Review of "Sea ice transport and replenishment across and within the Canadian Arctic Archipelago: 2016-2022" by Howell et al.

Summary:
This study focuses on quantifying sea ice transport and replenishment across and within the Canadian Arctic Archipelago (CAA), and particularly along the critical segment of the Northwest Passage shipping route, spanning from the Queen Elizabeth Islands to the Parry Channel. Results indicate that the CAA functions as both a source and sink for sea ice, exporting significant amounts to the Arctic Ocean and Baffin Bay. The study underlines the resilience of multi-year ice (MYI) replenishment within the CAA, with ongoing import from the Arctic Ocean and retention of first-year ice (FYI). The authors emphasize the persistent risk that sea ice poses to key shipping routes in the CAA, including the Northwest Passage, due to substantial ice flux and sustained MYI replenishment.

This study makes use of high-resolution drift data from SAR as well as CryoSat-2 altimetry and can serve as a baseline study of sea ice fluxes in the CAA. While the method itself (sea ice flux estimation) is not new, the study region, especially inside the CAA is rather understudied compared to Fram Strait for example.

General Comments:
To my knowledge there is no comparable study for ice fluxes within the CAA currently available. Therefore, I think it potentially deserves publication. I also had no problems to follow the text in general. The applied methods seem generally solid, but there are some details and decisions that I find disputable and that need clarification and more in-depth descriptions and discussion. Here and there, the paper lacks explanations. I also find the figures could partly contain more information. Major comments are:

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We thank the Reviewer for their comments and have tried to implement all the suggestions.

1. More information on the input data is needed. The authors use two sea ice thickness data sets to compute volume fluxes. The all-year CryoSat-2 summer sea ice thickness retrieval from Landy et al. (for the outer gates) and the proxy-record from Glissenaar et al. (for the inner gates of the CAA). I think it should be discussed how consistent these data sets are. How do they compare at intersections? Because any inconsistency might introduce biases here. I also suggest introducing acronyms or at least make it clearer when and where which data set is used (See also in the specific comments). It is also not entirely clear over which period data have been used. Under "2) Data", it is stated that volume fluxes have been calculated until 2021, but later in Figure 4, it is only until 2020, while the caption mentions until 2022. This is confusing. It should be possible to provide volume fluxes until 2022, I assume.

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We have been able to update the outer gates temporal domain to match the inner gate temporal domain for volume flux. The time series of sea ice thickness data is October 2016 to September 2021 for both gates therefore, the area flux is 6-years and volume flux is 5-years. We make this

clear in the text. The proxy-record from Glissenaar et al. for the inner gates was actually generated from the winter observations in the Landy et al. CryoSat-2 product. The CryoSat-2 observations were used as training data for the machine learning algorithm in Glissenaar et al. Thus, when the ice thickness products are compared against each other there is understandably no bias, but the RMSE is 41 cm (Glissenaar et al. 2023) which was also added to the text. We refrain from acronyms which we feel they make papers more confusing (i.e. spelling it out is better especially for casual readers). We have revised the dataset section as follows:

Sea ice thickness estimates for the outer flux gates were acquired from the CryoSat-2 radar altimeter from October 2016 to September 2021 (Landy et al., 2022) that uses a combination of data from Landy et al., (2020) for the 'cold' season (October to April) and Dawson et al., (2022) for the summer period (May to September). A bias correction based on radar model simulations (Landy et al., 2022) is applied to the summer radar freeboards. The entire time series of radar freeboards is then converted to a continuous pan-Arctic record of sea ice thickness using snow loading information from SnowModel-LG (Stroeve et al., 2020) and assuming constant ice-type dependent densities for sea ice (Landy et al., 2022). All CryoSat-2 ice thickness data are available from https://data.bas.ac.uk/full-record.php?id=GB/NERC/BAS/PDC/01613. No outer gate sea ice thickness estimates were available from October 2021 to September 2022 (i.e. the 2021/2022 ice season).

Sea ice thickness estimates for the inner flux gates within the CAA were obtained from the ice thickness proxy record developed by Glissenaar et al. (2023), which is available from https://doi.org/10.5281/zenodo.7644084. This proxy sea ice thickness dataset uses the CryoSat-2 observations of sea ice thickness from Landy et al. (2022) in the open seas of the Canadian Arctic to train a random forest regression model to estimate sea ice thickness from information in the Canadian Ice Service ice charts (Tivy et al., 2011) within the channels of the CAA. The uncertainty of the proxy sea ice thickness values ranges from 30 to 50 cm. When the proxy dataset is compared against independent CryoSat-2 thickness values, not used for training, the root mean square error (RMSE) is 41 cm (Glissenaar et al. 2023). Unlike direct CryoSat-2 observations, this proxy sea ice thickness dataset is available in all channels in the CAA from 2016 to 2021 but only for the months of November to April. No inner gate sea ice thickness estimates were available from October 2021 to September 2022 (i.e. the 2021/2022 ice season).

2. I find the method description of how area and volume fluxes are computed lacks information. How are sea ice motion, concentration, and thickness co-registered along the gate? Are you using a nearest-neighbor scheme? How are data gaps handled? Are you filling those by interpolation? I also recommend adding a figure showing the drift, concentration, and thickness along a few gates, to get an impression of spatial resolution of input data and how thickness is distributed along the gates.

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Admittedly, we were too vague on the methods because they have been described in previous papers going back to 2013. We have added a Figure (Figure 2) to show the flux across the gate but showing thickness is not really helpful as it is just an average within the buffer. We have updated the methods as follows:

Our approach to estimate the sea ice area flux from sequential pairs of SAR imagery is robust and based on previous work (e.g. Kwok, 2006; Agnew et al., 2008; Howell et al., 2013). For each SAR image pair, sea ice motion was estimated using the Environment and Climate Change Canada Automated Sea Ice Tracking System (ECCC-ASITS; Howell et al., 2022) that is based on the Komarov and Barber (2013) feature tracking algorithm. Sea ice motion estimates are then interpolated to a 30 km buffer region around each gate using inverse distance weighting. Both sea ice motion and Canadian Ice Service ice concentration values are then sampled at 5 km intervals along the gate as shown in Figure 2.

…

The sea ice volume flux of the CAA's outer gates from October 2016 to September 2021 was determined from the product of the monthly ice area flux and the monthly average CryoSat-2 sea ice thickness within the 200 km buffer around each gate. For the inner gates the volume flux was determined from the product of monthly ice area flux and the monthly average proxy sea ice thickness. Note we use the larger (i.e. 200 km) buffer for volume flux given the coarse spatial resolution of the thickness products (i.e. 50-80 km).

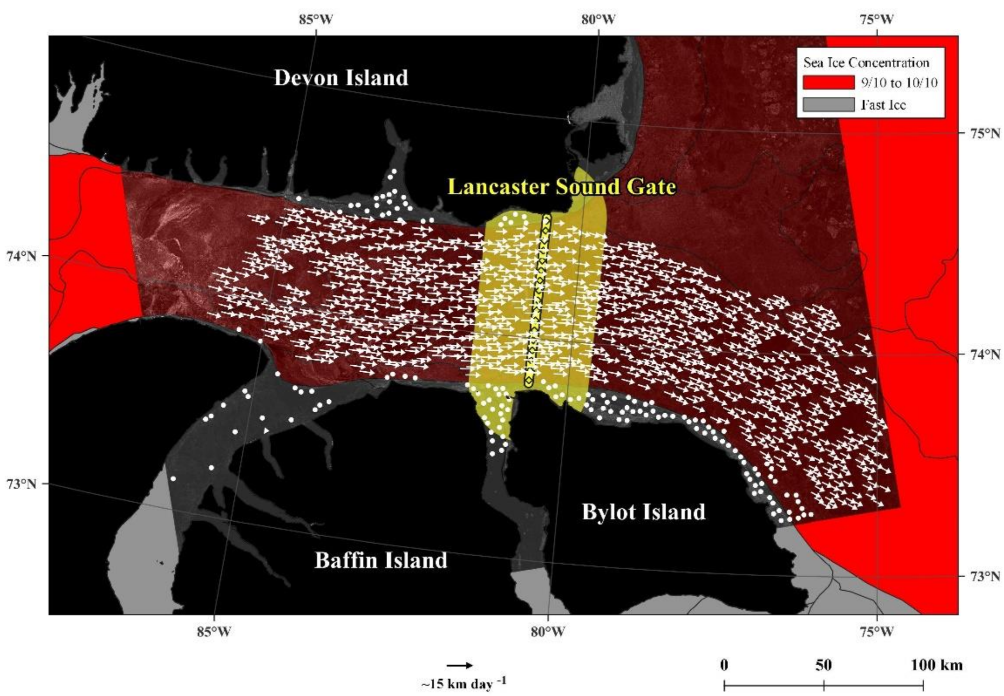

Figure 2. Sea ice motion vectors overlayed with sea ice concentration from the Canadian Ice Service ice charts for the Lancaster Sound gate. The yellow region represents the 30 km buffer zone around the gate. RADARSAT Constellation Mission (RCM) imagery on April 8, 2022 (RCM © Government of Canada).

3. I find the approach of using a linear trend to bridge the summer gap for the thickness at the inner gates is daring. Are there in situ measurements like from buoys or other observations that support this approach? At least uncertainties should be significantly higher.

Howell et al.
We agree it is "daring" but there are no buoys or in situ measurements to compare against. In fact, there is an overall lack of sea ice thickness measurements in the CAA except for a few winter survey's (Melling, 2002; Haas and Howell, 2015), landfast ice locations (Howell et al., 2016). In the summer months there is pretty much nothing. Therefore, we would like to keep the volume flux estimate in the paper because it would be considered a baseline estimate until it can be refined. Linear interpolated thickness uncertainty is unquantifiable in a meaningful way therefore, we provide a Figure (Figure 3) to indicate and state that the volume flux estimates are likely overestimated over the annual cycle and have revised the text as follows:

Since sea ice thickness values from the proxy ice thickness dataset were not available from May to October, accordingly we used the linear trend of April to November to approximate those values. This follows the climatological record of landfast ice thickness loss through melt in summer that was reported for Eureka by Dumas et al. (2006) in their Figure 9. The reduction in ice thickness at Eureka follows an approximate linear trend between June and September. Figure 3 here shows a time series of plot of CryoSat-2 sea ice thickness at the QEI gates (in black) followed by the time series proxy ice sea ice thickness at Byam Martin Channel (in red), and the linear interpolated ice thickness at Byam Martin Channel (dashed red). Note the thickness decrease with latitude is similar to what has been reported in previous studies (Melling, 2002; Haas and Howell, 2015). With the exception of 2016-2017, the linear thickness approximation likely overestimates thickness for 1-3 months per year (Figure 3) and as a result the inner gate annual volume flux estimates are likely to be overestimated.

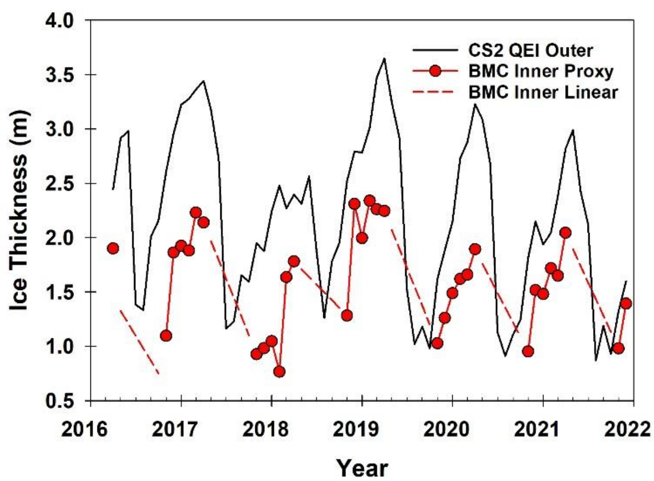

Figure 3. Time series of CryoSat-2 ice thickness for the Queen Elizabeth Islands (QEI; black) outer gates, proxy ice thickness for the Byam Martin Channel (BMC, red) inner gate, and linearly interpolated ice thickness for BMC inner gate (dashed red) from 2016-2022.

4. The authors calculate uncertainties for both area and volume fluxes, and provide estimates in a table, but it is quite difficult to relate them to the flux estimates in the figure. I strongly recommend adding error bars in the figures where you provide flux estimates.

Howell et al.
Agreed. We have placed error bars on the flux Figures.

5. There is the study of Agnew et al. (2008) that provides area fluxes across the CAA. Can you compare area fluxes with those of Agnew et al.?

Howell et al.
That comparison, in addition to ice area fluxes from Kwok (2006) was done in a previous study for the Arctic Ocean outer gates (Howell et al., 2013). We could compare with Lancaster Sound and Jones Sound but we are not really looking at those gates at the monthly scale and Agnew et al. (2008) did not have sufficient data for annual estimates (i.e. losing the ice surface at 89 GHz). The comparison for the Arctic Ocean facing gates was good and the approach is identical so they should be comparable.

More specific comments:
L96: I thought the Landy et al. data set already combines summer and winter sea ice thickness from CryoSat-2: “A year-round satellite sea-ice thickness record from CryoSat-2”? Did you use these data? In the text it sounds like you did the combination of summer and winter data yourself.

Howell et al.
Landy et al. (2022) does do that as it combines Landy et al. (2020) and Dawson et al. (2022). We clarified this in the text as follows:

Sea ice thickness estimates for the outer flux gates were acquired from the CryoSat-2 radar altimeter from October 2016 to September 2021 (Landy et al., 2022) that uses a combination of data from Landy et al., (2020) for the ‘cold’ season (October to April) and Dawson et al., (2022) for the summer period (May to September). A bias correction based on radar model simulations (Landy et al., 2022) is applied to the summer radar freeboards. The entire time series of radar freeboards is then converted to a continuous pan-Arctic record of sea ice thickness using snow loading information from SnowModel-LG (Stroeve et al., 2020) and assuming constant ice-type dependent densities for sea ice (Landy et al., 2022).

L118: The information on the apertures can be provided either in a table or better in Fig. 1, avoiding listing it in the text.

Howell et al.
We do not feel a table is needed for this basic information.

L154: “was determined from the product of the monthly ice area flux and the monthly average CryoSat-2 sea ice thickness” – In the method section you write that you use different thickness data sets (The Landy record and the proxy record) for the inner and outer gates. Please clarify.

Howell et al.
Agreed we clarified as follows:

The sea ice volume flux of the CAA's outer gates from October 2016 to September 2021 was determined from the product of the monthly ice area flux and the monthly average CryoSat-2 sea ice thickness within the 200 km buffer around each gate. For the inner gates the volume flux was determined from the product of monthly ice area flux and the monthly average proxy sea ice thickness. Note we use the larger (i.e. 200 km) buffer for volume flux given the coarse spatial resolution of the thickness products (i.e. 50 km for inner gates and 80 km for outer gates).

L155: This is because you use the "proxy record" here, right? Perhaps mention that. However, I wonder how robust it is to just interpolate between April and October. How do you estimate the volume flux uncertainties in the CAA in summer? Are there any in-situ data to compare with?

Howell et al.
We addressed this in response to Major Comment 3 above.

Figure 2: I suggest adding error bars with the calculated uncertainties. Moreover, in the caption and/or the figure itself, it should be written more clearly which flux and gates/regions are considered here.

Howell et al.
Agreed.

Figure 3: I suggest to also add error bars here. Moreover, in the caption, I assume it should be "NET export/import"?

Howell et al.
Agreed.

Figure 4: Same comment as for Fig. 3. Moreover, the caption says "for 2017 to 2022" – but only 2017-2020 is shown?

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Changed.