Multi-Year Sea-Ice Conditions in the Western Canadian Arctic Archipelago Region of the Northwest Passage: 1968–2006

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ABSTRACT *Numerous studies have reported decreases in Arctic sea-ice cover over the past several decades and General Circulation Model (GCM) simulations continue to predict future decreases. These decreases — particularly in thick perennial or multi-year ice (MYI) — have led to considerable speculation about a more accessible Northwest Passage (NWP) as a transit route through the Canadian Arctic Archipelago (CAA). The Canadian Ice Service Digital Archive (CISDA) is used to investigate dynamic import/export and in situ growth of MYI within the western CAA regions of the NWP from 1968 to 2006. This analysis finds that MYI conditions in the western CAA regions of the NWP have remained relatively stable because the M'Clintock Channel and Franklin regions continuously operate as a drain-trap mechanism for MYI. Results also show that in addition to the Queen Elizabeth Islands (QEI) region, the Western Parry Channel and the M'Clintock Channel are also regions where a considerable amount of MYI forms in situ and combined with dynamic imports contributes to heavy MYI conditions. There is also evidence to suggest that more frequent dynamic import of MYI appears to have occurred since-1999 compared to the formation of more MYI in situ before 1999. As a result, the drain-trap mechanism that has historically maintained heavy MYI conditions in the NWP is perhaps operating faster now than it was in the past. Based on the 38-year MYI record examined in this study, it is likely that the mechanisms operating within the western CAA regions of the NWP can facilitate the continued presence of MYI for quite some time.*

RÉSUMÉ *[Traduit par la rédaction] De nombreuses études ont signalé des diminutions dans la couverture de glace de mer arctique au cours des dernières décennies et les simulations des modèles de circulation générale (MCG) continuent de prévoir d'autres diminutions. Ces diminutions — en particulier dans la glace de plusieurs années épaisse et pérenne — ont vivement laissé miroiter la possibilité d'un passage du Nord-Ouest (PNO) plus accessible en tant que route pour traverser l'archipel Arctique canadien (AAC). Les archives numériques du Service canadien des glaces (ANSCG) permettent d'étudier l'importation/exportation et la croissance sur place de la glace de plusieurs années dans les segments du PNO situés dans l'ouest de l'AAC de 1968 à 2006. Cette analyse montre que les conditions de glace de plusieurs années dans les segments du PNO situés dans l'ouest de l'AAC sont restées assez stables parce que les régions de Franklin et du détroit de M'Clintock agissent continuellement comme un mécanisme de drain à siphon pour la glace de plusieurs années. Les résultats montrent aussi qu'en plus de la région des îles de la Reine-Élisabeth, l'ouest du détroit de Parry et le détroit de M'Clintock sont aussi des régions où se forme sur place une quantité considérable de glace de plusieurs années qui, combinée avec l'importation dynamique, contribue à créer de difficiles conditions de glace de plusieurs années. Certains indices donnent également à penser que la fréquence des importations dynamiques de glace de plusieurs années a augmenté depuis 1999 alors qu'avant 1999, il se formait davantage de glace de plusieurs années sur place. Par conséquent, le mécanisme de drain à siphon qui, historiquement, a maintenu des conditions difficiles de glace de plusieurs années dans le PNO opère peut-être plus rapidement maintenant qu'il ne le faisait dans le passé. D'après les 38 ans de données sur la glace de plusieurs années examinées dans cette étude, il apparaît probable que les mécanismes en action dans les segments du PNO situés dans l'ouest de l'AAC continueront d'y favoriser la présence continuelle de glace de plusieurs années pendant un bon bout de temps.*

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1 Introduction

Numerous studies have documented decreases in northern hemisphere sea-ice cover over the past several decades (e.g., Cavalieri et al., 1997; Johannesen et al., 1999; Parkinson et al., 1999; Comiso, 2002; Serreze et al., 2003; Cavalieri et al., 2003; Barber and Hanesiak, 2004; Francis et al., 2005; Stroeve et al., 2005; Comiso, 2006; Nghiem et al., 2006; Serreze et al., 2007). Simulations by most General Circulation Models (GCMs) predict continued and potentially rapid decreases in sea-ice cover (Walsh and Timlin, 2003; Holland et al., 2006; Zhang and Walsh, 2006). Both observed and predicted decreases have raised many questions about a climatically forced opening of the Northwest Passage (NWP) through the Canadian Arctic Archipelago (CAA) (ACIA, 2004). However, these observed and predicted changes are likely to vary from region to region and one cannot extrapolate evidence for change in one region to the next, and the CAA is no exception.

The CAA is composed of an intricate series of islands located on the North American continental shelf that are divided by Parry Channel with the Queen Elizabeth Islands (QEI) being located to the north (Fig. 1). The CAA exhibits a different sea-ice regime compared to that of the Arctic Ocean. Sea ice in the CAA is predominately landfast for six to eight months of the year and therefore is less affected by wind and warm-ocean waters than the pack ice of the Arctic Ocean (Falkingham et al., 2001; Melling, 2002). Wind driven sea-ice movement in the CAA is hindered because of numerous shallow and narrow water channels; internal ice pressure caused by horizontal constrictions usually stops ice drift (Melling, 2002). During the melt season when the sea ice is not landfast it travels very slowly southeastward across the CAA adjusting to local climatic conditions but reflecting the characteristics of its region of origin (Melling, 2002). Blocking landfast sea ice plays a dominant role in CAA sea-ice dynamics by restricting movement; sea ice can only move when a route of ice-free water is available (Marko, 1977). The annual melt process is greatly affected by the spatio-temporal distribution of the ice type and concentration makeup of the sea-ice matrix in the CAA (Howell et al., 2006).

Previous studies within the CAA have noted that sea ice has exhibited marked spatio-temporal changes over the past several decades (Agnew et al., 2001; Jeffers et al., 2001; Falkingham et al., 2001; Falkingham et al., 2002; Howell and Yackel, 2004; Moore, 2006; Alt et al., 2006). These changes include both increases and decreases in sea ice, and several studies have suggested that GCM predictions of an Arctic free of sea ice may lead to a false sense of optimism regarding the potential exploitation of the NWP for commercial and/or recreational navigation (e.g., Falkingham et al., 2001; Melling, 2002; Howell and Yackel, 2004; Wilson et al., 2004; Howell et al., 2006).

The NWP lies in the middle of the CAA linking the North Atlantic and North Pacific oceans, providing a route between Europe and Asia that is 9000 km shorter than the Panama Canal route and 17 000 km shorter than travelling around Cape Horn, South America. The NWP was discovered by Sir Robert M'Clure in the 1850s, but ever-present sea ice always prevented its practical navigation. The western CAA contains three potential routes through the NWP: two deepwater draft routes through M'Clure Strait and Prince of Wales Strait, and the shallow water draft route via Peel Sound (Fig. 1). The major problem for successful navigation through these regions is the presence of high concentrations of multi-year ice (MYI).

Some of the MYI in these regions is formed in situ (Maxwell, 1981; McLaren et al., 1984; Melling, 2002) but some is also the result of a direct influx from the Arctic Ocean (McLaren et al., 1984; Kwok, 2006; Howell et al., 2006) and/or flushed southward from the QEI (Melling, 2002; Howell and Yackel, 2004; Howell et al., 2006; Alt et al., 2006). MYI from the Arctic Ocean is continually forced against the QEI creating some of the oldest and thickest MYI in the world (Bourke and Garret, 1987; Agnew et al., 2001) and based on this The Arctic Marine Transport Workshop (2004) suggests that this is likely where the last MYI in the northern hemisphere will remain as we move toward an Arctic free of summertime ice. Even in small concentrations, MYI represents a serious hazard to transiting ships, therefore a better understanding of MYI in the western CAA regions of the NWP is clearly warranted.

A previous study by Kwok (2006) found that from 1997 to 2002 the flow of MYI from the Arctic Ocean directly into the M'Clure Strait region of the NWP was minor. Howell et al. (2006) found that from 2000 to 2004 the entire CAA and the western regions of the NWP gained a considerable amount of MYI. Unfortunately, these previous studies do not differentiate between how much MYI was formed in situ and how much was imported, not to mention they only consider a short temporal domain. Both Howell and Yackel (2004) and Atkinson et al. (2006) point out that following years of considerable removal of MYI within the western CAA, MYI concentrations can remain low for two to five years which may explain the contrasting results of Kwok (2006) and Howell et al. (2006) as the CAA recovered from the extreme low of 1998. Despite this, previous studies have also not isolated a potential mechanism to explain why the western CAA section of the NWP has historically contained high concentrations of MYI. Specifically, is the recovery of MYI following a major clearing event representative of an accelerated recovery mechanism that is responsible for the historically heavy MYI conditions in these regions? If such a mechanism exists, how will it continue to operate under a warmer Earth scenario?

The objective of this analysis is to investigate MYI conditions within the western CAA region of the NWP from 1968 to 2006 in order to draw a more complete picture of MYI regional variability. We focus specifically on MYI in the five regions that make up the western portion of the NWP in the CAA: the Western Parry Channel, the Beaufort sea, M'Clintock Channel, Franklin, and the Western Arctic Waterway (Fig. 1). For each region we discuss its MYI composition which includes percent total, ice grown in situ,

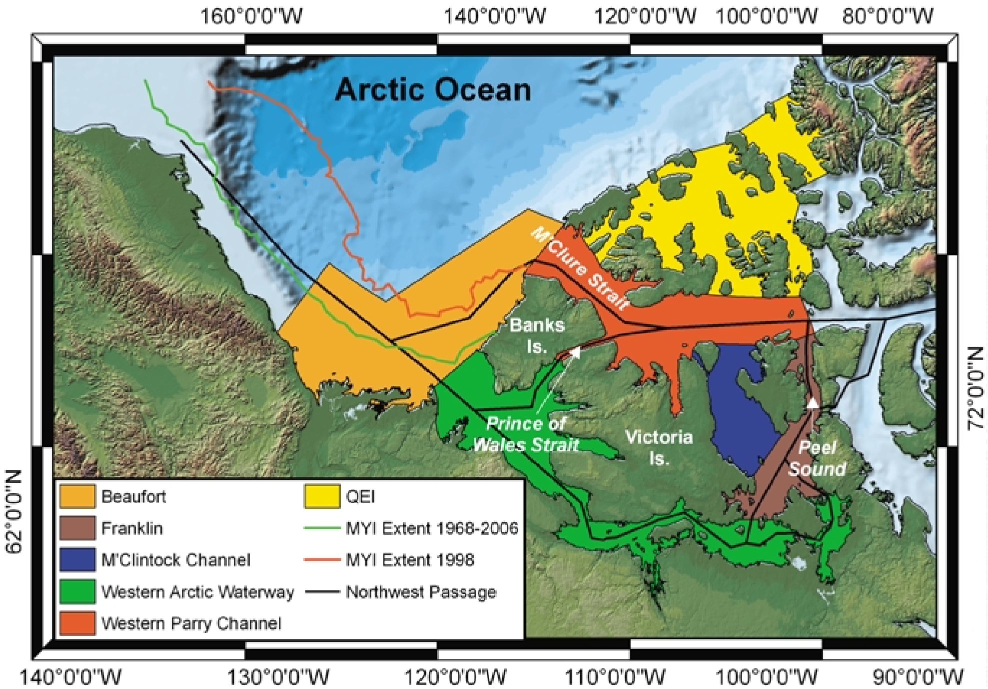

Fig. 1 The location of the Northwest Passage routes in the western Canadian Arctic Archipelago.

dynamically imported/exported, and net seasonal change. We then isolate and discuss the mechanism responsible for the historically heavy MYI conditions in the western CAA regions of the NWP. Next, we provide evidence for recent changes in this mechanism and subsequently discuss how this mechanism may continue to operate under a warmer Earth scenario. Finally, we conclude with a general summary and suggest the changes that would have to occur for a more accessible NWP route through this region of the CAA in the future.

2 Data

a *Canadian Ice Service Digital Archive*

MYI data were obtained 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 remote sensing satellite sensors, aerial reconnaissance, ship reports, operational model results and the expertise of the experienced ice forecasters from 1968 to present (Canadian Ice Service Archive Documentation Series, 2007a). These digital ice charts are topologically complete polygon ArcInfo Geographic Information Systems (GIS) coverages and are available from the CIS.

For this study we selected the sea-ice regime regions recently established by CIS (CIS-IRRs)(Canadian Ice Service Archive Documentation Series, 2007a). These regions were defined in consultation with Canadian sea-ice experts and represent areas for which a time series of 30 years or longer can be constructed with confidence. The caveat in utilizing CISDA and inherently the CIS-IRRs to assess long-term variability is that the source information used in preparing the weekly ice charts has changed over the years due to advances in sensor technology and changes in regional shipping routes (Table 1). The changing source data can make the CISDA subject to periodic shifts in bias and variance, and unfortunately there is no re-analysis data available. The effect of a sensor change on the CISDA sea-ice time series is unquantifiable since there are no other reliable long-term data available for comparison. Errors in passive microwave sea-ice concentrations are dependent on ice conditions which unfortunately change throughout the season in the CAA, especially during the melt season (see Agnew and Howell (2003) for a review) so they cannot be used as a baseline. As a result, in order to provide a measure of the accuracy of the various regions of the CISDA, the CIS developed a quality index from 1968 to 2006 to take into account the availability and quality of ship observations, airborne observations, airborne synthetic aperture radar (SAR) and/or side-looking airborne radar (SLAR), and satellite observations for each region. This quality index ranges from 0 (poor) to 5 (excellent) with 3 being the average; the index calculation procedure is fully described in the Canadian Ice Service Archive Documentation Series (2007b). The quality indices for our selected regions of the western CAA are shown in Table 2. The Canadian Ice Service Archive Documentation Series (2007b) suggests that trend analysis is appropriate for our selected regions in the Beaufort Sea, Western Parry Channel, M'Clintock Channel, Franklin and the Western Arctic Waterway regions but not in the high Arctic regions of the QEI. Despite this, we follow Melling (2002) and Alt et al. (2006) and minimize potential technological changes on this analysis by ignoring trends in these regions.

TABLE 1. Remote sensing available during the six time periods identified as being significant in the history of the Canadian Ice Service Digital Archive. (Note: SMMR-SSM/I data were available but not used in ice chart preparation.) (Source: Canadian Ice Service Archive Documentation Series, 2007b).

Time Period	Available Sensors
1968–74	infrequent availability of satellite data (NOAA VHRR); intense shipping and airborne observations in shipping areas.
1975–77	increasing availability of near-real-time and real-time satellite data (NOAA VHRR, Landsat MSS); intense shipping and airborne observations in shipping areas.
1978–82	availability of real-time satellite data (NOAA AVHRR, Landsat, Nimbus-7 SMMR); introduction of airborne SLAR in addition to airborne observations; intense shipping and airborne observations in shipping areas.
1983–90	availability of real-time satellite data (NOAA AVHRR, Landsat MSS / TM, Nimbus-7 SMMR, limited operational use of SSM/I); airborne SLAR in addition to airborne observations; intense shipping and airborne observations in shipping areas.
1991–95	availability of real-time satellite data (NOAA AVHRR, Landsat MSS / TM, limited operational use of ERS-1 and SSM/I); introduction of airborne SAR in addition to airborne SLAR and observations; intense shipping and airborne observations in shipping areas.
1996–2006	availability of real-time satellite data (NOAA AVHRR, RADARSAT-1, QuikSCAT; limited operational use of ERS-2;) airborne SAR / SLAR in addition to airborne observations; intense shipping and airborne observations in shipping areas.

TABLE 2. Quality index scores for regions of the western Canadian Archipelago for the six time periods identified as being significant in the history of the Canadian Ice Service Digital Archive. The overall quality index is also included. The quality index has been rounded to two significant figures. (Source: Canadian Ice Service Archive Documentation Series, 2007b.)

Time Period	Beaufort Sea	Western Parry Channel	M'Clintock Channel	Franklin	Western Arctic Waterway	QEI
1968–2006	3.6	2.9	2.5	3.5	3.7	2.6
1968–74	2.8	1.5	0.7	2.9	3.1	0.9
1975–77	3.2	2.5	2.1	3.1	3.2	2.2
1978–82	3.2	2.4	2.1	3.0	3.2	2.1
1983–90	3.2	2.5	2.1	3.0	3.2	2.2
1991–95	3.6	2.9	2.5	3.4	3.5	2.5
1996–2006	4.7	4.5	4.4	4.7	4.8	4.4

b *Extended AVHRR Polar Pathfinder Surface Air Temperature*

Surface air temperature (SAT) for these regions of the NWP were extracted from the extended Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder (APP-x; Wang and Key, 2005a). The APP-x dataset is an extension of the APP project (Fowler et al., 2000) and offers surface, cloud, and radiation parameters over the Arctic at a 25 km spatial resolution from 1982 to 2004. The parameters are retrieved using the Cloud and Surface Parameter Retrieval (CASPR) system fully described by Key et al. (2001) and Key (2002a). Surface parameters are calculated in CASPR using FluxNet (Key and Schweiger, 1998), which is a neural network version of a radiation transfer model called Streamer (Key, 2002b). Streamer uses the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data (Kalnay et al., 1996) for atmospheric profiles of temperature and humidity.

The APP-x data have been validated with in situ data from the Surface Heat Budget of the Arctic Ocean (SHEBA) field experiment (Maslanik et al., 2001), the Collaborative Interdisciplinary Cryospheric Experiment (C-ICE), and the Canadian Arctic Shelf Exchange Study (CASES) (Howell et al., 2006). APP-x data have also been used to assess trends and spatio-temporal variability in surface parameters for Arctic regions (Wang and Key, 2003; Wang and Key, 2005b). Maslanik et al. (2001) note that the APP-x data set can be used to observe coupled relationships between surface state conditions and atmospheric forcings at a relatively fine spatio-temporal resolution. However, Key et al. (1997) caution that the satellite-derived surface parameters at high latitudes may still result in some added uncertainty.

3 Methods

For each year, a 17-week time window from 25 June to 15 October was defined for our selected regions. This 17-week time window represents the optimal time period for the navigation season within the NWP (Falkingham et al., 2001; Howell and Yackel, 2004). The CISDA was used to determine the total accumulated ice coverage for each year from 1968 to 2006. Total accumulated coverage is defined as the sum of the weekly ice coverage (i.e., concentration multiplied by area). Ice coverage takes into account reductions in ice concentrations from inside the ice edge whereas ice extent does not. Total Accumulated Multi-Year Ice Coverage (TAMC) was determined by summing MYI coverage (km^2) for each of the weekly ice charts. This parameter is relatively insensitive to anomalies in individual ice charts and is the most stable and robust parameter in the database (Crocker and Carrieres, 2000; Falkingham et al., 2001; Falkingham et al., 2002; Canadian Ice Service Archive Documentation Series, 2007b). Higher TAMC indicates that more ice was present throughout the year. The results are presented as standardized anomalies.

The CISDA was also used to estimate the percentage of MYI either grown in situ or dynamically imported into regions of the CAA. By definition, seasonal first-year ice (FYI) that survives the summer graduates to MYI on 1 October. Therefore, an approximate estimate of MYI grown in situ for regions of the CAA is given by taking the difference in MYI coverage across 1 October (i.e., MYI coverage the week after, minus MYI coverage the week prior). Positives values indicate that MYI formed in situ and negative values represent melting or export. Dynamically imported MYI is estimated by subtracting MYI coverage the week before 1 October from the coverage at the start week of the summer season, typically 25 June. A positive value indicates import, whereas a negative value indicates melting or export and the results are presented as a percent change.

4 Results and discussion

a *Regional Multi-Year Ice Composition*

The percentage of MYI that occupies our selected western CAA regions of the NWP from 1968 to 2006 is presented in Table 3. MYI accounted for, on average, 56%, 57%, and 30% of the total ice in the Western Parry Channel, M'Clintock Channel, and Franklin regions, respectively. The QEI contained the largest portion of MYI at 76%. The annual net percentage change in MYI from 1968 to 2006 for the QEI, Western Parry Channel, M'Clintock Channel and Franklin regions is small, between 3 and 7% (Table 4).

The QEI, Western Parry Channel, M'Clintock Channel, and Franklin regions experience between 7 and 15% in situ growth (Table 4) and it is apparent from the time series of in situ growth, dynamic import, and net seasonal change (Fig. 2) that in addition to in situ growth, dynamic import also contributes to increases in MYI (Fig. 2). An example of MYI dynamic import compared to in situ growth for the Western Parry Channel is shown in Figure 3. Notice the marked increase in MYI following 1 October 1986 (i.e., when FYI is promoted to MYI) indicative of considerable in situ growth whereas in 1996 MYI steadily increases several weeks prior to 1 October indicating dynamic import (Fig. 3). Within the QEI a considerable portion of the MYI is attributed to in situ formation (Fig. 2) that was previously identified by Melling (2002). However, in the other regions of the CAA considerable amounts of MYI form in situ, particularly in the Western Parry Channel region but also in the M'Clintock Channel and even the Franklin regions (Fig. 2). All regions experience between 5 to 8% dynamic losses (or melt) (Table 4) suggesting that MYI makes a gradual progression through these regions of the CAA. Looking at the time series (Fig. 2) confirms this notion as there are several cases where, for the same year, dynamic export from a higher latitude region corresponds to dynamic import in an adjoining lower latitude region (Fig. 2).

The Beaufort Sea region off the western coast of Banks Island represents another region susceptible to high concentrations of MYI (Falkingham et al., 2001; Howell and Yackel, 2004). This region contains a significant portion of the Arctic Ocean polar pack of which MYI comprises 65% from 1968 to 2006. The Western Arctic Waterway region contains mainly seasonal FYI and contained the lowest amount of MYI from 1968 to 2006 at 8%.

Looking at the time series of TAMC for each of the six regions illustrates that it is relatively stable with light TAMC years interspersed with heavy TAMC years from 1968 to 2006 (Fig. 4). It is clearly apparent that following a low TAMC year there is a period of recovery as previously pointed out by Howell and Yackel (2004) and Atkinson et al. (2006). The years that experienced considerable MYI losses include 1973, 1980, 1981 1998, and 2005 (Fig. 2) and there are no more than two to three consecutive years of net losses of MYI for the Western Parry Channel, M'Clintock Channel, and Franklin regions (Fig. 2). Following the depleted MYI in the Western Parry Channel, M'Clintock Channel, and Franklin regions for 1973, the subsequent recovery period is mostly attributed to in situ MYI formation (Fig. 2). For the same regions, in 1980 and 1981 MYI losses also exhibit a recovery period that is again primarily due to in situ MYI formation (Fig. 2). These regions again experience losses of MYI in 1998 (Fig. 2) which Atkinson et al. (2006) identified as the result of an anomalous warming event. Since 1998 all regions then regained a considerable amount of MYI, some of which was formed in situ but dynamic import accounts for more of the gain compared to the previous recovery periods (Fig. 2). Considerable losses of MYI occurred again in 2005 but increases are apparent in the QEI for 2006 (Fig. 2). The question that therefore needs to be answered is why is the variability in MYI relatively stable in these western CAA regions of the NWP?

TABLE 3. Percentage of MYI concentration from 1968 to 2006 (standard deviation in brackets) for regions of the Northwest Passage in the Canadian Arctic Archipelago. Note: these percentages represent the mean from 1968 to 2006 and the quality index is lower during the earlier period of the Canadian Ice Service Digital Archive.

Region	Percent MYI
QEI	76% (8)
Western Parry Channel	56% (14)
M'Clintock Channel	57% (19)
Franklin	30% (18)
Western Arctic Waterway	8% (6)
Beaufort Sea	65% (11)

TABLE 4. Percentage of dynamic, thermodynamic and net seasonal change in MYI from 1970 to 2006 (standard deviation in brackets) for selected regions in the western Canadian Arctic Archipelago section of the Northwest Passage. Note: these percentages represent the mean from 1970 to 2006 and the quality index is lower during the earlier period of the Canadian Ice Service Digital Archive.

Region	Dynamic	Thermodynamic	Net Change
QEI	–5% (10)	7% (9)	3% (13)
Western Parry Channel	–5% (16)	14% (16)	7% (23)
M'Clintock Channel	–8% (21)	15% (21)	6% (34)
Franklin	–6% (15)	13% (17)	7% (25)

b *Multi-Year Ice Recovery Mechanism*

In order to answer this, it is first important to remember that even in the absence of MYI grown in situ and/or direct MYI influx from the Arctic Ocean via M'Clure Strait, MYI can flow southward from the QEI into the channels of the NWP. Melling (2002) provides evidence for a modest ice export during the second half of the year and rapid flushing events during the summer and autumn of a single year with a potentially compensating influx from the Arctic Ocean. Rapid flushing events from the QEI were reported in 1971,

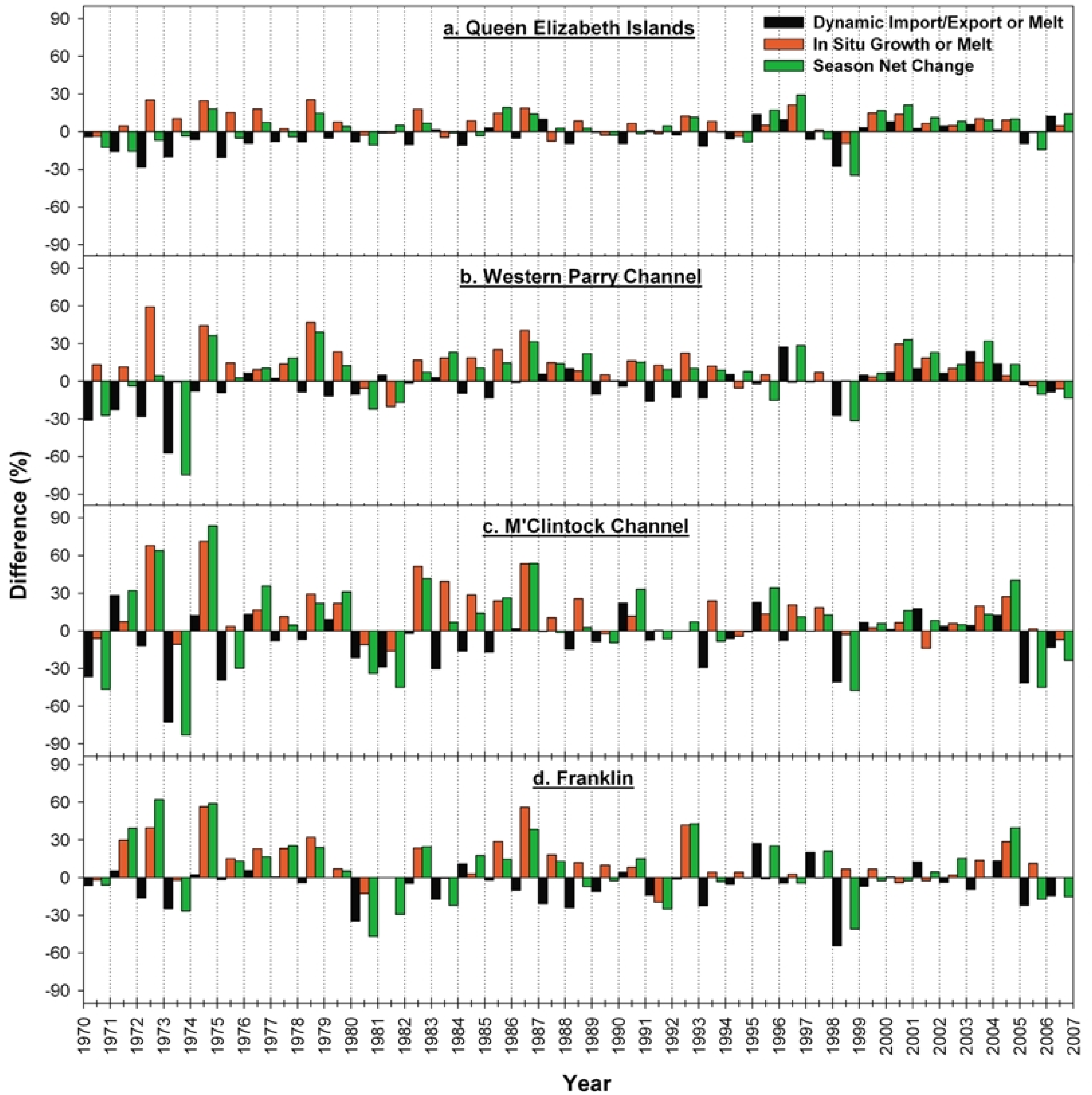

Fig. 2 Time series of changes in MYI coverage (%) for regions of the Canadian Arctic Archipelago from 1970 to 2006.

1975–1978, and 1998–2000 (Melling, 2002; Alt et al., 2006). Modest export from all regions is more common and appears to have occurred for most years up until 1998 which marked the largest net MYI loss in the QEI (Fig. 2).

Prior to 1998, MYI concentrations were very high in the Western Parry Channel region, extending far southward into the M'Clintock Channel and Franklin regions (Fig. 5). In 1998 we observe a considerable retreat of the Arctic Ocean polar pack and the loss of MYI in the entire CAA which is realized in 1999 (i.e., very little MYI in the CAA survived the 1998 melt season; Figs 2, 4, and 5). Kwok (2006) reported that there was a large export of MYI out of the QEI into the Arctic Ocean in 1998. This has been attributed to the fracturing of the high latitude ice barrier that impedes the exchange of MYI between the QEI and the Arctic Ocean (Alt et al., 2006). However, large-scale sea-ice dynamics continually forces the Arctic Ocean polar pack up against the QEI (Bourke and Garrett, 1987; Agnew et al., 2001) facilitating a continuous supply of MYI to the QEI region provided that there are prevailing northwesterly winds (Alt et al., 2006). Moreover, MYI does grow in situ within the QEI region (Melling, 2002) (Fig. 2). Since 1998, TAMC has gradually increased in the Western Parry Channel, M'Clintock Channel, and Franklin regions reaching a maximum in 2005, followed by a slight decrease in 2006 (Fig. 4). We suggest that this MYI recovery can be attributed to some MYI that formed in situ (particularly in the Western Parry Channel region) but more importantly to gradual MYI import from either the Arctic Ocean via M'Clure Strait and/or the QEI. The likely mechanism is that the seasonal FYI within these regions melts earlier than the MYI and the currents and wind then very slowly transport MYI southeastward from the Western Parry

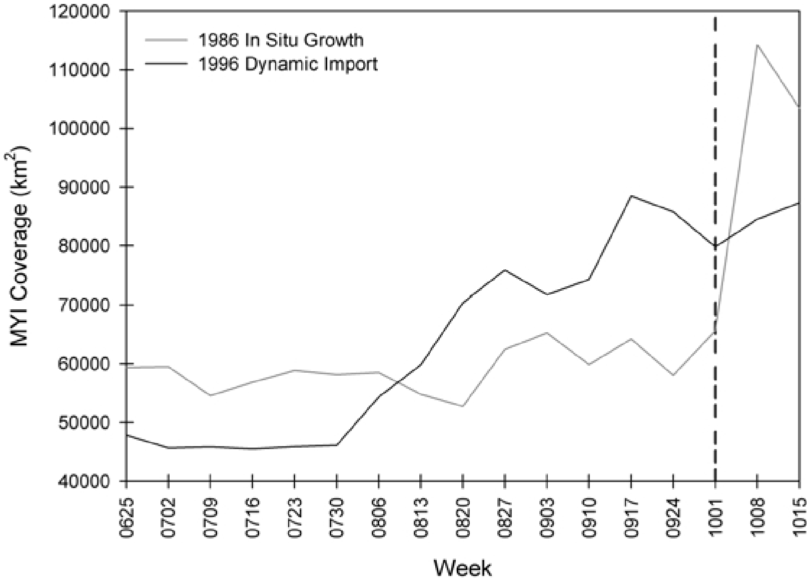

Fig. 3 Weekly MYI coverage for the western Parry Channel region illustrating MYI grown in situ (1986) or dynamically imported (1996). The vertical dashed line indicates the date (1 October) when FYI is promoted to MYI.

Channel region. The M'Clintock Channel and the Franklin regions, act as a drain trap for this MYI.

Evidence for this mechanism at work begins in 1999 when Kwok (2006) found a positive MYI flux into the QEI region for 1999 and 2000. Kwok (2006) also observed an influx of MYI from the Arctic Ocean into M'Clure Strait in 2000 but not in 2001 or 2002. In Fig. 5 we can see that from 2000 to 2002 MYI begins to increase slowly within the Western Parry Channel region. Some of this increase is attributed to in situ formation (Fig. 2) but in the absence of a dynamic influx from the Arctic Ocean via M'Clure Strait the remaining increases must be from the QEI region. Dynamic MYI import continues for the Western Parry Channel region from 2002 to 2004 and both the M'Clintock Channel and the Franklin regions exhibit dynamic MYI increases providing evidence for the southeastward transport of MYI (Fig. 2).

In 2005, these drain-trap regions are filled and since ice movement in the CAA can only occur when a route of ice-free water is available, very little, if any, MYI could further accumulate (Fig. 5). This congestion likely prevented a compensating MYI flux from the Arctic Ocean into the CAA. The result is that MYI now occupies these lower latitude regions that would normally contain seasonal FYI. MYI is thicker and takes longer to melt than seasonal FYI, therefore the availability of open water during the 2005 melt season was reduced, and ice motion was impeded. As such, no net dynamic import of MYI was observed for these regions in 2005 or in 2006 (Fig. 2). At this point, the MYI had experienced several melt seasons and had likely ablated and reduced in thickness, but high concentrations still remained in the drain-trap regions (Fig. 5). Sufficient atmospheric forcing in 2006 melted most of the MYI in these drain-trap regions (Fig. 6), and we would expect this to then re-initialize MYI movement in upcoming years.

When MYI conditions are investigated from 1972 to 1997, they also appear to support this drain-trap mechanism. In 1973 and 1980, the Western Parry Channel, M'Clintock Channel, and Franklin regions contained a considerable amount of MYI similar to the congested nature of 2005. During the course of the 1973 and 1980 melt seasons, these regions exhibited a considerable loss of MYI (Fig. 2) only to recover gradually over the next five to six years. Witness the weekly MYI coverage values for 1976 illustrating that losses of MYI from the QEI and Western Parry Channel regions occur during the first week of September (Fig. 7). This is followed by subsequent increases indicative of an MYI flux event that corresponds to increases in the M'Clintock Channel and Franklin drain-trap regions (Fig. 7). This process of MYI migration is also realized in 1974 (not shown) and in 1984 (Fig. 7). While 1974 and 1984 represent recovery years from the low MYI conditions of 1973 and 1982, even when the drain-trap regions are not recovering from low MYI years such as 1990 and 1995, MYI is still transported to them (Fig. 7).

Based on relative stability in MYI conditions for these western CAA regions of the NWP, it appears that indeed this mechanism is responsible for maintaining the regions' historically heavy ice conditions. Regardless of whether MYI in the Western Parry Channel region is dynamically imported or formed in situ, it gradually flows into these drain-trap regions.

c *A Tipping Point within regions of the NWP?*

Changes in sea-ice conditions are reflective of changes in both thermodynamic (e.g., SAT) and dynamic (e.g., ice motion related to atmospheric circulation) processes. The available observational MYI record exhibits record lows for the northern hemisphere since 2001 (e.g., Stroeve et al., 2005; Nghiem et al., 2006; Serreze et al., 2007) but we find

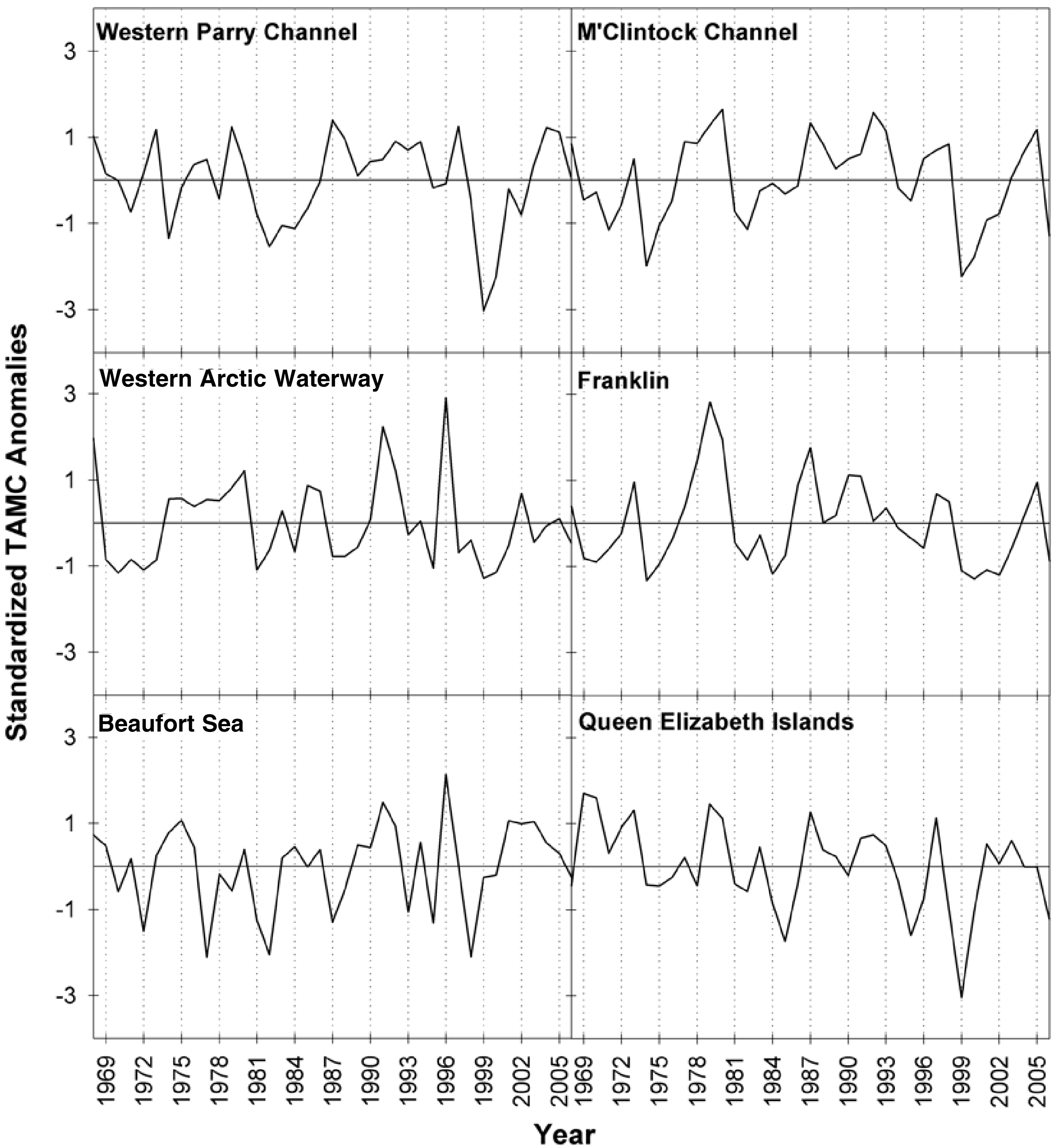

Fig. 4 Total Accumulated Multi-Year Ice Coverage (km^2) standardized anomalies from 25 June to 15 October for western Canadian Arctic Archipelago regions of the Northwest Passage, 1968 to 2006.

contrasting increases in MYI for the CAA. Such a contrast illustrates considerable regional variability and indicates that not all Arctic regions are experiencing decreases in sea ice. The Arctic Oscillation (AO; Thompson and Wallace, 1998) was believed to be the dominant mode of atmospheric circulation affecting Arctic sea ice but it has remained close to neutral since 1997 even though changes that reflect the positive phase of the AO continue to occur (e.g., Serreze et al., 2007). Based on this, Lindsay and Zhang (2005) suggested that the Arctic climate system has reached a tipping point and that the AO no longer controls sea-ice cover, instead local thermodynamic processes, such as the sea ice-albedo feedback, dominate. However, it should be mentioned that Maslanik et al. (2007) found that the winds and transport patterns that facilitated changes in sea ice during a high AO phase are still present but the AO is no longer a reliable indicator of these patterns. Despite this uncertainty, the processes of change are still occurring, and this raises the question as to how or if the sections of the NWP located in the western CAA are reacting to this suggested tipping point?

The QEI and Western Parry Channel regions, from 1999–2004, appear to exhibit no dynamic export of MYI

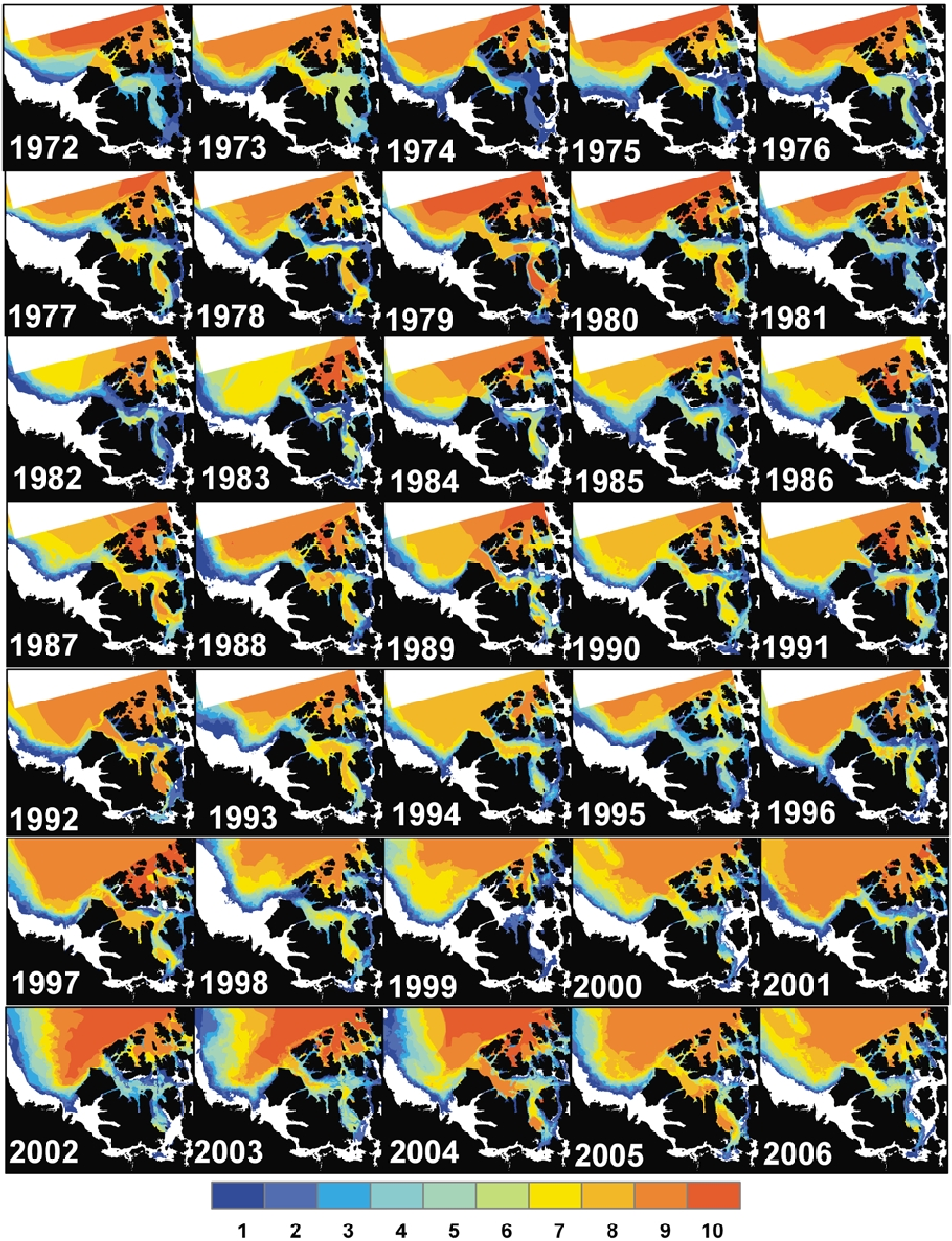

Fig. 5 Average MYI concentration from 25 June to 15 October for 1972 to 2006 for the western Canadian Arctic Archipelago. Legend is concentration in tenths. The extent of Canadian Ice Service ice charts did not fully cover the Arctic Ocean from 1972 to 1996.

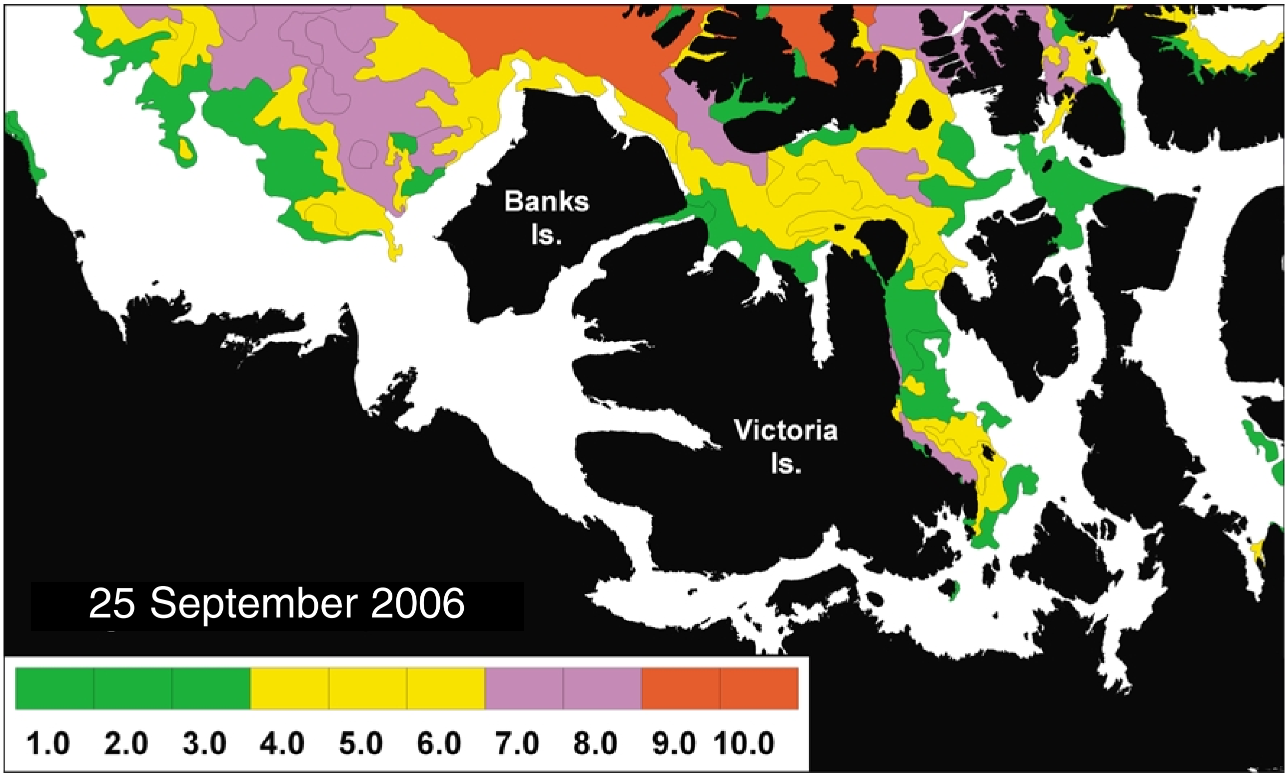

Fig. 6 MYI conditions in the southwestern Canadian Arctic Archipelago on 25 September 2006. Legend is concentration in tenths.

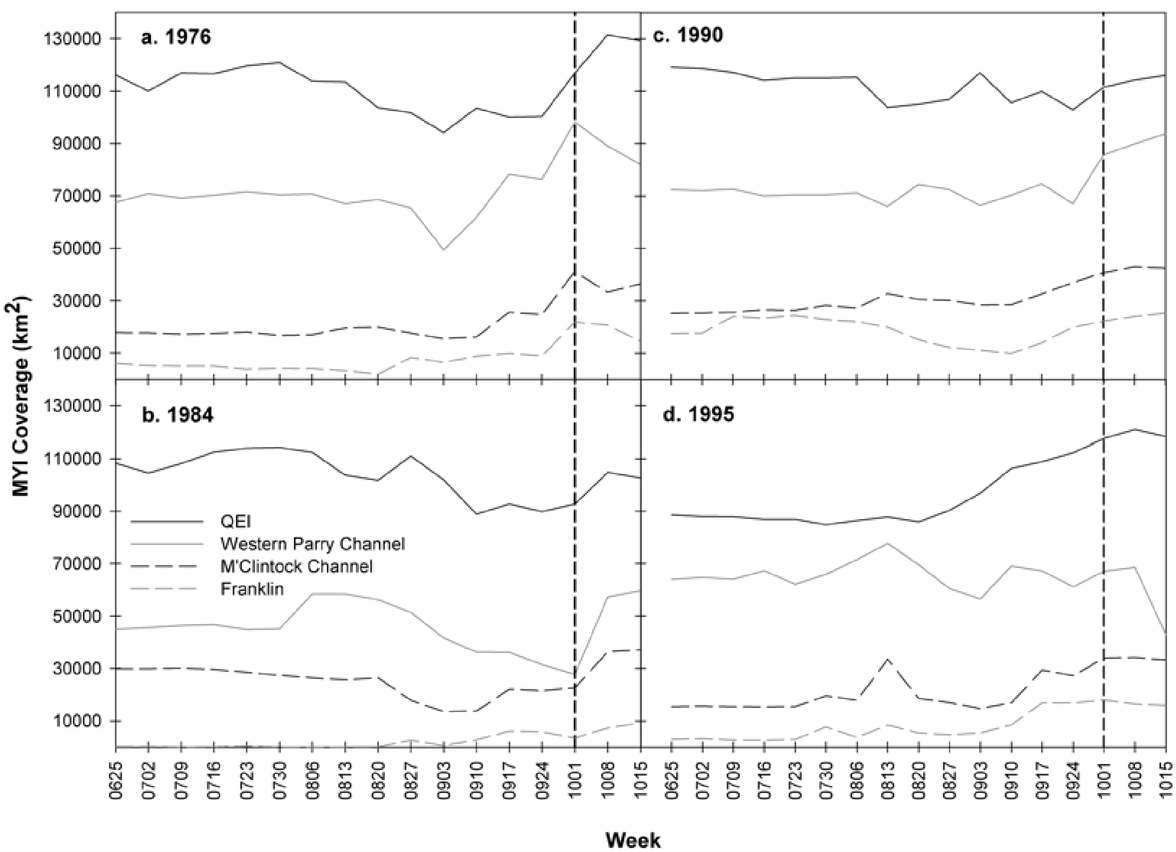

Fig. 7 Weekly MYI coverage in the QEI, western Parry Channel, M'Clintock Channel, and Franklin regions for (a) 1976, (b) 1984, (c) 1990, and (d) 1995. The vertical dashed line indicates the date (1 October) when FYI is promoted to MYI.

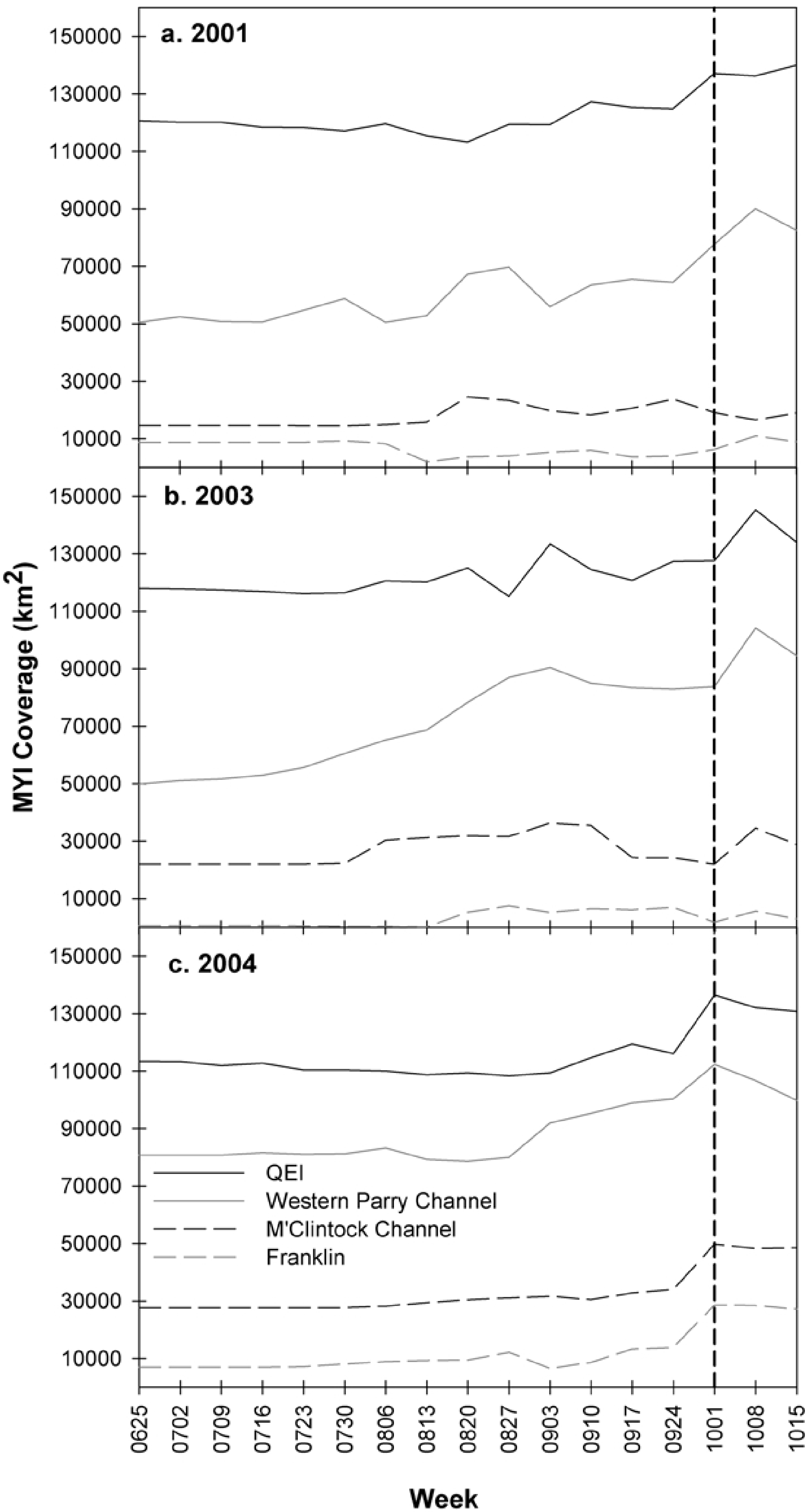

Fig. 8 Weekly MYI coverage in the QEI, western Parry Channel, M'Clintock Channel, and Franklin regions for (a) 2001, (b) 2003, and (c) 2004. The vertical dashed line indicates the date (1 October) when FYI is promoted to MYI.

while dynamic increases are observed during this same time period in almost every other region (Fig. 2). Yet, we have shown no net dynamic export to have occurred from both regions not to mention that QEI flushing events have also been observed by Howell et al. (2006) and Alt et al. (2006) during this time. This suggests that: i) when dynamic export takes place a compensating MYI flux from the Arctic Ocean occurs to offset the loss, and/or ii) the MYI flux within these regions is less intermittent in recent years than in the past. Evidence for these processes is presented in Fig. 8. With respect to the QEI, both 2001 and 2003 exhibit gains and losses of MYI during the course of the season, followed by corresponding increases in the Western Parry Channel region (Fig. 8). The compensating MYI flux is also found in the Western Parry Channel region in 2001. In 2003, MYI in the Western Parry Channel region increases steadily over the season (even prior to the QEI flushing event) with increases observed in the M'Clintock Channel and Franklin regions; a similar situation also occurs in 2004 (Fig. 8). These observations suggest that MYI import from the Arctic Ocean via M'Clure Strait must be steadily occurring as MYI is being pushed into these drain-trap regions.

There are several possible explanations for this increased MYI flux. The first is the recently observed increases in cyclonic motion during summertime for the Beaufort Sea region (Lukovich and Barber, 2006) and above average west-to-east Arctic Ocean sea-ice transport since 1997 (Maslanik et al., 2007) could be facilitating an increased flux of MYI in the Arctic Ocean toward the CAA. This, coupled with reported decreases of MYI (hence, more seasonal ice) in the western Beaufort Sea region (Francis et al., 2005; Melling et al., 2005), makes the polar pack more susceptible to wind-driven forcings which drives MYI against Banks Island (Howell and Yackel, 2004). Figure 5 is indicative of this mechanism as the polar pack has been, on average, generally closer to Banks Island since 2001.

It could also be a two-pronged effect such that in addition to wind, slightly warmer SATs in the QEI, Western Parry Channel, M'Clintock Channel and Franklin regions are melting the FYI earlier, facilitating more open water and a subsequent pathway for ice movement. Looking at SATs within the Western Parry Channel, M'Clintock Channel, Franklin and QEI regions from 1982 to 2004 we find increasing relationships but they are not significant at $p < 0.10$ (Fig. 9). However, the increasing SATs for the aforementioned regions correlate with decreases in MYI formed in situ and this relationship is significant at $p = 0.05$ for all regions, except the Western Parry Channel region which is significant at $p = 0.06$. This suggests that for these regions, the warmer SATs are reducing the amount of MYI grown in situ and despite this, the time series of TAMC remains stable (Fig. 4) lending support to the process of increased dynamic import of MYI. These warmer temperatures in the QEI region could also be responsible for weakening the QEI ice barriers that impede the exchange of MYI between the Arctic Ocean and the CAA. Alt et al. (2006) provide evidence for the weakening of these barriers from 2000 to 2005 following complete fracture in 1998. Melling (2002) suggests that weakened ice barriers in the QEI region may actually increase flushing events from the QEI and the MYI could be thicker (i.e., less seasonal ablation) due to decreases in transit time. Our analysis supports this theory by illustrating that dynamic MYI import seems to be more apparent in recent years.

Even with less in situ MYI formation for the western CAA regions of the NWP, changes are occurring such that dynamic import seems to be compensating for the formation of less MYI in situ. As a result, the mechanism that has historically maintained heavy MYI conditions in the NWP is perhaps operating faster now than in the past.

5 Conclusions

This analysis finds that over the past 38 years the M'Clintock Channel and Franklin regions continuously operate as a drain trap for MYI and this mechanism is responsible for maintaining the heavy MYI conditions in the western CAA regions of the NWP. This finding supports initial cautious claims by Falkingham et al. (2001) and Melling (2002) that a warming climate may not bring lighter ice conditions to the CAA, especially in regions relevant to the NWP. Results of this analysis also find that in addition to the QEI, Western Parry Channel and M'Clintock Channel are also regions where a considerable amount of MYI forms in situ and, combined with dynamic imports, contribute to heavy MYI conditions.

There is some speculation that if the polar pack retreats north past the entrance to M'Clure Strait the flux of MYI to the region would stop, thus improving navigation through the Western Parry Channel region. This scenario seems unlikely in the near future, because the historical record shows that the extent of the polar pack has typically remained near the southern end of Banks Island during the season (Fig. 1). Melling (personal communication, 2007) suggests that there is actually a net export of MYI from the CAA via M'Clure Strait that was further supported by the recent analysis of Kwok (2006). Even in the absence of an MYI influx from the Arctic Ocean via M'Clure Strait, MYI can flow into the channels of the NWP from the QEI region. Moreover, this analysis finds a considerable amount of MYI actually grows in situ within the Western Parry Channel region.

Based on the MYI processes identified as operating within the western CAA over the past 38 years and providing there are no major changes in atmospheric circulation, we are likely to see the continued presence of MYI within the NWP for quite some time. Even predictions of future sea-ice conditions within the northern hemisphere as far into the future as 2040 exhibit high concentrations of MYI within the CAA (Holland et al., 2006). In situ growth would have to cease and the Arctic Ocean polar pack would likely have to retreat past the QEI to allow practical and safe navigation of the NWP. This is because large-scale sea-ice dynamics continuously force MYI up against the QEI and until this process stops, MYI from the Arctic Ocean can still flow through the QEI region and then southward into the NWP.

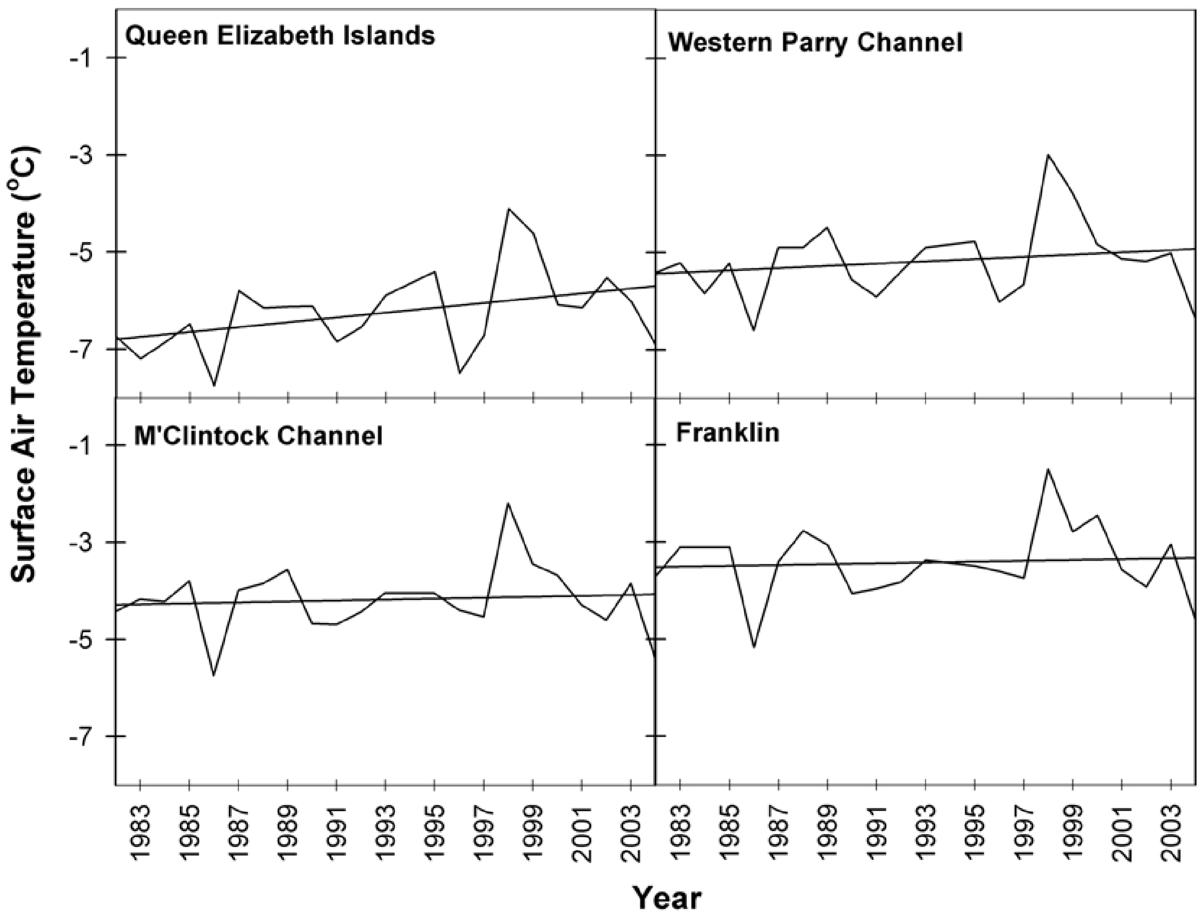

Fig. 9 Time series and trend of APP-x surface skin air temperature averaged over 25 June to 15 October for the period 1982 to 2004 for the QEI, Western Parry Channel, M'Clintock Channel, and Franklin regions.

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