Multi-decadal analysis of sea ice type, extent and distribution patterns in Tuvaijuittuq and adjacent regions

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MULTI-DECADAL ANALYSIS OF SEA ICE TYPE, EXTENT AND DISTRIBUTION PATTERNS IN TUVAIJUITTUQ AND ADJACENT REGIONS

by

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Pućko, M., Larter, J., Michel, C. 2023. Multi-decadal analysis of sea ice type, extent and distribution patterns in Tuvaijuittuq and adjacent regions. Can. Tech. Rep. Hydrogr. Ocean Sci. 352: xi + 89 p.

Tuvaijuittuq area and adjacent regions hold the oldest and thickest sea ice in the Arctic, however, information on spatio-temporal sea ice composition and distribution patterns as well as their inter-annual variability are missing. Here, we present First-Year Ice (FYI) versus Multiyear Ice (MYI) composition and areal extent data within three analysis areas, A1, A2, and A3, delineated north of the Queen Elizabeth Islands (QEI), on maximum and minimum ice extent dates between 1999 and 2018, based on the Canadian Ice Service (CIS) weekly ice charts. We further show maximum extent of open water for each of these years, and the date on which it was recorded. We also present distribution maps of FYI, MYI and open water on maximum and minimum ice extent dates in all three analysis regions between 1999 and 2018. To better represent relative occurrence of FYI and MYI, frequency of occurrence maps on maximum and minimum ice extent dates are presented for MYI and FYI in all three analysis areas. Finally, maps of frequency of occurrence of open water are created to uncover regions of relative prevalence of open water in A1, A2, and A3. Spatio-temporal analysis of sea ice composition and distribution patterns in the Tuvaijuittuq Marine Protected Area (MPA) and adjacent regions presented herein can inform the decision-making process should permanent protection be established and provide fundamental contextual data for future management and monitoring of this area.

RÉSUMÉ

Pućko, M., Larter, J., Michel, C. 2023. Multi-decadal analysis of sea ice type, extent and distribution patterns in Tuvaijuittuq and adjacent regions. Can. Tech. Rep. Hydrogr. Ocean Sci. 352: xi + 89 p.

La zone de protection marine de Tuvaijuittuq et les régions adjacentes renferment la glace de mer la plus ancienne et la plus épaisse de l'Arctique. Toutefois, on ne dispose d'aucun renseignement sur les tendances spatio-temporelles de la composition et de la distribution de la glace de mer ni sur la variabilité interannuelle connexe. Dans le présent article, on compare les données sur la composition et l'étendue de la glace de première année et de la glace de plusieurs années dans trois zones d'analyse, soit A1, A2 et A3, délimitées au nord des îles de la Reine-Élisabeth, lors des dates correspondant aux étendues minimale et maximale annuelles de la glace entre 1999 et 2018, d'après les cartes des glaces hebdomadaires du Service canadien des glaces (SCG). On montre aussi l'étendue maximale de l'eau libre pour chacune de ces années, ainsi que les dates d'observation connexes. De plus, on présente des cartes de la distribution de la glace de première année, de la glace de plusieurs années et de l'eau libre aux dates correspondant aux étendues minimale et maximale annuelles de la glace dans les trois régions d'analyse entre 1999 et 2018. Pour mieux représenter l'occurrence relative de la glace de première année et de la glace de plusieurs années, on présente des cartes de la fréquence d'occurrence de ces deux types de glace aux dates correspondant aux étendues minimale et maximale annuelles dans les trois zones d'analyse. Finalement, on a créé des cartes de la fréquence d'occurrence de l'eau libre pour déterminer les régions où l'eau libre est relativement présente dans les zones A1, A2 et A3. L'analyse spatio-temporelle des tendances relatives à la composition et à la distribution de la glace de mer dans la zone de protection marine de Tuvaijuittuq et les régions adjacentes présentée dans l'article pourrait orienter le processus de prise de décisions si des mesures de protection permanentes étaient établies, et fournir des données contextuelles fondamentales pour les futures activités de gestion et de suivi de la zone.

1 Introduction

Presence of sea ice cover, arguably, is the single most defining element of Arctic marine ecosystems (Wadhams 2000). Unlike in many other parts of our planet, presence of year-round or almost year-round ice cover affects virtually every aspect of Arctic systems including air-water exchanges of heat, momentum and moisture (Taylor et al. 2018), salt redistribution (Toudal and Coon 2001), local and global oceanic and atmospheric circulation (Spreen et al. 2011), and ecosystem structure and productivity (Grebmeier et al. 2010; Lange et al. 2015; Mundy and Meiners 2021). However, due to continuous climate warming related changes, the multi-year ice (MYI; ice that survived one or more melt seasons) cover has not only retreated dramatically in its areal extent in the last few decades, but it has also become much thinner and younger (Kwok 2018; Stroeve and Notz 2018). In spring of 2018, only about 2 % of the sea ice cover consisted of sea ice older than 5 years, compared to almost 30 % in 1984 (Stroeve and Notz 2018). This compelling trend of decreasing MYI extent and thickness in the Northern Hemisphere was first clearly apparent in the Arctic's peripheral seas starting with the East Siberian, Chukchi, Kara and Laptev Seas (Stroeve et al. 2014), subsequently encompassing the majority of the Eastern Arctic Ocean (Nghiem et al. 2006), and later including large parts of the Canada Basin and the Beaufort Sea (Maslanik et al. 2011; Galley et al. 2016). Recent changes in atmospheric forcings to the Beaufort Gyre and pan-Arctic ice drifts (Petty et al. 2016; Kaur et al. 2018), oceanic borealization caused by anomalous advection from sub-Arctic seas (Maslanik et al. 2011; Polyakov et al. 2020), and overall mechanical weakening of the Arctic sea ice (Gimbert et al. 2012) concomitantly resulted in further decreases in coverage of the Arctic Ocean with MYI. The Arctic Ocean now is primarily covered by first-year ice (FYI), while a spatially and temporally continuous MYI pack (>80 % MYI concentration) remains present in and adjacent to the Tuvaijuittuq region (Kwok 2018).

Tuvaijuittuq, meaning 'the place where sea ice never melts' in Inuktut, is an area of the Canadian High Arctic located north of the Queen Elizabeth Islands. This area was traditionally used by Inuit for travel and harvesting due to the presence of uniquely thick sea ice. Since August 2019, Tuvaijuittuq has been under interim protection by ministerial order under Canada's *Oceans Act* while Canada works with its partners to complete a joint assessment of the feasibility and desirability of long-term protection in the area (Charette et al. 2020).

While Tuvaijuittuq continues to hold the oldest and thickest sea ice and is the last refuge of perennial ice cover in the Arctic Ocean (Kwok 2018), the sea ice type composition and its spatio-temporal variability as well as the extent of open water occurrence remain vastly unknown in this extremely remote region (Moore et al 2018; Charette et al. 2020). Only recently, it has been postulated that the Tuvaijuittuq area is actually undergoing profound changes including losing its ice mass at an alarming rate of two times faster than that observed in other parts of the Arctic Ocean (Moore et al. 2018). Profound regional differences were also described within Tuvaijuittuq with regards to timing of the sea ice minimum extent and related ice motion patterns (Moore et al. 2018). It has been recently postulated that increasing weakening of the MYI pack in Tuvaijuittuq and directly adjacent areas along with decreased strength and predictability of the ice arch in Nares Strait is causing increased sea ice mobility, enhanced MYI export through Nares Strait, and increased marine hazards to vessel traffic as far downstream as the East Coast of Newfoundland (Barber et al. 2018; Moore et al. 2021). However, spatio-temporal patterns of FYI, MYI, and open water coverage and their interannual variability at regional scales in Tuvaijuittuq and adjacent regions remain virtually unknown.

Here, we use the Canadian Ice Service (CIS) ice charts to describe historical interannual variability in sea ice type composition (MYI *versus* FYI) and distribution on maximum and minimum ice extent dates as well as maximum extent and frequency of occurrence of open water within three geographic regions established north of Queen Elizabeth Islands (A1, A2, A3) between 1999 and 2018 (Figure 1).

2 Data and methods

2.1 Study areas

The study area encompasses the marine waters located to the north of Queen Elizabeth Islands, and was divided into 3 separate analysis areas which are referred to as A1, A2, and A3 (Figure 1). The northern boundary of the study area was determined by the northern-most span of the CIS charts. Analysis area 1 (A1) spans over 185,296 km^2, with the 630 km long northern boundary extending offshore by approximately 30 km at its closest and 170 km at its furthest point. The A1's southern boundary runs 345 km across Ellesmere Island. The eastern boundary along Robson and Kennedy Channels is 380 km long, and the western boundary, coincident with analysis area 2 (A2) eastern boundary, is 480 km long. Land within the analysis area A1 consists of the northern part of the Ellesmere Island and accounts for 117,961 km^2, and the marine waters account for 67,335 km^2 and consist primarily of the Tuvaijuittuq MPA. Analysis area 2 (A2) spans over 193,070 km^2 (Figure 1), and its northern boundary line runs 390 km across, but contains a triangular gap where chart data is lacking. The northern boundary is located approximately 230 km offshore of the Queen Elizabeth Islands. The southern boundary extends 570 km through the southern end of Axel Heiberg Island, through the middle of Amund Ringnes Island, across the southern tip of Ellef Ringnes Island and across Maclean Strait. Analysis area A2's western boundary, coincident with analysis area 3 (A3) eastern boundary, is 470 km long. Land within the analysis area A2 occupies 50,347 km^2, while marine waters account for 142,723 km^2 and partially encompass the Tuvaijuittuq MPA. Analysis area 3 (A3) consists of 192,286 km^2 with its northern boundary extending 540 km across and located approximately 150 km offshore. The southern boundary extends 364 km across Melville Island. The western boundary is 440 km long and extends 10 km off the southwest shore of Prince Patrick and Melville Islands. Land within the analysis area accounts for 47,806 km^2 and marine waters for 144,480 km^2 which are not part of the Tuvaijuittuq MPA.

2.2 Data acquisition

After a review of available remotely-sensed sea-ice extent and concentration data products, the Government of Canada's Canadian Ice Service (CIS) archive was selected to acquire FYI and MYI concentration and extent data as well as open water areal extent data due to this archive's optimal coverage and satisfactory spatial resolution. The CIS archive contains weekly regional ice charts of the Canadian Arctic in a GIS ready Esri® .e00 data format dating back to 1969. The GIS data sets are projected as Lambert Conformal Conic using the Clarke 1866 spheroid and the North American Datum of 1927 (NAD27). The eastern and western Arctic regions are coincident with the identified analysis areas A1-A3. The archive page allows to compress up to 200 charts per data set query result page and create .zip compression files for download. In 1999 the CIS extended the northern offshore range of both the eastern and western weekly regional ice chart data products, thus, 1999 was set as the beginning of the analysis period presented herein.

2.3 Data processing

Esri® ArcGIS software was used for data processing and map graphing. The following steps were taken to convert the .zip files downloaded from the CIS archive to Esri® ArcGIS software geodatabase format: 1) storage of 15 downloaded compressed regional chart files in NSC's file system, 2) batch decompression of the 15 Esri® .e00 files to the NSC file system using

7-Zip software to determine overall file size, 3) batch conversion from Esri® .e00 files to Esri® ArcInfo coverage using Esri® using ArcGIS ModelBuilder, 4) batch conversion of Esri® ArcInfo coverage format to Esri® ArcGIS geodatabase polygon feature class format in separate Eastern and Western geodatabases using ArcGIS ModelBuilder, 5) batch geoprocessing of weekly regional ice charts in geodatabase polygon feature class format using an `Intersect` overlay routine to limit the spatial analysis extent of the charts to the boundaries of the three analysis areas (A1, A2, A3) for both the eastern and western region geodatabases, 6) batch append (merging) of all data sets in the eastern and western region geodatabases into a single file containing all regional ice charts (1999-2018), and 7) export of merged (1999-2018) eastern and western Arctic files to .CSV format. The analysis files for the merged eastern and western Arctic were converted to Microsoft Excel .xlsx format in order to conduct summary analyses of the data sets. Additional attributes were added to the suite of existing CIS attributes to assist in summary and analysis of the sea ice data. The 'DATE_CARTE' date field (YYYYMMDD format) was used to derive YEAR, MONTH, DOY (day of year), and WOY (week of year), attributes. Additional attributes were added to indicate presence/absence of ice and to differentiate FYI from MYI. Esri® ArcGIS software was also used to conduct additional spatial analyses to illustrate spatial patterns in open water, FYI and MYI by frequency of occurrence maps on maximum and minimum extent dates over the 1999-2018 period.

Preliminary analyses indicated a change in the area of polygons classified as land in the weekly regional charts. The area of land class changed in 2007 to include more detail, and less land overall. Land area changed on November 26, 2007 in the eastern and western Arctic charts resulting in an overall increase of 263 km^2 of sea ice for the eastern Arctic and 254 km^2 of sea ice in the western Arctic. These areas were applied as a correction factor to the FYI for the outputs produced prior to November 26, 2007 in order to account for the change in detail of the land mask used.

2.4 Statistical analysis

Regression analysis was done using Excel's Data Analysis ToolPack at the confidence level of 95%. Coefficient of variation used in this study as a measure of dispersion was defined and calculated as the ratio of the standard deviation to the mean. The higher the coefficient of variation, the greater the dispersion of data.

3 Results and discussion

3.1 Inter-annual variability of MYI, FYI and open water extent

Minimum and maximum sea ice extent dates observed in A1, A2, and A3 are summarized in Table 1. Maximum ice extent dates were identical in all three analysis regions ranging from March 28 to April 3. On average, maximum ice extent day occurred on day of year (DofY) 91 ± 2 SD (Standard Deviation) in A1, A2, and A3. Minimum ice extent DofY were more variable than minimum ice extent DofY in all regions and occurred on average on 238 ± 8 or between August 11 and September 7 in A1, on 233 ± 19 or between June 13 and September 10 in A2, and on 231 ± 26 or between June 5 to September 13 in A3.

All analysis areas were covered primarily by MYI on maximum and minimum ice extent days between 1999 and 2018 (Figure 2). In A1, the MYI area on maximum ice extent day reached between 47,125 km^2 in 2010 and 62,099 km^2 in 2002 (Figure 2A), accounting for 70.0 % – 92.2 % of the marine area of this analytical region. In A2 and A3, respectively, the MYI area on maximum ice extent day reached between 97,588 km^2 (68.4 %) in 1999 and 138,817 km^2 (97.3 %) in 2002 (Figure 2B), and between 107,160 km^2 (74.2 %) in 2018 to 138,023 km^2 (95.5 %) in 2005 (Figure

2C). The MYI area on minimum ice extent day in A1 ranged from 42,875 km^2 in 2015 to 57, 980 km^2 in 2002 (Figure 2D), covering between 63.7 % and 86.1 % of the marine portion of the analysis area A1. In A2 and A3, respectively, the MYI area on minimum ice extent day ranged from 109,907 km^2 (77%) in 2011 to 138,669 km^2 (97.2 %) in 2002 (Figure 2E), and from 111,670 km^2 (77.3 %) in 2015 to 132,305 km^2 (91.6 %) in 2014 (Figure 2F).

The FYI areal coverage on maximum ice extent day ranged from 5,871 km^2 (8.7 %) in 2002 to 20,845 km^2 (31.0 %) in 2010 in A1 (Figure 2A), from 3,896 km^2 (2.7 %) in 2002 to 45,125 km^2 (31.6 %) in 1999 in A2 (Figure 2B), and from 6,455 km^2 (4.5 %) in 2005 to 37,318 km^2 (25.8 %) in 2018 in A3 (Figure 2C). The FYI areal coverage recorded on minimum ice extent day was between 282 km^2 (0.4 %) in 2005 and 13,099 km^2 (19.5 %) in 2015 in A1 (Figure 2D), between 1,880 km^2 (1.3 %) in 2005 to 18,068 km^2 (12.7 %) in 2008 in A2 (Figure 2E), and from 1,226 km^2 (0.8 %) in 2010 to 21,350 km^2 (14.8 %) in 2009 in A3 (Figure 2F).

The maximum area of open water ranged from 1,977 km^2 (2.9 %) in 2001 to 13,270 km^2 (19.7 %) in 2011 in A1, from 1,631 km^2 (1.1 %) in 2004 to 19,601 km^2 (13.7 %) in 1999 in A2, and from 3,102 km^2 (2.1 %) in 2003 to 22,302 km^2 (15.4 %) in 2012 in A3 (Table 2, Figure 3A). In analysis area A1, the day of year of the maximum open water area occurrence ranged from day 224 (August 11, 2008) to day 250 (September 7, 2009), averaging 238 ± 8 (Standard Deviation) (Figure 3B). In A2, the maximum area of open water occurred on average on day 233 ± 19, and ranged between day 165 (June 13, 2016) and day 254 (September 10, 2012). In A3, the maximum area of open water was recorded on day 231 ± 26, ranging between day 156 (June 5, 2017) and day 256 (September 13, 1999). There were no statistically-significant trends observed in the maximum area of open water, nor in the day of its occurrence as a function of time in any of the analysis areas.

3.2 Spatio-temporal distribution of MYI, FYI and open water

Maps depicting the distribution of MYI, FYI and open water on maximum and minimum ice extent days between 1999 and 2018 are presented in Figures 4 – 23 for A1, Figures 24 – 43 for A2 and Figures 44 – 63 for A3. On maximum ice extent days, all regions were covered primarily with MYI, with FYI present consistently in certain fjords and along the northern coast of QEI. On minimum ice extent days, parts of the FYI covered areas melt and become open water. In A1, Nansen Sound/Greely Fjord Complex and Archer/Conybeare Fjords were frequently covered with FYI on maximum ice extent days and FYI/open water on minimum ice extent days. In 2008 and 2014, a flaw lead system was apparent along the northern coast of Ellesmere Island either as FYI on maximum ice extent days or FYI/open water on minimum ice extent days (Figures 13 and 19). In A2, open water occurred in Svedrup and Peary Channels and Maclean Strait, as well as in Danish Strait and Strand and Middle Fjords on minimum ice extent days. The A2 region was particularly ice-free on minimum ice extent days in 1999, 2005-2008, and 2011 (Figures 24, 30-33, 36). In 2014 and 2016, the flaw lead was opened along the northern coast of Axel Heiberg and Ellef Ringnes Islands (Figures 39 and 41). A2 regions where open water was present on minimum ice extent days coincided with areas where FYI was reported on maximum ice extent days. In A3, distribution of open water on minimum ice extent day was more variable between years than in other analysis areas. Open water often occurred on the west side of Prince Patrick, Eglinton, and Melville Islands and into the Fitzwilliam Strait, which was particularly apparent in years 1999-2001, 2010-2013, 2016, and 2018 (Figures 44-46, 55-58, 61, 63). In years 1999 and 2002 the flaw lead as recorded on the minimum ice extent days north of the Prince Patrick Island (Figures 44 and 47), and extended even further east along the northern coast of Brock and Borden Islands in 2006, 2007, 2009, 2010, and 2017 (Figures 51, 52, 54, 55, 62). In 2005, 2008, and 2016, south of Prince

Patrick Island was ice-free on minimum ice extent days including the fjord located along that coast (Figures 50, 53, 61). Similar to other analysis areas, overall distribution of FYI on maximum ice extent days resembled the distribution of open water on minimum ice extent days.

To summarize the patterns and relative frequency of MYI and FYI distribution on maximum and minimum ice extent days in regions A1-A3 between 1999 and 2018, frequency of occurrence maps were created (Figures 64-69). Area A1 north of QEI was MYI-covered in >80 % of years both on maximum and minimum ice extent days. Nansen Sound/Greely Fjord Complex was the least MYI-covered region of A1, with an apparent decreasing gradient of frequency of MYI occurrence from outer to inner part of the complex both on maximum and minimum ice extent days, with the most inner parts being completely MYI-free (Figure 64). A similar gradient was recorded for Archer/Conybeare Fjords on minimum ice extent days, however, the frequency of MYI occurrence was higher in this region compared to Nansen Sound/Greely Fjord Complex. Maps of FYI occurrence in A1 on maximum and minimum ice extent days reflect the patterns observed for MYI distribution with increased frequency of occurrence of FYI where MYI was less dominant (Figure 65). In addition, a flaw lead region along the coast of QEI is clearly distinct on both minimum and maximum ice extent days, with FYI frequency of occurrence within 5 % – 25 % range. Area A2 was also most frequently (>80 %) covered with MYI both on minimum and maximum sea ice extent days except for coastal fjords of Axel Heiberg and Ellef Ringnes Islands, in particular Strand and Middle Fjords (Figure 66). The most inner parts of these fjords were always MYI-free on minimum ice extent days between 1999 and 2018. Danish Sound was another area of relatively lower frequency of MYI occurrence compared to the rest of A2. A flaw lead region with decreased frequency of occurrence of MYI to 55 % – 75 % was present on maximum ice extent days north of Axel Heiberg and Ellef Ringnes Islands. Regions of decreased frequency of occurrence of MYI in A2 are reflected in increased frequency of occurrence of FYI both on minimum and maximum ice extent days (Figure 67). In A3, the west side of Prince Patrick, Eglinton, and Melville Islands and into the Fitzwilliam Strait was least frequently covered by MYI on maximum and minimum ice extent days (Figure 68) and more frequently covered with FYI compared to the rest of A3 (Figure 69). A flaw lead region, reflected in decreased frequency of occurrence of MYI to 55 % – 75 % and increased frequency of occurrence of FYI up to 50 %, was present both on maximum and minimum ice extent days. The only region of A3 which was always MYI-free between 1999 and 2018 on minimum ice extent days was Murray Inlet.

3.3 Frequency of occurrence of open water

To describe the patterns of distribution of open water, the frequency of occurrence maps of open water were created and are presented in Figures 70-71 for A1, A2, and A3, respectively. The most frequent ice-free regions of A1, A2 and A3 were the Nansen Sound/Greely Fjord Complex in A1, and the marine waters to the west of Prince Patrick, Eglinton, and Melville Islands in A3. These regions were open for > 50 % of the time, with some inner parts and fjords being open for > 75 % of the time. The flaw lead system was present in all regions with frequency of occurrence of open water between 5 % and 25 %. These open water regions within an otherwise ice-covered environment may have fundamental implications at multiple levels of the Arctic ecosystem, however, very little is known about them. Some of the implications documented in other parts of the Arctic include enhanced ice formation resulting in high rates of brine rejection, increased gas fluxes and nutrient dynamics, and increased biological productivity (e.g., Smith and Barber 2007). They may also play a critical role to Arctic marine mammals and birds for feeding, reproduction, and migration.

4 Conclusion

The three analysis areas presented in this study show multiple similarities in sea-ice composition and distribution patterns between 1999 and 2018, while also exhibiting some essential differences. All of the areas were dominated by MYI year-round. MYI constituted > 68 % and > 63 % of sea ice present on maximum and minimum ice extent days within the general study region, respectively. In all areas, general patterns of FYI and FYI/open water distribution and relative extents were similar, with FYI and open water occurring typically in coastal fjords and within the flaw lead region north of QEI. Maximum open water area on a single day constituted up to 20 %, 14 %, and 15 % of total marine area in A1, A2, and A3, respectively. Maximum sea ice extent dates were identical for all three areas, and occurred between March 28 and April 3. However, inter-annual variability in minimum sea ice extent date as well as FYI/open water distribution increased substantially along the south-west geographic gradient form A1 to A3. While the coefficient of variation in minimum ice extent DofY was only 3 % in A1, it increased to 8 % in A2, and 11 % in A3. Distribution of FYI on maximum ice extent days and FYI/open water on minimum ice extent days was also more variable between years moving across the south-west geographic gradient. While FYI/open water occurrence within A1 was quite consistently concentrated within the Nansen Sound/Greely Fjord Complex and Archer/Conybeare Fjords, it was more dispersed spatially and temporally variable between years in A3. These findings point to decreasing predictability of FYI/open water occurrence as well as minimum ice extent date along a south-west geographic gradient extending from A1 to A3.

Consistent lack of MYI in certain regions of A1, A2, and A3 draws special attention. In particular, the inner part of the Nansen Sound/Greely Fjord Complex is the largest and most consistently MYI-free region in this study. Ecosystems of FYI-covered versus MYI-covered

Arctic regions differ dramatically (Nicolaus et al. 2012; Lange et al. 2019; Kohlbach et al. 2020). Consistent lack of MYI in the Nansen Sound/Greely Fjord Complex on maximum and minimum ice extent dates may make this area unique with regards to biological productivity and suitability of habitat for marine wildlife including certain species of marine mammals and birds.

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Table 1. Date and day of year (DofY) of maximum and minimum sea ice extent (Max Ice Ext and Min Ice Ext, respectively) between 1999 and 2018 in A1, A2, and A3.

	A1				**A2**				**A3**			
	Max Ice Ext		Min Ice Ext		Max Ice Ext		Min Ice Ext		Max Ice Ext		Min Ice Ext	
Year	Date	DofY	Date	DofY	Date	DofY	Date	DofY	Date	DofY	Date	DofY
1999	1 Apr	91	6 Sep	249	1 Apr	91	23 Aug	235	1 Apr	91	13 Sep	256
2000	1 Apr	92	28 Aug	241	1 Apr	92	28 Aug	241	1 Apr	92	4 Sep	248
2001	1 Apr	91	13 Aug	225	1 Apr	91	20 Aug	232	1 Apr	91	20 Aug	232
2002	1 Apr	91	2 Sep	245	1 Apr	91	2 Sep	245	1 Apr	91	9 Sep	252
2003	1 Apr	91	25 Aug	237	1 Apr	91	25 Aug	237	1 Apr	91	18 Aug	230
2004	1 Apr	92	23 Aug	236	1 Apr	92	23 Aug	236	1 Apr	92	23 Aug	236
2005	1 Apr	91	15 Aug	227	1 Apr	91	15 Aug	227	1 Apr	91	5 Sep	248
2006	1 Apr	91	21 Aug	233	1 Apr	91	21 Aug	233	1 Apr	91	3 Jul	184
2007	2 Apr	92	27 Aug	239	2 Apr	92	10 Sep	253	2 Apr	92	23 Jul	204
2008	31 Mar	91	11 Aug	224	31 Mar	91	18 Aug	231	31 Mar	91	8 Sep	252
2009	30 Mar	89	7 Sep	250	30 Mar	89	31 Aug	243	30 Mar	89	20 Jul	201
2010	29 Mar	88	16 Aug	228	29 Mar	88	16 Aug	228	29 Mar	88	23 Aug	235
2011	28 Mar	87	5 Sep	248	28 Mar	87	5 Sep	248	28 Mar	87	22 Aug	234
2012	2 Apr	93	3 Sep	247	2 Apr	93	10 Sep	254	2 Apr	93	13 Aug	226
2013	1 Apr	91	19 Aug	231	1 Apr	91	5 Aug	217	1 Apr	91	9 Sep	252
2014	31 Mar	90	18 Aug	230	31 Mar	90	11 Aug	223	31 Mar	90	25 Aug	237
2015	30 Mar	89	31 Aug	243	30 Mar	89	17 Aug	229	30 Mar	89	31 Aug	243
2016	28 Mar	88	29 Aug	242	28 Mar	88	13 Jun	165	28 Mar	88	5 Sep	249
2017	3 Apr	93	28 Aug	240	3 Apr	93	28 Aug	240	3 Apr	93	5 Jun	156
2018	2 Apr	92	3 Sep	246	2 Apr	92	3 Sep	246	2 Apr	92	10 Sep	253
Avg		91		238		91		233		91		231
SD		2		8		2		19		2		26
Min		87		224		87		165		87		156
Max		93		250		93		254		93		256

Table 2. Maximum open water area (Max_{OW}) along with the date and day of year (DofY) of its occurrence between 1999 and 2018 in A1, A2, and A3.

Year	A1			A2			A3		
	Max_{OW} [km^2]	Date	DofY	Max_{OW} [km^2]	Date	DofY	Max_{OW} [km^2]	Date	DofY
1999	5,214	6 Sep	249	19,601	23 Aug	235	17,708	13Sep	256
2000	9,305	28 Aug	241	4,105	28 Aug	241	9,322	4 Sep	248
2001	1,977	13 Aug	225	4,210	20 Aug	232	7,985	20 Aug	232
2002	8,536	2 Sep	245	1,886	2 Sep	245	6,004	9 Sep	252
2003	9,264	25 Aug	237	4,526	25 Aug	237	3,102	18 Aug	230
2004	3,290	23 Aug	236	1,631	23 Aug	236	3,322	23 Aug	236
2005	11,894	15 Aug	227	14,503	15 Aug	227	11,717	5 Sep	248
2006	7,698	21 Aug	233	9,928	21 Aug	233	4,746	3 Jul	184
2007	9,037	27 Aug	239	15,055	10 Sep	253	9,720	23 Jul	204
2008	8,418	11 Aug	224	13,395	18 Aug	231	14,716	8 Sep	252
2009	11,644	7 Sep	250	3,996	31 Aug	243	6,170	20 Jul	201
2010	11,982	16 Aug	228	14,700	16 Aug	228	13,856	23 Aug	235
2011	13,270	5 Sep	248	19,322	5 Sep	248	18,373	22 Aug	234
2012	11,544	3 Sep	247	11,051	10 Sep	254	22,302	13 Aug	226
2013	3,580	19 Aug	231	3,000	5 Aug	217	9,913	9 Sep	252
2014	13,048	18 Aug	230	5,670	11 Aug	223	5,173	25 Aug	237
2015	11,995	31 Aug	243	7,286	17 Aug	229	13,285	31 Aug	243
2016	11,299	29 Aug	242	7,386	13 Jun	165	19,925	5 Sep	249
2017	5,242	28 Aug	240	8,290	28 Aug	240	9,982	5 Jun	156
2018	10,133	3 Sep	246	8,072	3 Sep	246	7,730	10 Sep	253
Avg	8,919		238	8,881		233	10,753		231
SD	3,425		8	5,588		19	5,631		26
Min	1,977		224	1,631		165	3,102		156
Max	13,270		250	19,601		254	22,302		256

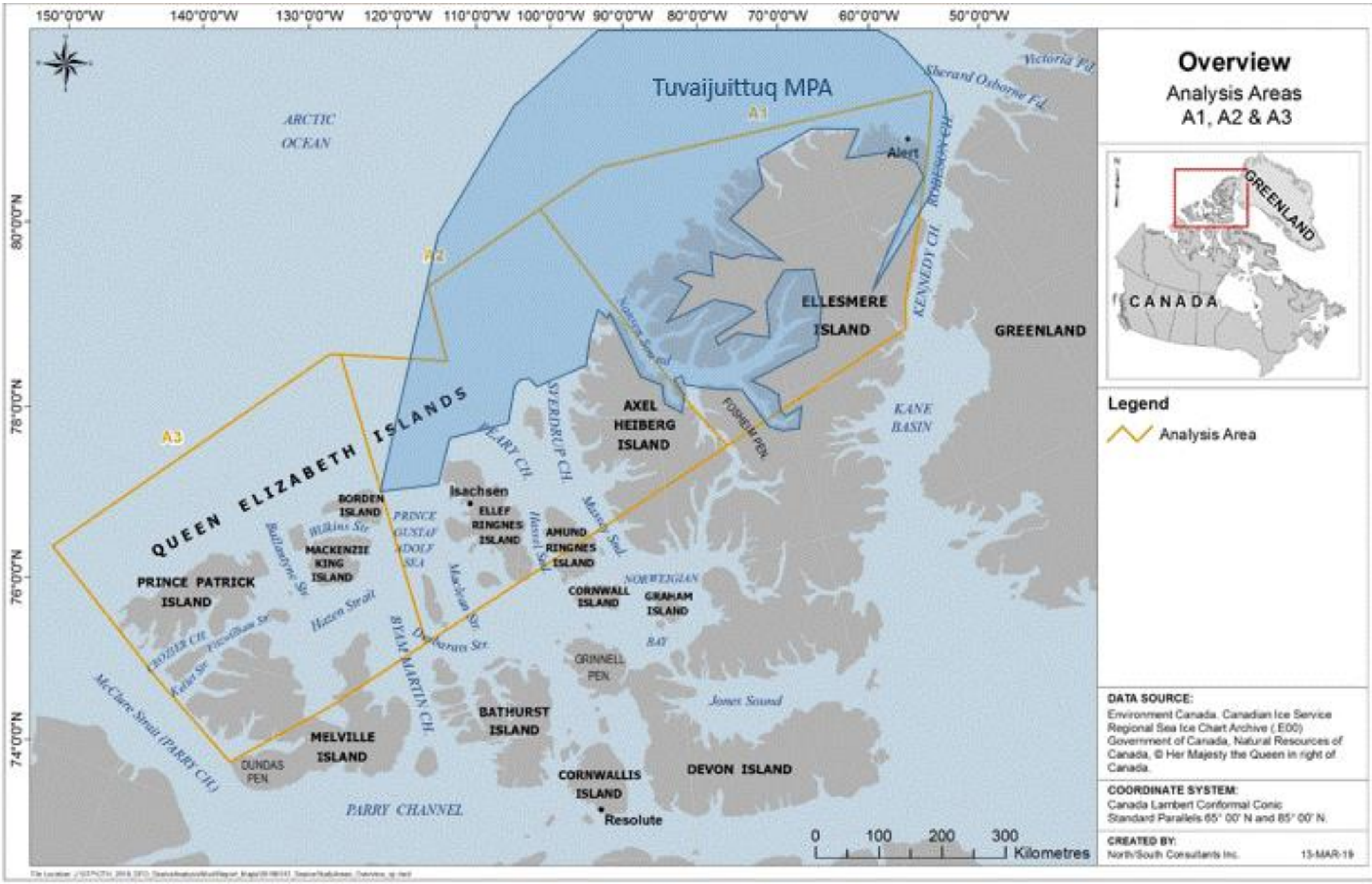


Figure 1. Geographic boundaries of analysis regions A1, A2, and A3, along with the portion of Tuvaijuittuq MPA boundary located within the study region.

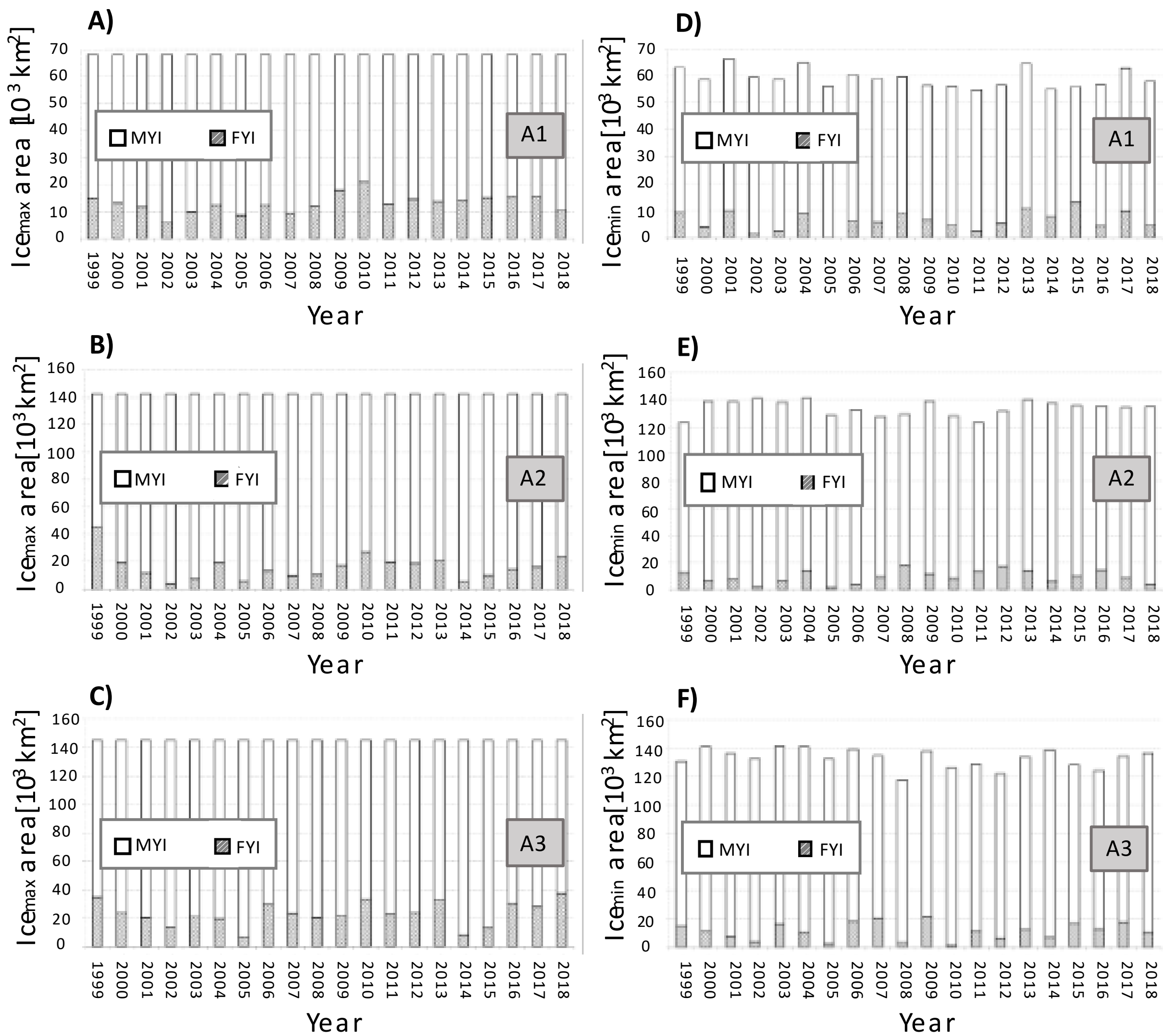
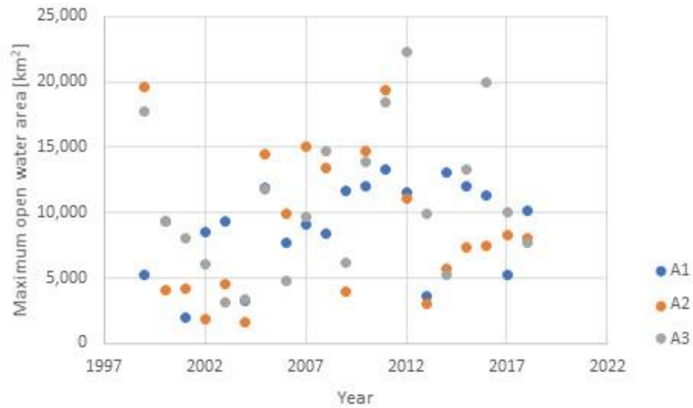


Figure 2. The area of first-year ice (FYI) and multi-year ice (MYI) on maximum ice extent day (Ice_{max}area) in A1, A2 and A3 analysis areas (A, B, and C, respectively) and on minimum ice extent day (Ice_{min}area) in A1, A2 and A3 analysis areas (D, E, and F, respectively) between 1999 and 2018.

A)



B)

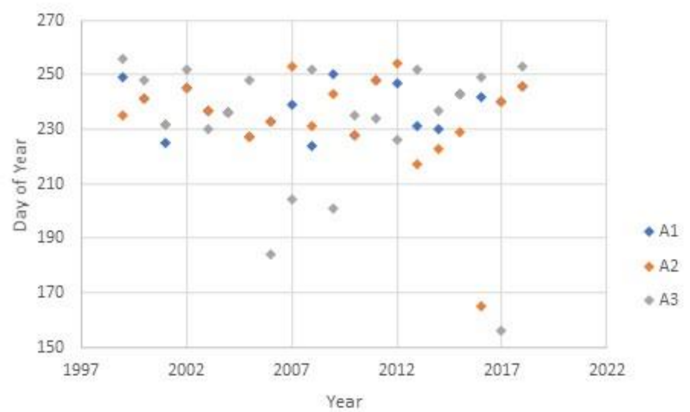


Figure 3. Maximum annual open water area (A) and the Day of Year of its occurrence (B) between 1999 and 2018 in A1, A2, and A3.

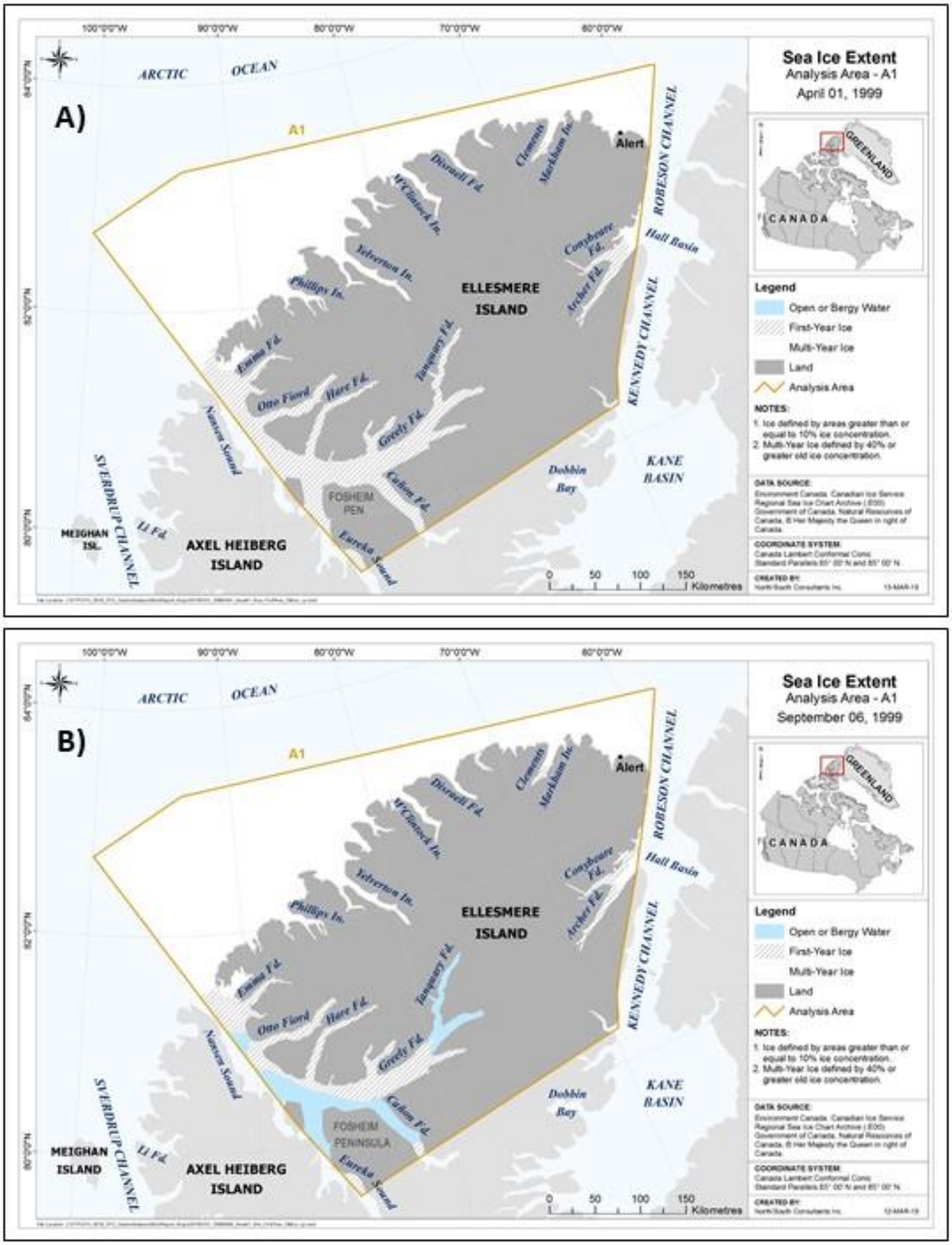


Figure 4. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 1999 within region A1.

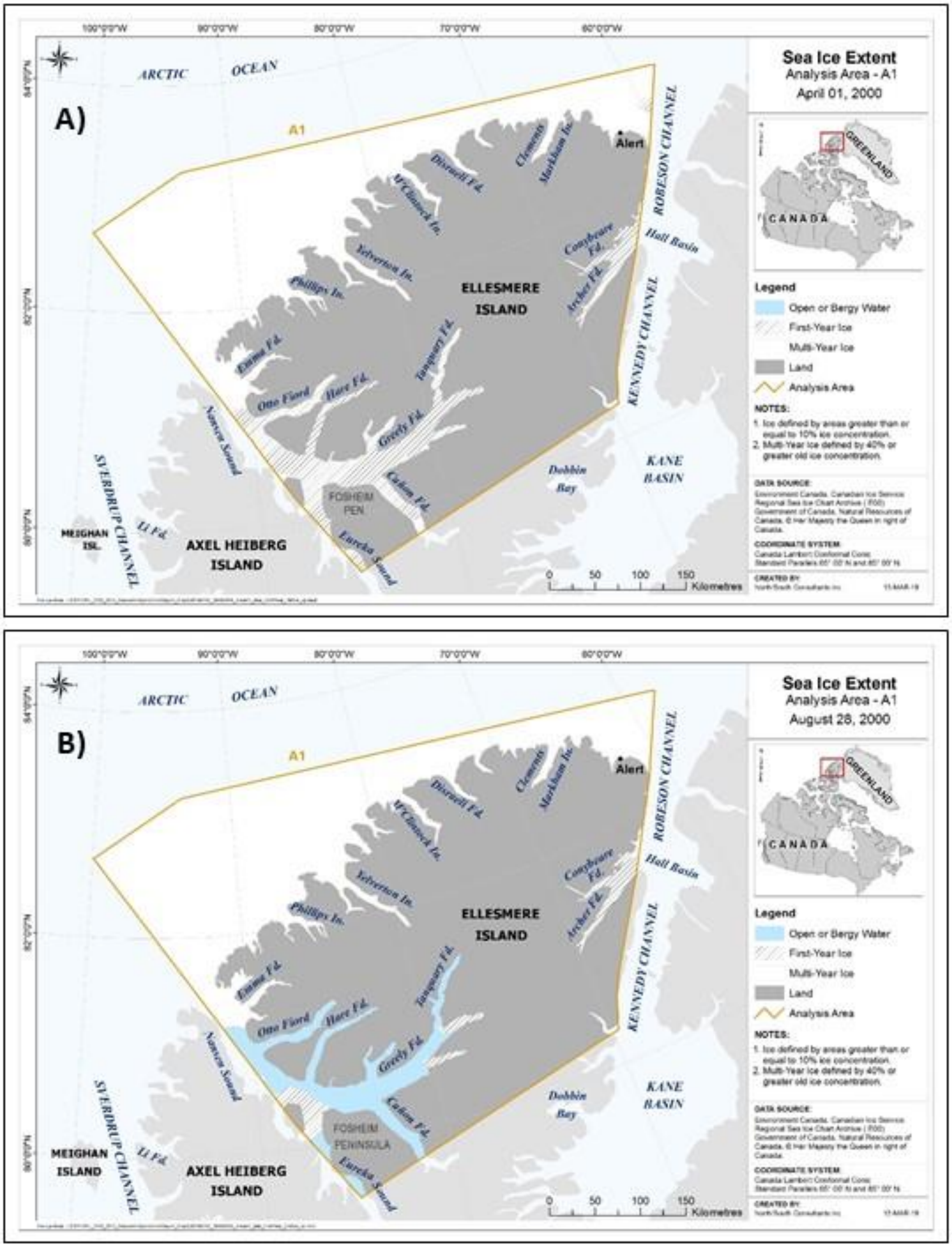


Figure 5. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2000 within region A1.

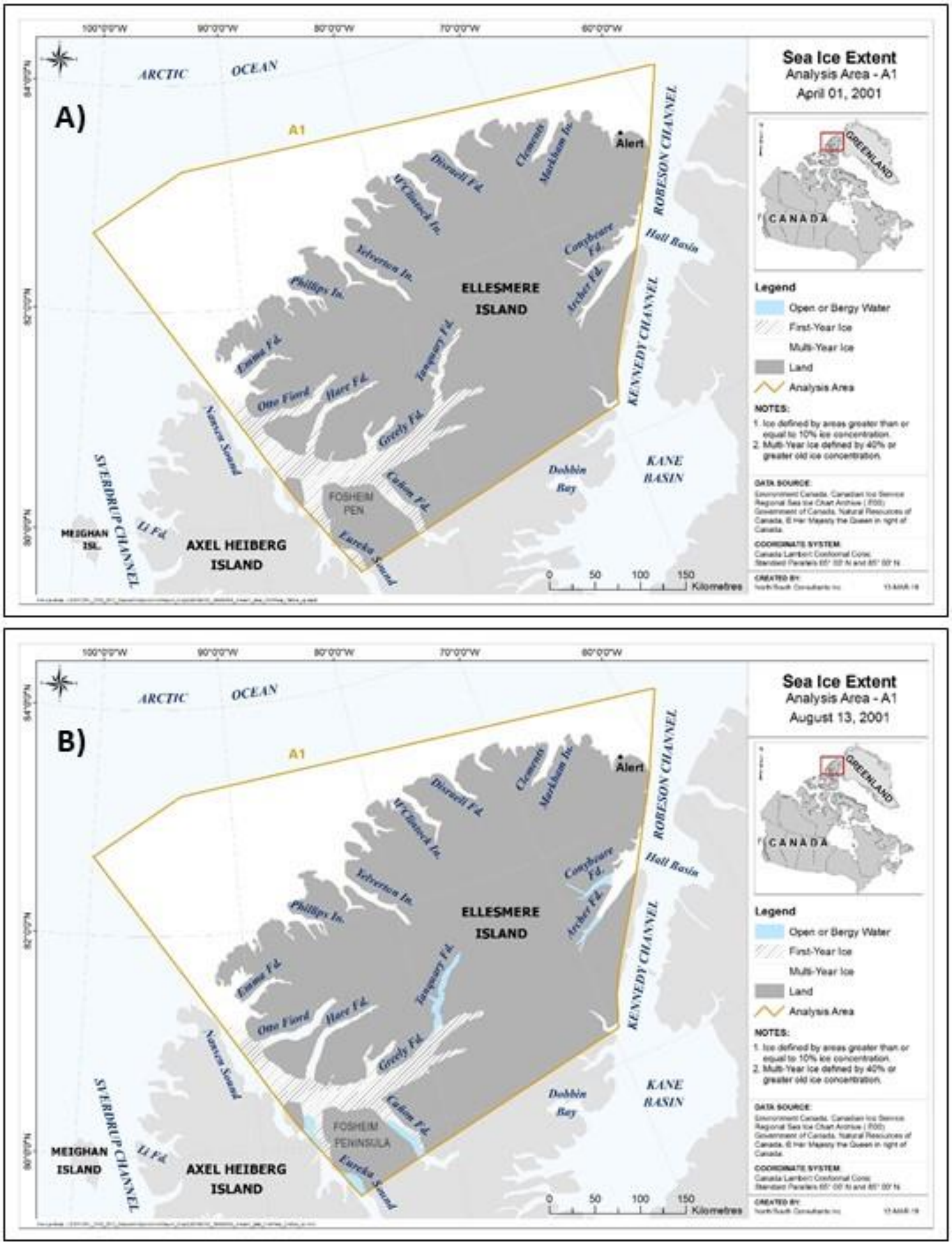


Figure 6. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2001 within region A1.

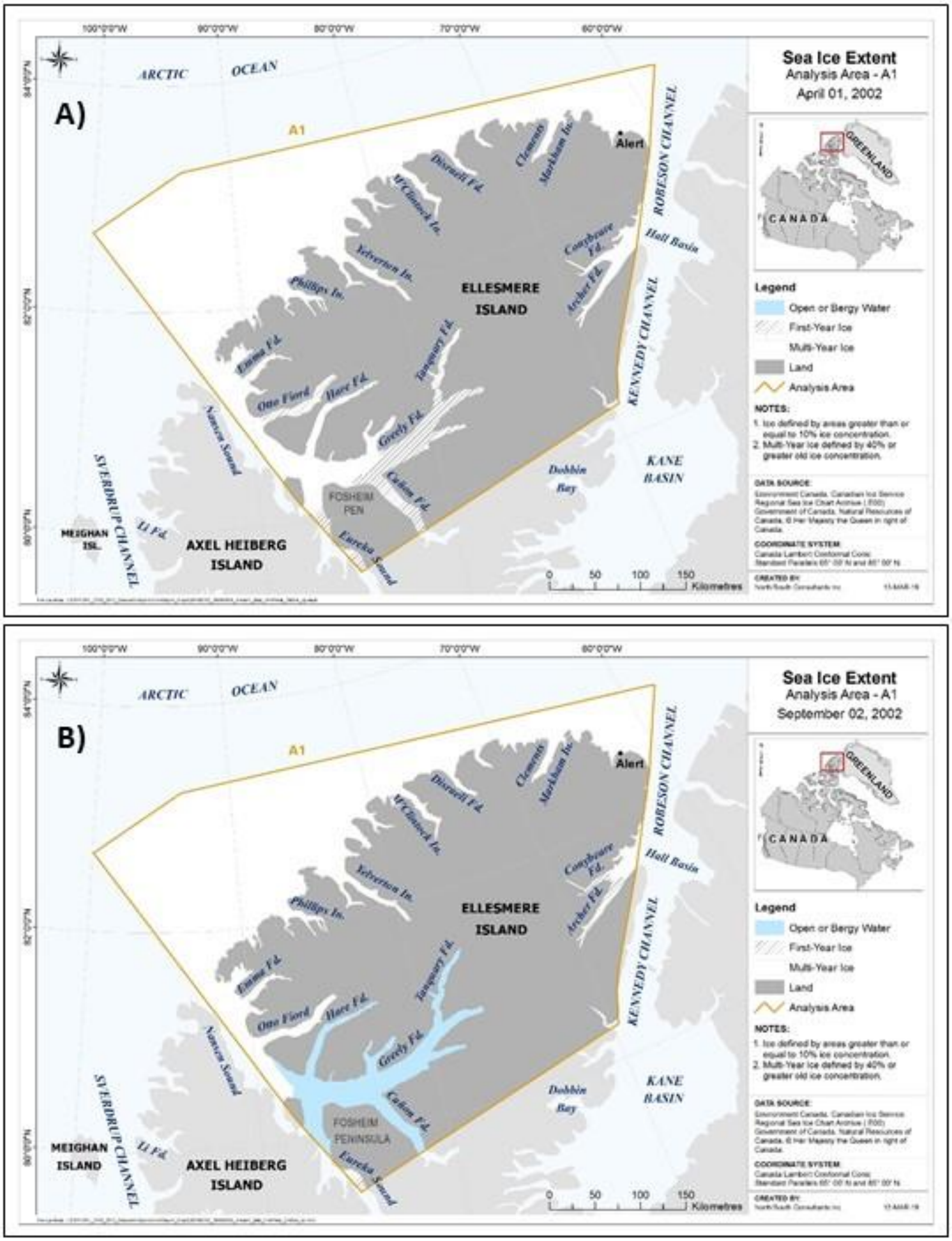


Figure 7. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2002 within region A1.

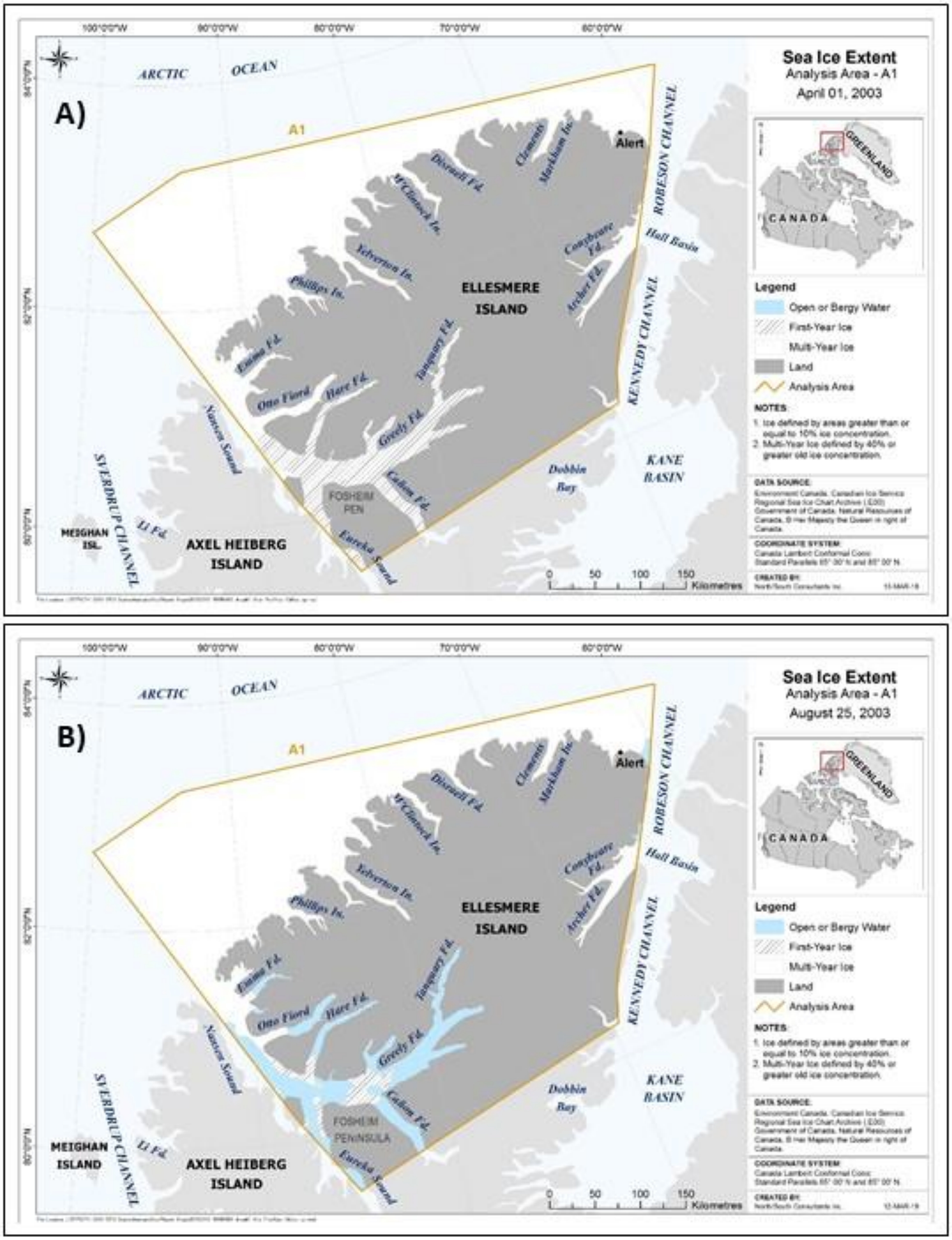


Figure 8. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2003 within region A1.

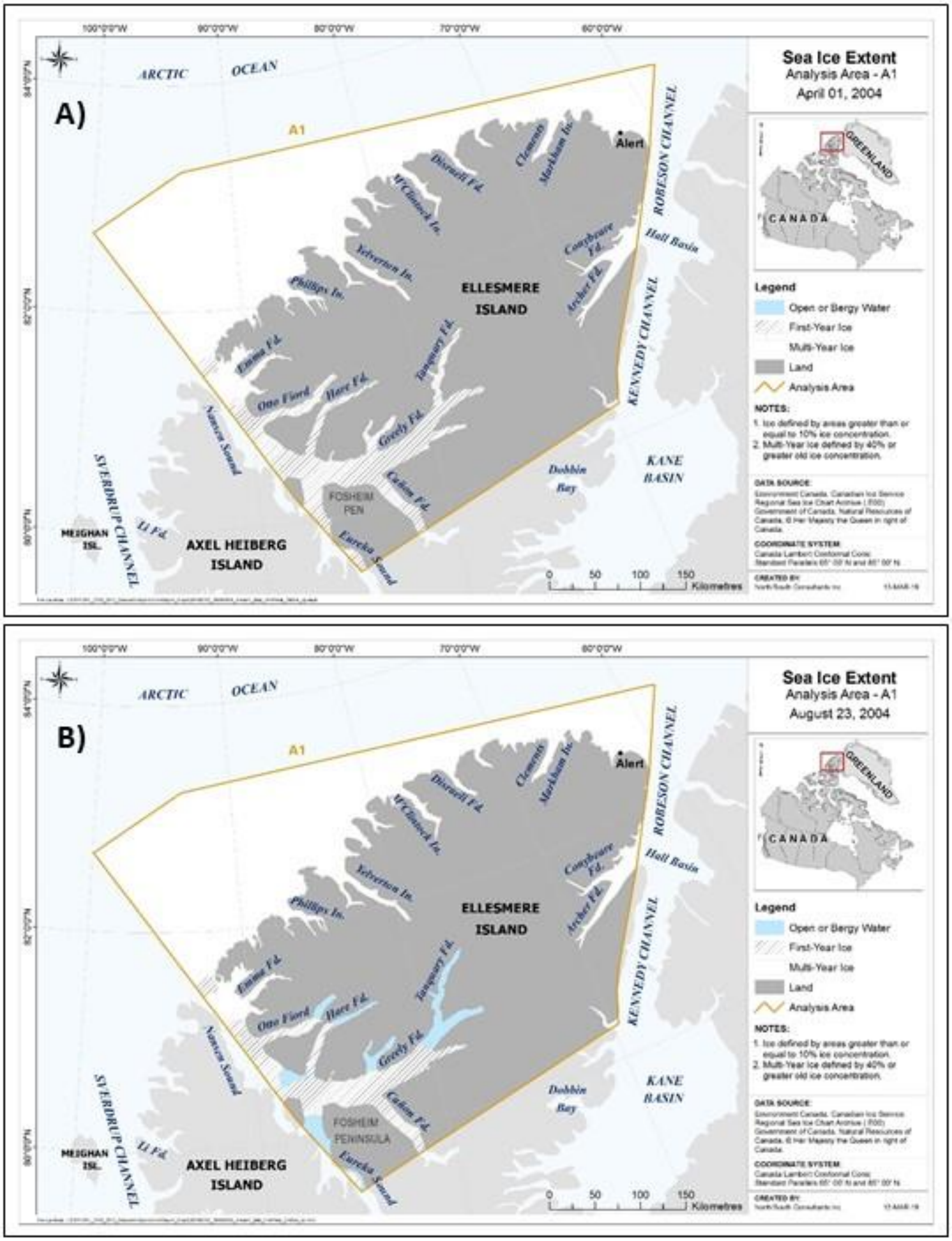


Figure 9. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2004 within region A1.

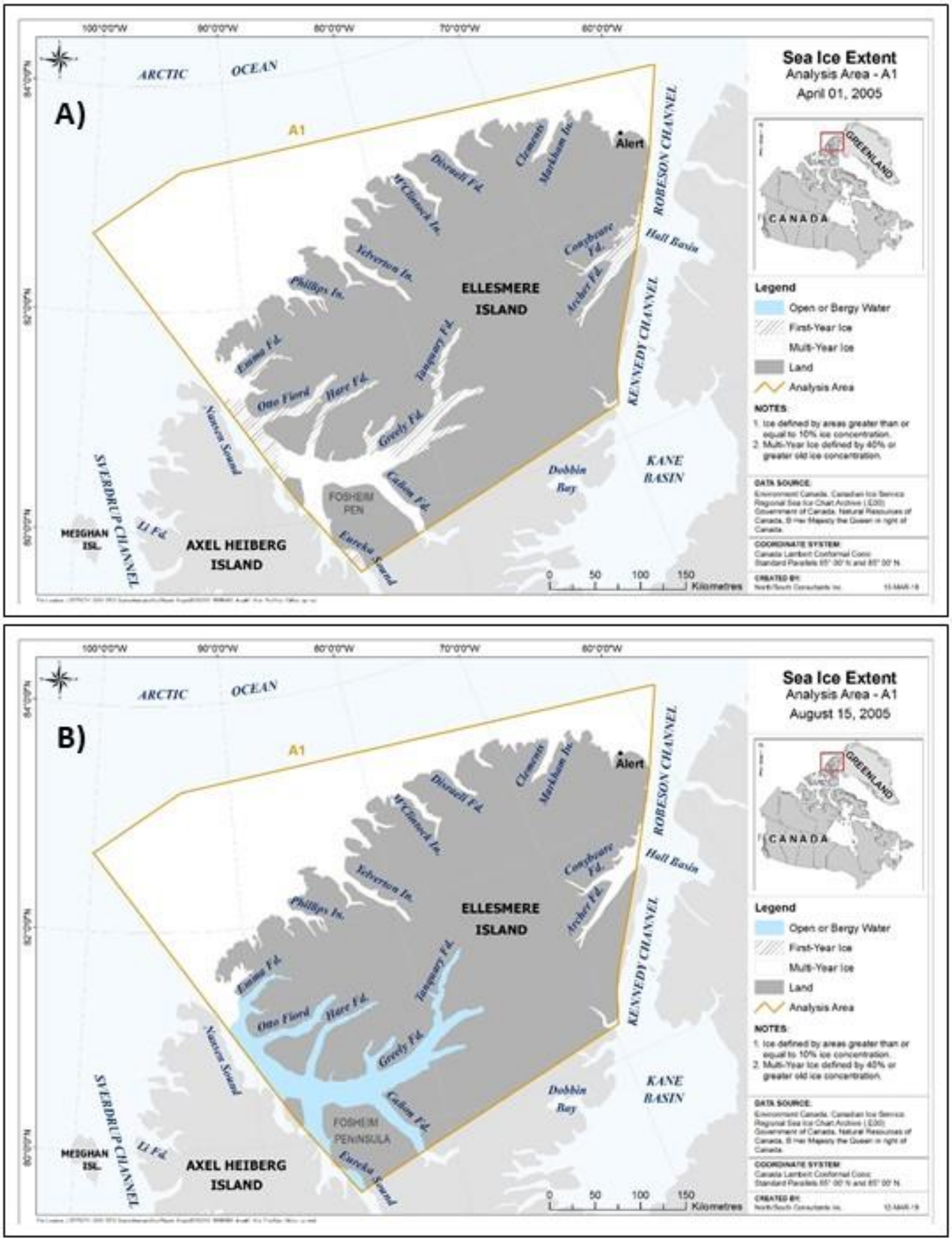


Figure 10. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2005 within region A1.

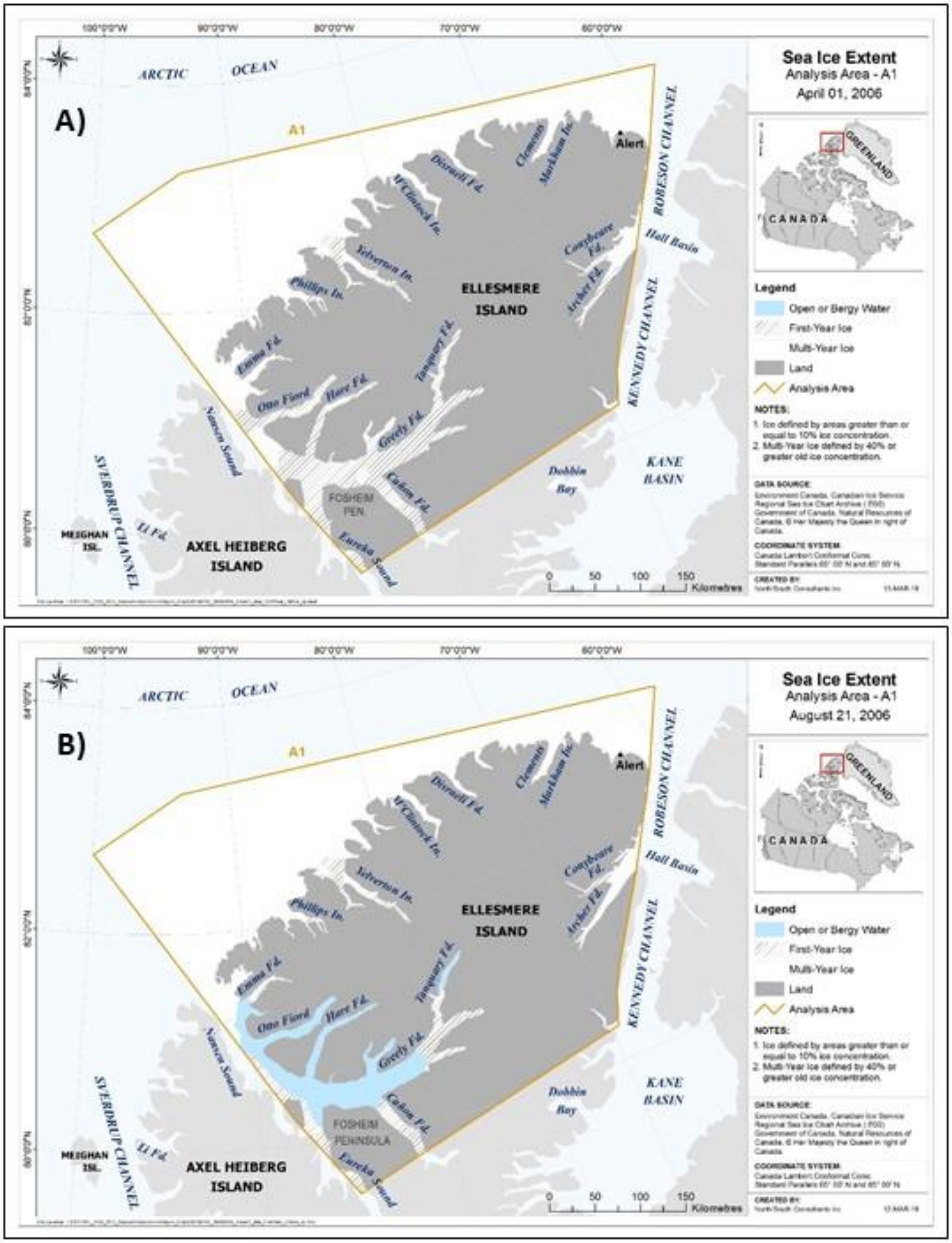


Figure 11. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2006 within region A1.

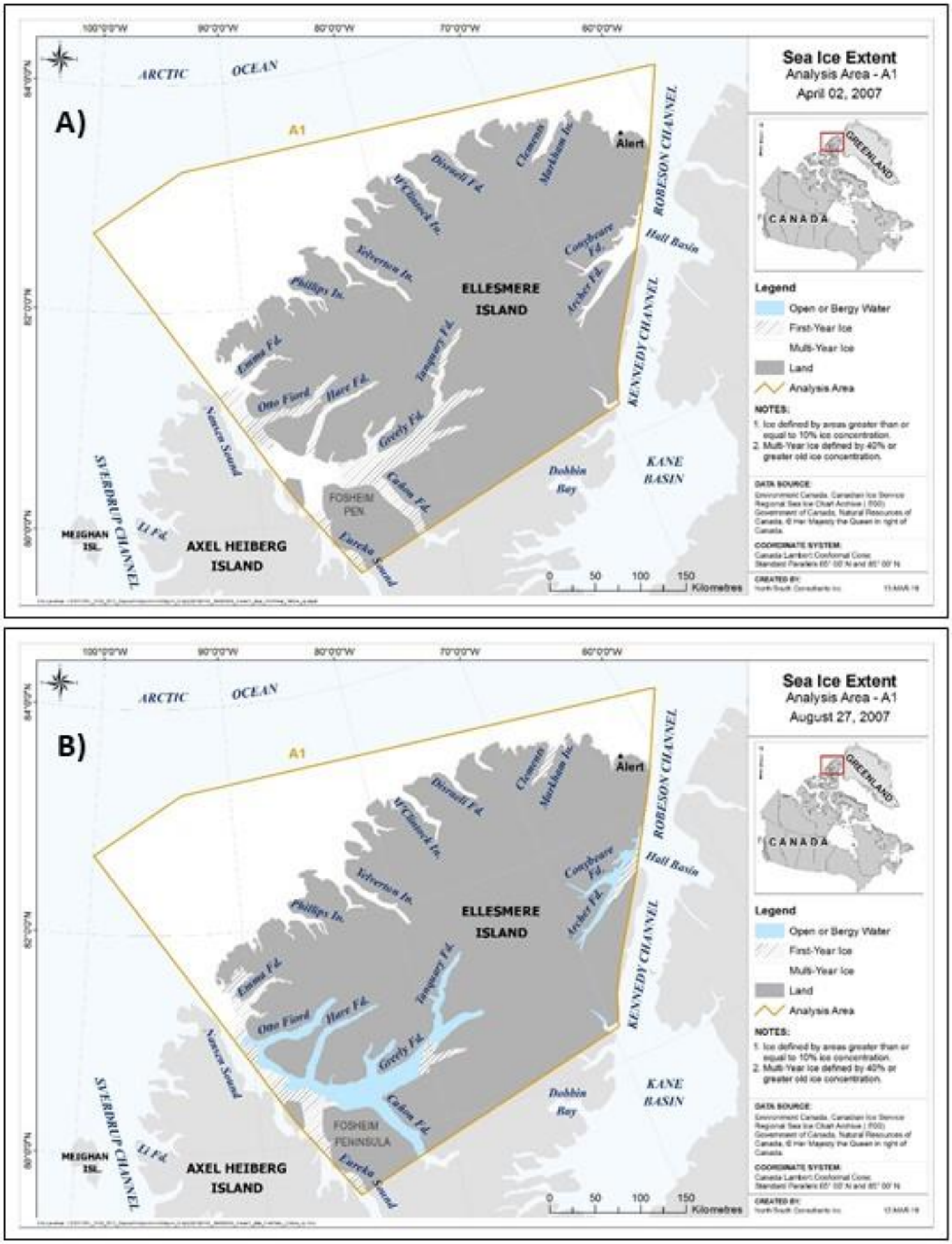


Figure 12. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2007 within region A1.

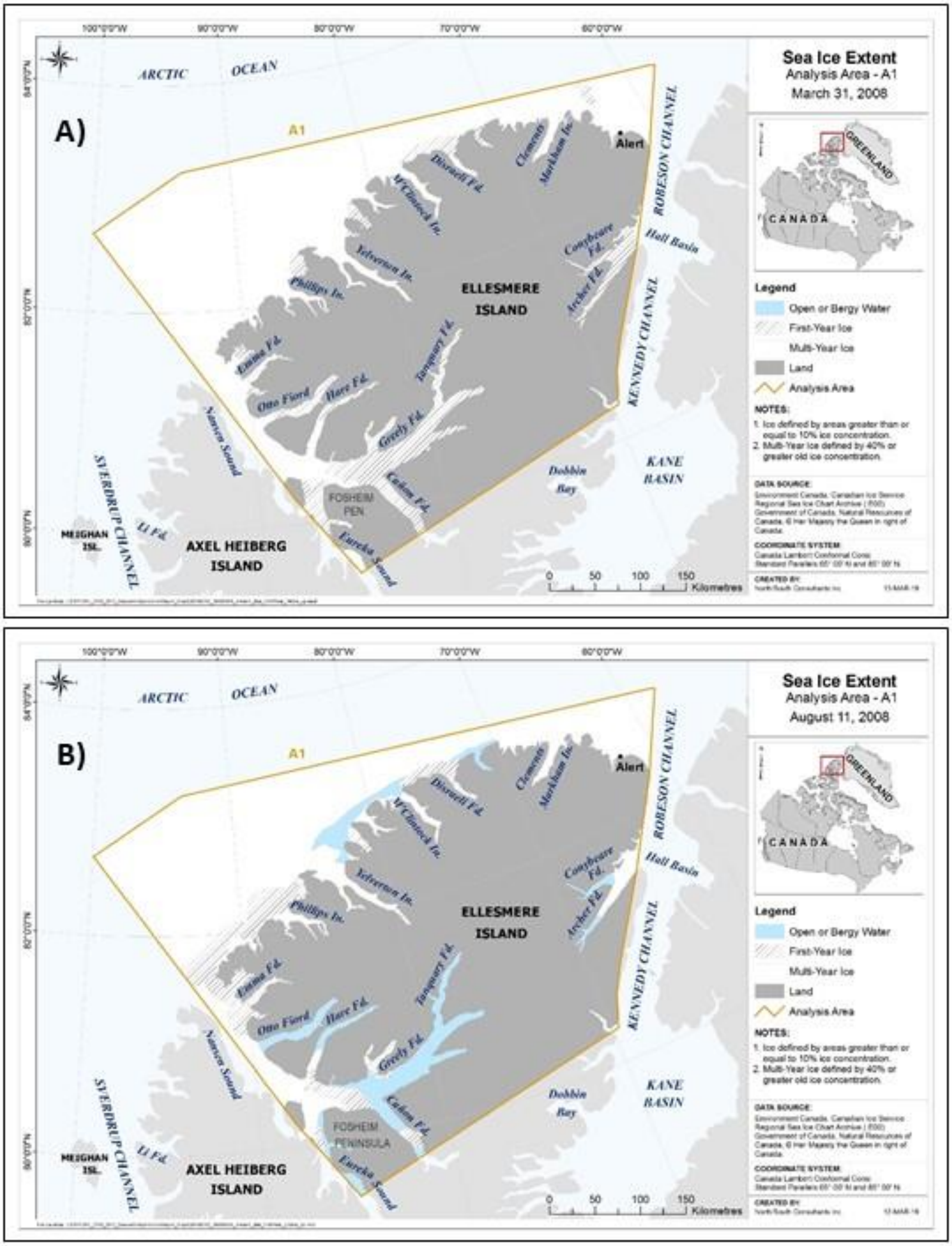


Figure 13. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2008 within region A1.

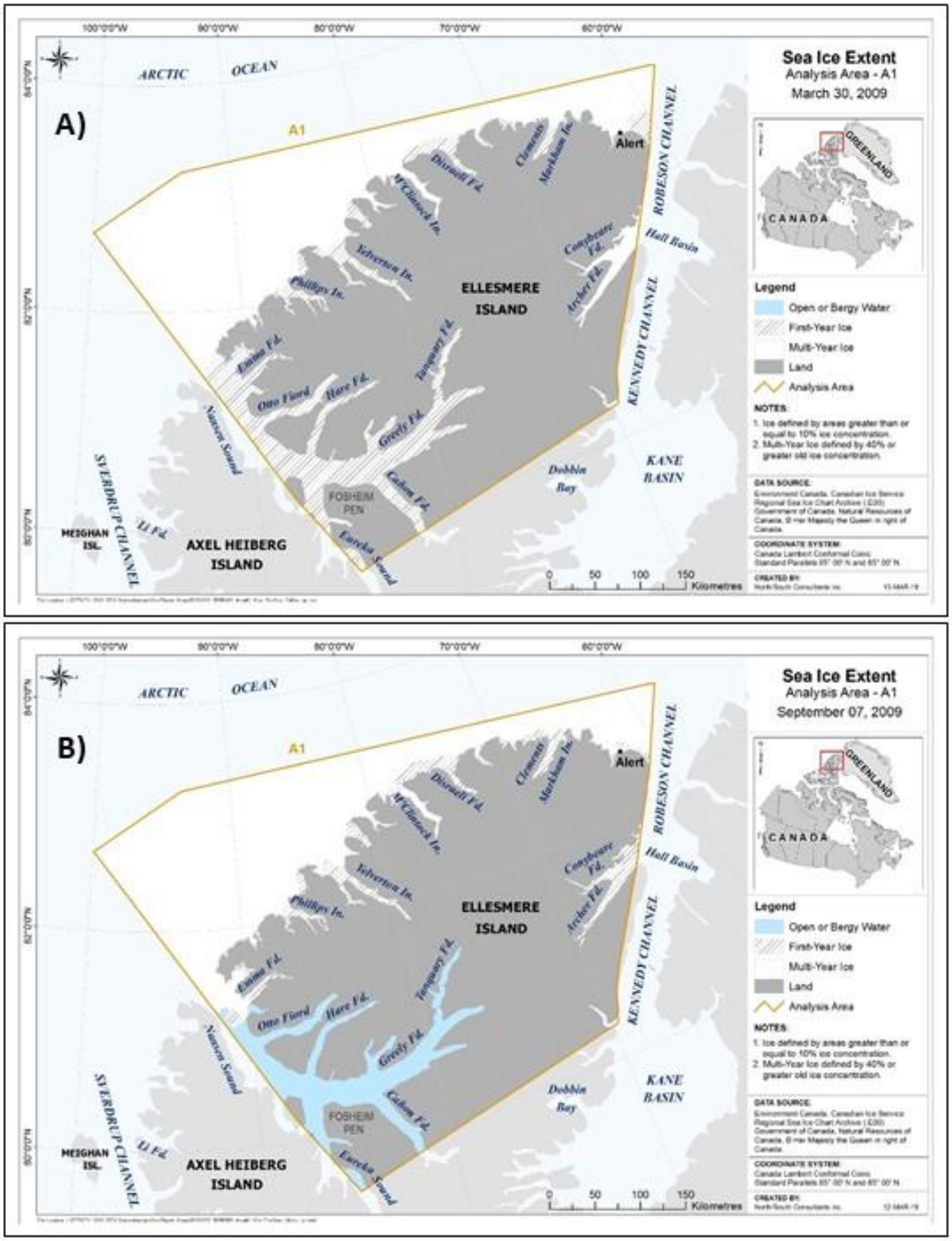


Figure 14. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2009 within region A1.

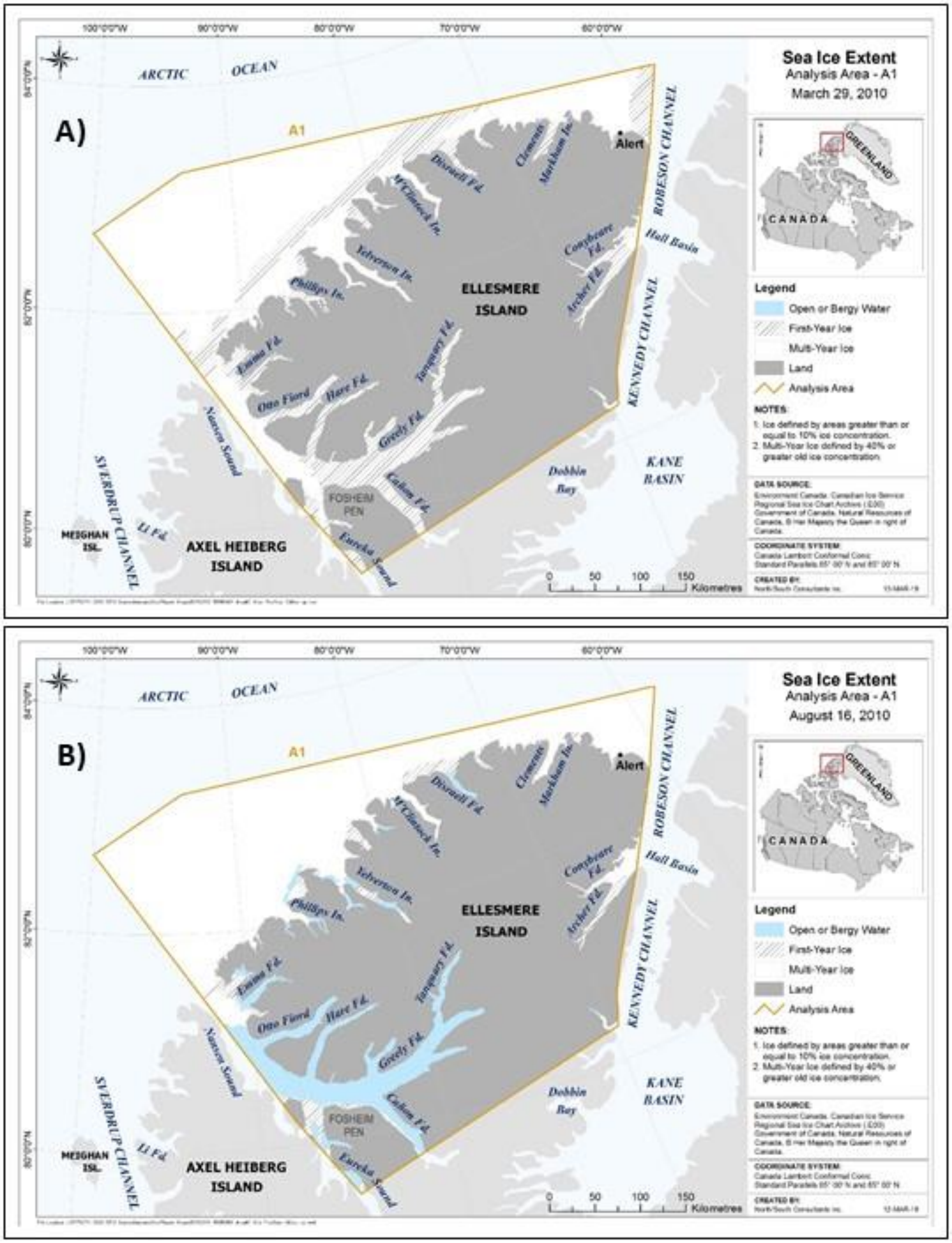


Figure 15. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2010 within region A1.

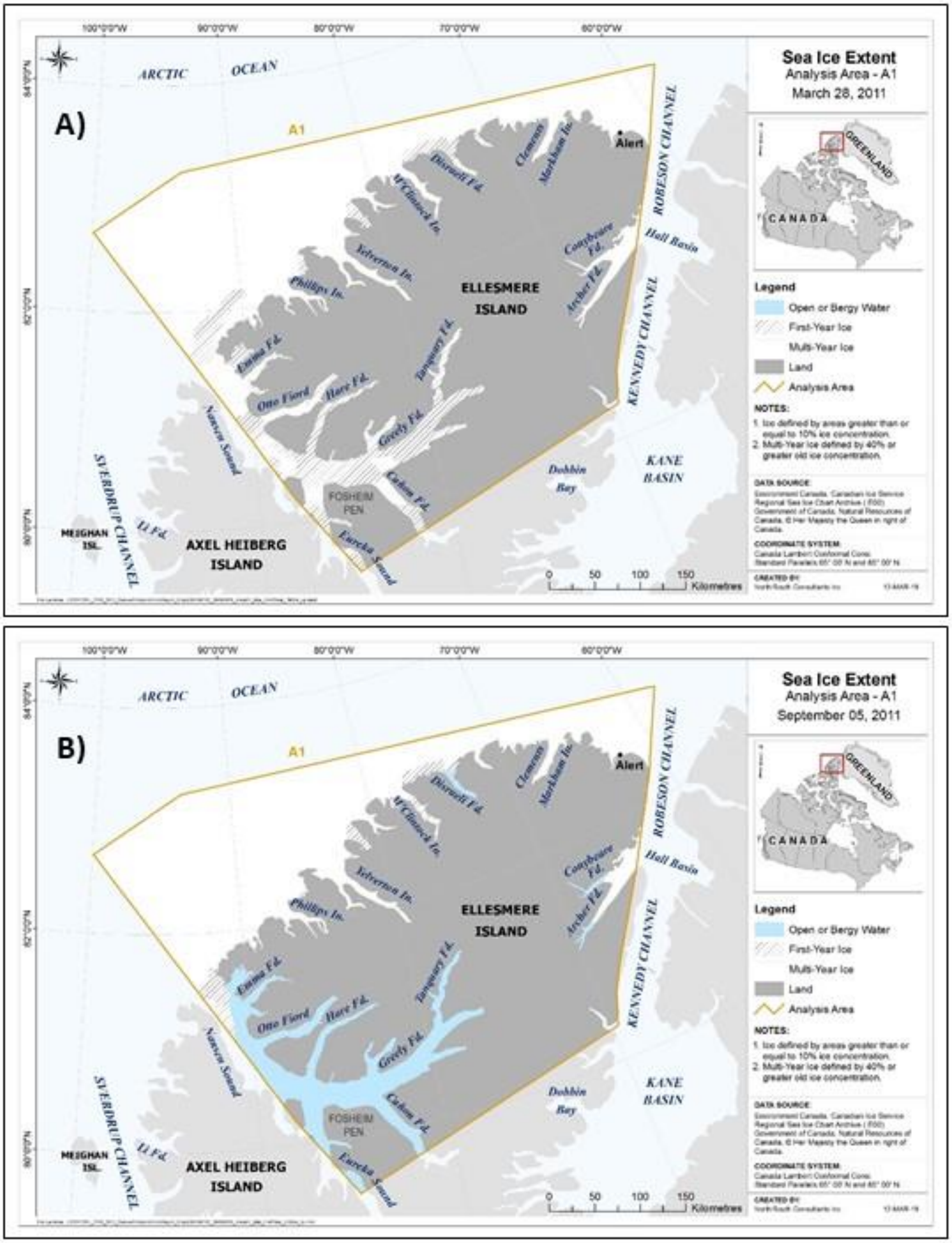


Figure 16. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2011 within region A1.

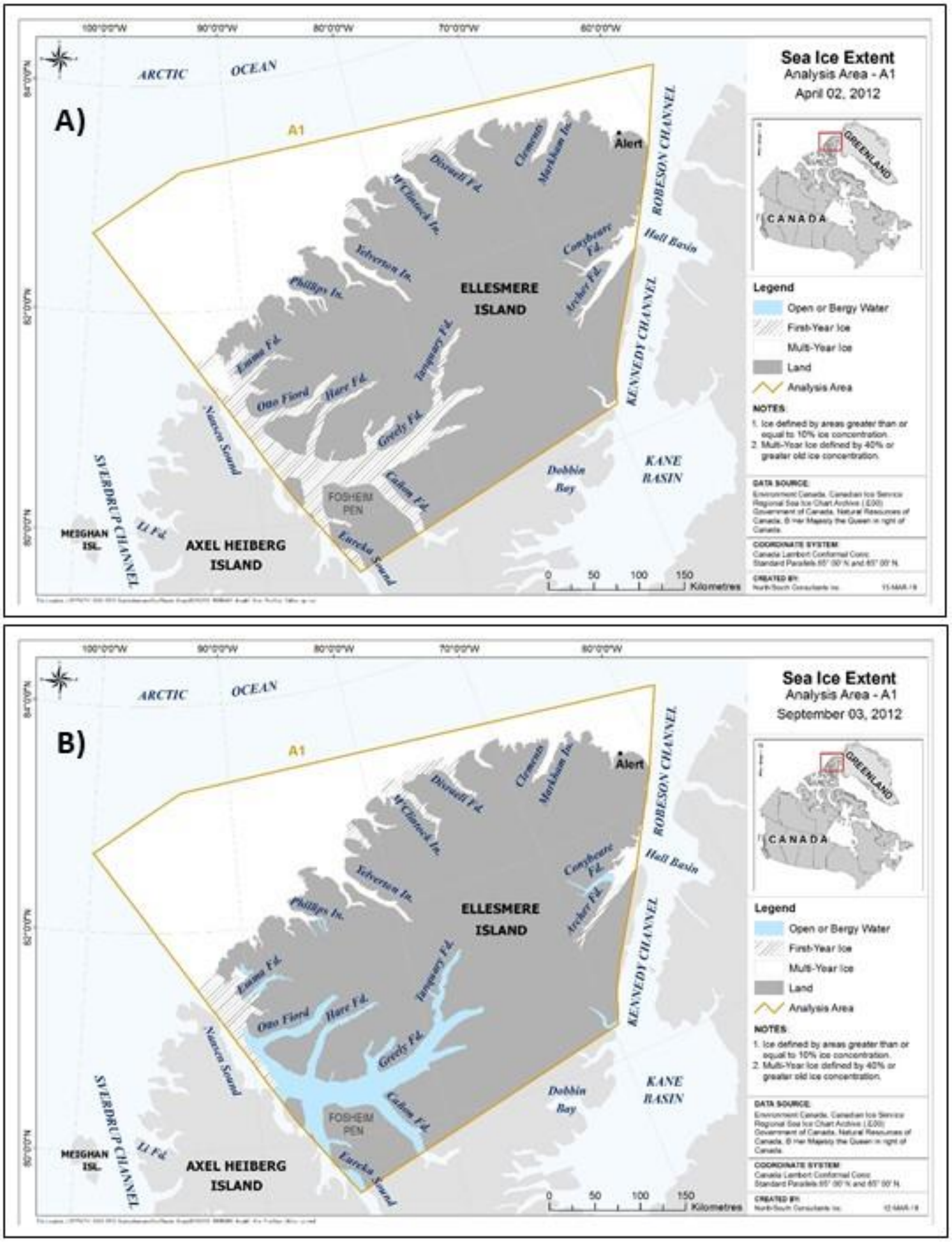


Figure 17. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2012 within region A1.

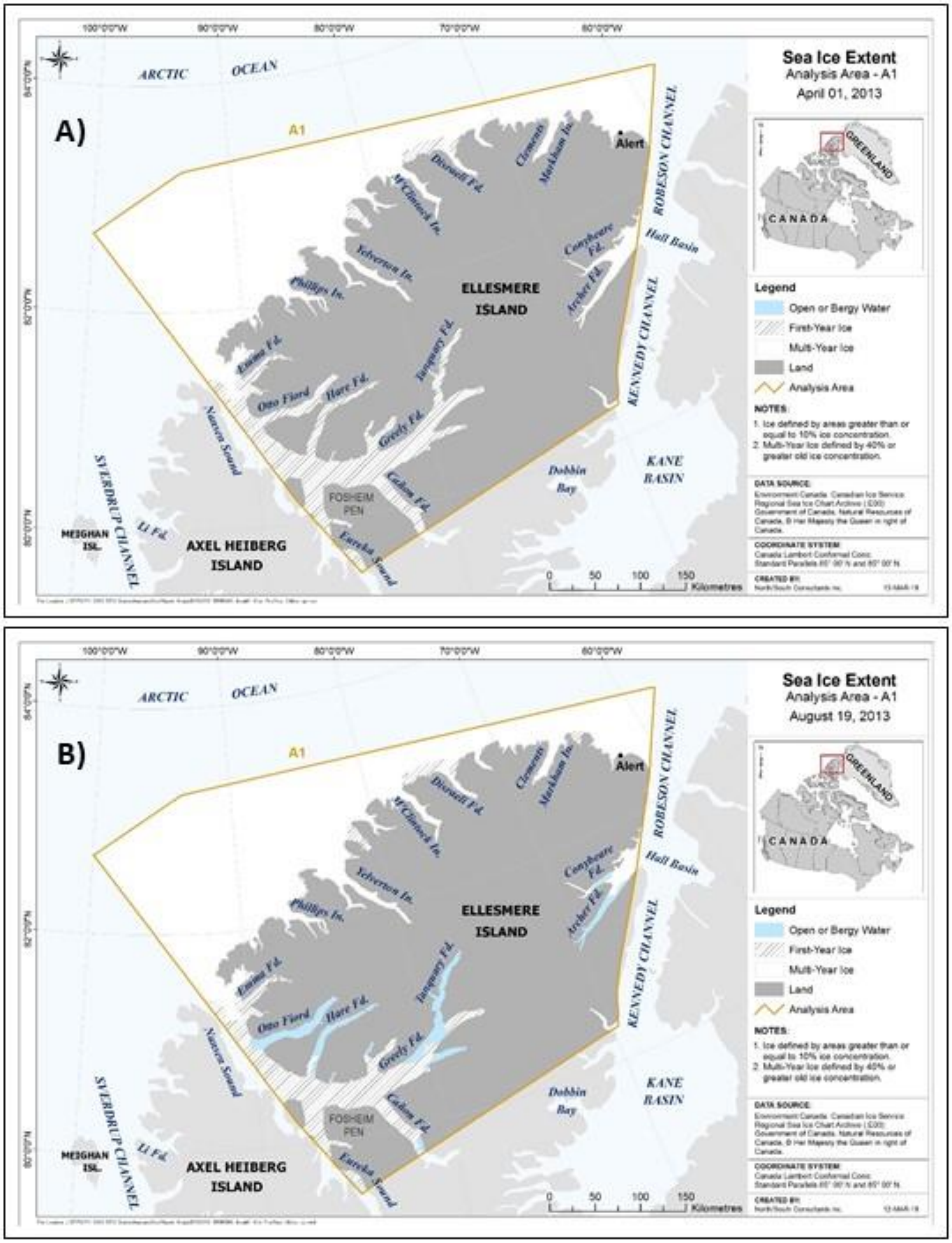


Figure 18. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2013 within region A1.

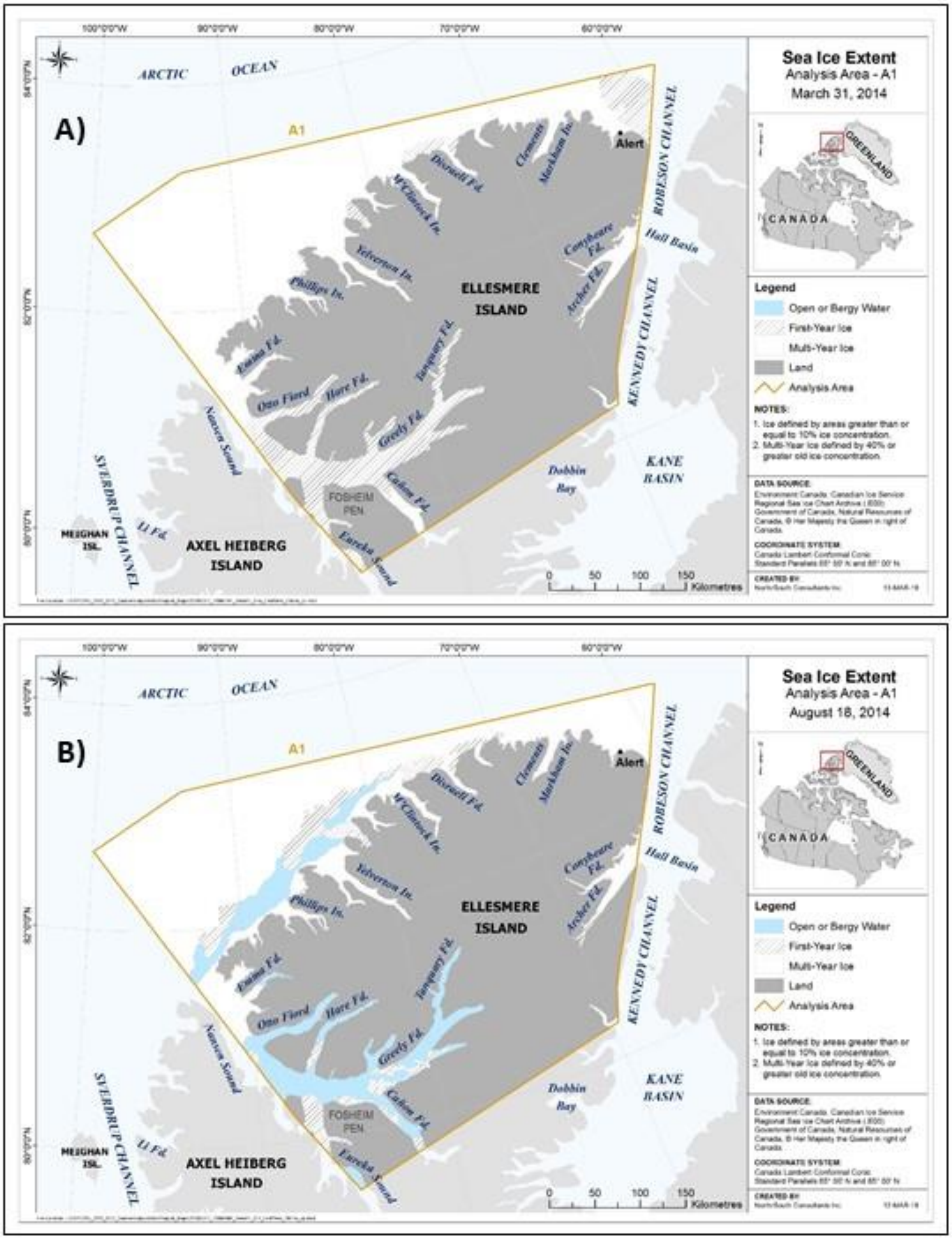


Figure 19. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2014 within region A1.

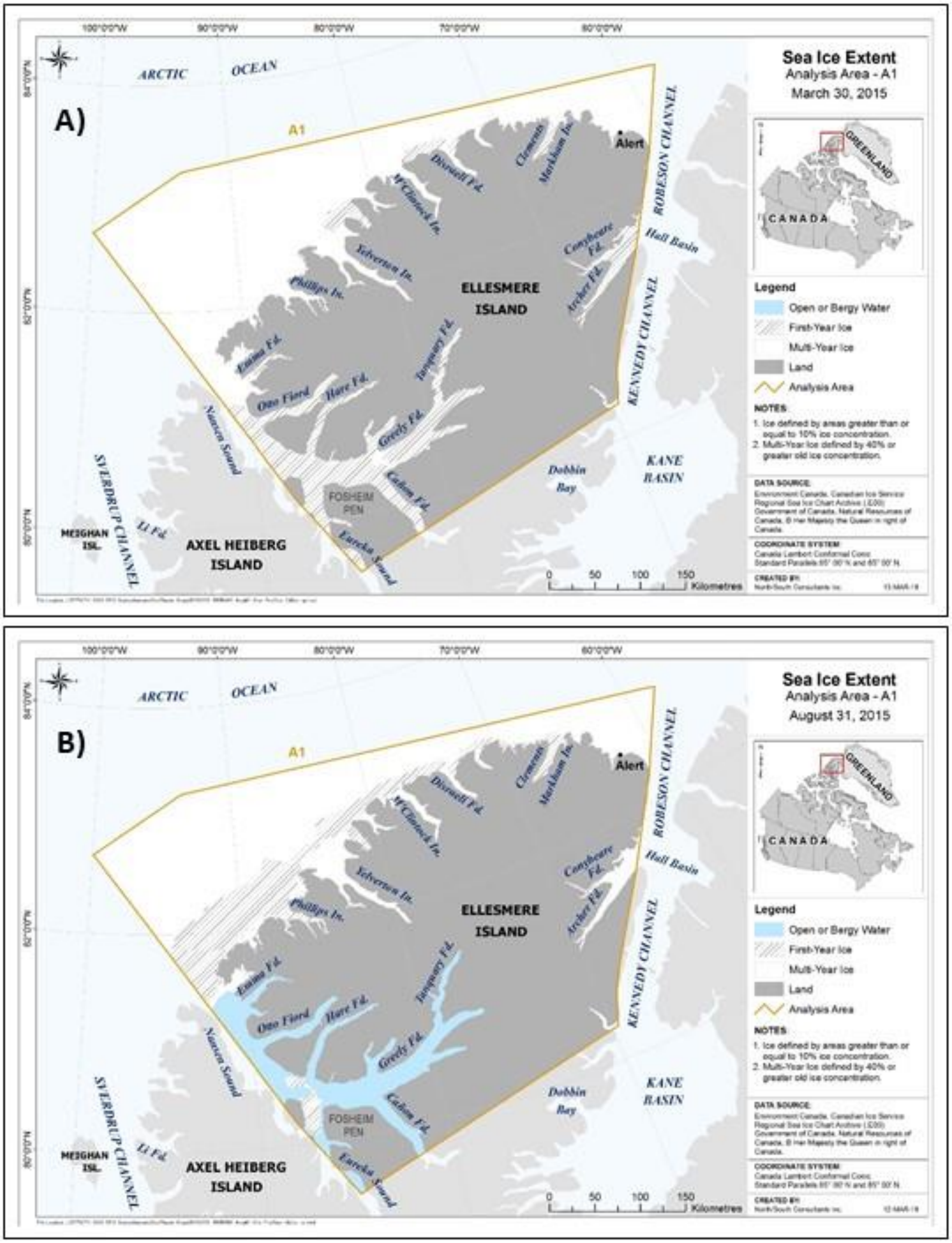


Figure 20. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2015 within region A1.

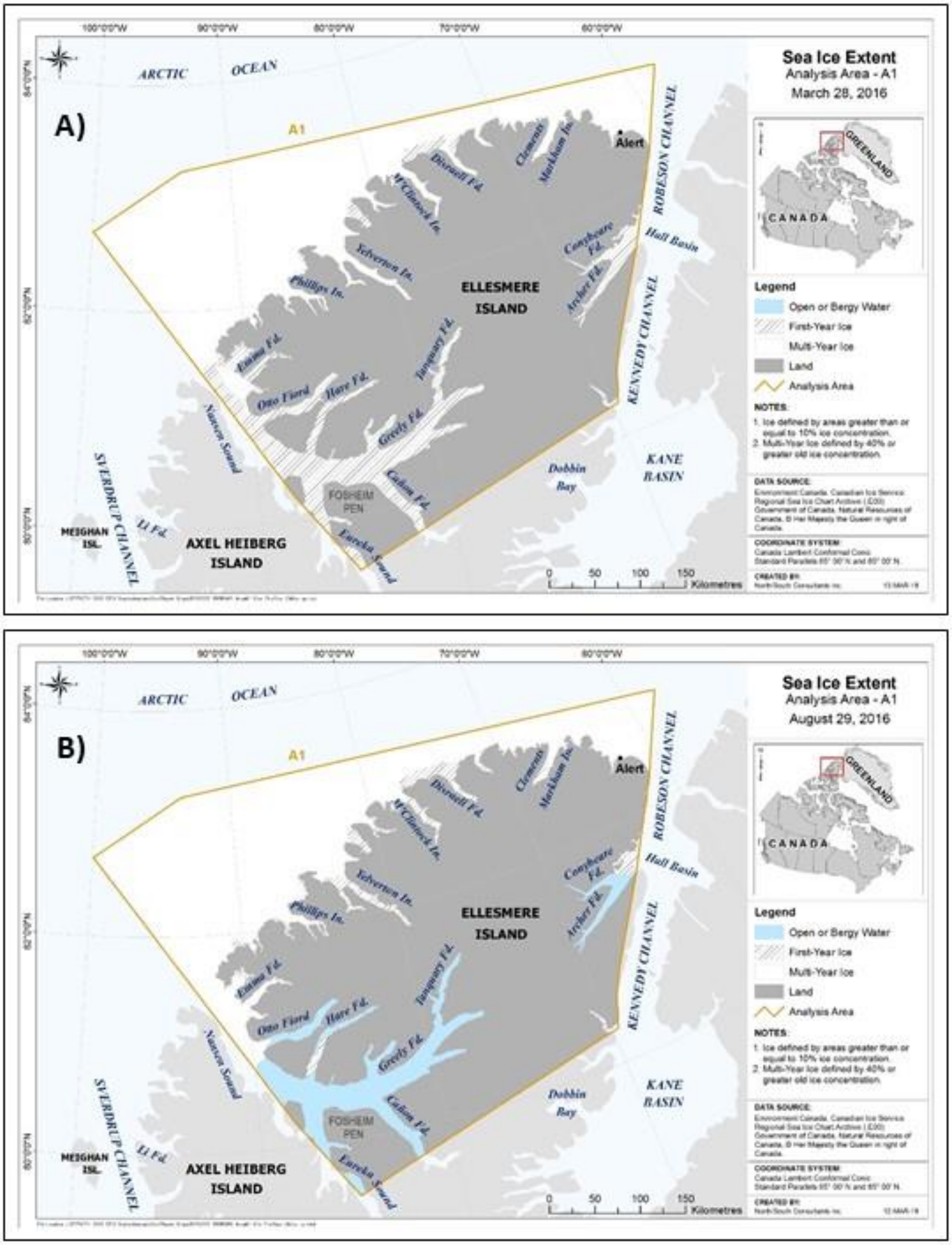


Figure 21. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2016 within region A1.

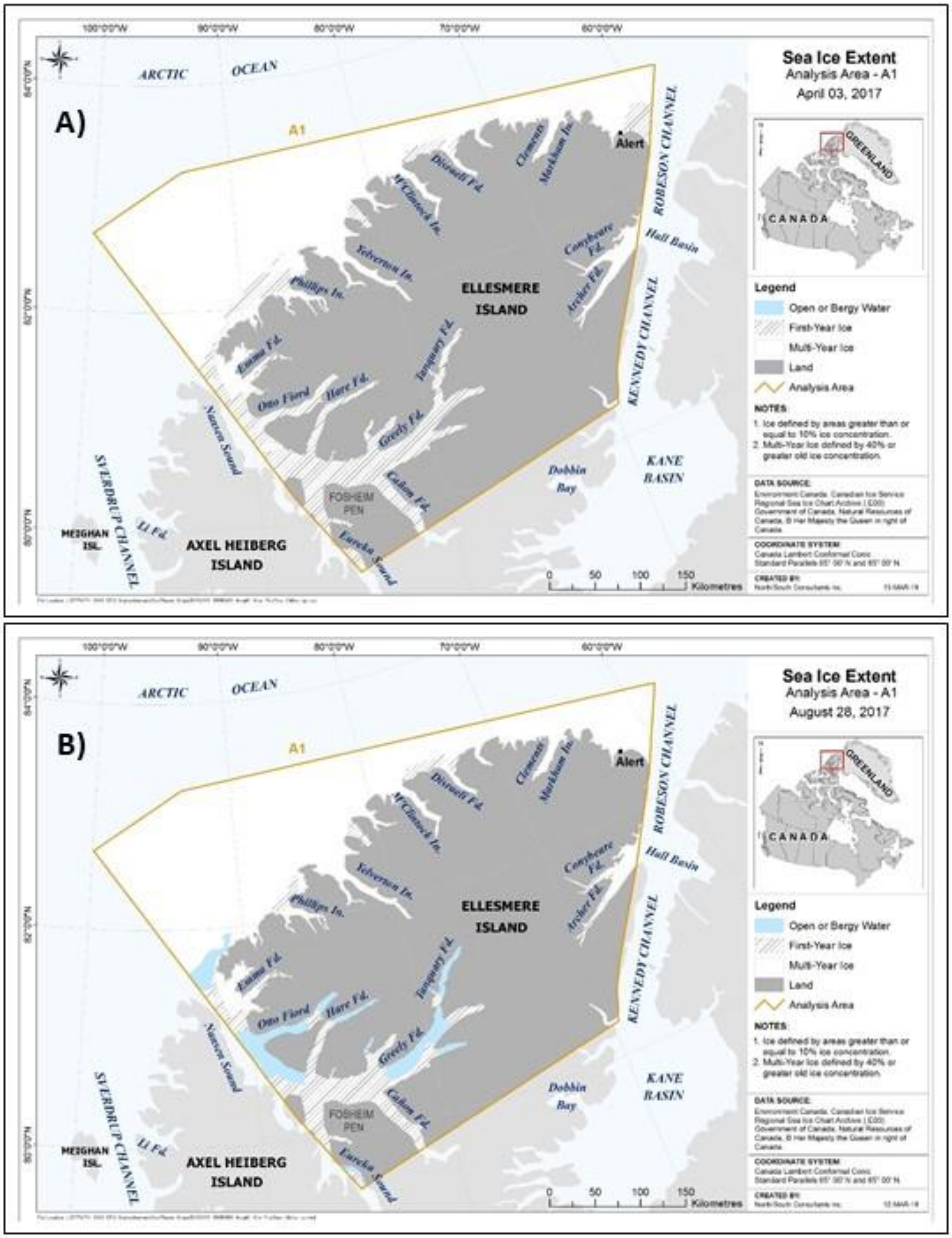


Figure 22. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2017 within region A1.

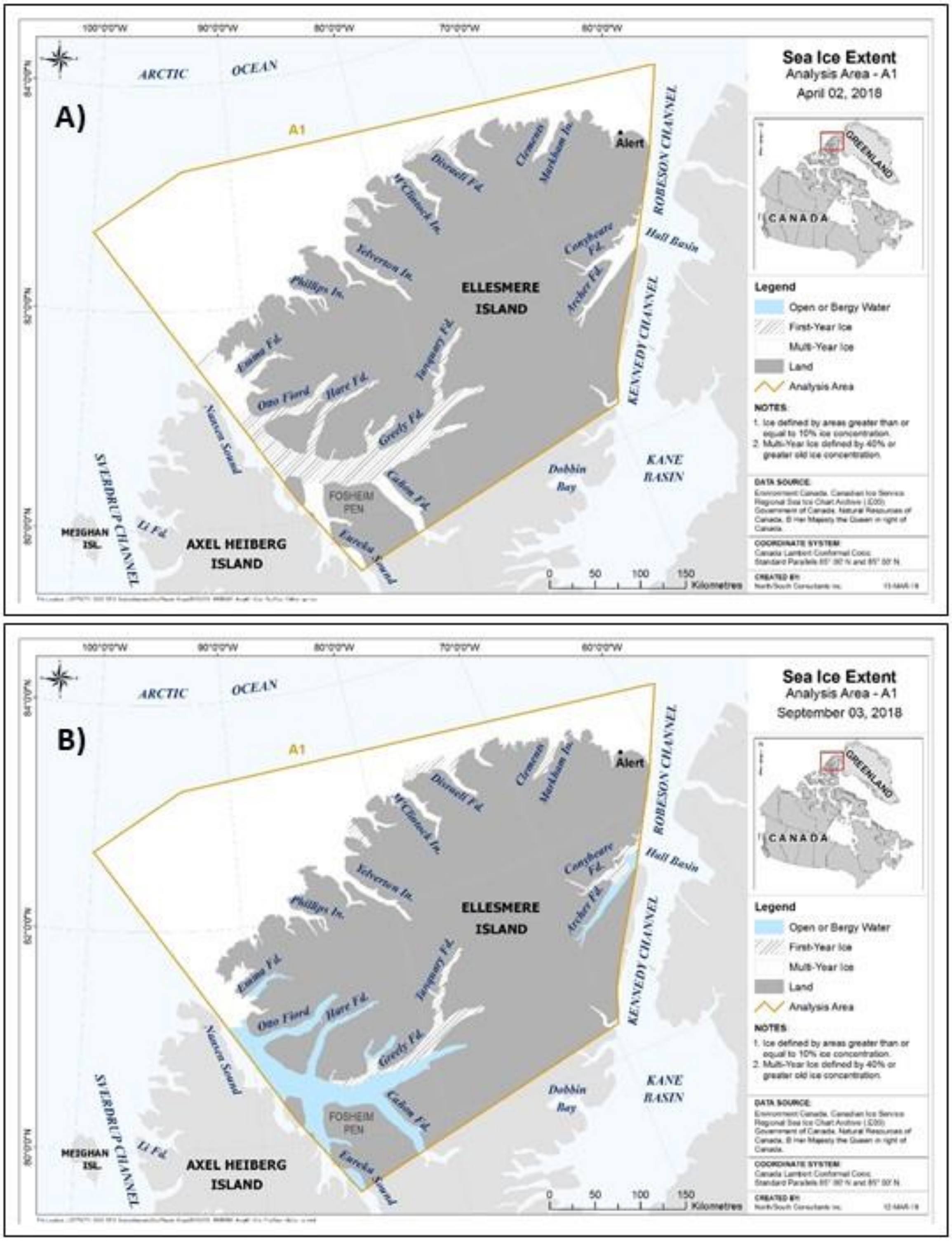


Figure 23. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2018 within region A1.

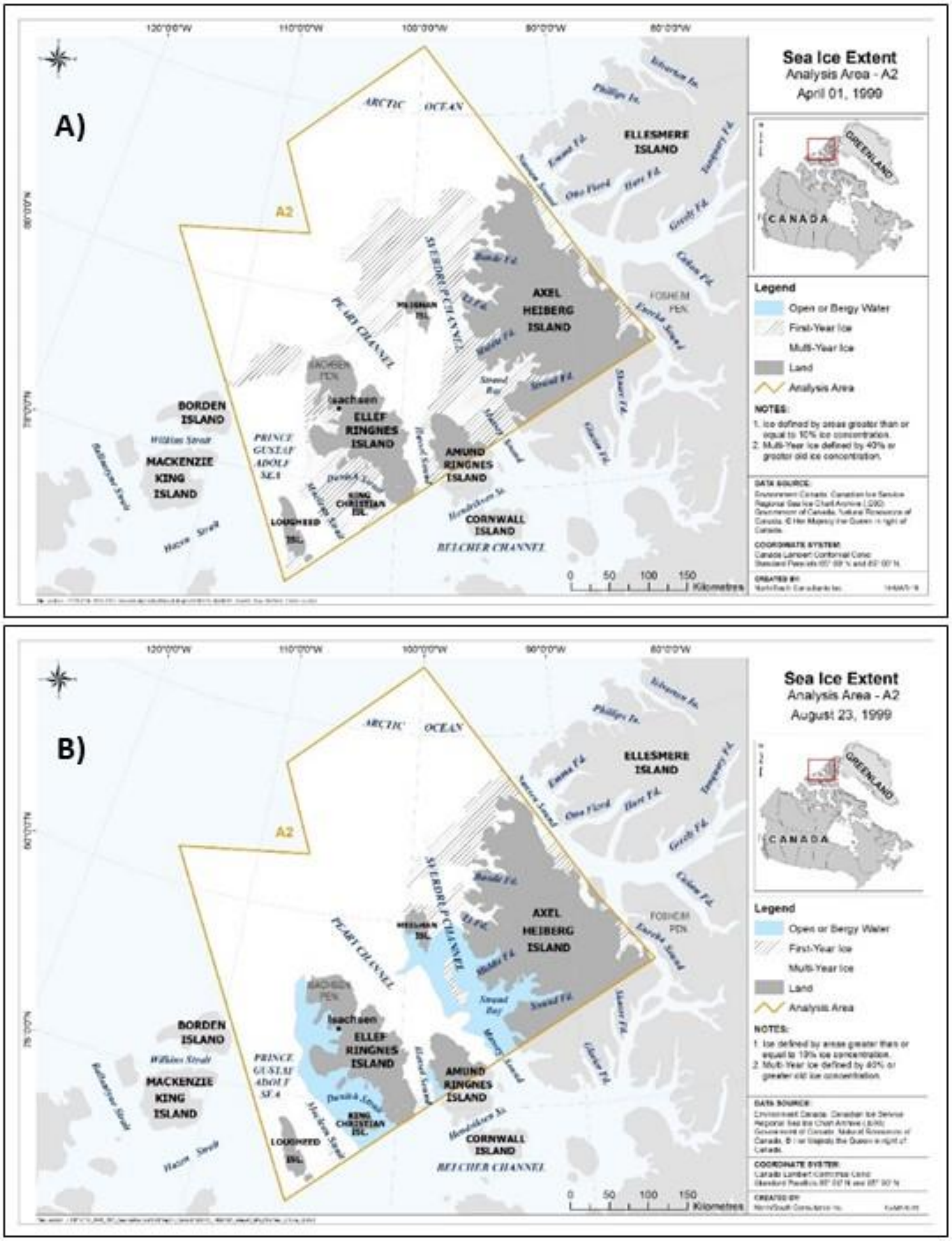


Figure 24. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 1999 within region A2.

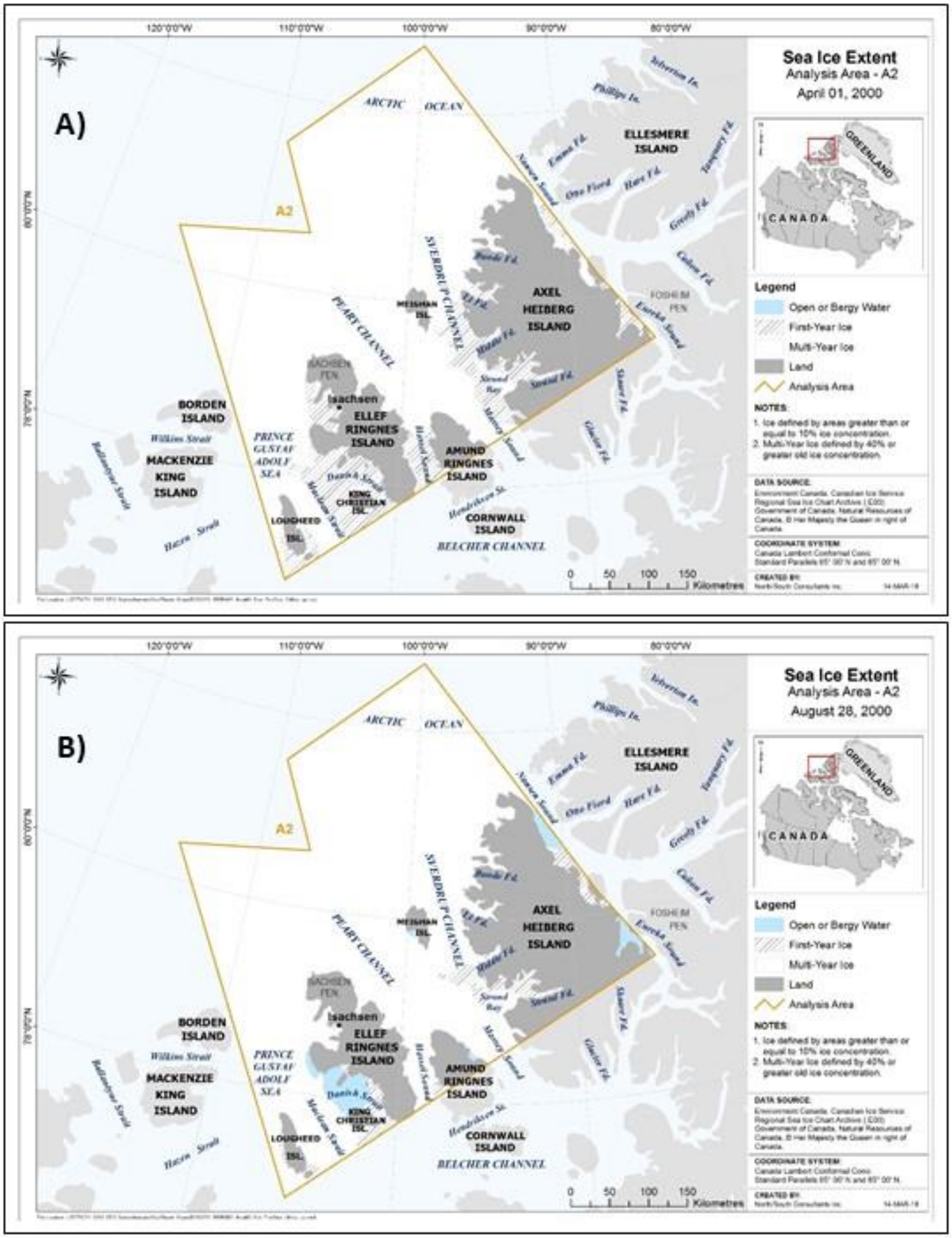


Figure 25. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2000 within region A2.

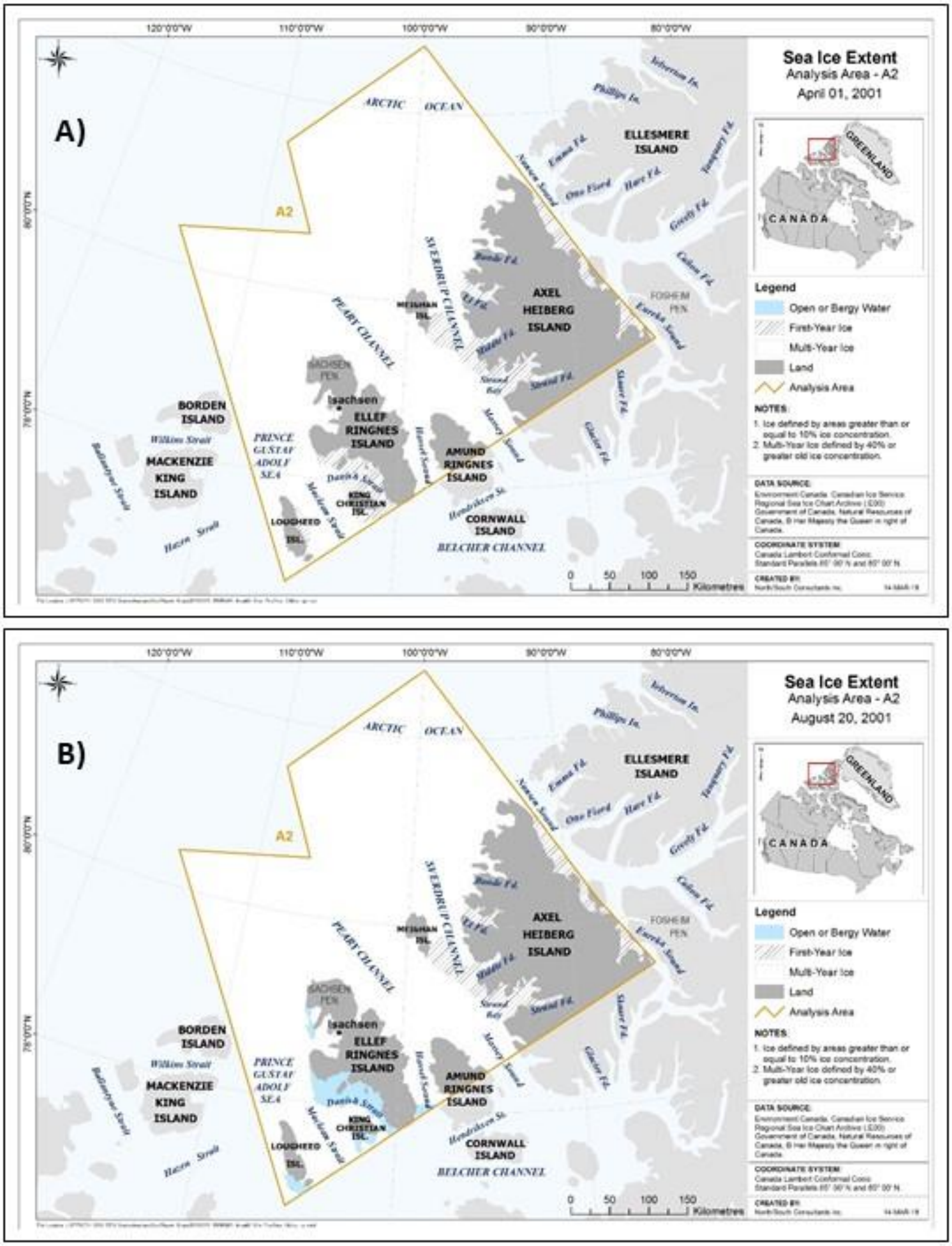


Figure 26. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2001 within region A2.

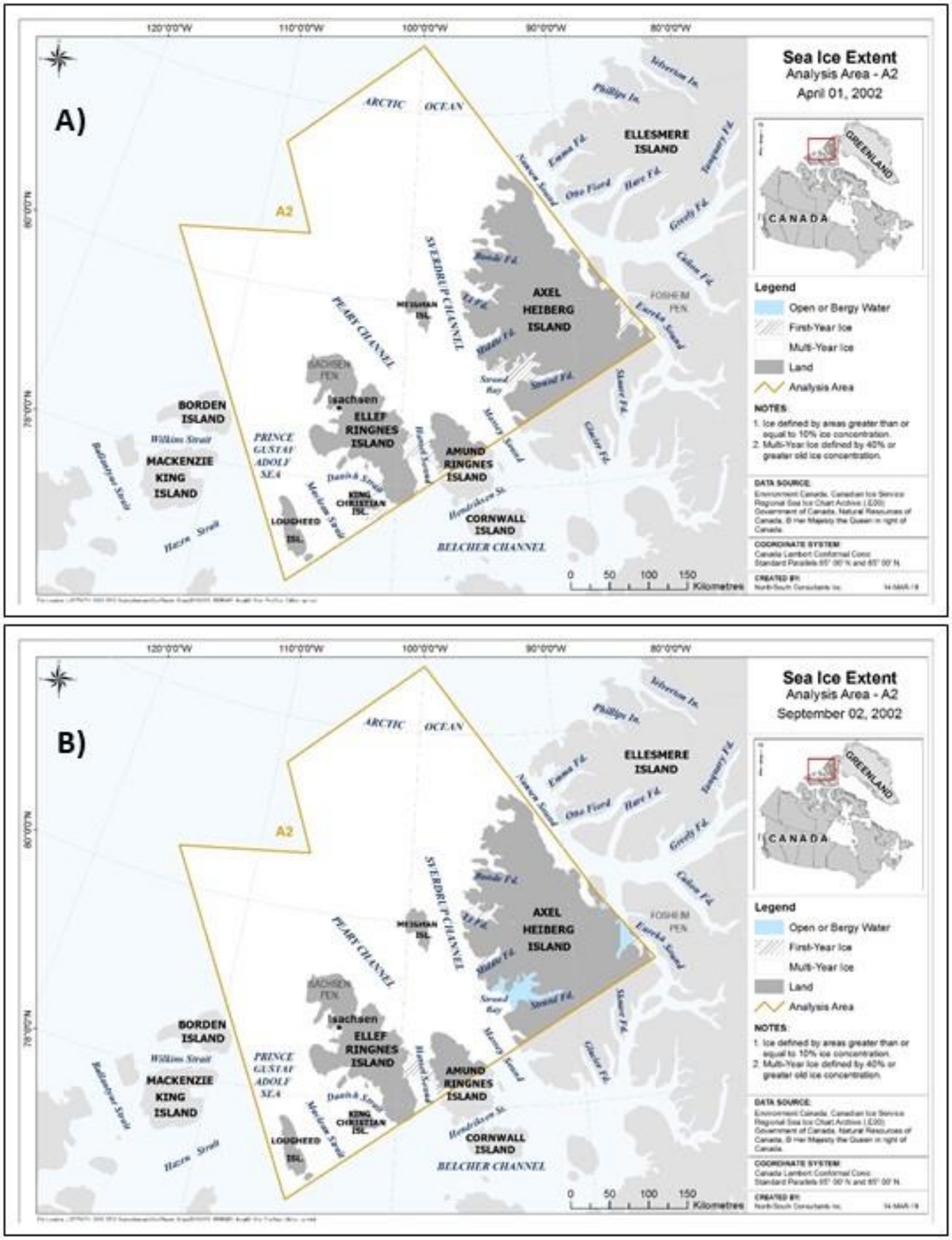


Figure 27. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2002 within region A2.

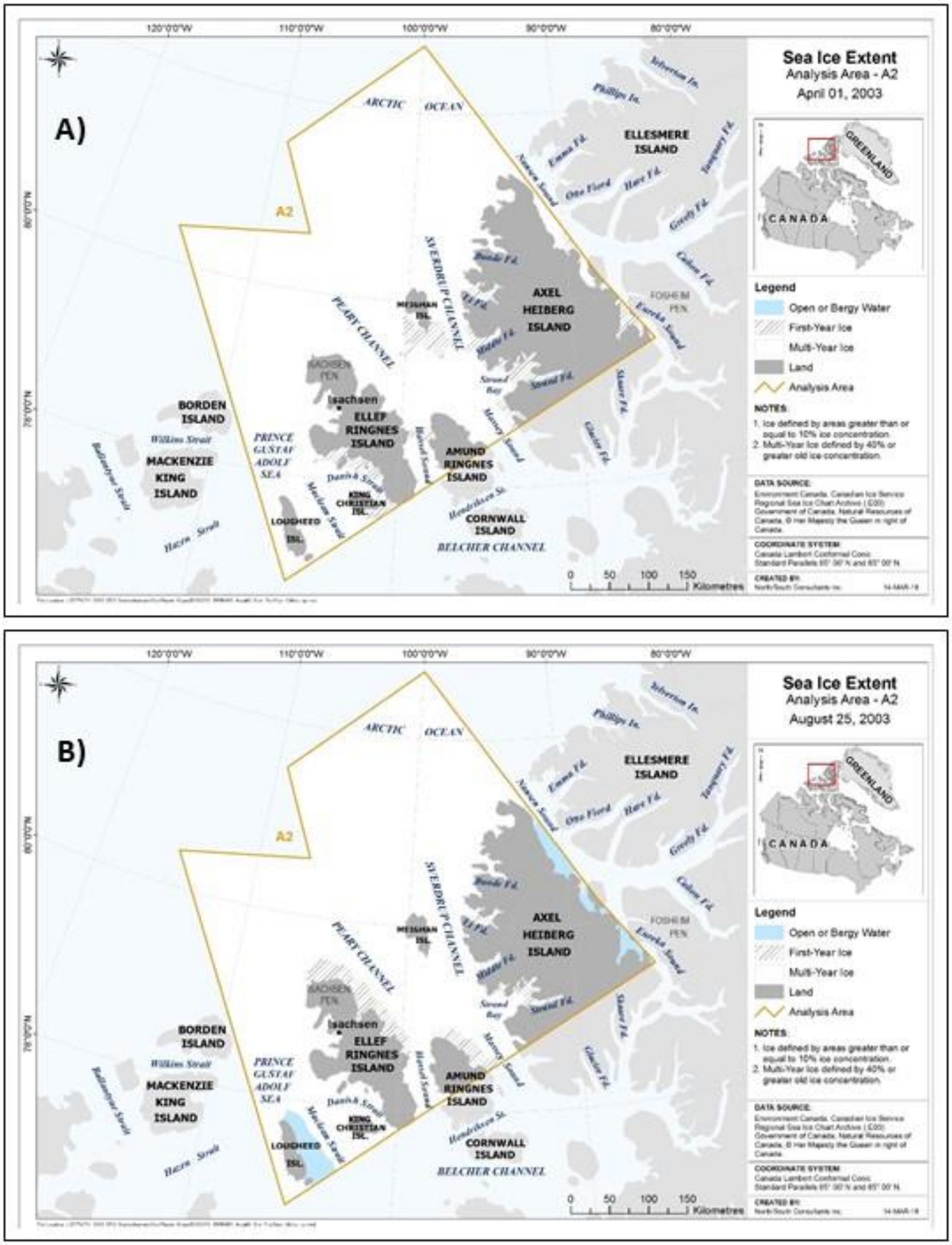


Figure 28. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2003 within region A2.

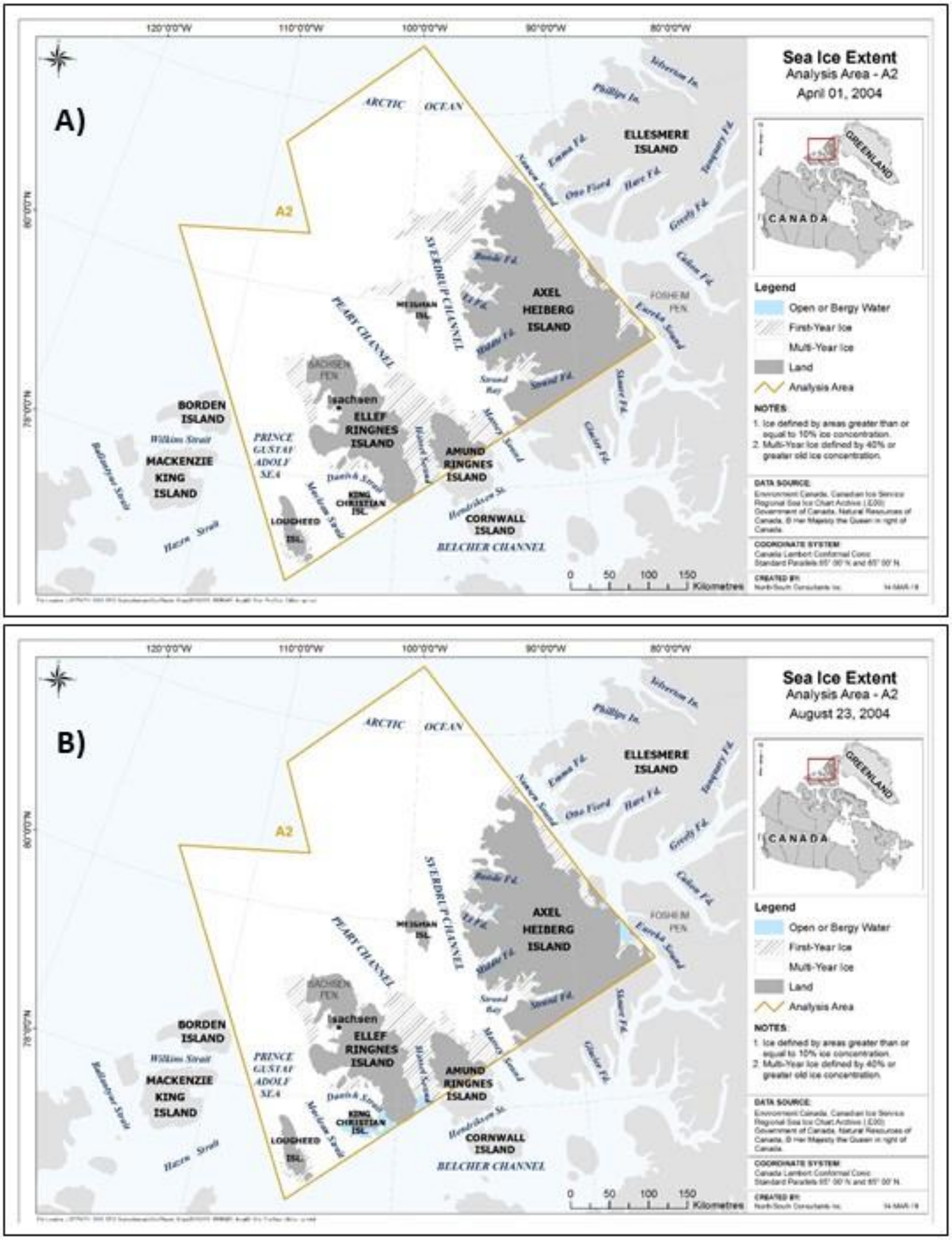


Figure 29. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2004 within region A2.

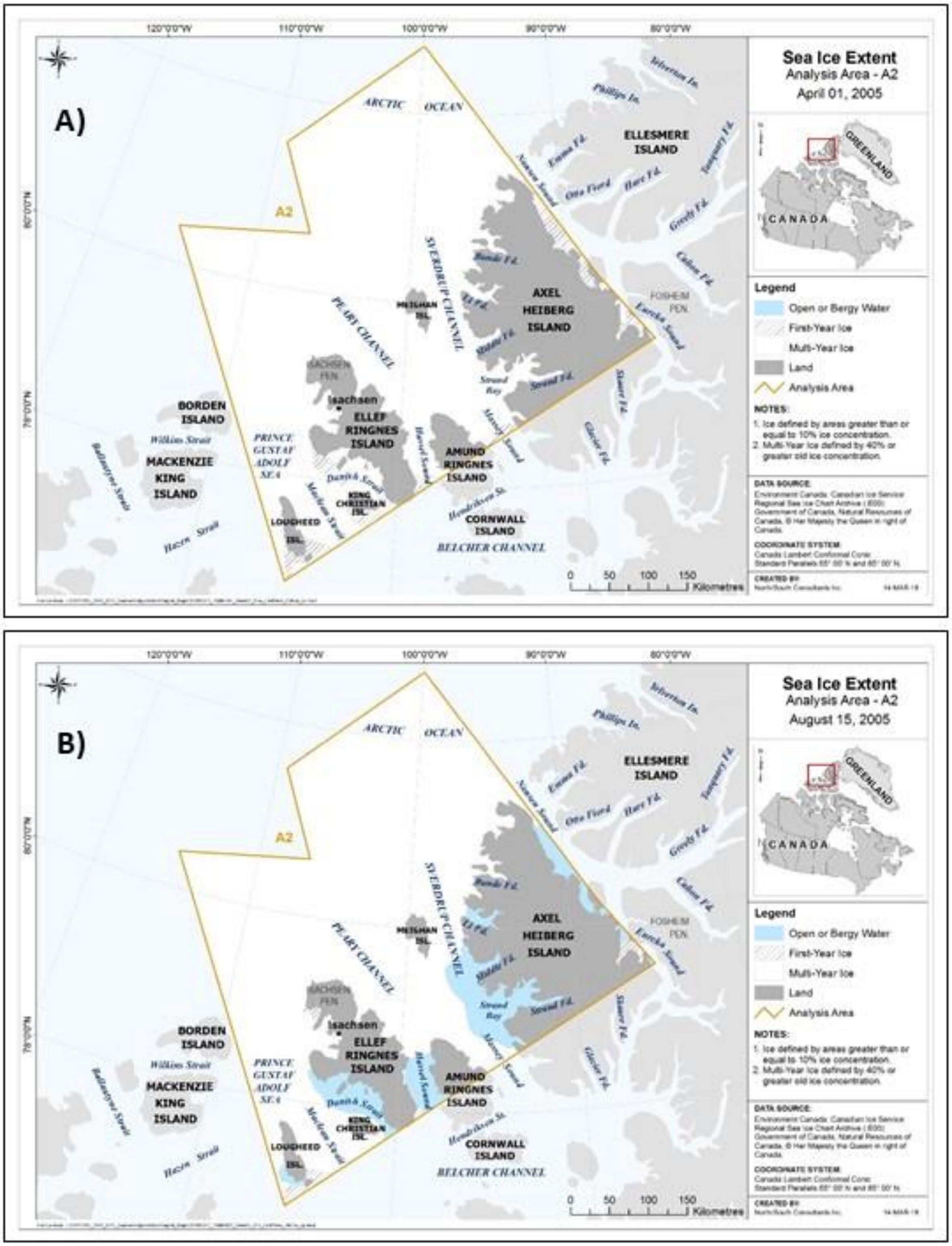


Figure 30. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2005 within region A2.

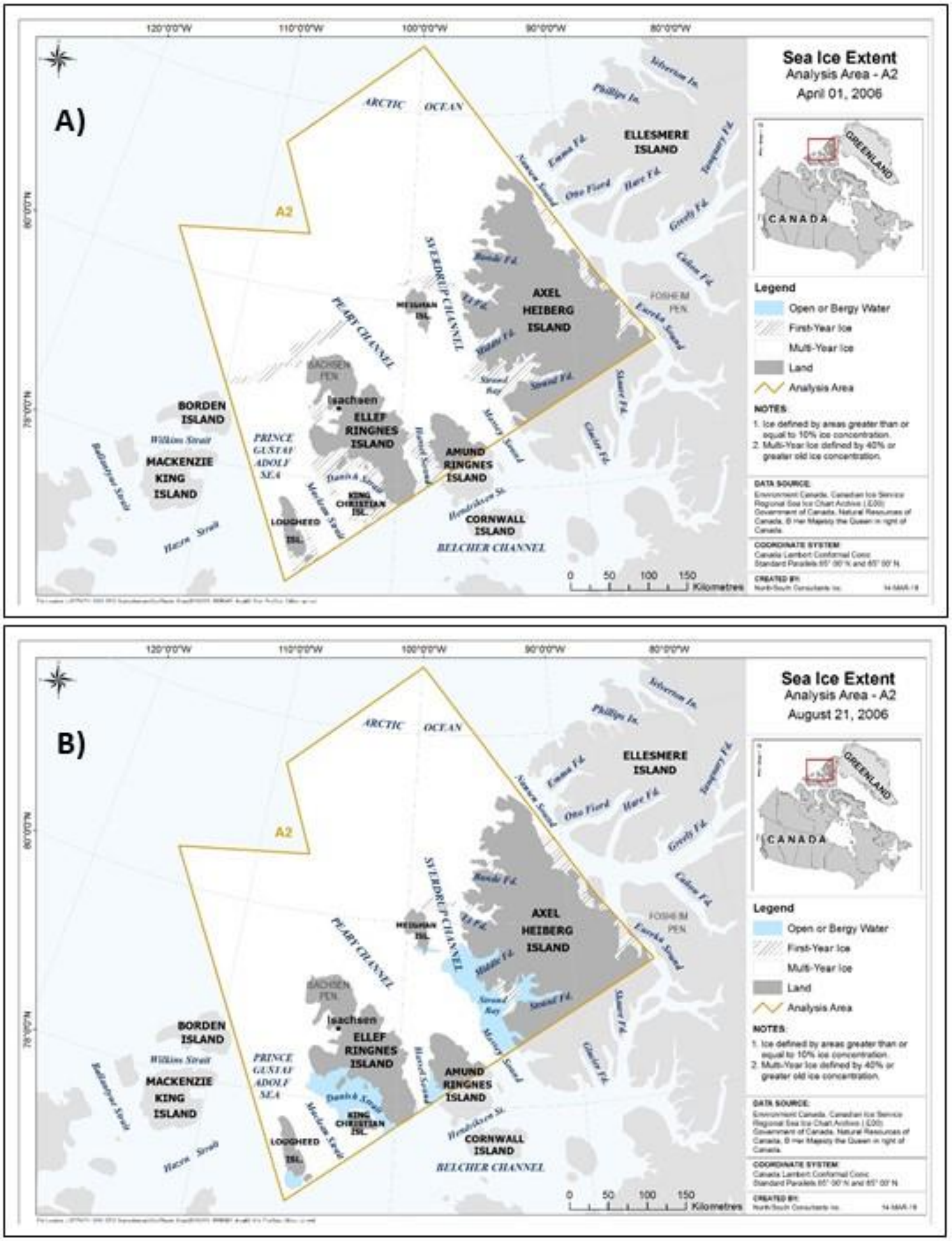


Figure 31. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2006 within region A2.

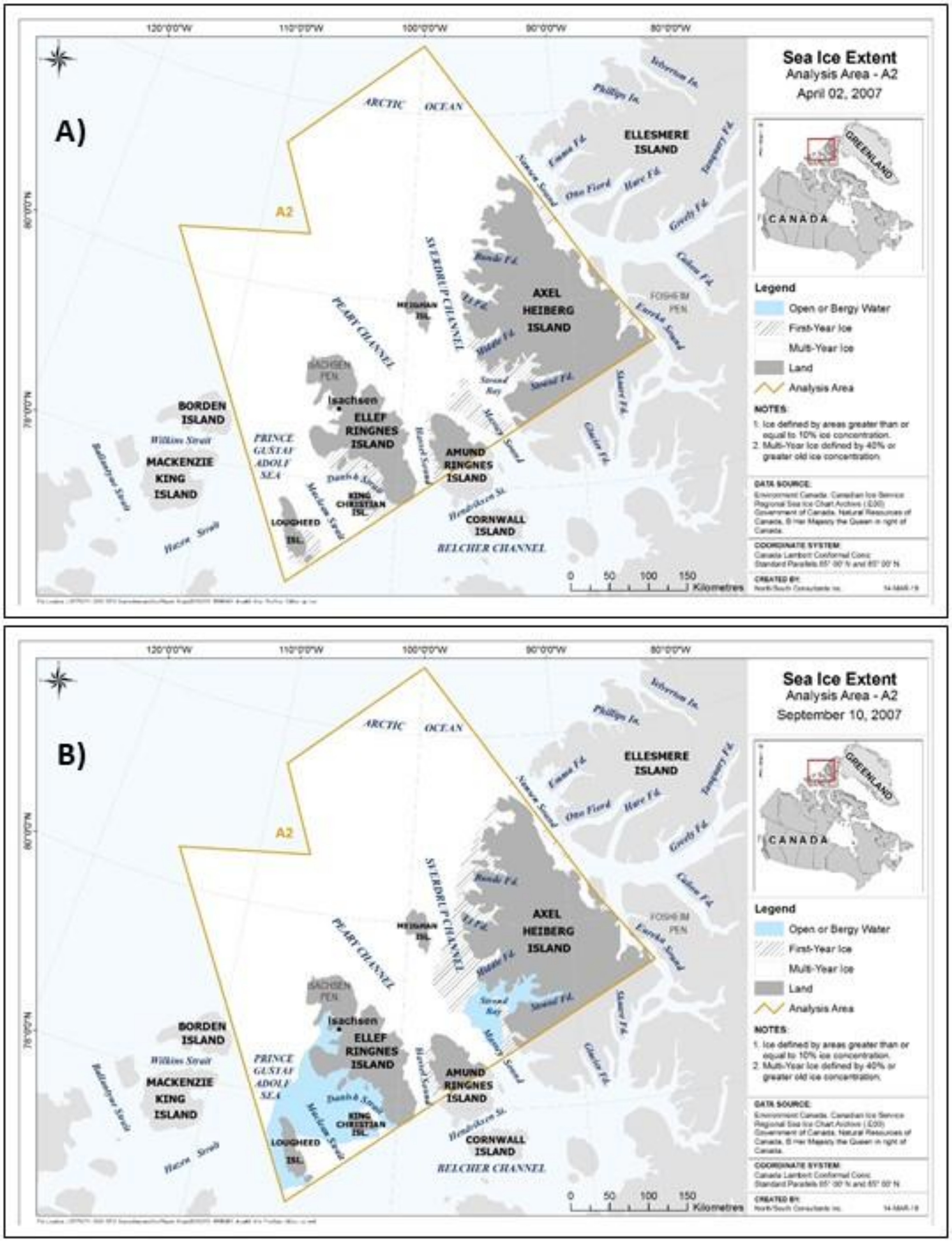


Figure 32. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2007 within region A2.

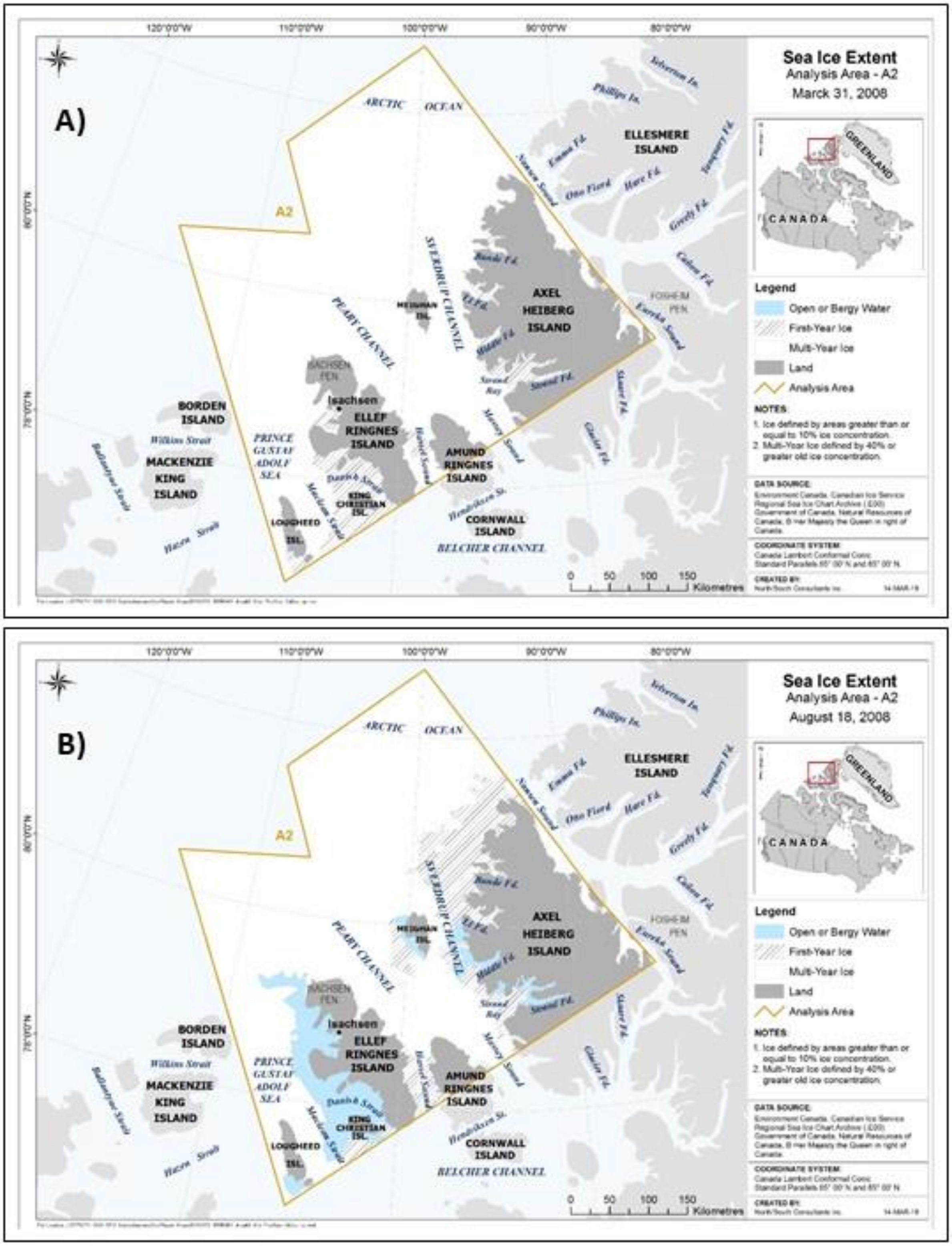


Figure 33. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2008 within region A2.

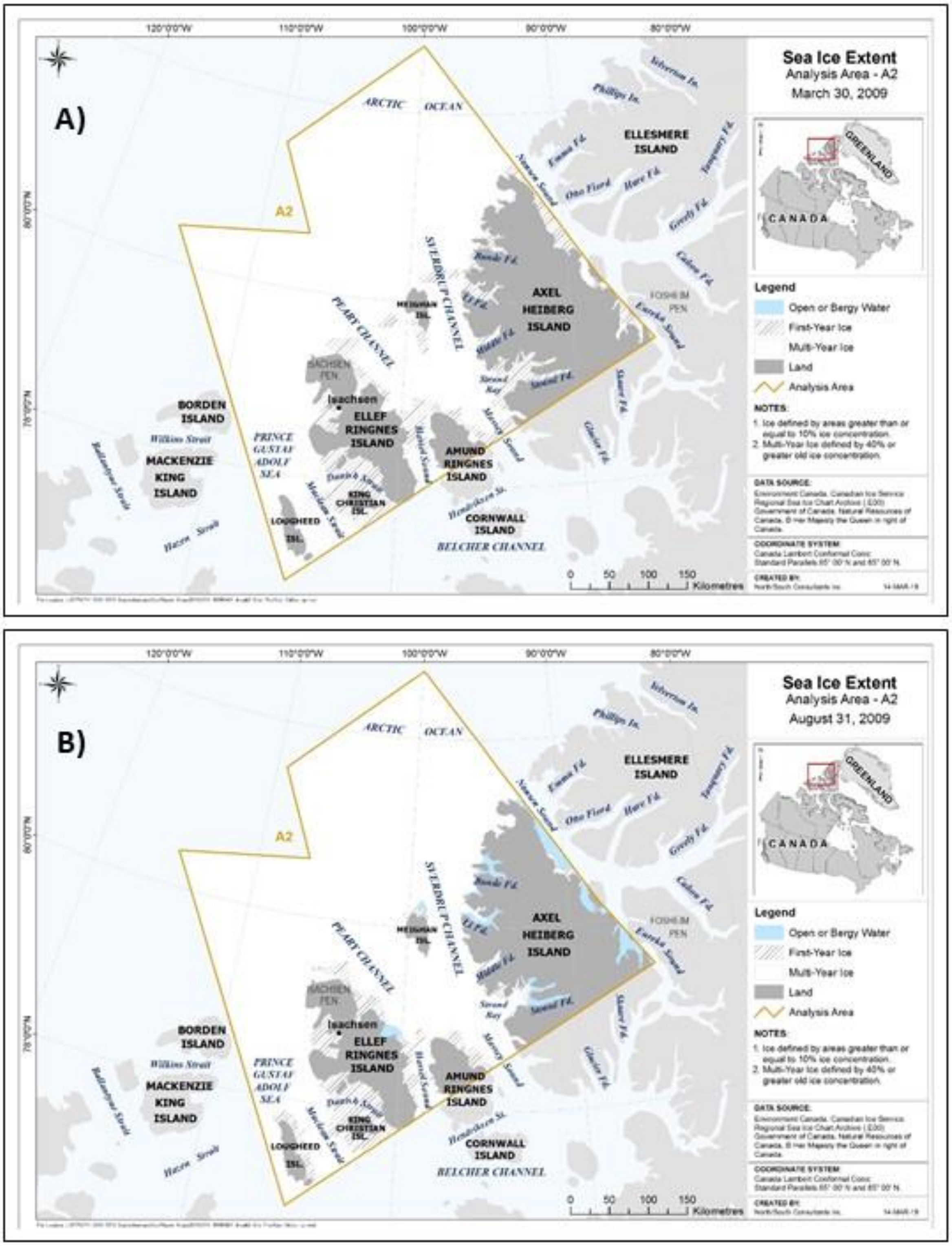


Figure 34. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2009 within region A2.

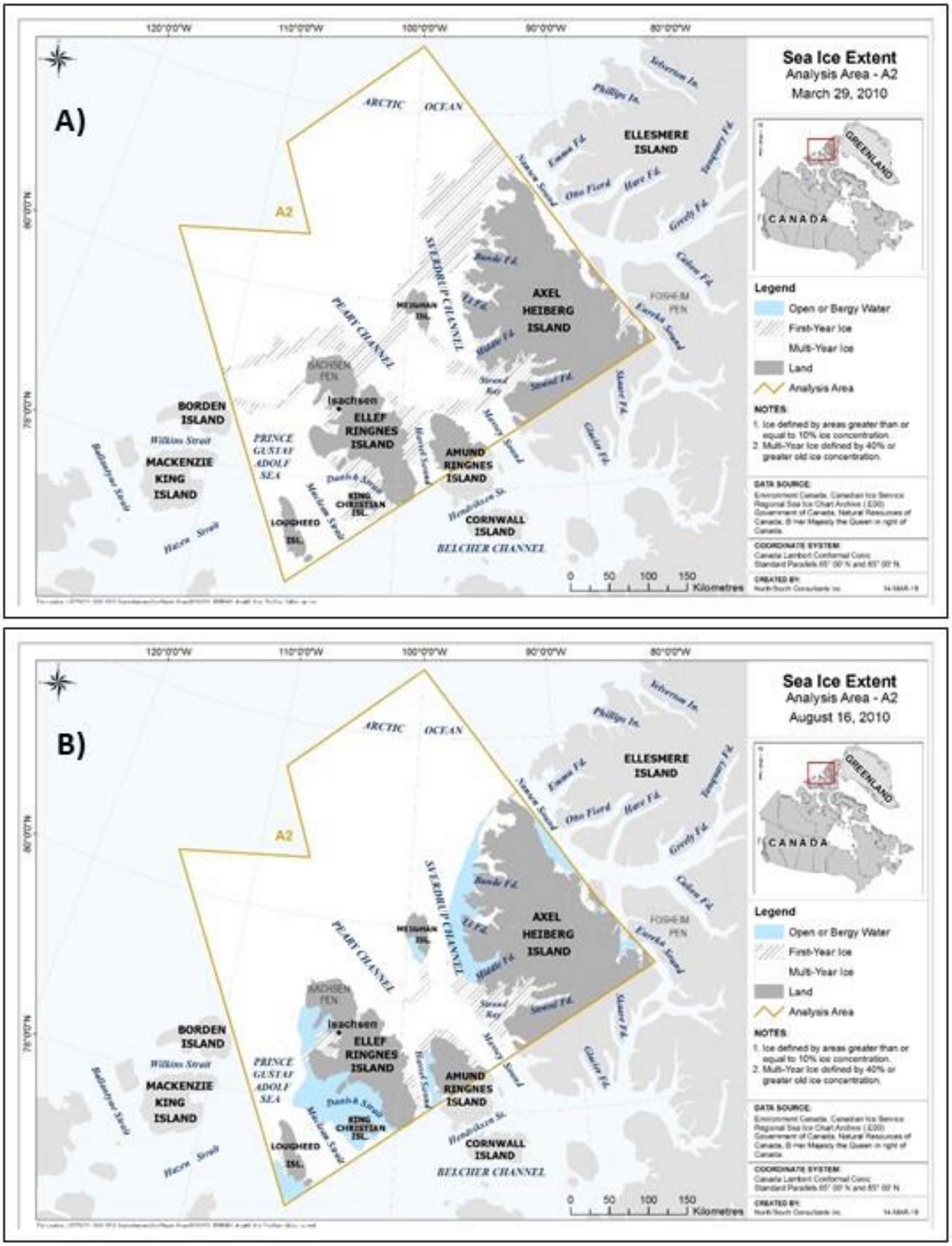


Figure 35. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2010 within region A2.

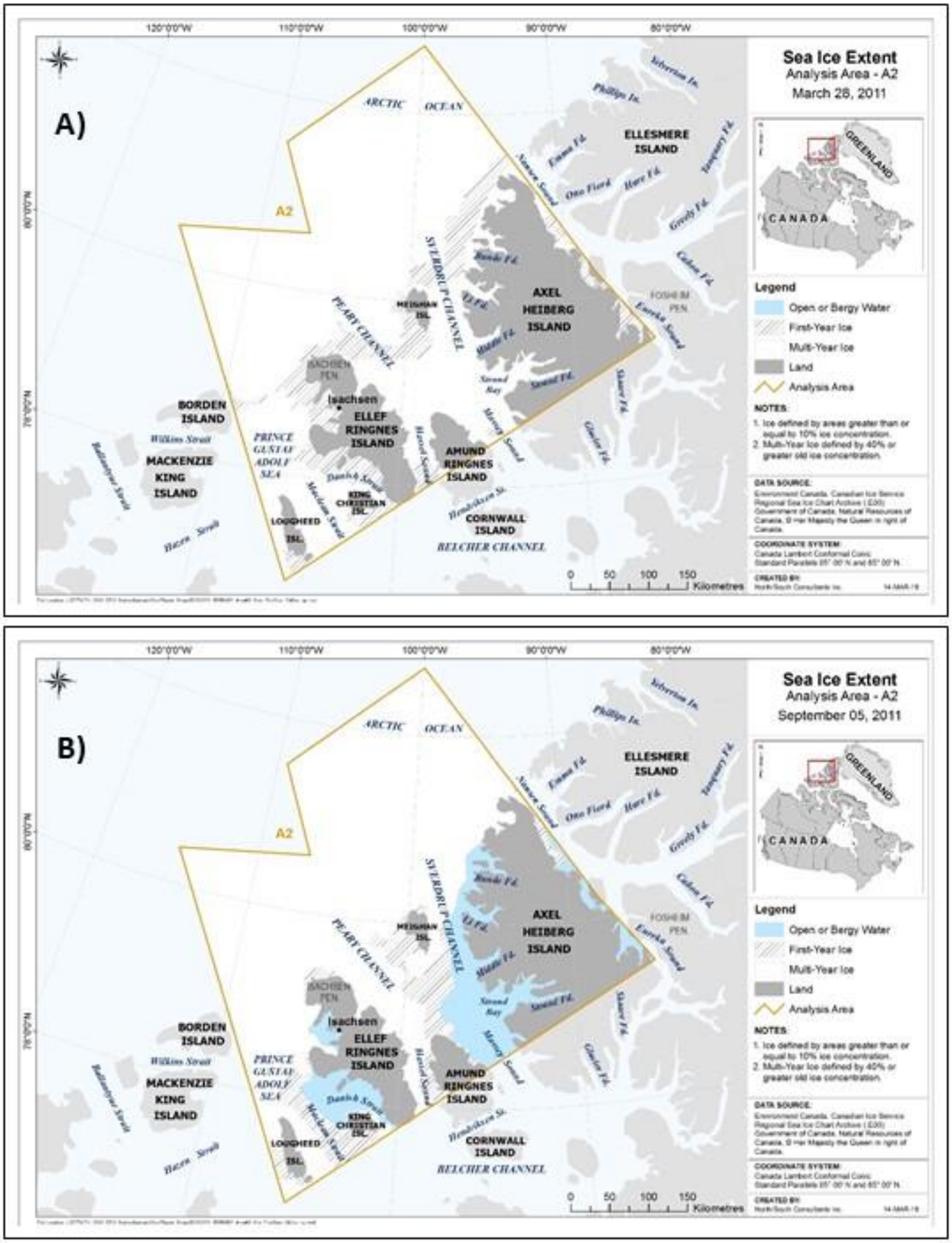


Figure 36. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2011 within region A2.

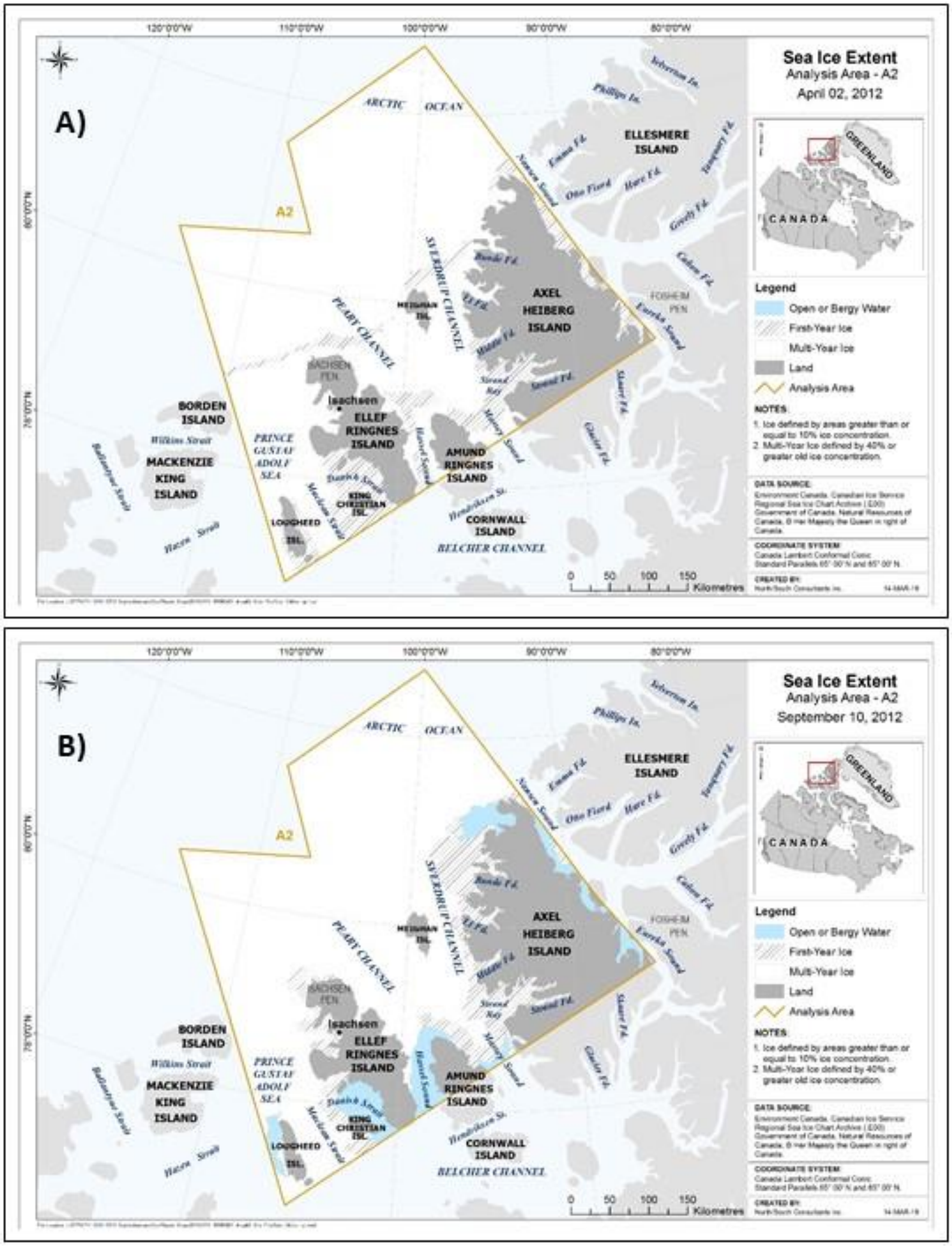


Figure 37. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2012 within region A2.

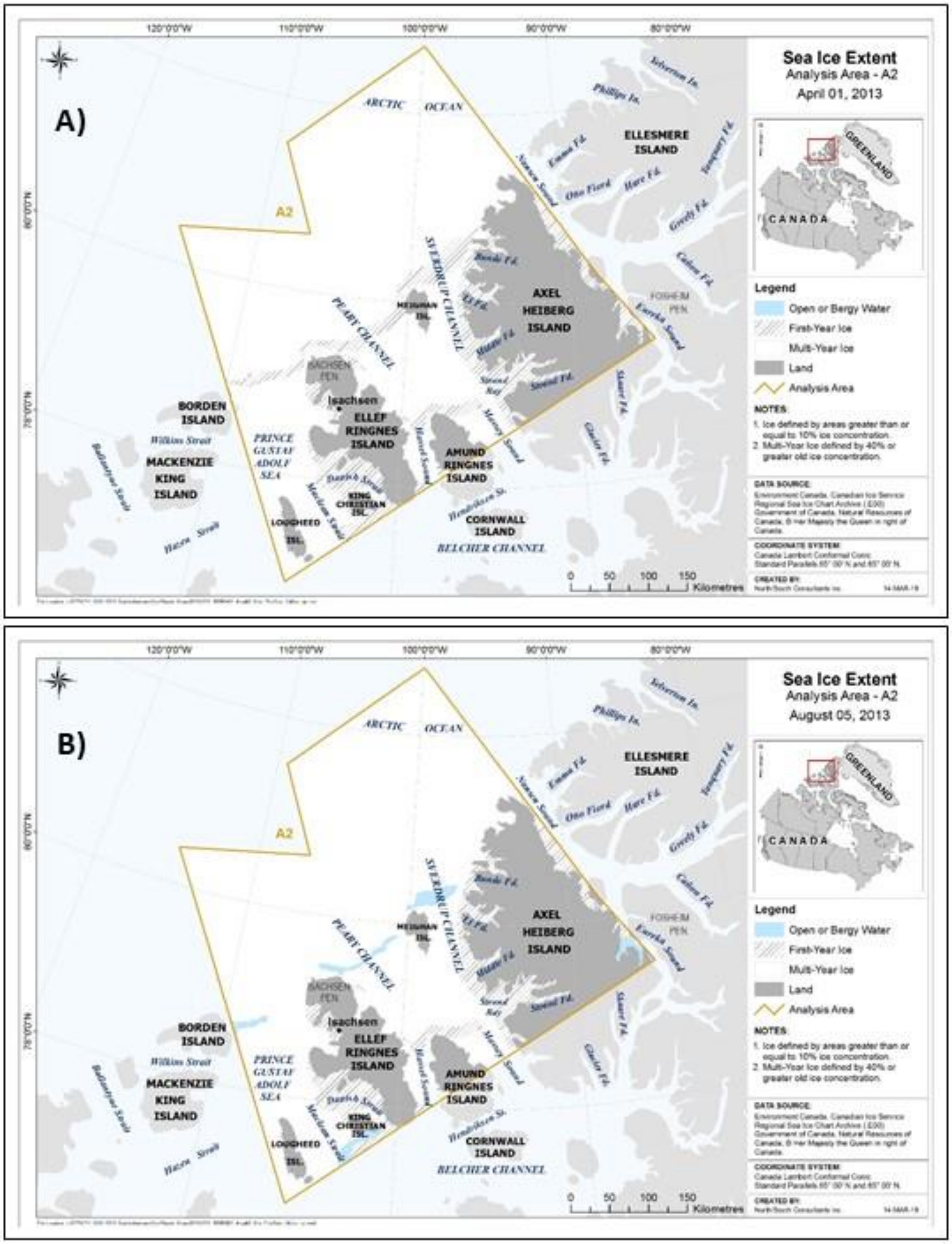


Figure 38. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2013 within region A2.

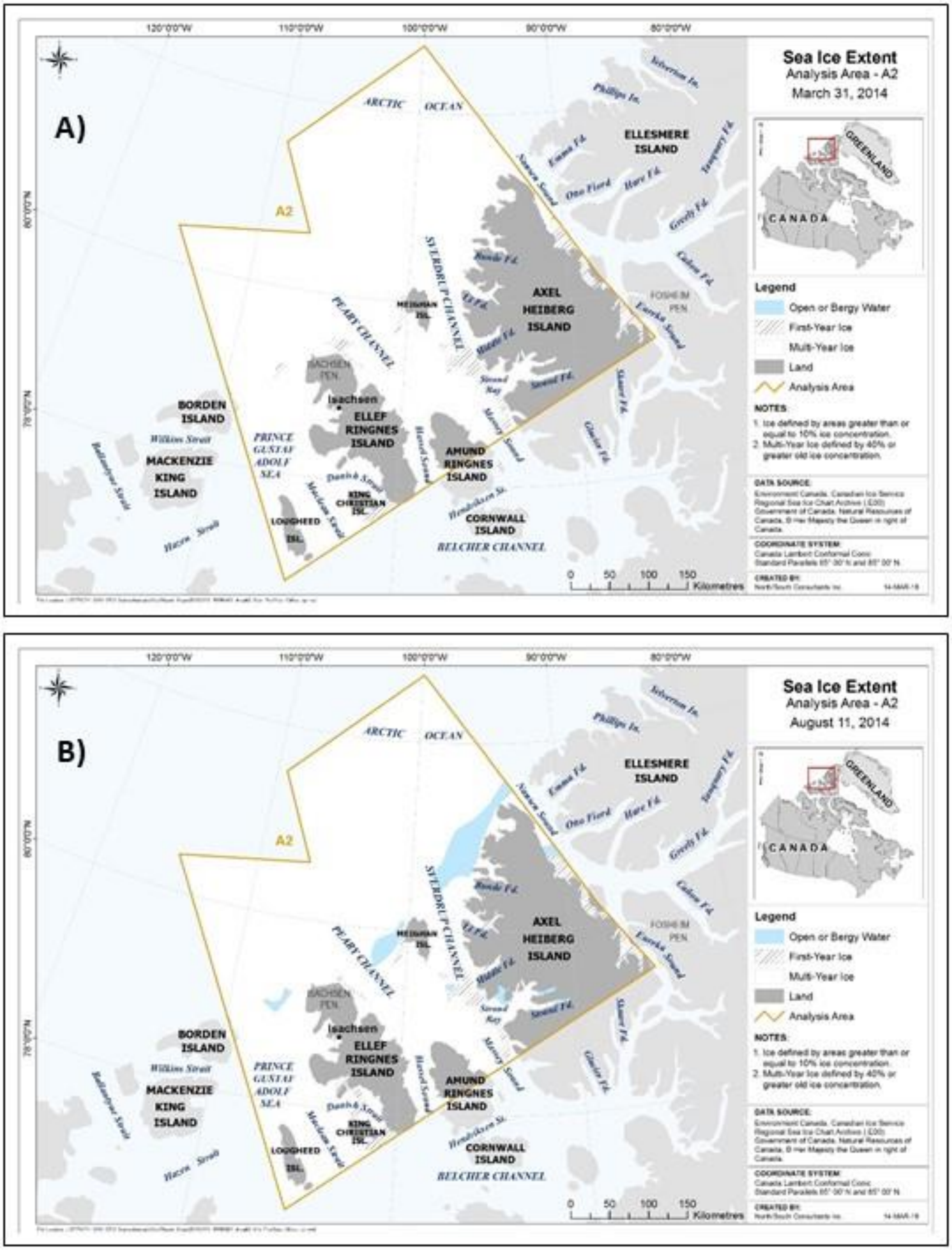


Figure 39. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2014 within region A2.

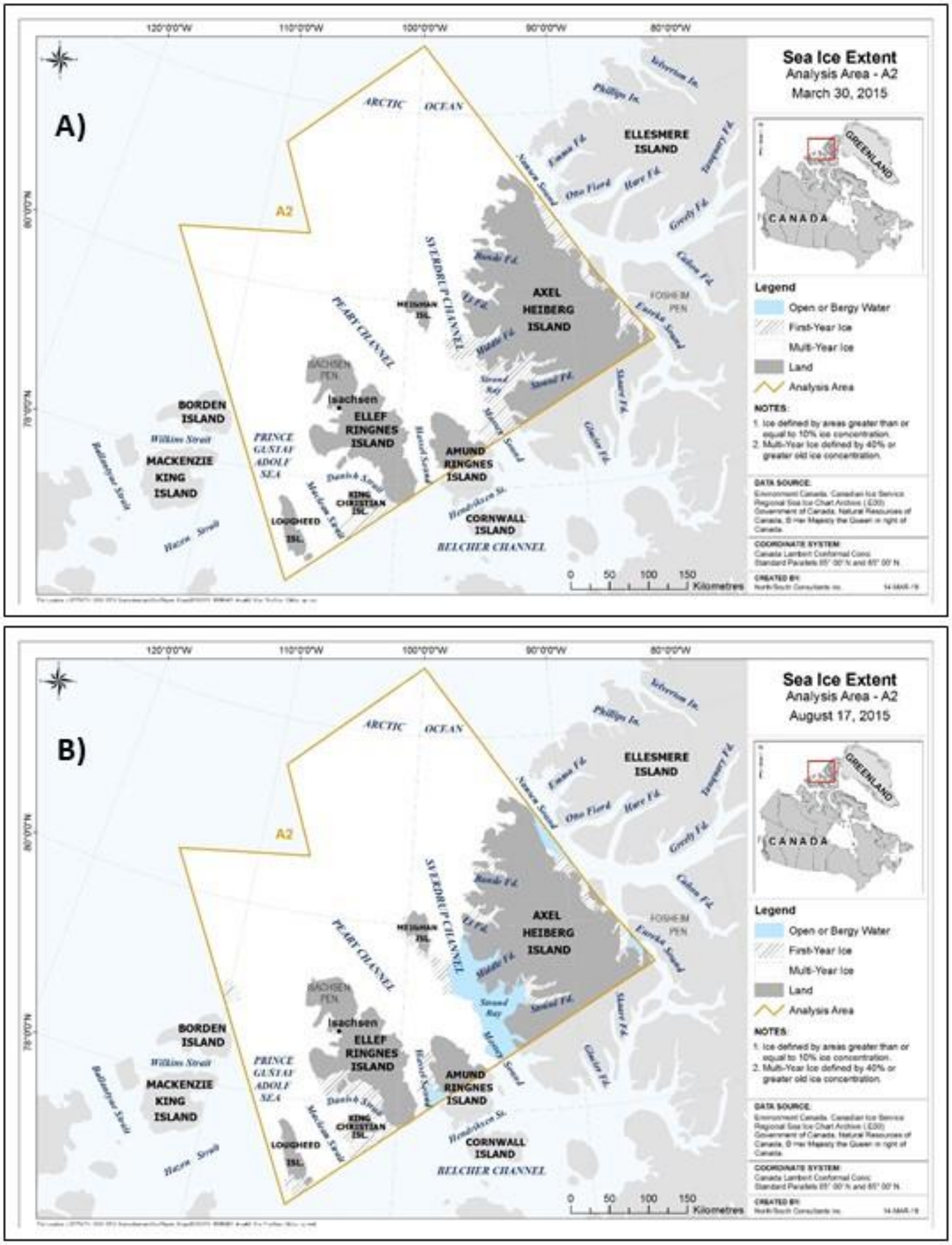


Figure 40. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2015 within region A2.

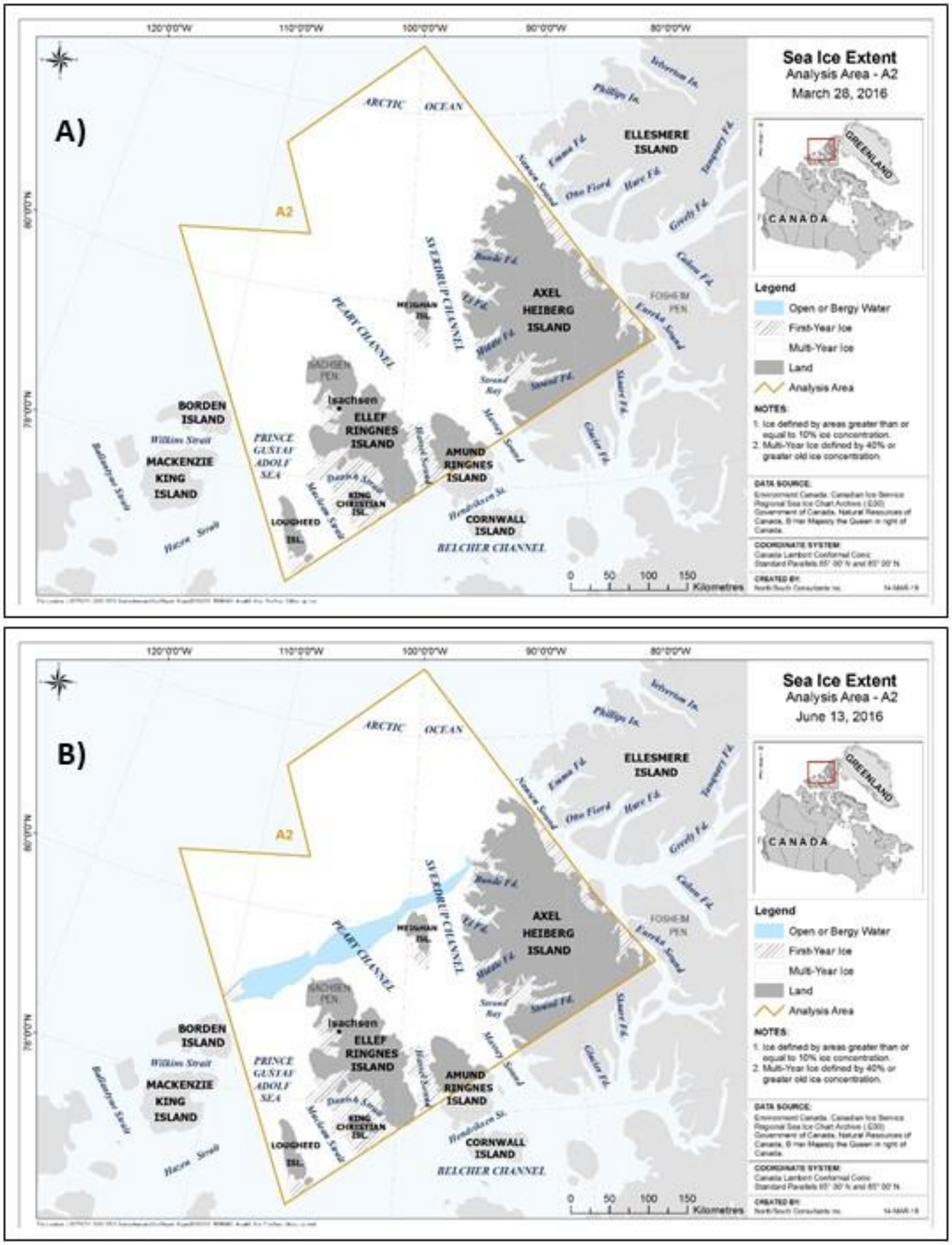


Figure 41. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2016 within region A2.

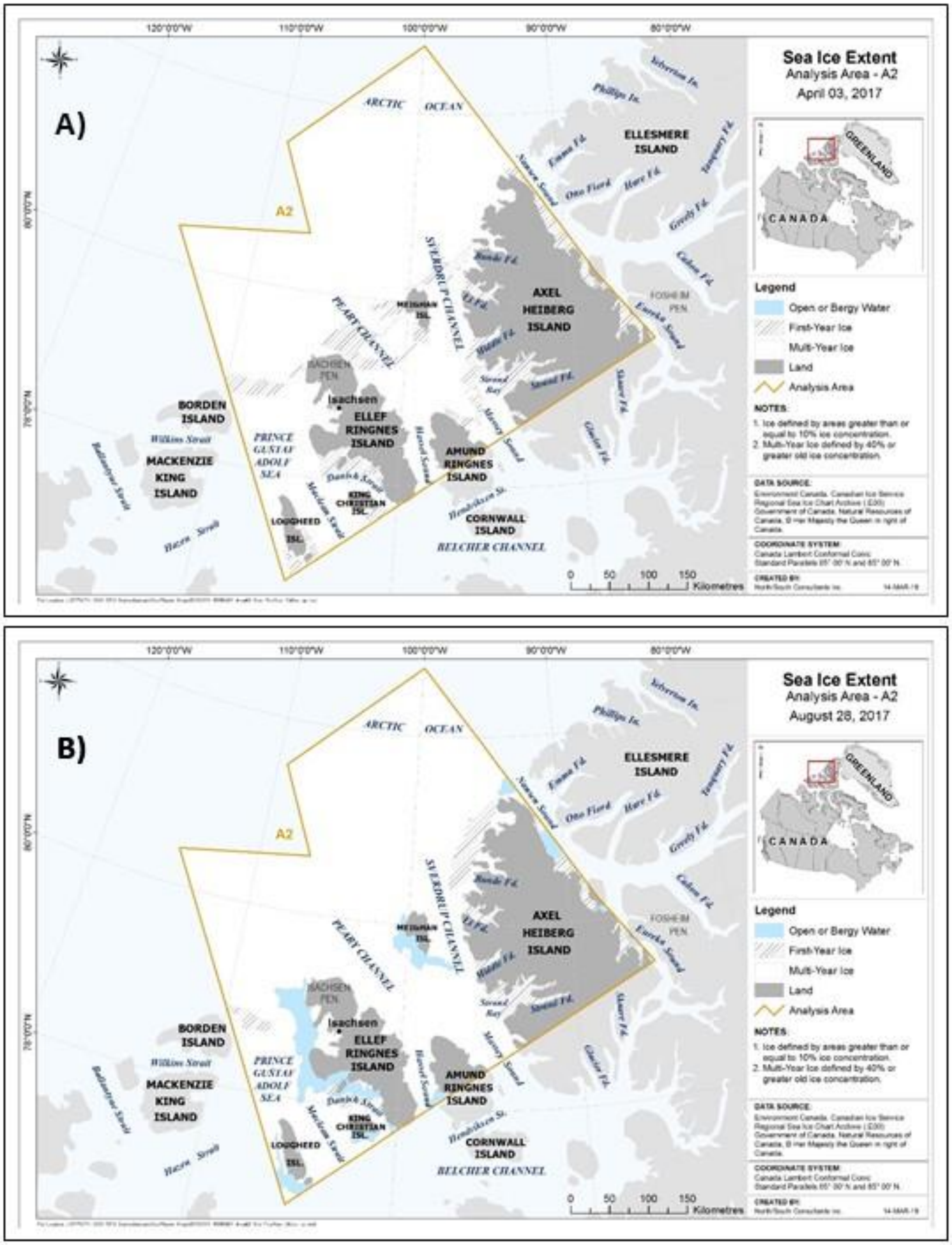


Figure 42. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2017 within region A2.

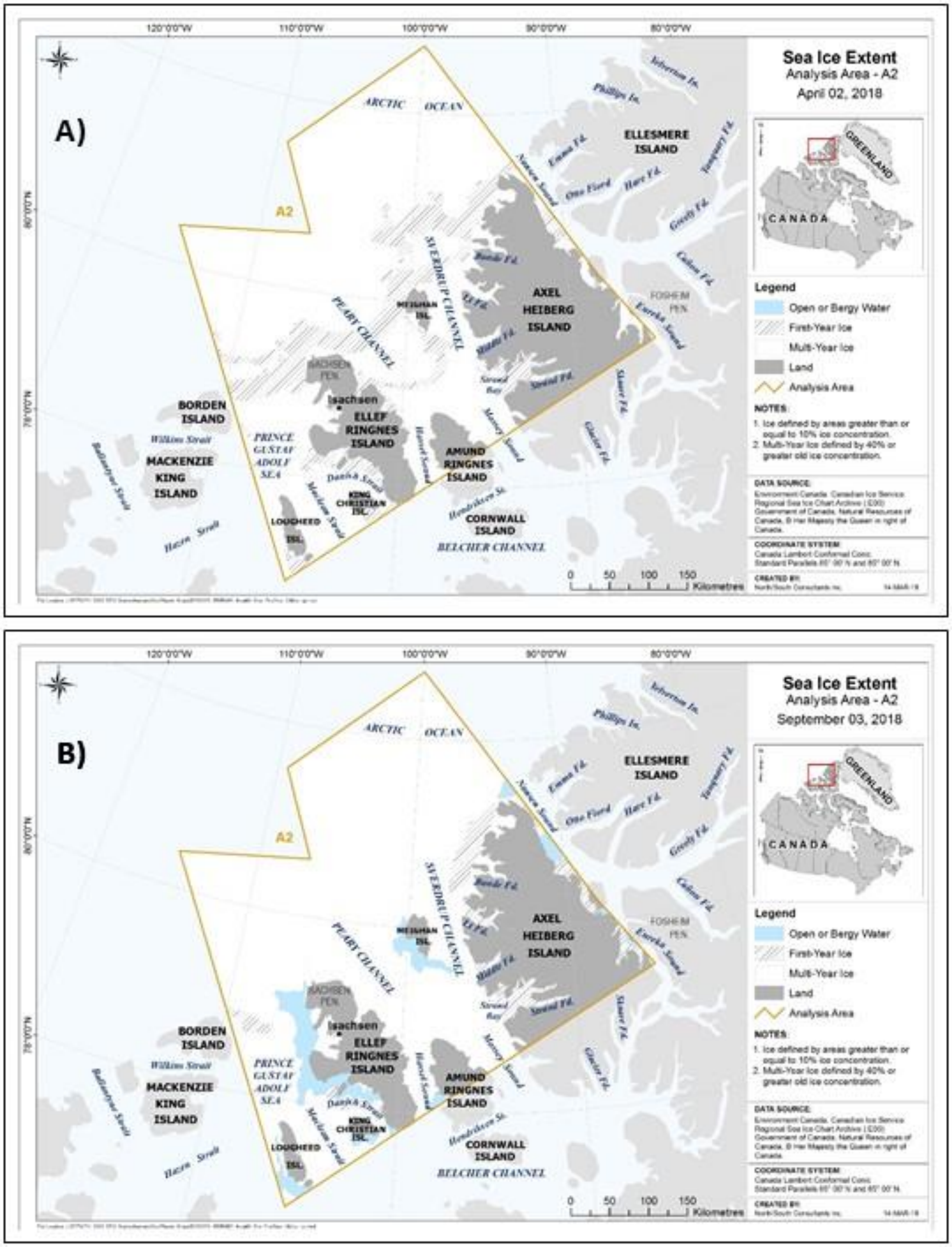
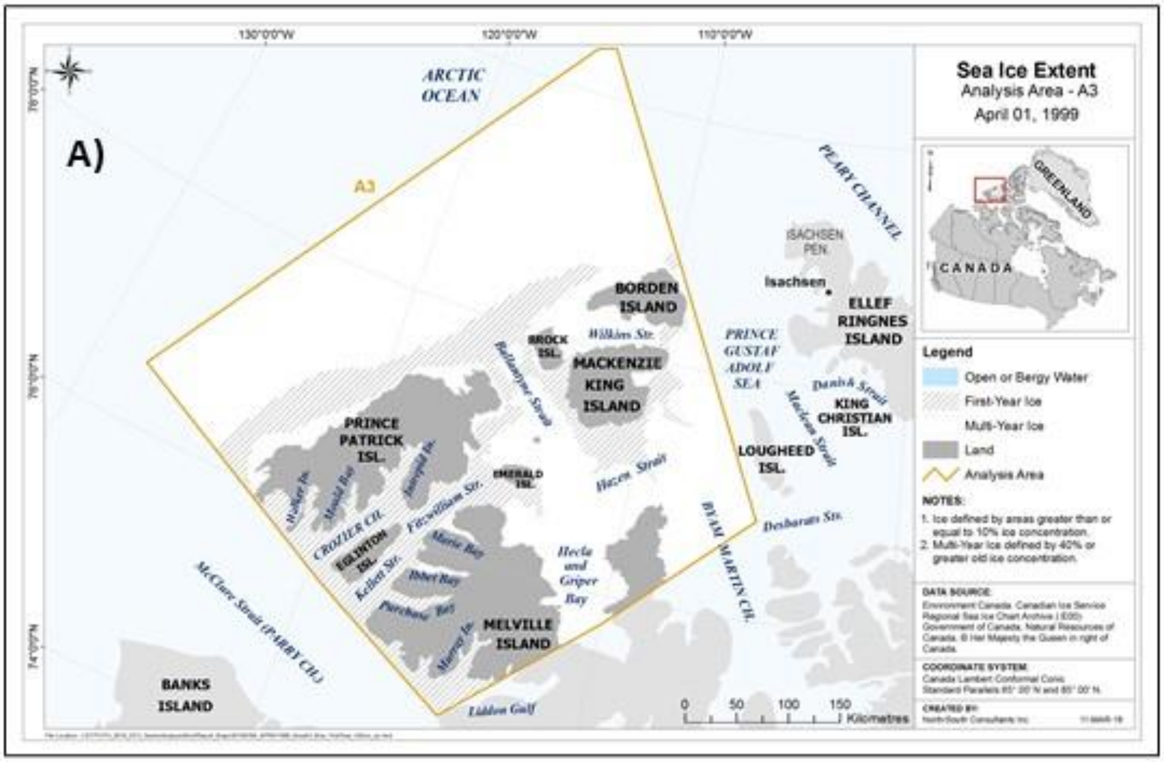


Figure 43. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2018 within region A2.



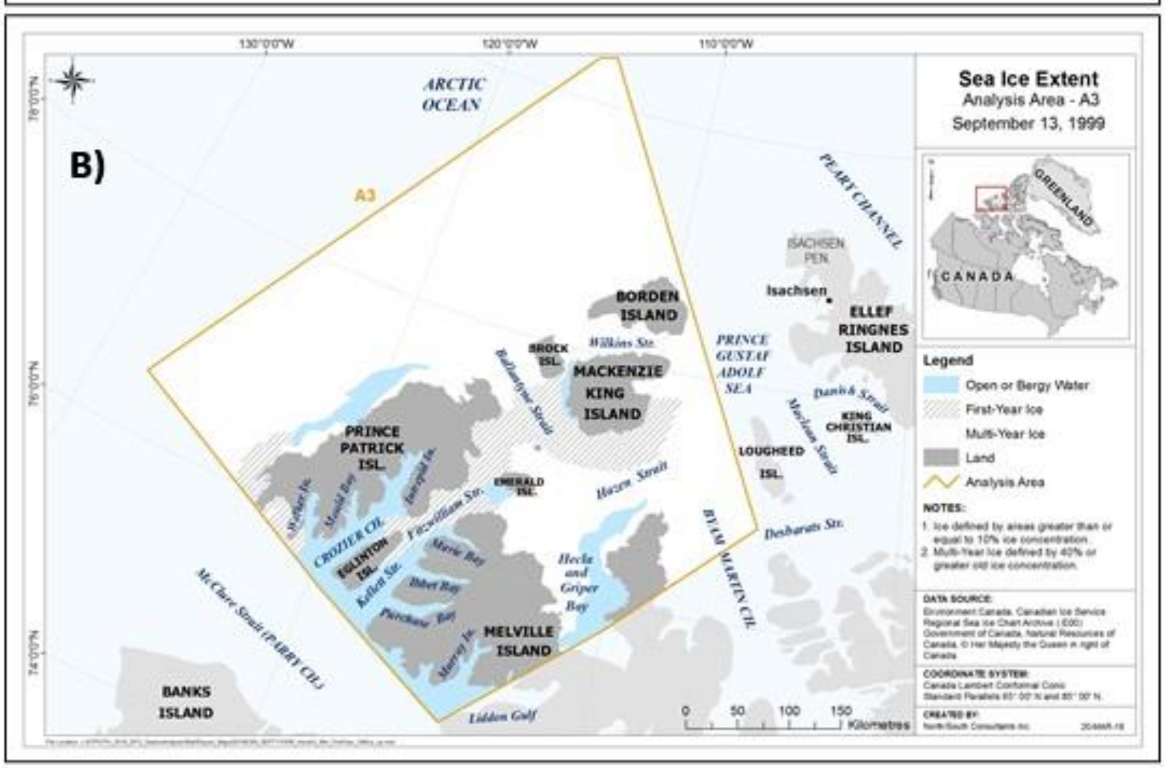


Figure 44. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 1999 within region A3.

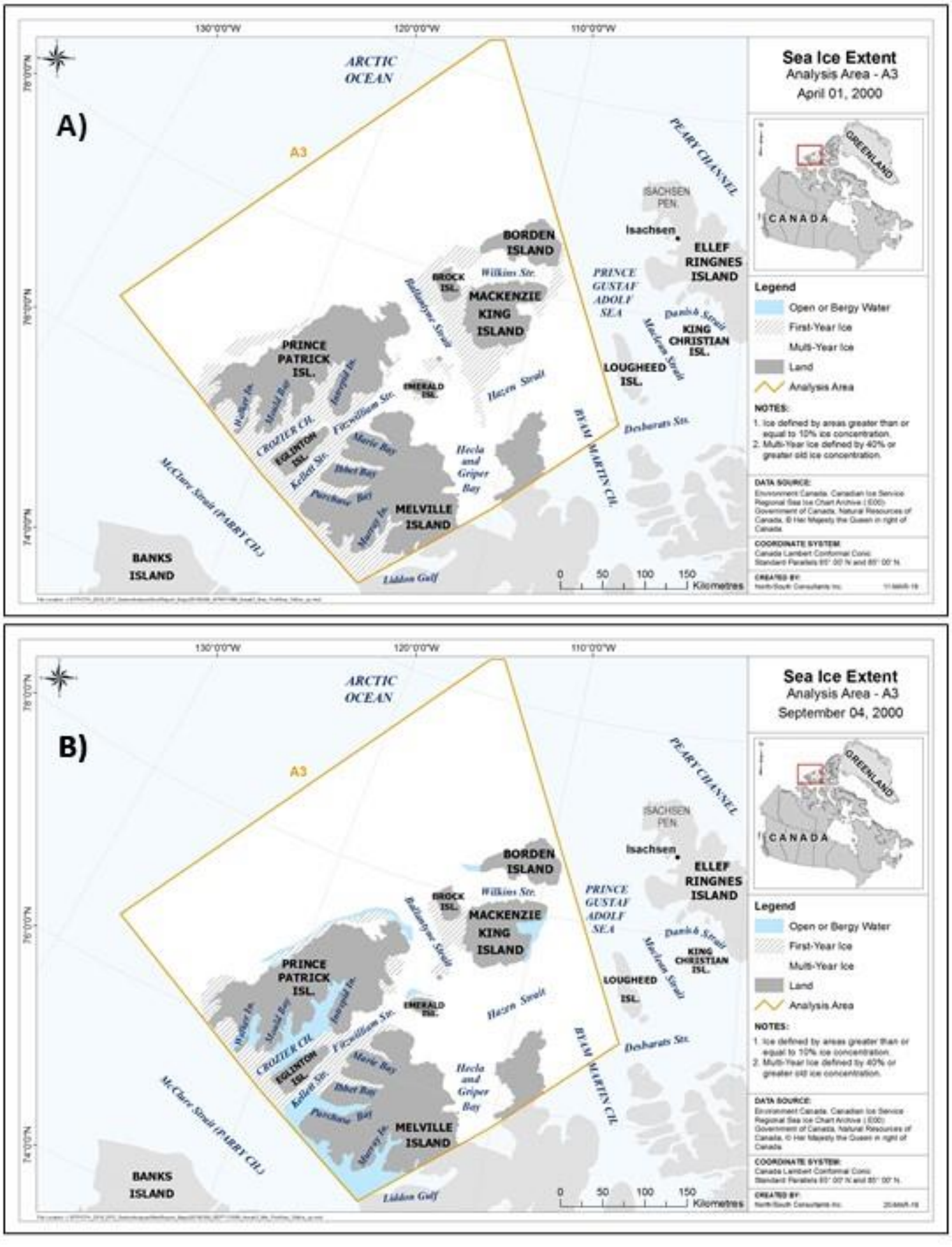


Figure 45. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2000 within region A3.

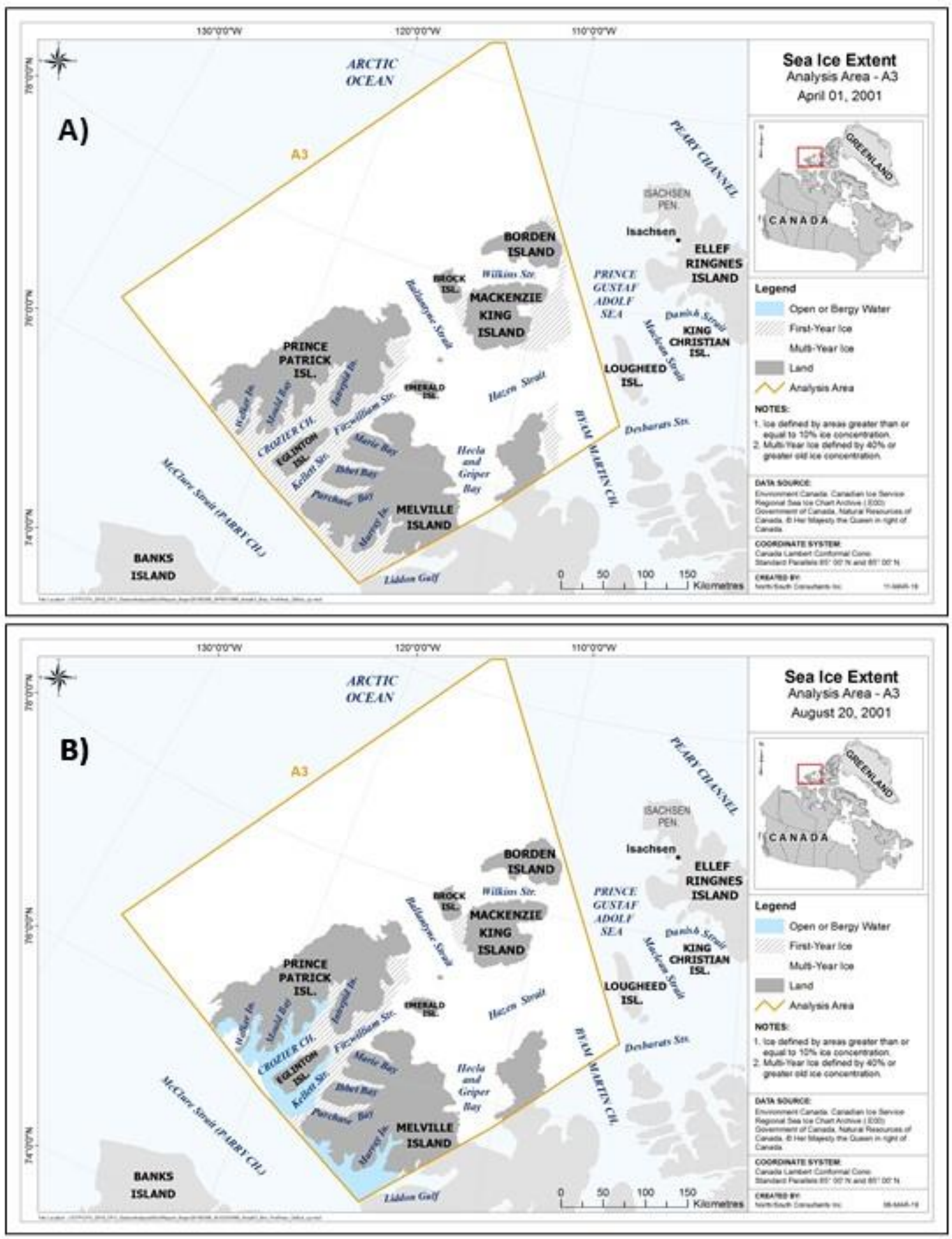


Figure 46. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2001 within region A3.

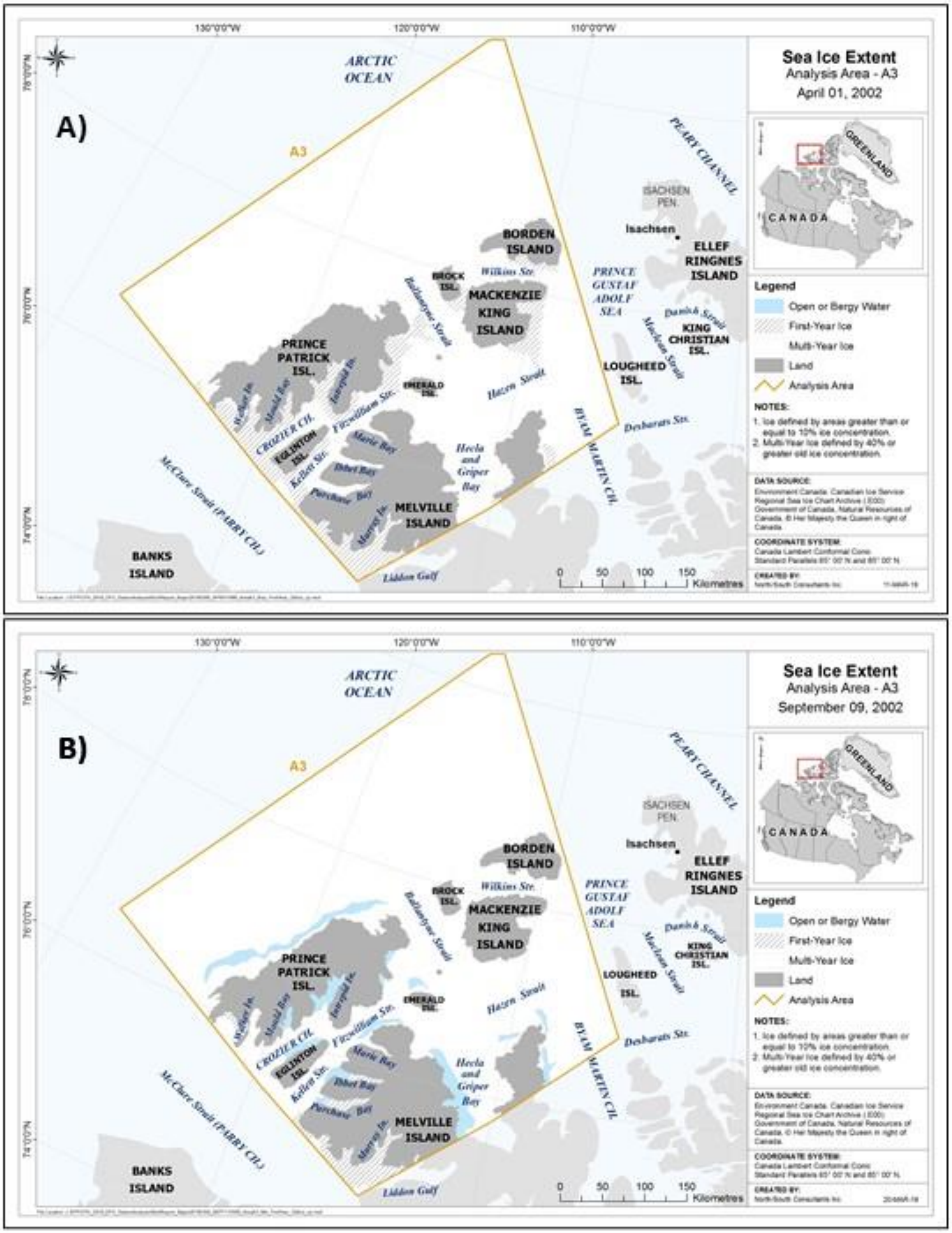


Figure 47. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2002 within region A3.

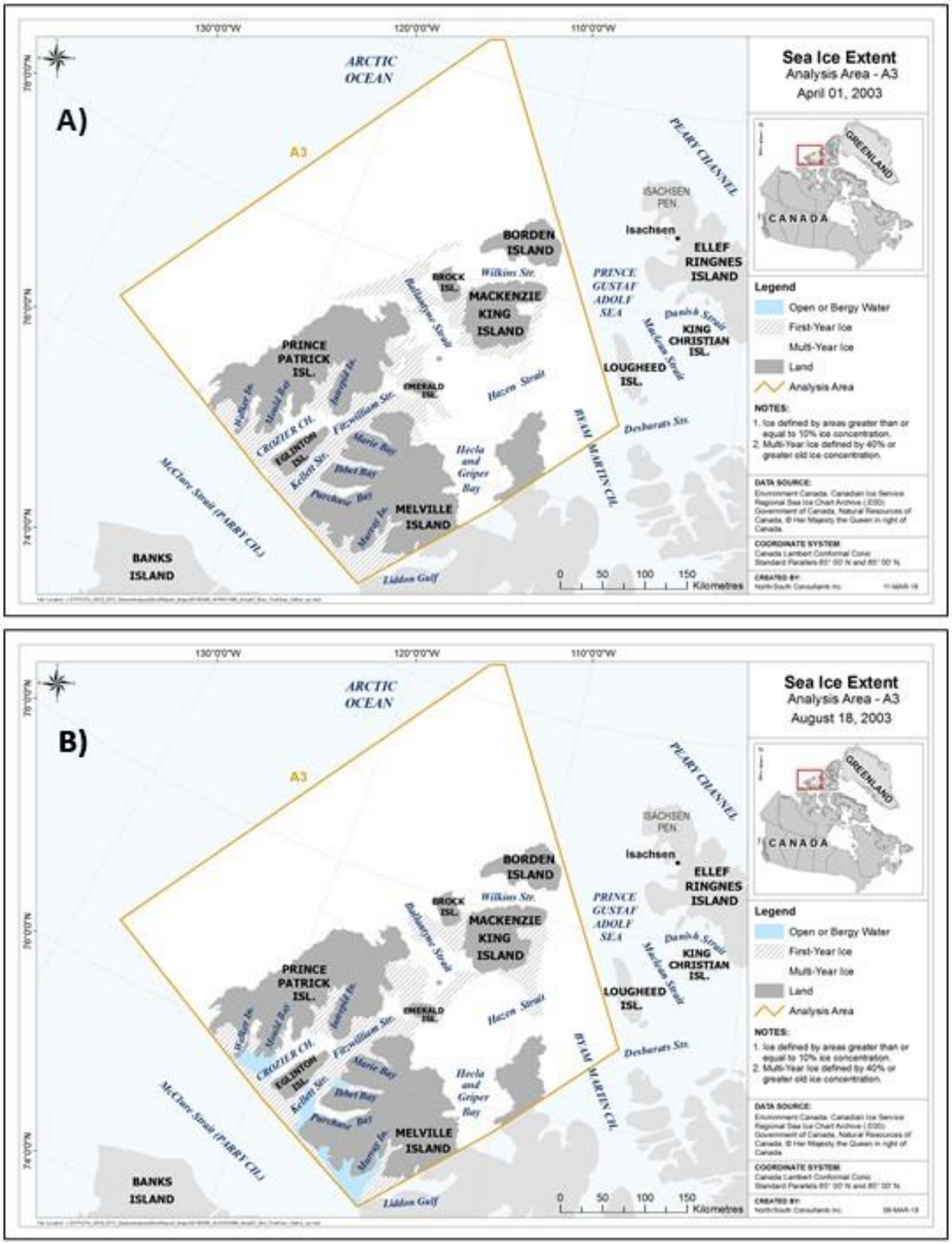


Figure 48. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2003 within region A3.

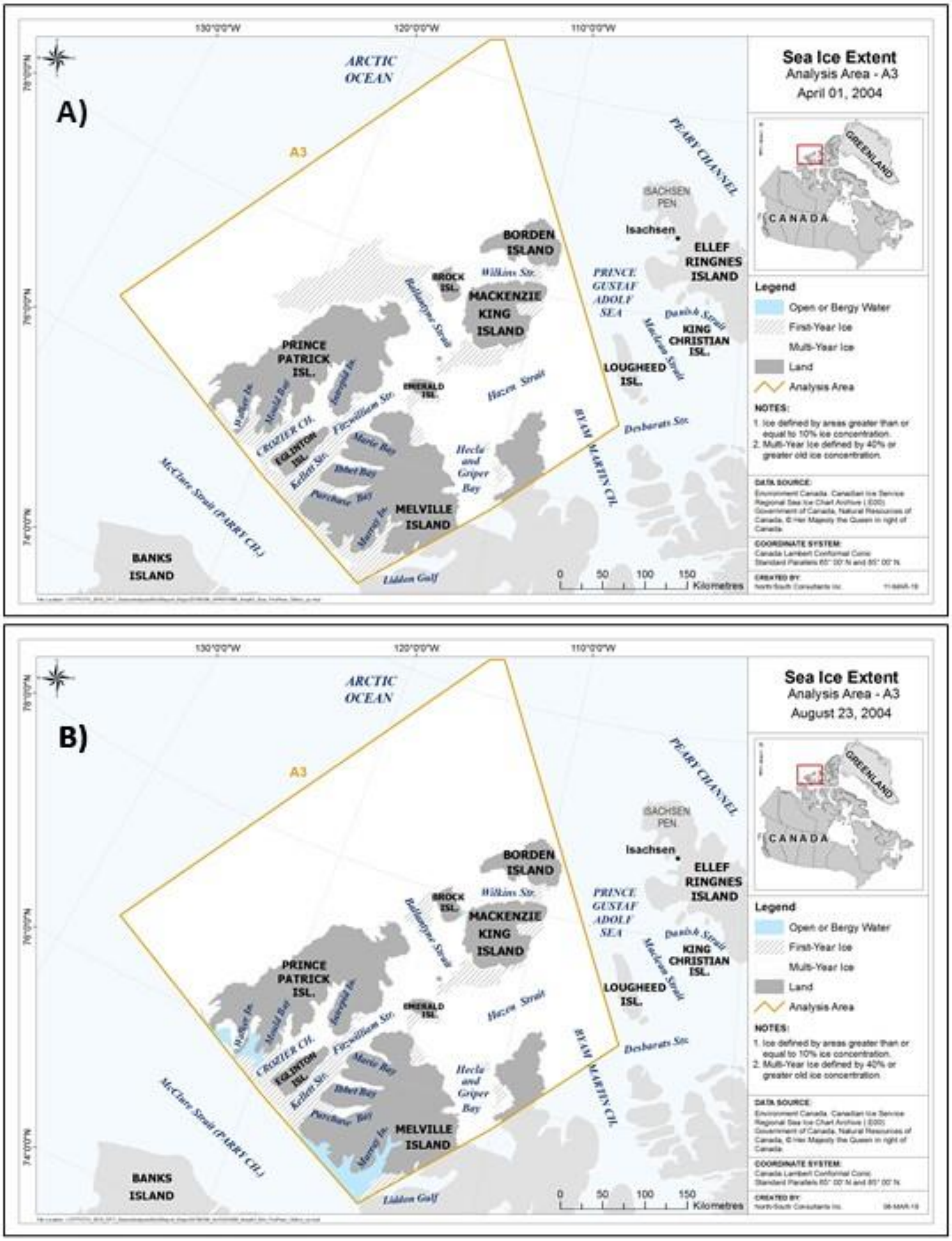


Figure 49. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2004 within region A3.

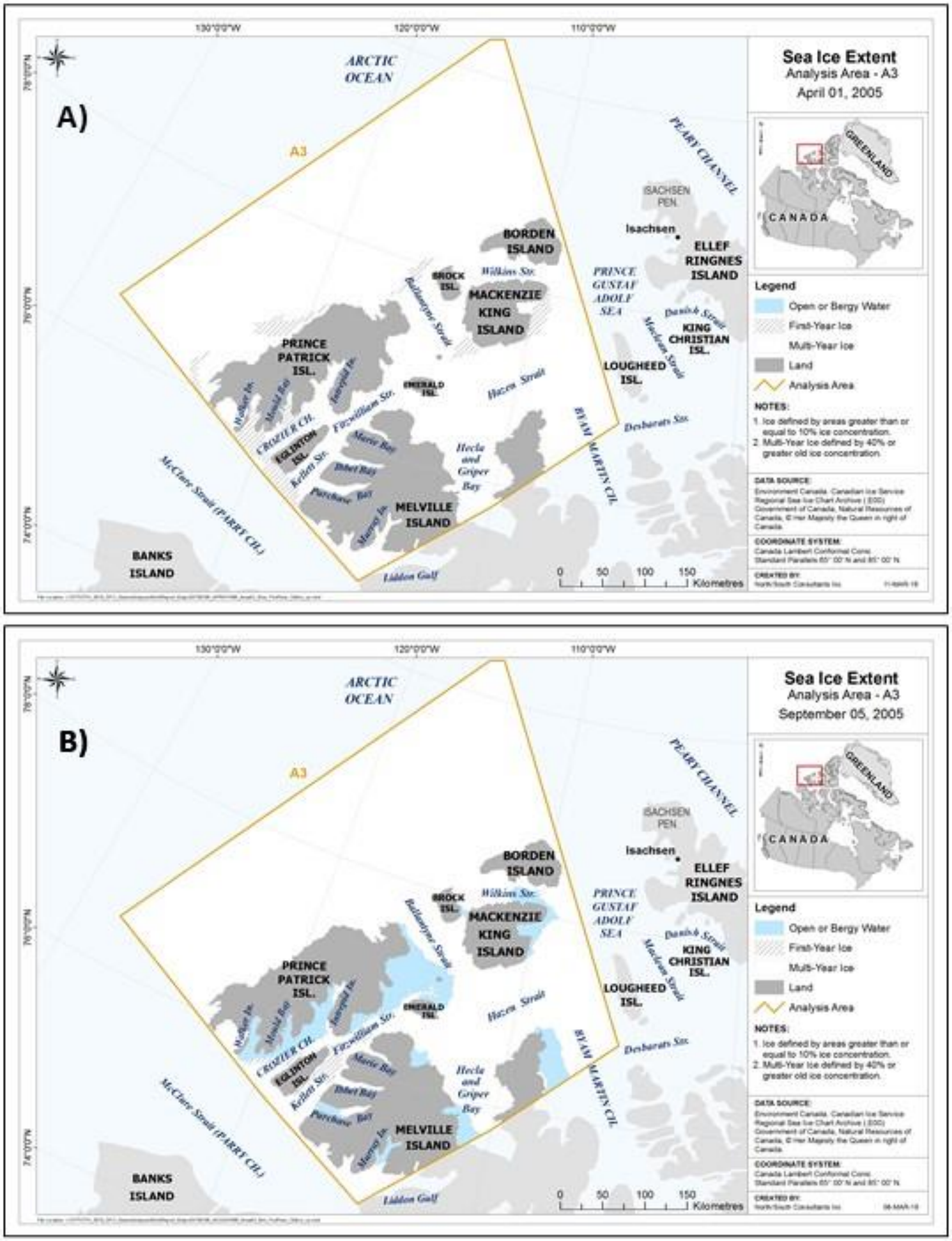


Figure 50. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2005 within region A3.

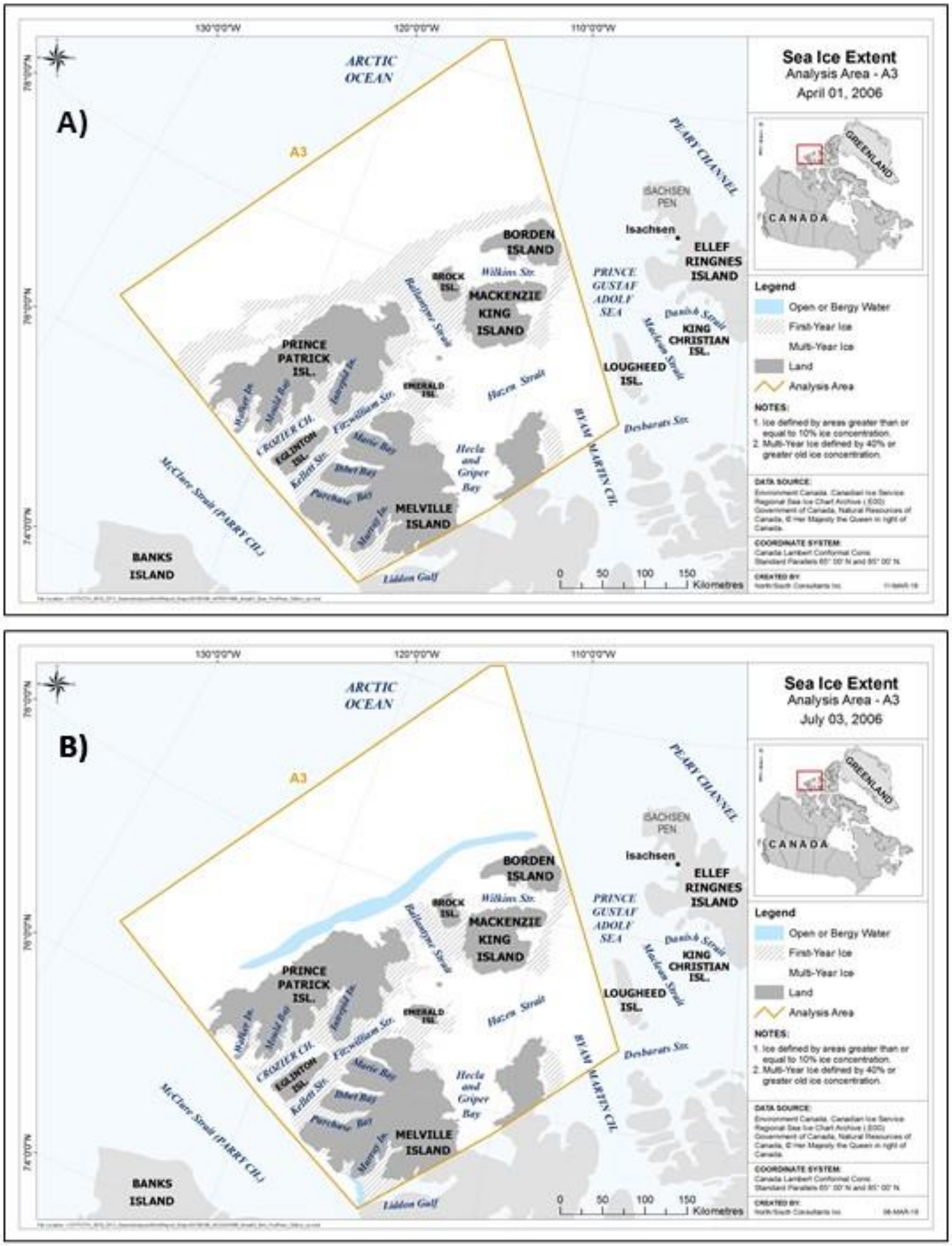


Figure 51. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2006 within region A3.

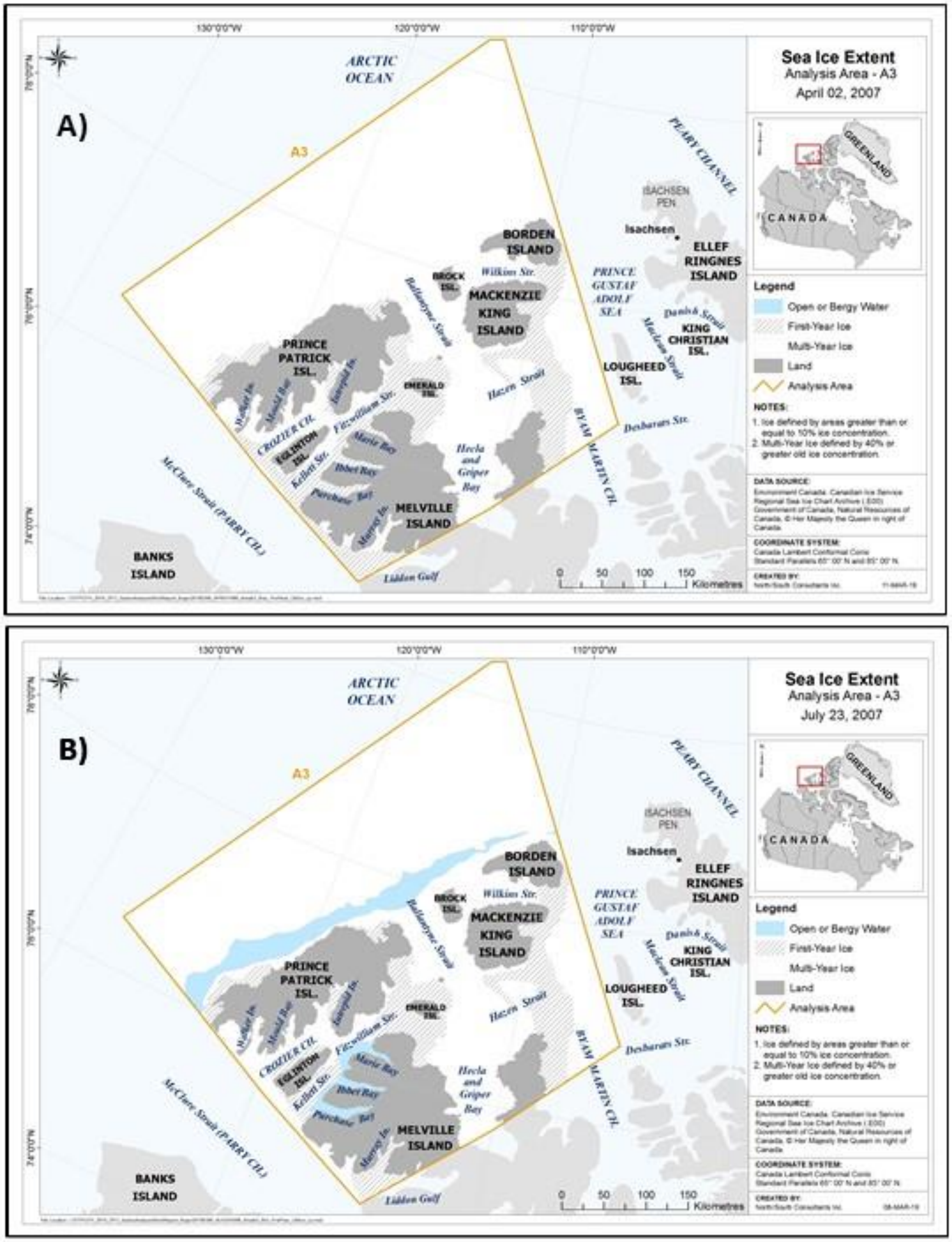


Figure 52. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2007 within region A3.

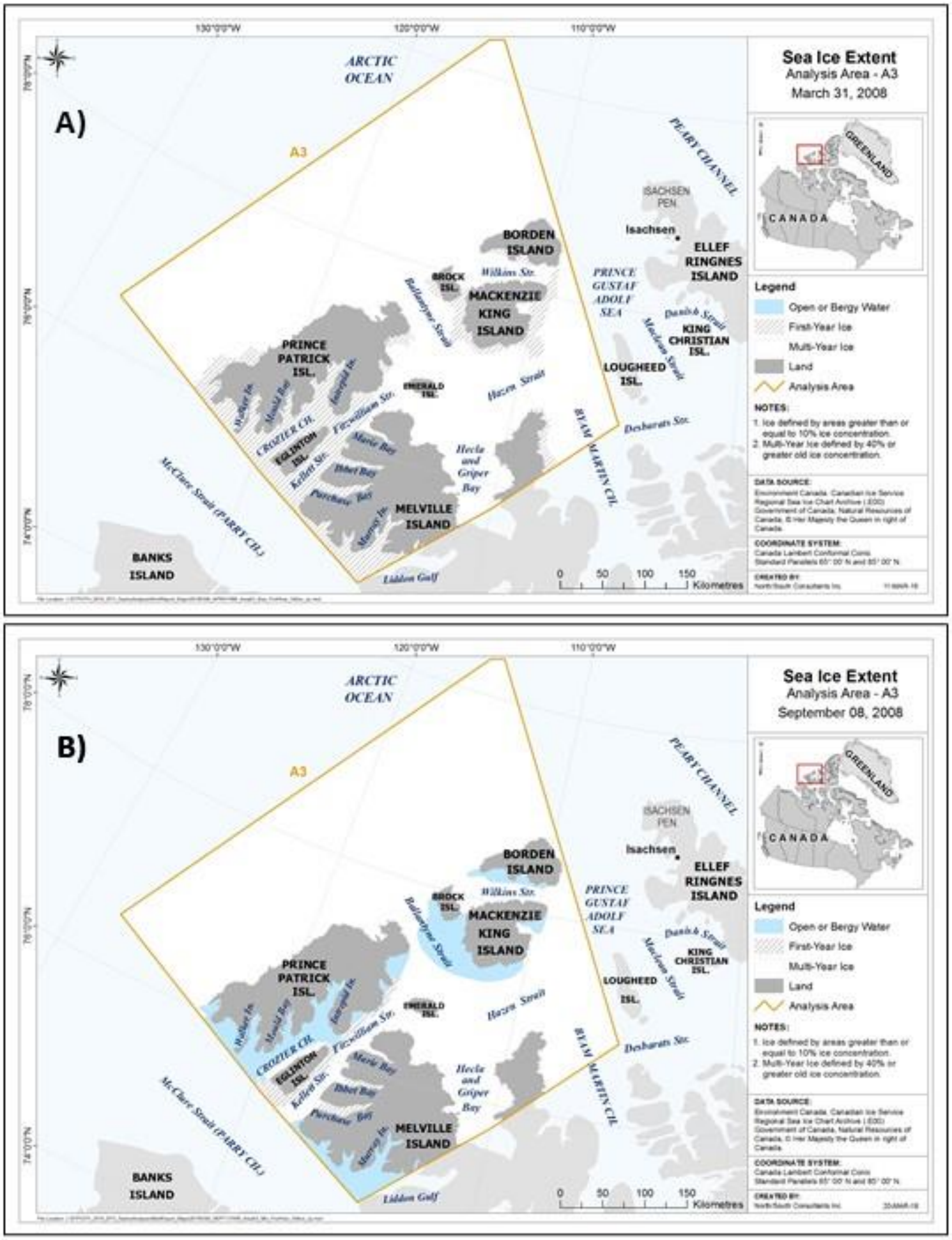


Figure 53. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2008 within region A3.

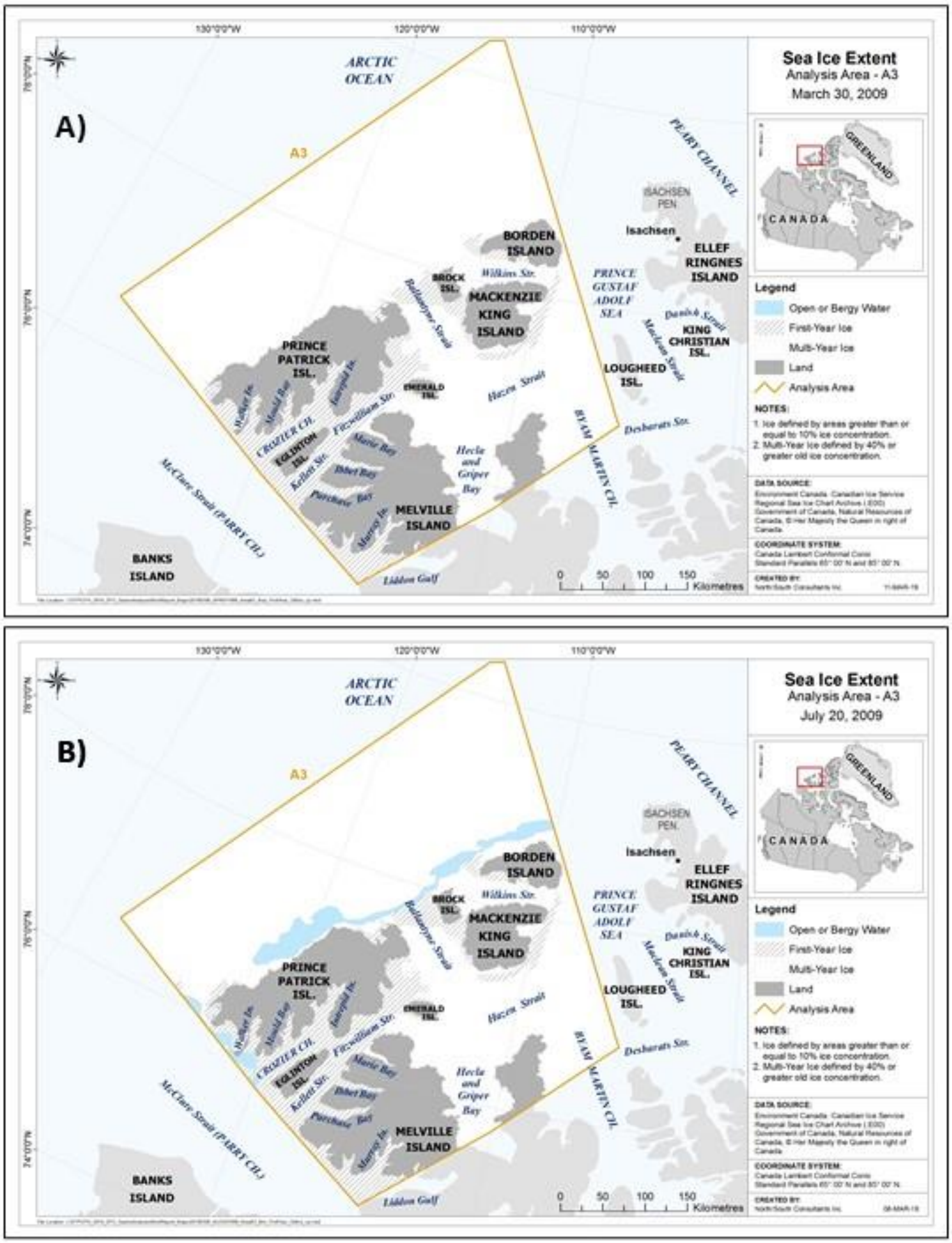


Figure 54. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2009 within region A3.

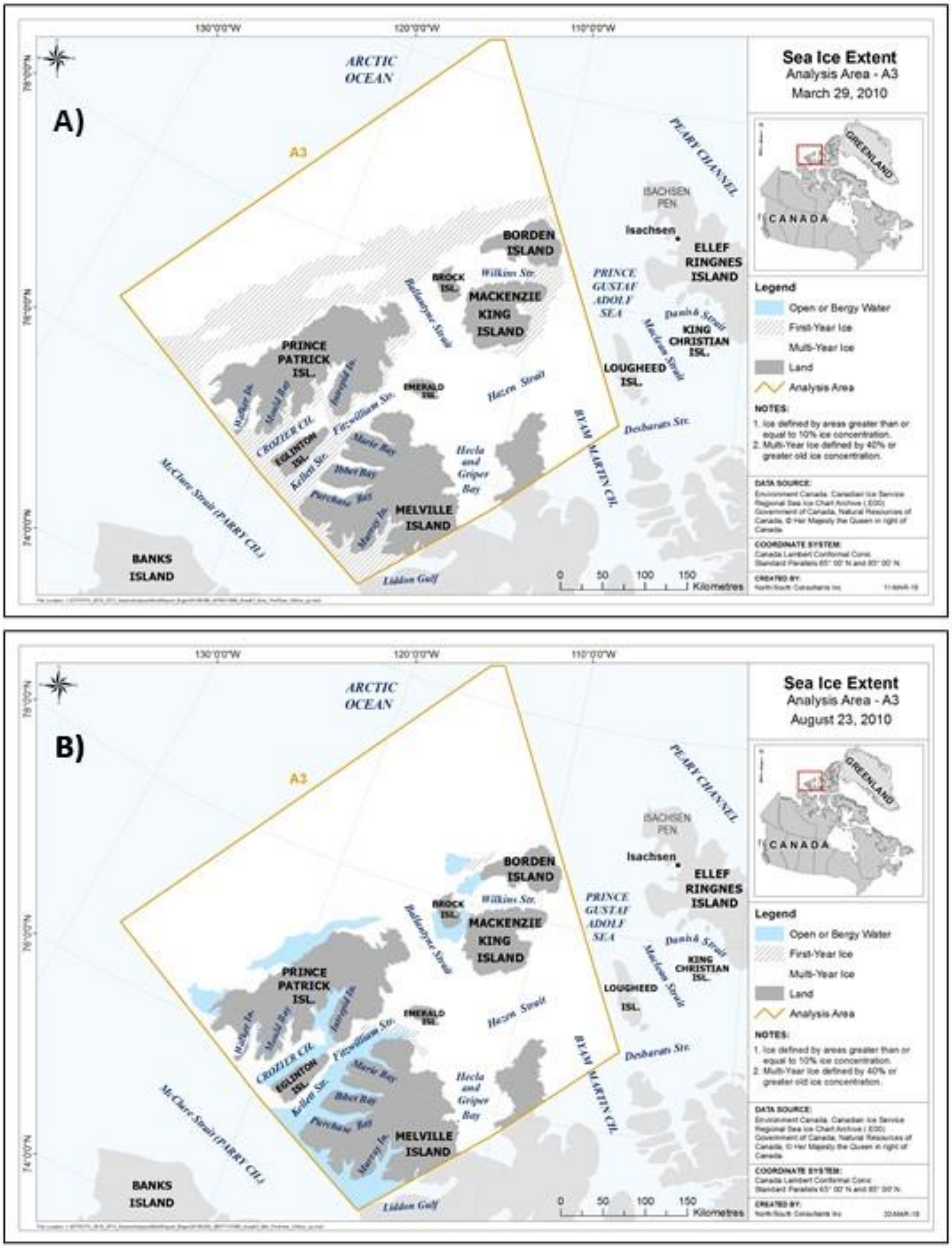


Figure 55. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2010 within region A3.

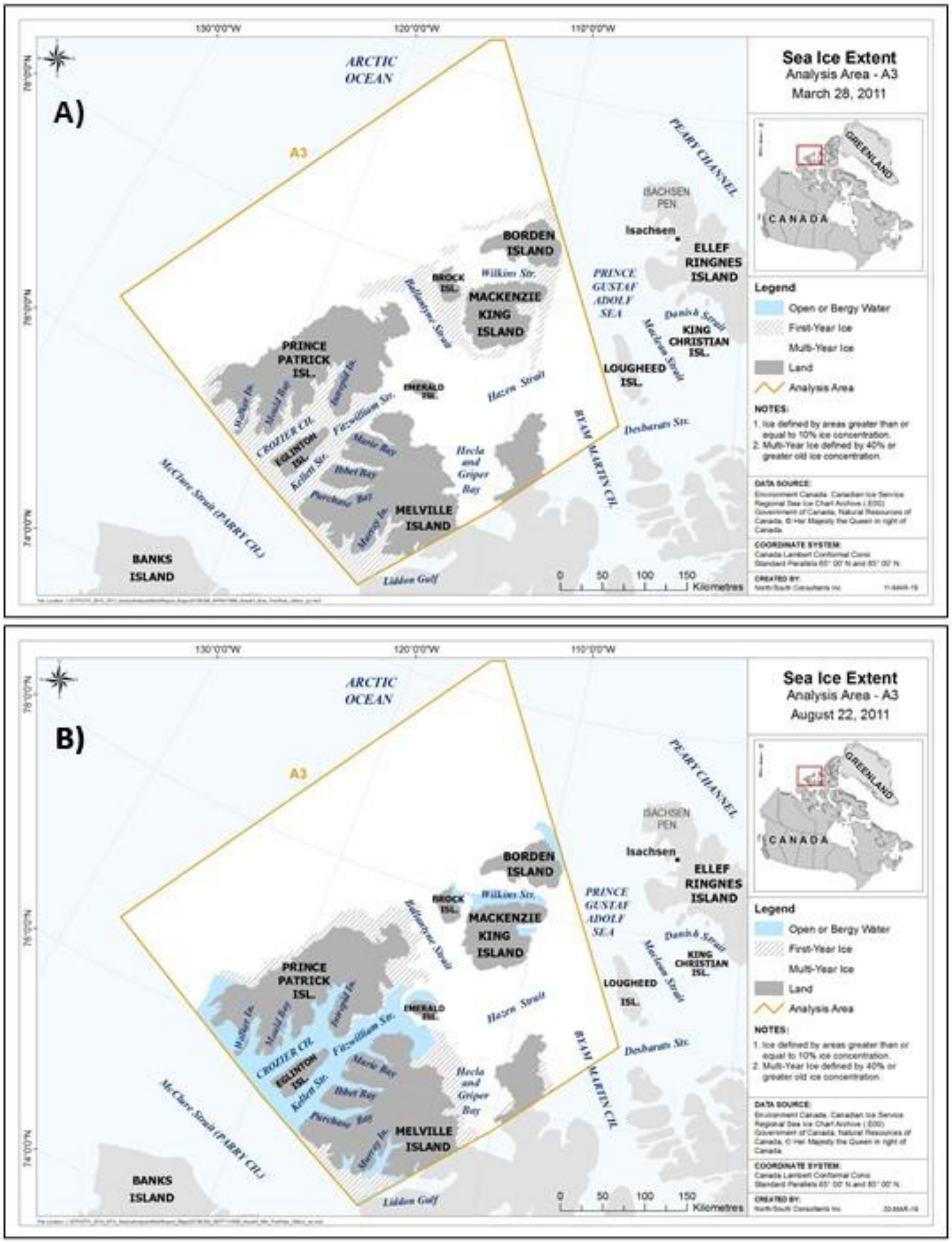


Figure 56. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2011 within region A3.

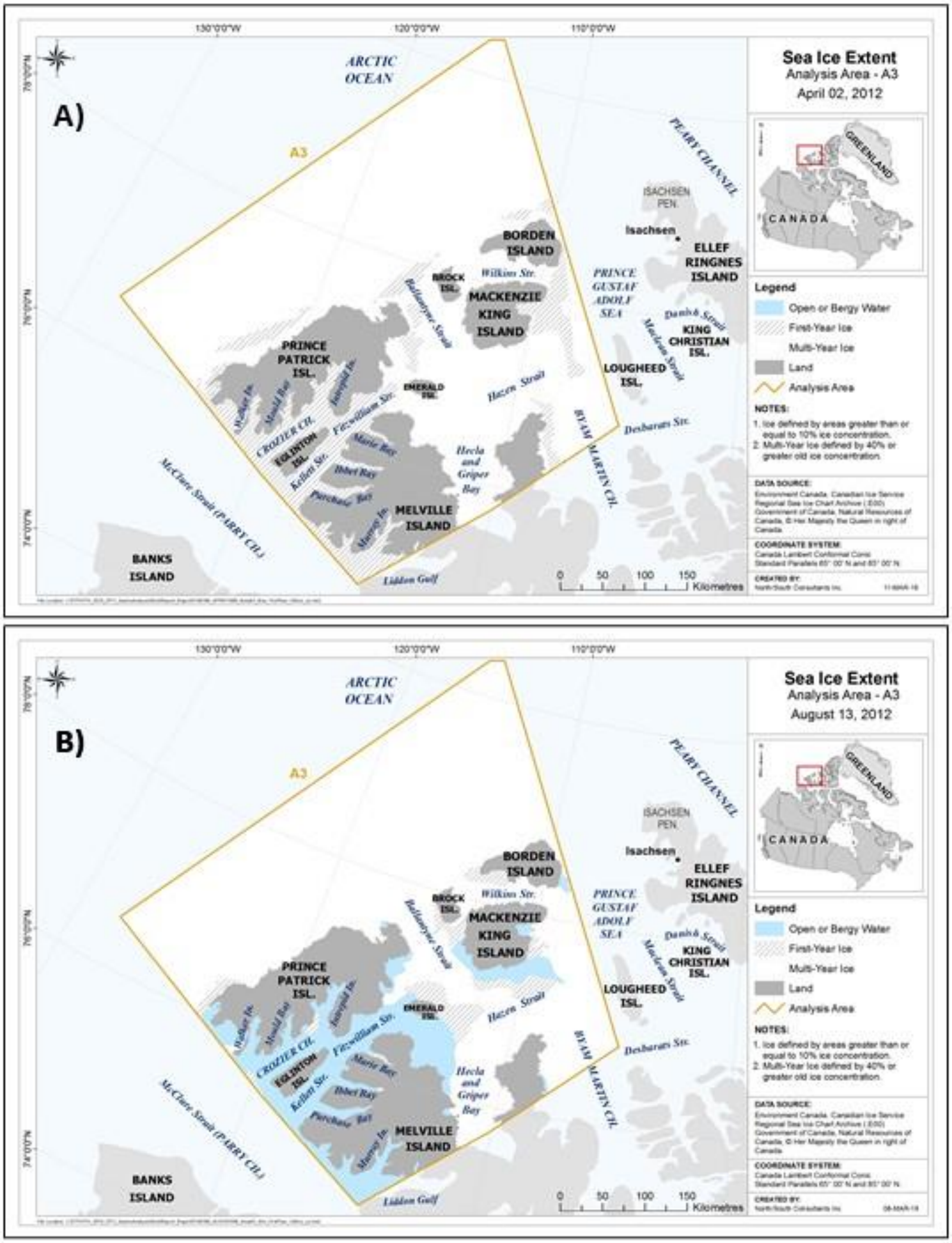


Figure 57. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2012 within region A3.

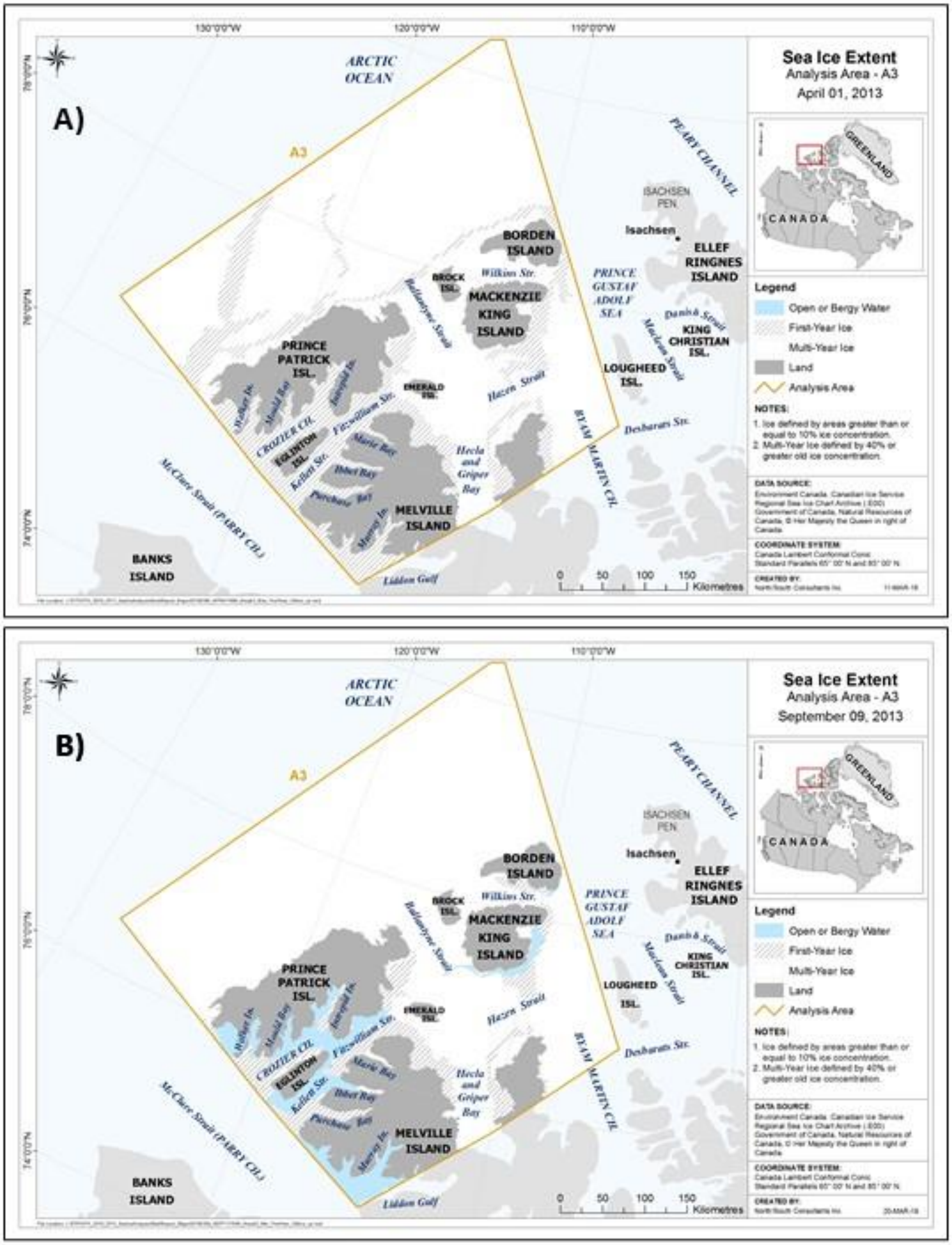


Figure 58. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2013 within region A3.

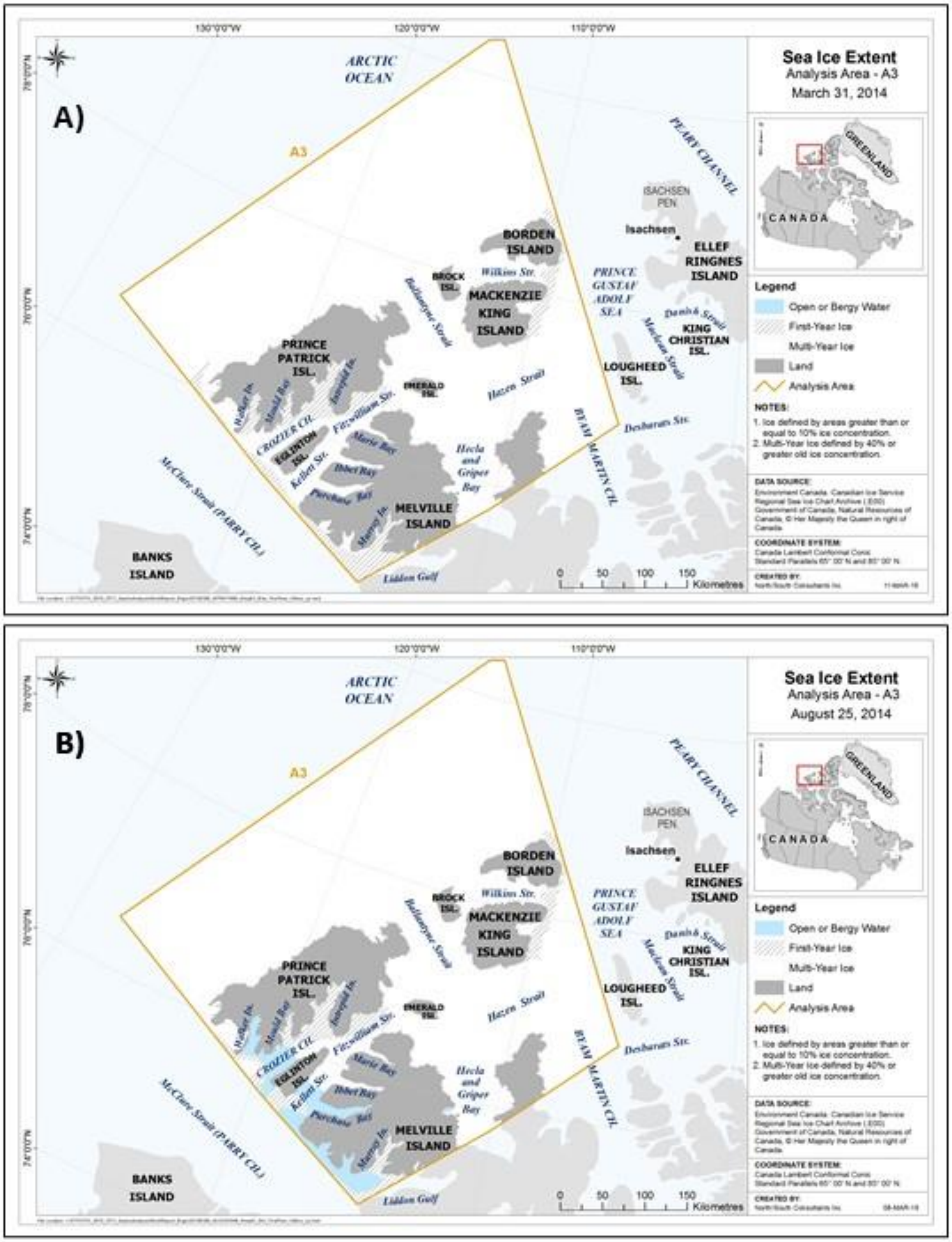


Figure 59. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2014 within region A3.

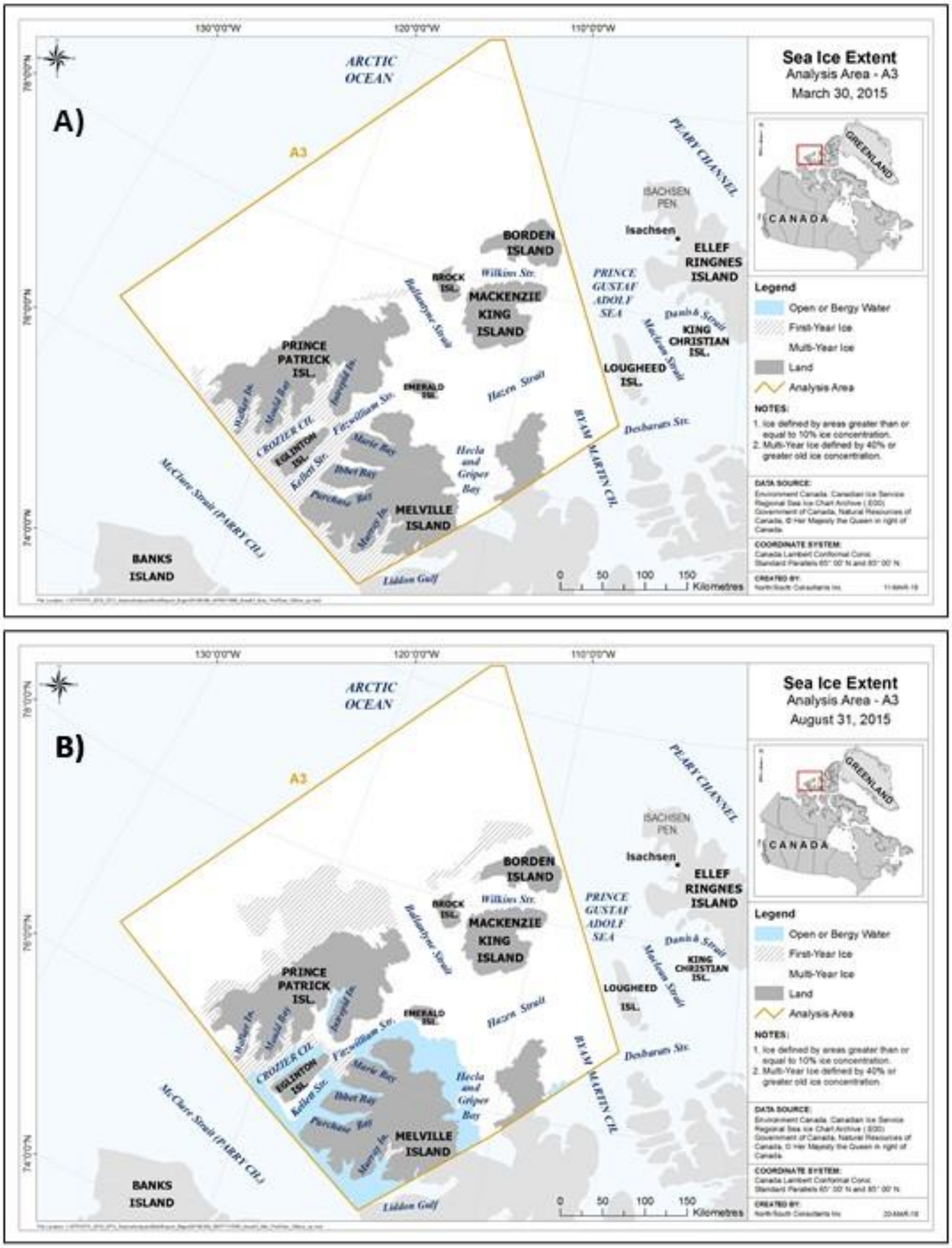


Figure 60. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2015 within region A3.

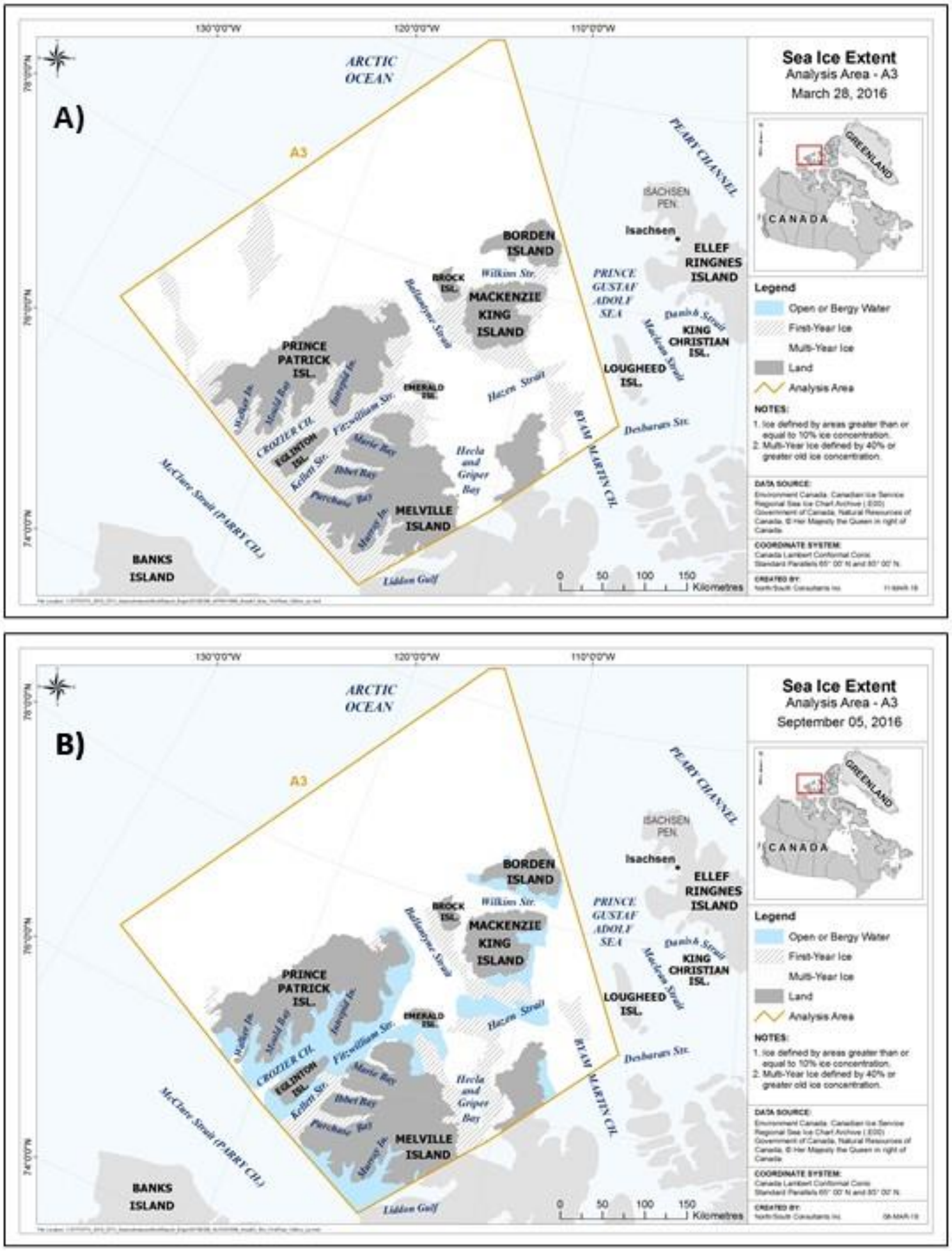


Figure 61. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2016 within region A3.

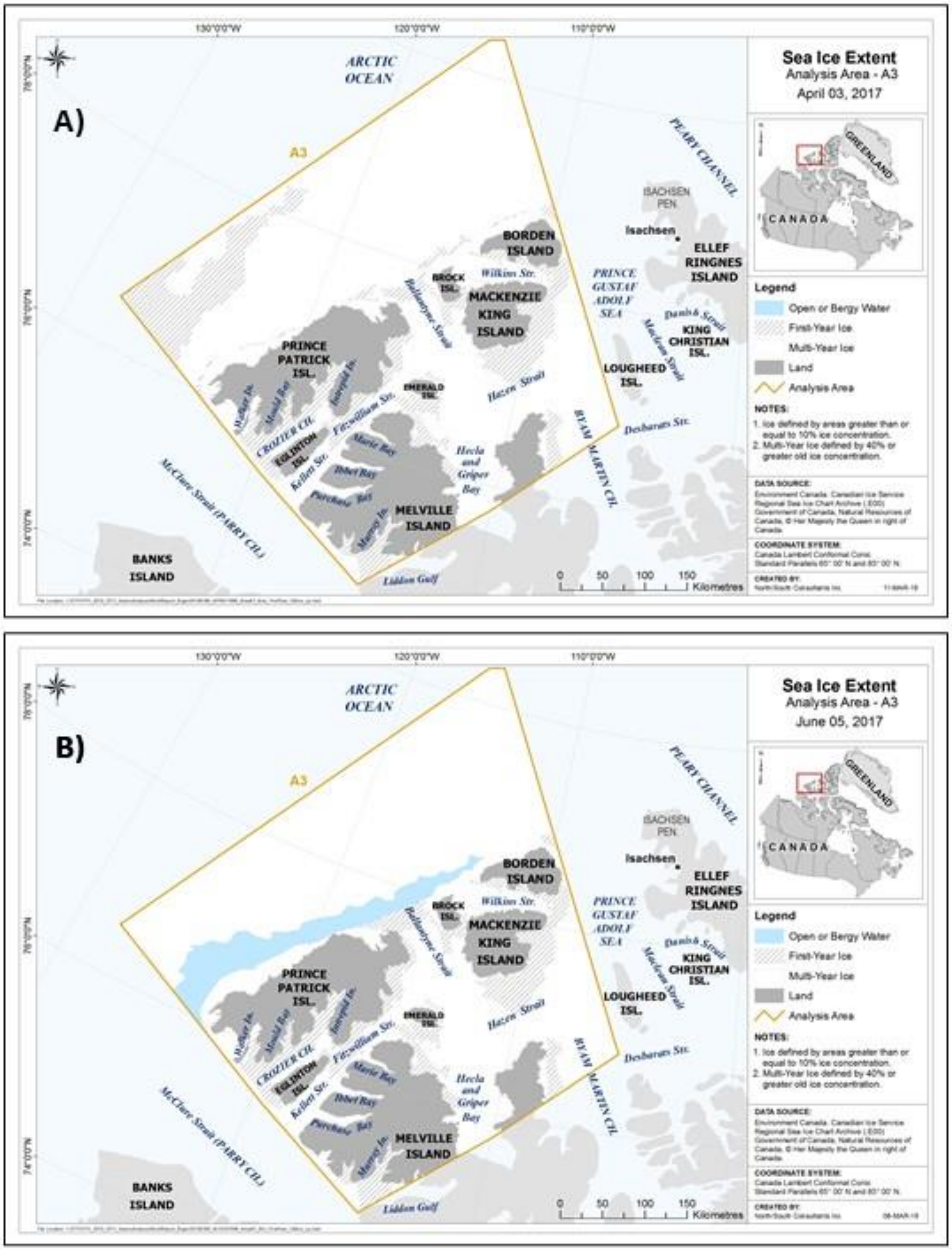


Figure 62. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2017 within region A3.

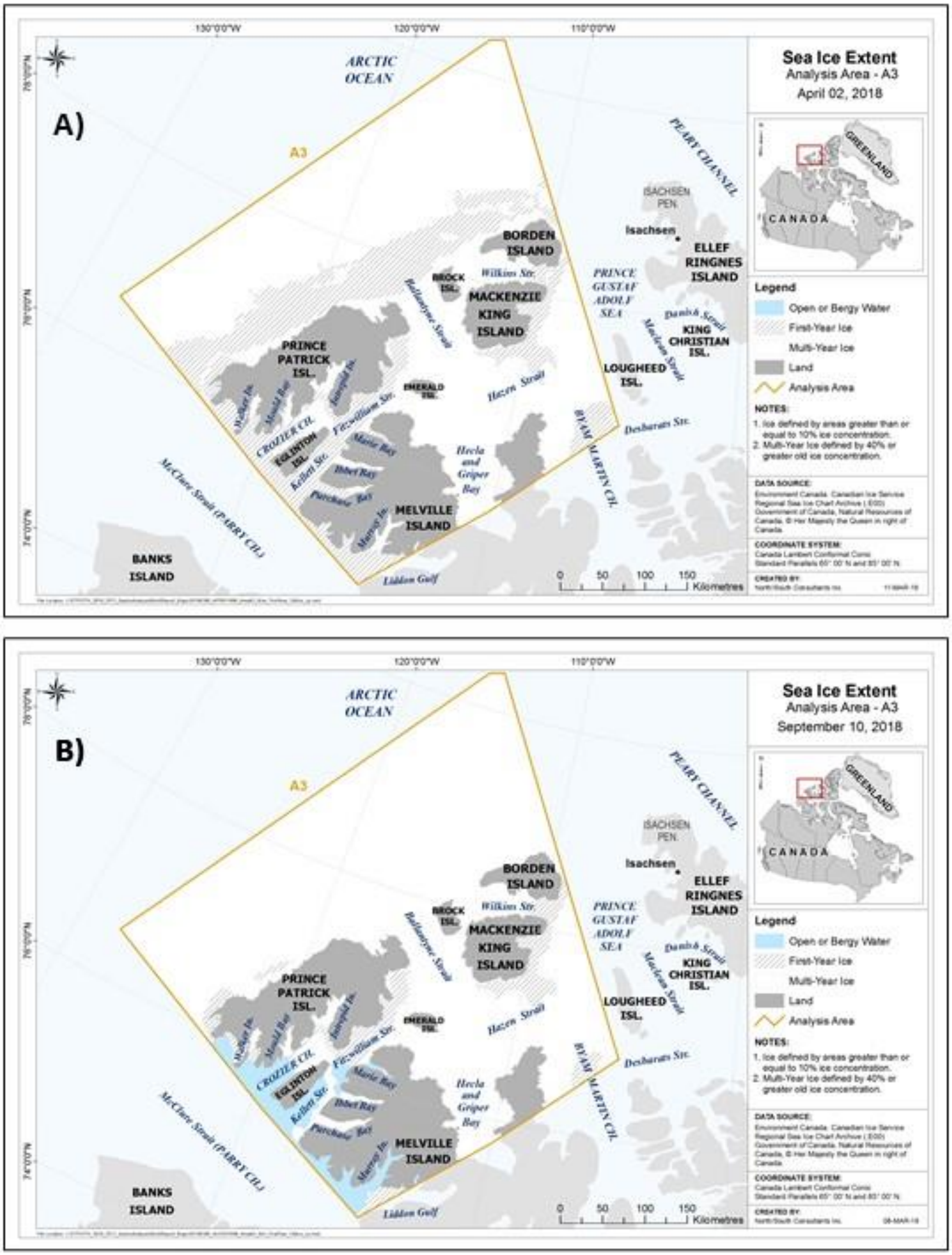


Figure 63. Extent of MYI, FYI and open water on maximum sea ice extent date (A) and minimum sea ice extent date (B) in 2018 within region A3.

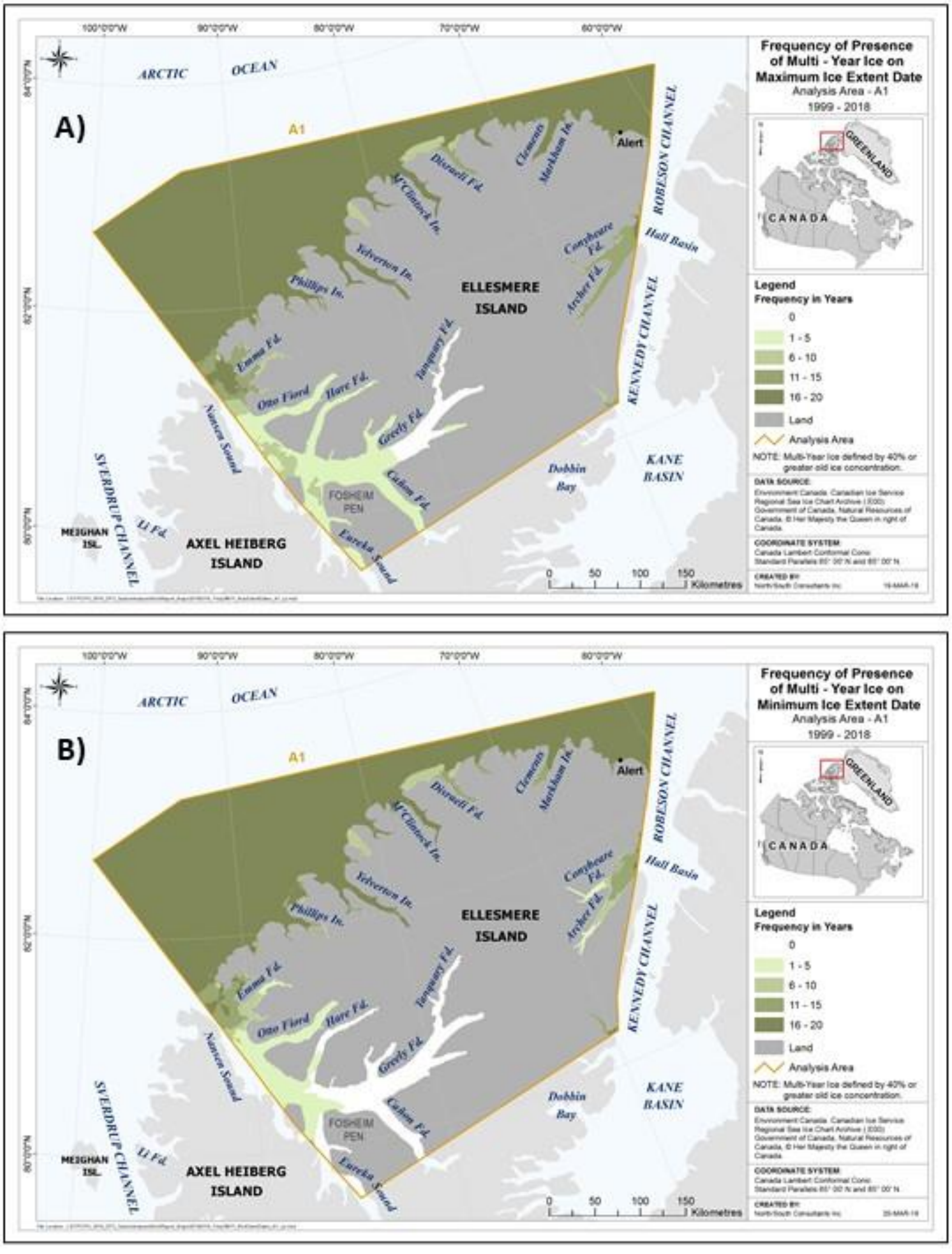


Figure 64. Frequency of occurrence of MYI on maximum sea ice extent date (A) and minimum sea ice extent date (B) between 1999 and 2018 within region A1.

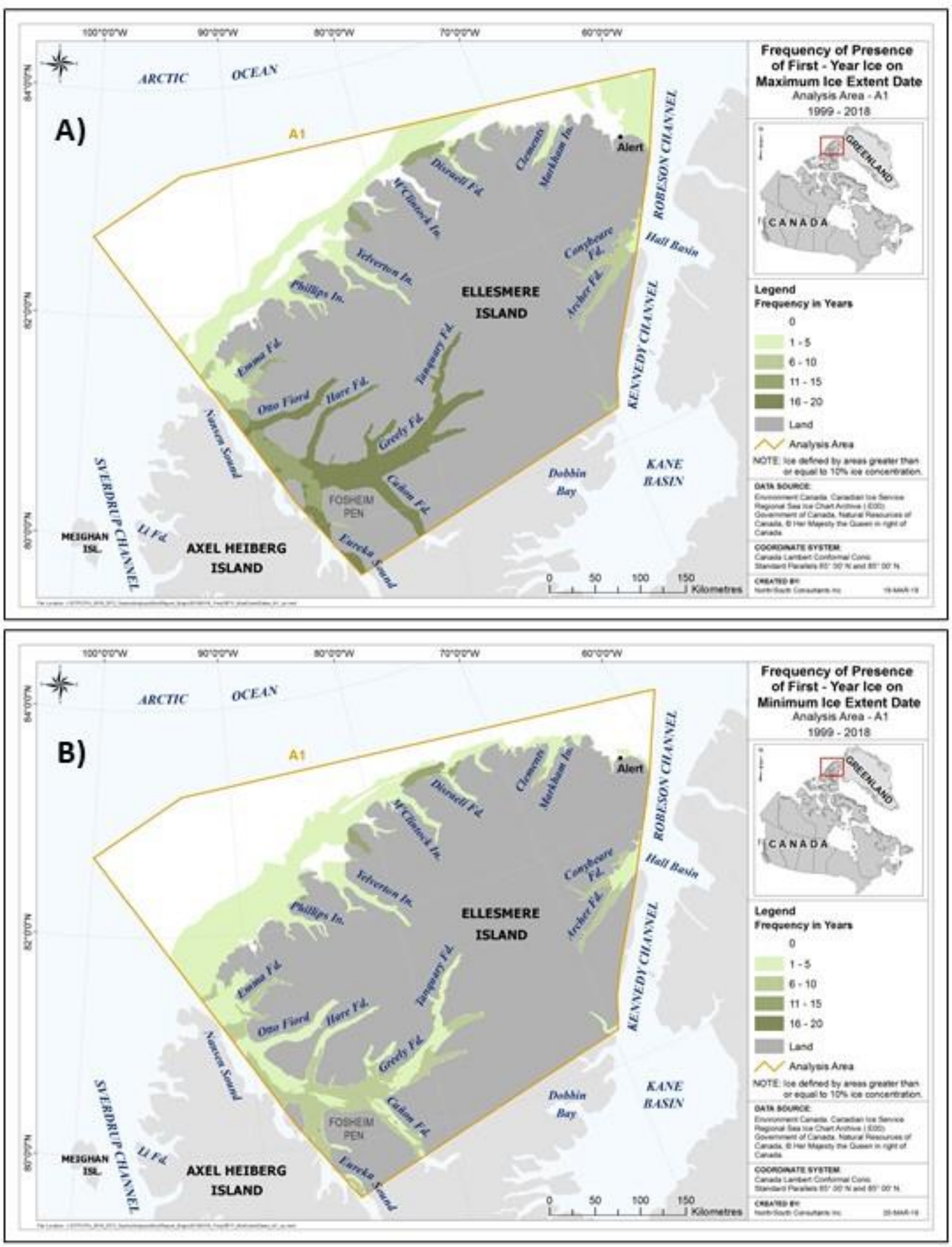


Figure 65. Frequency of occurrence of FYI on maximum sea ice extent date (A) and minimum sea ice extent date (B) between 1999 and 2018 within region A1.

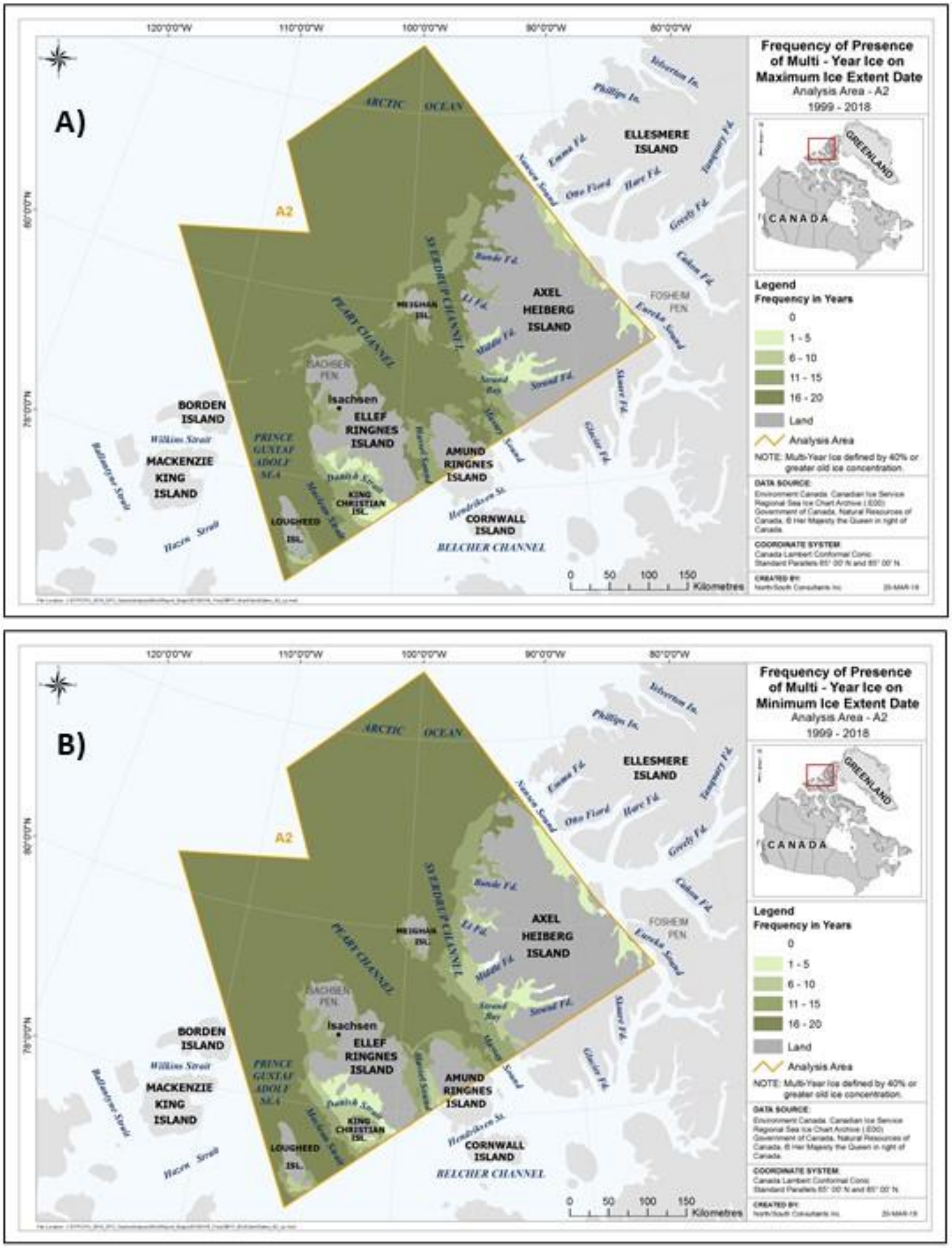


Figure 66. Frequency of occurrence of MYI on maximum sea ice extent date (A) and minimum sea ice extent date (B) between 1999 and 2018 within region A2.

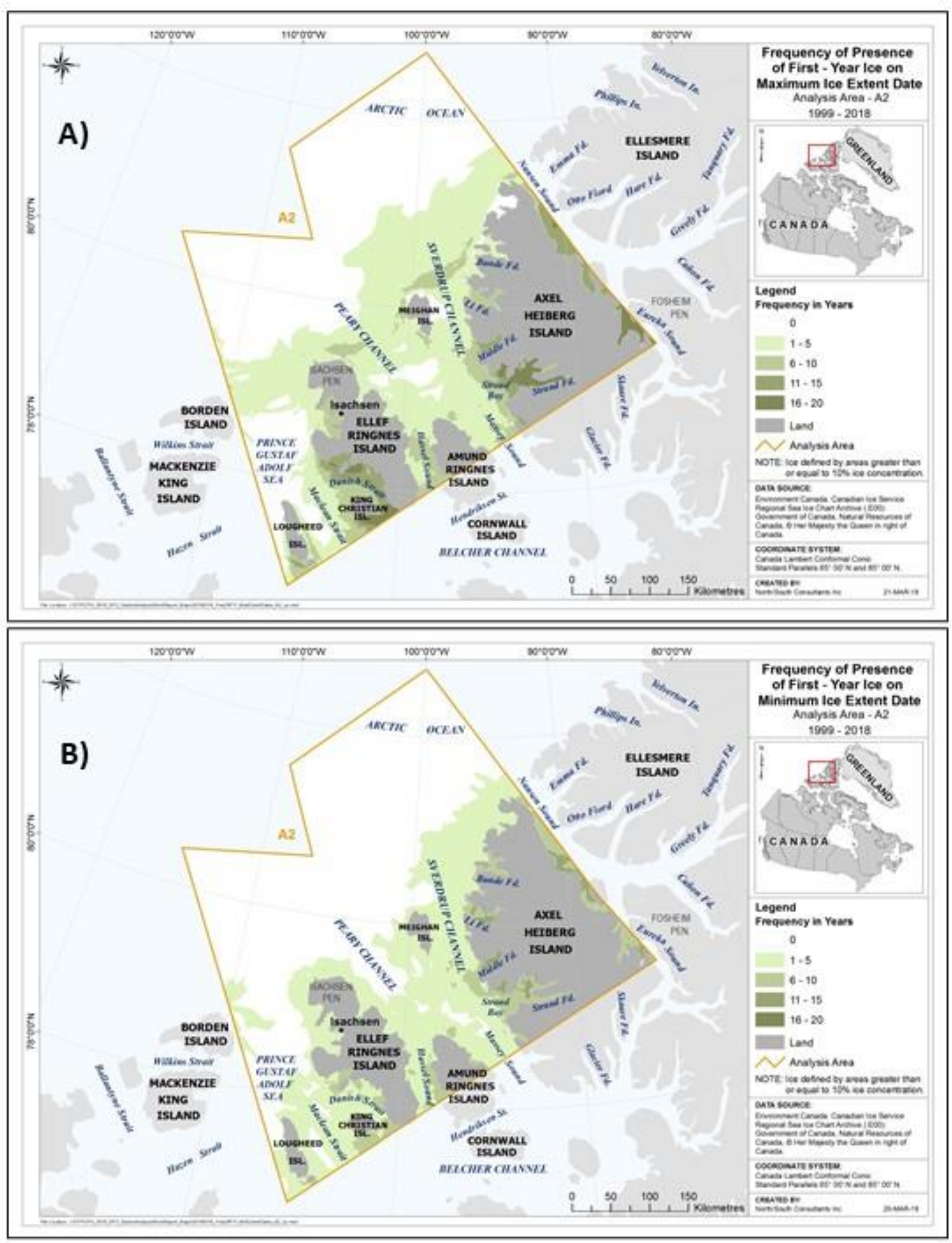


Figure 67. Frequency of occurrence of FYI on maximum sea ice extent date (A) and minimum sea ice extent date (B) between 1999 and 2018 within region A2.

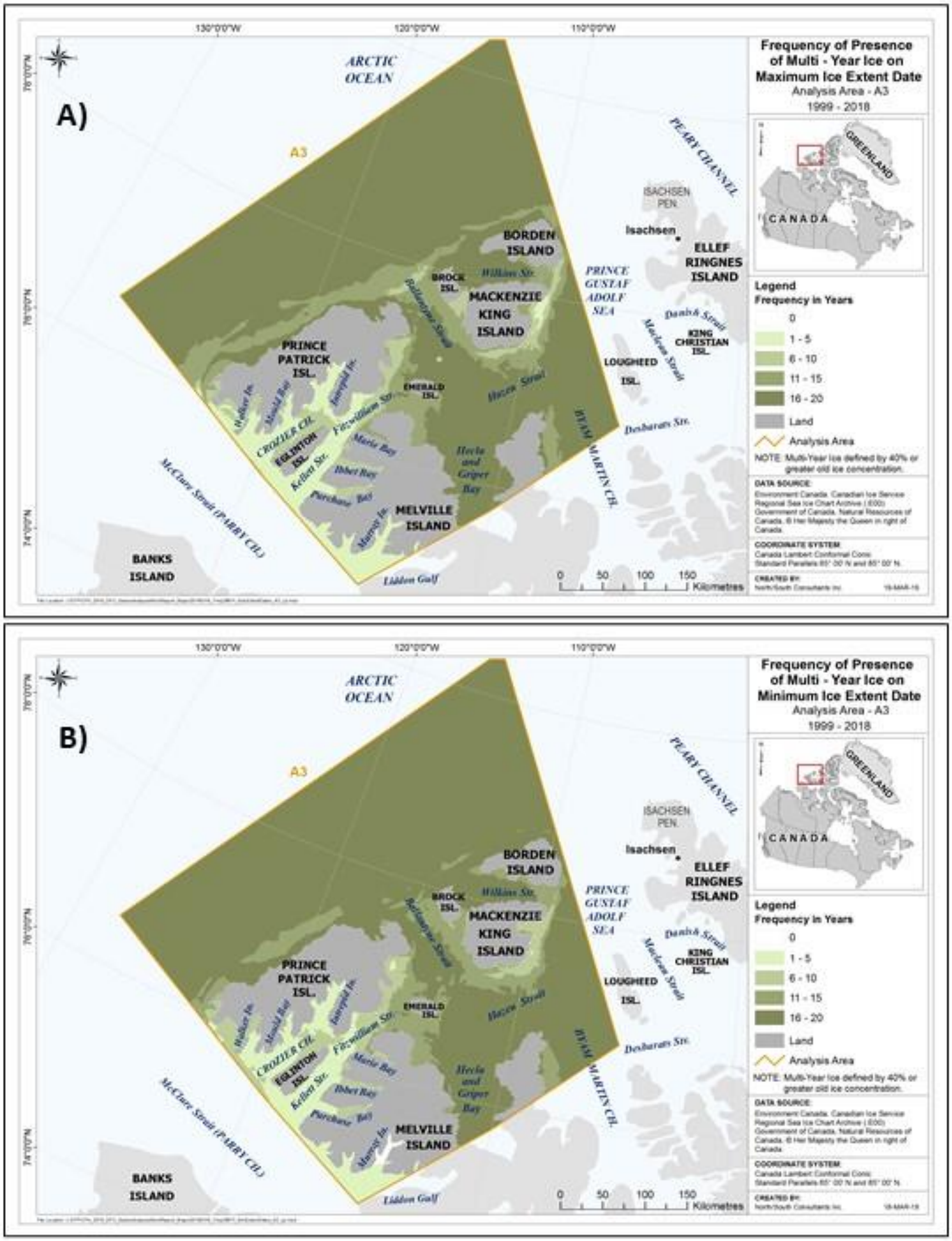


Figure 68. Frequency of occurrence of MYI on maximum sea ice extent date (A) and minimum sea ice extent date (B) between 1999 and 2018 within region A3.

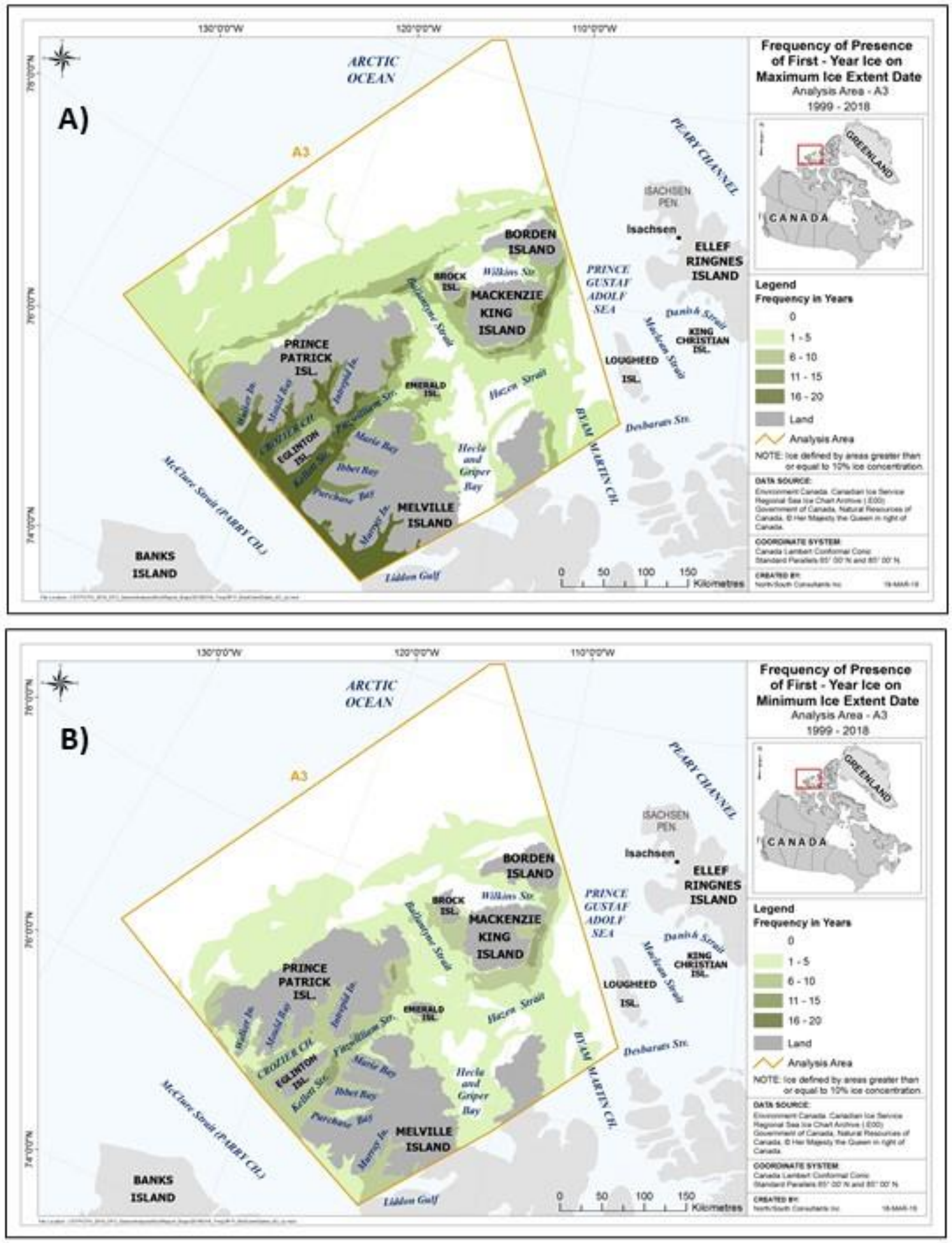


Figure 69. Frequency of occurrence of FYI on maximum sea ice extent date (A) and minimum sea ice extent date (B) between 1999 and 2018 within region A3.

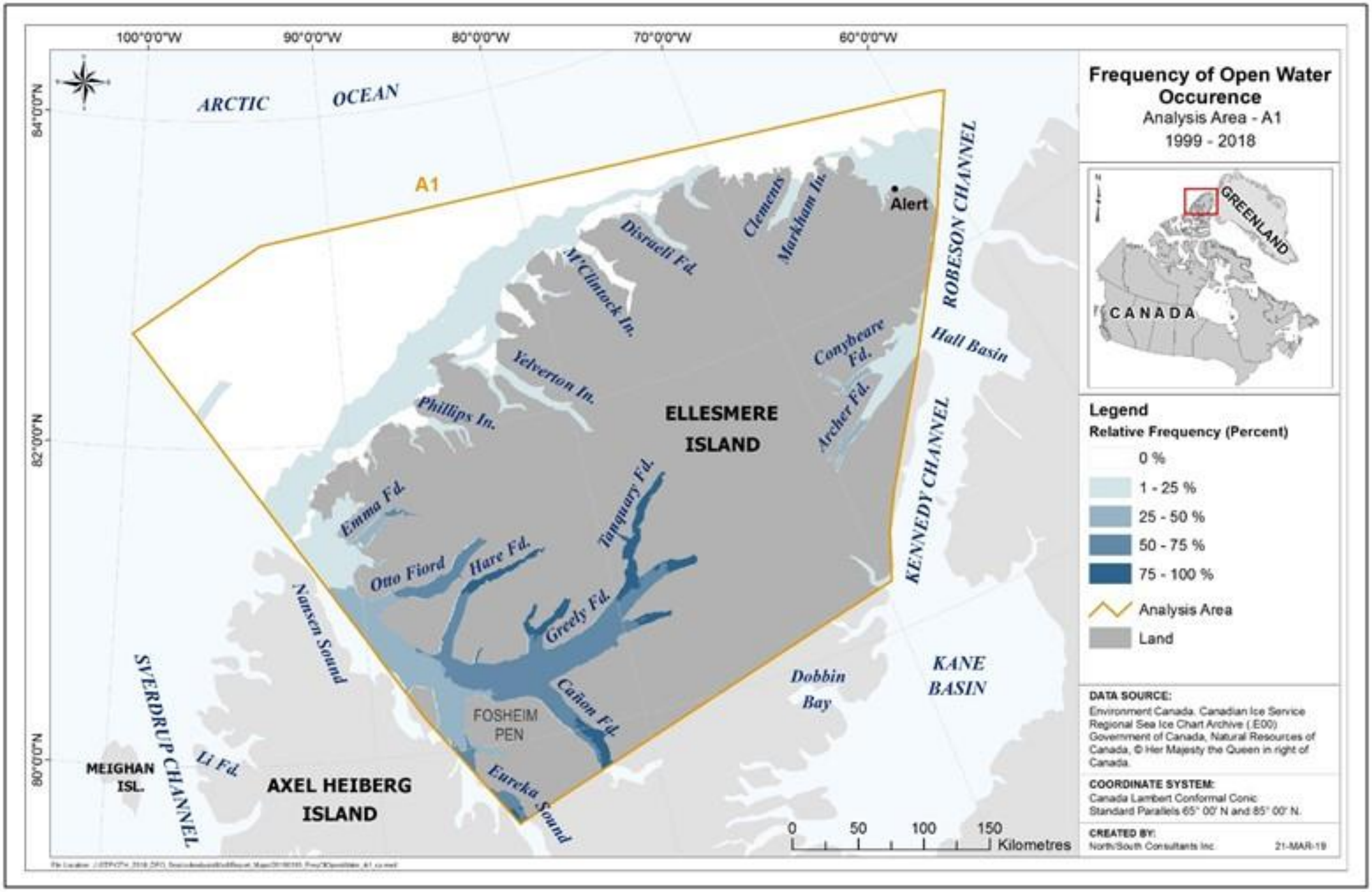


Figure 70. Frequency of occurrence of open water between 1999 and 2018 within region A1.

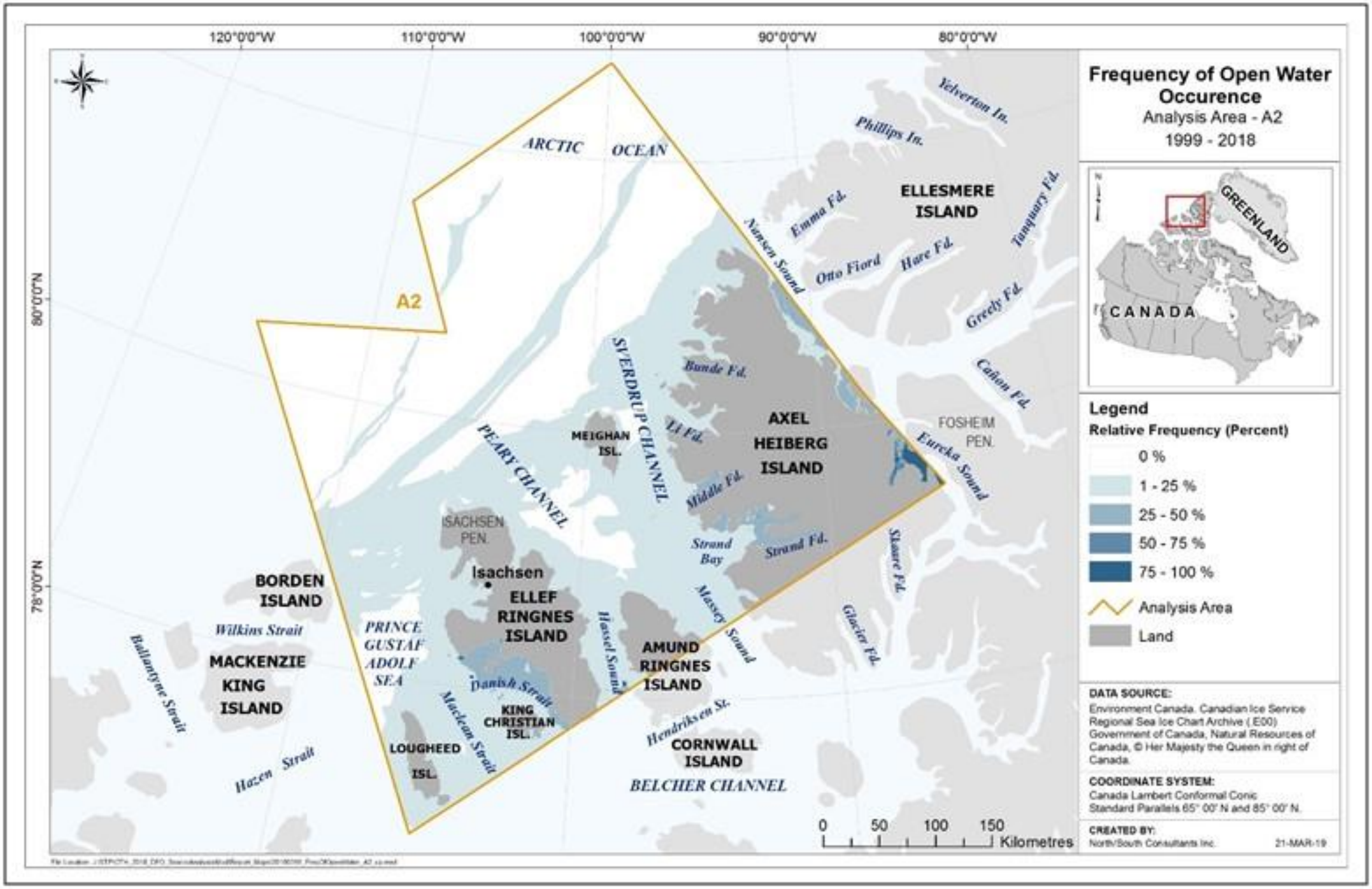


Figure 71. Frequency of occurrence of open water between 1999 and 2018 within region A2.

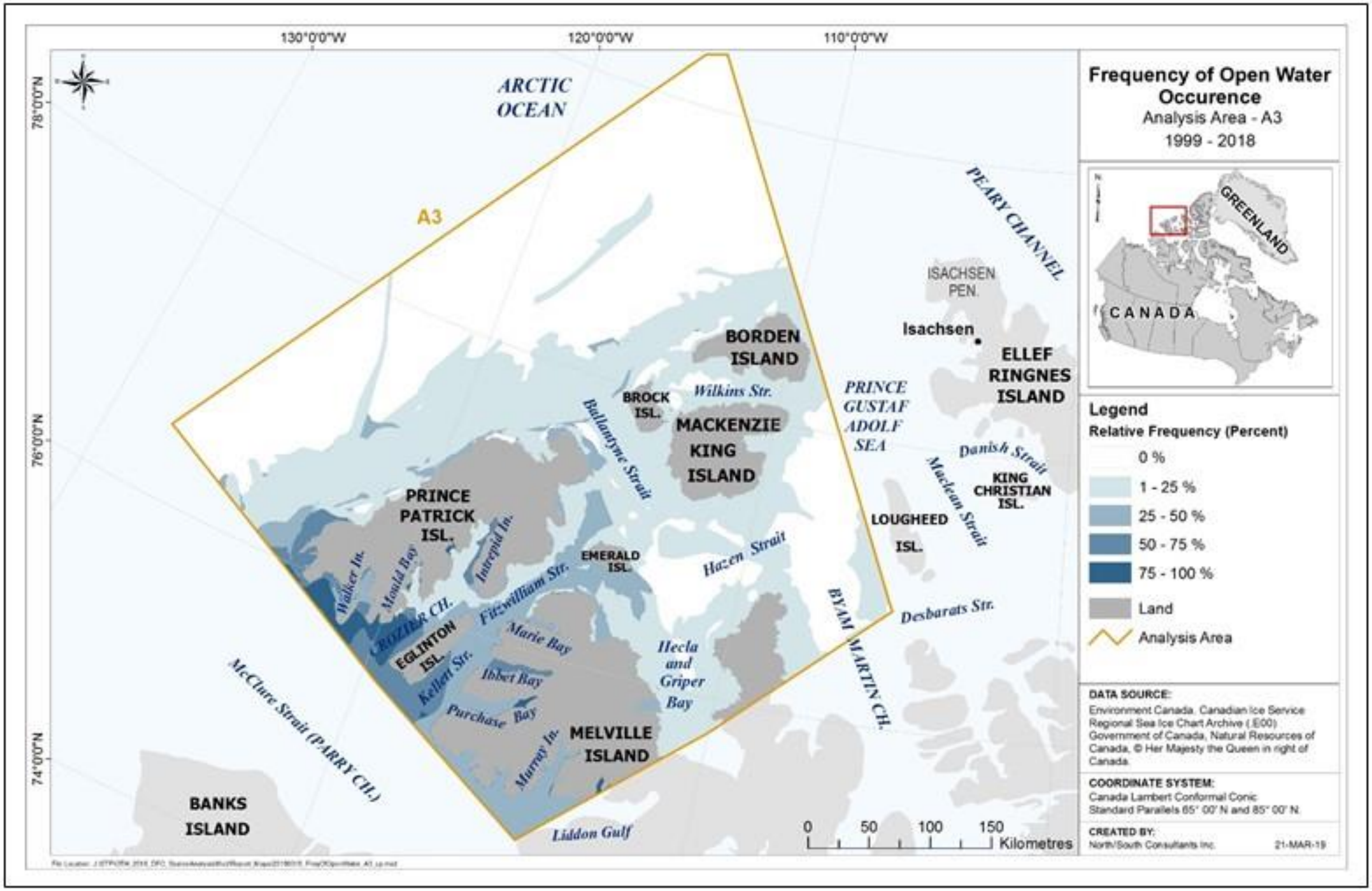


Figure 72. Frequency of occurrence of open water between 1999 and 2018 within region A3.