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Landfast ice properties over the Beaufort Sea region in 2000-2019 from
MODIS and Canadian Ice Service data

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Abstract. Two decades (2000-2019) of the landfast ice properties in the Beaufort Sea region in the Canadian Arctic were analyzed at 250-m spatial resolution from two sources: 1) monthly maps derived at the Canada Centre for Remote Sensing from the Moderate Resolution Imaging Spectroradiometer clear-sky satellite image composites; 2) Canadian Ice Service charts. Detailed comparisons have been conducted for the landfast ice spatial extent, the water depth at and the distance to the outer seaward edge from the coast in four sub-regions: 1) Alaska coast; 2) Barter Island to Herschel Island; 3) Mackenzie Bay; 4) Richards Island to Cape Bathurst. The results from both sources demonstrate good agreement. The average spatial extent for the entire region over the April-June period is $48.5 (\pm 5.0) \times 10^3 \text{ km}^2$ from Canadian Ice Service data vs $45.1 (\pm 6.1) \times 10^3 \text{ km}^2$ from satellite data used in this study (7.0% difference). The correlation coefficient for April-June is 0.73 ($p = 2.91 \times 10^{-4}$). The long term linear trends of the April-June spatial extent since 2000 demonstrated statistically significant decline: $-4.45 (\pm 1.69) \times 10^3 \text{ km}^2/\text{decade}$ and $-4.73 (\pm 2.17) \times 10^3 \text{ km}^2/\text{decade}$ from Canadian Ice Service and satellite data respectively. The landfast ice in the Beaufort Sea region showed the general tendency for an earlier break-up, later onset and longer ice-free period. The break-up date has decreased by 7.6 days/decade in the Mackenzie Bay region. The western part of the study area did not demonstrate statistically significant changes since 2000.

Key words: Landfast ice, Beaufort Sea, Mackenzie Bay, Canadian Arctic, satellite data

42 Introduction

43 Landfast ice (LFI), also known as shore-fast ice, primarily forms in shallow coastal waters. The
44 definition of the landfast ice is provided by the World Meteorological Organization (WMO) in the
45 document “Sea Ice Nomenclature” (WMO, 2014). It is also included in the Manual of Ice (MANICE,
46 2009) compiled by the Canadian Ice Service (CIS). The LFI is generally defined as ice that is attached
47 to the shore, to the bottom of the sea or to the ice wall or grounded icebergs. It may consist of first-
48 year or multi-year ice and can spread from a few meters to several hundred kilometres. The LFI
49 extends along the entire coast of the Beaufort Sea during the cold season and a large part of the
50 summer and represents an important component of the Beaufort Sea climate system (Mahoney,
51 2018). It occupies most of the Canadian Arctic archipelago area in the winter season. The LFI zone
52 serves as an important area that supports the traditional and cultural livelihood of the Inupiat and
53 Inuit people, many Arctic communities and wildlife ecosystems. It provides transportation routes for
54 fishing, hunting and communications between remote and isolated communities, as well as other sea-
55 ice related services for several months each year (Ford et al., 2009; Gearheard et al., 2006; Huntington
56 et al. 2016; Mahoney, 2018; Eicken et al., 2009). It is also an important factor in regulating erosion
57 rates of coastline because the loss of sea ice enhances wave action (Overeem et al. 2011).

58 The LFI is built tightly into the chain of ecosystem functions and services. It serves as important
59 habitat for marine mammals (Laidre and Regehr, 2016; Laidre et al., 2008). The enhanced ecological
60 productivity has been also observed under the LFI and its seaward edge (Mundy et al., 2009; Mundy
61 et al., 2014). The impact of climate change on landfast ice is considered to be one of the most
62 significant factors affecting the Arctic coastal communities and the movement of marine mammals
63 (Loseto et al. 2018; Cooley et al. 2020). It is a well-known fact that the Arctic is warming at a rate
64 almost twice the global average (Overland et al., 2019). This warming trend has a significant impact

on landfast ice extent, formation and break-up. The timing of landfast ice break-up controls the travel patterns and accessibility of beluga whales to the coastal zone. This is an important subsistence species for the Inuvialuit people in the region (Loseto et al. 2018). As such, quantitative information about the spatial and temporal dynamics of coastal zone landfast ice is needed to better assess the impacts of climate change in the Arctic.

The Global Climate Observing System (GCOS) generally requires spatial resolution of 1-5 km and weekly temporal frequency for sea ice extent/edge products (GCOS, 2016). The operational sea-ice mapping, including the landfast ice, is conducted by specialized national agencies, such as the Canadian Ice Service (<https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations.html>) and the U.S. National Ice Center (<https://www.natice.noaa.gov>). These agencies generate daily and weekly products that represent the best estimate of ice properties produced by an integration of data from multiple sources of information including spaceborne, airborne and marine observations. (ECCC, 2020; Tivy et al., 2011). The U.S. National Snow and Ice Data Center (NSIDC) in collaboration with the U.S. National Ice Center generates the daily 4-km and 1-km sea ice products over the Northern Hemisphere termed the Multi-sensor Analyzed Sea Ice Extent - Northern Hemisphere (MASIE-NH) (Fetterer et al. 2010).

The historical archives of ice charts and maps from the national agencies serve as a good source of data for deriving landfast ice climatology and long-term trends. For example, Galley et al. (2012) analyzed the timing of landfast ice conditions in the Canadian Arctic for the period of 1983 – 2009 using the CIS ice charts. They rasterized data to a 2×2 km grid and identified landfast ice using the total sea-ice concentration labelled as 10/10ths following recommendations from Melling (2002) and Tivy et al. (2011). Galley et al. (2012) have reported statistically significant trends for LFI onset (later start by 2.78 week/decade) and break-up (earlier start by 0.65 week/decade) in the Beaufort Sea. Yu et al. (2014) have analyzed the variations of LFI extent in the Arctic coastal areas for 1976

to 2007 from weekly sea ice charts provided by the U.S. National Ice Center. The input data were digitally rasterized to the Equal Area Scalable Earth Grid (EASE-Grid) format at 25-km spatial resolution (Brodzik and Knowles, 2002). The mean LFI extent for the entire Beaufort Sea region in winter (January - May) was found to be $50.04 \times 10^3 \text{ km}^2$, with an absolute negative trend $-0.39 (\pm 0.16) \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ or a relative negative trend at $-7.79 (\pm 3.20) \text{ \%/decade}$ for the annual mean area over the 1976-2007 period. Li et al. (2020b) used the methodology developed by Yu et al. (2014) and extended a similar analysis to the 1976–2018 interval and the same 25-km spatial resolution. The ice charts produced by the Arctic and Antarctic Research Institute (AARI) in St. Petersburg (Borodachev, 1998) and mapped on 12.5 km grid have been utilized by Divine et al. (2003) to analyze the landfast ice extent in the north-eastern part of the Kara Sea from 1953 to 1990.

The LFI has been studied at higher resolution with satellite data from the Synthetic Aperture Radar (SAR) and optical/thermal systems, such as Sentinel-2, LANDSAT and WorldView (Barry et al.; 1979; Karvonen, 2018; Li et al., 2020a; Mäkynen et al., 2020). Dammann et al. (2019) used Sentinel-1 interferometry to map the pan-Arctic LFI in spring 2017. They utilized image pairs to map three LFI categories: a) bottomfast ice, b) stabilized floating landfast ice, c) nonstabilized floating coastal ice. This study emphasized the importance of considering the dynamic LFI stability rather than near-instantaneous ice concentration maps because these may lack sufficient information related to ice mobility at the highest concentration level $10/10^{\text{th}}$.

Mahoney et al. (2014) conducted a very comprehensive study of landfast ice in the Chukchi Sea and the western areas of the Beaufort Sea up to Mackenzie Bay using SAR imagery for the period of 1996–2008. By extending their previous research (Mahoney et al. 2007 a, b), they reported the mean width of the LFI zone in the western part of the Beaufort Sea in April to be about 31 km. In the Chukchi Sea, it was close to 14 km. They detected positive trends in the LFI freeze-up time and negative trends in break-up time, i.e. shorter duration of the LFI existence in this region. The above

results related to the LFI spatial scale derived from high-resolution satellite data, clearly demonstrated that the application of 25-km spatial resolution data for LFI studies in the Beaufort Sea region could be questionable due to insufficient ability to resolve the LFI spatial features.

This paper extends our research on the application of the Moderate Resolution Imaging Spectroradiometer (MODIS) 250-m clear-sky composites produced at the Canada Centre for Remote Sensing (CCRS) (Luo et al., 2008; Trishchenko and Luo, 2021). Trishchenko and Luo (2021) developed a method to delineate the LFI using monthly mean and standard deviation maps of MODIS reflectances. They produced a 20-year time series of LFI properties for the Banks Island area and compared them with the Canadian Ice Service (CIS) charts. The comparison demonstrated good agreement between the MODIS-based CCRS and the CIS results. The average correlation coefficients between the CIS and the CCRS time series of LFI properties were within 0.87-0.88. The relative differences (CIS minus CCRS) of LFI spatial extent, the ocean depth at the LFI edge and the width of the LFI zone ranged from 6.3% to 10%. The current paper advances the application of the developed method to the entire Beaufort Sea area with a detailed analysis for several sub-regions along the southern coast. In addition, it conducts the correlation analysis of derived time series with surface-level air temperatures from the European ERA5 reanalysis (Hersbach et al., 2020).

The application of the CCRS MODIS composites for LFI mapping was initially inspired by the observation of a well-identified zone, closely matching the 20 – 30m isobaths, with an increased probability of sea ice presence along the Beaufort Sea coastline (Fig. 1a-b). A strong relationship between the location of the 20-m isobath and the average boundary of the LFI zone has been reported for Banks Island (Trishchenko and Luo, 2021) and the western part of the Beaufort Sea region (Mahoney et al., 2014). The seasonally aggregated probability maps can serve as a useful proxy for the general location of the LFI zone in the Beaufort Sea region. However, due to the dynamic nature

136 of landfast ice, these results are true only in a qualitative climatological sense, and the better
137 characterization of LFI properties requires more detailed temporal resolution.

138 The main objective of this study is to improve the characterization of landfast ice properties (total
139 area, water depth at outer edge and its distance from shore) over the Beaufort Sea and its sub-regions
140 along the southern coast by extending the method developed by Trishchenko and Luo (2021) to gain
141 a better understanding of multi-year LFI properties and trends in the Beaufort Sea region. Results
142 are based on the 250-m resolution maps derived for the 20-year period: 2000-2019. To our
143 knowledge, this is the first time that LFI in the entire area of the Beaufort Sea is studied at 250-m
144 spatial resolution for such a long time span using data independent of operational ice products.
145 Previous long-term studies utilized data with a very coarse spatial resolution (grid size of 25 x 25
146 km), which raises questions about their ability to adequately describe the LFI cover as the typical size
147 of spatial features is much smaller than grid cell size. Available high-resolution studies do not
148 provide similar spatial and/or temporal coverage for the entire Beaufort Sea area. Comparison of
149 independent data with the CIS ice charts can provide important insights into the potential
150 uncertainties of the operational product. Results are also useful for improving the knowledge of
151 multi-year LFI trends in the Beaufort Sea region since 2000.

152 Study region

153 The coastal ice regime in the Beaufort Sea region (Fig.1 a-c) is generally driven by the
154 bathymetry of the ocean floor in the shallow water zone, by a large-scale ocean circulation system
155 persistent over the region called the Beaufort Gyre (Proshutinsky et al., 2002) and by the seasonal
156 meteorological cycle. The central zone of the Beaufort Sea (Canada Basin) is deeper than 2000m,
157 while shallow (<100 m) shelf and coastal waters extend tens of kilometres from shore (Fig. 1c). The
158 variability in sea ice spatial distribution over the region (Fig.1 a) reflects interannual variations in the

properties of the Beaufort Gyre and associated meteorological conditions. The 2012 summer minimum sea ice cover in the region (Fig. 1 a) occurred as a result of anomalously large solar absorption combined with some other factors (Babb et al., 2016). Reduced summer sea ice cover in 2008 and 2016 can be also observed. Babb et al. (2019, 2020) found a link between the Beaufort Gyre reversal and the preceding summer sea ice minimum in 2016. This reversal caused eastward ice motion in the region, leading to convergence of sea ice in the vicinity of Banks Island. The overall reduction of the summer sea ice cover over the western Beaufort Sea observed in Fig. 1 a is consistent with observations made by Steele et al. (2015). They reported that in recent years, the sea ice in this area has become younger and thinner that resulted in an earlier break-up. Also, the date of ice cover retreat, when concentration falls below 0.15 out of 1, tends to occur earlier, although the trend is not statistically significant (Steele et al. 2015).

Once the landfast ice is formed, its general dynamics are mostly controlled by thermodynamic factors (Barry et al. 1979). The outer seaward ice edge is affected by the ocean surface conditions (waves) and currents, as well as atmospheric circulation that transfers energy and momentum fluxes to sea ice (Carmack and Chapman 2003).

Five sub-regions of the Beaufort Sea were selected for detailed analysis. Region 1 (Alaska coast) stretches from Point Barrow to Barter Island. There is no well-defined LFI zone on the multi-year average probability map for this region (Fig. 1b). This reflects the complexity of coastal zone ice dynamics in this area and explains why the LFI delineation based on optical satellite images can be quite challenging in this region. Region 2 stretches from Barter Island to Hershel Island. The increased probability of the coastal sea ice is pronounced relatively well here. The characteristic feature of this region is the narrow shallow zone with water depths less than 30 m (Figs.1 b-c). Region 3 (Mackenzie Bay) is a shallow zone bordering the Mackenzie River delta, known for its prominent economic and ecological significance. The Mackenzie River provides the largest fresh

183 water and sediment input into the Arctic Ocean from the North American continent. Region 4
184 extends from Richards Island to Cape Bathurst. It has a well-defined zone of an increased presence
185 of coastal ice which closely follows the 20 m isobath. This zone is slightly wider than in other
186 regions. The Banks Island coastal zone (Region 5) demonstrates a very good example of the near-
187 shore sea ice separated from the interior Beaufort Sea ice field by a distinct low probability zone
188 (mostly open water). It has a sharp outer gradient line that closely follows the 20-m – 30-m isobaths.
189 We do not specifically discuss results for the Banks Island region in this paper, as they can be found
190 in Trishchenko and Luo (2021).

191 **Data**

192 **CCRS MODIS composite products**

193 The primary source of satellite data for this study is the MODIS imager operated by the US
194 National Aeronautics and Space Administration (NASA) on the TERRA spacecraft. This is one of
195 the most advanced sensors utilized for a wide range of land, ocean and atmosphere applications
196 (Salomonson et al. 1989). The instrument includes thirty six spectral bands with spatial resolution
197 ranging from 250 m to 1 km at nadir. The MODIS bands 1 (B1, visible) and 2 (B2, near-infrared) are
198 available at 250 m spatial resolution, additional five spectral bands in the solar spectrum (bands B3
199 to B7) are available at 500 m spatial resolution. The remaining twenty nine bands have 1 km spatial
200 resolution at nadir. Two MODIS instruments are currently operational: 1) MODIS on TERRA
201 spacecraft and 2) MODIS on AQUA spacecraft. The regular MODIS observations begun in early
202 2000. They continue to the present time with daily coverage of the globe.

203 This study utilizes the MODIS clear-sky composite products over Canada that are produced at
204 the CCRS from the original MODIS Level 1 (1B) swath data distributed by NASA
205 (<https://ladsweb.modaps.eosdis.nasa.gov/>). The MODIS 500 m bands (B3-B7) are downscaled to

250-m spatial resolution (same as of bands B1 and B2) using adaptive regression and normalization scheme (Trishchenko et al., 2006). They are re-projected into regular map projection using the method of Khlopenkov and Trishchenko, (2008). The re-projected images for bands B1-B7 are composited as 10-day (three per month, thirty six per year) clear-sky products for Canada and the Northern Circumpolar area using a clear-sky, cloud and cloud shadow detection technique developed by Luo et al., (2008) and Trishchenko et al. (2009). The data from the MODIS sensor on TERRA but not on AQUA satellite are regularly processed in this study because the latter has substantial band-to-band misalignment and a significant number of dead detectors (Khlopenkov and Trishchenko, 2008; Xiong et al., 2005, 2006). Clear-sky composites are produced separately for the backward (i.e. sun-satellite relative azimuth angle range -90° to $+90^{\circ}$) and the forward (sun-satellite relative azimuth angle range 90° to 270°) scattering directions.

The main intended use of the CCRS clear-sky composites is for land applications (Beaudoin et al., 2014; Bernier et al., 2011; Betts et al., 2014, 2019; Colditz et al., 2012, 2014; Fontana et al., 2010; Hanesiak et al., 2011; Ji et al., 2010; Liu et al., 2020; Talbot and Meades, 2011; Trishchenko et al., 2009; Trishchenko et al., 2016; Trishchenko and Wang, 2018; Trishchenko and Ungureanu, 2021; Way and Lewkowicz, 2016). The CCRS MODIS processing system has also been successfully applied to lake water quality and algal bloom mapping (El-Alem et al., 2012, 2014, 2019; Ratté-Fortin et al., 2018, 2020), lake ice mapping (Gignac et al., 2017) and some other applications.

An important high-level product derived from the CCRS MODIS time series is the melting season (April-September) snow/ice probability maps designed to study the annual dynamics of Minimum Snow/Ice (MSI) extent (Trishchenko et al., 2016; Trishchenko, 2020; Trishchenko and Ungureanu, 2021). These time series are available at 250-m spatial resolution since 2000 for two regions: a) Canada and neighbouring landmass, $5,700 \text{ km} \times 4,800 \text{ km}$; b) the Northern Circumpolar area, $9,000 \text{ km} \times 9,000 \text{ km}$. Trishchenko and Wang (2018) demonstrated that MSI extent variations

230 over the Canadian Arctic region derived from CCRS warm season snow/ice probability maps are
231 very well correlated to variations in the local climate dynamics, such as warm-season average
232 temperature, energy fluxes, and snow cover. Figs. 1a-b demonstrate that CCRS MODIS composites
233 also have a good potential for landfast ice mapping in the coastal zone.

234 We utilized 10-day 250-m MODIS image clear-sky composites produced for the backward and
235 the forward scattering directions and aggregated them to monthly intervals for the LFI identification.
236 The average cloud fraction observed from MODIS and other sources during the spring and early
237 summer period over the coastal areas of the Beaufort Sea is typically below 0.7, i.e. 70% (Jin et al.,
238 2007; Platnick et al., 2015; Wang and Key, 2005). As such, there is a sufficient number of clear-sky
239 pixels (~30%) each month to observe the landfast sea ice over this region in our images. This value
240 compares favourably with the average global total cloud amount observed from satellites, which is
241 equal to 0.68 (± 0.03) (Stubenrauch et al., 2013) and allows the generation of surface-level products
242 from satellite observations on a routine basis (Liu et al., 2017).

243 The mean (μ) and standard deviation (σ) values of spectral reflectances for MODIS bands B1
244 (red), B2 (near-infrared), B4 (green) and B6 (shortwave infrared) have been computed for each
245 month. The composite maps of the mean reflectances can be utilized for the identification of sea
246 ice, as MODIS bands B1, B2 and B6 have good capability to separate water bodies and snow-free
247 land from snow/ice-covered surfaces. The monthly maps of standard deviations for bands B1, B2 and
248 B4 are used for the identification of variability in spectral reflectances. The areas with high σ -values
249 indicate unstable sea ice conditions (i.e. changes between ice and water) because of large differences
250 in spectral reflectances of water and sea ice and snow. The areas with low σ -values indicate
251 persistently similar surface reflectance and, therefore, point to stable sea ice or open water conditions.
252 Comparisons of high and low σ -values (Fig. 2) for April 2016 show differences in monthly mean

reflectances (bands B6, B2 and B1) and standard deviations of reflectances (bands B4, B2 and B1) composed as false-colour RGB images.

Due to inconsistent results from attempted automated classifications, we have mapped the landfast ice zones manually, employing visual spatial contrasts synchronously observed in two images (μ and σ). Dammann et al. (2019) and Meyer et al. (2011) reported similar approach and recommendations. We limited the application of our method for LFI identification to the April - September time frame because the quality of images in solar bands B1 - B7 is low in the high Arctic zone during the October to March period. Further details of the LFI delineation method can be found in Trishchenko and Luo (2021). The CCRS LFI data are available at this link <ftp://ftp.ccrs.nrcan.gc.ca/ad/Trishchenko/BeaufortSeaLandfastIce.2000-2019/>.

The spatial uncertainty in the delineation of the LFI boundary position using manual mapping is estimated to be ± 1 pixel, which is equivalent to ± 250 m for our imagery and selected map projection. Due to the random nature of errors coming from the manual delineation, we do not expect any systematic spatial biases in the mapping of the LFI boundary position. An additional potential source of uncertainty in the LFI delineation could be incorrect identification of the boundary line separating the stabilized ice from nonstabilized sea ice zones in ambiguous cases. In complex situations, we normally select the LFI position that was consistent with the preceding image history and was located closer to the coast. These rules cannot be easily quantified and converted into uncertainty estimates. Comparison with alternative and independent sources of the LFI edge position would be the best approach to evaluate potential uncertainties in the LFI spatial extent. It constitutes one of the objectives of this study.

276 Canadian Ice Service charts

277 The Canadian Ice Service charts in ArcInfo E00 format were obtained from the CIS archive
278 (<https://iceweb1.cis.ec.gc.ca/Archive/>). These vector data are generated using a map scale of up to
279 1:400,000, which theoretically could correspond to a raster pixel resolution of about 200 metres. The
280 coding of parameters in E00 files follows recommendations of the Sea Ice Geo-Referenced
281 Information and Data (SIGRID) standard (JCOMM, 2014). For mapping the landfast ice we utilized
282 the “form of ice” (F) codes. The landfast ice is coded by value 8 in any of the form of ice fields FA,
283 FB and FC etc. This method is different from the one chosen by Galley et al. (2012) who utilized the
284 “ice concentration” (C) codes CT, CA and CB etc. There are no official recommendations in the
285 SIGRID to link the landfast ice and the ice concentration, although the landfast ice is normally
286 associated with the highest ice concentration 10/10th (i.e. 100%).

287 ArcInfo vector files were converted into raster data on a 250-m spatial grid in map projection
288 compatible with the CCRS MODIS clear-sky composites using the FORTRAN-90 code developed
289 in this project. Most of the CIS data files for the 2000-2019 period are available at weekly temporal
290 resolution. Before 2008, some data for January-April period were available at monthly or bi-weekly
291 intervals. Weekly CIS ice charts over the Beaufort Sea study region were rasterized with four classes:
292 1) open water, 2) landfast ice, 3) ice in any concentration, form and age, and 4) land (Fig 3). Time
293 series of raster files have been produced from January 2000 to December 2019. Because of uneven
294 temporal spacing (weekly, semi-monthly and monthly) of the CIS data, we replicated the low-
295 frequency data points to a weekly temporal resolution when computing monthly and seasonal
296 statistics. This procedure ensures the proper weighting of observations and reduces possible biases
297 due to unequal sampling.

298

Bathymetry and ERA5 temperature

Bathymetry data were required to obtain information about the water depth at the edge of the LFI zone. There is a correspondence between the average seaward LFI edge location and the 20 m isobaths reported for some parts of the Beaufort Sea (Mahoney et al., 2014; Trishchenko and Luo, 2021), but a relationship between water depth and location of the landfast ice edge has not been analyzed yet for the entire Beaufort Sea region.

We used the general bathymetric chart of the oceans (GEBCO, 2020) for bathymetry of the ocean floor and land surface topography from the British Oceanographic Data Center (BODC, <https://www.bodc.ac.uk>). Image tiles were extracted and re-projected from geographic into Lambert Conformal Conic (LCC) projection at 250 m spatial resolution and merged over the study region (Fig. 1c).

We utilized the monthly mean surface air temperature fields at 2m height (T2m) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) in the framework of the latest climate reanalysis ERA5 (Copernicus Climate Change Service (C3S), 2020; Hersbach et al., 2020) to study a possible correlation between time series of the LFI spatial extent and climate conditions. The ERA5 T2m dataset with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ were remapped at 250m spatial resolution into the LCC map projection using a bilinear resampling scheme as described by Trishchenko (2019). Linear trends of mean temperature for the January-May, the April-June and the annual time series over the period of 2000-2019 were computed for a joint analysis with the LFI data showing positive trends over the whole region since 2000 (Fig. 4). Regions 1 - 4 along the southern coastal zone have the highest T2m increase rates. The largest annual trends have been detected over the Mackenzie Bay area where the annual mean rate is about 2K/decade and can be even larger during the January-May season.

Derived parameters

For all of the Beaufort Sea sub-regions we have estimated the following parameters: a) the LFI spatial extent, b) the distance of outer seaward LFI edge from the coast, c) the water depth at the outer seaward LFI edge, d) the date of LFI onset, e) the date of LFI break-up, f) the length of the ice-free period (as a conjugate parameter to the LFI duration period). The timing parameters (d-f) have been derived from the Canadian Ice Service time series, as the CCRS monthly data have no sufficient temporal resolution for this purpose. We utilized the threshold area of 0 km² for the total LFI extent (S) over the entire sub-region to determine the onset and break-up dates (i.e. S=0 km²). This approach differs from the one implemented by Galley et al. (2012) who determined the onset and break-up dates for each grid cell 2 km × 2 km and then aggregated results over a specific study region. For each sub-region we displayed time series of the above parameters with an original temporal resolution, multiannual time series of January-May mean values (winter season as defined by Yu et al., 2014) and April-June mean values (spring season as defined by Trishchenko and Luo (2021) for comparison between the CIS and the CCRS results), as well as their seasonal cycle (monthly mean values).

Results

Region 1: Alaska coast

The CCRS and CIS time series of spatial LFI extent for Region 1: Alaska coast (Fig. 5 a-c) show a generally high degree of consistency with a correlation coefficient of about 0.65 (Fig. 5 b). There is higher variability in the CIS results relative to the CCRS time series (Fig.5 a), which can be attributed to the higher temporal frequency of the CIS data (weekly CIS versus monthly CCRS maps), as well as to the different length of data collection interval (one day in CIS ice chart versus one month

in CCRS method). A much shorter data collection period may lead to the possible inclusion of nonstabilized ice with high concentration at the outer ice edge into the landfast category because the ice stability can not always be reliably determined using the data collected on a specific date. The monthly aggregated interval employed in the CCRS LFI retrievals provides better discrimination of stabilized vs nonstabilized sea ice based on monthly statistics of reflectance. As a consequence, the CCRS LFI maps systematically underestimate the area relative to the CIS results (on average by ~7.2% for Region 1, see Table 1).

The linear trend for the CIS winter spatial extent is small and positive: $+0.58 (\pm 1.41) \times 10^3$ km²/decade (Table 2). Trends for the spring spatial extent are small and negative $-0.45 (\pm 1.22) \times 10^3$ km²/decade (CIS) and $-0.57 (\pm 1.01) \times 10^3$ km²/decade (CCSR). All trends for Region 1 in Table 2 are not statistically significant, which is in general agreement with Mahoney et al. (2014) conclusion for the 1996–2008 period.

Despite the good general agreement between the CIS and the CCRS results, a few outliers were observed in the spring of 2009, 2010 and 2019. An example of this comes from April 2009 dataset (Fig. 6) which shows large variability in the weekly extents of the CIS LFI zones for Regions 1 - 3 and the western part of Region 4. The CIS LFI area for April 27, 2009, is the smallest among the three charts. The area for April 20, 2009, is the largest one. Because the CCRS method uses monthly variability to determine stable areas corresponding to low values of standard deviations, it maps the minimum envelope, i.e. infimum, of LFI spatial extent for that month. It is clear that although the CIS operational ice product provided an adequate identification of the landfast zone for each date, on a monthly time scale, the large LFI areas displayed in violet-purple shades in Figs. 6 a-b correspond to nonstabilized fractured ice identified using the CCRS monthly composite images (Fig 6 c-d).

The agreement between the CCRS and the CIS results for the average water depth at the outer seaward LFI edge (Figs. 5 e, f, g) is good with an average correlation coefficient of 0.61 (Fig. 5 f)

368 and the average difference in spring equal to 7.74 m (CIS: -38.24 m versus CCRS: -30.5 m; Table 3).
369 The main reason for the CCRS-CIS bias stems from the fact that the CIS characterise the ice as
370 landfast further toward the outer seaward edge. In Region 1 the ocean depth increases sharply
371 converting small differences in the CCRS and the CIS positions of LFI outer edge into large
372 differences in the associated water depth.

373 The average distances of the outer seaward LFI edge from the coast (Figs. 5 i-k) demonstrate
374 general agreement between the CCRS and the CIS data with correlation coefficient for the spring
375 months equal to 0.65 (Fig. 5 j). The average difference is 2.81 km or 10.2% (CIS: 27.66 km versus
376 CCRS: 24.85 km; Table 4). Comparison of the annual cycle of all three parameters (spatial extent,
377 ocean depth and distance from coast) clearly shows underestimation of CCRS results for the outer
378 LFI edge position relative to the CIS data (Fig 5).

379 The timing of spring LFI break-up, autumn LFI onset and duration of LFI-free season and their
380 long-term trends over the 2000-2019 period for Region 1 (Alaska) show the later onset, the earlier
381 break-up and the longer ice-free period (Fig 7). However, all these trends are not statistically
382 significant

383 **Region 2: Barter Island - Hershel Island**

384 Region 2 has the smallest area among all regions. The multi-annual mean distribution of sea ice
385 probability (Fig.1 b) shows that this region belongs to a transition zone where the coastal LFI
386 properties are not easily separated from the mobile ice zone at least over its western part. The
387 characteristic feature of this region is the very narrow zone of 30 m isobath (Figs.1 b, c) that embraces
388 most of LFI extent in the Beaufort Sea region. Figs.8 a-c display time series of the LFI spatial extent
389 for Region 2 (Barter – Hershel). The overall agreement between the CIS and the CCRS results is
390 reasonable, but not as good as for other sub-regions. The difference in the spring LFI extent is

0.42×10³ km² (2.32×10³ km² from CIS versus 1.90×10³ km² from CCRS) or 18.1%. The correlation coefficient is 0.20 (Fig. 8 b). The CIS time series contain a significant number of outliers. Close analysis shows that the main reason for differences between the CCRS and the CIS LFI delineation relates to the characterization of ice at the outer edge which is similar to discrepancies found in Region 1 (Alaska). The long-term trends of the LFI spatial extent in Region 2 are negligible and statistically not significant (Table 2).

Results for the water depth at the outer seaward LFI edge are shown in Figs. 8 e-g. The level of agreement between the CIS and the CCRS results reflects the situation for their LFI spatial extent. The difference for the April-June depth is equal to 10.98 m (-32.48 m for the CIS data and -21.50 m for the CCRS data). This difference is 33.8% relative to the CIS value. The big difference is mainly driven by a very large outlier described earlier for April 2009, and also by a significant outlier observed in 2019. The correlation coefficient (largely affected by these two outliers) between the CCRS and the CIS spring data is -0.24 (Fig. 8 f). Except for these two cases, the variations of CCRS and CIS data follow each other closely in the -20 m to -30 m depth range. Two outliers identified in 2009 and 2019 are not only the outliers in terms of large differences between the CCRS and the CIS data, but these outliers are also large anomalies relative to the Region 2 bulk CIS results which vary mostly within a depth range from -20 m to -30 m.

Figs. 8 i-k show the average distance of the outer seaward LFI edge from the coast for Region 2. The level of agreement is reasonable and reflects the situation described for the LFI spatial extent. The correlation coefficient is equal to 0.19 (Fig. 8 j). The absolute difference is 2.37 km (11.31 km from CIS versus 8.94 km from CCRS) or 21% relative to the average CIS distance in spring.

The seasonal cycle (monthly mean values) of all three parameters for Region 2 (Figs. 8 d, h, l and Tables 1, 3, 4) are in reasonable agreement except multi-annual monthly mean CIS values for April that are not consistent with the rest of the CIS and CCRS data. The trends in LFI break-up and

415 onset dates and length of the ice-free period agree with general warming trends, i.e. earlier break-up,
416 later onset and longer ice-free interval, although these trends are not statistically significant (Fig.7 b).

417 **Region 3: Mackenzie Bay**

418 Region 3 has two interesting features of LFI extent: 1) contours of increased sea ice presence
419 follows closely the shape of the 20 m isobath; 2) there is a noticeable area of reduced sea ice presence
420 along the boundary of the Mackenzie River delta (Fig. 1 b). The first feature is consistent with
421 findings reported by Trishchenko and Luo (2021) for Banks Island landfast ice properties and the
422 conclusion of Mahoney et al., (2014) for the western part of the Beaufort Sea. The second feature is
423 associated with the role of large freshwater discharge from the Mackenzie River in spring break-up
424 and its effect on the LFI melting because the Mackenzie River can transport an enormous amount of
425 heat across immense continental watersheds into the Arctic Ocean (Nghiem et al., 2014). The
426 agreement between the CCRS and the CIS data is generally very good for this region (Fig. 9 a). The
427 difference in the LFI spatial extent for the spring season (April-June) is $0.68 \times 10^3 \text{ km}^2$ ($9.17 \times 10^3 \text{ km}^2$
428 from CIS data and $8.49 \times 10^3 \text{ km}^2$ from CCRS data) or 7.4% relative to CIS value. The correlation
429 coefficient between the CIS and the CCRS data for the spring is 0.84 despite a few outliers including
430 the one already described for April 2009 (Fig. 9 b). The multi-annual linear trends (Fig. 9 b) show
431 a statistically significant decrease in the spring LFI area for both sources: CIS and CCRS. The linear
432 trends for the springtime series are $-1.68 (\pm 0.60) \times 10^3 \text{ km}^2/\text{decade}$ ($p=0.01$) for the CIS data and -1.88
433 $(\pm 0.79) \times 10^3 \text{ km}^2/\text{decade}$ ($p=0.03$) for the CCRS data. The linear trend for the winter period is less
434 significant: $-0.73 (\pm 0.57) \times 10^3 \text{ km}^2/\text{decade}$ ($p=0.22$). The April-June LFI spatial extent shows a
435 strong and statistically significant negative correlation with the ERA5 T2m temperature time series
436 for the Mackenzie Bay area which is consistent with physics describing the impact of the warming

environment on the cryosphere. The correlation coefficient between the CCRS and ERA5 time series is -0.45 ($p=0.048$) and -0.66 ($p=0.001$) between the CIS and ERA5 time series.

The CIS and CCRS comparison of the water depth at the outer seaward LFI edge shows a difference for the April-June mean values of 8.00 m (-33.26 m from CIS data and -25.26 m from CCRS data) or 24% (Fig 9). The correlation coefficient is 0.22 (Fig. 9 f), however, if the outliers for 2009 were removed, the correlation would increase to 0.80.

The CIS and CCRS time series with original temporal resolution show good general agreement to the calculated average distance to the seaward edge (Figs 9 i-k) with only a few significant outliers (observed in April 2009, and on January 30, 2012). These one-point anomalies had a very significant impact on all three analyzed LFI parameters. The January anomaly had no effect on the CIS-CCRS comparison conducted for April-June data. The difference between the CIS and the CCRS mean values of the average outer seaward LFI edge distance from the coast is 2.74 km (28.76 km from CIS data and 26.02 km from CCRS data) or 9.5%. The correlation coefficient for the April-June time series is 0.79 (Fig. 9j). The impact of these two outliers is observed as large standard deviations for winter seasons 2009 and 2012 as shown in Fig. 9 k.

Analysis of the seasonal cycle and monthly mean standard deviations can serve as a good consistency check for the quality of input data. This is shown in Figs. 9 d, h, l and in Tables 1, 3 and 4. Large standard deviations of the CIS values for all three parameters (extent, depth and distance) for January and April may indicate possible inconsistencies with LFI delineation in the CIS data. Large standard deviations in June are expected due to intensive melt and rapid decrease of LFI cover during this period.

Trends in the break-up and onset dates and duration of the ice-free season for Region 3 (Mackenzie Bay) reveal no evident trend in the timing of freeze-up onset (Fig. 7c). It shows only a minor indication of earlier start: $-0.11 (\pm 0.30)$ day/year with $p=0.72$ (i.e. not statistically significant).

461 However, there is a statistically significant signal of an earlier break-up: $-0.76 (\pm 0.26)$ day/year
462 ($p=0.01$). The combination of these two trends leads to a noticeable increase in the duration of the
463 ice-free season for the Mackenzie Bay region by $0.64 (\pm 0.47)$ day/year, although this is not very
464 significant in the statistical sense ($p=0.19$).

465 **Region 4: Richards Island - Cape Bathurst**

466 The Region 4 time series of the LFI spatial extent from the CIS and the CCRS show a high level
467 of agreement (Fig 10 a-c). Only one noticeable outlier can be seen for January 2012 in the CIS data
468 with no impact on comparison between the CIS and the CCRS springtime series. A very high degree
469 of correlation (0.93) exists between the CIS and CCRS time series for the April-June season (Fig.
470 10b). The average difference between the CIS and the CCRS mean values of LFI spatial extent is
471 $0.47 \times 10^3 \text{ km}^2$ ($12.92 \times 10^3 \text{ km}^2$ from the CIS data and $12.45 \times 10^3 \text{ km}^2$ from the CCRS data) or 3.6%
472 relative to the CIS LFI mean. Both data sources demonstrate statistically significant negative trends
473 for the April-June period: $-2.12 (\pm 0.83) \times 10^3 \text{ km}^2/\text{decade}$ with $p=0.02$ for the CIS LFI spatial extent
474 and $-2.06 (\pm 0.96) \times 10^3 \text{ km}^2/\text{decade}$ with $p=0.05$ for the CCRS LFI spatial extent (shown as dashed
475 lines in Fig. 10 b). Together with Region 3 (Mackenzie Bay) this region contributes toward
476 statistically significant negative trends in the April-June LFI spatial extent for the entire Beaufort
477 Sea. The LFI spatial extent for Region 4 shows a strong correlation with the ERA5 T2m
478 temperatures. The correlation coefficient between the April-June CIS and the ERA5 T2m time series
479 over the 2000-2019 period is -0.62 ($p=0.003$). The correlation between the CCRS and the ERA5
480 April-June time series is -0.51 ($p=0.02$). The correlation between the CIS LFI extent for the winter
481 period (January-May) and the ERA5 is -0.37 and less statistically significant than the other two
482 ($p=0.11$).

Comparison of the average water depth at the outer seaward LFI edge shows a high degree of consistency between the two products (Fig 10 e-g). Time series from the CIS and the CCRS sources demonstrate a high degree of consistency with a correlation coefficient equal to 0.93 ($p = 3.98 \times 10^{-9}$) (Fig. 10 f) and the value of average difference equal to 1.99 m (-20.56 m from CIS data and -18.57 m from CCRS data). The average water depth varies mostly between 10 m and 30 m. The 20 m isobath position is remarkably consistent with increased sea ice presence in this region, as shown in Fig. 1b.

The results for the distance from the coast for the outer seaward LFI edge show a very high level of agreement between the CIS and the CCRS time series ($r = 0.93$, $p = 4.34 \times 10^{-9}$) for the April-June data (Fig. 10 i-k). The difference of the April-June mean values is 2.76 km (28.77 km for the CIS data and 26.01 km for the CCRS data) or 9.6% of the CIS average value. There is an overall negative trend in the 2000 - 2019 time series for the distance, which is consistent with the negative trend for the LFI spatial extent and increase in the surface air temperature as shown in Fig. 4 for the ERA5 T2m.

The seasonal cycle for Region 4 (Figs. 10 (d, h, l)) does not show any noticeable deviations of from the regular annual cycle pattern. We attribute it to the lack of any significant outliers in the data except the anomaly on January 30, 2012, in the CIS time series. This single anomaly has been averaged out considerably in the monthly means. The LFI spatial extent reaches a maximum during the April-May period ($13.76 \times 10^3 \text{ km}^2$ and $14.14 \times 10^3 \text{ km}^2$ for CIS data versus $13.15 \times 10^3 \text{ km}^2$ and $13.67 \times 10^3 \text{ km}^2$ for CCRS data). The ocean depth at the outer seaward LFI edge reaches minimum values in the April-May period (-21.49 m and -22.28 for CIS data and -19.43 m and -20.54 m for CCRS data). The distance from the coast reaches maximum values (30.06 km and 31.12 km for CIS data and 27.06 km and 28.54 km for CCRS data).

506 The trends in LFI break-up and onset dates as well as the duration of the ice-free period indicate
507 tendencies for the later onset, earlier break-up and longer ice-free period (Fig.7 d), however, none of
508 the results are statistically significant.

509 **Beaufort Sea LFI spatial extent**

510 This section provides the Beaufort Sea region-wide summary for the LFI extent, which can be
511 considered mathematically as an additive parameter. The derivation of region-wide properties related
512 to the water depth at the outer seaward LFI edge, the distance of the outer seaward LFI edge from the
513 coast and the LFI timing features is not as straightforward as the LFI spatial extent. Zones of
514 stabilized landfast ice over the Beaufort Sea region are frequently found in the mouth of M'Clure
515 Strait, Amundsen Gulf and around Prince Patrick Island (Fig. 1). These zones of stabilized ice are
516 located over deep-water areas. Its evolution cycle is different from the LFI in the southern coastal
517 areas and may include multi-year ice. For these reasons, it makes sense to provide the mapping of
518 detailed LFI properties separately for each region, but mixing them together for the entire Beaufort
519 Sea could lead to misrepresentation of LFI properties that are not linear and not additive.

520 Due to the large size of the region, only the major outliers can be observed in the CIS data, such
521 as those that occurred in January 2009, January 2012 and April 2019 (Figs. 11 a-c). Despite these
522 anomalies, the overall agreement between the CIS and the CCRS results is very good. The correlation
523 coefficient for April-June LFI spatial extent time series is 0.73 ($p=2.91\times10^{-4}$) (Fig. 11 b). The mean
524 difference between the CIS and the CCRS average April-June results is 3.33×10^3 km² (48.44×10^3
525 km² from CIS and 45.11×10^3 km² and CCRS data) or 6.7% relative to CIS mean value. The
526 systematic underestimation seen in the CCRS data with respect to the CIS results happens due to the
527 large difference in sampling intervals used for mapping of ice properties (one day in the CIS ice chart
528 production and one month in the CCRS method). Negative linear trends in the average April-June

multi-year time series of the LFI spatial extent for 2000-2019 are statistically significant, and are detected in both the CIS and the CCRS data: $-4.45 (\pm 1.69) \times 10^3 \text{ km}^2/\text{decade}$ ($p=0.02$) and $(-4.73 (\pm 2.17) \times 10^3 \text{ km}^2/\text{decade}$ ($p=0.04$), respectively (Table 2 and Fig. 11 b). The trend for average LFI spatial extent for January-May is smaller and not statistically significant: $-1.03 (\pm 1.66) \times 10^3 \text{ km}^2/\text{decade}$ ($p=0.54$).

The mean annual cycle of the LFI spatial extent for the entire Beaufort Sea region (Fig. 11 d) show peaks occurring in April-May with the average CIS values of $53.43 \times 10^3 \text{ km}^2$ and $52.66 \times 10^3 \text{ km}^2$, and the CCRS values of $47.67 \times 10^3 \text{ km}^2$ and $49.14 \times 10^3 \text{ km}^2$, respectively. The annual mean LFI extent over the entire Beaufort Sea region is $26.72 \times 10^3 \text{ km}^2$, i.e. it is about half of the maximum value.

Yu et al. (2014) reported the average value of $50.04 \times 10^3 \text{ km}^2$ for the January-May season over the 1976 to 2007 period and a negative trend of $-0.39 (\pm 0.16) \times 10^3 \text{ km}^2/\text{yr}$. Projecting their average value with the reported trend leads to the estimate of the 2000 - 2019 average LFI area equal to $43.02 \times 10^3 \text{ km}^2$ which is close (within 5%) to the average value of $45.95 \times 10^3 \text{ km}^2$ derived from the CIS data in this study. This is a somewhat surprising finding taking into account that the results of Yu et al. (2014) have been derived from very coarse resolution data (25 km grid cell). Data with such a coarse spatial resolution cannot adequately capture the properties of a phenomenon with typical spatial size (distance from the coast) that ranges from a few km to about 32 km (Table 3). For the additive parameters, such as the areal extent, it is still possible to obtain accurate overall results if coarse spatial resolution data include accurate fractional coverage values within each grid cell. However, the determination of the accurate fractional values still requires high-resolution input. Another important fact is that our analysis for the January-May season over 2000-2019 (Table 2) showed a much weaker trend $-0.103 (\pm 0.166) \times 10^3 \text{ km}^2/\text{yr}$ which is not statistically significant. As such, it is also possible that close agreement between projected and observed results reported above

can be explained by compensation of errors in the absolute values and their trend derived from coarse resolution data. The re-analysis of historical CIS data at their original high spatial resolution could shed more light on this issue.

Dammann et al. (2019) reported the LFI extent (bottomfast, stabilized and nonstabilized coastal ice) derived from high-resolution SAR imagery over the Beaufort Sea between March and May 2017 equal to $67 \times 10^3 \text{ km}^2$. This included $35 \times 10^3 \text{ km}^2$ of stabilized ice and $2.5 \times 10^3 \text{ km}^2$ of bottomfast ice. The total LFI area (bottomfast and stabilized ice) was, therefore, $37.5 \times 10^3 \text{ km}^2$. Our estimates for the March-May period of 2017 derived from results presented in Fig. 11 a show the mean LFI spatial extent of $53.35 (\pm 1.42) \times 10^3 \text{ km}^2$ with a maximum of $60.08 \times 10^3 \text{ km}^2$, minimum $44.68 \times 10^3 \text{ km}^2$ and the median value of $52.10 \times 10^3 \text{ km}^2$. The CCRS-derived LFI extent for April-May 2017 is equal to $53.41 \times 10^3 \text{ km}^2$, which is close to the CIS mean value for March-May. This comparison shows that Dammann et al. (2019) estimates of the LFI extent from SAR are generally lower than ours by about 30%, and our results are about 25% lower than Dammann et al. (2019) estimates of the total coastal ice extent that include nonstabilized LFI zone. This fact requires further investigation and may be attributed to more conservative LFI identification using SAR interferometry than our approach with optical images.

Discussion and conclusions

Despite a long history of operational landfast ice mapping, some important issues related to detailed accuracy and climatology of the LFI in the Beaufort Sea region remain to be addressed. Several recent studies based on high-resolution satellite data pointed to a few important issues:

- 1) Reported long-term trends, such as changes in the LFI spatial extent and timing parameters related to the LFI annual cycle, are not always consistent between different sources and may

vary from one sub-region to another due to regional climate variations (Galley et al. 2012; Mahoney et al., 2014; Yu et al., 2014; Li et al., 2020b; Trishchenko and Luo, 2021);

2) The typical width of the LFI zone along the coast at the peak season (April-May) in the Beaufort Sea ranges from less than 10 km to about 30 km (Mahoney et al., 2014; Trishchenko and Luo, 2021). The outer edge of the LFI zone generally follows the 20 m - 30 m isobaths;

3) Reliable identification of the LFI zone requires multi-temporal data analysis that should include not only the ice concentration but also the assessment of ice stability, especially at the outer LFI edge (Dammann et al., 2019).

This study addresses some of these issues based on the approach developed by Trishchenko and Luo (2021) for the LFI mapping around Banks Island using MODIS 250-m imagery and extended it to the entire Beaufort Sea region. The 250-m spatial resolution imagery resolves very well the LFI spatial features with a typical size of several kilometres.

Monthly time series of the landfast ice parameters (spatial extent, average distance from the coast and average water depth at the outer seaward edge) for 2000-2019 were produced for the April-September period each year. The statistics for water depth and distance of the outer seaward LFI edge from the coast were systematically derived for the entire Beaufort Sea region over a 20-year period for the first time to the best of our knowledge. Results were compared with the Canadian Ice Service (CIS) ice charts and were found to be in good agreement. On average, the CCRS results showed systematic bias (6.7%) toward a smaller LFI area, as well as the shallower depth and shorter distance of the LFI edge from the coast. We attribute this to a better ability of the CCRS method to discriminate nonstabilized ice at the edge of the LFI zone.

Comparison of the Beaufort Sea region-wide LFI spatial extent derived in this study with data from Yu et al. (2014) also showed good agreement for January-May average value. This is a somewhat surprising finding taking into account that Yu et al. (2020) used a coarse resolution 25-km

599 spatial grid, which cannot adequately resolve the LFI spatial features over most parts of the Beaufort
600 Sea coastline, where the width of the LFI zone on average is below 30 km (Table 4), (Mahoney et
601 al., 2014; Trishchenko and Luo, 2021). The coarse resolution data should likely lead to an
602 underestimation of the LFI total area unless these data include accurate fractional values of LFI for
603 each grid cell. The other possibility is that the Beaufort Sea boundary is defined over a larger region
604 in Yu et al. (2014) than in our study. In Fig. 1 of Yu et al., (2014) the weekly ice map over the
605 Beaufort Sea region also included a large area of Amundsen Gulf which usually contains significant
606 amounts of landfast ice. It is also possible that the coarse resolution data contain some uncertainties
607 that lead to error compensation during the extrapolation of historical results. This hypothesis requires
608 further investigation and re-analysis of historical CIS data at their original high spatial resolution.

609 The derived long-term trends in the LFI properties from different sources are generally consistent
610 in detecting the overall negative trend in the LFI spatial extent over the entire Beaufort Sea region.
611 However, they differ in the magnitude of the trend and assessment of its statistical significance. Yu
612 et al. (2014) reported a negative trend $-0.39 (\pm 0.16) \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ (not significant at 0.05) for the
613 January-May interval over the 1976-2007 period. Li et al. (2020b) reported $-0.35 (\pm 0.20) \times 10^3 \text{ km}^2$
614 yr^{-1} trend for a similar parameter over the 1976-2018 period and found it statistically significant at
615 0.01 level, which is difficult to interpret taking into account that the stated magnitude and error should
616 indicate even less statistical significance than the one reported by Yu et al. (2014). Our results also
617 show the negative trend for the January – May period in 2000-2019, however, it is about four times
618 smaller and is not statistically significant: $-0.103 (\pm 0.166) \times 10^3 \text{ km}^2/\text{yr}$ ($p=0.54$). Statistically
619 significant negative trends are detected for the April-June multi-year time series: $-4.45 (\pm 1.69) \times 10^3$
620 $\text{km}^2/\text{decade}$ ($p=0.02$) and $-4.73 (\pm 2.17) \times 10^3 \text{ km}^2/\text{decade}$ ($p=0.04$), from the CIS and the CCRS data
621 respectively (Table 2). The western part (Region 1: Alaska coast and Region 2: Barter – Hershel)
622 shows a much smaller magnitude of trends than the eastern part (Region 3: Mackenzie Bay, Region

4: Richards – Bathurst). The eastern part because of its large size drives the trend for the entire Beaufort Sea.

Similar to Mahoney et al., (2014), our study confirms that 20 m to 30 m isobaths generally correspond to the average position of the outer seaward LFI edge for the entire southern coastline of the Beaufort Sea and Banks Island regions (Regions 1-5) during the LFI peak season.

The long-term trends in the timing parameters of the LFI annual cycle show generally earlier break-up and the later freeze-up onset dates, and longer ice-free periods for the Beaufort Sea area. However, all these trends are not statistically significant, except the earlier break-up trend $-0.76 (\pm 0.26)$ day/yr ($p=0.01$) for Region 3 (Mackenzie Bay). The declining LFI extent and trends in the timing parameters are generally consistent with the trends observed in the ERA5 surface air temperature at 2 m height (T2m) shown in Fig.4. The large-scale analysis of the LFI properties across the Beaufort Sea region highlights the sensitivity of the Mackenzie Estuary (Region 3) to climate change. Improved accuracy of landfast ice mapping in this region, in particular, will enhance the safety, livelihood and ability of the Inuvialuit people in this region to adapt.

The analysis of long-term monthly mean values and standard deviations of the LFI parameters combined with a visual inspection of time series at the original temporal resolution revealed a few large outliers in the CIS time series. These outliers correspond to rare cases of the CIS LFI maps that extend well beyond the average boundary. These anomalies may originate from the inclusion of nonstabilized ice with a high concentration located at the edge of the stable LFI zone into the landfast category.

Our study confirmed the advantage of using operational full-resolution maps of landfast ice at sub-kilometre spatial resolution for adequate studies of climatology in the Beaufort Sea region. The mapping consistency of landfast ice spatial features can also benefit from the multi-temporal analysis and availability of satellite imagery with high temporal frequency (Trishchenko and Garand, 2011,

647 2012; Trishchenko et al., 2016, 2019) that can better classify the areas of stabilized and nonstabilized
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Tables

Table 1. Monthly, seasonal and annual mean values of the total LFI area (10^3 km^2) derived from the CIS and the CCRS data for 2000-2019.

Month	Region 1 Alaska		Region 2 Barter - Hershel		Region 3 Mackenzie Bay		Region 4 Richards - Bathurst		Beaufort Sea entire region	
	CIS	CCRS	CIS	CCRS	CIS	CCRS	CIS	CCRS	CIS	CCRS
1	10.66	-*	1.24	-	7.64	-	9.66	-	33.71	-
2	15.05	-	1.49	-	8.68	-	11.48	-	42.59	-
3	16.52	-	1.88	-	9.77	-	12.95	-	47.39	-
4	19.09	16.83	2.80	1.94	10.99	10.00	13.76	13.15	53.43	47.67
5	18.91	17.23	2.41	2.14	10.87	10.11	14.14	13.67	52.66	49.14
6	15.12	15.27	1.76	1.63	5.65	5.35	10.85	10.53	39.25	38.51
7	1.56	0.16	0.10	0.01	0.15	0.03	0.45	0	5.01	4.32
8	0	0	0	0	0	0	0	0	0.47	2.22
9	0	0	0	0	0	0	0	0	0.42	0.92
10	0.97	-	0.05	-	0.46	-	0.49	-	3.54	-
11	4.65	-	0.47	-	4.10	-	3.93	-	16.00	-
12	7.91	-	0.71	-	5.89	-	7.81	-	26.14	-
1-5	16.05	-	1.96	-	9.59	-	12.40	-	45.95	-
4-6	17.71	16.44	2.32	1.90	9.17	8.49	12.92	12.45	48.44	45.11
1-12	9.20	-	1.08	-	5.35	-	7.13	-	26.72	-

* dash “-” denotes no data available from CCRS retrievals due to solar zenith angle limitations

Table 2. The long-term linear trends ($10^3 \text{ km}^2/\text{decade}$) and their uncertainty for LFI spatial extent over the 2000-2019 period. Statistical significance ($p=\text{Prob}>|t|$ or p-value) is shown in parentheses. Numbers in bold indicate statistically significant trends at $p \leq 0.05$.

Region		Season	
		Winter (Jan-May)	Spring (Apr-June)
1 - Alaska	CIS	0.58 ± 1.41 (0.69)	-0.45 ± 1.22 (0.72)
	CCRS	-	-0.57 ± 1.01 (0.58)
2 - Barter - Hershel	CIS	0.21 ± 0.25 (0.42)	0.00 ± 0.25 (0.99)
	CCRS	-	-0.08 ± 0.20 (0.69)
3 - Mackenzie Bay	CIS	-0.73 ± 0.57 (0.22)	-1.68 ± 0.60 (0.01)
	CCRS	-	-1.88 ± 0.79 (0.03)
4 - Richards - Bathurst	CIS	-0.95 ± 0.59 (0.12)	-2.12 ± 0.83 (0.02)
	CCRS	-	-2.06 ± 0.96 (0.05)
Beaufort Sea	CIS	-1.03 ± 1.66 (0.54)	-4.45 ± 1.69 (0.02)
	CCRS	-	-4.73 ± 2.17 (0.04)

Table 3. Monthly, seasonal and annual mean values of the average ocean depth (m) at the outer seaward LFI edge derived from the CIS and the CCRS data over the 2000-2019 period.

Month	Region 1 Alaska		Region 2 Barter - Hershel		Region 3 Mackenzie Bay		Region 4 Richards - Bathurst	
	CIS	CCRS	CIS	CCRS	CIS	CCRS	CIS	CCRS
1	-14.28	-	-18.19	-	-24.51	-	-12.18	-
2	-26.63	-	-18.12	-	-22.99	-	-16.12	-
3	-32.97	-	-21.06	-	-27.27	-	-19.48	-
4	-49.43	-36.11	-50.92	-21.48	-44.72	-28.53	-21.49	-19.43
5	-37.24	-31.16	-25.30	-23.18	-35.52	-28.45	-22.28	-20.54
6	-28.06	-24.22	-21.21	-19.85	-19.54	-18.78	-17.90	-15.73
7	-18.19	-	-16.73	-12.09	-7.49	-	-9.58	-
8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-
10	-1.54	-	-2.42	-	-1.50	-	-1.67	-
11	-3.54	-	-7.19	-	-5.51	-	-4.14	-
12	-8.72	-	-10.60	-	-10.76	-	-9.36	-
1-5	-32.11	-	-26.72	-	-31.00	-	-18.31	-
4-6	-38.24	-30.50	-32.48	-21.50	-33.26	-25.26	-20.56	-18.57
1-12	-22.06	-	-19.18	-	-19.98	-	-13.42	-

Table 4. Monthly, seasonal and annual mean values for the average distance (km) of the outer seaward LFI edge from the coast derived from the CIS and the CCRS data over the 2000-2019 period.

Month	Region 1 Alaska		Region 2 Barter - Hershel		Region 3 Mackenzie Bay		Region 4 Richards - Bathurst	
	CIS	CCRS	CIS	CCRS	CIS	CCRS	CIS	CCRS
1	14.83	-	5.98	-	20.17	-	17.63	-
2	22.47	-	6.80	-	23.35	-	22.83	-
3	24.87	-	8.72	-	27.73	-	27.14	-
4	29.68	25.19	13.45	8.74	31.82	26.90	30.06	27.06
5	29.35	25.77	11.45	9.85	31.10	27.88	31.12	28.54
6	23.96	23.59	9.02	8.23	23.37	23.27	25.12	22.42
7	15.76	-	6.62	-	11.82	-	12.99	-
8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-
10	4.22	-	1.97	-	4.96	-	3.00	-
11	5.95	-	2.91	-	9.73	-	5.77	-
12	10.24	-	3.81	-	14.29	-	12.99	-
1-5	24.24	-	9.28	-	26.84	-	25.76	-
4-6	27.66	24.85	11.31	8.94	28.76	26.02	28.77	26.01
1-12	18.13	-	7.07	-	19.84	-	18.87	-

Figure captions

Fig. 1. Region of interest in the Beaufort Sea. a) 2000-2019 snow/ice probability maps for the melting season (April-September); b) 2000-2019 mean snow/ice probability map with overlaid boundaries of 5 sub-regions and 20 m and 30 m isobaths; c) the ocean floor bathymetry and surface elevation map (GEBCO, 2020). Five sub-regions are selected: 1) Alaska coast, 2) Barter Island to Hershel Island stretch, 3) Mackenzie Bay, 4) Richards Island to Cape Bathurst stretch, 5) Banks Island. The digital shapefile for the Beaufort Sea boundary was obtained from the open database published by the Flanders Marine Institute (2019). The Beaufort Sea boundary (b-c) follows the International Hydrographic Organization (IHO) definition (IHO, 1953).

Fig. 2. Monthly mean (μ) and standard deviation (σ) maps of MODIS reflectances for April 2016. Panel a) displays the false-colour image for mean reflectances of bands B6, B2, and B1, panel b) for standard deviations for bands B4, B2, and B1.

Fig.3. Weekly CIS ice charts over the Beaufort Sea study region for April 2016. Panels a - d show ice conditions with four classes: 1) open water, 2) landfast ice, 3) ice in any concentration, form and age, and 4) land.

Fig. 4. Maps of linear trends in the ERA5 surface air temperature T2m (K/yr) over the Beaufort Sea region for 2000-2019. a) January-May average; b) April-June average; c) annual mean. The ERA5 data were acquired from the European Copernicus data archive (C3S, 2020; Hersbach et al., 2020).

Fig. 5. Time series of the LFI parameters for Region 1: Alaska: a- d) - the total spatial extent; e-h) – the mean ocean depth at the LFI edge; i-l) – the mean distance of LFI edge from the coast.

Fig. 6. CIS and CCSR MODIS data for April 2009: a) CIS ice charts for April 13, 20, and 27, 2009 combined in one RGB image for the entire Beaufort Sea region; b) subset of a) showing a zoom for the selected rectangular area; subset c-d) false-colour image of CCRS MODIS monthly mean (μ) and standard deviation (σ) of reflectances for the subset in b). The green curve marks the CCRS LFI delineation for April, which closely resembles the minimum LFI area in combined CIS results.

Fig. 7. Trends in break-up (boxes) and onset dates (circles), and duration of the ice-free season (triangles). Lines denote the linear trends. Numbers show the absolute values (day/yr) with errors and statistical significance (p-value).

Fig. 8. Similar to Fig.5, but for Region 2: Barter Island to Herschel Island.

Fig. 9. Similar to Fig.5, but for Region 3: Mackenzie Bay. Dashed lines show the linear trends

Fig.10. Similar to Fig. 9, but for Region 4: Richards Island to Cape Bathurst.

Fig. 11. Time series and monthly mean values of the LFI extent for the entire Beaufort Sea region:

a) original time series; b) April-June (spring) average values; c) January-May (winter) average values; d) monthly means.

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R1: Alaska

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678x625mm (118 x 118 DPI)

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399x684mm (118 x 118 DPI)

Fig.3. Weekly CIS ice charts over the Beaufort Sea study region for April 2016. Panels a - d show ice conditions with four classes: 1) open water, 2) landfast ice, 3) ice in any concentration, form and age, and 4) land.

861x484mm (118 x 118 DPI)

Fig. 4. Maps of linear trends in the ERA5 surface air temperature T2m (K/yr) over the Beaufort Sea region for 2000-2019. a) January-May average; b) April-June average; c) annual mean. The ERA5 data were acquired from the European Copernicus data archive (C3S, 2020; Hersbach et al., 2020).

338x850mm (118 x 118 DPI)

Fig. 5. Time series of the LFI parameters for Region 1: Alaska: a- d) - the total spatial extent; e-h) - the mean ocean depth at the LFI edge; i-l) - the mean distance of LFI edge from the coast.

774x387mm (236 x 236 DPI)

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713x662mm (118 x 118 DPI)

Fig. 7. Trends in break-up (boxes) and onset dates (circles), and duration of the ice-free season (triangles). Lines denote the linear trends. Numbers show the absolute values (day/yr) with errors and statistical significance (p-value).

358x494mm (118 x 118 DPI)

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774x387mm (236 x 236 DPI)

Fig. 9. Similar to Fig.5, but for Region 3: Mackenzie Bay. Dashed lines show the linear trends.

774x387mm (236 x 236 DPI)

Fig.10. Similar to Fig. 9, but for Region 4: Richards Island to Cape Bathurst.

774x387mm (236 x 236 DPI)

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350x512mm (236 x 236 DPI)