

Supporting Information for “Sediments in sea ice drive the Canada Basin surface Mn maximum: insights from an Arctic Mn ocean model”

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Text S1. Reversible Scavenging parameterization details.

Dissolved Mn adsorbs to particle surfaces (pMn) and oxidises to oMn forming larger aggregates which sink. dMn is regenerated through the release of Mn from particles through desorption and by the reduction of oMn. These processes constitute the reversible scavenging of Mn and can be represented as follows (expanded from Van Hulst et al., 2017):

$$\frac{\partial[dMn]}{\partial t} = -k_{ox} \cdot [dMn] + k_{re} \cdot [oMn] - k_{ad} \cdot [dMn] + k_{de} \cdot [pMn] + \text{physics} + S \quad (1)$$

$$\frac{\partial[pMn]}{\partial t} = k_{ad} \cdot [dMn] - k_{de} \cdot [pMn] - s_p \frac{\partial[pMn]}{\partial z} + \text{physics} + S \quad (2)$$

$$\frac{\partial[oMn]}{\partial t} = k_{ox} \cdot [dMn] - k_{re} \cdot [oMn] - s_{ox} \frac{\partial[oMn]}{\partial z} + \text{physics} \quad (3)$$

where s_p and s_{ox} are the pMn and oMn sinking rates, respectively, and k_{ad} , k_{ox} , k_{de} , and k_{re} are the rate constants for adsorption, oxidation, desorption, and reduction. In our model, we trace dMn and oMn explicitly, while we only take the indirect effect of particle-bound Mn on dissolved Mn concentrations into account.

The physics term represents mixing and advection processes, and S represents the contribution from sources and sinks. Away from sources and sinks, assuming steady state, negligible impact of mixing and advection, and a weak vertical gradient in Mn concentrations, the equations are decoupled and we can estimate the scavenging rates from Eqn. 2 and 3:

$$[dMn] = \frac{k_{re}}{k_{ox}} \cdot [oMn] \quad (4)$$

$$[dMn] = \frac{k_{de}}{k_{ad}} \cdot [pMn] \quad (5)$$

Using the ratio of observed dissolved and oxidized (Eqn. 4) or particulate Mn (Eqn. 5) concentrations in the Canadian Arctic (Colombo et al., 2020; Li, 2017), we can estimate

the background scavenging rates for oxidation or adsorption, $k_p = k_{ox}$ or k_{ad} , and for reduction or desorption, $k_d = k_{de}$ or k_{re} , respectively. We consider only observations in regions far away from coastal processes and the ocean surface where the assumptions hold. This condition reduces the available observations to those from stations in deeper areas of Baffin Bay and Canada Basin (Fig. S4) which have relatively small particle fluxes and are far away from sources. We match observations of dissolved and oxidized or particulate Mn at equal depths and fit a linear regression through the origin (Fig. S5). Using this method, the ratio of scavenging rates, k_p/k_d , is estimated to be 1.47 ± 0.25 (uncertainty estimate is the root-mean-square error) and with a k_d of $4.7 \cdot 10^{-7} \text{ s}^{-1}$ (Bruland et al., 1994), k_p is estimated as $7.0 \cdot 10^{-7} \text{ s}^{-1}$.

Since we model dMn and oMn, the final reversible scavenging equations in our Mn model are:

$$\frac{\partial[dMn]}{\partial t} = -k_p \cdot [dMn] + k_d \cdot [oMn] + \text{physics} + S \quad (6)$$

$$\frac{\partial[oMn]}{\partial t} = k_p \cdot [dMn] - k_d \cdot [oMn] - s_{ox} \frac{\partial[oMn]}{\partial z} + \text{physics} \quad (7)$$

These equations do not incorporate a dependence on the dissolved oxygen concentration since Arctic waters are generally well oxygenated.

Text S2. Calculation of Net Mn transport through Parry Channel.

In this study, we calculated net Mn transport from Canada Basin into Parry Channel and from Parry Channel into Baffin Bay via Lancaster Sound. The boundaries are defined along lines of constant i or j indices (Fig. S10). The Mn flux across each of the boundaries, ϕ_{bdy} , is the sum of the dissolved Mn concentration at the boundary grid points with indices i, j, k , multiplied by the volume flux:

$$\phi_{bdy}(t) = \sum_{i,j,k} [dMn]_{i,j,k}(t) \cdot u_{i,j,k}(t) \cdot A_{i,j,k} \quad (8)$$

where u is the velocity perpendicular to the boundary at time, t , and A is the grid cell area. These time series were calculated from 5-day modelled velocity and tracer fields, interpolated onto the U grid.

Mn transport into and out of Parry Channel fluctuates seasonally, with a peak in the late summer (Fig. S13). The flux of Mn in the “clean” sea ice experiment is consistently smaller than for the experiment with sediment in sea ice. To compare the experiments, we calculate the percent contribution of the sea ice component to the net transport:

$$p = \left(1 - \frac{\phi_{off}}{\phi_{on}}\right) \cdot 100\% \quad (9)$$

where ϕ_{off} is the Mn transport from an experiment with the component “off”, i.e. the “clean” sea ice experiment, and ϕ_{on} is the Mn transport from an experiment with the component on, i.e. the reference experiment with dirty sea ice. Based on these calculations, the sediment released by sea ice contributes about 87% to the Mn transported from Canada Basin into Parry Channel and about 34% for the Mn transported from Parry Channel into Baffin Bay (Fig. S14). The sea ice contribution to Mn flux does not vary significantly between 2002-2019.

Text S3. Comparison of estimate of magnitude of biological uptake.

We estimate that uptake can account for a difference in Mn concentrations of up to about 0.3 nM (Fig. S15). In order to assess our estimate, we can compare the nitrogen uptake from our model forcing with that estimated from observed primary production in the CAA.

Michel et al. (2006) estimate primary production in the CAA as 53-57 MtC yr⁻¹. Using the average, 55 MtC yr⁻¹, and an area of 2.5·10⁶ km² for the CAA, this primary production corresponds to 22 gC m⁻² yr⁻¹. Taking into account the molecular weight of carbon (12 g mol⁻¹) and the Redfield ratio (106C : 16N), primary production accounts for an uptake of 0.28 moles of N m⁻² yr⁻¹. Our estimate of uptake from the CanOE model is on the order of 5 mmol N m⁻³, and with a euphotic zone depth of 100 m, this is roughly 0.5 moles of N m⁻² yr⁻¹. This nitrogen uptake, and thus the derived Mn uptake, is similar in magnitude to that estimated based on the primary production from Michel et al. (2006).

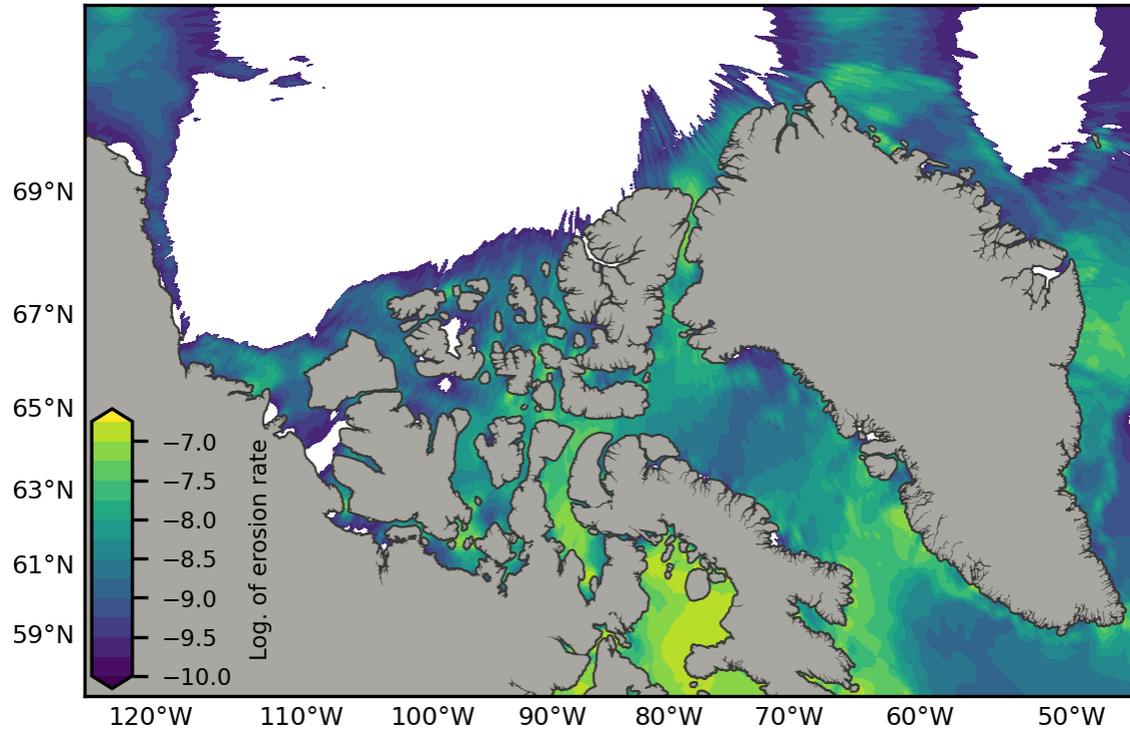


Figure S1. Erosion rates (units of $\text{kg m}^{-2} \text{s}^{-1}$) are heterogeneous across the Canadian Arctic. Regions west of Barrow Sill in central Parry Channel have lower erosion rates than eastern Parry Channel, as seen in observations (Colombo et al., 2020). We use tidal stress to estimate the spatially variable erosion rate for the sediment resuspension parameterization of our Mn model (Eqn. 6). Tidal stress is calculated as the squared barotropic tidal speeds derived from the MOG2D-G model (Carrère and Lyard, 2003). Erosion rate is zero (white) in regions where tidal speeds are below 1 cm s^{-1} . Note that the colorbar scale is logarithmic.

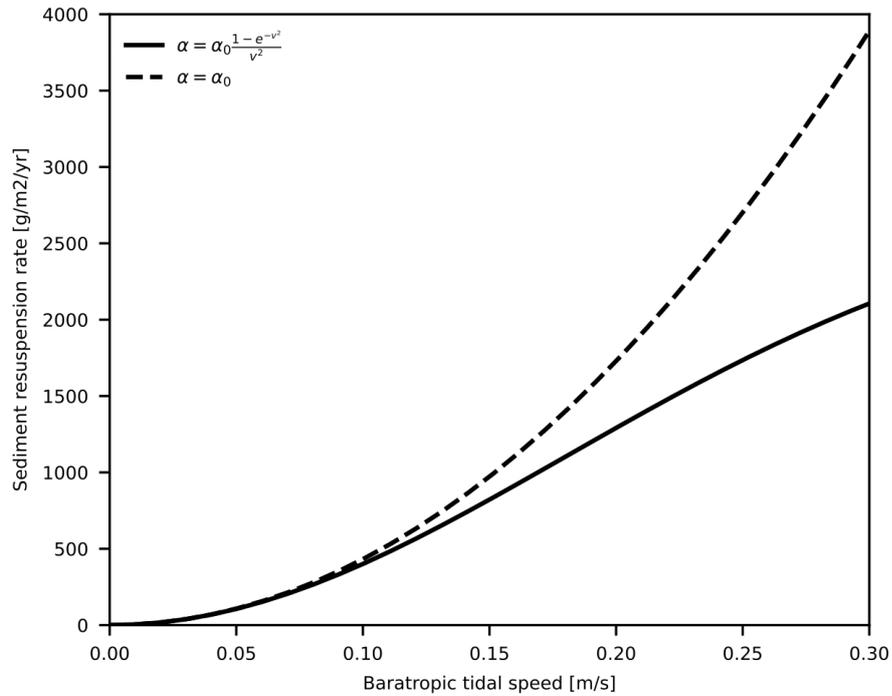


Figure S2. Sediment resuspension is modelled proportional to tidal stress (barotropic tidal speed, U_{tidal} , squared; Eqn. 5 and 6). In regions with strong tidal speeds, the readily available Mn has been dissolved from particles, and the solubility is effectively reduced. We modulate the sediment resuspension rate by solubility, α , which decreases as tidal speed increases (Eqn. 7). The resulting sediment resuspension rate levels off at a maximum value at high tidal speeds (solid line), while with a constant solubility, sediment resuspension increases indefinitely (dashed line).

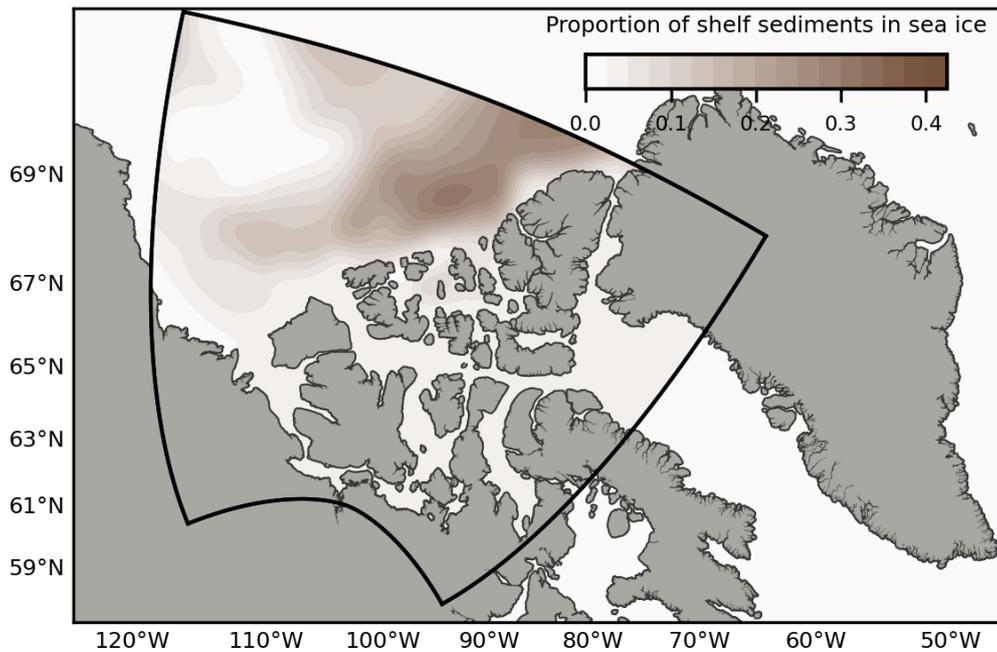


Figure S3. The sediment content of sea ice is highest along the outer edges of the Canada Basin, while the older sea ice at the core of the Beaufort Gyre is relatively “clean” in our model forcing field. The parameterization for sediment content in sea ice consists of a constant characteristic shelf sediment density, multiplied by the proportion of Siberian shelf-origin sediments in sea ice (colored contours in figure), estimated with backwards particle tracking. Within the CAA, we assume a constant, low background content.

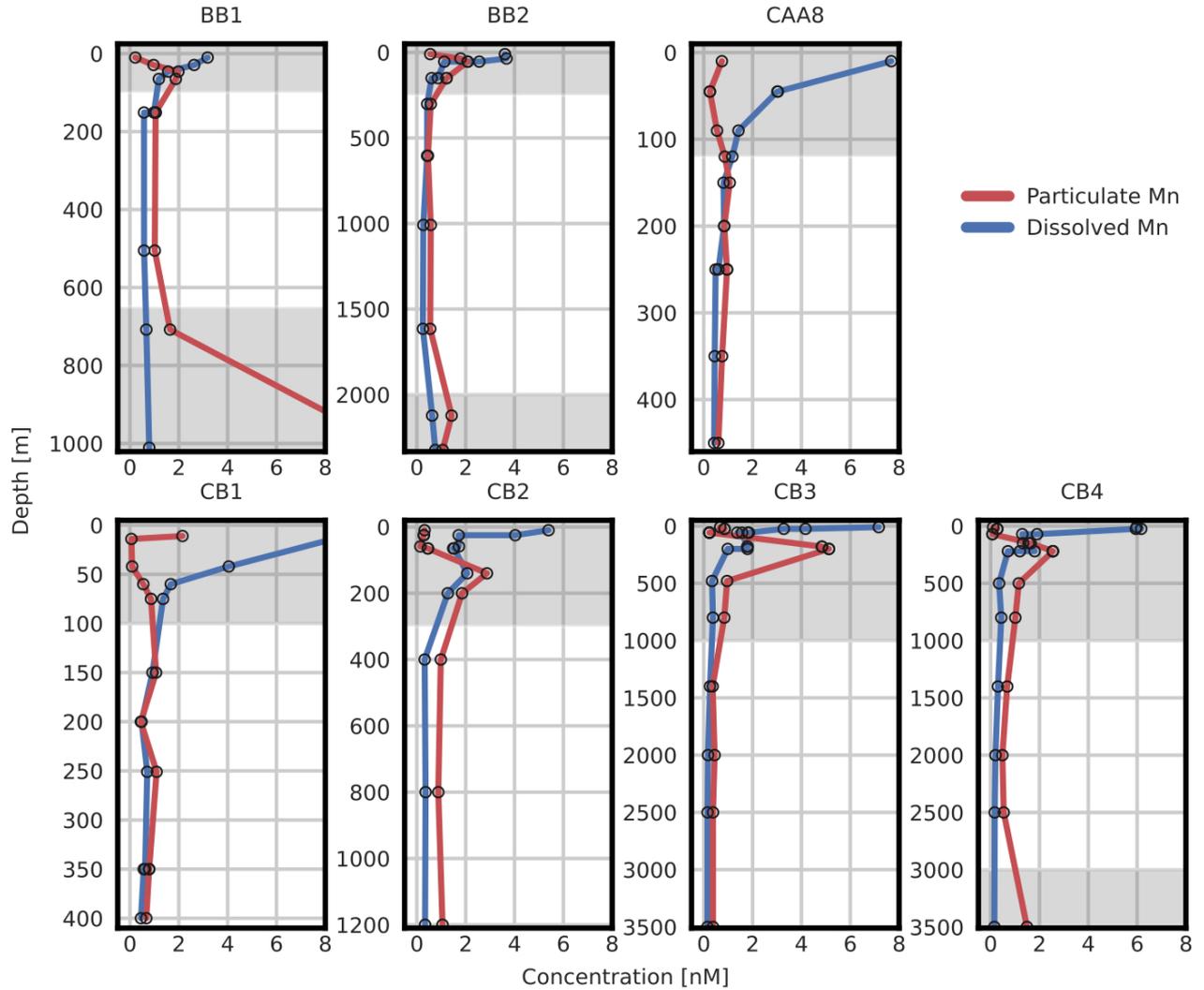


Figure S4. Scavenging rates are estimated using dissolved and particulate Mn observations far away from sources and sinks, and at depths with a negligible vertical gradient in particulate concentrations. Here, we show profiles of dissolved Mn (blue) and particulate Mn (red) from 2015 at stations in Baffin Bay, the Canadian Arctic Archipelago, and Canada Basin, that match these criteria. The depths at which external sources affect the Mn concentrations are highlighted in gray and are excluded from the scavenging rate estimate. Note that the depth scale varies between plots.

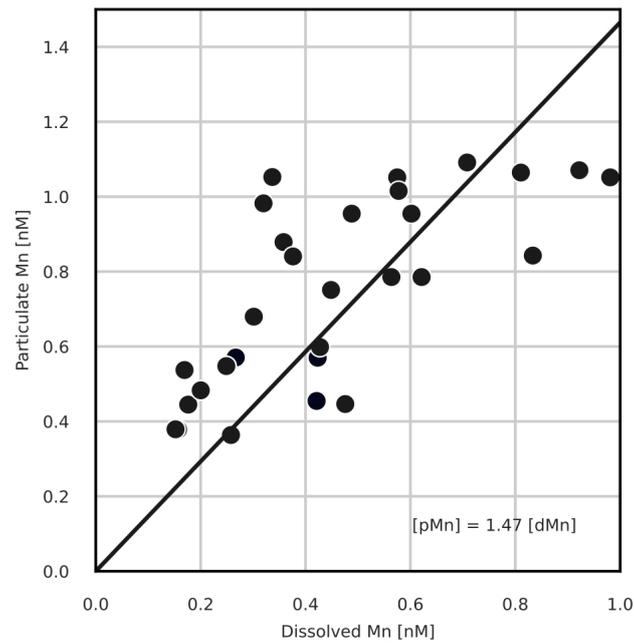


Figure S5. Far away from sources and sinks, dissolved and particulate Mn occur at ratios set by the scavenging rates. We estimate the scavenging rates from 2015 Canadian GEOTRACES observations that satisfy these criteria (profiles shown in Fig. S4) by applying a linear fit with a zero intercept (solid black line); the slope is 1.47 ± 0.25 [dMn] [pMn] $^{-1} = k_{de} (k_{ad})^{-1}$ (Eqn. S5).

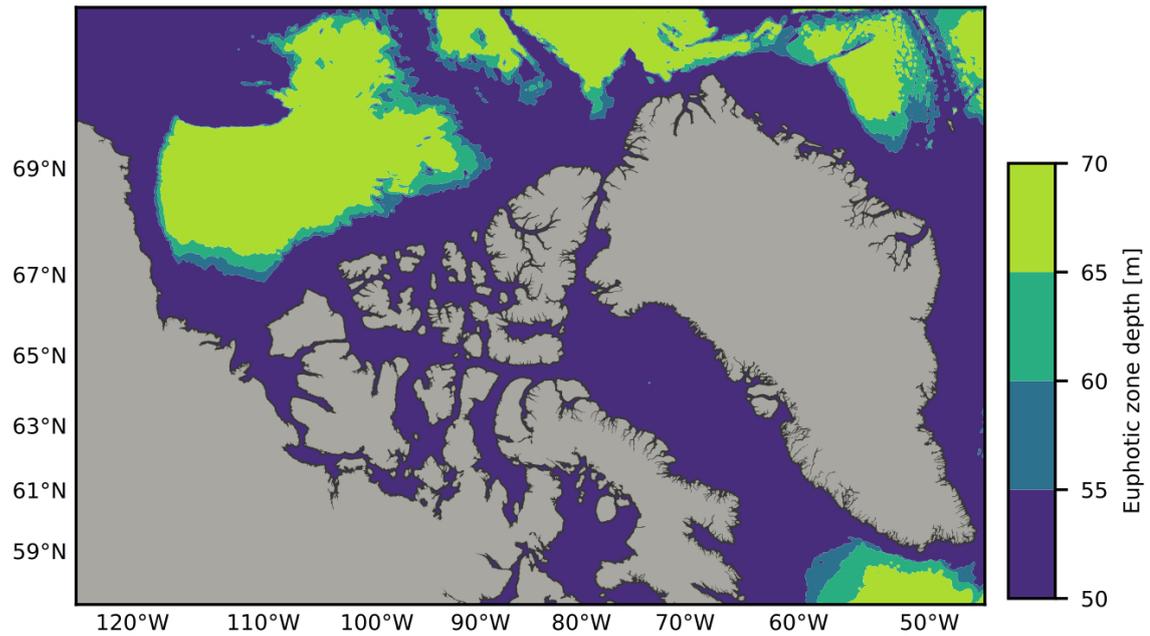


Figure S6. The euphotic zone forcing in our model gradually transitions from 70 m in the Canada Basin (shallow limit observed by Laney et al., 2017) to 50 m in the CAA based on bathymetry depth (euphotic depth from Bhatia et al., 2021). Photo-enhanced reduction is applied within the euphotic zone.

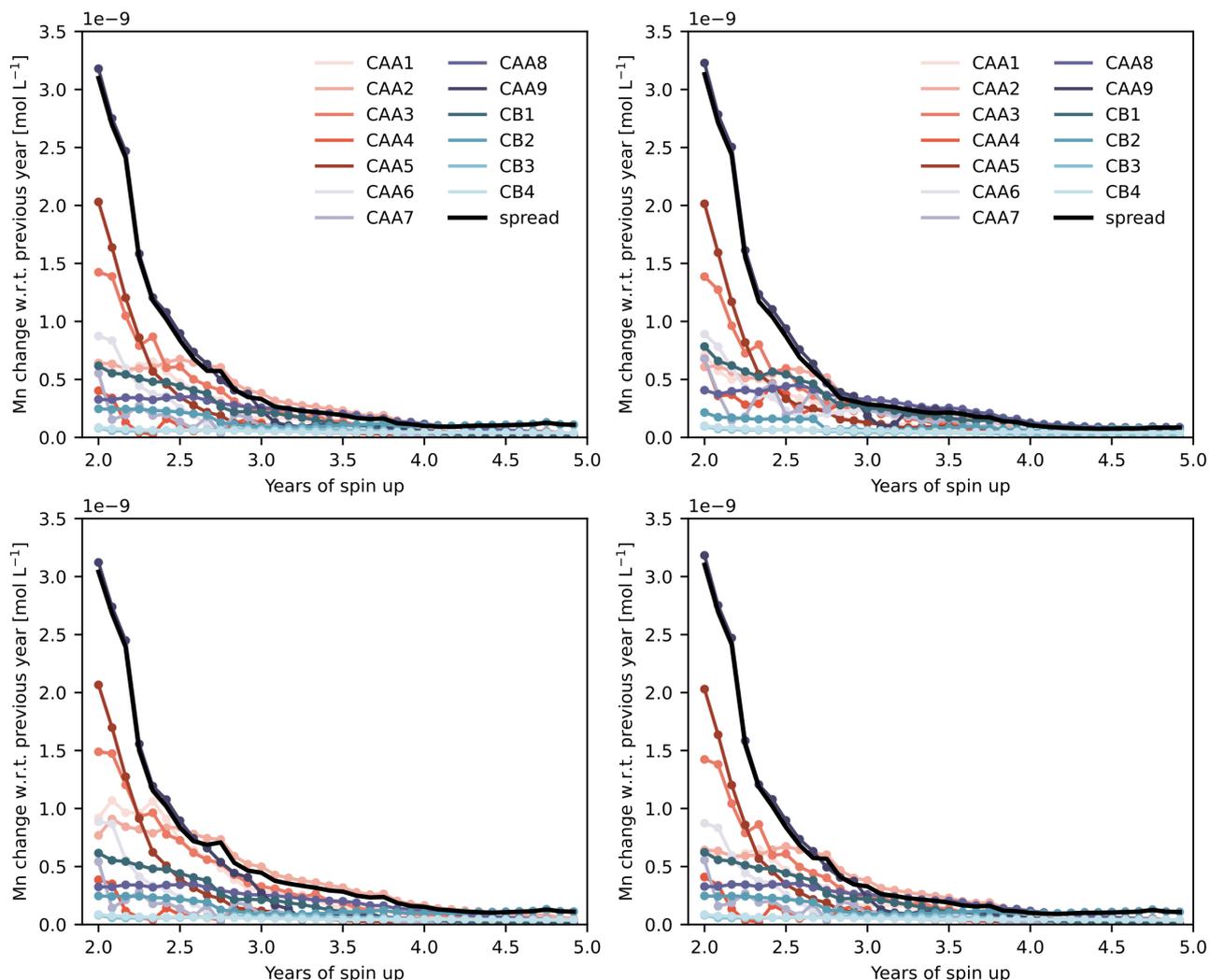


Figure S7. For each simulation (top left: reference, top right: “clean” sea ice, bottom left: upper bound river, and bottom right: biology), the Mn model is spun up by repeating the year 2002 until the year-to-year change in profile shape, estimated as the average Mn difference in the water column, at evaluation stations from 2015 Canadian GEOTRACES cruises (names in legend) is minimal. It takes about three years to achieve spin-up, after which the full experiments from 2002 to 2019 start. The “spread” is the difference between the maximum and minimum change at each month (solid black line).

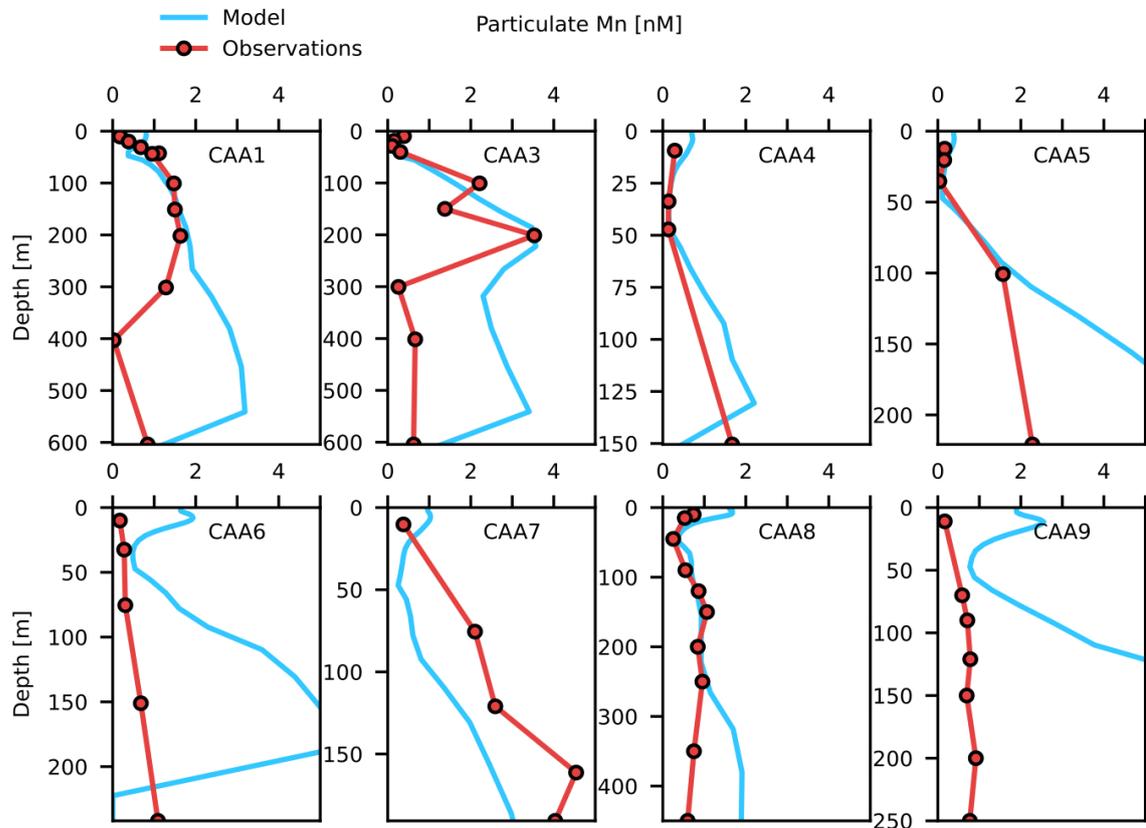


Figure S8. Modelled oxidised Mn (blue) and observed particulate Mn (red) profiles in the Canadian Arctic Archipelago for 2015 Canadian GEOTRACES stations. Observed pMn data are from Li (2017). Particulate Mn sources are not directly incorporated into the model; instead, we modelled oMn through the coupling of scavenging with dMn. The model captures a range of behaviour within the upper 100 m of stations CAA1, CAA3, CAA4, CAA5, and CAA8, while it typically overestimates oMn in the lower water column in locations with strong sediment resuspension.

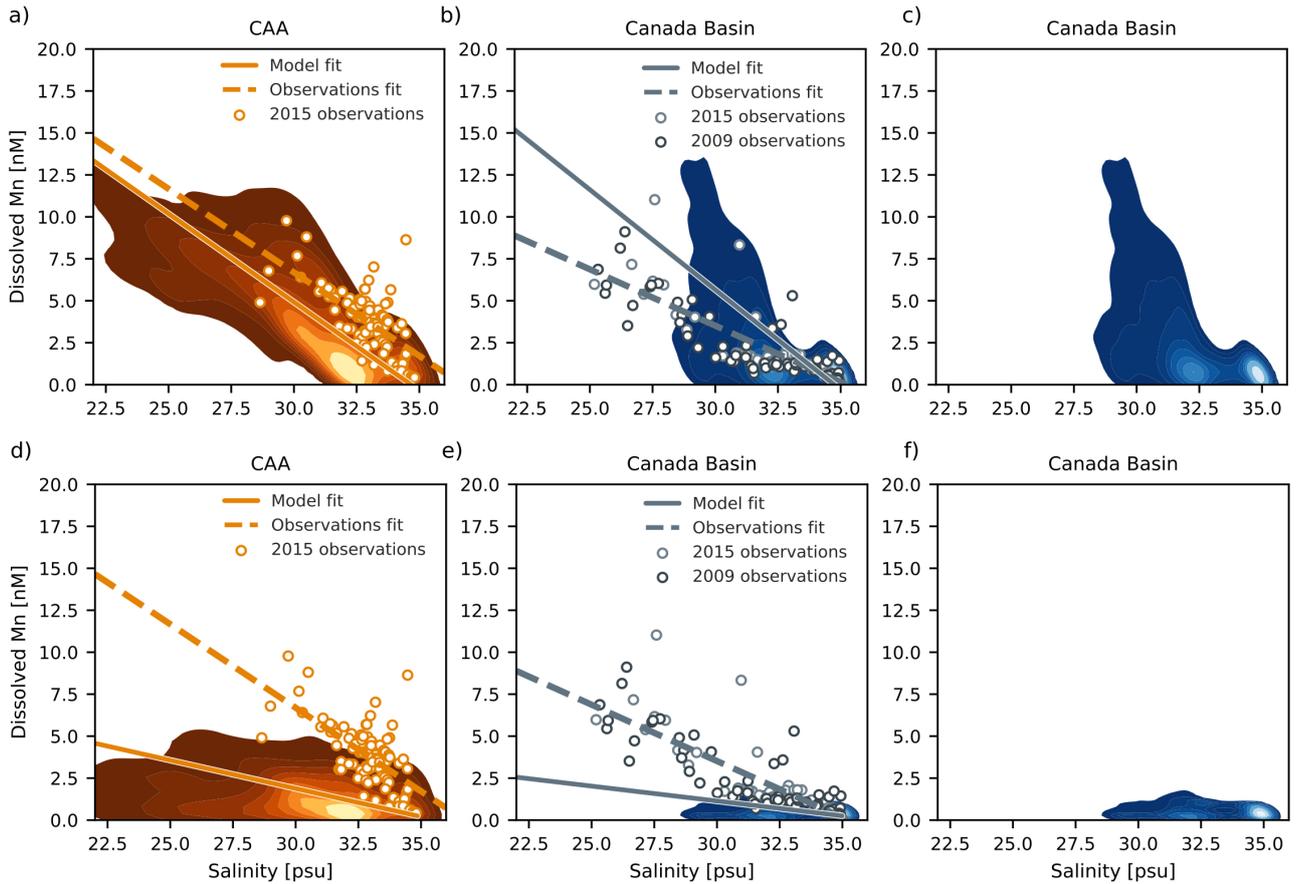


Figure S9. Modelled Mn-salinity relationship for one in five grid points at all depths (contour levels correspond to iso-proportions of the density of points) averaged over August-September, 2015, in the Canada Basin and the Canadian Arctic Archipelago (CAA) alongside observations from 2009 and 2015 (scatter points). The reference experiment (panels a, b, and c) represents the low-salinity endmember more accurately than the experiment without sediment in sea ice (panels d, e, and f). The solid lines are linear regression fits for the model estimates. The dashed lines are fits from observations collected in 2009 and 2015 (Sim, 2018; Colombo et al., 2020). Panels c and f show the Canada Basin contour levels alone for clarity. Note that the evaluation of the Canada Basin Mn-salinity relationship is complicated by an underestimation of surface freshwater in the model.

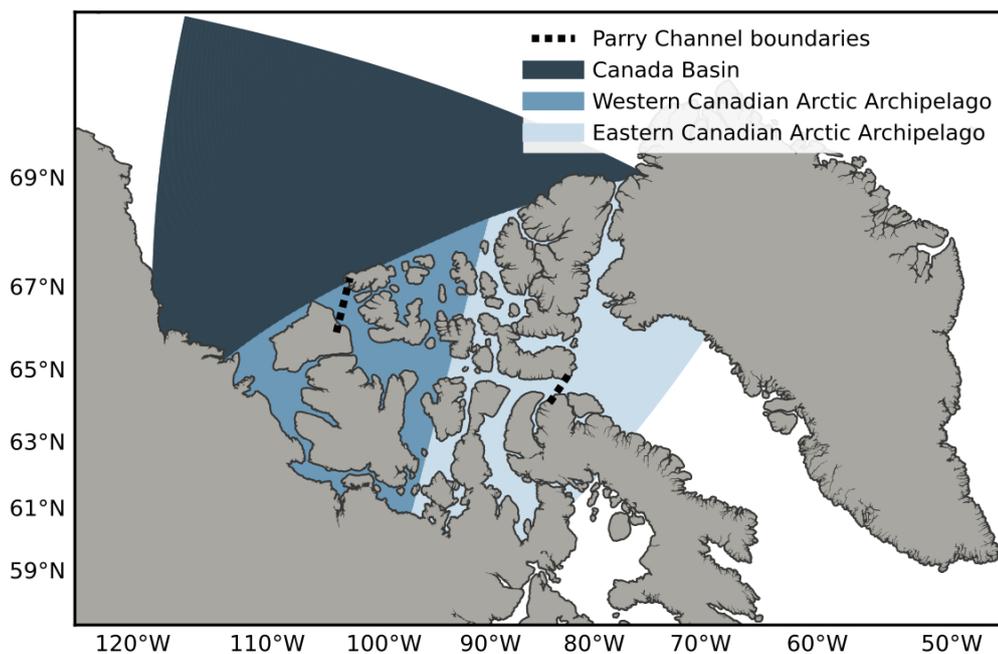


Figure S10. Region definitions for the component contribution calculations in Tables 2, 3, and S2. The CAA is divided into west and east approximately along 100°W. The boundaries indicated by black dashed lines were used for the calculations of net Mn transport into and of Parry Channel in Fig. S13 and S14.

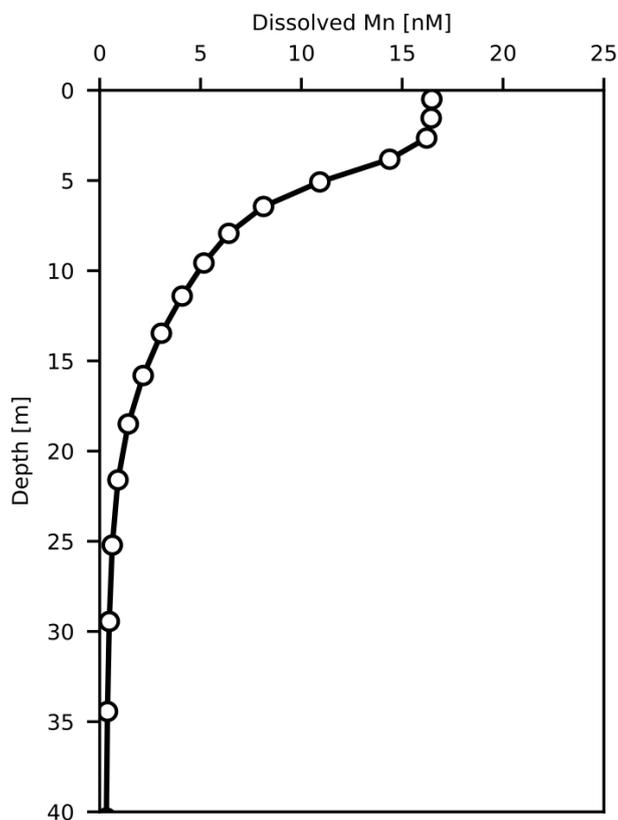
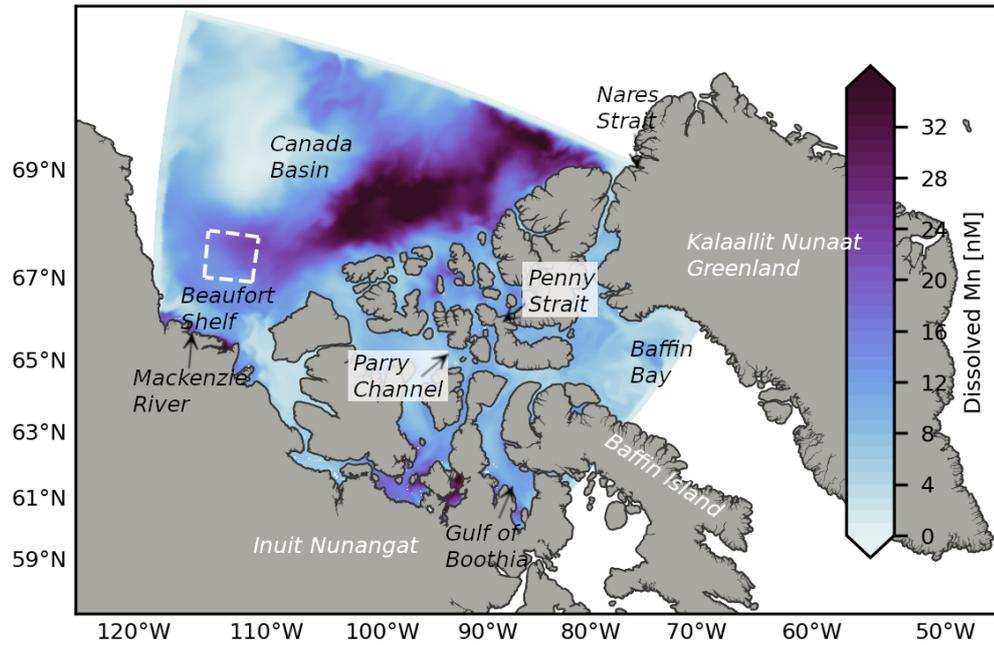


Figure S11. Dissolved Mn concentrations are highest at the surface and decrease strongly within the upper 5 m. These gradients are most visible during periods of strong surface source input, i.e. during sea ice melt. This mean profile was calculated over a sub-region of the Canada Basin (dashed white line in Fig. S12) for July, 2015. The markers indicate the model depth levels.

a) August



b) January

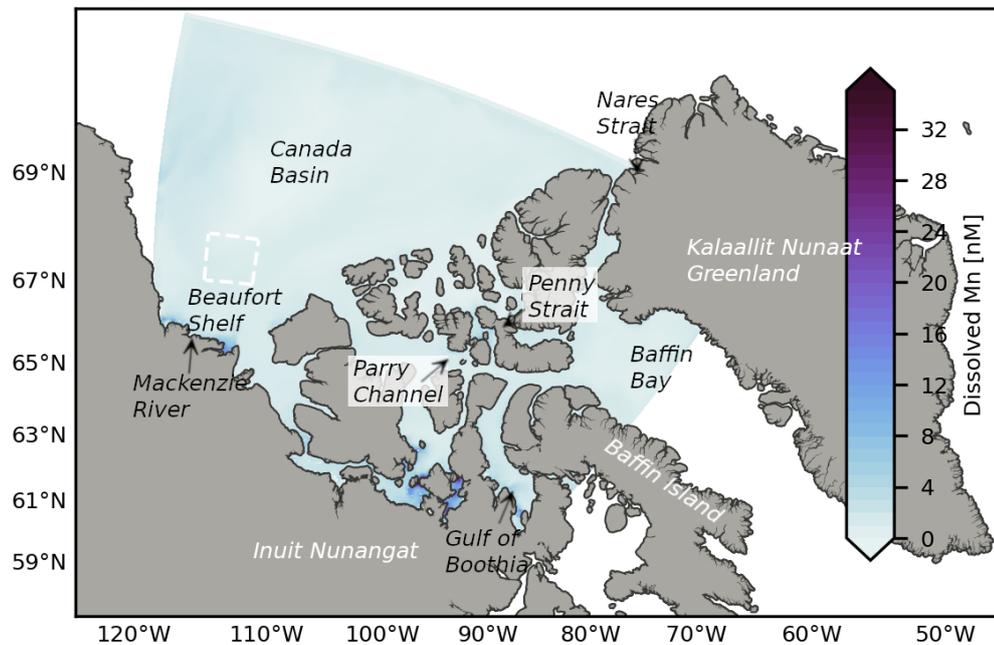


Figure S12. Simulated Mn concentrations in the ocean surface (top 1 m) in (a) August, 2015 and (b) January, 2015. The region outlined by a white dashed line is used to calculate a mean Mn profile with depth (Fig. S11). Note that the surface concentrations are much higher than for the polar mixed layer fields presented in Fig. 9, since there is a strong surface Mn gradient (as shown in Fig. S11).

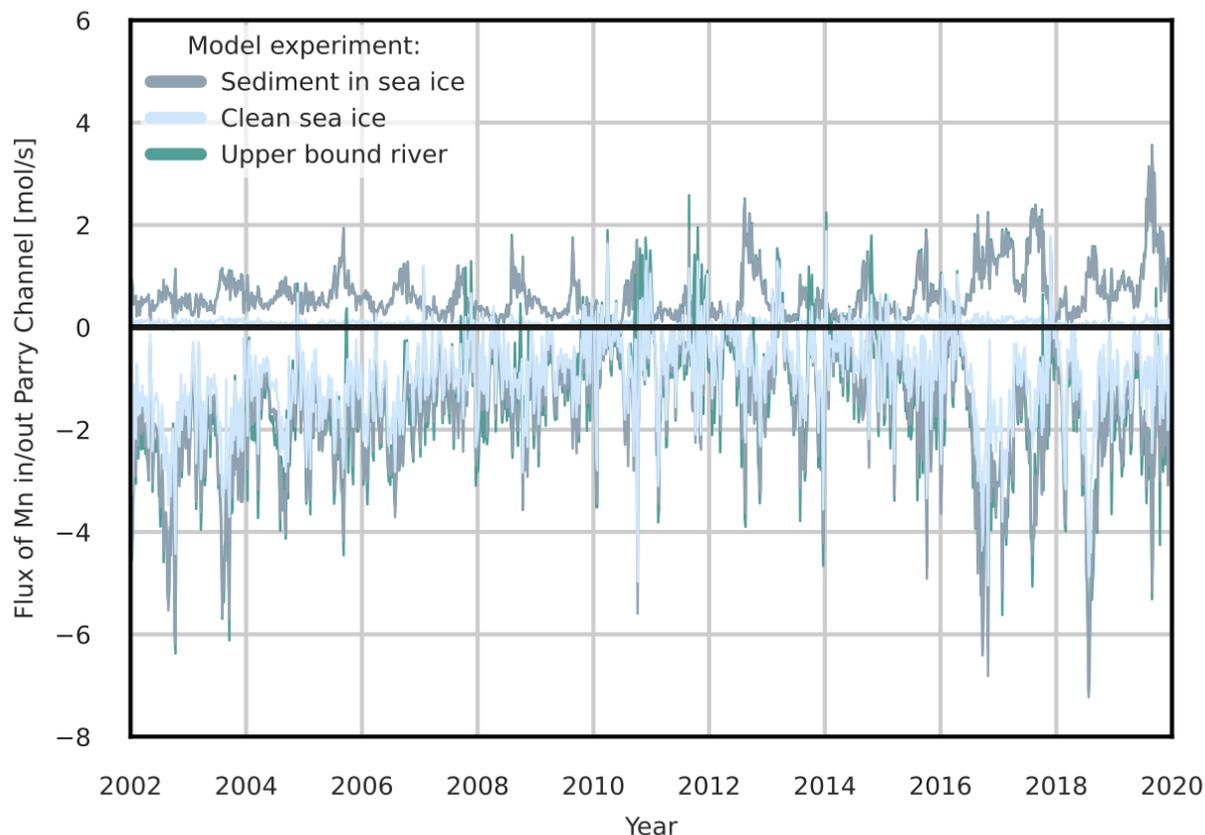


Figure S13. Mn flux into and out of Parry Channel along the boundaries defined in Fig. S10 for each of the main model experiments. The experiment with sediment in sea ice is the “reference” and uses a lower bound river estimate which incorporates only the direct dissolved Mn contribution. The clean sea ice experiment does not include sediment in ice. The upper bound river experiment has sediment in ice and incorporates the additional contribution of suspended matter from rivers. A positive flux represents transport into Parry Channel (typically from the Canada Basin) while a negative flux is transport out of Parry Channel (towards Baffin Bay). Mn transport into and out of Parry Channel fluctuates seasonally, with a peak in the late summer.

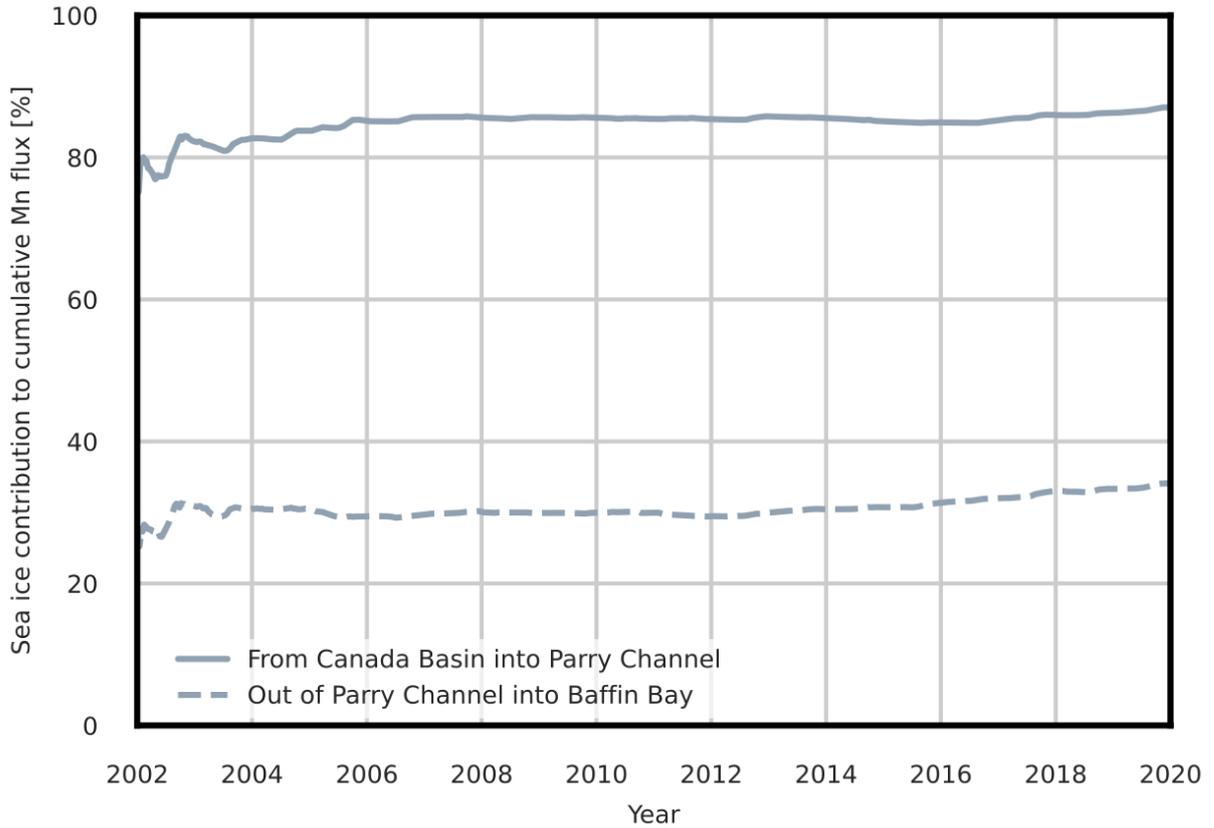


Figure S14. The percent contribution of sea ice melt to cumulative transport of Mn into and out of Parry Channel (boundaries shown in Fig. S10), estimated from the relative difference in transport between the clean sea ice and reference experiments. Almost 87% of Mn flowing into Parry Channel comes from sea ice melt, while it comprises about 34% of the outflow.

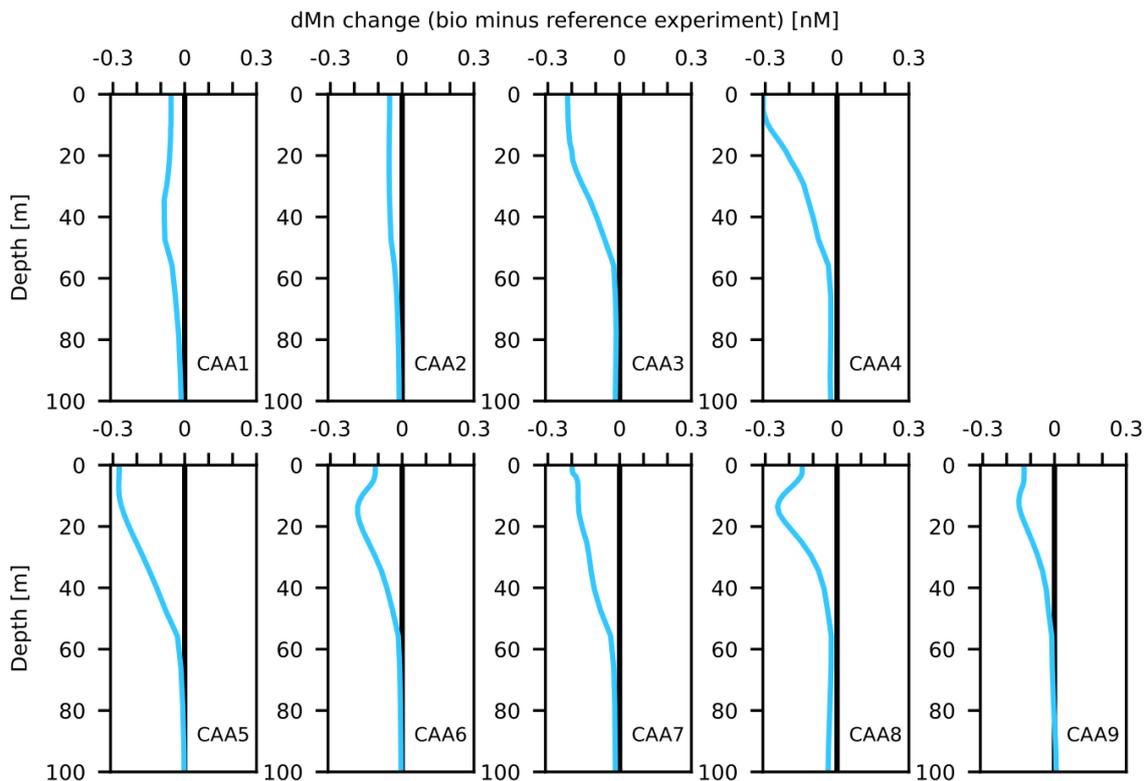


Figure S15. Difference in dissolved Mn from August-September 2015 in the upper 100 m of the water column between the experiment with uptake and remineralization of Mn (“bio” experiment) and the reference experiment for stations in the Canadian Arctic Archipelago. Uptake within the euphotic zone accounts for a reduction of up to 0.3 nM in dissolved Mn concentrations. Remineralization does not clearly appear in this figure because it occurs deeper and over a broad range of depths, and because of our coarse method of estimation using nitrate. The estimate of the magnitude of nitrate uptake is comparable to an estimate based on primary production from Michel et al. (2006) (Text S3).

Table S1. A summary of average sediment loads and suspended particulate matter (SPM) concentrations measured in sea ice cores in the Arctic Ocean. The range of measured values are in brackets. Observed sediment content in sea ice is highly heterogeneous and can span multiple orders of magnitude. Where two estimates are given for the average content, the lower number is from “clean” ice cores and the higher number from turbid ice.

Sediment load (g m^{-2})	SPM (g m^{-3})	Location	Source
179 (0-972)	142 (24-192)	Laptev Sea	Eicken et al., 2000
-	149 (5-500+)	Lena delta	Hölemann et al., 1999
16 (9-46)	70 (8-600+)	Laptev sea	Eicken et al., 1997
-	45, 349 (0-964)	Laptev Sea	Nürnberg et al., 1994
(0-7000+)	-	NW of Alaska	Darby et al., 2011
128 (69-203)	342 (91-508)	Chukchi Sea	Eicken et al., 2005
232 (2-384)	564 (24-1474)	Alaska coast	Stierle et al., 2002
289	157 (31-593)	Beaufort Sea	Reimnitz et al., 1993
1400	-	Central Arctic	Darby et al., 2011
32 (8-84)	360 (7-2228)	Central Arctic	Tucker et al., 1999
-	68, 6800 (1-31013)	Central Arctic	Nürnberg et al., 1994
-	24 (0-725)	Fram Strait	Dethleff et al., 2010
-	11 (2-137)	Kara Sea	Dethleff et al., 2009

Table S2. The spatial average annual dissolved Mn contributed by external model source components for the full water column ($\mu\text{mol m}^{-2} \text{yr}^{-1}$) in the reference experiment, averaged over the years 2002-2019, separated by region (Fig. S3). Sediment release by sea ice is the only component that varies significantly year-to-year. Estimates from the upper bound river experiment are indicated in brackets.

Component contribution	Canada Basin		Canadian Arctic Archipelago	
	$\mu\text{mol m}^{-2} \text{yr}^{-1}$	%	$\mu\text{mol m}^{-2} \text{yr}^{-1}$	%
River discharge	5.3 (22)	2.1 (7.8)	19 (178)	2.3 (18)
Sediment resuspension	34	13 (12)	662	81 (68)
Sediment from sea ice	221	85 (80)	138	17 (14)
Dust released by sea ice	0.2	0.1	0.3	0.0
Direct dust deposition	0.0	0.0	0.0	0.0
Total	261 (277)	100	819 (978)	100