Response to Reviewer 1#

This paper tries to monitor the sea ice flux (SIC) changes in Baffin Bay from 1988 to 2015 using the NSIDC sea ice concentration (SIC) and sea ice motion (SIM) datasets. The authors also try and link these changes in SIF to climate variables from the NCEPNCARR dataset. Thought the datasets used for this study are very relevant and results can be very relevant to understanding the climate variability of sea ice conditions in Baffin Bay, after reading the paper, I do not think the authors understand the sea ice conditions in Baffin Bay and the drivers of the sea ice fluxes properly.

Response: Following the suggestion, a introduction of the sea ice conditions in Baffin Bay is depicted in Section 3 in the revised manuscript. Section 3.1 gives a brief description of sea ice coverage. Section 3.2 make a introduction about the general sea ice drift pattern. Section 3.3 presents the trends in concentration and sea ice motion in Baffin Bay. These facts complement the understanding of the changes and the driving forcing of sea ice flux appropriately for different gates as seen in the discussion (Section 5).

My first concern is why the authors keep comparing the SIF of Baffin Bay with the SIF of Fram Strait. The ice regimes of those two regions are very different. The source of the SIF from Fram Strait comes directly from the Arctic Ocean and a large portion of the ice that flows there is comprised of multi-year ice all year round. In the case of Baffin Bay, the ice flows from Lancaster Sound and Nares strait in the summer months and is a mix of multi-year ice and first-year ice but in the winter, the ice mainly comes from first-year ice generated in polynyas of Lancaster Sound and the northern part of Baffin Bay. A major driver in Baffin Bay is the North Water Polynya (NOW) and nowhere do the authors mention this. Also, that polynya exists because of the ice bridge that is created in Nares Strait in the winter which blocks the inflow of thicker multi-year ice from the Arctic Ocean. Fram Strait and Baffin Bay are thus not comparable in terms of SIF.

Response: Thanks for the insightful suggestions. Recognizing that Fram Strait is a totally different areas for sea ice export, in the revised manuscript we remove the comparison with the flux in Baffin Bay. Considering the fact that North Water Polynya (NWP) is the primary ice source to the Bay during cold-freezing periods, we altered the positions of the North fluxgate (Figure 4) to further higher latitudes and quantify the sea ice inflow components originating from Lanscater Sound and NWP. The mitigating effects of sea ice flux though Nares Strait owing to the appearance of ice bridge (arch) during winter period are demonstrated in CIS maps (Figure S1) and reiterated in Section 2.1.3. Quantitatively, our ultimate estimates showing that 78%~85% (Section 5.1.3) of the ice inflow through the North Gate consists of ice grown in NWP. This fact outlines the recurring polynyas during cold seasons as a major contributor to ice area entering into the northern Baffin Bay.

Another issue is the separation between before and after the year 2000. The selection of the year 2000 seems arbitrary to me. Many climate change studies (including the IPCC report) state that there was a climate shift around 1998. Why did the authors not look at before and after 1998? Why don’t there results show this climate regime shift (it should appear in the NCEP-NCARR dataset).

Response: In the revised manuscript, we focus on the issue of interannual variability and the long-term trends of sea ice area flux over the past nearly four decades and discuss the primary causes for the observed interannual variations and trends. As suggested by the reviewer, the inter-period changes, as previously separated by 2000, is not proper and excluded in the revision. Instead, we concentrate on the variability of the month-to-month ice transport of the past four decades (Figure 10) as well as the long-term trends (Figure 11). In particular, the climate changes associated with a warmer Northern Hemisphere over time, as shown in the NCEP-NCAR SAT data (Figure 16), are related to a thinner ice cover (Figure 15) and thus the increased area flux (Figure11).

Also, some results can be explained by the sea ice conditions themselves. For example, the low SIM values on the Greenland coast in the winter months can be explained by the ice conditions. The sea ice along the coast is land fast, i.e. attached to the Greenland coast and does not move (note: the extent varies each year). I would strongly recommend that the authors visit the Canadian Ice Service website (https://www.canada.ca/en/environment-climate-change/services/iceforecasts-observations/latest-conditions.html) and specifically their 30-year ice atlas (https://www.canada.ca/en/environment-climate-change/services/ice-forecastsobservations/latest-conditions/climatology/30-year-climatic-atlases.html) to better interpret the SIF results.

Response: This piece of comment is vital to this study. Accordingly, we inspect the CIS maps for the ice conditions in Baffin Bay. Especially important is the knowledge of spatial distribution of land-fast ice around the coasts of the bay, as provided in the CIS ice atlas. The land-fast ice extent benefits our study in that it helps to identify the zero flux grid cells which generally appears around the endpoints of one fluxgate adjacent to coasts. Secondly, it provides a thread to understand the slow ice motion, as introduced by reviewer, in the region attached to the Greenland coast (Figure 2, red arrows).

Overall, I would not reject this paper since it is very relevant to the studied field of climate change but I suggest major reviews after the authors better describe the region of interest and its different drivers. I would suggest to remove the comparison with Fram Strait as they don't have the same ice regimes. I would also study a bit more in detail the ice conditions which can be obtained on a weekly basis from the Canadian Ice Service in order to improve the interpretation of the results.

Response: As suggested by the reviewer, a major review is conducted by the authors. We remove the comparison with ice export through Fram Strait for its totally geophysical setting for sea ice. More information about the ice conditions in Baffin Bay is given (Section 3), such as the appearance and distribution of ice bridges in Nares Strait (Figure s1), the annual sea ice extent of the bay and coverage of NWP (Figure 6), the typical current circulation systems (Figure 1), and so on.

Specific comments: In the figure caption, I suggest adding more detailed descriptions of the figures. Specify what the a), b), c) and d) subfigures are etc. For Figure 7, what is the reference to generate the anomaly map? Usually it's a specific period that is used but it was not specified in the text. Also, what are the units if any for this anomaly map?

Response: Revised as suggested. To make it clear and direct to readers, we add captions to Figures with multiple subfigures (such as Figure 10). Figure 7 in the original submission has been removed in the new version of manuscript. Moreover, in the revision, we specify for each examined period or time interval anywhere mentioned in case of any ambiguity. For instance, we analyze the sea ice area flux for the four different seasons including Winter

(December-February), Spring (March-May), Summer (June-August), and Autumn (September-November). In some places , we refer the cold-period to include winter and spring or warm-period to cover summer and autumn seasons, if no particular annotation is given (See 5.3.2). Note that in the comparison of accumulated sea ice flux between our and previous studies (Figure 5), the cold period spans a time interval from Nov to May. Therefore, we try every effort to give an additional explanation about the time range to ensure that the alternatively used time period will not confuse the readers.

Response to Reviewer 2#

General Comments:

In reference to the review criteria provided by The Cryosphere (https://www.thecryosphere.net/peer_review/review_criteria.html), I submit the following general commentary on this work.

The scientific quality of this work is Fair. The purpose of the work is articulated, however the objectives laid out in the second-to-last paragraph of the introduction section do not strike this reviewer as testable hypotheses. They are rather statements resulting in the paper becoming something of a data report. The analyses presented are somewhat perfunctory, and potentially these points indicate a lack of understanding of the physical atmospheric and/or oceanic processes acting on the surface (ocean or sea ice) within Baffin Bay.

Response: Thanks for the overall insightful comments. In the revised manuscript, we make it clear that our primary attempt is to quantify the sea ice inflow and outflow components through the key fluxgates of Baffin Bay and to investigate the related causes for their variability and trends. According the suggestions of reviewers, the fluxgates have been reslected to account for different sources of ice (Figures 1 and 4). In addition to the interannual variability, the trend of sea ice area flux for different gates are discussed and possible causes are analyzed.

Compared with the first submission, we try to present our study in a form of investigation rather than a data report. We present more knowledge with regard to the atmospheric and/or oceanic process. For instance, the general circulation pattern of ocean currents in the bay is shown in Figure 1. The description of NWP (Figure 6) and associated ice bridges in Nares Strait are given (Figure s1). Additionally, the fast-ice extent is presented in Figure 2 to discriminate the grid cells with a zero flux and interpret the slow ice motion in the areas nearby the coast. For the first time, the inflow and outflow components through Baffin Bay over the past nearly four decades (1978/79-2016/2017) are quantified (Sec.4, Figures 10 and 11). Further investigation suggests that, the warmer atmosphere are found to be a main driver to the increased sea ice motion as well as the area flux to a thinner ice floe in the bay (Figures 15 and 16). Therefore, in the new submission we made efforts to improve the understanding of the variability and trends of Baffin Bay sea ice area flux associated with inflow and outflow components (See the discussion section, Sec.5) for more details).

The first mention of the hemispherically significant North Water Polynya does not occur until Line 6 on page 23 of this work. In this vein, it's not really explained that the sea ice in Baffin Bay may be as a result of import from the Lincoln Sea as a result of motion through Nares Strait, Kane Basin, and then Smith Sound before it might either enter Baffin Bay, or encounter an ice-bridge blocking inflow to Baffin Bay from the north. The annual and seasonal presence/absence of this very important ice-bridge feature and the amount of MYI imported from the North is not explicitly investigated in this work.

Response: As North Water Polynya (NWP) is an important scenario in the northern Baffin Bay (Figures 1 and 6). In this study, we outline its importance and location not only in the introduction section, but also in the description of sea ice condition in Section 3.1 (Figure 6, panel for April). Moreover, the contribution to the sea ice inflow into Baffin Bay is quantified. The presence and absence of ice-bridge in Nares Strait are illustrated in Figure S1 and its importance to sea ice flux stoppage is discussed in the relevant texts. Anyway, the significance of NWP and ice bridge are reiterated in the new submission.

The importance and effects of sea ice bridge to block ice inflow are outlined in the revised manuscript (Section 2.1.3). Figure S1 gives a typical case of ice bridge formed in Nares Strait. However, due to the coarseness of NSIDC ice motion data (25km), compared to smith sound (~30 km), it is unlikely to accurately estimate sea ice flux in such a narrow gate. For narrow fluxgate like Smith Sound, land contamination would be a server problem to satellite observations. Instead, with reference to a published result of between 1996/97 and 2008/2009 about ice flux via Nares Strait that was derived high-resolution satellite observations (such as SAR in Kwok (2007), with a spatial resolution of several hundred meters), we get an estimate of ice grown in NWP. That is, by subtracting the inflow from Nares Strait and inflow from Jones Sound from the ice inflow across the North Gate, the part of sea ice grown in NWP is then obtained as, on average, 78%~85% of the inflow through the North Gate

First-year stages of development of sea ice in Baffin Bay may then also have been grown in place within the North Water and exported southward, depending on the formation of the ice-bridge, and the amount of ice in the Bay, which has been imported from the Canadian Arctic Archipelago (CAA), mostly through Lancaster Sound.

Response: In the revised manuscript, the sea ice area inflow to the Baffin Bay and ice produced from NWP are both quantified. Please see Section 5.1 for the investigation of the possible ice sources for sea ice entering into the Baffin Bay.

Since the authors chose a position for their northernmost ‘Gate A’ south of Lancaster Sound, the flux of sea ice from the CAA in the west, or from Smith Sound in the north, cannot be differentially discerned. Other important considerations that occur to this reviewer include sea ice melt during transport southward within Baffin Bay, especially considering that new and young stages of development (<30cm thick) may be grown and exported from the North Water Polynya.

Response: Following the suggestions and in order to discern the diverse Baffin Bay sea ice inflow ice sources, we redefined the North Gates to a further north location (Figure 4). Examination of sea ice inflow through the North Gate reveals that NPW is the main contributor of inflow (Section 5.3) and a smaller fraction of inflow come from Nares Strait (Section 5.1) and/or Jones Sound. In addition, sea ice inflow through the Lanscater Sound is also obtained (Section 5.2). Meanwhile, taking into account the outflow of sea ice via the South Gate, we find a net gain of sea ice between the regime of ~65 °N and ~75 °N within the bay during cold periods (winter and spring) and a net loss during warm melting period (autumn and summer). The addition of sea ice is mainly through the freezing mechanism whereas the ice loss is caused by enhanced melt during transport southward within the Bay.

Please refer to section 4.2 for more information.

Finally, it might be that the authors have not accounted for the presence of fast ice around Baffin Bay in fall, winter and spring, especially on the Greenlandic (east) ends of their passages A, B, and C. All of these points above make the comparison of these presented data in Baffin Bay to the data presented from Fram Strait a bit of a stretch to this reviewer. I appreciate that Kwok 2007 makes a comparison of the annual volume export he calculated for Baffin Bay and Davis Strait to the annual export of sea ice through Fram Strait, but it's my opinion that Kwok made that comparison in his 2007 work to simply highlight the amounts of sea ice exported southward in the two regions, and not to compare the processes or sea ice stages of development that typically are exported in the two areas which are not physically similar.

Response: In the new submission, land-fast ice distribution is discerned from Canadian Ice Service (CIS) atlas (as shown in Figure 4). According to the suggestions, we remove the comparison with sea ice area flux through Fram Strait.

The fluxgates are reselected. The North Gate and Lanscater Sound are chosen to stand for ice inflow while the South Gate is selected to represent the ice outflow via Baffin Bay. The middle gate is not useful to convey new knowledge and not kept. The North Gate is different from the first submission for its relocated place toward further north. This gate is designed to provide valuable information about ice inflow from different ice sources, including Jones Sound, Nares Strait, as well as NPW.

The significance of this work is Poor. I think especially a re-worked version of this paper could improve our understanding of sea ice flux form this important region, but as it stands this work falls short of improved scientific understanding of the region and its relevant physical oceanographic, atmospheric, and/or sea ice processes. The analyses are comparative rather than investigative, and their presentation is in the style of a data report.

Response: Compared with the first submission, we try to present our study in a form of investigation rather than a data report. We present more knowledge with regard to the atmospheric and/or oceanic process. For instance, the general circulation pattern of ocean currents in the bay is shown in Figure 1. The description of NOW (Figure 6) and associated ice bridges in Nares Strait are given (Figure s1). The fast-ice extent is presented in Figure 2 to discriminate the grid cells with a zero flux and interpret the slow ice motion in the areas nearby the coast. For the first time, the inflow and outflow components through Baffin Bay are quantified for the past nearly four decades (1978/79-2016/2017) (Sec.4, Figures 10 and 11). Further investigation suggests that, the warmer atmosphere are found to be a main driver to the increased sea ice motion as well as the area flux to a thinner ice floe in the bay (Figures 15 and 16). Anyway, in the new submission we made every effort to advance the understanding of the variability and trends of Baffin Bay sea ice area flux associated with inflow and outflow components (See the discussion section, Sec.5) for more details).

The presentation quality of this work is Fair. The figures are too numerous, and each conveys too little information. The authors convey too much data in Tables, while the text does not explain either the figures or tables more than superficially. This work is way too long, and clarity of direction is missing from the objectives onward through the results and discussion sections. The reason for the decadal period break at 2000/2001 is not obvious to this reviewer. It seems a break of convenience rather than scientific reasoning. Little in the way of conclusions is presented in that section of the text, though "*: : :*A comparison shows that our SIF estimates are reasonable consistent with previous results" (page 25 Line 8) is encouraging, it's not a conclusion. There are two more conclusions stated in Lines 9-11 of Page 25, but their validity is brought into question for this reviewer by the changing definition in the work (Oct or Nov to May depending on the section I read). The conclusions based on the three defined Gate locations make this reader interested in why their locations were chosen (especially given my previous note on the position of the northernmost Gate)? The last two paragraphs of the conclusions section are statements, which cannot be concluded as a result of the new work presented here.

Response: Based on the suggestions, we remove the numerous figures and Tables that convey little usefule information. The main objective of this study is clarified in the Introduction section, including the quantification of sea ice inflow and outflow of Baffin Bay, the examination of the variability and trends of ice area flux, as well as the investigation of causes for the observed trends in ice motion and area flux. We remove the discussion of area flux associated with climate change with a break of decadal period at 2000/2001 since this simplified partition has no clear geophysical implications rather than for the convenience of calculation. Rather, the month-to-month variability of sea ice area flux across the fluxgate for different decadal periods are given in Figure 10 (Sec. 4.1). Throughout the revised manuscript, the definition of seasonal and annual fields, as in reference to sea ice area flux, are clarified in the associated texts, with Winter spans from December to February, spring (March-May), summer (June-August), autumn (September-November), and the annual cycle (September-next August). We remove the middle gate since the little useful information is conveyed by the comparison with other gates. Besides, comparing with the first submission, the location of the fluxgates to study the sea ice area flux are relocated, especially for the northward shift for the North Gate (Figure 4). The redefinition of the North Gate is favorable to the quantification of ice production in NWP (see 5.1.3 for more details), the well-known recurring polynyas in the northern Baffin Bay.

Specific Comments: P1. L12: This sentence should make some reference to sea ice melt? L14: Why three passages, this really isn't useful information in the abstract given there is no geographical reference to their actual positions. L20: Causation is not shown in the work. Could the decline in SIM be a result of the fact that the SIM data are calculated in part from the SIC data? L24: Unclear what you mean here.

Response: P1. L12: we have rewritten the sentence to refer the exported sea ice from Baffin Bay as one of important **solid** fresh waters input to the seas downstream.

L14: The passages are redefined in the new submission and renamed with a reference to its location: North Gate, South Gate, and Lanscater Sound, etc.

L20: The causation of the increased SIM is presented in the revision.

L24: The ambiguous sentence has been removed.

L28FF: The data exist to determine if the sea ice is in free drift in Baffin Bay and Fram Strait, but quantification is not attempted. Not sure why the authors insist on acronyms, especially for Fram Strait?

Response: This sentence is removed since the comparison with Fram Strait conveys limited knowledge. The acronyms 'FS' for Fram Strait is not saved in the revision.

P2. L7: What is the potential impact? L9: Does outflow imply melt?

Response: Since outflow does not necessarily represent melting, we remove the sentences.

P3: L1: “passages” is a poor word choice, my opinion only. L2: Is there an effect to the trends/forcing? L5: What is the point of the comparison to Fram Strait? L7: “preferred*: : :*” Whose preference? Why? L28: I wonder what causes the discrepancy in the SMMR and SSM/I records with respect to sea ice motion data?

Response: L1: we use fluxgate or gate instead of passage. L2: There is not an effect to the trend from the atmosphere (Section 5.1 or Figure 14) and the causes for the trend are examined with respect to ice thickness changes (Section 5.3). L5: The comparison is removed. L7: The analysis with large-scale atmospheric index is not held in the revision according to suggestions of the reviewer. In the revision, connections with regional atmosphere variability, with reference to cross-gate SLP difference, is taken as an important predictor for the variability in Baffin Bay sea ice area flux. L28: The sea ice concentration is available every other day for the period of SMMR which would bring a discrepancy. A temporal interpolation method is used to fill the gap and daily SIC is obtained for the period Nov 1978 to July 1987. Thereby we can extend the whole study time series to 1978/1979-2016/2017.

P4. L5-9: this whole section is worded like the authors actually did this processing?

Response: The relevant reference has been added in the revision.

L10: Maybe use the whole words? Especially in a Section Heading? Figure 1: The position of Gate A is too far south to allow for quantification of ice flux from Lancaster Sound. I’m not really sure of the point of Gates B and C unless there’s some quantification of melt? There’s no scale for the magnitude of the vectors displayed on the figure.

Response: L10: the whole words is used in all Section Heading. The position of the North Gate is moved to further north and the ice flux from Lanscater Sound is quantified. Gates B is removed as no information of melt can be derived. The scale of the magnitude of ice motion vectors are added on the relevant figures.

The fluxgates are rearranged in the revision (Figure 4). The North Gate and Lanscater Sound are chosen to assess ice inflow while the South Gate is selected to study the ice outflow via Baffin Bay. The middle gate is not useful to convey new knowledge and not kept in the revision. The North Gate is different from the first submission for its northwardly relocated place. This gate is designed to provide valuable information about ice inflow from different ice sources, including Jones Sound, Nares Strait, as well as NPW (Section 5.1.3).

P5. L8-10: What is the mechanism for ice motion through Baffin Bay with the NAO atmospheric patterns? Especially considering the height of the Greenland Ice Sheet that separates the Icelandic low from Baffin Bay? Does it even make sense that the NAO should drive ice drift in Baffin Bay? Some justification of this use of the NAO should be made?

Response:L8-10: Based on the suggestions, we remove the analysis with regard to the connections between NAO and sea ice drift in Baffin Bay.

L17-24 and Table 1: Why order the Gates A, C, B, in the explanation of their positions? Why are all their lengths different in the text and the table? Seems like those lengths should be consistent?

Response: The gates have been redefined and relocated for A (the North Gate), and the middle gate (B) is removed in the revision. Gate C is renamed as the South Gate. The reasoning to rearrange the fluxgate is mentioned above. In addition, we examine the texts and table to ensure a consistent use of the length for the Gates.

P6. L2-3: Is this assumption valid? L11: Maybe call the Gates “North”, “Mid”, and “South” if you’re going to continue using three so their positions are immediately apparent to the reader?

Response: L2-3:The assumption is widely adopted in previous studies and especially one may refer to Kwok’s studies associated with sea ice area flux. L11: The Gates are renamed following the suggestions to specify the geographic information.

L14, L16: Here’s where I first noticed that the months used for “winter” change constantly through the work. Nov-May vs. Dec-May? There’s got to be a consistent set of winter months used I think? This really reduced my trust in the analysis presented. L18: Where is the Cuny Gate in relation to Gates B, or C?

Response: L14, L16: In the revision, four seasons are considered, including the winter (Dec-Feb), Spring (Mar-May), summer (Jun-Aug), and autumn (Sep-Nov). Also, the cold period is referred to include the winter and spring months while the warm period spans the summer and autumn months, if no particular annotation is given. These definitions hold constantly in the new submission unless particular indication is shown. L18: Cuny’s estimate is related to the South Gate in the revision (Figure 4). In Figure 5, the comparisons are confined to a time span from Nov to May in the following year.

P7. Figure 2: The lines, colours are too hard to discern. Now winter is Nov-May. L12: Now winter is Oct-May? There are a bunch of typos in this paragraph. L13: It’d be nice to see the sea ice concentration data? L14: Where is the wind forcing data?

Response: The figure is modified to make a discernable color. To neatly convey information about sea ice drift pattern in Baffin Bay, this part has been reworked in the new submission (see section 3.2)

P8. Figure 3: The previous figure was in cm/s, now we’ve changed to km/day, and we have a legend for the magnitude of the quivers. Maybe add the Gates to the figure? It would be nice to see the actual sea ice concentration? What portion of the sea ice motion in Baffin Bay is driven by ocean currents? L3: Doesn’t the data exist to determine this? Even the magnitude of the gradient? L6: Could the pattern not be visible due to your use of monthly averages? Seems like the higher the ice concentration the more likely that ice motion events might be temporally discrete due to the magnitude of the forcing required?

Response: Figure 3: The unit has been changed to km/day throughout the manuscript. The sea ice concentration changes of an annual cycle are shown in Figure 6. The portion of sea ice motion driven by ocean currents can be observed through the comparison with Figure 1 and Figure 6. Relevant explanations have been given in associated texts in the revision. Besides, the sea level pressure (SLP) fields are overlaid on Figure 6. The presence of SLP is helpful to distinguish the effects of wind forcing on facilitating the sea ice motion ice motion in Baffin Bay.

P9. L5: Why 4c before 4b? Figure 4: I don’t understand why the comparison to Fram Strait. Probably should specify the Gates in the figure caption? L16-17: Why not quantify this? Also now winter is Dec-May?

Response: Following the suggestions, the comparison with Fram Strait is removed and the figure captions as depicted in Figure 10 is specified. The season discrimination is redefined (see response above).

P10. L7: There seems no scientific reason to break at 2000? L9: Now December is in the autumn? L15: What use the sci.notation? Why not just write -21km2/day? L31: Not really a decadal change, it’s a change between two decades.

Response: Based on the relevant suggestions, we removed this part of results.

P11.L12: Now winter is Nov-May

P12. L10-11: This is not a result of this work and is left unsubstantiated.

Response: in the revision, the delayed ice freezing period due to warmer climate is refer to the published literature of Stroeve et al. (2014) (see P22. L21 in the revised manuscript)

L8: I don’t know where this statement comes from. It’ unsubstantiated by the work presented.

Response: the summer or autumn trend in ice flux is negligible and no further analysis is given in the revision.

P14. Table 1: There’s a better way to graphically display the pertinent/important parts of this Table. You’re asking the reader to do too much work to understand your analysis.

Response: The table is removed for a clear interpretation but rather a comprehensive figure is provided (Figure 14)

P15-16. Figures 8, 9, 10: These figures are to small, to hard to read. Why use the three different significance levels? Figure 10: the y-axis keeps changing, makes it hard to compare within the columns.

Response: Since these figures show little useful information, we remove them and integrate them into a comprehensive one (Figure 14). More details are given in the following associated texts.

P17. L3: The increasing sea ice motion trend is not caused by a positive sea ice flux trend; you’ve put the cart before the horse here. L12: now winter is from Oct-May

Response: Reformulated as suggested.

P18. L3: What’s the point of this section? L4: What does this sentence actually mean? Maybe this is some reference to melt within an area between two Gates?

Response: This part is reworked and relevant explanation is reformulated in the revision, please see section 4.2 for more details.

P20. L15FF: What about the source of the exported sea ice? Smith Sound? Grown in the Northwater? From the CAA through Lancaster Sound? Surface winds in Baffin Bay are tricky to model because of the elevation of the Greenland ice sheet and the CAA islands? How well do these model winds actually represent reality? L16: What do all these acronyms mean? L20: Surface winds towards the southeast are northwesterly winds.

Response: The inflow components to Baffin Bay from diverse sources, Nares Strait, Lanscater Sound, or grown in the North Water Polynya are discussed in Section 5.1. Wind data is not used in the revision.

P22. This whole page seems like conjecture, it should all actually be borne out by some analysis. Kind of seems like the authors are listing possibilities rather than elucidating processes.

Response: In order to understand the associated air and physical processes, we investigate the connections of sea ice flux variability with cross-gate SLP difference (Sec. 5.2), and examine the linkage between ice motion and ice thickness through a preliminary simulation (Sec. 5.3).

P23. L16-17: isn’t the NAO calculated from the pressure difference between these two atmospheric phenomena? Hurrell 1995?

Response: NAO is not considered in the revision based on the above comments of the reviewer.

P24. L16-18: The internal stress of the sea ice pack should be able to be approximated at least. This sentence seems like conjecture as is.

Response: The linkage to a faster movement of ice pack is mostly attributable to ice thickness decline and the analysis with internal stress is beyond our scope of this study.

P25. Figure 17. Any actual information in these panels is undiscernable due to their size.

Response: This Figure is removed in the revision.

There's no mention of the North Water Polynya in the conclusions section. L15-20: I think the statements in this paragraph remain unsubstantiated by this work. What about fast ice extent? The last two sentences are not conclusions of this work. I don't really understand why you've listed surface winds and sea level pressure because they're two sides of the same coin, same goes for SAT and SST?

Response: The NWP is reiterated in the revision. For instance, one may refer to Figure 1 and 6 and associated texts. In particular, Section 5.1.3 also specify the contribution of sea ice grown in NWP. We kept well-demonstrated SLP and SAT fields, and remove the SST and winds. As suggested, SLP and winds (or SAT and SST), reflect the same climatic scenario.

P26: These are not new results. As indicated in part by your reference to Kwok's papers. The last sentence of this paragraph is not a conclusion that is supported by the work presented

Response: The conclusions are reworked and the associated unproven texts are eliminated.

Response to Reviewer 3#

The paper investigates sea ice area flux through Baffin Bay from 1988-2015, using satellite observations of sea ice motion and sea ice concentration (NSIDC). In particular, the authors calculate the ice area flux at three gates in the north, middle and south of Baffin Bay. They evaluate variability and trends of ice area flux as well as links to sea level pressure (SLP) and the North Atlantic Oscillation (NAO) index.

Response: According to the comments of reviewers, we rework the study with the primary focus on the subject regarding the sea ice inflow and outflow through Baffin Bay (Figures 1 and 4). Hence, three fluxgates are considered in the revision, including the North Gate, South Gate, and Lanscater Sound. The Gates were renamed with a reference to geographic location to facilitate the direct understanding of readers. Moreover, the inflow components from different ice sources is examined, including sea ice area flux from Smith sound (Nares Strait), Lanscater Sound, as well as ice grown in North Water Polynya (NWP) (Section 5.1). The interannual variability is connected to the cross-gate sea level pressure (SLP) difference (Section 5.2). The linkage with NAO is not held in the new submission, since reviewer 2# suggests a fragile relation between NAO and sea ice flow in Baffin Bay exists because the effects of NAO is likely kept away from Baffin Bay by the high elevation of Greenland ice sheets. Furthermore, causes for the increased sea ice area flux are related to the sea ice thickness decline associated with a warmer climate. Therefore, the new submission represents for a substantial revision of the initial work.

General Comments:

I don't really see that the paper is following a particular thread. The formulation of the goals in the introduction is very brief and general. The authors should make clear if this is rather a method paper, introducing a new data set, or a scientific study to investigate sea ice fluxes and related processes in the Baffin Bay.

Response: In the new submission, we make a straightforward attempt of this study to investigate the sea ice inflow and outflow through Baffin Bay and related causes for the observed interannual variability and the trend in sea ice area flux over the nearly 40-yr time series record (Section 1).

I find many motivations and conclusions questionable. For example, what is the motivation to compare the derived Baffin bay fluxes with the fluxes in the Fram Strait? I don't see why this is relevant. At most, one could compare the net fluxes of different gates in the Arctic and estimate the total sea ice export. But the mechanisms in both regions are very different. The Fram Strait ice flux is characterised by multiyear sea ice, which is advected by the transpolar drift and exported through the Fram Strait. In contrast, the Baffin Bay ice fluxes are characterised by first-year ice in winter, when no multiyear ice is exported through the Nares Strait due to an ice bridge. During summer, this ice bridge is collapsing, and multiyear ice can be exported through the Nares Strait. These processes are not well explained in the paper, but are very relevant to understand ice fluxes in this region. Another debatable point is the decadal change around the year 2000. This seems arbitrary. The interannual variability seems to be quite substantial and therefore I don't think that there is a significant change in SIF between those particular decades (see Figure 2).

Response: These comments are very insightful. Following the suggestions, the comparison with Fram Strait is not saved in the revision. The importance and effects of sea ice bridge to block ice inflow are reiterated in the manuscript (Section 2.1.3). For instance, Figure S1 gives a typical case of ice bridge formed in Nares Strait. However, due to the coarseness of NSIDC ice motion data (25km), compared to smith sound (~30 km), it is unlikely to accurately estimate sea ice flux in such a narrow gate. For narrow fluxgate like Smith Sound, land contamination would be a severe problem to satellite observations. Instead, in reference to a published result of between 1996/97 and 2008/2009 about ice flux via Nares Strait that was derived high-resolution satellite observations (such as SAR in Kwok (2007), with a spatial resolution of several hundred meters), we get an estimate of ice grown in North Water Polynya (NWP). That is, by subtracting the inflow from Nares Strait and inflow from Jones Sound from the ice inflow across the North Gate, the part of sea ice grown in NWP is then obtained.

Based on the suggestions, the simply separation in 2000 do not have scientific implications. Rather, the results about the decadal changes with respect to the annual month-to-month variability for four different decades are described in section 4.1 and shown in Figure 10.

Another major concern is the presentation. There are too many figures, sometimes of low quality, and with too little significance. I strongly recommend to revise the figures in order to better support the findings and main messages of the paper. For example, Figures 8, 9 and 10: It is neither explained the meaning of the lower case letters in the brackets, nor the meaning of the rows (i guess the different gates + Fram Strait?). I would also suggest to better separate results and discussions. In the results section, findings are often discussed. Considering all these concerns, I suggest very substantial revisions. Actually, I think that many parts of the paper need to be rewritten, and also the analysis and conclusions need to be reconsidered, before it may be suitable for publication.

Response: Thanks for these valuable suggestions. In the revision, we remove lots of figures and rewritten most of the parts. The results and discussion are further adjusted for a clearer separation. Indeed, the new submission represents for a reworked version of the study. The analysis and conclusions are considered after a prudent consideration.

Detailed Comments:

P3L1: What is the motivation to consider three passages at the chosen locations?

Response: The fluxgates are reselected in the revision. The North Gate and Lanscater Sound are chosen to stand for ice inflow while the South Gate is selected to represent the ice outflow via Baffin Bay. The middle gate is not useful to convey new knowledge and not held then. The North Gate is different from the first submission for its relocated place toward a further north position. This gate is designed to provide valuable information about ice inflow from different ice sources, including Jones Sound, Nares Strait, as well as NPW.

Please add some explanation.

Figure 1: There are Chinese (?) letters in the figure.

Response: Modified as suggested

P5L21: What do you mean here (and in other places) with “grid”? Do you mean grid cells, pixels? This needs to be explained better, i.e. use grid cells or pixels.

Response: Corrected as suggested

P10L6-7: can you proof that this change is significant? In view of Figure 2, I would doubt. See my major concern above.

Response: Please refer to the relevant response to the major concern

Figure 2: Make the figure larger, please!

Response: Modified as suggested. See Figure 5 in the revision

Figure 3: The scaling of the arrows changes between 0.1 km/day and 10 km/day. Please use a uniform scaling. Otherwise, the different months are hard to compare.

Response: Modified as suggested. See Figure 7 in the new submission.

Figure 7: What are a, b, c and d? There is no information in the figure caption.

Response: This Figure is removed but other Figures with multiple panels are all added with the figure caption (For example, Figures 10, 13, and 14).

Figure 14: Make the figure larger, please!

Response: This Figure is removed

P17L3: “For passages A and B, the increasing SIM trend (Figure 10b and f) is primarily caused by a positive SIF trend” *: : :* This doesn’t make sense. SIF is derived using SIM.

Response: This is a wrong sentence and has been reformulated.

P24L4-5: “However, Figure 16 suggests that the monthly SIF is only slightly 5 correlated with the NAO index for the three passages through Baffin Bay (R = 0.23∼0.32)”
: : : Why should they be correlated? See my major concern above.

Response: The NAO effects are kept away due to the height of Greenland ice sheets. Therefore, we remove the concerning discussion of the linkage with it.

Baffin Bay sea ice inflow and outflow:1978/1979-2016/2017

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Abstract.

Baffin Bay serves as a huge reservoir of sea ice which would provide the solid fresh water sources to the seas downstream. Employing satellite-derived sea ice motion and concentration fields, we obtain a nearly 40-yr record (1978/1979-2016/2017) of the sea ice area flux through key fluxgates of Baffin Bay. Based on the estimates, Baffin Bay sea ice area budget in terms of inflow and outflow are quantified and possible causes for its interannual variations and trends are analyzed. On average, the annual (September-August) inflows through the North Gate and Lancaster Sound are on the order of 205.8(±74.7)×10^{3}km^2 and 55.2(±17.8)×10^{3}km^2, respectively. In particular, a comparison with published results seem to suggest that about 75%~85% of the inflow through the North Gates is newly-formed ice produced in the recurring North Water Polynya (NWP), in addition to the inflow via Nares Strait and Jones Sound. Meanwhile, the mean outflow via the South Gate approaches to 394.3(±110.2)×10^3 km^2. The distinct interannual variability for ice area flux through the North Gate and South Gate is partly explained by wind forcing associated with cross-gate sea level pressure difference, with a correlation of 0.62 and 0.68, respectively. Also, significant increasing trends are found for the annual sea ice area flux through the three gates, amounting to 38.9×10^3 km^2/de, 82.2×10^3 km^2/de, and 7.5×10^3 km^2/de for the North Gate, South Gate, and Lancaster Sound, respectively. These trends are chiefly related to the increasing ice motion which is associated with a thinner ice owing to the warmer climate over the past decades (i.e. higher surface air temperature and shortened freezing period).

1. Introduction

Baffin Bay is a semi-enclosed ocean basin that connects the Arctic Ocean and the Northwest Atlantic (Figure 1). It covers an area of 630 km^2 and is bordered by Greenland to the east, Baffin Island to the west, and Ellesmere Island to the north. From the north to the south, the bay spans approximately 1280 km. In the north, it connects the Arctic Ocean through Nares Straits and the channels of the Canadian Arctic Archipelago (CAA). In the south, the bay is separated from the Labrador Sea by Davis Strait (~350 km in width). The width of the bay varies greatly, with a range of approximately 100 km to 600 km.

The mean circulation of Baffin Bay is characterized by a cyclonic pattern (Figure 1) (Melling et al., 2001; Dunlap and Tang, 2006). In the east side of the bay, a northward flowing West Greenland Current (WGC) along the Greenland coast carries warm and salty water from the North Atlantic. On the west side, the Baffin Current (BC) flows southward along the coast of Ellesmere and Baffin Island, bringing cold and fresh Arctic water and sea ice through Baffin Bay to Labrador Sea. Therefore, Baffin Bay serves as an important sea ice reservoir and is an important fresh water source to Labrador Sea downstream (Curry et al., 2014; Qian et al., 2016; Cuny et al., 2002). A direct potential consequence of sea ice outflow is the formation of lighter sea-water that will strengthen the stratification of Labrador Sea through stabilizing the water column (Goosse et al., 1997; Rudels, 2010; Curry et al., 2014; Qian et al., 2016). These changes will potentially influences on the strength of the meridional overturning circulation mechanism of the North Atlantic Ocean which ultimately affects global deep-water circulation and exchanges (Aagaard and Carmack, 1989; Holland et al., 2001; Jahn et al., 2010; Hawkins et al., 2011; Cimatoribus et al., 2012; Yang et al., 2016).

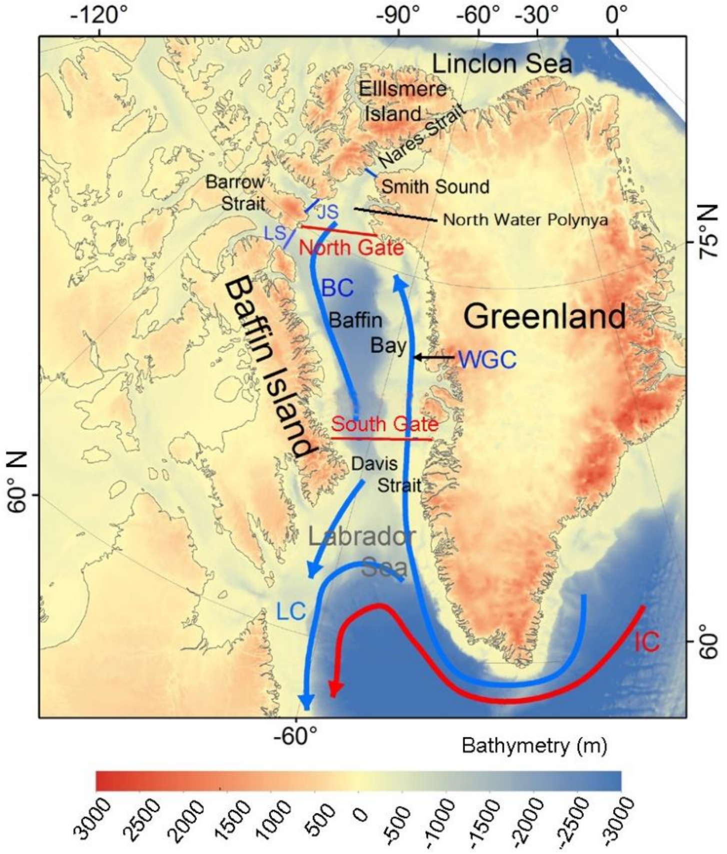

Figure 1. The mean circulation pattern in Baffin Bay (blue and red arrows) and the locations of the key fluxgates to assess sea ice area flux through the bay. The colder west Greenland current (WGC), Baffin Current (BC), and Labrador Current (LC) are marked with blue arrows. The warmer Iriminger Current (IC) is represented by the red arrow. The key fluxgates through which sea ice floats into the bay includes Nares Strait, Jones Sound (JS), and Lancaster Sound (LS). Area flux

through a defined North Gate together with the LS flux is used to quantify the sea ice area inflow to the bay. The outflow fields are depicted using flux via the South Gate.

Sea ice inflow and outflow have been considered as important variables for interpreting the sea ice area balance of the Arctic Ocean (Kwok et al., 2005; Spreen et al., 2006; Kwok, 2007; Kwok, 2009; Kwok et al., 2010; Smedsrud et al., 2011; Krumpen et al., 2013; Kwok et al., 2013; Bi et al., 2016a; Bi et al., 2016b; Krumpen et al., 2016; Smedsrud et al., 2017; Zhang et al., 2017). For instance, satellite-derived sea ice export has been investigated in some key water fluxgates around the periphery of the Arctic Basin, with Fram Strait being the primary focus of study owing to its significant contribution to the changes of the Arctic sea ice extent (Smedsrud et al., 2011; Smedsrud et al., 2017). In Baffin Bay, sea ice loss due to outflow through Davis Strait can be largely replenished by the inflows from the north though the Lancaster Sound (LS), Jones Sound (JS), and Nares Strait (Figure 1). Additionally, North Water Polynya (NWP), approximately located between Smith Sound and the North Gate (Figure 1 and S1), is deemed as an important source of newly-formed sea ice to the bay.

Baffin Bay sea ice inflow and outflow have significant implications for understanding the current radical climate change, becasue a strong atmospheric warming trend has been widely noted in the northern high latitudes (Serreze et al., 2009; Stroeve et al., 2014; Graham et al., 2017; Stroeve et al., 2018). In Baffin Bay, surface air temperature has increased by 2 to 3 ℃/de since the late 1990s (Peterson and Pettipas, 2013), resulting in prolonged days of sea ice melting there (i.e. earlier melting onset and delayed ice-freezing startup) (Stroeve et al., 2014). Accordingly, a rapid decline of sea ice coverage in all seasons has been clearly identified in the bay (Comiso et al., 2017b; Parkinson and Cavalieri, 2017). Within the context of such a pronounced climate change, examining the variability and trends in sea ice outflow through Baffin Bay over a long time series is of particular interest. Although interannual variability in sea ice inflow and/or outflow components in Baffin Bay has been reported in several studies (Cuny et al., 2005; Kwok, 2007; Curry et al., 2014), robust knowledge of their trends is of necessary to predict future changes and validate model results. This study attempts to provide an extended record of the satellite-derived sea ice inflow and outflow over nearly four decades (1978/1979-20116/2017) through the key fluxgates of Baffin Bay and to examine the possible causes of the trends.

2. Data description

2.1 Data

2.1.1 Sea ice motion

The Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors product was provided by the National Snow and Ice Data Center (NSIDC) (Tschudi et al., 2016). This product has been widely used by the modeling and data assimilation communities (http://nsidc.org/data/NSIDC-0116). It is derived from a variety of sensors on satellite platforms, including the Advanced Very High Resolution Radiometer (AVHRR), Scanning Multichannel Microwave Radiometer (SMMR), Special

Sensor Microwave Imager (SSM/I), Special Sensor Microwave Imager Sounder (SSMIS), and Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), and merged with buoy measurements from the International Arctic Buoy Program (IABP) to obtained estimates determined from the reanalyzed wind data. When conducting the present study this product was available for the period from November 1978 to February 2017 (Tschudi et al., 2016).

To assess the NSIDC data, a reference product of sea ice motion, which is visually retrieved from high-resolution (~100 m) Envisat wide-swath (~450 km) observations, is employed. The Envisat estimates, sampled on a 10 km grid cell, have an overall uncertainty of ~300 m (Kwok, 2007). To facilitate a direct comparison, the final Envisat estimates are smoothed to a 25-km grid, and then spatially registered to the NSIDC data.

Two examples of Envisat ice motion fields, acquired on February 2007, are shown in Figure 2. One example covers a cyclonic circulation along the west coast of Greenland (red arrow) and the other is located in the area next to Davis Strait (blue arrow). Comparative results (Figure 3a) present a mean bias of -0.68 km/day in ice speed between the two records (i.e., slightly slower NSIDC) but a relatively large standard deviation of difference (3.11 km/day). Furthermore, there is a small average difference of 3.4 ° in vector angle (Figure 3b), indicating that the NSIDC motion is likely biased to the right. A large standard deviation exists in the difference of motion vector angle (38 °), which is mostly caused by data pairs for the slower Envisat motions of less than 3 km/day (Figure 3b). Despite these phenomena, the two estimates agree well as a whole, as indicated by the high correlation between them (R = 0.87).

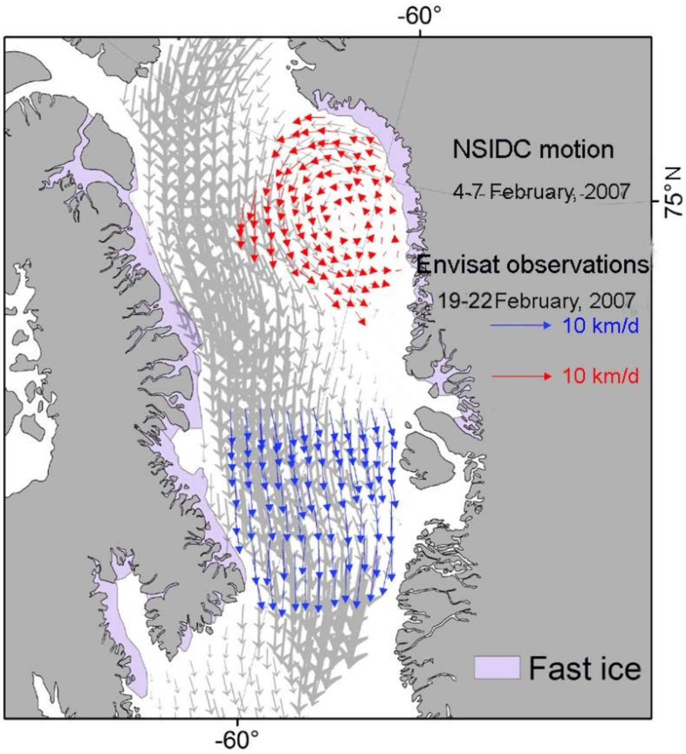

Figure 2. Sea ice motion examples from NSIDC and Envisat. Gray arrows corresponds to the NSIDC data on 4~7 February 2007. The superimposed arrows, one for 4~7 February 2007 (red) and the other for 19~22 February 2007 (blue), denote the smoothed Envisat estimates. The in-phase fast ice extent is marked as purple polygons.

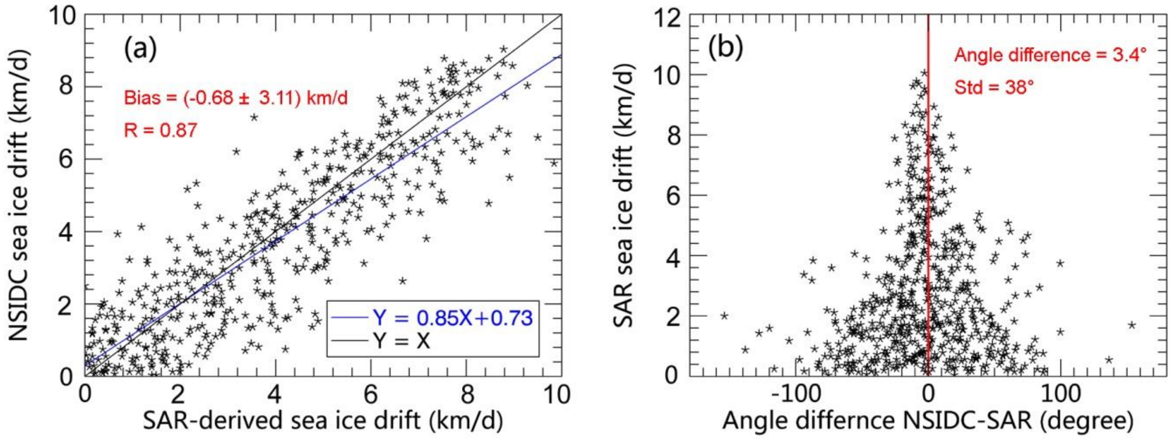

Figure 3. Comparison between NSIDC ice motion and Envisat estimates in terms of (a) drifting speed and (b) angular direction.

2.1.2 Sea ice concentration

Satellite-derived daily sea ice concentration records (1978-2017) were obtained from NSIDC (http://nsidc.org/data/NSIDC-0079). These data are derived from the passive microwave observations from SMMR onboard the Nimbus-7, the SSM/I onboard the Defense Meteorological Satellite Program (DMSP) -F8, F11 and F13, and SSMIS aboard DMSP-F17 by the application of Bootstrap algorithm (Comiso et al., 2017a). For the period November 1978 to July 1987 the ice concentration is available every other day. The data gap is filled using a temporal interpolation from the data of the two adjacent days (i.e. the previous and subsequent days). The concentration field utilized here is an up-to-date version (v3.1), offering improved consistency among the estimates from the different sensors through the use of daily varying tie points. Furthermore, the product has been optimized to provide enhanced removal of weather and land contaminations (Cho et al., 1996). The data are available with an equal-area grid cell structure (25 km×25 km) on a polar stereographic projection.

2.1.3 Sea ice map of the Canadian Ice Service

Weekly sea ice maps were provided by the Canadian Ice Service (CIS). As shown in Figure S1, sea ice classification and concentration in Baffin Bay are depicted in details on the CIS map. The CIS ice map benefits this study in the following three aspects. First, it is useful for identifying sea ice location and coverage for the NWP. Second, it enables the separation of fast ice from floating sea ice. The retrieved CIS fast ice extents are useful for detecting those coastal grid cells where ice motion should be set to zero before the calculation of sea ice area flux. As shown in Figure 4, the eastern and western endpoint grids of the North and South Gates, which is possibly covered by fast ice, is expected to have zero motion. This verification serves to reduce possible systematic errors in the estimation of total area flux. In addition, the fast ice extent identified from CIS can be used to interpret the slower ice motions adjacent to the west coast of Greenland (around 75 °N, Figures 2). Third, the CIS map facilitates the identification of ice bridges (or ice arches) which typically form in Nares Strait

(Figure S1). The formation of ice bridge is a common scenario during the cold freezing period in the strait and the CAA channels, which can substantially restrain Arctic sea ice inflow into Baffin Bay. Typically, two distinct bridges form: one at the northern entrance of Nares Strait adjacent to Lincon Sea (the north bridge) and one near the southern exit of the strait (the south bridge, Figure S1a). The formation of the south bridge can fully restrict the sea ice inflow into northern Baffin Bay, as indicated by the recurring low-concentration regime just downstream of the south bridge (Figure S1b).

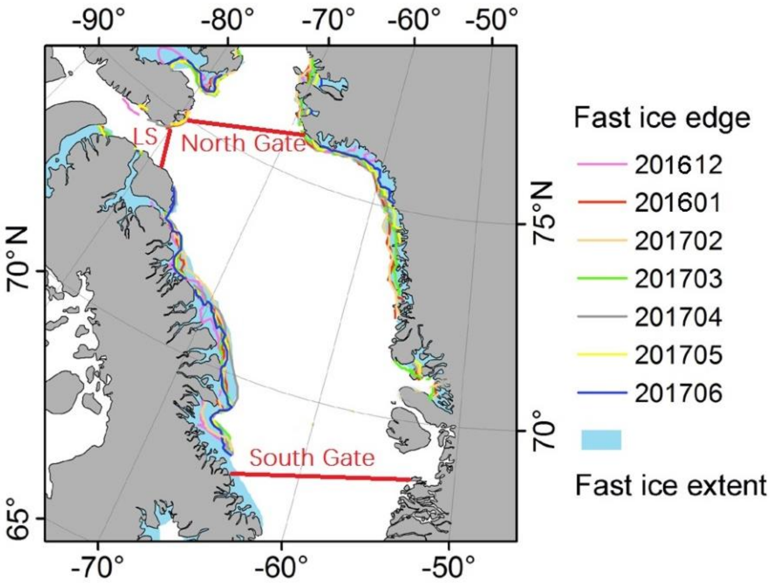

Figure 4. Monthly mean fast ice extent obtained from the CIS map for the period from December 2016 to June 2017.

2.1.4 Reanalysis data

The reanalysis data of sea level pressure (SLP) and surface air temperature (SAT), used to analyze the impacts of climate changes on ice area flux, were provided by the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al., 1996). The data are available with a spatial resolution of 2.5 °×2.5 °.

2.2 Sea ice area flux estimation

2.2.1 Methods to estimate sea ice area flux and its uncertainty

Sea ice area flux is estimated by taking the integral of the product between the gate-perpendicular component of the sea ice motion and concentration across one fluxgate (Kwok, 2007). The area fluxes through the North Gate and the Lancaster Sound (Figure 1) are deemed as the two sea ice inflow components for Baffin Bay. The North Gate (Figure 1), spanning ~320 km in width, is positioned at ~75 °N between 79 °W and 68 °W, where sea ice inflow originates from three components: Jones Sound, Nares Strait, and ice produced from the NWP. Another important source of sea ice inflow is Lancaster Sound, which has a gate width of ~80 km and can be computed with the 25-km NSIDC sea ice fields. In contrast, reliable estimates of sea ice area flux for Jones Sound and Smith Sound are not practical due to their small widths (~40 km) with respect to the

25-km pixel resolution of the NSIDC data. Therefore, the results of several studies of the two gates are used to analyze the possible ice inflow contributions to northern Baffin Bay (see 5.1 for more details). For the outflow component, sea ice area flux across the South Gate is estimated. The gate spans ~480 km and is located at ~68 °N between 63 °W and 53 °W, close to Davis Strait (Figures 1 and 4).

Before computing the area flux, the NSIDC ice motion is first interpolated to a gate to retrieve the gate-perpendicular component of ice motion. Sea ice concentration is used to weight the influences of the open water fractions on the area flux estimates. Following the trapezoidal rule, sea ice area flux (*F*) integrated across a fluxgate is derived as,

$$F = G \sum_{i=1}^{N-1} u_i c_i (i = 1,2, \dots, N) \qquad (1)$$

where *N* is the number of along-gate grids. G corresponds to the width of a grid cell (25 km), u_i is the perpendicular component of the sea ice motion, and c_i is the sea ice concentration at the *i*-th grid cell. As mentioned above, prior to the calculation, the sea ice motion fields at the endpoints of the fluxgate should be set to zero if they are covered by fast ice as recognized in the CIS maps.

The monthly sea ice area flux is calculated as the cumulative daily flux over a calendar month. Similarly, the annual flux denotes the sum of the monthly area flux of one year (September-August). The errors in the daily area flux estimate can be calculated as follows (Kwok, 2009): $\sigma_D = \sigma_u L/\sqrt{N_S}$, where L is the width of the defined gate, σ_u is the uncertainty in daily motion and N_s is the number of independent grid cells across the gate (Table 1). For σ_u, we use the uncertainty (3.11 km/day) determined as described above through comparisons with the Envisat ice motion estimates. The uncertainty of monthly area flux is calculated as $\sigma_m = \sigma_D\sqrt{N_D}$, where N_D is the number of days over the month of interest. The annual flux uncertainty is calculated as $\sigma_a = \sigma_m\sqrt{N_m}$, where N_m = 12, i.e., is the number of calendar months from September to the following August, representing a complete seasonal cycle of sea ice growth and decay. The mean uncertainties for different temporal intervals are summarized in Table 1. On average, the annual uncertainties for the North Gate, the South Gate, and LS correspond to small proportions (2.5%, 2.0%, and 2.4%, respectively) of the corresponding annual mean flux estimates (provided in Section 4).

Table 1. Mean uncertainty estimates for sea ice area flux in terms of daily (σ_D), monthly (σ_m), and annual (σ_a) fields for the period of 1978/1979-2016/2017. N_s is the number of grid cells covered by the corresponding gate.

Passages	Width (km)	N_s	σ_D (km^2)	σ_m (10^3 km^2)	σ_a (10^3 km^2)
North Gate	320	13	276	1.51	5.2
South Gate	480	19	414	2.27	7.86
LS	80	3	69	0.38	1.31

2.2.2 Comparisons with published results

Based on SSM/I estimates of sea ice motion, Cuny et al. (2005) obtained the sea ice area flux from November through May across Davis Strait over the period 1991/1992-1999/2000 (Figure 2, cyan line). During that period, sea ice area outflow was estimated to be 496×10^3 km^2. By comparison, our NSIDC-derived flux through the South Gate (close to Davis Strait) for the same winter months of the same period is on average approximately 380×10^3 km^2. This large difference can be mainly attributed to the distinct contrast in spatial resolution between the two sea ice motion datasets (~70 km for the SSM/I motion data based on 37 GHz observations versus 25-km pixels for the NSIDC data), since larger uncertainty is expected in flux estimates based on a spatially coarser motion. The expected uncertainty in monthly flux based on SSM/I observations was computed as 6.52×10^3 km^2, whereas the uncertainty based on NSIDC motion is 2.27×10^3 km^2 (Table 1). However, the similarity of interannual behavior between the two sets of records is relatively high (R=0.56).

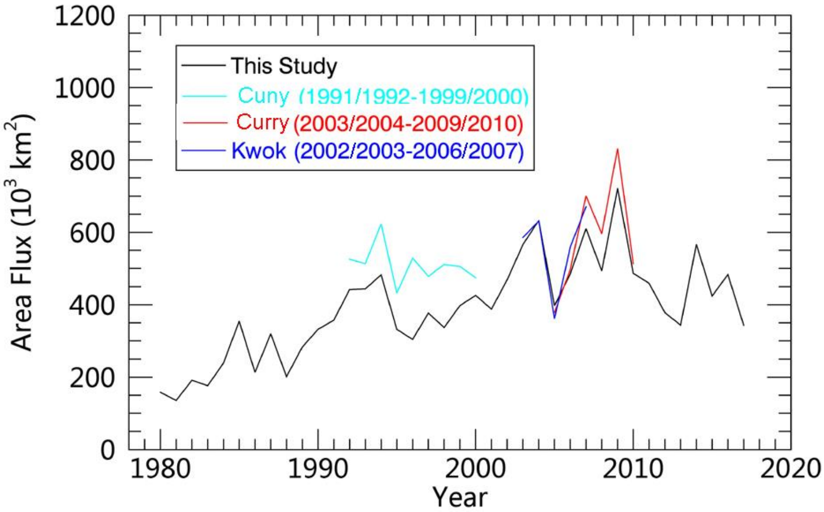

Figure 5. Comparison of sea ice area flux (November to the following May) with estimates from Cuny et al. (2005), Curry et al. (2014), and Kwok (2007)

Kwok (2007) used AMSR-E data to examine sea ice drift and export in Baffin Bay over the period 2002/2003-2006/2007. These estimates were extended to 2009/2010 in Curry et al. (2014). On average, our estimate of the sum of ice area flux for the November-to-May period through the South Gate is -24.3 ($\pm$63.7) $\times10^3$ km^2 lower than that provided by Kwok, and -45.5 ($\pm$61.0) $\times10^3$ km^2 lower than Curry's estimate (Figure 5). Quantities after "$\pm$" are the standard deviation of the difference. Possibly, the differences are primarily caused by the differences in data inputs and slightly due to the small differences in the locations of the defined gates among the different studies. In percentages, the biases are rather small, corresponding to small proportions (4.5% and 8.9%) of the average winter (November- May) estimate based on NSIDC data (511×10^3 km^2) for the time range between 2002/2003 and 2009/2010. Moreover, good agreement between the interannual variations of the NSIDC-based results and the AMSR-E-based estimates is identified (Figure 5). There is a high correlation of 0.93 between the NSIDC results and the AMSR-E estimates provided by Curry et al. (2014). Overall, the good consistency with the higher-resolution AMSR-E estimates suggests the results of this study are credible.

2.3 Methods to simulate ice thickness changes and investigate the impacts on ice motion

Based on the Zubov ice growth model ($h^2+5h=8\theta$, where θ is C_{Fd}-3C_{Md}, where C_{Fd} and C_{Md} are the cumulative degrees of SAT for freezing and melting days, respectively; for the ice growth period, C_{Md} is set to 0), we obtain preliminary estimates of the ice thickness changes in Baffin Bay. The value of C_{Fd} for an ice growth period can be derived from the NCEP/NCAR reanalysis SAT product. To define a freezing day, we follow Stroeve et al. (2014).

Changes in sea ice thickness impact the sea ice motion fields. To assess the ice motion changes when ice thickness is altered, the standard Quadratic drag laws (Equation 2) are used to examine the ice floe acceleration due to wind (τ_a) and current forcing (τ_w) as follows,

$$\boldsymbol{\tau}_\mathbf{a} = \frac{\rho_a C_a}{\rho_i h_i}\left|\mathbf{V}_a - \mathbf{V}_\mathbf{i}\right|(\mathbf{V}_\mathbf{a} - \mathbf{V}_\mathbf{i})$$
$$\boldsymbol{\tau}_w = \frac{\rho_a C_a}{\rho_i h_i}\left|\mathbf{V}_w - \mathbf{V}_\mathbf{i}\right|(\mathbf{V}_w - \mathbf{V}_\mathbf{i}) \qquad (2)$$

where ρ_a is air density, C_a is the air-ice drag coefficient, V_a is the wind velocity vector, ρ_a is the seawater density, C_w is the water-ice drag coefficient, V_w is the surface ocean velocity vector, ρ_i is the sea ice density, and h_i is the ice floe thickness.

2.4 Sea ice divergence approximation

To gain further insight into the sea ice production due to the ice dynamics in Baffin Bay (see section 4.2 for more details), the divergence ($\nabla \cdot \vec{\mathrm{V}}$) of the sea ice motion vector field is calculated. The derivative of the ice motion field in the x and y direction is calculated by use of the Sobel operator. The Sobel operator is convoluted with the x and y components $\mathrm{V_x}$ and $\mathrm{V_y}$ of the ice motion field to calculate the divergence,

$$\nabla \cdot \vec{\mathrm{V}} = \frac{1}{8}\begin{bmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{bmatrix} * \mathrm{V_x} + \frac{1}{8}\begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} * \mathrm{V_y} \qquad (3)$$

where * is the convolution operator. The Sobel operator smoothes the field perpendicular to the derivation direction.

3. Sea ice conditions in Baffin Bay

3.1 Sea ice coverage

The characteristic features (2016) of annual sea ice coverage of Baffin Bay are shown in Figure 6. The bay is generally ice-free between July and October. From November, the coverage advances rapidly from the west to the east and, from the north to the south. It reaches maximum coverage in later winter (March). The retreat westward around the South Gate starts in April. The southerly circulation and the warm WGC are responsible for the lower ice cover in the east of the South Gate

(Figure 1). The identifiable low sea ice concentration fields in the northern part during the cold months are associated with the occurrence of NWP (such as in April in Figure 6).

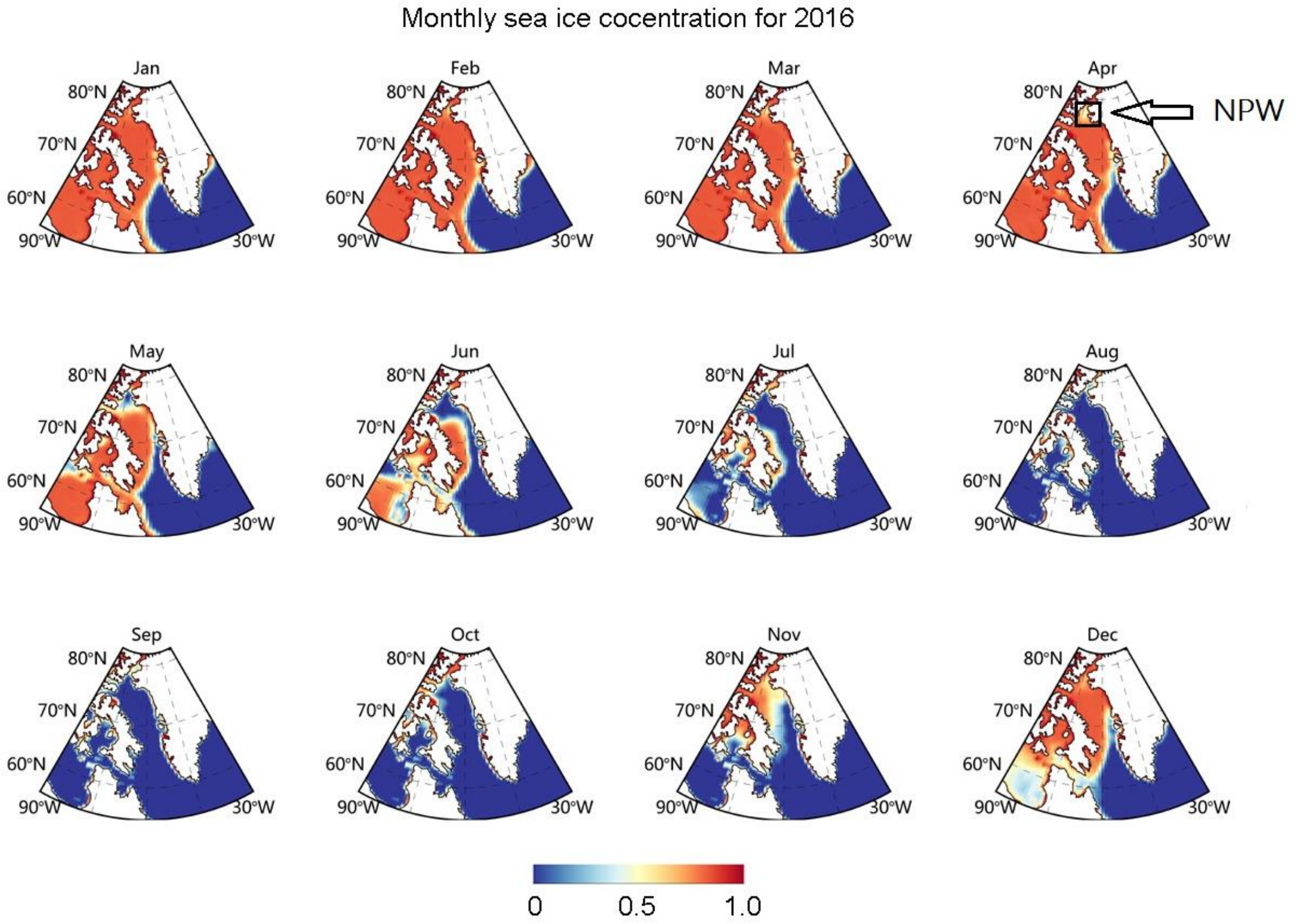

Figure 6. Spatial variations of mean sea ice concentration fields for the calendar months in 2016. In the panel for April, NWP is outlined.

3.2 Sea ice drift pattern

Two selected examples of sea ice drift in Baffin Bay are shown in Figure 7. The March and June cases in 2016 are chosen to represent ice circulation under cold and warm conditions, respectively. Overall, sea ice drift in Baffin Bay is characterized by a cyclonic pattern. To the west, the sea ice motion (Figure 7a) is connected to the northerly Baffin Current (BC, Figure 1). To the east, the slower drift (Figure 7a) and even southerly drift (Figure 7b and Figure 2), especially in the northeast corner of the bay (around 75 °N), is associated with the southerly West Greenland Current (WGC, Figure 1).

In March, the prevailing drift pattern in the bay is southward (Figure 7a). Sea ice starts from Smith Sound and the south end of Nares Strait and extends southward along the coast of Baffin Island. From the northern end of the bay to Davis Strait, the sea ice motion gradually accelerates, reaching the maximum speeds around Davis Strait (Figure 7a). The mean sea ice speed in the North Gate is 3.2 km/day, whereas sea ice in the South Gate attaines a speed of 8.5 km/day. Moreover, the CIS map demonstrates that the thicker multiyear ice from either the Arctic through Nares Strait (Figure S4a) or Lancaster Sound

(Figure S4b) is mostly confined to the west of the bay. In contrast, most of the ice motion fields in June have decreased sharply to less than 0.8 km/day, but the basin-scale cyclonic pattern is still observable (Figure 7b).

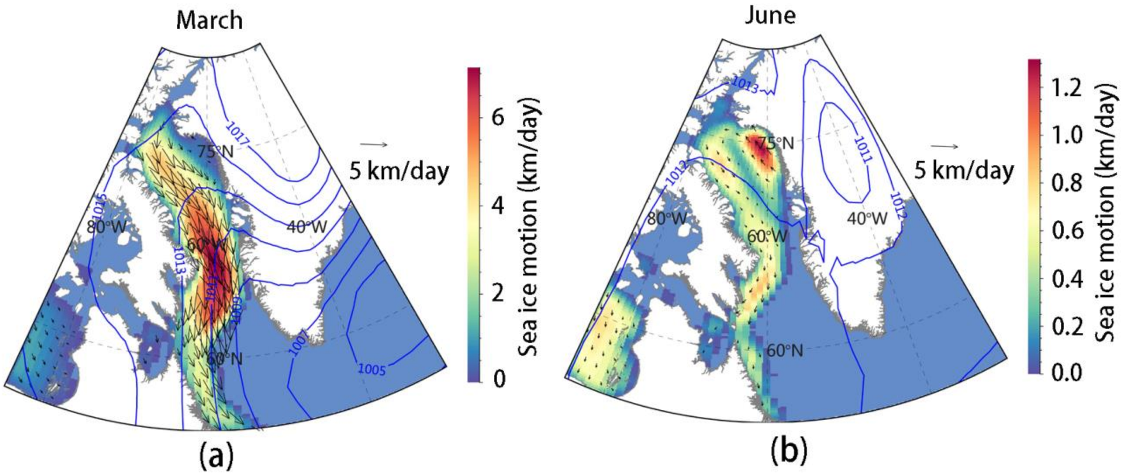

Figure 7. Sea ice drift patterns (arrows) in (a) March and (b) June 2016. Background color denotes the magnitudes of sea ice speeds. Superimposed bold curves represent the SLP distribution patterns of the corresponding month.

The general cyclonic sea ice movement pattern can be attributed to the wind forcing associated with the SLP distribution (blue curved lines in Figure 7). The associated denser isobars in the bay imply a stronger geostrophic wind flow in March (Figure 7a). The deep SLP trough (as apparent in March, Figure 7a) begins to emerge in October (not shown) and is gradually enhanced until the end of March. The trough enters to a weak stage from April until the end of summer, as evident in June in Figure 7b. The spatial distribution of the trough in June is responsible for the remarkable features of ice circulation, such as the southeasterly flows in the northeast part of the bay and the northwesterly flows in Davis Strait (Figure 7b). Owing to modulation by the structure of the coastline, the actual sea ice drift direction in the bay tends to be on the right of the isobars (Figure 7a).

3.3 Trends in sea ice motion and concentration fields

During cold seasons over the period 1978/79-2016/17, the sea ice concentration fields in Baffin Bay show a basin-scale average declining trend ranging from -1.2%/de (winter, December-February, Figure 8a) to -3.1%/de (spring, March-May, Figure 8b). During the warm seasons (summer: June-August; autumn: September- November), the sea ice decrease is stronger, with an average change rate of -10.4% (not shown). Clear regional variations in the trend fields are apparent in Figure 8. Around the southeastern edge during the winter period, sea ice retreats northward and eastward, with a significant decreasing trend in ice concentration, in excess of -10%, relative to the 2.8%/de decline reported earlier along this edge for the period 1951-2001 (Stern and Heide-Jørgensen, 2003). However, sea ice concentration in other regions of the bay shows a quite declining trends weaker than -2.0%/de (Figure 8a).

A small enclosed area of the NWP region in the north end of the bay also displays a declining trend in sea ice concentration fields (Figure 8a and 8b). In the NWP region, there is an average sea ice concentration decrease in winter

(-3%/de) and a stronger decrease during spring (-8%/de). This seasonal difference is primarily associated with the appearance of the ice bridge near the Smith Sound in late winter or early spring (February or March). More new ice can be produced from NWP during the spring period than the winter, and the recurring ice bridge can largely recede into the ice inflow from the Nares Strait into Baffin Bay. Therefore, higher fractions of the sea ice inflow component originating from NWP production seem to occur in spring than in winter. The more recently-produced ice thus contributes to the observed fields of lower concentration in the NWP region in spring (Figure 8b). Additionally, the decline in sea ice concentration in the NWP seems to be partially associated with the southward sea ice motion (Figure 9a and 9b). In the broad regions just south of the NWP, the increased southward ice advection provides more chances for the creation of newly-formed ice in polynyas. Therefore, the enhanced southward ice advection through Baffin Bay (~1.0 km/d/de) may also have contributed to the decrease in ice concentration over the NWP regime.

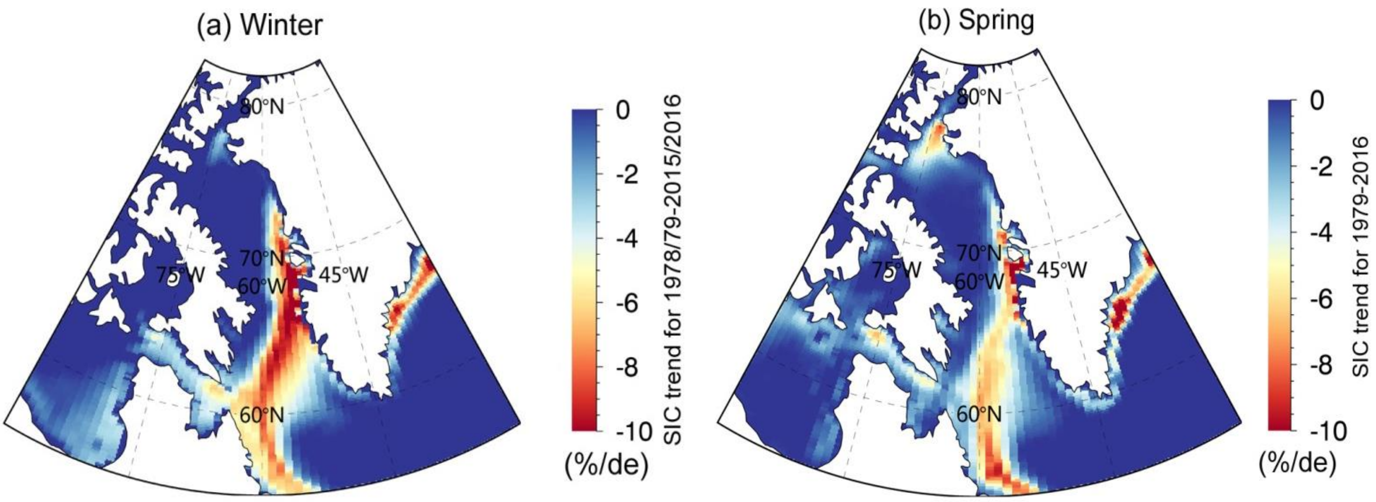

Figure 8. Sea ice concentration trends during (a) winter and (b) spring over the period 1978/1979-2016/2017.

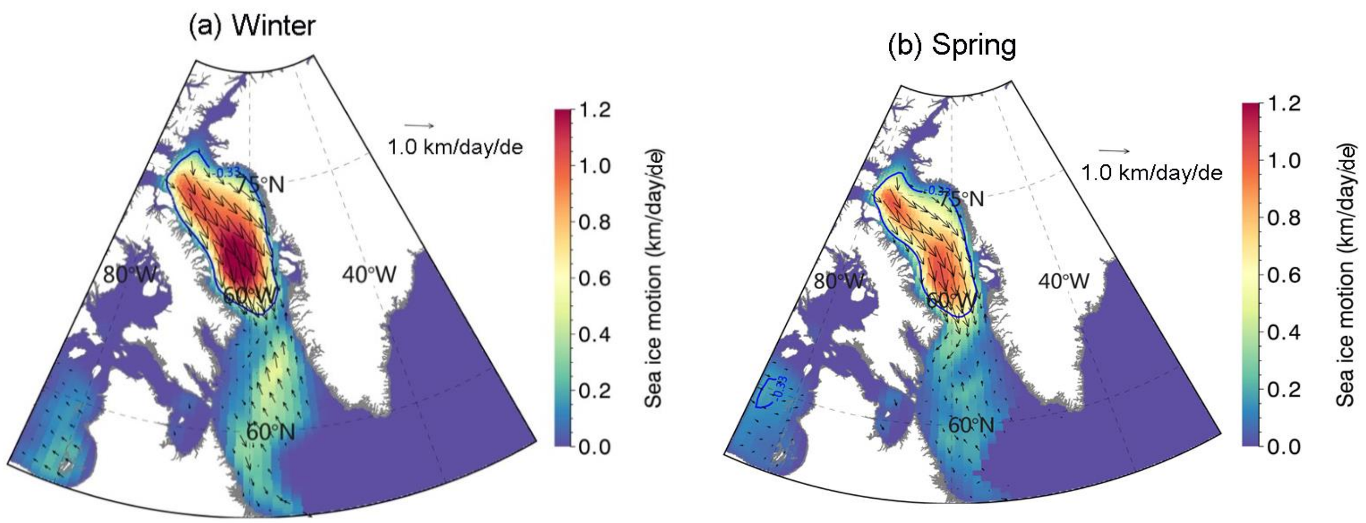

Figure 9. As Figure 8 but for sea ice motion fields.

4. Sea ice flux through different fluxgates in Baffin Bay

In this study, sea ice area flux across three gates is obtained. Sea ice inflows to the bay are measured across the North Gate and Lancaster Sound, and the sea ice outflow is estimated across the North Gate (Figure 4). The obtained sea ice flow budget (outflow-inflow) provides knowledge of sea ice production or loss associated with the dynamic and thermodynamic processes in the regions between the South and North Gates.

4.1 Monthly variability of sea ice area flux

Figure 10 shows the monthly mean sea ice area export at the three gates over the period 1978/79-2016/2017. Large monthly variations in sea ice area flux are observed. The average monthly inflow through the North Gate is 17.2×10^3 km^2, with monthly inflow ranging between -0.04×10^3 km^2 (August) and 39.4×10^3 km^2 (January) (Figure 10a). The sea ice flux across the South Gate is greater (Figure 10b). For this gate, the mean monthly export is 32.9×10^3 km^2, nearly twice of that the North Gate, and varies from -0.13×10^3 km^2 (August) to 80.0×10^3 km^2 (January). In comparison, the sea ice area flux across Lancaster Sound is smaller than that of either gate, with an average of 4.6×10^3 km^2 and a range of zero flux (August) to ~10.0×10^3 km^2 (December) (Figure 10c).

The seasonal behaviors of monthly flux for the three gates are similar (Figure 10). In general, the sea ice area flux for the warm period from June to October is low and sometimes reaches to zero. For the cold period from November through next May, it is much larger and varies significantly. Furthermore, there are clear decadal changes as observed for the cold months (November-May). Relative to monthly sea ice flux during the cold months in the first decade (1978-1987), enhanced monthly sea ice flux is observed for the subsequent three decades (since 1988), with average flux values of ~20 $\times10^3$ km^2 through the North Gate (Figure 8a), ~50×10^3 km^2 through the South Gate (Figure 8b), and ~5 $\times10^3$ km^2 through Lancaster Sound (Figure 8c). Among the recent three decades, the monthly sea ice flux remains high and does not show significant interdecadal variation.

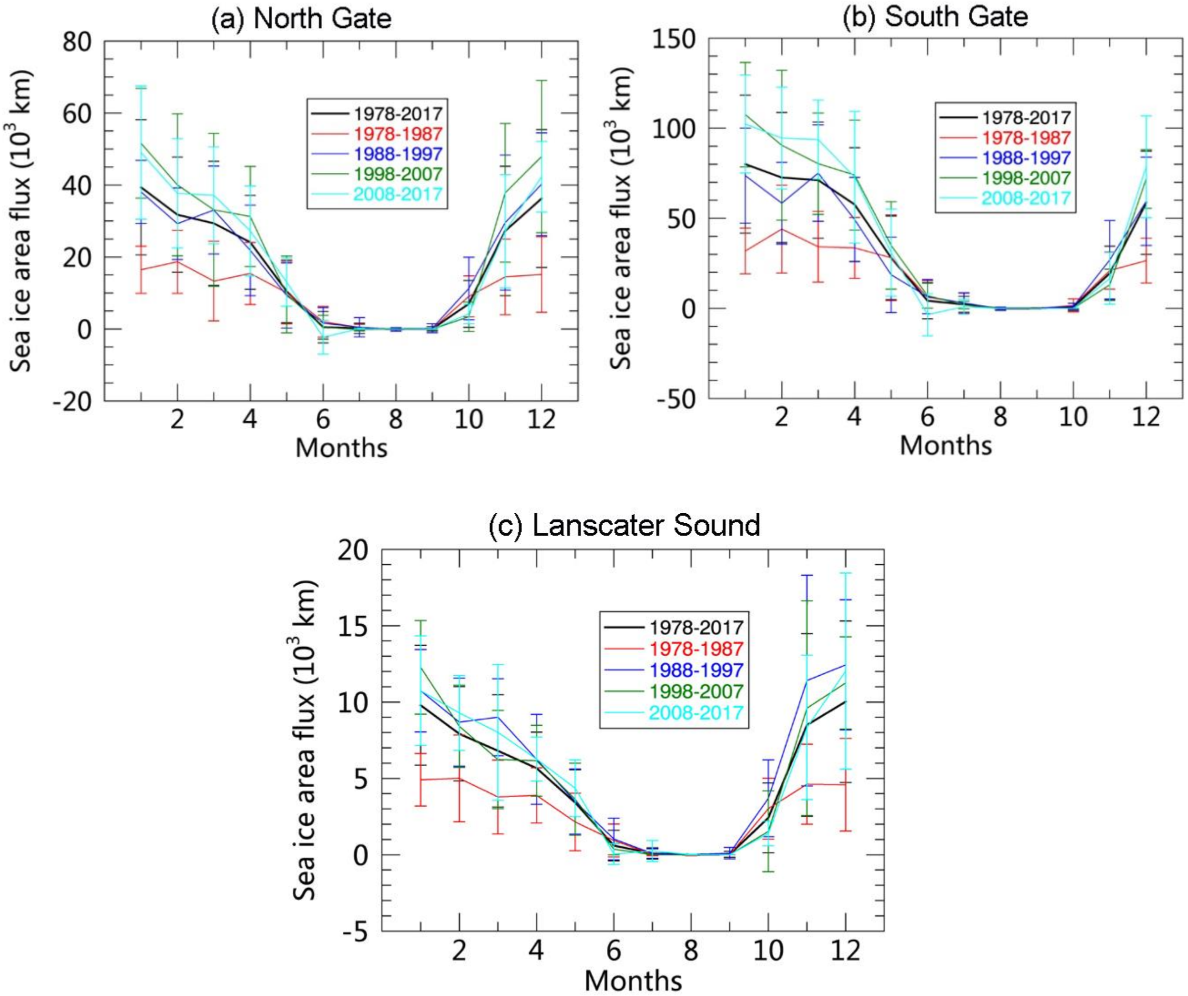

Figure 10. Monthly mean sea ice area export in (a) the North Gate, (b) the South Gate, and (c) Lancaster Sound. Both the climatology (1978/1979-2016/2017) and decadal mean fields are given in the panels.

4.2 Variability and trends of seasonal and annual inflow and outflow

Figure 11 shows the seasonal and annual sea ice area flux across the three gates. The seasonally accumulative flux fields are obtained for the months of spring (March-May), summer (June- August), autumn (September-November), winter (December-February). The annual sea ice flux refers to the sum of monthly flux from September to next August.

Distinct interannual variations is evident in the annual sea ice flux fields as well as the winter and spring fluxes (Figure 11). Table 2 shows that the average annual inflow across the North Gate is 205.8 (± 74.7) $\times 10^3 km^2$, with minimum annual inflowin 1980/1981 (64.1 $\times 10^3 km^2$) and maximum annual inflow (414.8 $\times 10^3 km^2$) in 2006/2007. The South Gate shows a mean annual outflow of 394.3 (± 110.2) $\times 10^3 km^2$, with annual outflow ranging between 140.6 $\times 10^3 km^2$ (1980/1981) and 727.4 $\times 10^3 km^2$ (2008/2009). The mean annual inflow through Lancaster Sound is 55.2(±17.8) $\times 10^3 km^2$, with outflow varying between 20.7 $\times 10^3 km^2$ (1978/1979) and 94.3 $\times 10^3 km^2$ (2014/2015). The difference between the inflow (through the North Gate and Lancaster Sound) and outflow (through the South Gate), -133.3 $\times 10^3 km^2$, is suggestive of annual net loss of sea ice area in the regions between ~65 °N and ~75 °N in Baffin Bay.

We obtain a total sea ice inflow of 214.7×10^3 km^2 during the cold seasons (winter and spring) through the North Gate and Lancaster Sound and an outflow of 368.0×10^3 km^2 via the South Gate. The difference of 153.3×10^3 km^2 is largely balanced by newly-formed ice within the bay, revealing the Baffin Bay itself as an important source regime of sea ice. Using ~690×10^3 km^2 as the area of Baffin Bay, this newly formed ice within the bay represents a noteworthy fraction of 22.2% of the coverage of Baffin Bay. As mentioned above, the sea ice motion fields in the bay gradually increase from north to south (Figure 7a), resulting in a distinct ice speed gradient and possibly the occurrence of new leads (not shown). Therefore, the sea ice dynamics of the central and western regions of the bay are dominated by a sea ice diverging pattern (as exemplified in Figure 12) where new ice can form from the freezing process in leads. For the warm period (summer and autumn), both sea ice inflow (46.3×10^3 km^2) and outflow (26.3×10^3 km^2) are small. The difference of -20.0×10^3 km^2 represent net sea ice loss that is likely due to enhanced melting in the bay. This finding emphasizes that Baffin bay serves as an important ice sink area during the warm seasons.

Table 2. Seasonal and annual mean sea ice area flux across different gates. (Unit: 10^3 km^2)

Passages	Spring	Summer	Autumn	Winter	Annual
North Gate	63.8	0.63	34.08	107.3	205.8
LS	15.9	0.68	10.9	27.7	55.2
South Gate	156.8	6.2	20.1	211.2	394.3

Note: Spring (March-May); Summer (June-August); Autumn (September-November); Winter (December-February); Annual (September-August).

Figure 11 shows that all three gates experienced significant positive trends in annual flux over the past four decades, with the major contributions originating from the flux increases during the cold seasons (winter and spring). The trend for the North Gate, approximately 38.9×10^3 km^2/de (or 19.0%/de), is significant (Figure 11a). The percentage trend denotes the fractional change relative to the climatological estimate of flux for 1978/1979-2016/2017. A larger annual increase of 82.2×10^3 km^2/de (or 21.1%/de) is observed for the South Gate (Figure 11b). The increase of ice flux through Lancaster Sound, 7.5×10^3 km^2/de (or 13.6%/de), is small but significant (Figure 11c). All these trend estimates have passed the 99% confidence test. Therefore, the increased sea ice outflow across the South Gate has been partly compensated by the enhanced inflows via the North Gate and Lancaster Sound. The increased outflow across this gate is also partially compensated by the increased occurrence of new ice area formed within the bay.

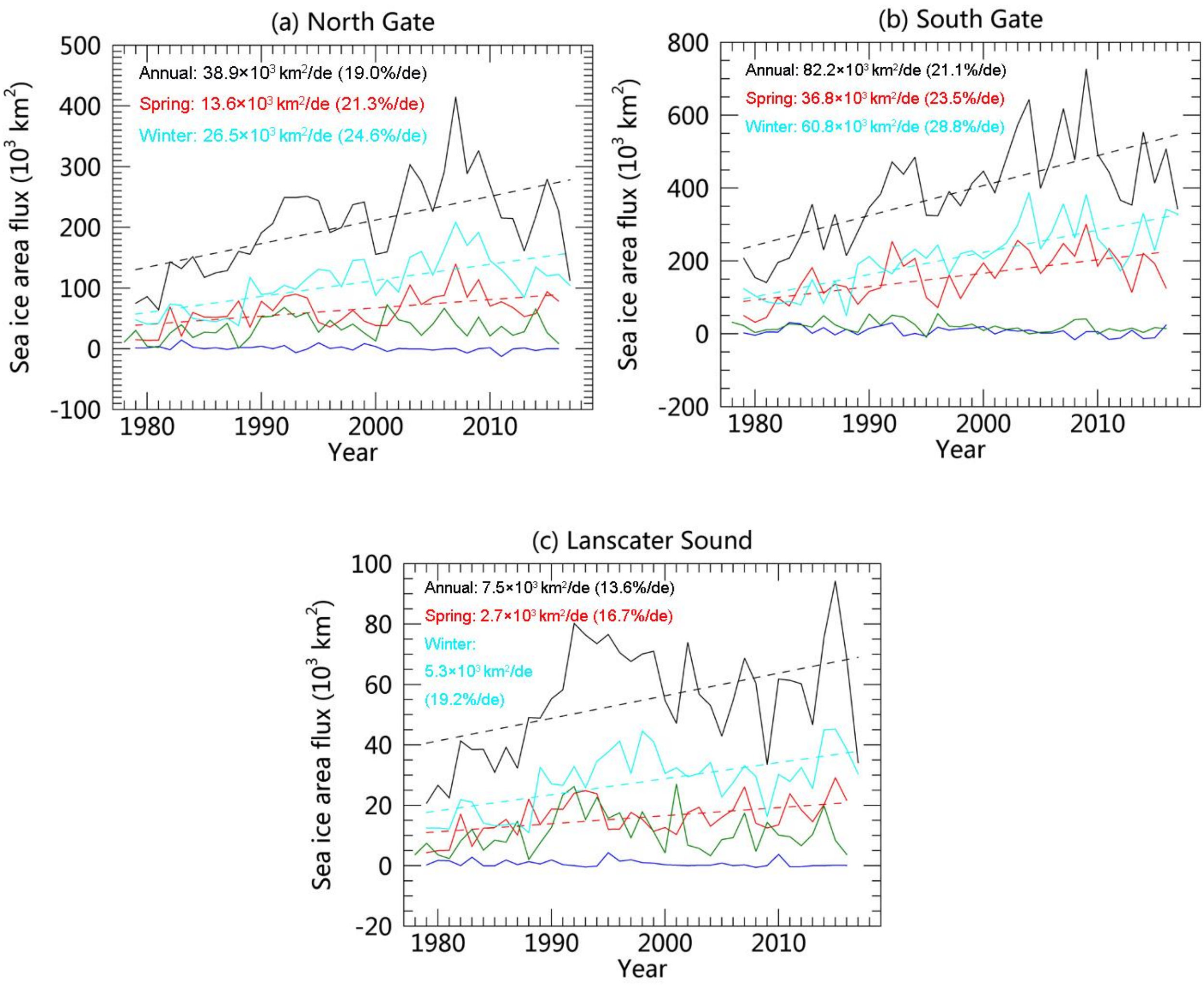

Figure 11. Time series of annual (September-August) sea ice area flux (black bold line) across (a) the North Gate, (b) the South Gate, and (c) Lancaster Sound. Seasonal flux is estimated for winter (December – February, cyan line), spring (March-May, red line), summer (June-August, green line), and autumn (September-November, blue line). The dashed lines represent the linearly fitted trends. The annual and cold-season (winter and spring) trends are all significant at the 99% level. However, for the warm seasons (summer and autumn), the trends are not statistically significant and are not shown in the panels.

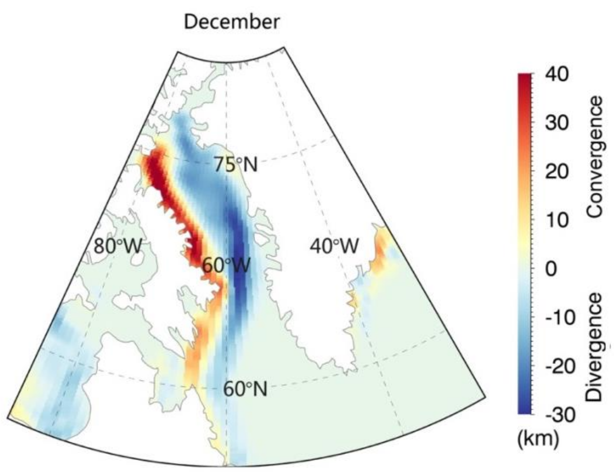

Figure 12. Divergence/convergence fields derived from the climatological (1978/1979-2016/2017) sea ice motion vector fields in December using Equation 3.

5. Discussion

5.1 Possible sources of sea ice inflow into northern Baffin Bay

There sources contribute to the ice area changes in northern Baffin Bay, i.e. the area flux through the North Gate: (1) inflow from the Arctic Ocean through Nares Strait; (2) inflow from the Canadian Arctic Archipelago (CAA) across Lancaster Sound and Jones Sound (JS); and (3) ice production in NWP in the bay;

5.1.1 Nares Strait sea ice inflow through Smith Sound

Sea ice transport in Nares Strait is controlled by the formation of ice bridges in Nares Strait. As reported based on RADARSAT SAR imagery by Kwok (2007), ice bridges form due to increases in the strength of ice arches in the middle to late winter, and collapse due to warm temperatures in early summer. Arching is commonly observed in Kane Basin to the south end of Nares Strait and another occurs in the north end. Over a 13-year period (1997-2009), the South arch formed in all years except 2009, whereas half of the winters lacked the North arch (Kwok, 2007). The formation of the South arch may depend on upstream ice conditions, and the formation of the North arch in the northern inlet of Nares Strait may be favored by the creation of the South arch. The locations of the two ice arches are shown in Figure S1a.

It is clear that when the south arch forms, there exist conditions where sea ice inflow through Nares Strait into the Baffin Bay is strongly restricted under some conditions. Seasonal stoppages of Nares Strait ice flux into Baffin Bay are associated with the formation of the South arch. The immediately mitigating effects due to the formation of ice bridges are apparent from the cases in 2007. During that winter, no locations had conditions suitable for the formation of ice bridges, and area flux through Nares Strait reached to a record high (87×10^3 km^2). This large outflow accounted for 21.0% of the annual ice flux (414.8×10^3 km^2) through the North Gate of Baffin Bay in 2006/2007.

Owing to the small width of Smith Sound (~30 km), the sea ice area flux through Nares Strait cannot be accurately estimated using the coarse NSIDC drift data (25-km resolution) which may be subject to coastal contamination. With high-resolution SAR ice motion data (sampled on a 5-km grid), Kwok (2005) and Kwok et al. (2010) obtained Arctic sea ice inflow through Nares Strait. They estimated an average annual (September-August) ice area flux of 33×10^3 km^2 for a six-year period (1996-2002) and an annual average area flux of 42×10^3 km^2 for a longer, 13-year period (1996-2009). Therefore, sea ice area export via Nares Strait into northern Baffin Bay between 1996/97 and 2008/2009 may contribute a notable fraction (23.3%) of the total ice area flux via the North Gate for the same period (280.2×10^3 km^2).

5.1.2 Sea ice inflow from the Canadian Arctic Archipelago

The sea ice exchange between the CAA and Northern Baffin Bay mainly through Lancaster Sound and the Jones Sound. However, sea ice inflow from the two sounds to the Baffin Bay is difficult to quantify. In an early study for the 1970s, Dey (1981) roughly estimated the average annual inflows of 170×10^3 km^2 and 20×10^3 km^2 for the Lancaster and Jones Sounds, respectively. The sea ice motion fields used were derived from diverse sources, including coarse satellite imagery, airborne observations measurements, as well as field measurements. Therefore, their estimates only correspond to a rough estimate.

In a recent study, Agnew et al. (2008) applied a spatially enhanced AMSR-E sea ice motion (13.5 km) to assess the sea ice area flux across CAA for the period from 2002/2003 to 2006/2007. During the 5-year period, sea ice is exported 68×10^3 km^2 for each year across the Lancaster Sound into Baffin Bay. By contrast, the average sea ice inflow across Jones Sound approaches to zero. In our estimate, the Lancaster Sound sea ice inflow is estimated to be 58.2×10^3 km^2 for the same period, which is comparable to the Agnew's results based on the AMSR-E imagery. Therefore, the Lancaster Sound constitutes one of important ice sources for the sea ice into the Northern Baffin Bay.

5.1.3 Sea ice production in North Water Polynyas

The NWP is a distinct feature in northern Baffin Bay. As shown in Figure 6, it usually occupies an area in the north end of Baffin Bay (north of 75°N) and serves as a large ice production area during freezing periods. As mentioned above, its emergence is largely attributable to the formation of an ice bridge in the south end of Nares Strait (Figure S1a) which controls the sea ice inflow. Maintained by strong northerly winds and ocean currents, this large polynya is frequently exposed, and new sea ice grows within it; this new ice is then transported southward. Based on previously reported CAA inflow through Smith Sound (42×10^3 km^2) and Jones Sound ($0\sim20\times10^3$ km^2), we obtain a preliminary estimate of annual mean area production in the NWP ($218\sim238\times10^3$ km^2) for the period 1996/1997-2008/2009. To obtain this estimate, sea ice from the two inflow sources are subtracted from the mean annual ice flux of the North Gate (280.2×10^3 km^2) of the corresponding period. The results suggest the major part (approximately 78~85%) of the sea ice entering via the North Gate is likely produced in the polynya.

5.2 Connections to cross-gate sea level pressure gradient

If free drift conditions are allowed, sea ice motion is mainly wind-driven and parallel to the sea level pressure isobars (Thorndike and Colony, 1982). In this study, the response of daily sea ice flux to the cross-gate pressure gradient was investigated. The gradient is defined as the difference of mean sea level pressure (SLP) between the east and west endpoints of each fluxgate. The positive (negative) gradient corresponds to positive (negative) sea ice flux. The data pairs of SLP gradient difference and ice area flux for each gate are shown in Figure 13. Clearly, the cross-gate SLP difference is a good predictor of the variance of sea ice flux for the North (Figure 13a) and South Gates (Figure 13b), with a correlation of 0.62

and 0.68, respectively. These correlations are statistically significant at the 99% confidence level. The stronger slope in the South Gate (0.27) is suggestive of an ice condition that is thinner and perhaps closer to free drift than that of the North Gate (0.23). Lancaster Sound, however, reveals an overall counter gradient ice motion (R = -0.23), although it is not significant (Figure 13c). Sea ice in this narrow channel is largely controlled by internal ice stresses caused by local sea ice interactions and orographic conditions. As a consequence, sea ice floes in the sound can not move as freely as those in the interior part of Baffin Bay.

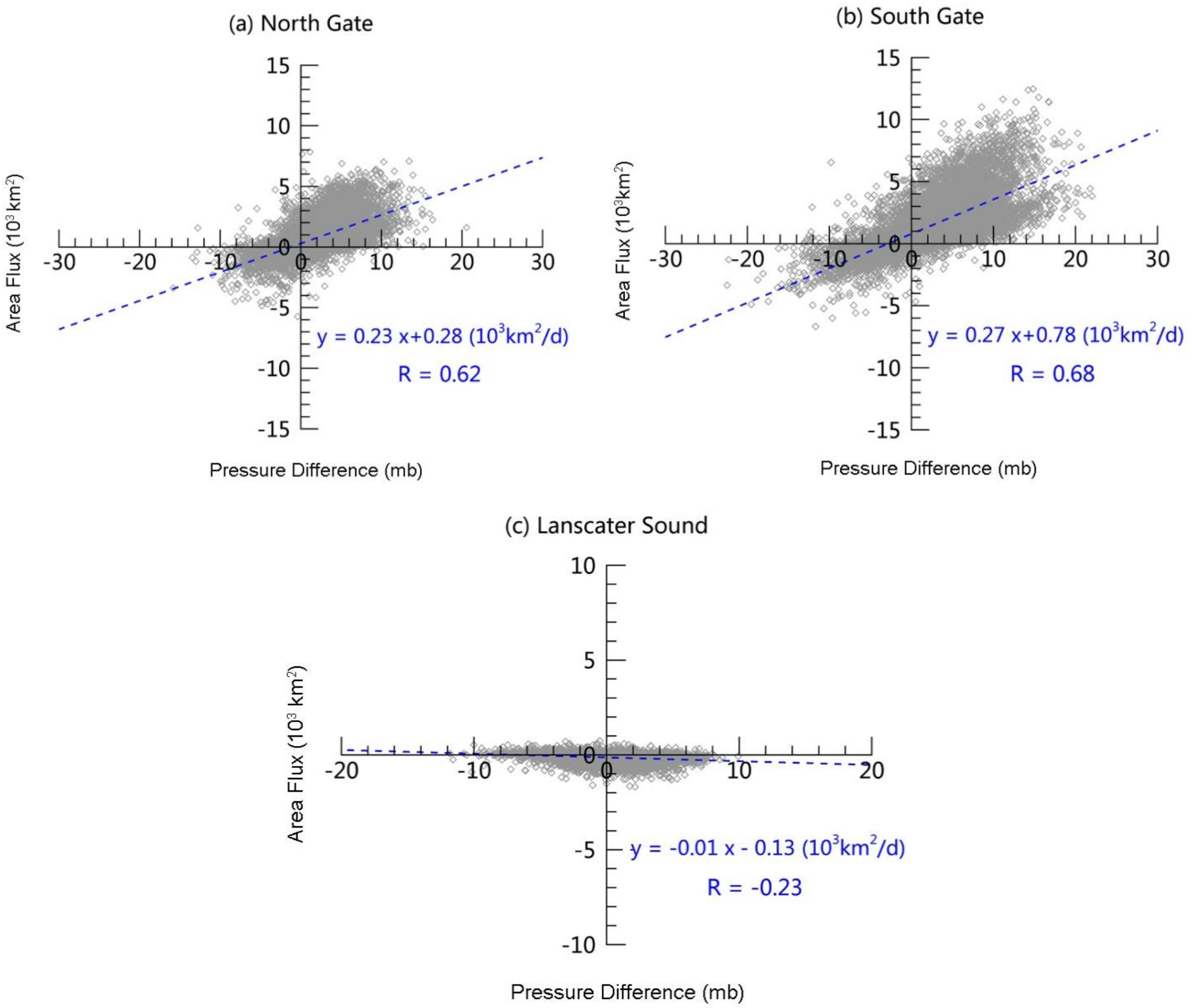

Figure 13. Scatterplot of daily sea ice area flux and cross-gate pressure differences for (a) the North Gate, (b) the South Gate, and (c) Lancaster Sound.

5.3 Causes of the enhanced sea ice area flux

5.3.1Potential contribution of geostrophic winds

According to Equation 1, sea ice motion and concentration are the two essential input parameters to estimate area flux. Potentially, their changes would be reflected in the variations of flux. Figure 14 depicts the interannual variations and trends of the two relevant sea ice parameters for the cold seasons (winter and summer) at the North and South Gates. As mentioned above and shown in Figure 11, all three fluxgates show significant increases in sea ice area flux during the cold seasons. This is mainly caused by the increasing trend in sea ice motion (Figure 14). On the other hand, the decreasing trend in sea ice concentration may contributed negatively to ice area flux. The trends are all significant at the 99% level. The increasing or decreasing trends of different parameters at each fluxgate in the context of the entire bay are illustrated in Figures 8 and 9.

Figure 14 displays the records of cross-gate SLP difference (red bold line), a proxy for the strength of geostropic winds. Although the SLP difference is a good predictor of the interannual variability in ice motion (see section 5.2 for more details), it does not show any significant trend over the nearly 40-yr period. This observation eliminates wind force as a main driver of the positive trends in ice motion and area flux fields.

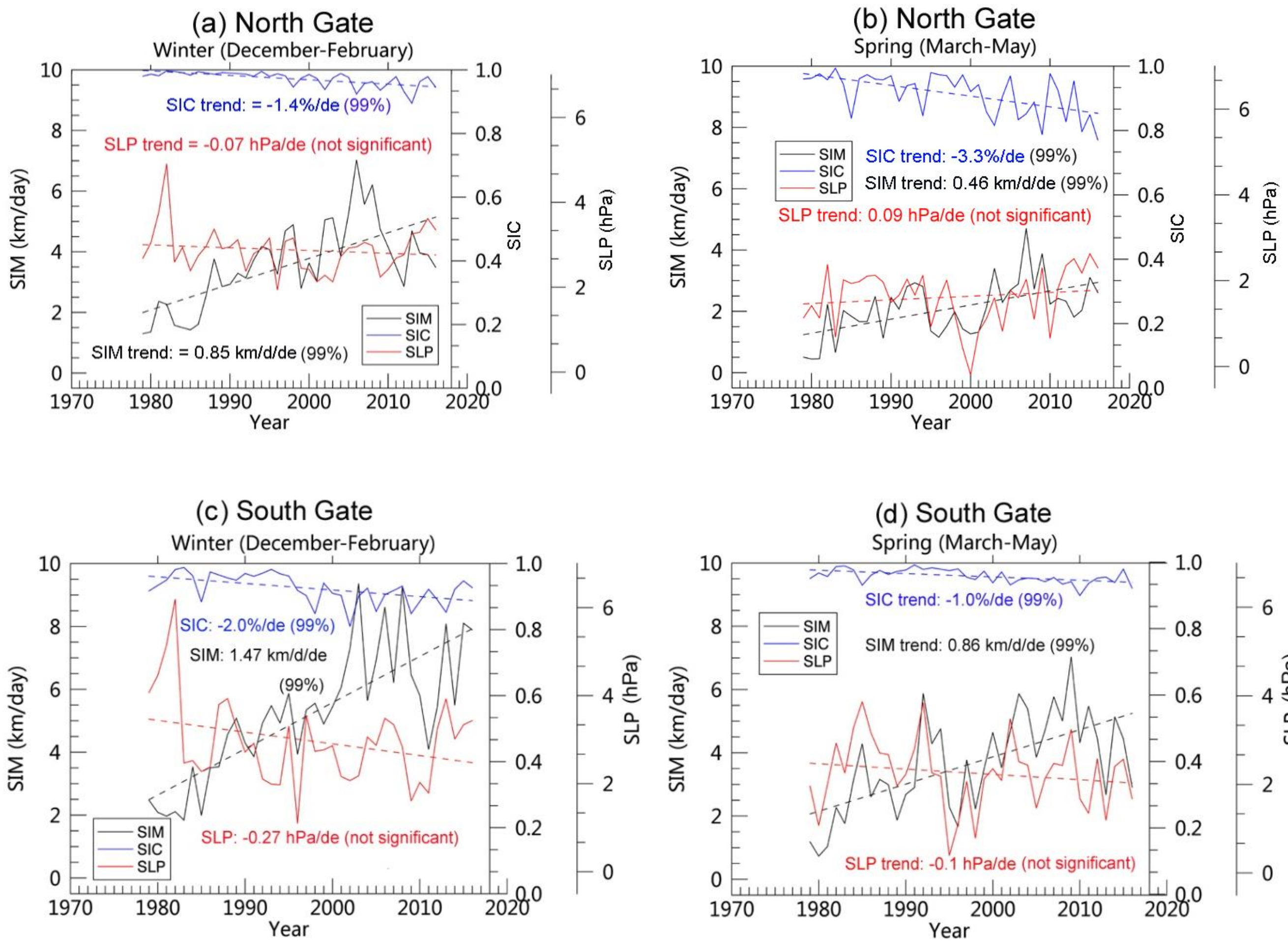

Figure 14. Trends and variability of cross-gate mean sea ice motion (black bold line) and concentration (blue bold line) for the (a) North Gate and (b) South Gate. The linear fit line for each parameter is shown as a dashed line. Cross-gate sea level pressure (SLP) difference (red) is shwon to facilitate the analysis of causes of the significant trends in sea ice motion.

5.3.2 Changes in sea ice

Here we examine the changes of sea ice itself, specifically, (1) the changes in sea ice concentration and (2) the changes in sea ice thickness. A reduced sea ice concentration is expected to cause a decreased area flux across the fluxgates. On the other hand, it implies a less compacted ice pack and facilitates sea ice drift and, perhaps, an increase in area flux. Despite the decline in sea ice concentration at each gate during the cold periods, the sea ice generally remains at a compact level above 90% (Figure 14), at which large ice internal ice stress is still expected. Therefore, sea ice concentration changes cannot be a primary driver of the enhanced ice motion and area flux.

Due to the scarcity of direct ice thickness measurements, we obtain an approximation of ice thickness changes with time following the Zubov ice growth model. The associated cumulative freezing degree (C_{Fd}) is derived from surface air temperatures . This variable is directly related to the level of sea ice growth. Modeled ice thickness fields for different periods are shown in Figure 15 as a function of ΔC_{Fd}, where ΔC_{Fd} denotes the average daily freezing degree (℃) of the whole growth period. That is, $\Delta C_{Fd} = C_{Fd}/F_d$, where F_d is the total days of an ice growth period.

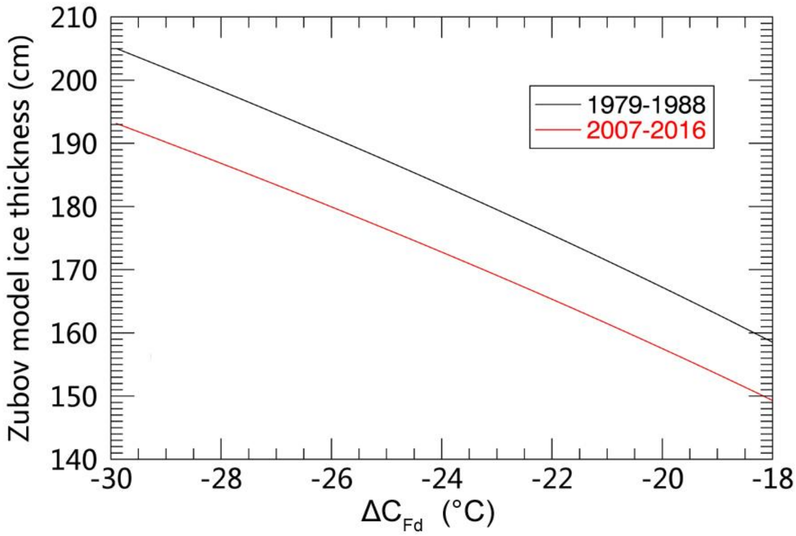

Figure 15. Modeled sea ice thickness change as a function of freezing degree (daily average, ΔC_{Fd}) for early (1979-1987) and recent (2007-2016) decades.

The downward slope of each line in Figure 15 (-3.83 cm/℃ and -3.75 cm/℃ for early and recent decades, respectively) represents the changes in thickness with the freezing air temperature. There is an increasing trend in SAT in the bay of 0.95 ℃/de (Figure 16). Based on estimates displayed in Figure 15, this air temperature enhancement implies a SAT increase in the bay of 3.8 ℃ in the recent decade, which can be expected to cause a thickness decline of 14.6 cm and 14.3 cm (i.e. multiplying slope by 3.8 ℃) for the early and recent decade, respectively.

The systematic bias between the two lines in Figure 15 one for each decade, corresponds to the ice thickness change in association with the change in the length of the freezing period. Due to warmer surface air in the recent decade, a difference in ice growth period of approximately 20 days is observed between the two decades (i.e., approximately -5 days/de), which is consistent with the delayed freezing and earlier melting dates in Baffin Bay (Stroeve et al., 2014). When taking into account the freezing period changes, a further ~10 cm decline is identified due to the shortened days of freezing (Figure 10). Therefore, the increased SAT, together with the shortened length of the ice freezing period, can be expected to cause an average reduction in sea ice thickness of 24.6 cm.

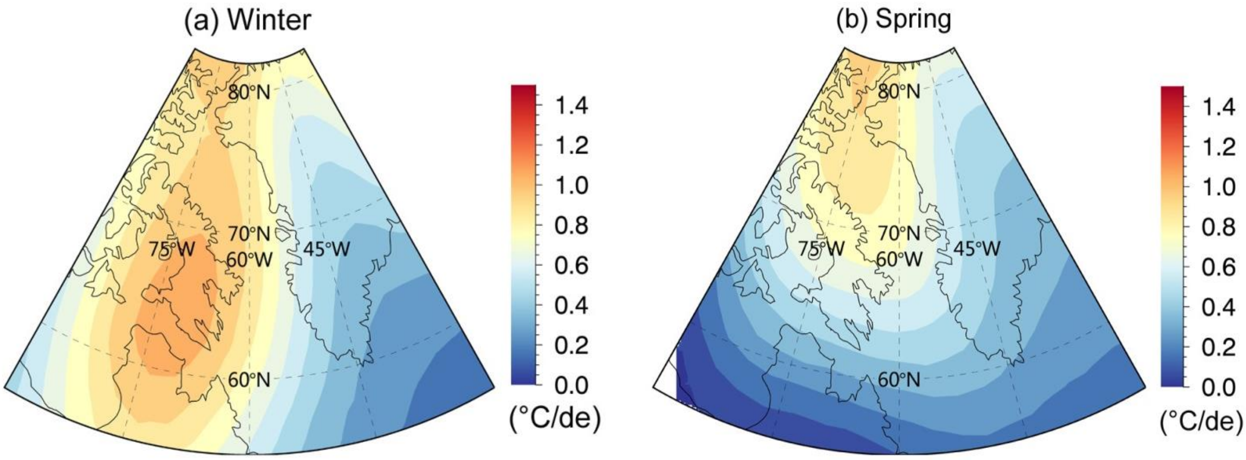

Figure 16. Surface air temperature trends for the period 1978/1979-2016/2017 during (a) winter and (b) spring periods

According to Equation (2), sea ice motion acceleration due to air and current dragging force ($\boldsymbol{\tau}_\mathbf{a}$ and $\boldsymbol{\tau}_\mathbf{w}$) is proportional to the inversion of thickness change (i.e. 1/h). Therefore, the recent ice thickness decline of 24.6 cm for an ice with a typical thickness of 1.8 m would lead to enhanced ice motion, 1.4 times that of the early decade. Our results prove that winter and spring sea ice motion in Baffin Bay in the recent decade are on average 1.6 times greater than those in the early decade (not shown). This is comparable in magnitude to the ice motion changes that are dependent on the thickness changes as we simulated. The remaining small part of ice motion acceleration can be explained by ice concentration decline. To summarize this section, the sea ice motion and area flux increases in Baffin Bay over the past four decades are mainly attributable to a thinner sea ice thickness which is primarily associated with the increase in surface air temperature. This is consistent with findings in the Arctic Ocean (Rampal et al., 2009; Spreen et al., 2011; Kwok et al., 2013).

6. Conclusions

. With satellite-derived sea ice parameters, we estimated the sea ice inflow and outflow through the key fluxgates of Baffin Bay. The record of sea ice area flux was extended to span a nearly 40-yr period from 1978/1979-2016/2017. On the basis of the estimates, the variability and trends of sea ice area flux through the three fluxgates (North Gate, Lancaster Sound, and South Gate) for different timescales (monthly, seasonal, and annual flux) are examined in detail. Large interannual variations are detected for the different flux fields. Moreover, significant increasing trends are identified for the annual ice flux for the three gates, with the primary contributions from those during winter (December-February) and spring (March-May).

The spatiotemporal differences are obvious for the sea ice flux through different gates. On average, there is an inflow though North Gate ($205.8\times10^3 km^2$) and Lancaster Sound ($55.2\times10^3 km^2$) and an outflow via South Gate ($394.3\times10^3 km^2$). During cold seasons (winter and spring), the difference between inflow and outflow (i.e. inflow minus outflow) amounts to $-153.3\times10^3 km^2$ and is largely replenished by new ice formed within the bay that is likely associated with the divergence mechanism. For the warm period (summer and autumn), the sea ice inflows (46.3×10^3 km^2) and outflows (26.3×10^3 km^2) are small, pointing to a net ice area loss of 20.0×10^3 km^2 that is connected to melting process in the bay. This emphasizes that the Baffin bay serves as not only an area of ice source during cold periods and but also an area of ice sink during warm periods. The sea ice growth and melting processes could have vital influences on the ocean current properties in Baffin Bay. With regard to the diverse ice inflow sources into the northern Baffin Bay through the North Gate, the comparisons with published results seem to tally well with the fact that the majority of (about 75%~85%) of ice area originates from ice growth in NWP, in addition to the ice inputs via Nares Strait, Lancaster Sound, and Jones Sound.

The interannual variability of ice flux across the North and South Gates is in part linked to wind forcing associated with the cross-gate SLP differences, while the ice flow through Lancaster Sound is largely determined by orographic conditions. The trends for the three gates (North Gate: 38.9×10^3 km^2/de; South Gate: 82.2×10^3 km^2/de; Lancaster Sound: 7.5×10^3 km^2/de) are significant, which are primarily explained by the increasing ice motion and to a small fraction by the decreasing ice concentration. The preliminary simulation demonstrates that the sea ice motion, which has been accelerated over the past four decades, is mainly attributable to the decline in ice thickness in Baffin Bay. Furthermore, modeling results unveiled that the warmer climate plays a decisive role in generating a thinner ice in the bay.

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Supplement figures:

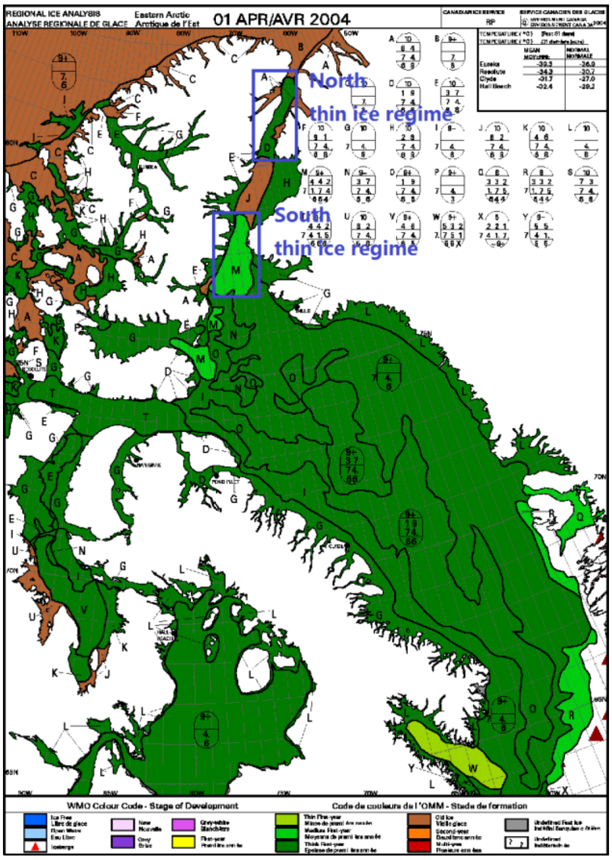

Figure S1a. CIS map for sea ice category in April 2014. The young ice south of the two bridges are shown.

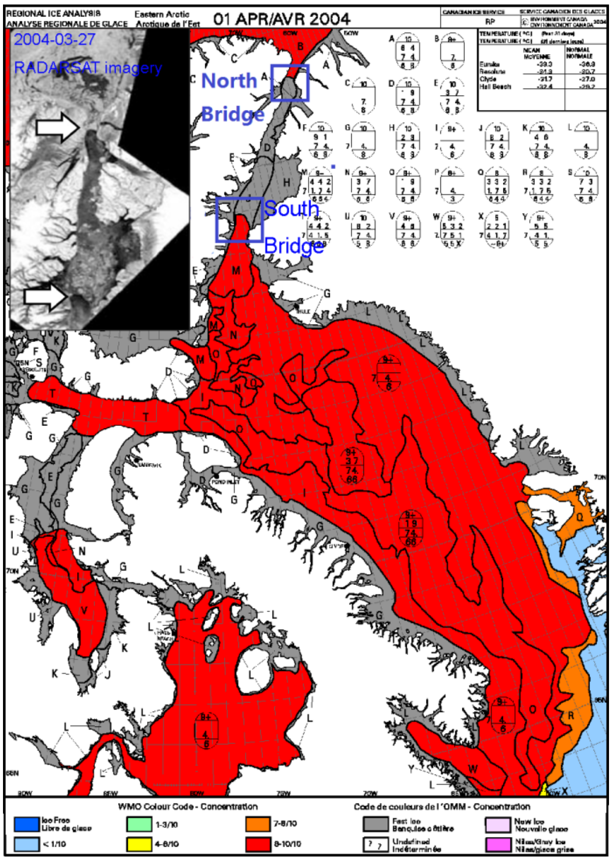

Figure S1b. CIS map of sea ice concentration in April 2014. The two ice bridges are shown. The corresponding RADARSAT imagery is displayed in the inset grey figure.