Recent changes in the exchange of sea ice between the Arctic Ocean and the Canadian Arctic Archipelago

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Received 15 April 2013; revised 27 May 2013; accepted 3 June 2013.

[1] Sea ice is exchanged between the Arctic Ocean and Canadian Arctic Archipelago (CAA) but has not been quantified over long time periods. The corresponding mechanisms responsible for recent variability and change also remain unidentified. To address this, we estimated the sea ice area flux between the Arctic Ocean and the M'Clure Strait and Queen Elizabeth Islands (QEI) from 1997 to 2012 for the months of May to November. Over the period, there was a mean flux of -1×10^3 km^2 ($\pm 21 \times 10^3$ km^2) at the M'Clure Strait and mean flux of $+8 \times 10^3$ km^2 ($\pm 8 \times 10^3$ km^2) at the QEI (positive and negative flux signs correspond to Arctic Ocean ice inflow and outflow, respectively). The M'Clure Strait had a mean flux of $+5 \times 10^3$ km^2 from May to September and a mean flux of -7×10^3 km^2 from October to November. The QEI gates had a mean flux of $+4 \times 10^3$ km^2 from August to September with negligible ice exchange from May to July and October to November. More frequent high sea level pressure anomalies over the Beaufort Sea and Canadian Basin since 2007 have reduced Arctic Ocean multiyear ice (MYI) inflow into the M'Clure Strait. The presence of MYI in the CAA originating from the Arctic Ocean has been maintained by inflow at the QEI, which has increased since 2005. These recent increases in Arctic Ocean MYI inflow into the QEI can be attributed to increased open water area within the CAA that have provided more leeway for inflow to occur.

Citation: Howell, S. E. L., T. Wohlleben, M. Dabboor, C. Derksen, A. Komarov, and L. Pizzolato (2013), Recent changes in the exchange of sea ice between the Arctic Ocean and the Canadian Arctic Archipelago, *J. Geophys. Res. Oceans*, *118*, doi:10.1002/jgrc.20265.

1. Introduction

[2] The Canadian Arctic Archipelago (CAA) is a collection of islands located on the northern North American continental shelf (Figure 1a). Sea ice within the CAA is a mix of seasonal first-year ice (FYI) and perennial multiyear ice (MYI), where the latter category in some years can make up more than 50% of the total ice covered area prior to the melt season [*Canadian Ice Service*, 2011]. The majority of the MYI is located in the Queen Elizabeth Islands (QEI), Western Parry Channel, and M'Clintock Channel where ice concentration often remains high even at the end of the melt season (Figure 1b). Sea ice within the CAA is almost entirely landfast during the winter months: climatologically it breaks up in July, only to then refreeze again in late-October [*Falkingham et al.*, 2001; *Canadian Ice Service*, 2011]. When CAA sea ice is not landfast, it is exchanged with the Arctic Ocean to the north and west, a process that primarily occurs during the summer months [*Melling*, 2002; *Kwok*, 2006; *Agnew et al.*, 2008]. Ice exchange with the Arctic Ocean is important to the CAA because it provides the region with another source of MYI in addition to the in situ production of MYI via FYI aging [*Howell et al.*, 2008; *Howell et al.*, 2009]. Quantifying recent changes in Arctic Ocean MYI that pass through the CAA is vital for the validation of global climate model outputs that have difficultly resolving ice dynamics within the narrow channels of the CAA. Arctic Ocean MYI also represents the most significant hazard to transiting ships through the CAA. Knowledge of changes in Arctic Ocean-CAA ice exchange is therefore important operationally for the continued updating of safety guidelines for CAA shipping routes, particularly those that make use of the Northwest Passage.

[3] The Arctic's sea ice cover has experienced considerable declines, particularly during the summer months, since the late 1970s when passive microwave satellites began acquiring systematic measurements [*Meier et al.*, 2007;

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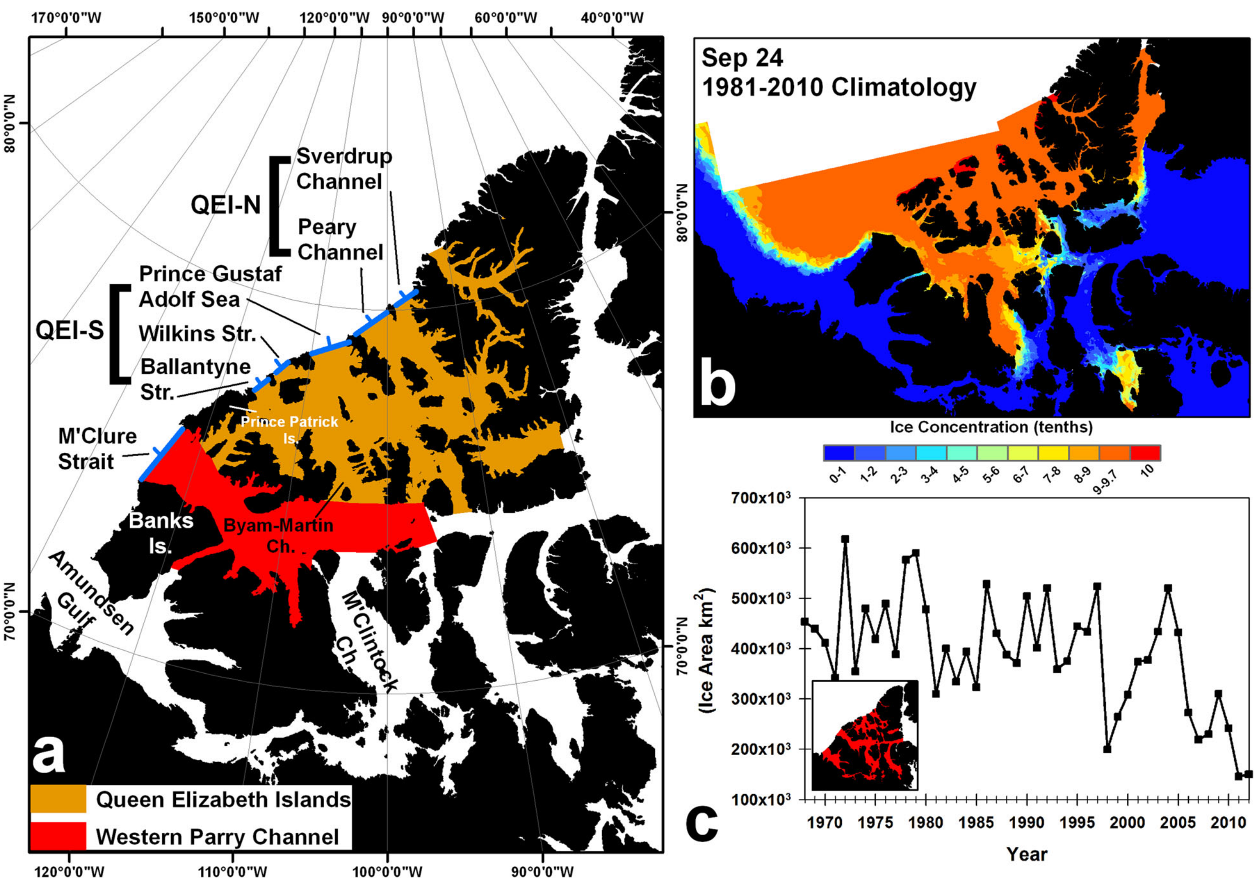

Figure 1. (a) Map of the Canadian Arctic Archipelago with the location of the primary Arctic Ocean exchange gates (in blue). (b) 1981–2010 climatology of median total ice concentration on 24 September. (c) Time series of mean September sea ice area in the Canadian Arctic Archipelago, 1968–2012.

Serreze et al., 2007; *Parkinson and Cavalieri*, 2008, *Comiso*, 2012]. Regionally, sea ice within the CAA during the summer months is also declining but statistically significant decreases in MYI have yet to be realized because of Arctic Ocean MYI inflow that replaces ice lost due to melt [*Howell et al.*, 2009; *Tivy et al.*, 2011; *Derksen et al.*, 2012]. *Melling* [2002] initially suggested that a warmer climate may not immediately result in sustained reductions in sea ice within the CAA: while a warmer climate would cause the FYI in the CAA to break up earlier in the melt season, open water gaps would then be filled with MYI flowing in from the Arctic Ocean. *Howell et al.* [2009] confirmed Melling's hypothesis by demonstrating that since 1995 the primary source of CAA MYI changed from in situ FYI aging to a combination of FYI aging and MYI inflow from the Arctic Ocean, attributed to longer melt seasons providing more opportunity for Arctic Ocean MYI inflow. However, the estimates of Arctic Ocean MYI inflow used by *Howell et al.* [2009] were only based on the end-of-September amount of MYI derived from operational ice charts. These estimates did not provide information about monthly variability in MYI inflow or about the source gateways through which Arctic Ocean ice enters the CAA, both of which are of greater interest.

[4] *Kwok* [2006] provided an initial investigation of sea ice exchange between the Arctic Ocean and the CAA from 1997 to 2002 using RADARSAT imagery. *Agnew et al.* [2008] then examined Arctic Ocean-CAA ice exchange from 2002 to 2007 using Advanced Microwave Scanning Radiometer-EOS (AMSR-E) imagery. These previous studies only represent short 6 year time periods which need to be placed within a longer record given that Arctic sea ice conditions, especially in recent years, have changed considerably [*Kwok and Rothrock*, 2009; *Stroeve et al.*, 2011a; *Maslanik et al.*, 2011]. Even historically relatively stable September sea ice area within the CAA has experienced considerable declines in recent years (Figure 1c). The objectives of this study are to quantify sea ice exchange between the Arctic Ocean and the CAA over a 16 year record (1997–2012) using ice area flux estimates derived from RADARSAT imagery. Links to atmospheric circulation are then explored to explain recent variability and change in ice area flux at the key exchange gates.

2. Data and Methods

2.1. Sea Ice Area Flux Estimation

[5] Ice exchange between the CAA and the Arctic Ocean during the months of May to November was estimated at the M'Clure Strait and the QEI gates (Figure 1a). The M'Clure Strait gate is a 183 km aperture between Banks Island and Prince Patrick Island. The QEI south (QEI-S) gates are made up Ballantyne Strait, Wilkins Strait and Prince Gustaf Adolf Sea and have a total aperture of

219 km. The QEI north (QEI-N) gates are made up of the Peary Channel and Sverdrup Channel and have a total aperture of 151 km. We restricted our analysis to the months of May to November because of landfast conditions persisting within the CAA for most of the year [*Canadian Ice Service*, 2011]. Although ice exchange does occur from December to April but it is relatively small compared to the nonlandfast months [*Kwok*, 2006; *Agnew et al*., 2008]. Arctic Ocean-CAA ice exchange also occurs between the Amundsen Gulf and the Arctic Ocean [*Kwok*, 2006; *Agnew et al*., 2008] but the Amundsen Gulf becomes ice free during the summer months (Figure 1b) and provides a negligible source of CAA ice replenishment during the melt season. However, Arctic Ocean-Amundsen Gulf ice exchange, which is predominantly ice outflow [*Kwok*, 2006; *Agnew et al*., 2008], is important for the ice mass balance Arctic Ocean because of ice production by the Cape Bathurst Polynya during the winter months.

[6] Ice exchange was derived from RADARSAT synthetic aperture radar imagery using the Canadian Ice Service's Automated Sea IceTracking System (CIS-ASITS). Complete technical details of the CIS-ASITS algorithm as well as an evaluation of its performance are available in [*Wohlleben et al*., 2013] and [*Komarov and Barber*, 2013]. Coincident RADARSAT imagery with a spatial resolution of $\sim$200 m pixel^{-1} over the Arctic Ocean-CAA exchange gates was available every 2–5 days. Sea ice area flux at each exchange gate was estimated using an approach similar to that of *Kwok* [2006] and *Agnew et al*. [2008]. First, sea ice motion for each image pair was interpolated to each exchange gate (including a buffer region of $\sim$30 km on each side of the gate). Second, sea ice motion was then sampled at 5 km intervals across the gate. Finally, sea ice area flux (F) at each gate was then calculated using the following equation:

$$F = \sum c_i u_i \Delta x \tag{1}$$

where, Δx is the spacing along the gate (i.e., 5 km), u_i is the ice motion normal to the flux gate at the *i*th location and c_i is the sea ice concentration.

[7] Assuming the errors of the motion samples are additive, unbiased, uncorrelated and normally distributed, the uncertainty in ice area flux across the gates (σ_f) can be estimated using the following equation:

$$\sigma_f = \sigma_e L / \sqrt{N_s} \tag{2}$$

where, σ_e $\sim$0.43 km d^{-1} is the error in RADARSAT derived ice velocities taken from [*Komarov and Barber*, 2013], L is the width of the gate (km) and N_s is the number of samples across the gate. From (2) the ice area flux uncertainty for the M'Clure Strait, QEI-N and QEI-S, is approximately $\pm$13 ($\pm$390 km^2 month^{-1}), $\pm$12 ($\pm$354 km^2 month^{-1}), and $\pm$14 km^2 d^{-1} ($\pm$427 km^2 month^{-1}), respectively. For each exchange gate, sea ice flux estimates from all available image pairs were summed over each month for May to November.

2.2. Ancillary Data

[8] Sea ice concentration (i.e., total ice and MYI) was extracted from the Canadian Ice Service Digital Archive (CISDA). The CISDA is a compilation of Canadian Ice Service (CIS) regional weekly ice charts that integrate all available real-time sea ice information from various satellite sensors, aerial reconnaissance, ship reports, operational model results and the expertise of experienced ice forecasters, spanning 1968 to present [*Canadian Ice Service*, 2007]. The CISDA was found to be more accurate than Scanning Multichannel Microwave Radiometer and Special Sensor Microwave/Imager passive microwave ice concentration retrievals that can underestimate sea ice concentration by as much as 44% during the shoulder seasons [*Agnew and Howell*, 2003]. The CISDA contains a technological bias (related to advances in sensor technology and changes in regional focus due to the emergence of important shipping routes) but *Tivy et al*. [2011] performed an extensive evaluation of the CISDA and found no evidence of time-varying biases in the period since 1979. The time period of this study is entirely within the RADARSAT era (i.e., 1997 to present) of CIS ice chart production therefore, the impact of any technological and methodological changes with respect to CISDA is negligible.

[9] Sea level pressure (SLP) and zonal wind were extracted from National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) Reanalysis [*Kalnay et al*., 1996; *Kistler et al*., 2001] were also utilized.

3. May to November Arctic Ocean-CAA Sea Ice Area Flux, 1997–2012

3.1. M'Clure Strait

[10] The May to November monthly mean time series of sea ice exchange (i.e., ice area flux) between the Arctic Ocean and the CAA at the M'Clure Strait gate from 1997 to 2012, plotted sequentially for each of the 16 years is presented in Figure 2. In this and all subsequent figures, positive flux values correspond to Arctic Ocean ice inflow into the CAA, and negative flux values correspond to ice outflow from the CAA. The corresponding monthly May to November ice area flux time series (averaged over the 16 years from 1997 to 2012) and the range is presented in Figure 3. Over the 1997–2012 period, the seasonal mean of the May to November ice area fluxes was small at -1×10^3 km^2 but the standard deviation was high at 22×10^3 km^2 indicating considerable interannual variability (as illustrated by Figure 2). Ice flux variability was the greatest during the months of August and October with 1997–2012 mean flux values of $+5 \times 10^3$ and -5×10^3 km^2, respectively (Figure 3). Individual monthly mean ice inflow or outflow values can be large, reaching values of $+15 \times 10^3$ km^2 in August of 2002 and -38×10^3 km^2 in October 2007 (Figure 2). Very little ice area flux occurred for the months of May to July ($<1 \times 10^3$ km^2) largely due to landfast ice conditions which restricted ice exchange (Figure 3).

[11] There is a contrast in ice area exchange at the M'Clure Strait between the summer months (August and September) and fall months (October and November) (Figure 3). Over the study period, the summer months of August and September experienced a mean net area ice influx of $+6 \times 10^3$ km^2 from the Arctic Ocean, but during the fall months of October and November there was a mean

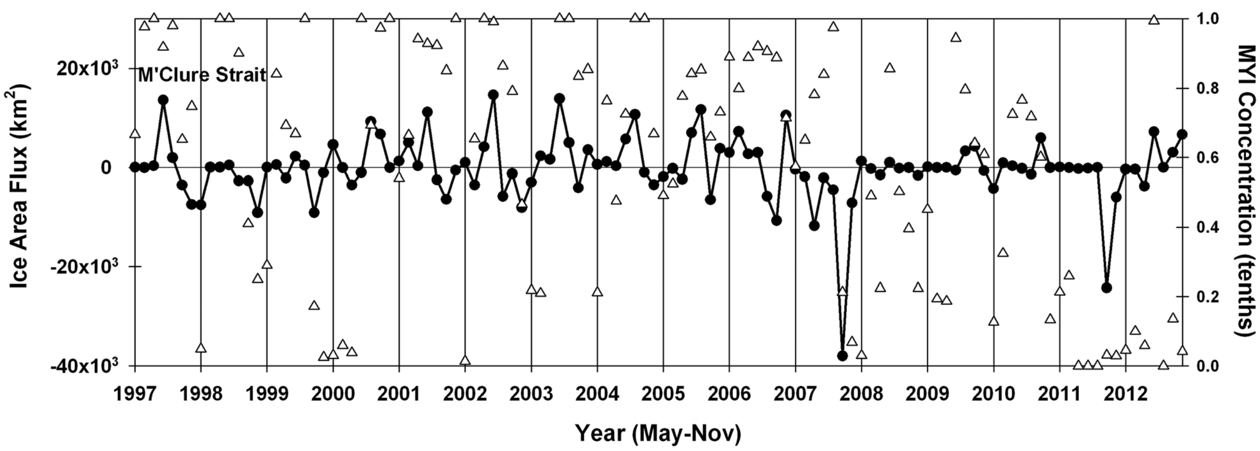

Figure 2. Time series of May to November sea ice area flux (solid circles) and multi-year ice fraction (triangles) at the Arctic Ocean-M'Clure Strait exchange gate, 1997–2012. Positive and negative flux signs correspond to Arctic Ocean ice inflow and outflow, respectively.

net area outflow of -7×10^3 km^2. It is thus apparent that Arctic Ocean ice is primarily imported into the CAA via the M'Clure Strait gate during the period leading up to minimum September sea ice conditions within the CAA. Ice export then dominates during October and November, which can subsequently lead to a partial loss of MYI that has survived the melt season.

3.2. Queen Elizabeth Islands

[12] The May to November mean monthly time series of sea ice exchange (i.e., ice area flux) between the Arctic Ocean and the CAA at QEI-N and QEI-S gates, plotted sequentially for each of the 16 years from 1997 to 2012, is presented in Figure 4. The corresponding monthly May to November ice area flux time series (averaged over the 16 years from 1997 to 2012) is presented in Figure 5. Over the 1997–2012 period, the seasonal mean of the May to November ice area flux at the QEI-N and QEI-S and gates were $+3 \times 10^3$ km^2 and $+5 \times 10^3$ km^2, respectively. Both

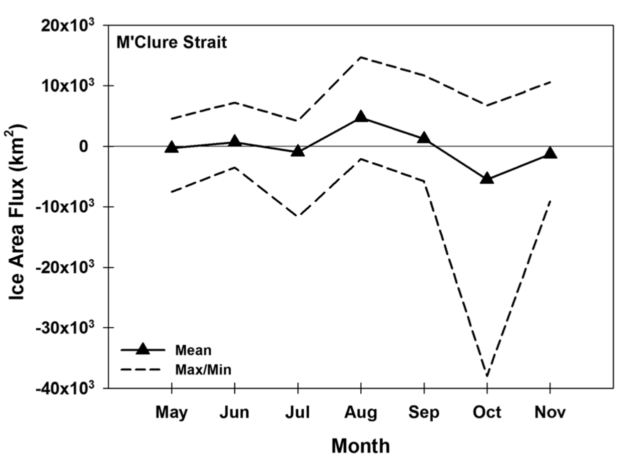

Figure 3. 1997–2012 mean monthly sea ice area flux at the Arctic Ocean-M'Clure Strait exchange gate. Positive and negative flux signs correspond to Arctic Ocean ice inflow and outflow, respectively.

QEI gates have similar standard deviations of $\sim 4 \times 10^3$ km^2 that are considerably smaller than the M'Clure Strait gate (22×10^3 km^2) indicating less seasonal variability.

[13] Although the monthly variability in the ice area flux time series at the QEI gates was considerable, a net ice import from the Arctic Ocean was almost always exhibited (Figures 4a and 4b). The Arctic Ocean polar ice pack is almost always continuously forced up against the QEI by prevailing atmospheric circulation [*Agnew et al*., 1997; *Melling*, 2002] which plays a key role in feeding ice inflow to the CAA when the QEI ice cover is not landfast. In the 1997–2012 mean, Arctic Ocean ice import peaked during September with values of $+2 \times 10^3$ and $+3 \times 10^3$ km^2 for the QEI-N and QEI-S, respectively (Figures 5a and 5b). The largest monthly value occurred in September 2011 for both the QEI-N ($+9 \times 10^3$ km^2) and QEI-S ($+11 \times 10^3$ km^2) (Figures 4a and 4b). When outflow did occur, the magnitude was typically larger at the QEI-N gates than at the QEI-S gates (Figures 5a and 5b). Analogous to the M'Clure Strait, there was almost net no ice exchange between Arctic Ocean and QEI from May to July due to landfast ice conditions within the QEI impeding exchange.

4. Recent Variability and Change in Arctic Ocean-CAA Ice Exchange

4.1. M'Clure Strait

[14] Sea ice exchange between the Arctic Ocean and the CAA via the M'Clure Strait is clearly highly variable but a distinguishing a feature of the 1997–2012 monthly time series is less ice exchange with the Arctic Ocean, particularly with respect to inflow since 2007 (Figure 2). During the early period of the record, sea ice conditions at the M'Clure Strait gate were a mix of FYI and MYI but since 2007, MYI concentrations are much lower (Figure 2). RADARSAT imagery show the M'Clure Strait gate was ice free for a period in September in 2007, and subsequently again in 2008, 2010, 2011, and 2012 (Figure 6). 1998 was the only other year in the time series with an ice free period in September (Figure 6). Following these ice free conditions in 1998, there was a return to variable ice exchange through

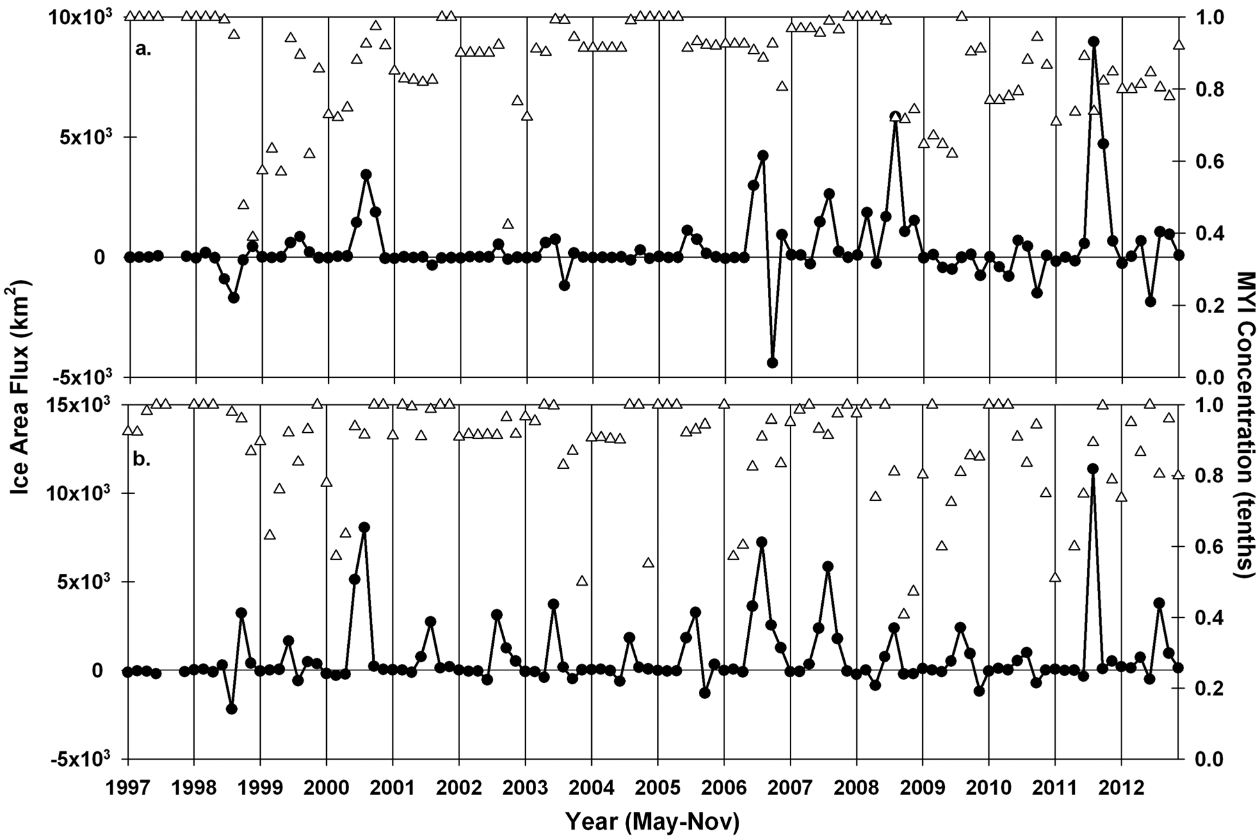

Figure 4. Time series of May to November sea ice area flux (solid circles) and multi-year ice fraction (triangles) at the Arctic Ocean-Queen Elizabeth Islands (a) North and (b) south exchange gates, 1997–2012. Positive and negative flux signs correspond to Arctic Ocean ice inflow and outflow, respectively.

2007, but there is little evidence of appreciable ice exchange following the near-continuous series of September ice free events since 2007 (Figure 2).

[15] A comparison of 1997–2012 mean net ice area flux for May to September versus October to November reveals that reduced ice exchange in recent years has occurred primarily during the spring and summer months (Figure 7). From 1997 to 2006, the net May to September Arctic Ocean total ice import into the M'Clure Strait was $+105 \times 10^3$ km^2 with MYI making up 95% ($+100 \times 10^3$ km^2) of this amount; only in 1998 was there net ice outflow (Figure 7a). From 2007 to 2012 the net May to September Arctic Ocean total sea ice flux was -15×10^3 km^2. The years of 2008, 2009, and 2012 did experience positive May to September net ice inflow from the Arctic Ocean but this amount was small relative to 1997–2006 (Figure 7a).

[16] Considerable Arctic Ocean ice inflow occurred at the M'Clure Strait in 1997, 2000–2006, and 2009 and a key feature was that a continuous tongue of the Arctic Ocean polar pack ice extended almost to the middle of Western Parry Channel by late September, connecting sea ice in the CAA to the Beaufort Sea (Figures 8a, 8d–8j, and 8m). When net ice exchange was small, or when net ice outflow occurred (i.e., 1998; 1999; 2007–2008; 2010–2011) this connection was not present and the Arctic Ocean polar pack was displaced to the west of Banks Island (Figures 8b, 8c, 8k, 8l, 8n, and 8o). The exception was 2012, a season characterized by net ice import even though the Arctic Ocean polar pack retreated north of Banks Island by the end of September. The pack ice advected into the CAA via the M'Clure Strait in 2012 did not survive the melt season and the channel was again ice free (Figure 8p) by the end of September.

[17] There is an inverse statistically significant (95% confidence level) relationship between May to September net open water within the Western Parry Channel and net May to September ice area flux at the M'Clure Strait gate, with a correlation coefficient (r) between the two time series of -0.60 (Figure 9). We suggest that less open water in the Western Parry Channel is associated with more ice exchange because the tongue of Arctic Ocean polar pack is connected to the Western Parry Channel and the required open water leeway for Arctic Ocean ice import to occur is available in the M'Clintock Channel located to the southeast. Conversely, when there are increases in the open water area within the Western Parry, the Arctic Ocean polar pack is disconnected from Western Parry Channel, which results in less ice exchange.

[18] The Arctic Ocean-Western Parry Channel ice connection (positive ice flux) or disconnection (reduced ice flux) can in part be attributed to large-scale atmospheric circulation. When ice is not landfast (typically during August and September), SLP provides a useful indicator of ice motion because ice drift generally occurs parallel to the isobars [*Thorndike and Colony*, 1982]. Ocean currents at the M'Clure Strait gate do flow into the CAA, but are weak

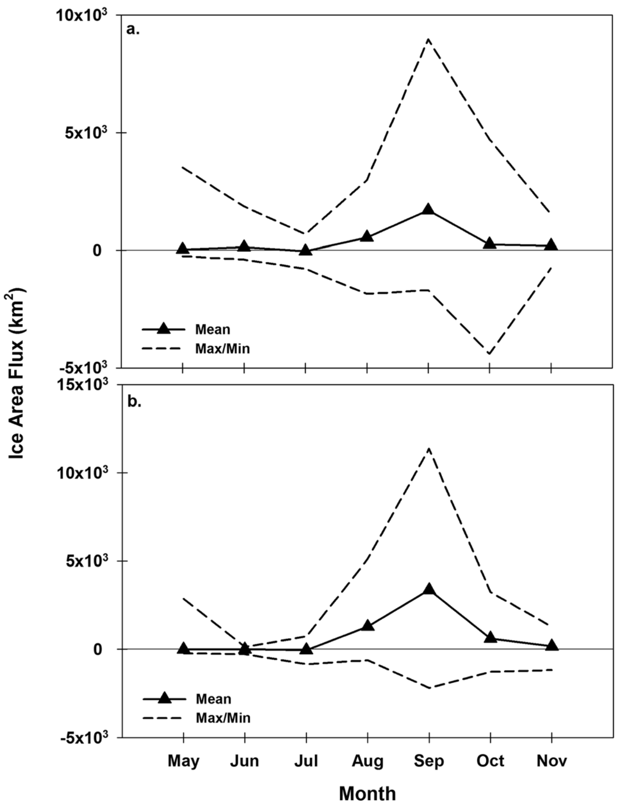

Figure 5. 1997–2012 mean monthly sea ice area flux at the Arctic Ocean-Queen Elizabeth Islands (a) North and (b) South exchange gates. Positive and negative flux signs correspond to Arctic Ocean ice inflow and outflow, respectively.

(~2–6 km^2 day^{-1}) [*Canadian Ice Service*, 2011]. *Kwok* [2006] and *Agnew et al.* [2008] found that the daily cross-gradient SLP at the M'Clure Strait (i.e., between Prince Patrick Island and Banks Island) explained ~50% of the sea ice area flux. The correlation between monthly zonal wind anomalies in the Beaufort Sea and Canadian Basin and ice exchange at the M'Clure Strait is 0.54 and 0.50 for August and September, respectively and statistically significant at the 95% confidence level (Figure 10). Additionally, although the correlation between the mean August and September Arctic Oscillation (AO) index [*Thompson and Wallace*, 1998] and net August and September ice area flux is only 0.42, it is statistically significant at the 95% confidence level. The positive correlation with the AO indicates a strong Beaufort Gyre (i.e., low AO and high SLP anomalies) corresponds to more CAA ice outflow to the Arctic Ocean from the M'Clure Strait contrasted against weak Beaufort Gyre (i.e., high AO and lower SLP anomalies) that corresponds to more Arctic Ocean import. *Agnew et al.* [2008] also reported statistically significant correlations of 0.4 between the AO and Arctic Ocean-M'Clure Strait ice exchange and suggested a similar process. Despite the aforementioned statistical associations, the aperture between Prince Patrick Island and Banks Island is only ~181 km and therefore small interannual differences in the exact location of atmospheric circulation anomalies (i.e., high or low SLP centers of action) during August and September can be important with respect to ice inflow and outflow

4.1.1. Pronounced Arctic Ocean Ice Inflow Period, 1997–2006

[19] The majority of the Arctic Ocean ice inflow in 1997 and 2001–2003 occurred in August and was associated with low SLP anomalies located to the northwest of the CAA (Figure 11a). For 2000 and 2004, the majority of the Arctic Ocean ice inflow occurred in September, also associated with low SLP anomalies to the northwest of the CAA (Figure 11b). 1999 is a good example of negligible ice inflow despite low SLP anomalies in September because their primary center of action extended southward over the central CAA and so it did not favor ice inflow through the M'Clure Strait (Figure 11c).

[20] The association between low SLP anomalies and ice inflow for 2005 and 2006 was not as straightforward. In 2005, high SLP anomalies located to the northwest of the

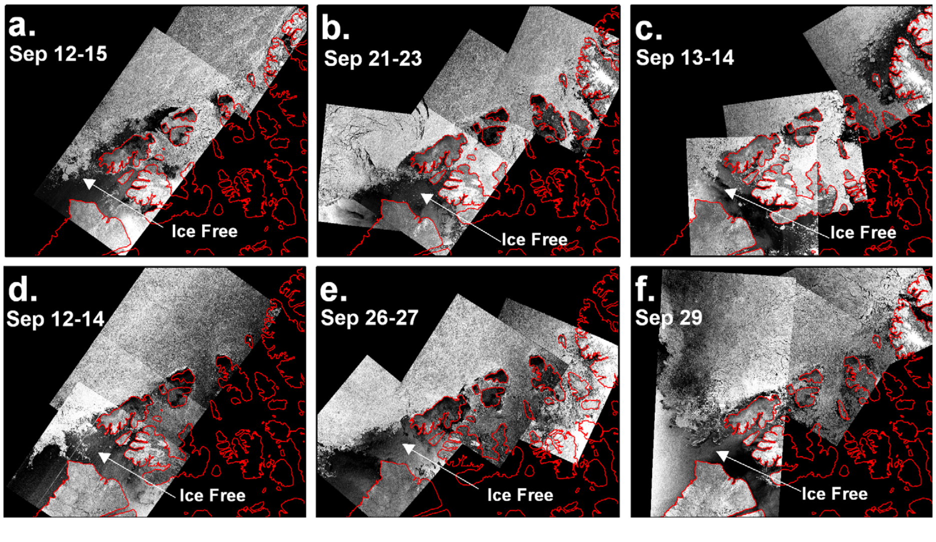

Figure 6. RADARSAT imagery illustrating sea ice free conditions at the Arctic Ocean-M'Clure Strait exchange gate for (a) 1998, (b) 2007, (c) 2008, (d) 2010, (e) 2011, and (f) 2012. (RADARSAT imagery© Canadian Space Agency).

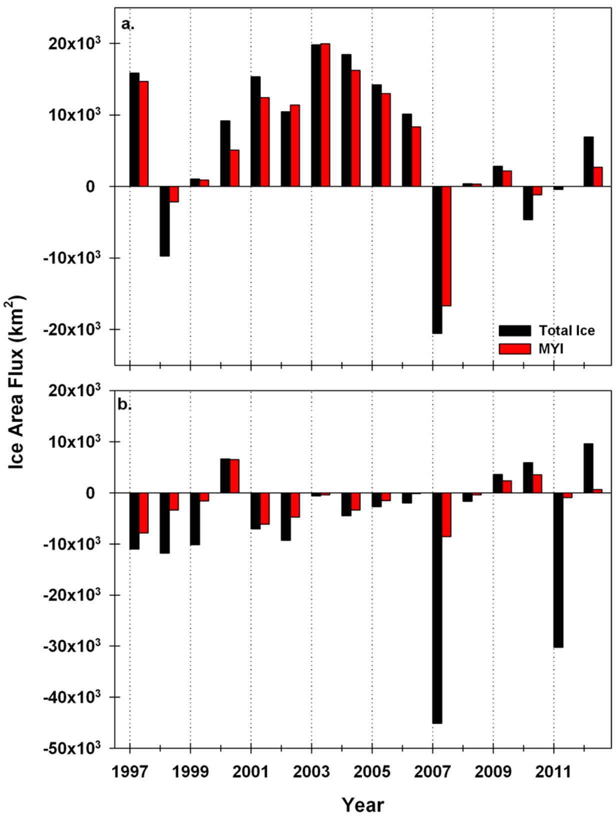

Figure 7. Time series of Arctic Ocean-M'Clure Strait gate net total ice and multi-year ice area flux from (a) May to September and (b) October to November, 1997–2012. Positive and negative flux signs correspond to Arctic Ocean ice inflow and outflow, respectively.

CAA dominated in August and September (Figure 11d) but from the last week of August to the first week September low SLP anomalies were present (not shown) facilitating the majority of the Arctic Ocean ice import which was not offset by ice outflow during remainder of September. In 2006, high SLP anomalies were also present for August and September (Figure 11d) facilitating ice outflow but negative SLP anomalies during June and July, combined with an early fracture of landfast ice in the M'Clure (not shown) drove a period of early season ice inflow.

4.1.2. Reduced Arctic Ocean Ice Inflow Period, 2007–2012

[21] High SLP anomalies were present over the CAA and Canadian Basin in both August and September for 2007, 2008, 2010, and in August for 2011, which are associated with net ice outflow or reduced net ice inflow (Figure 11e). The low SLP anomalies over the CAA in September 2011 (see Figure 11f) are also another good example of the location of low pressure SLP anomalies not always being able to facilitate Arctic Ocean ice inflow through the narrow aperture of the M'Clure Strait. In 2009, high SLP anomalies in August contributed to ice outflow and the small amount of ice import that occurred was in September was associated with low SLP anomalies that were particularly apparent in the August and September zonal wind anomaly time series (Figure 10).

[22] The year 2012 was an exception to the aforementioned processes because even though there was a net ice inflow from the Arctic Ocean, ice free conditions prevailed within the Western Parry Channel by the end of September. In August, a very strong low SLP system tracked across the Arctic Ocean and into the CAA [*Simmonds and Ruveda*, 2012]. This system facilitated the net import of Arctic Ocean ice into the CAA in August but in September there was virtually net zero exchange with the Arctic Ocean (Figure 2). By the end of September the MYI that had been advected into the CAA melted and the Arctic Ocean polar pack clearly showed considerable ice loss in the Beaufort Sea (Figure 8p). Summer surface air temperatures in the CAA during 2012 were ~2°C warmer than the 1981–2010 climatology (not shown), and thereby contributed to the ablation of the imported MYI. Moreover, previous studies have demonstrated that the Arctic Ocean MYI is now thinner and weaker and hence more prone to melt than in previous years [*Kwok and Cunningham*, 2010; *Stroeve et al.*, 2011b; *Maslanik et al.*, 2011].

4.2. Queen Elizabeth Islands

[23] Since 2005, more frequent ice inflow occurred at both the QEI-S and QEI-N gates (Figure 4). Unlike the observed reductions in MYI at the M'Clure gate (Figure 2), the MYI fraction at both QEI gates remained near or above 60% throughout the entire 16 year record. Even during periods when the M'Clure Strait gate was ice free (September 1998, 2007, 2008, and 2010–2012), Arctic Ocean sea ice was still dynamically forced against the QEI exchange gates (Figure 6). The coastlines of QEI are only temporarily cleared when flaw leads open [*Canadian Ice Service*, 2011] and therefore MYI conditions are almost always high at the Arctic Ocean-QEI exchanges gates.

[24] The 1997–2012 time series of mean net ice area flux from May to September for the QEI illustrates large net positive ice inflow for 5 out of the 8 years since 2005 (as opposed to only 1 in the 8 years between 1997 and 2004; Figure 12a). The October to November net ice flux was considerably smaller and exhibited no distinct characteristics over the period (Figure 12b). The 1997–2004 May to September net inflow was 26×10^3 km^2 (93% MYI) compared to 77×10^3 km^2 (87% MYI) from 2005 to 2012. A common spatial characteristic over the 2005–2012 period was that there were more years with large areas of open water in the CAA compared to years from 1997 to 2004 (Figure 8). The time series of the May to September net accumulated open water within the QEI and the May to September ice net ice area flux at the QEI exchange gates exhibits a moderately strong correlation of 0.64, significant at the 95% confidence level (Figure 13). We suggest that the recent increases in open water within the QEI for most years since 2005 are providing more leeway for atmospherically driven Arctic Ocean ice import to occur. This ice subsequently flows southward into the Western Parry Channel with Byam-Martin Channel being the main exit point from the QEI. Ice congestion in most summers during 1997–2004 restricted the latter process. Although ocean currents at the QEI gates flow southeastward they are weak (~2–6 km^2 d^{-1}) [*Canadian Ice Service*, 2011] and atmospheric forcing is likely more influential with respect ice inflow as long there is leeway within the QEI. *Kwok* [2006]

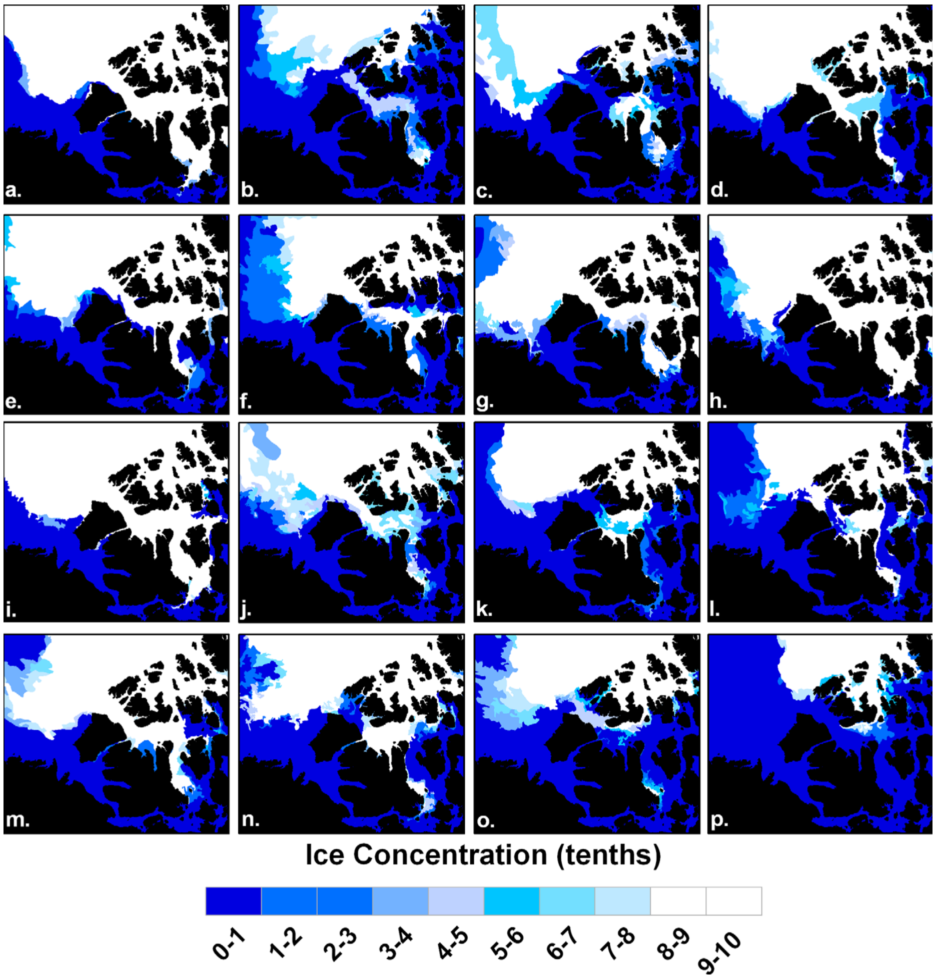

Figure 8. Spatial distribution of total sea ice concentration at the end of September in the western Canadian Arctic, 1997–2012. (a) 25 September 1997. (b) 28 September 1998. (c) 27 September 1999. (d) 25 September 2000. (e) 24 September 2001. (f) 23 September 2002. (g) 29 September 2003. (h) 27 September 2004. (i) 26 September 2005. (j) 25 September 2006. (k) 24 September 2007. (l) 22 September 2008. (m) 21 September 2009. (n) 27 September 2010. (o) 27 September 2011. (p) 24 September 2012.

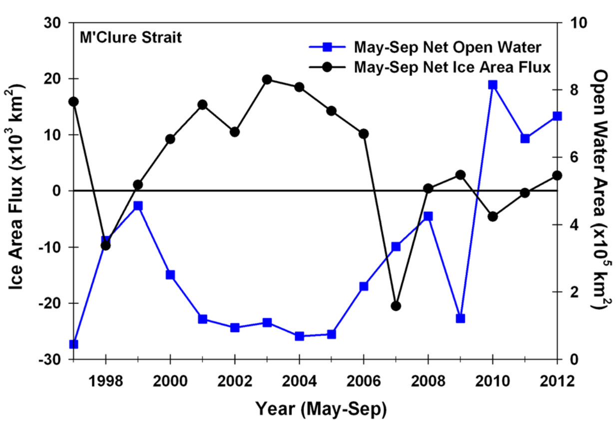

Figure 9. Time series of May to September net open water within the Western Parry Channel and May to September Arctic Ocean-M'Clure Strait net ice area flux, 1997–2012. Positive and negative flux signs correspond to Arctic Ocean ice inflow and outflow, respectively.

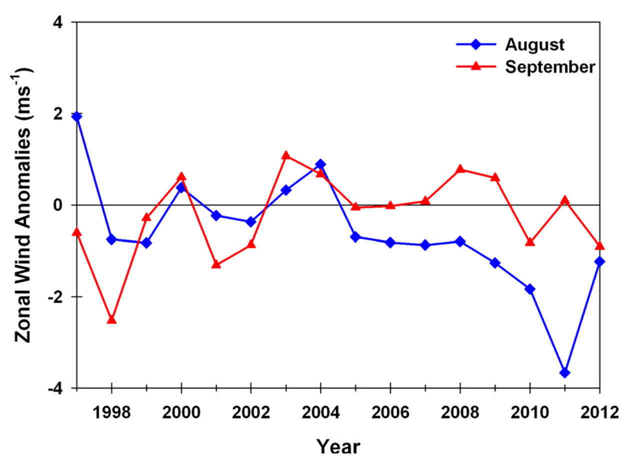

Figure 10. Time series of NCEP-NCAR mean August and September zonal wind (70°N–80°N and $-130°$W to $-100°$W) anomalies (ms^{-1}), 1997–2012. Anomalies calculated with respect to the 1981–2010 climatology.

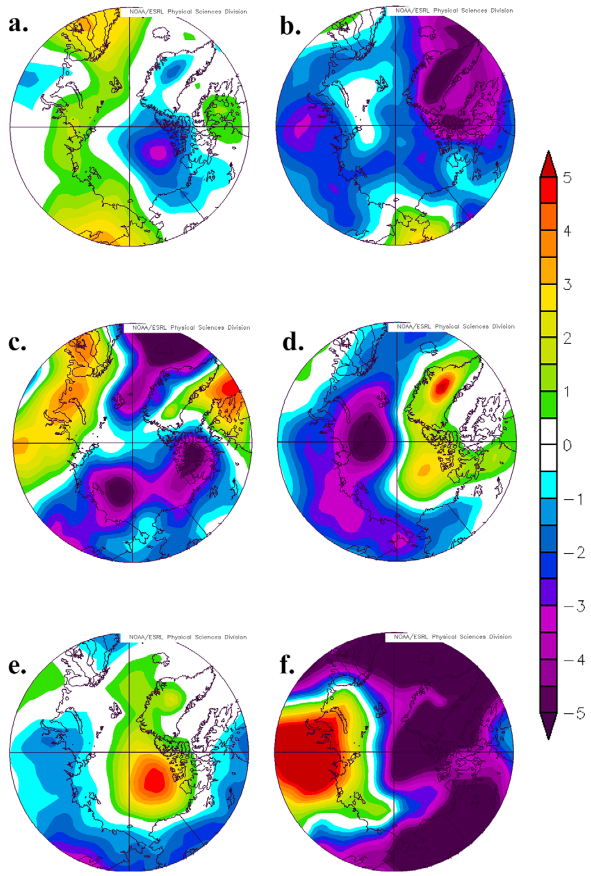

Figure 11. Spatial distribution of NCEP-NCAR mean SLP (mb) composite anomalies for pronounced Arctic Ocean ice inflow period at the M'Clure Strait: (a) August 1997, 2001, 2002, and 2003, (b) September 2000 and 2004, (c) September 1999, (d) August and September 2005 and 2006, and reduced Arctic Ocean ice inflow at the M'Clure Strait: (e) August and September 2007, 2008, 2010, and 2011, and (f) September 2011. Anomalies calculated with respect to the 1981–2010 climatology.

and *Agnew et al.* [2008] found that the daily the cross-gradient SLP at the QEI explained ~60% of the sea ice area flux. However, the correlations between Beaufort Sea and Canadian Basin monthly zonal wind anomalies and QEI ice area flux for August and September are weak (~0.35), even more so than at the M'Clure Strait. No statistically significant correlations between the AO and net ice flux into the QEI were found, consistent with *Agnew et al.* [2008]. The persistence of extended landfast conditions and narrow apertures within the QEI impedes appreciable ice exchange and likely contributes to lower correlations at the monthly time scale.

4.2.1. Low Arctic Ocean Ice Inflow Period, 1997–2004

[25] Reduced ice inflow into the QEI in 1997 can be attributed to ice congestion and lower fractions of open water, which impeded ice inflow (Figures 8a and 13). Anomalously high SLP anomalies over the central Arctic Ocean in September favored ice import into the QEI but ice already filled the majority of the CAA's channels and

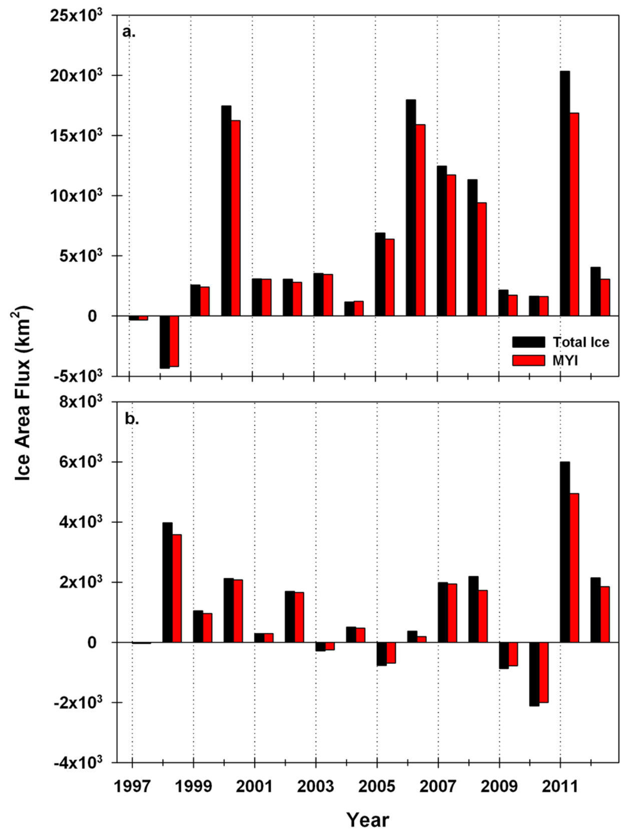

Figure 12. Time series of Arctic Ocean-Queen Elizabeth Islands (North and South) gate net total ice and multi-year ice area flux from (a) May to September and (b) October to November 1997–2012. Positive and negative flux signs correspond to Arctic Ocean ice inflow and outflow, respectively.

straits in 1997, which impeded inflow (Figures 8a and 14a). For 2001 and 2002 the majority of the Arctic Ocean ice inflow occurred in September although net open water areas for these years were low (indicative of ice

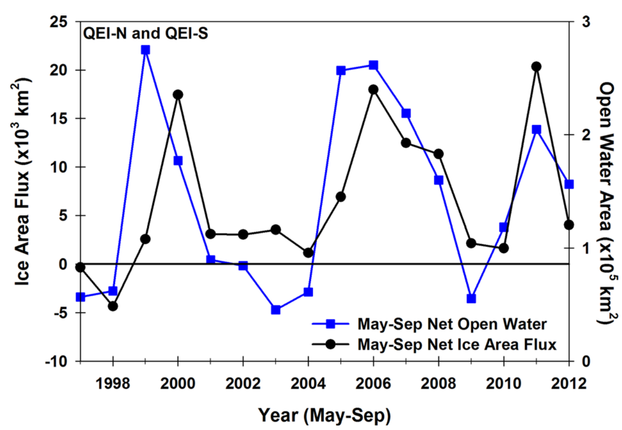

Figure 13. Time series of May to September net open water within the Queen Elizabeth Islands and May to September Arctic Ocean-Queen Elizabeth Islands (North and South) net ice area flux, 1997–2012. Positive and negative flux signs correspond to Arctic Ocean ice inflow and outflow, respectively.

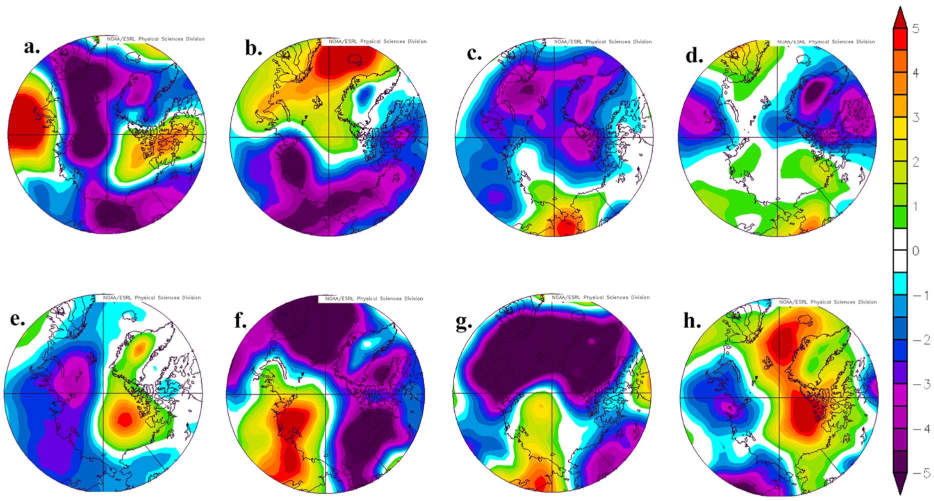

Figure 14. Spatial distribution of NCEP-NCAR SLP (mb) anomalies composite anomalies for the low Arctic Ocean ice inflow period at the Queen Elizabeth Islands: (a) September 1997, (b) September 2001 and 2002, (c) September 2003 and 2004, (d) August and September 2000, and for the increased Arctic Ocean ice inflow period at the Queen Elizabeth Islands: (e) August and September 2005, 2006, 2007, and 2008, (f) September 2012, (g) September 2009, and (h) August and September 2010. Anomalies calculated with respect to the 1981–2010 climatology.

congestion) (Figure 13) and SLP anomalies in both August and September did not promote appreciable inflow (Figure 14b). In 2003 and 2004, slightly more favorable SLP anomalies should have facilitated Arctic Ocean ice inflow but ice congestion was even higher than 2001 and 2002 resulting in minimal net ice inflows (Figures 13 and 14c).

[26] The May to September net ice outflow in 1998 can be attributed anomalously high SLP anomalies over Greenland that facilitated ice outflow, a process that has been reported by several previous studies [e.g., *Alt et al*., 2006; *Kwok*, 2006; *Howell et al*., 2010]. 1998 was an anomalously light ice year within the CAA (especially in the QEI) which witnessed the removal of the decade old landfast-ice plug in the Sverdrup Channel [*Agnew et al*., 2001; *Jeffers et al*., 2001]. Subsequently, 1999 experienced the largest net open water area within the QEI from May to September (Figure 13). This can be directly attributed to the removal of considerable amounts of MYI in 1998 which left the area covered primarily in thinner FYI [*Howell et al*., 2010]. Despite the presence of large open water areas in the QEI during the summer of 1999 (Figure 13), atmospheric circulation did not favor appreciable ice influxes from the Arctic Ocean (see Figures 10 and 11c) highlighting the importance of atmospheric forcing with respect to ice inflow into the QEI.

[27] The year 2000 was the only year during 1997–2004 that experienced considerable Arctic Ocean ice inflow during the May to September period (Figure 12a). This net inflow can be attributed to less ice congestion and low SLP anomalies over Greenland, the latter being particularly effective at facilitating import at these gates (Figures 13 and 14d).

4.2.2. Increased Arctic Ocean Ice Inflow Period, 2005–2012

[28] The majority of ice inflow that occurred from 2005 to 2008 was associated with high August and September SLP anomalies located to the northwest of the CAA (Figure 14e) combined with less ice congestion within the CAA (Figures 8i–8l and 13). Although by end of September in 2005 the CAA was heavily covered with ice (Figure 8i), appreciable import still occurred earlier in the month. The May to September net open water area in 2005 was fairly high and the open gaps in the pack ice were refilled via Arctic Ocean ice inflow and that the ice in the QEI was then gradually transported southward.

[29] During 2011, anomalously high SLP pressures over the central Arctic Ocean in August initially restricted ice inflow but when atmospheric circulation changed in September to low SLP anomalies over the eastern CAA and Greenland (see Figures 10 and 11f) considerable ice inflow then occurred. Ice inflow in September 2011 also indicates that low SLP anomalies can facilitate ice import into the QEI as long as open water leeway is available in the southern channels. Low SLP anomalies in August 2012 facilitated ice outflow but in September an additional low SLP anomaly in Baffin Bay facilitated moderate ice inflow into the QEI (Figure 14f).

[30] The only years from 2005 to 2012 that did not experience appreciable net ice inflow from May to September were 2009 and 2010 (Figure 12a). In 2009, ice congestion within the Western Parry Channel immediately south of the QEI blocked the drainage of ice from the QEI southward and the subsequent flow of ice from the Arctic Ocean into the QEI (Figure 8m). This occurred despite favorable SLP anomalies during September (Figure 14g). More open water area existed in the CAA in 2010 than in 2009 but SLP anomalies during August and September did not facilitate strong ice inflow in 2010 (Figures 13 and 14h). Ice area exchange during August and September 2009 and 2010 illustrate that SLP forcing alone is insufficient to drive ice exchange into the CAA at these gates—atmospheric forcing must be coupled with open water leeway.

5. Previous Studies

[31] Here we briefly compare the results of our ice area flux estimates to the previous studies of *Kwok* [2006] and *Agnew et al*. [2008]. There was generally good agreement with *Kwok* [2006], in terms of interannual variability at all exchange gates (Figures 15a and 15b). The coefficient of determination (r^2) between the two sets of results was larger for the M'Clure Strait than for the QEI gates, with values of 0.81 and 0.64, respectively but both were statistically significant at the 95% confidence level. The main noticeable difference between the time series occurs for the QEI, where *Kwok* [2006] reported larger magnitude fluxes for certain events. Agreement with the results of *Agnew et al*. [2008] were also strong, but were characterized by a lower r^2 value of 0.63 at the M'Clure and 0.44 the QEI gates however, both were statistically significant at the 95% confidence level (Figures 16a and 16b).

[32] The differences between our ice flux estimates and previous studies is likely the result of a combination of factors that include the geographic definitions of ice exchange gate locations, the source of ice concentration information used to derive area flux (passive microwave derived used in *Kwok* [2006] and *Agnew et al*. [2008] versus CISDA used in this study), and inherent technical algorithm differences all of which can impact flux values. Moreover, *Agnew et al*. [2008] used AMSR-E data to derive ice motion which has more difficultly at resolving the surface than RADARSAT data, because of issues with atmospheric water vapor during the melt season, which may explain the large differences between our results and those of that study during September within the QEI.

[33] Direct comparisons of seasonal mean flux values from the estimates of *Kwok* [2006] and *Agnew et al*. [2008] for their respective study periods (i.e., 1997–2002 and 2002–2007) to that of our 16 year study period are not meaningful as sea ice conditions have changed considerably from 1997 to 2012. However, a consistent scenario is emerging, in which the QEI almost always experiences a net positive inflow from the Arctic Ocean, while ice exchange at the M'Clure Strait is much more variable. Net Arctic Ocean ice outflow at the M'Clure Strait occurs over the annual cycle only because ice outflow during the fall months is greater than ice inflow during the spring and summer months.

6. Conclusions

[34] We utilized 16 years of RADARSAT imagery to estimate the sea ice area flux between the Arctic Ocean and the CAA at the M'Clure Strait and QEI (north and south) exchange gates for the months of May to November from 1997 to 2012. Over this period, the M'Clure Strait ice area flux was -1×10^3 km^2 indicating net outflow to the Arctic Ocean but it is important to note that the interannual variability is high (i.e., $\pm 21 \times 10^3$ km^2). An examination of seasonal differences revealed that while Arctic Ocean ice inflow primarily occurred during the summer months (May to September) outflow dominates in the fall months (October to November). The QEI gates experienced a mean flux of $+3 \times 10^3$ km^2 from August to September with negligible ice exchange from May to July and October to November. These results indicate that Arctic Ocean ice inflow at the M'Clure Strait and QEI exchange gates during August and September play an important role in determining the annual sea ice minimum within the CAA.

[35] Since 2007, Arctic Ocean ice inflow at the M'Clure Strait gate during the summer months has reduced considerably. We attribute the decrease to the increased frequency

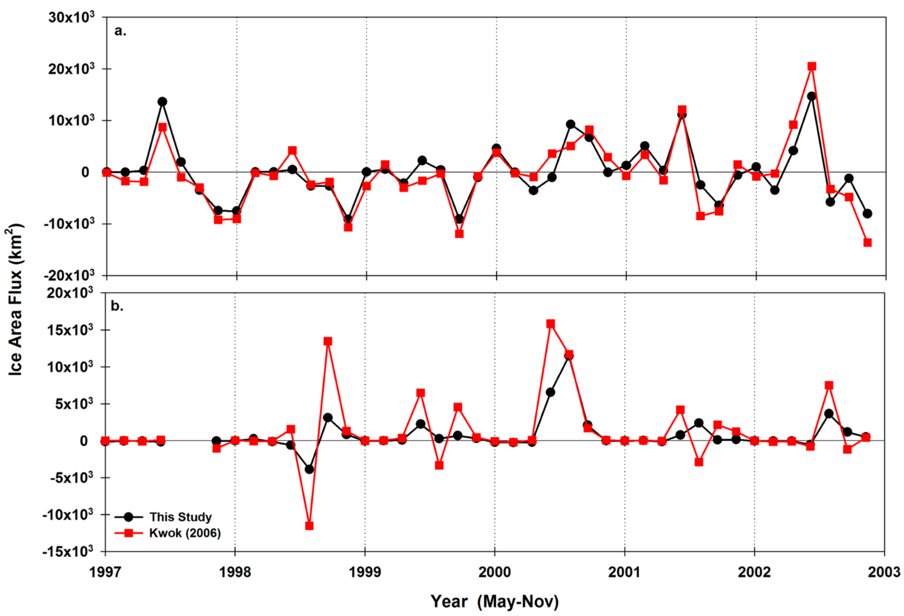

Figure 15. Comparison of 1997–2002 monthly May to November ice area flux at (a) the Arctic Ocean-M'Clure Strait and (b) the Arctic Ocean-Queen Elizabeth Islands (North and South) exchange gates between *Kwok* [2006] and this study. Positive and negative flux signs correspond to Arctic Ocean ice inflow and outflow, respectively.

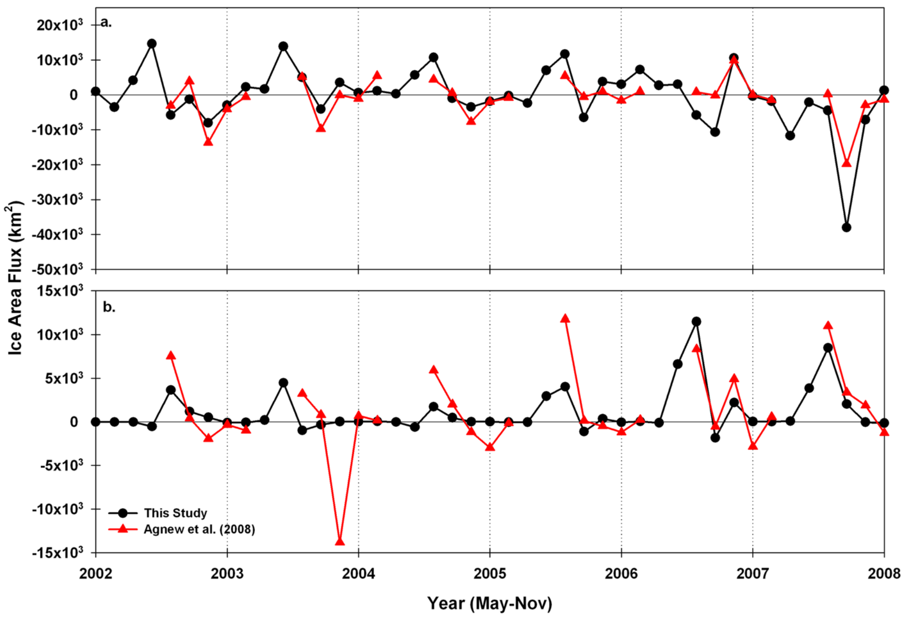

Figure 16. Comparison of 2002–2008 monthly May to November ice area flux at (a) the Arctic Ocean-M'Clure Strait and (b) the Arctic Ocean-Queen Elizabeth Islands (North and South) exchange gates between *Agnew et al*. [2008] and this study. Positive and negative flux signs correspond to Arctic Ocean ice inflow and outflow, respectively.

and location of high SLP anomalies over the Beaufort Sea and Canadian Basin that disconnect the Arctic Ocean polar pack ice from ice within the Western Parry Channel. While Arctic Ocean ice inflow has decreased at the M'Clure Strait in recent years, the QEI gates have experienced increases since 2005. The increase at the QEI gates can be attributed to increased open water within the QEI (and the channels to the south of the QEI) providing more leeway for atmospherically driven Arctic Ocean ice import to occur.

[36] The opening of the Northwest Passage in 2007, 2008, 2010, and 2011 can in part be attributed to the lack Arctic Ocean ice inflow at the M'Clure Strait. Recent modeling studies suggest that the Northwest Passage could be a viable shipping route during September by mid-century [*Smith and Stephenson*, 2013; *Stephenson et al*., 2013]. However, the presence of Arctic Ocean MYI stills remains on the north facing coast of the CAA when the remainder of the Arctic Ocean is ice free [*Wang and Overland*, 2012]. Our analysis points out that despite reduced Arctic Ocean ice inflow into the CAA at the M'Clure Strait, ice inflow at the QEI has continued, thus maintaining the presence of Arctic Ocean MYI within the CAA. Although younger and thinner [*Maslanik et al*., 2011], this MYI has continued to flow southward into the channels of the Northwest Passage (Figure 8). As long as MYI still remains on the north facing coast of the CAA caution needs to be taken with respect the practical usage of the Northwest Passage in upcoming years.

[37] Sea ice conditions within the CAA during September have begun to decrease considerably in recent years (Figure 1c), and the lack of Arctic Ocean ice inflow at M'Clure Strait has likely played a role. In order to better understand the recent reductions in September sea ice within the CAA attention must now be focused on investigating (i) how much Arctic Ocean MYI inflow into the CAA survives the melt season and (ii) how much in situ FYI within the CAA survives the summer melt to then be promoted to MYI. Quantifying these changes, and understanding the reasons behind them, will undoubtedly prove helpful not only for future sea ice modeling studies of the region but also for establishing more up-to-date ship routing guidance for the CAA region.

[38] **Acknowledgments.** This work was funded by the Canadian Space Agency through the Government Related Initiatives Program. RADARSAT data for 1997–2007 were provided by the Alaska Satellite Facility, Fairbanks, Alaska.

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