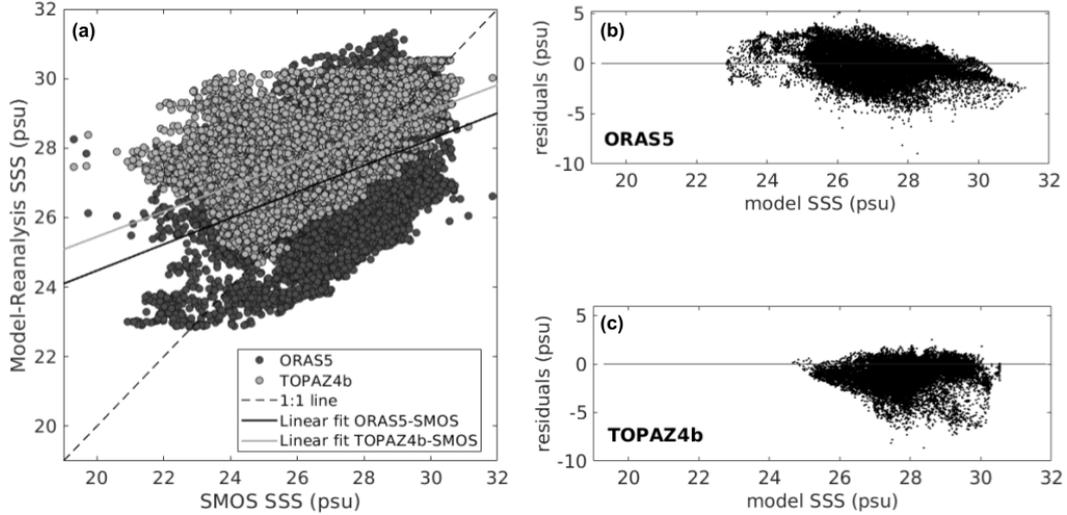


Figure 4: a) Co-located observed (SMOS) versus modeled (ORAS5 and TOPAZ4b) monthly means of SSS. b) and c) SSS residuals (SMOS-Model) against modeled ORAS5 and TOPAZ4b SSS, respectively. To get the correct view of the model performance, the x-axis limits in b) and c) are those of SMOS-observed SSS.

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Both ORAS5 and TOPAZ4b models exhibit significant deviations from observed SMOS SSS, failing to capture the freshest waters detected by the satellite (monthly mean SSS of 19.3 psu) (Fig. 4a). The correlation slopes for observed-modeled SSS are approximately 0.37 in both models, with intercepts of 16 and 18 psu, and  $R^2$  values of 0.2 and 0.4 for ORAS5 and TOPAZ4b, respectively, indicating a poor agreement between observed and modeled SSS. The difference in the correlation coefficient between the two models is attributed to the distribution of their outputs. Specifically, ORAS5 displays a wide range of residuals (Fig. 4b), ranging from +5 to -9 psu, with mean SSS of  $27.1 \pm 1.3$  psu, and values spanning 22.8 to 31.3 psu. In contrast, TOPAZ4b (Fig. 4c) exhibits a more restricted range of positive residuals (approximately +2 psu) and a similar range for negative values. However, TOPAZ4b provides mean SSS of  $28.0 \pm 0.9$  psu, and values ranging from 24.7 to 30.5 psu, which show larger constrictions in the freshest waters compared to ORAS5. When comparing minimum salinity, ORAS5 (TOPAZ4b) reaches approximately 23 (25) psu, while SMOS measures near 19 psu. However, these minima are not synchronized. Notably, the most significant discrepancies between SMOS and modeled SSS, reaching up to -9 psu (Fig. 4b, c), precisely align with SMOS recording the minimum salinity, while the models indicate  $\sim 28$  psu (see Fig. 4a).

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The September surface distribution of SSS and its residuals (SMOS-Model) is shown in Fig. 5. For a more comprehensive analysis and to identify sea ice as a potential source

341 of freshwater inducing SMOS-Model mismatch, the number of days each pixel has been  
342 covered by sea ice is also included in Fig. 5a. Our results suggest a negative bias (model  
343 being saltier than observations) close to the coast in the two models (see also Fig. S2),  
344 as also shown in Hall et al. (2021). The fresher areas detected by SMOS SSS offshore  
345 are likely induced by the Mackenzie River plume (Juul-Pedersen et al., 2008; Pickart,  
346 2004; Doxaran et al., 2015; Nghiem et al., 2014), as previously reported for the Yukon  
347 River’s offshore waters (Vazquez-Cuervo et al., 2021). Considering that the SSS resid-  
348 uals’ distribution is masked by SMOS data (Fig. 5b), the absence of data (blanked re-  
349 gions in the northern and isolated areas) indicates that the ocean is covered by sea ice  
350 (see Fig. 5a). Thus, looking at Fig. 5c, negative bias are also found close to some ice edges  
351 and around small iced areas. Previous studies have documented enhancements in ocean  
352 salinity predictions with the incorporation of SMOS SSS assimilation into TOPAZ4b (Xie  
353 et al., 2023). Nevertheless, our findings suggest that the assimilation process falls short  
354 in accurately capturing the freshest SSS, as depicted in Figs. 4 and 5c. Despite being  
355 previously identified as the best performer in comparison to in situ SSS observations (Hall  
356 et al., 2021), our comparative analysis reveals that ORAS5 neither aligns with SMOS  
357 SSS in the freshest areas (Fig. S2). The challenge of aligning model solutions with ob-  
358 servations at the sea surface arises from the fact that the sea surface serves as a bound-  
359 ary within ocean models’ domains. Furthermore, since other variables, such as SST or  
360 SL, must be solved by the model in close proximity to the sea surface boundary, impos-  
361 ing a weak tolerance in SSS assimilation may result in divergences between model-derived  
362 and observed SSS values.

363 In summary, for all Septembers from 2011 to 2019 (see Fig. S3), SMOS SSS de-  
364 tects fresher patches of sea surface waters in two main areas: near the sea-ice edge, where  
365 sea ice was present for a limited number of days (monthly SSS of about 19 to 25 psu),  
366 and the influence area of the Mackenzie River discharge (monthly SSS around 26 psu).  
367 Analyzing the SMOS SSS distribution in the BG and whether a given grid cell was cov-  
368 ered by sea ice that eventually melted (see Fig. 5, and Movie S1 as an example), our re-  
369 sults suggest that models poorly represent river and sea-ice-melt waters, whereas SMOS  
370 demonstrates accurate representation. This is particularly noteworthy given the impact  
371 of the model limitations on estimating the FWC in the BG, which lead to its underes-  
372 timation (Umbert et al., 2023).

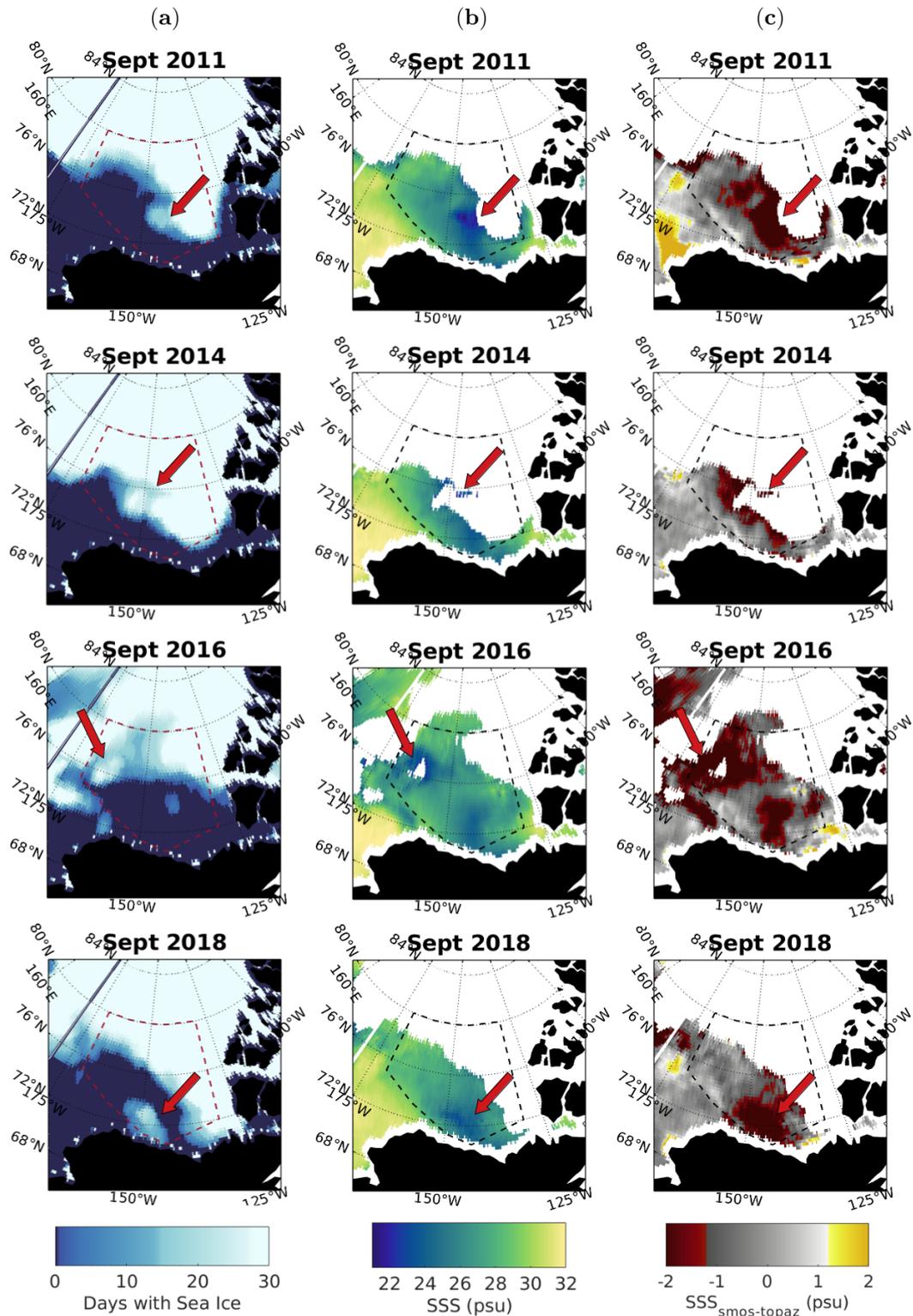


Figure 5: Spatial distribution of a) number of days covered by sea ice (SIC > 10%), b) SMOS SSS and c) SSS residuals: observed (SMOS) minus modeled SSS (TOPAZ4b). Dashed line delimits the Beaufort Gyre region. The colorbar in c) has been truncated (see full range of values in Fig. 4). The red arrows point the locations where SMOS SSS retrieves information of sea ice meltwaters.

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### 4.3 Estimations of Sea Ice Meltwater in the BG

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Sea ice meltwater constitutes a significant component of the FWC in the BG. Utilizing Eqns. 1 and 2, we computed the melted SIA and the corresponding  $V_{fw}$  released into the ocean for all Septembers. Our findings reveal interannual fluctuations in both the extent and thickness of melted sea ice, consequently leading to variations in the released  $V_{fw}$ , ranging from 0 to  $\sim 120 \text{ km}^3$  (Fig. 6). Minimum records are given in 2013, 2012 and 2017. The minima observed in 2012 align with high Arctic temperatures in the preceding autumn-winter (2011-2012), impeding the formation and thickening of sea ice (Overland et al., 2017; Perovich et al., 2017). Moreover, the sustained high atmospheric temperatures in early spring of 2012 (Jeong et al., 2022) led to an earlier onset of sea ice melting compared to a typical year, resulting in a reduced sea ice cover to be melted at the beginning of September (see Movie S2 in Supp. Information). The 2013 minimum, however, is attributed to a distinct cause: an Arctic cold event. This cold event resulted in a September characterized by a sea ice freshwater budget of  $0 \text{ km}^3$ , indicating no melting but sea ice formation (Movie S3). In 2014, increased SST anomalies in the North Pacific triggered a stage of Arctic warming (Overland et al., 2018). This warming, in turn, facilitated melting of such extensive and thick sea ice inherited from 2013. This phenomenon is reflected in our results as the most significant release of sea-ice meltwater in 2014 (Fig. 6c).

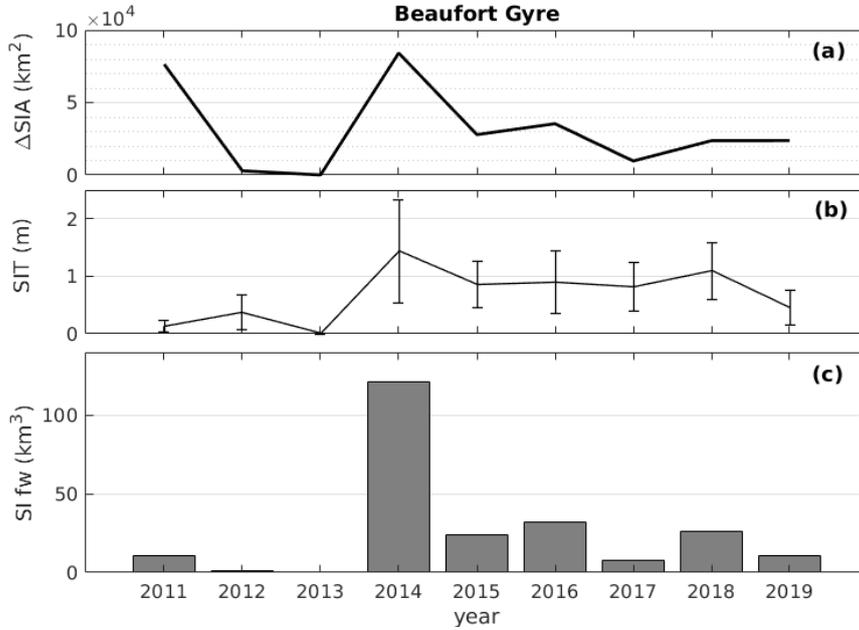


Figure 6: September sea ice budget from 2011 to 2019 in the Beaufort Gyre: a) melted sea-ice area, b) mean sea ice thickness within the melted sea-ice area, and c) freshwater volume released from sea ice melting (Eqn. 2).

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Our estimations indicate that the  $V_{fw}$  released into the ocean from sea ice melting during September in the BG could contribute up to  $\sim 30\%$  of the average annual rate of freshwater accumulation in the BG (Proshutinsky et al., 2019). However, this sea ice meltwater is partially incorporated in the water column, partially advected out of the region by wind-driven ocean currents, and partially susceptible to be refrozen. Recent model simulations suggest that sea ice serves as a minor freshwater source of the FW accumulation in the BG (Wang et al., 2019). Thus, while we cannot definitively deter-

399 mine the net contribution of September’s sea ice meltwater to either the total or the ac-  
 400 cumulation rate of FWC in the BG, we can analyze its distribution at the sea surface  
 401 using SMOS SSS.

402 **4.4 Monitoring Meltwater Lenses using SMOS SSS from 2011 to 2019**

403 We exploit the SMOS capability to detect MWLs from sea ice melting (Supply et  
 404 al., 2022) along with OSTIA SST and ORAS5 wind stress to investigate about mixing  
 405 drivers and residence time of sea-ice meltwaters at the sea surface. MWLs have been de-  
 406 fined following the methods in 3.4 and are shown in Fig. 7 contoured in cyan. The ex-  
 407 tent and distribution of MWLs exhibit inter annual variability. In 2012, 2017, and 2019,  
 408 the MWLs are notably scarce in number and extent, whereas the most substantial MWLs  
 409 are identified in 2011, 2015, and 2016. MWLs are usually found attached or close to the  
 410 ice edge, except for September 2018, when an isolated MWL is found at the southern-  
 411 most location of the BG.

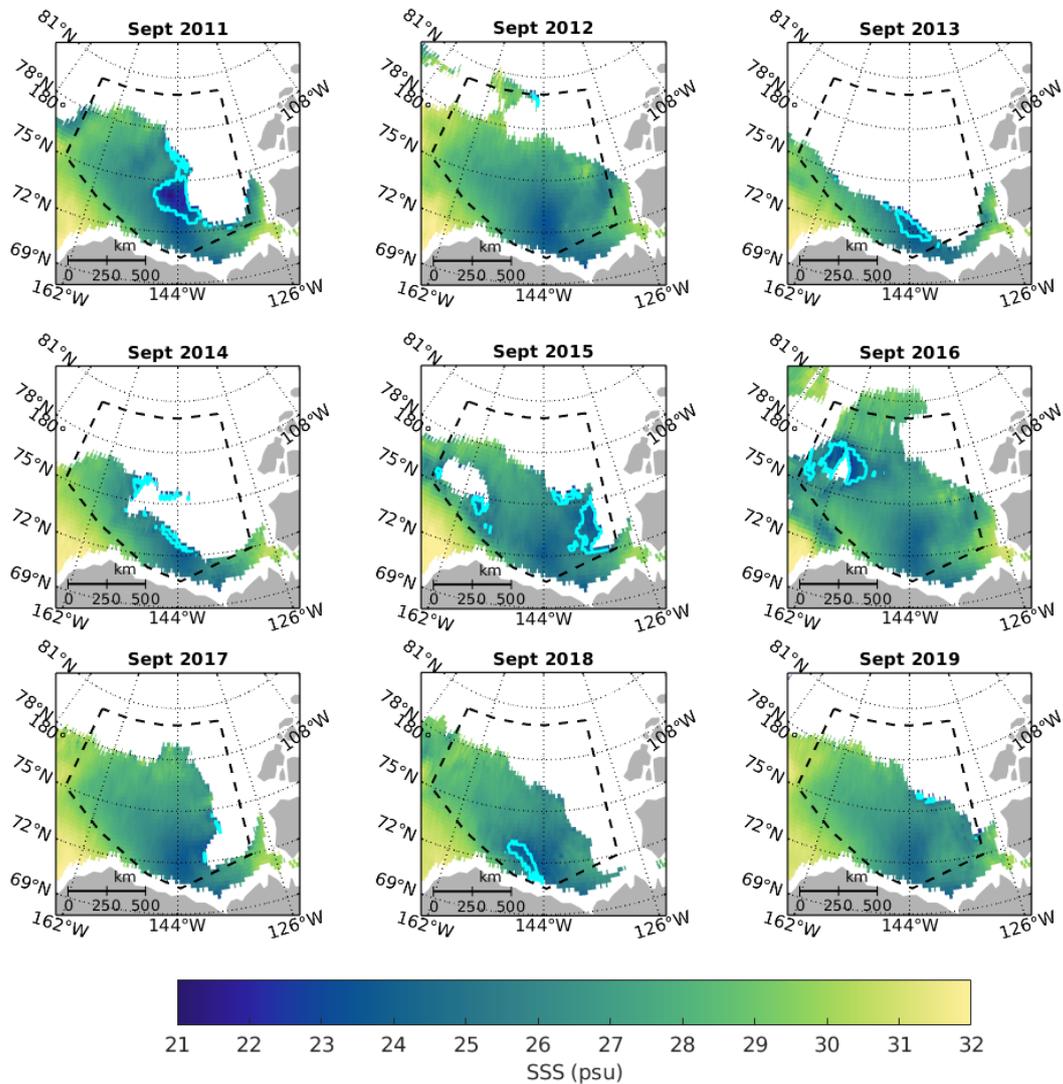


Figure 7: Location of the meltwater lenses (contoured in cyan) over September means of SMOS SSS from 2011 to 2019. The dashed black line delimits the BG region.

Some MWLs' properties are shown in Fig. 8. These properties include: SSS, area, SIT and the  $V_{fw}$  released from SI melting. Horizontal monthly means of SSS inside the MWLs are quite stable at  $\sim 24$  psu, with minimum and maximum grid-cell values ranging from 16 psu (in 2011) to 27 psu (in 2015), respectively (Fig. 8a). Given the methods used to locate the MWLs (Section 3.4), the primary source of freshwater would be the sea ice melting. The larger the meltwater lens, the wider the range of SSS variability (Fig. 8a, b), likely reflecting increased mixing with surrounding waters at the lens edges.

The total area covered by these MWLs also shows large variability during the study period (Fig. 8b). The MWL area shows minima values of  $< 10^4$  km<sup>2</sup> in 2012 and 2017, aligning with those minima observed in the BG (Fig. 6). However, the largest meltwater lenses, with an area of  $> 6 \times 10^4$  km<sup>2</sup>, take place in 2011 and 2015, which differs from the years of the largest sea ice extent in the BG. Horizontally averaged monthly means of SIT ranges from 0.1 to 1 m, with most of the years being  $\leq 0.5$  m (Fig. 6c). The  $V_{fw}$  released from sea ice melting (Section 3.3) within the meltwater lenses varies from  $\sim 0.1$  km<sup>3</sup> to  $\sim 3$  km<sup>3</sup> (Fig. 8d), which represents up to 10% of the estimations for the BG (Fig. 6c). The years of maximum meltwater release are 2011, 2016, and 2014, coincident with either larger MWL areas, thicker SI, or both.

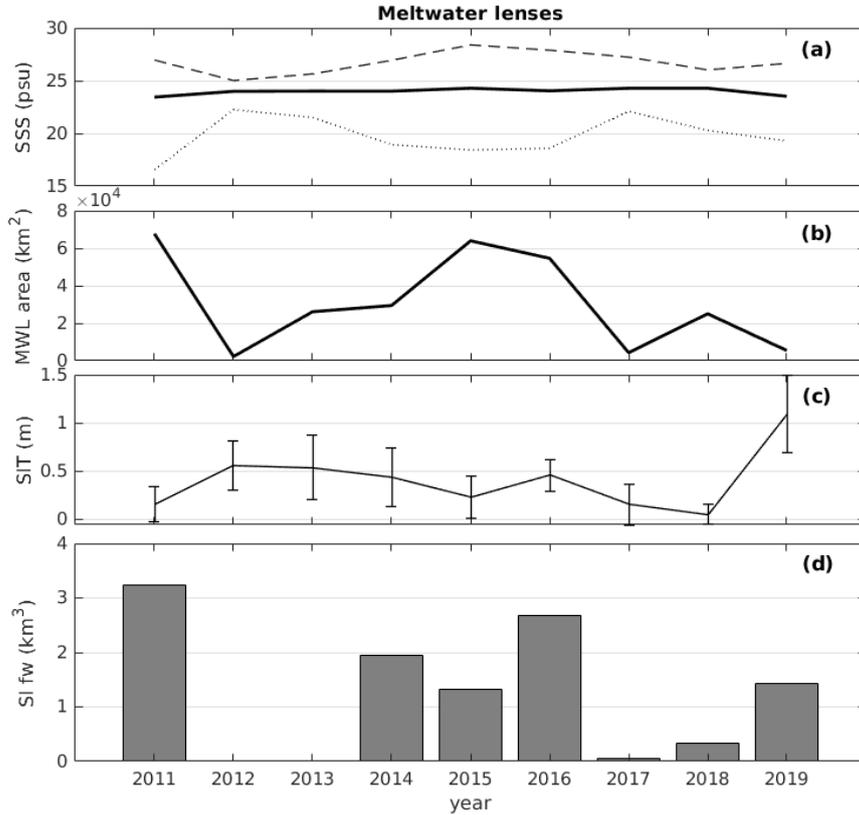


Figure 8: Characteristics of the meltwater lenses detected by SMOS in every September from 2011 to 2019: a) mean (solid dark line), minimum (dotted gray line) and maximum (dashed gray line) sea surface salinity; b) area; c) mean ORAS5 sea ice thickness ( $\pm 1$  Std bars); and d) Freshwater volume released from sea ice melting.

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#### 4.5 Studying Large Meltwater Lenses Detected in 2011 and 2016

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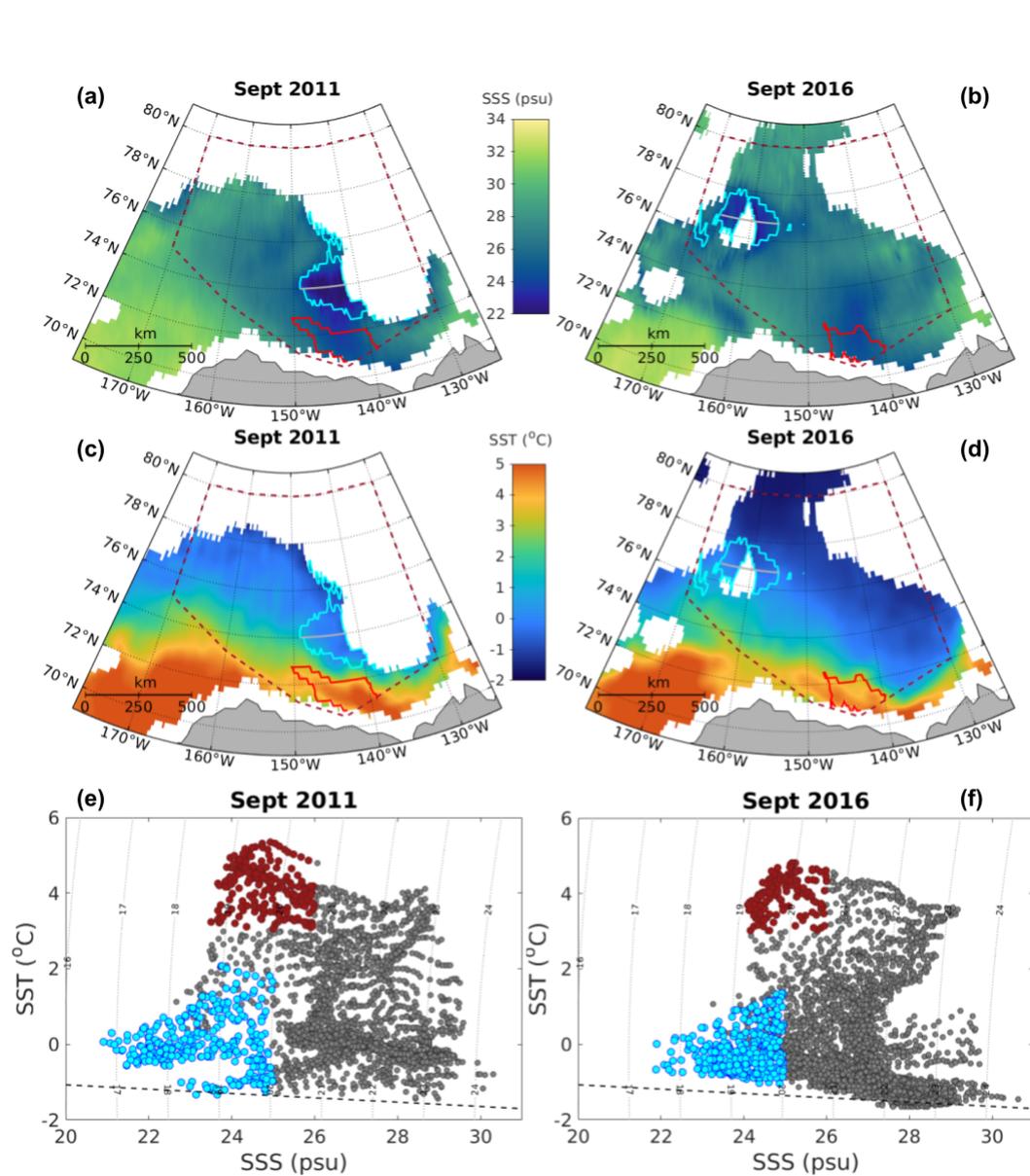


Figure 9: September monthly means of a, b) SMOS sea surface salinity; and c, d) OSTIA sea surface temperature in the BG, during September 2011. Dashed red polygon delimits the BG region, solid cyan line is the MWL perimeter, solid gray line indicates the transect used in Fig. 10, and solid red line delimits the river-influence area. e, f) Monthly SST vs SSS properties within the BG (gray dots), inside the MWL (light blue dots), and within the river-influence area (red dots). Dashed line indicates the freezing temperature for any given salinity according to Eqn. (3). Panels to the left (right) refer to 2011 (2016).

In Fig. 9 the hydrographic properties of large MWLs detected in 2011 and 2016 are shown. In September 2011, the MWL was localized in the southeast quadrant of the BG, while in September 2016, it was situated in the northwest quadrant (contoured in cyan in Fig. 9a-d). The freshest waters inside the MWLs (Fig. 9a, b) take lower SSS values than those observed in the whole BG region, with horizontally-averaged monthly mean SSS ranging from 21 to 25 psu. A different fresh patch (24 to 26 psu) south of the BG is detected (contoured in red), between 145°W and 150°W (contoured in red), which, due to the temperate SST of 3 to 5 °C (Fig. 9c, d), can be attributed to the influence of the Mackenzie River (Doxaran et al., 2015). In the SST-SSS diagram (Fig. 9e, f) the differentiation of these two water masses (sea-ice meltwater and riverine waters) becomes clear, with the lowest salinity and near-freezing SST properties corresponding to the MWL's water mass and the low salinity but relatively warm properties corresponding to the riverine waters (Nghiem et al., 2014). Looking at the SST-SSS diagram along with the SST spatial distribution (Fig. 9e, f and 9c, d), we see that the lowest and near-freezing temperatures of the sea surface waters in the BG are those spreading along the entire sea ice margin. Nonetheless, looking at the SSS distribution (Fig. 9a, b), we observe water salinification on large areas of the sea ice margin, so we can ensure that those sea-ice marginal waters have undergone some mixing, which is not reflected in SST. Therefore, SSS seems to be a better option than SST when trying to localize MWLs and analyze the time evolution of mixing/dilution processes of the meltwaters released from sea ice melting).

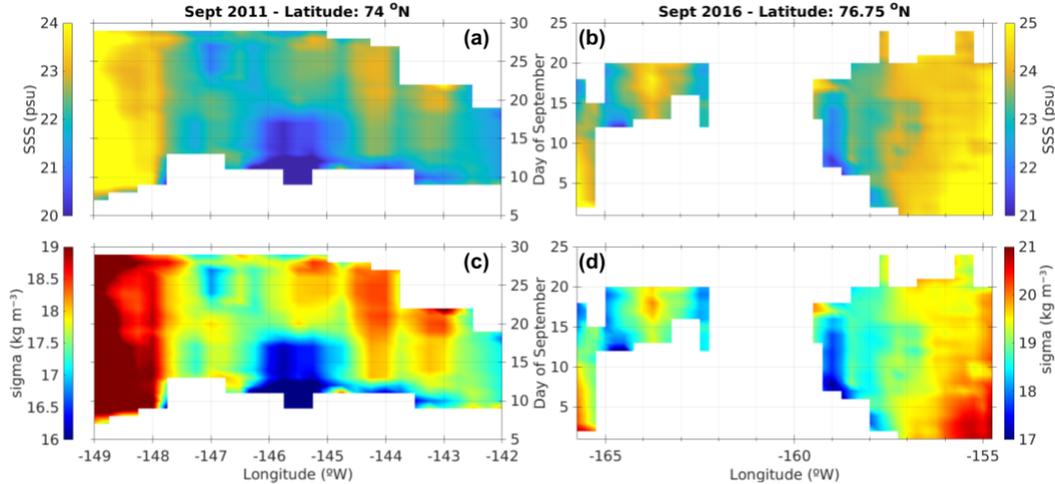


Figure 10: September Hovmöller diagrams of sea surface properties along transects of constant latitude inside the MWLs (see transects in Fig. 9): a, b) salinity from SMOS, and c, d) sigma calculated from SMOS SSS and OSTIA SST. Panels to the left (right) refer to 2011 (2016). Note that the colorbar limits differ between years and blanked areas indicate sea ice presence.

The daily evolution of sea surface salinity and sigma (i.e.  $\rho_{sw} - 1000 \text{ kg m}^{-3}$ ) within the MWL during September of 2011 and 2016 are shown in Fig. 10. It is noteworthy the strong correlation between density and salinity, denoting the minimal influence of temperature on density within these cold waters. The plots reveal different characteristics between both years. Concerning sea surface freshening, the imprint of sea ice melting in September 2011 (see Fig. 10a, b) manifested a conspicuous presence, characterized by a substantial expanse of comparatively fresh and low-density water (SSS  $\sim 21$  psu and sigma  $\sim 16.5 \text{ kg/m}^3$ ). This expanse persisted at the core of the meltwater lens for a duration of up to 10 days. This prolonged presence of low-mixing conditions within this region is indicative of the convergent regime associated with anticyclonic atmospheric

466 forcing (refer to Fig. 11a, c). Conversely, in the year 2016 (Fig. 10c, d), a significant sea  
467 ice mass continually occupied the central region of the meltwater lens throughout Septem-  
468 ber. The influence of sea ice meltwater was comparatively marginal, likely linked to the  
469 divergent dynamics resulting from cyclonic wind forcing (refer to Fig. 11b, d). The most  
470 extensive and freshest sector was located in the central-eastern portion (approximately  
471  $159^{\circ}\text{W}$ ). This sector persisted for a period of up to one week, which, due to the prevail-  
472 ing southwest wind forcing and the constant presence of sea ice in close proximity, can  
473 be attributed to a sustained source of sea ice meltwaters. Additionally, an area of fresh  
474 water was observed near  $165^{\circ}\text{W}$ , emerging on September 12, after the sea ice melting.  
475 This area of freshwater persisted until the formation of sea ice (water refreezing) on Septem-  
476 ber 20, likely denoting low-mixing conditions during that week.

477 Concerning the saltier areas, in September 2011, the majority of the saltiest and  
478 densest waters within the MWL (SSS  $\sim 24$  psu and sigma  $\sim 19$   $\text{kg m}^{-3}$ ), occupied the  
479 westernmost region of the MWL (Fig. 10a, b). This area was the farthest and isolated  
480 from the sea ice pack influence, being in permanent contact with surrounding (saltier and  
481 warmer) waters. In the easternmost sector, specifically at  $143$ ,  $144$  and  $145^{\circ}\text{W}$ , elevated  
482 salinity and density (SSS  $\sim 24$  psu and sigma  $\sim 19$   $\text{kg m}^{-3}$ ) were detected one to two weeks  
483 before sea ice formation. Such signal of increased salinity and density became even stronger  
484 on the day before sea ice formation. Given the prevailing northeast winds in that area  
485 (see Fig. 11a), it could be anticipated that some of the saltier waters, generated follow-  
486 ing brine rejection, might have been advected southwestward from the ice pack vicini-  
487 ty. Although denser and saltier water typically tends to sink, the influence of wind stress  
488 could counteract this tendency by inducing upwelling. This phenomenon also has im-  
489 plications for our understanding of brine rejection as detected by SMOS. Since Martínez  
490 et al. (2022) showed that sea ice presence might induce lower SSS values, our observa-  
491 tions lead us to conclude that the observed increase in SSS is not a consequence of sea  
492 ice contamination but rather originates from saline water sources. In 2016, the eastern-  
493 most region of the MWL predominantly contained the densest and saltiest waters, char-  
494 acterized by SSS  $\sim 25$  psu and sigma  $\sim 21$   $\text{kg m}^{-3}$ . Notably, a localized surge in salin-  
495 ity and density was recorded at around  $159.5^{\circ}\text{W}$  on September 17, just before the on-  
496 set of sea ice formation. As described above for 2011, this observed salinity increase could  
497 potentially be associated with brine rejection. However, validation through in situ mea-  
498 surements or high-resolution model outputs would be necessary to confirm this hypoth-  
499 esis.

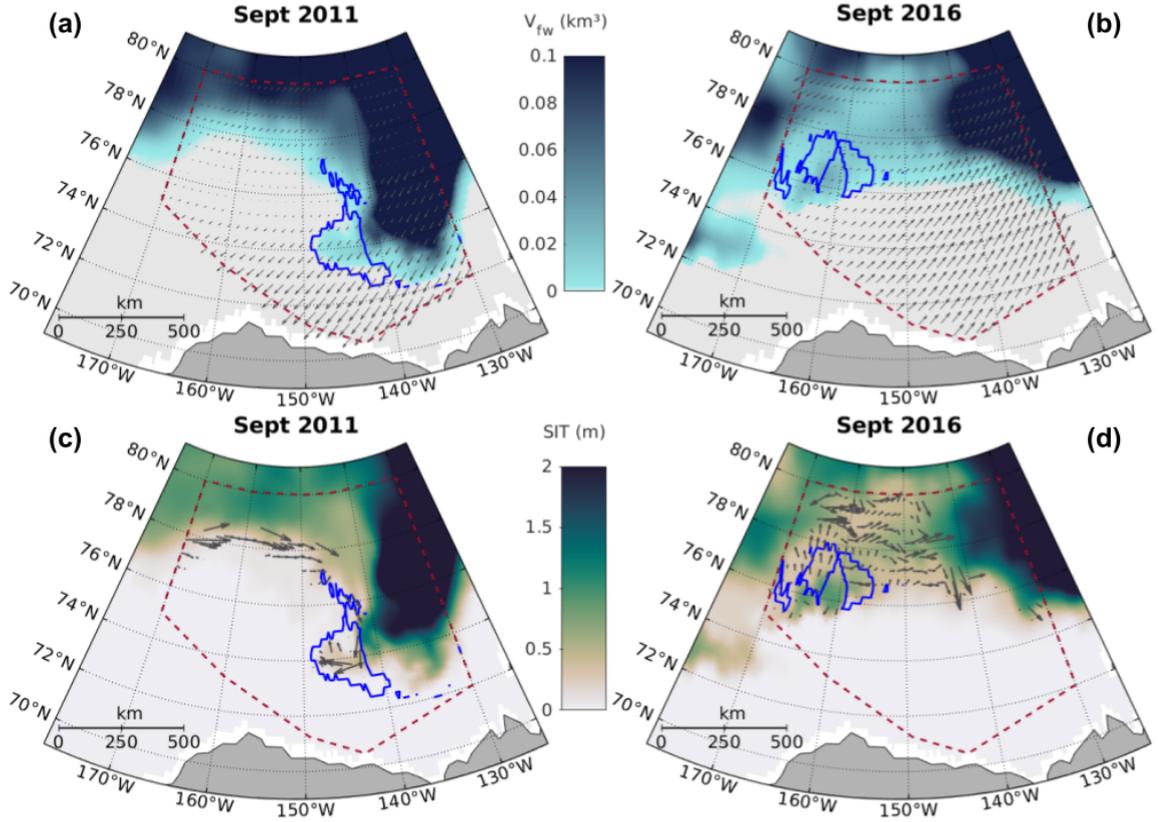


Figure 11: a, b) September monthly mean volume of solid freshwater at each grid cell and superimposed vectors of monthly wind stress. c, d) September monthly means of sea ice thickness, with sea ice velocity vectors on top of it. Dashed red polygon delimits the BG region and solid blue line is the MWL perimeter. Panels to the left (right) refer to 2011 (2016).

500 The monthly predominant wind maps over the BG reveal different patterns in September  
 501 ber 2011 and 2016 (Fig. 11a, b). September 2011 was characterized by an anticyclonic  
 502 regime associated with the high-pressure system over the BG, as reported in previous  
 503 studies (Serreze & Barrett, 2011; Timmermans & Marshall, 2020). Ice velocity maps in  
 504 September 2011 (Fig. 11c) show that a detached ice floe from the main pack experienced  
 505 convergent dynamics during the first half of the month, leading to the accumulation of  
 506 meltwater within the center of the MWL, with relatively low mixing, which was detected  
 507 by SMOS SSS. In contrast, during September 2016, dominant winds exhibited a cyclonic  
 508 pattern over the BG (Fig. 11b), resulting in a divergent sea ice movement within the MWL  
 509 (Fig. 11d). In Movie S4 of the *Sup. Info*, we can observe how at the beginning of September  
 510 2016, sea ice coverage was minimal, decreasing slightly until reaching the minimum  
 511 on September 5. Following that day, SIA started to rise in the northwest quadrant of  
 512 the BG. We speculate that the cyclonic wind pattern introduced cold north winds, po-  
 513 tentially promoting sea ice growth over the northwest quadrant of the BG (Fig. 11b).  
 514 Consequently, despite observing a larger area of ice-free ocean in September 2016 com-  
 515 pared to September 2011, both the melted SIA and the  $V_{fw}$  were smaller in September  
 516 2016 than in 2011 (Fig. 6a, c).

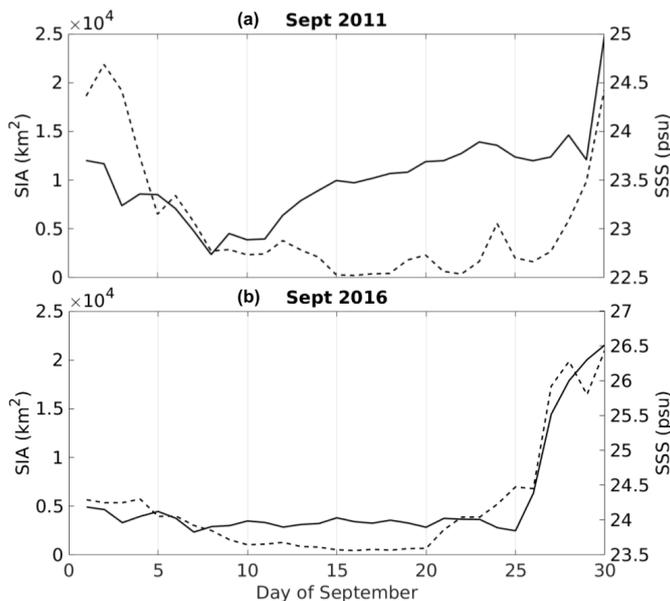


Figure 12: Daily evolution of sea ice area (SIA, dashed line) and mean sea surface salinity (SSS, solid line) inside the MWLs in a) 2011 and b) 2016 (see Figs. 9 and 11 to see the MWL region).

517 The daily evolution of SIA and SSS within the MWL is shown in Fig. 12. At the  
 518 beginning of September 2011, SIA exceeded  $2 \times 10^4 \text{ km}^2$ , and the average SSS was ap-  
 519 proximately 23.7 psu. The minimum salinity ( $\sim 22.7$  psu) occurred around September  
 520 7, while the minimum SIA ( $0 \text{ km}^2$  kilometers) was on September 16. Both variables reached  
 521 their maximum at the end of the month, with SSS around 25 psu and SIA approximately  
 522  $2 \times 10^4 \text{ km}^2$ . In September 2016, a piece of sea ice at the center of the MWL remained  
 523 unmelted, failing to strictly meet the criteria for inclusion in the MWL (refer to Section  
 524 3.4), therefore it was excluded from the SIA calculation. The behavior of SIA and SSS  
 525 during September 2016 was similar to that of 2011 but with different values: less ice and  
 526 higher salinity overall. At the beginning of the month, SSS was around 24.2 psu, and SIA  
 527 was  $0.5 \times 10^4 \text{ km}^2$ , with both variables starting to increase during the last third of the  
 528 month, reaching approximately 26.5 psu and  $2 \times 10^4 \text{ km}^2$ , respectively.

529 To conclude our investigation, we return to the analysis of the SSS-SIA relation-  
 530 ship at a local scale within the MWLs (Fig. 12). Our results reveal close synchrony in  
 531 the daily evolution of both variables throughout September in the two years. If sea ice  
 532 melts, the ocean surface reduces its salinity (this occurs roughly in the first ten days of  
 533 September). Conversely, if sea ice grows, the ocean surface becomes saltier (see Fig. 12  
 534 during the last third of the month). During the second third of the month, there is a tran-  
 535 sient state where the correlation in the daily evolution of SSS and SIA is not as tight.  
 536 During this transient state, when the ice-free area is at its maximum, water mixing in-  
 537 duced by winds or local circulation is more likely to have a pronounced impact on the  
 538 ocean surface, leading to increases in salinity. Additionally, the momentum associated  
 539 to this phenomena may temporarily inhibit sea ice formation (Roquet et al., 2022). There  
 540 seems to be a time lag between the response of the two variables: SSS appears to be more  
 541 reactive, while SIA requires a longer response time. Additionally, hysteresis associated  
 542 with phase changes in water could slow down the ice formation response compared to  
 543 SSS changes. This idea of a transient state is consistent with the outcomes presented in  
 544 Section 4.1. We can extend this concept to the BG by regarding it as a large MWL. In

545 this scenario, September could be viewed as the third period, corresponding to the sea  
546 ice formation stage. Consequently, both SIA and SSS are expected to increase and ex-  
547 hibit a positive correlation, aligning with our expectations and illustrated in Fig. S1.

## 548 5 Conclusions

549 In our temporal analysis spanning 2011 to 2019, utilizing OSISAF SIC and SMOS  
550 SSS data, we discovered a close synchronization and positive correlation between SIA  
551 and SSS at both large (Arctic region) and local (MWL) scales. However, on the regional  
552 scale of the BG, the temporal evolution of SIA and SSS diverged, likely due to prolonged  
553 ice coverage, and leading to significant space-time gaps in SSS data. The ice-free period  
554 is restricted to July to October, during which a complex interplay influenced by various  
555 freshwater sources occurs. SSS outputs from reanalysis models, namely ORAS5 and TOPAZ4b,  
556 were compared with SMOS SSS observations every September, revealing significant dis-  
557 crepancies. Notably, these models failed to accurately depict the freshening effects ob-  
558 served in SSS after sea ice melting, a phenomenon effectively captured by SMOS SSS.  
559 Our results suggest that sea ice melting in September may contribute up to 30% to the  
560 reported annual mean FWC accumulation within the Beaufort Gyre. Therefore, the model's  
561 inaccuracy could contribute to the previously reported mismatch between observational  
562 and model-based FWC estimations.

563 Exploiting the SMOS SSS capabilities on detecting sea surface freshening from sea  
564 ice melting, we identified MWL locations within the BG during September from 2011  
565 to 2019. MWLs exhibited annual variability, with notable scarcity in 2012, 2017, and 2019,  
566 contrasting with substantial presence in 2011, 2015, and 2016. These MWLs presented  
567 the freshest SSS within the BG, along with lower SST compared to areas influenced by  
568 the Mackenzie River plume. Daily SSS variations within MWLs not only indicated that  
569 SMOS SSS captures sea-ice meltwater but also suggested that it may capture events of  
570 brine rejection after sea ice formation. This discovery opens avenues for further stud-  
571 ies and the continuous monitoring of sea-ice-ocean interactions using SMOS SSS.

572 Wind patterns emerged as pivotal in mixing sea ice meltwater with surrounding  
573 waters and accumulating it at the surface through wind-driven convergent circulation.  
574 On a local scale within MWLs, the temporal evolution of SSS and SIA demonstrated a  
575 strong correlation during both stages of sea ice melting and sea ice formation. Transi-  
576 tional periods with reduced correlation were observed during the transition from sea ice  
577 melting to formation when ice-free area in the ocean is present, suggesting that drivers  
578 of water mixing might play a significant role in the SSS changes.

579 In summary, this research highlights the useful capabilities of SMOS SSS data in  
580 helping to unravel the intricate dynamics of sea ice melting, freshwater input, and sea  
581 surface salinity in the Arctic, which is especially valuable in the context of a changing  
582 climate.

## 583 Open Research Section

584 All data used in this study are freely available through different repositories. SMOS  
585 SSS data are freely distributed from the Barcelona Expert Center [https://doi.org/  
10.20350/digitalCSIC/12620](https://doi.org/10.20350/digitalCSIC/12620). SIC data were obtained from OSI-450 and OSI-430b prod-  
586 ucts at [https://doi.org/10.15770/EUM\\_SAF\\_OSI\\_0008](https://doi.org/10.15770/EUM_SAF_OSI_0008) and [https://doi.org/10.15770/  
EUM\\_SAF\\_OSI\\_NRT\\_2008](https://doi.org/10.15770/EUM_SAF_OSI_NRT_2008), respectively. Data set of OSTIA SST was downloaded through  
587 <https://doi.org/10.48670/moi-00165>. ORAS5 and TOPAZ 4b reanalysis data on SSS,  
588 SIT, wind stress and sea ice velocity can be downloaded from [https://doi.org/10.24381/  
589 cds.67e8eeb7](https://doi.org/10.24381/cds.67e8eeb7) and <https://doi.org/10.48670/moi-00007>, respectively.  
590  
591

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# Supporting Information for "Sea Ice Meltwater in the Beaufort Gyre: A Comprehensive Analysis Using SMOS SSS Data from 2011 to 2019"

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## Contents of this file

1. Figures S1 to S3

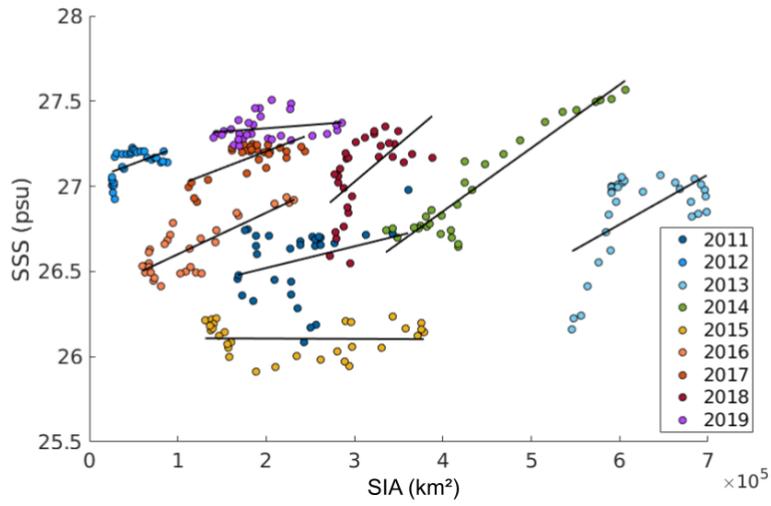
## Additional Supporting Information (Files uploaded separately)

1. Captions for Movies S1 to S4

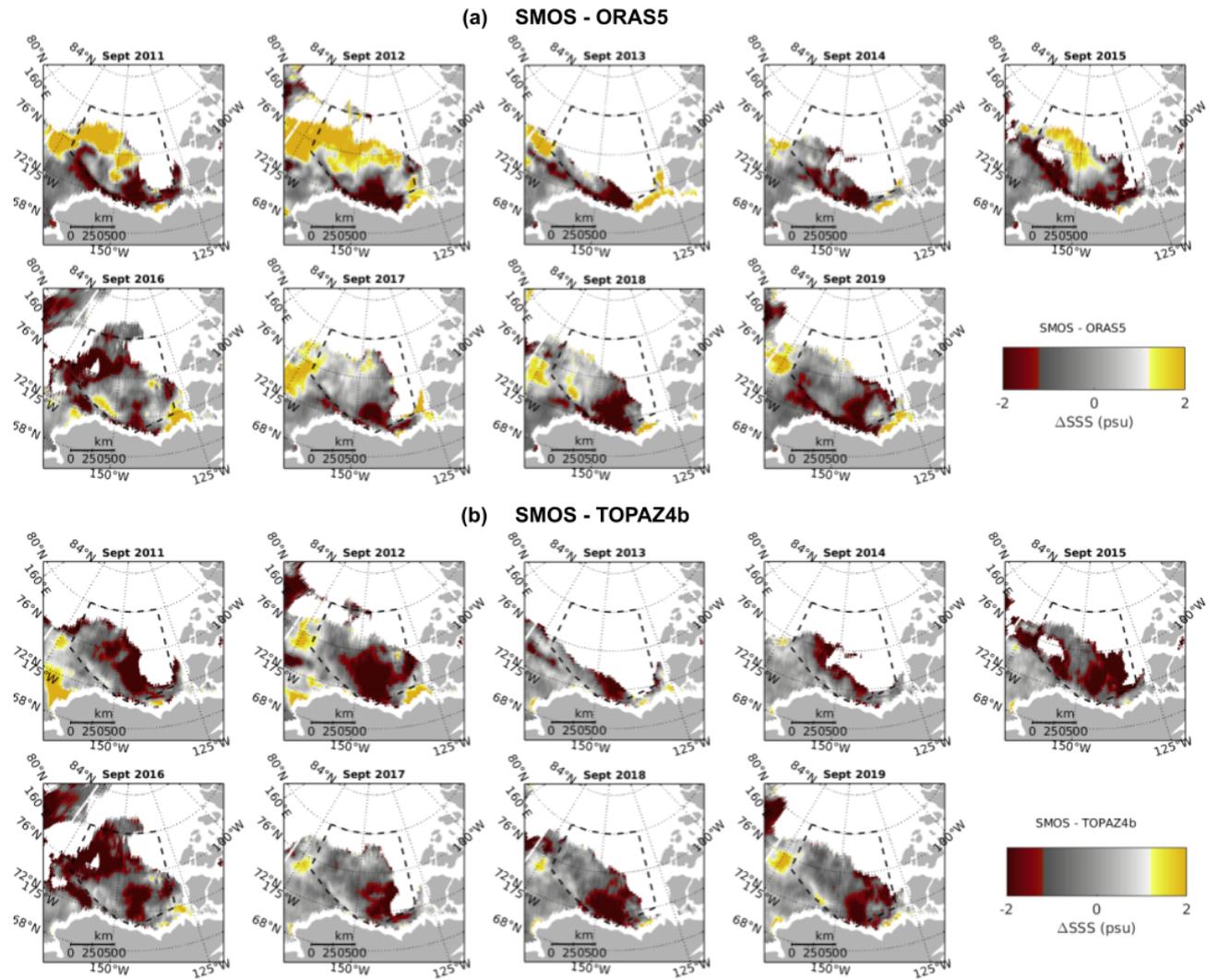
## **Introduction**

The information included in this set of files aims to give supplementary support to the main manuscript. We have included here the SIA-SSS relationship for every September from 2011 to 2019 in the BG. Also included are a set of September maps of the different variables assessed in the study for the whole study period: 2011 to 2019. These variables are the SMOS SSS, the number of SI days with OSISAF SIC <10%, and the pixel-by-pixel differences between SMOS SSS and modeled SSS (ORAS5 and TOPAZ4b). Videos can also be found on how MWLs are formed after sea ice melting, as well as different patterns observed on sea ice growth in different years.

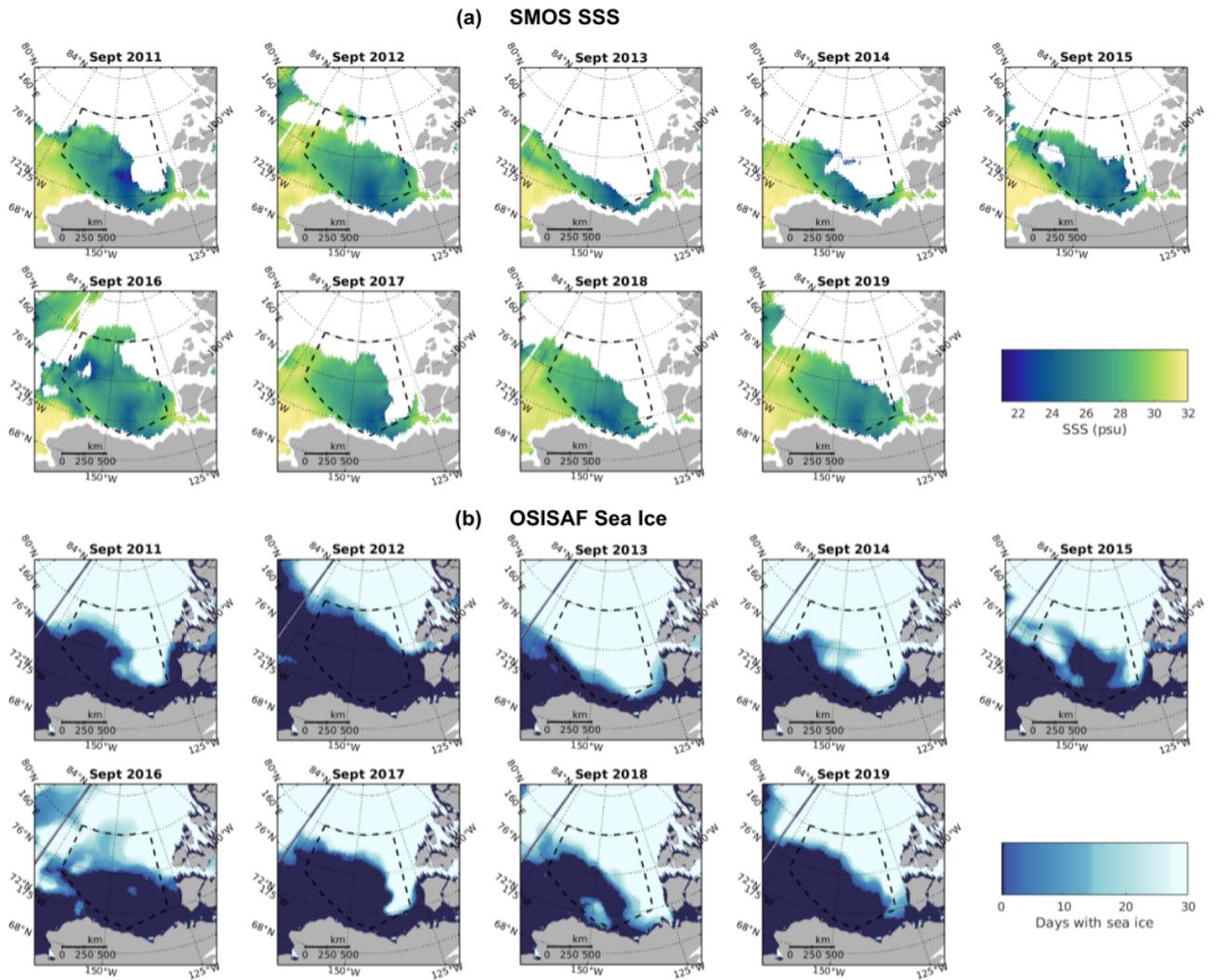
## Figures



**Figure S1.** Relationship between sea ice area (SIA) and sea surface salinity (SSS) throughout September grouped by year, from 2011 to 2019.



**Figure S2.** Spatial distribution of residuals: observed (SMOS) minus modeled SSS: a) SMOS-ORAS5 and b) SMOS-TOPAZ4b. Dashed black line delimits the Beaufort Gyre region. Truncated colorbar (see Fig. 4 in the main text).



**Figure S3.** Spatial distribution of a) SMOS-observed SSS, and b) number of days covered by sea ice in September (OSISAF SIC > 10%). Dashed black line delimits the Beaufort Gyre region.

### **Additional Supporting Information**

**Movie S1.** Daily evolution of SSS retrieved by SMOS in September 2011. Note that the ocean areas covered by sea ice are blanked (no data = white color). Therefore, more ocean surface is measured as sea ice melts. Sea surface freshening is observed after sea ice melting, specially in the center of the MWL, where a large piece of sea ice was present at the beginning of the month.

**Movie S2.** Daily evolution of SSS retrieved by SMOS in September 2012. Note that the ocean areas covered by sea ice are blanked (no data = white color). At the beginning of September the sea ice cover was already near its minimum, causing low monthly budget of  $V_{fw}$  released from sea ice melting.

**Movie S3.** Daily evolution of SSS retrieved by SMOS in September 2013. Note that the ocean areas covered by sea ice are blanked (no data = white color). Sea ice does not retreat, but grows, leaving null  $V_{fw}$  released from sea ice melting.

**Movie S4.** Daily evolution of SSS retrieved by SMOS in September 2016. Note that the ocean areas covered by sea ice are blanked (no data = white color). As for 2012, at the beginning of September the sea ice cover was already near its minimum, causing low monthly budget of  $V_{fw}$  released from sea ice melting. Sea ice starts growing on September 5 from the northwest quadrant, likely driven by cold north winds.