Minimum Snow/Ice Extent over the Northern Circumpolar Landmass in 2000–19

How Much Snow Survives the Summer Melt?

Alexander P. Trishchenko and Calin Ungureanu

ABSTRACT: A novel satellite image processing technique developed at the Canada Centre for Remote Sensing has been utilized to produce annual time series of the minimum snow/ice (MSI) extent over the northern circumpolar landmass area (9,000 km × 9,000 km) for 2000–19. The information has been derived from the Moderate Resolution Imaging Spectroradiometer 10-day clear-sky composites generated at 250-m spatial resolution over the April–September period. Derived interannual variations agree very well with the warm-season average surface air temperatures from the European reanalysis (ERA5). The region-average correlation coefficient is -0.78 . The total MSI extent demonstrated a statistically significant declining trend equal to $-1,477 \text{ km}^2 \text{ yr}^{-1}$. Results have been compared with data from the Randolph Glacier Inventory (RGI 6.0). The comparison points to a significant contribution of minimum seasonal snow cover relative to RGI glacierized areas. Quantitative estimates obtained for the first time showed that the region-average snow extent that survives the summer melt and resides outside of RGI area can be as high as 15% (or $53 \times 10^3 \text{ km}^2$) while in the northern Canadian Arctic it can reach 41% (or $43 \times 10^3 \text{ km}^2$). The derived MSI time series data can be recommended to the glacier and land-cover scientific community as a source of validation data and annual updates of snow and ice maps over the northern circumpolar landmass.

KEYWORDS: Land surface; Northern Hemisphere; Climate change; Snow cover; Glaciers; Remote sensing; Annual variations

<https://doi.org/10.1175/BAMS-D-20-0177.1>

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In final form 23 November 2020

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Snow and ice serve as important water resources for human populations and ecosystems in many regions. The presence of snow and ice controls the state of frozen soil; therefore, it can serve as proxy indicator of permafrost presence and thaw in high-latitude and alpine zones. Presently, there are significant concerns and uncertainty about greenhouse gas (GHG) emissions and storage, especially methane, in the permafrost (IPCC 2013; Hock et al. 2019; Meredith et al. 2019).

The snow/ice extent (SE) and snow water equivalent (SWE) are important parameters for characterization of the water budget and hydrological cycle. Numerous studies have focused on mapping of these parameters from spaceborne observations and modeling on global and hemispherical scales (Chiu et al. 2020; Kunkel et al. 2016; Mortimer et al. 2020; Mudryk et al. 2018; Ramsay 1998; Robinson et al. 1993, 2012; Romanov 2017; Saberi et al. 2020; Takala et al. 2011). The U.S. National Oceanic and Atmospheric Administration (NOAA) operates the Interactive Multisensor Snow and Ice Mapping System (IMS) for mapping of the snow and ice properties globally (www.natice.noaa.gov/ims/index.html) (Helfrich et al. 2007). The historical archives of snow extent are available from the NOAA's National Centers for Environmental Information (NCEI) operated by the National Environmental Satellite, Data, and Information Service (NESDIS) of NOAA (www.ncdc.noaa.gov/snow-and-ice/extent/) (Robinson et al. 1993, 2012). Many national and international weather, climate, and space agencies developed and maintained the space-based SE and SWE mapping systems and products. One can mention the Canadian snow depth product (Brasnett 1999), the NASA snow products derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Salomonson et al. 1989; Hall and Riggs 2016; Painter et al. 2009), the European Space Agency (ESA) GlobSnow project (www.globsnow.info/index.php?page=Home), the EUMETSAT Satellite Application Facility (SAF) snow products in support of operational hydrology and water management (H-SAF) (<https://landsaf.ipma.pt/en/products/snow-cover/sc/>), among others. Important global and regional snow products and analyses have been derived from spaceborne microwave sensors, such as the Special Sensor Microwave Imager (SSM/I), the Advanced Microwave Scanning Radiometer for EOS (AMSR-E), and the Advanced Microwave Scanning Radiometer-2 (AMSR2) (Kelly 2009; Pulliainen 2006; Semmens and Ramage 2013; Tedesco and Jeyaratnam 2016; Tedesco et al. 2004). The ESA GlobSnow retrievals also utilize the satellite passive microwave data (Takala et al. 2011).

Despite varying degrees of agreement between different datasets, the climate analyses of snow/ice time series report generally negative long-term trends in snow-cover extent and snow water equivalent (Mudryk et al. 2019; Richter-Menge et al. 2019). Analyses are mainly concentrated on a cold season and springtime when the greatest snow accumulation occurs. This is understandable as the focus of most research is a seasonal snow cover, not a perennial or semipermanent snow cover (Woo and Young 2014). Some studies do not even report data of sufficient accuracy over the summer months and limit the analyzed period to the October–June time frame (e.g., Kunkel et al. 2016). Nearly all large-scale snow products are generated at a coarse spatial and/or temporal scale, which limits their use for studying the snow distribution during the summer minimum.

The question “How much snow survives the summer melt?” is, however, interesting and important one to understand the baseline snow-cover characteristics and the state of land surface in general. For the remainder of this paper we will focus only *on the summer minimum of snow and ice spatial extent over the land surface*. Strictly speaking, the land ice or glacierized areas belong to a special land surface type: glaciers. Because the existence of glaciers depends on snow accumulation, their surface represents varying phases of snow ranging from fresh snow to glacial ice in most cases. This is the main reason for combining snow and ice, i.e., frozen water, over land into one land-cover type in our analysis. This is also the typical approach implemented in all major land-cover classifications. Another important reason for combining snow and ice into one class is the use of optical satellite imagery in most land-cover mapping

applications. As various states of frozen water, snow and ice exhibit a certain similarity in spectral properties observed from spaceborne sensors. The debris-covered glaciers represent a special spectral class (Racoviteanu and Williams 2012) as discussed in the last section.

Land cover is included in the list of terrestrial essential climate variables (ECV) developed by the Global Climate Observing System (GCOS) (Bojinski et al. 2014; GCOS 2006, 2011, 2015, 2016) and the Global Terrestrial Observing System (GTOS) of the Food and Agriculture Organization (FAO) of the United Nations (GTOS 2008). Most global land-cover classifications include snow and ice as a distinct land-cover type. The list of some popular land-cover products has been assembled by the Committee on Earth Observation Satellites (CEOS) Land Product Validation (LPV) subgroup and can be found online (<https://lpvs.gsfc.nasa.gov/producers2.php?topic=LC>). Typical requirements for land cover include an annual update cycle for moderate-resolution (250 m or coarser) maps and a 5-yr update cycle for high-resolution (10–30 m) maps (<https://gcos.wmo.int/en/essential-climate-variables/land-cover/ecv-requirements>) (GCOS 2016).

Despite apparent simplicity and wide usage, we have not been able to find a consistent definition and name for the snow/ice land-cover class among the various classification schemes. The Global Land Cover 2000 (GLC 2000) project uses the name “snow or ice” and defines it as land surface covered by natural or artificial, moving or stationary, snow or ice (Bartholomé and Belwar 2005; <https://forobs.jrc.ec.europa.eu/products/glc2000/legend.php>). This may be an adequate definition for single image classification, but it is not sufficiently precise for land-cover maps representing a long period, such as annual or multiannual maps. This definition does not specify exactly the duration of interval with snow or ice present or the time stamp associated with presence of snow or ice.

The ESA GlobCover projects completed global annual land-cover maps circa 2005 and 2009 at 300-m spatial resolution (Arino et al. 2008, 2011). They used the name “permanent snow and ice” for the land snow and ice category. The product developers stated that their definition of “permanent snow and ice” land-cover class is consistent with the UN Land Cover Classification System (LCCS) that uses the following terms: “artificial perennial snow,” “artificial perennial ice,” “perennial snow,” and “perennial ice.” In plain language, this interpretation highly likely means that the “permanent snow and ice” category has been assigned to an area where snow and ice has been observed in all input images utilized for production of the annual composite land-cover map. This interpretation is consistent with the definition used by the International Geosphere–Biosphere Programme (IGBP) Discover (IGBP-DIS) Land Cover Working Group, which defined “the snow and ice” class as “the lands under snow and/or ice cover throughout the year” (Hansen et al. 2000).

The ESA Climate Change Initiative (CCI) land-cover project also uses the name “permanent snow and ice” (Defourny et al. 2017; Hollmann et al. 2013; Popp et al. 2020). The ESA CCI land-cover global annual time series have been produced for the period from 1992 to 2015, i.e., for 24 years, with 300-m spatial resolution. The spatial distribution of the “permanent snow and ice” land-cover type came from the Randolph Glaciers Inventory (RGI). Based on the timeline of the ESA CCI land-cover project, this was likely the RGI database, version 4.0 (Arendt et al. 2014). The latest RGI database is version 6.0 (RGI 2017). The static data layer “permanent snow and ice” in the ESA CCI land-cover time series for the period of 24 years should be used with caution for climate change studies, as it represents only the glacierized areas from the RGI database. The RGI data are compiled over long periods of time that vary for different regions and may last for more than a decade (Arendt et al. 2014; RGI 2017).

The MODIS land-cover dataset (MCD12Q1) includes the global maps of land cover since 2001 at annual time steps and 500-m spatial resolution. The MODIS land-cover climate modeling grid product (MCD12C1) uses MCD12Q1 as input and spatially aggregates it to a coarser spatial resolution of 0.05° in geographic latitude–longitude projection (Sulla-Menashe and Friedl 2018). The MODIS land-cover products MCD12Q1/MCD12C1 use the name “permanent snow and ice”

for the snow and ice over land. The definition of this land-cover class is given as “at least 60% of area is covered by snow and ice for at least 10 months of the year.” The MODIS products MCD12Q1/MCD12C1 include several classifications that contain the “permanent snow and ice” class: MCD12Q1 IGBP legend, plant functional types (PFT), FAO Land Cover Classification System *land-cover* (LCCS1), FAO Land Cover Classification System *land use* (LCCS2), FAO Land Cover Classification System surface hydrology (LCCS3) legend. These all assume the same definition for the “permanent snow and ice” land-cover class. Latham et al. (2014) summarized a new FAO land-cover legend where they defined the land cover class “snow and glaciers” as the one that includes any geographic area covered by snow or glaciers persistently for 10 months or more on the annual basis.

Summarizing the above, we can make several key comments:

- 1) There are variations *in the name of snow/ice land-cover class* between different classification schemes: “snow and/or ice,” “permanent snow and/or ice,” and “perennial snow and/or ice,” “snow and glaciers.”
- 2) There are variations *in the definition of snow/ice land-cover class* ranging from “the lands under snow and/or ice cover throughout the year” to as “at least 60% of area is covered by snow and ice for at least 10 months of the year.” The ESA CCI land cover highly likely adopted the first definition, i.e., “throughout the year” but implemented it using the static RGI glacier layer.
- 3) The internationally agreed requirement for global (or continental scale) land cover is an annual or multiannual update cycle. As such, the logical approach for the mapping of snow/ice class should include the multitemporal analysis of the snow extent time series with sufficient spatial and temporal resolution. The *probability of snow/ice presence derived from such temporal analysis can be used for snow/ice class mapping* after applying a selected threshold value.

The term “permanent snow and/or ice” cannot be considered a perfect name, after taking into account the idea of climate change and climate variability. The term “perennial snow and/or ice” is somewhat better suited for multiyear maps, such as, for example, 5-yr high-resolution land-cover maps. Although it still contains some ambiguity related to the length of interval of perennial existence. We suggest the use of term “minimum snow/ice (MSI) extent” as suitable for both the annual and multiannual land-cover maps. This term is equally applicable for any other land-cover scheme that represents a certain interval of time. This approach also points to a methodology that links together the land snow/ice mapping products developed for operational weather forecasting and/or climate monitoring with land-cover mapping activities. Unfortunately, in many cases, these two activities are not always connected well to benefit each other. Because the annual snow/ice cover reaches its minimum extent at the end of the summer melt season, it may be necessary and sufficient to derive the MSI extent from the snow/ice time series only for the warm season, which can be defined as being from the beginning of April to the end of September in the Northern Hemisphere.

The purpose of this study is to advance our previous work on the mapping and analysis of the annual minimum snow/ice spatial extent over the northern landmass described by Fontana et al. (2010), i.e., in the pre-RGI era, with the approach described by Trishchenko et al. (2016) and Trishchenko and Wang (2018) for the Canadian landmass and neighboring regions. The basis of all these studies is the time series of the clear-sky composites over the northern circumpolar area, 9,000 km × 9,000 km at 250-m spatial resolution, generated since 2000 with the specialized MODIS image processing system developed at the Canada Centre for Remote Sensing (CCRS) (Trishchenko et al. 2009). The need for annual updates of snow/ice land cover based on the actual snow/ice cover extent properties is further illustrated

in Fig. 1 for part of the central Europe area defined by RGI as the first-order region 11 (RGI 2017). Figure 1 shows multiannual time series of the MSI extent derived from the MODIS imagery as described later in the text, and two examples of the MSI maps for the years with maximum (2001) and minimum (2017) spatial extends. The MSI extent shown for 20 years in Fig. 1a varies from 0.73 to 1.71 of the mean, and standard deviation equals to 23% of the mean. These variations are quite significant and can be easily identified in Figs. 1b and 1c where snow/ice pixels are displayed in cyan colors. As we show further, the variation are closely related to the climate thermal conditions pertinent to a specific year.

Study area, RGI regions, and other data sources

The study region is defined in Trishchenko et al. (2009) and Fontana et al. (2010). Figure 2 displays the false color composite image of the region generated from the MODIS imagery processed for the entire warm season (April–September) in 2019. The shortwave infrared (SW) MODIS band B6, the near-infrared (NIR) band B2 and the visible red band B1 are employed as the red–green–blue (RGB) color scheme. The snow and ice in Fig. 2 are displayed in various tones of turquoise and cyan colors. The color codes for these areas are obtained as average reflectances of the pixels that have at least 94% probability of snow/ice presence during the entire warm season. The region covers a rectangular area of 9,000 km × 9,000 km (36,000 pixels × 36,000 lines) centered over the North Pole. The map utilizes the Lambert azimuthal equal-area (LAEA) projection.

The location of the first-order regions as defined by the RGI (2017) is also displayed in Fig. 2. Altogether, our study region includes 13 RGI first-order regions. The glacierized areas for regions 1 to 11 from the RGI database fall almost completely inside our study region, while the glacierized areas for regions 12 (Caucasus and

Fig. 1. Example of minimum snow/ice (MSI) spatial extent variations for the area in central Europe (RGI first-order region 11): (a) multiannual time series derived in this study, (b) MSI map for 2001 (maximum), and (c) MSI map for 2017 (minimum). The MSI extent varies from 0.73 to 1.71 of the mean value with standard deviation equal to 23% of the mean. The RGI 6.0 and ESA CCI land-cover results for RGI region 11 are also shown for comparison. Snow/ice-covered pixels are shown in cyan colors.

Middle East) and 13 (central Asia) overlap with our study area only partially. The region 5 (Greenland periphery) is excluded from comparative analysis with RGI statistics because we have not been able to properly isolate the location of peripheral areas suitable for comparison (see later the section on construction of the spatial mask for temperature and correlation analyses). The Greenland ice sheet vector data are not included in the RGI 6.0 database. As such, we do not report any results for Greenland. The RGI statistics reported in this study have been derived by remapping and rasterizing the RGI 6.0 vectors into LAEA projection at 250-m spatial resolution. Coarser spatial resolution of the output projection relative to the original RGI data, and the rasterization procedure leads to some differences between our results and the ones reported by RGI 6.0 (RGI 2017). The overall agreement for all regions except regions 5, 12, and 13 is within 0.12% (351,959 km² as reported by RGI 6.0 vs 351,517 km² derived in this study). The largest difference due to partial coverage of region 10 (Asia, north) amounts to 880 km², an underestimation of 25%.

For classification of land and water pixels we utilized the Global Self-Consistent, Hierarchical, High-Resolution Shoreline Database (GSHHS), version 2.4 (Wessel and Smith 1996). The vector data have been remapped and rasterized into LAEA projection at 250-m spatial resolution in the same way as the RGI vector data. Substantial mismatches of the coastline positions up to a few kilometers have been detected in some northern regions between our MODIS composite imagery and the GSHHS data. This circumstance forced us to develop a special correction procedure to ensure that persistent coastal sea ice is not mapped as land ice. Details of this procedure are described later. We tested several other sources of land–water mask, including the ESA land-cover CCI. Generally, we always found some inconsistencies with our MODIS imagery in the polar areas and therefore decided to use the GSHHS database, also used in Fontana et al. (2010).

We utilized the monthly mean 2-m temperature fields (T2m) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) in the framework of latest climate reanalysis (ERA5; Copernicus Climate Change Service 2020; Hersbach et al. 2020) to study the correlation between MSI time series and climate conditions. The T2m dataset available from the ERA5 land product has a spatial resolution of 9 km. We remapped it at 1-km spatial resolution into LAEA projection using the nearest neighbor resampling scheme. The warm-season average T2m fields (May–September) have been employed for correlation analysis with our MSI time series as recommended by Trishchenko and Wang (2018). The month of April has been excluded because intensive melting starts in May in the polar and alpine regions.

MODIS data processing at CCRS

The details of MODIS data processing are given in Trishchenko et al. (2006, 2009, 2016) and Fontana et al. (2010). They are briefly summarized below. The MODIS 500-m bands (B3–B7)

Fig. 2. The study region shown as MODIS false-color composite image for the warm season (April–September) in 2019. Numbers denote the RGI first-order regions with boundaries indicated by white lines: 1—Alaska; 2—western Canada and United States; 3—Arctic Canada, north; 4—Arctic Canada, south; 5—Greenland periphery; 6—Iceland; 7—Svalbard; 8—Scandinavia; 9—Russian Arctic; 10—Asia, north; 11—central Europe; 12—Caucasus and Middle East; 13—Asia, central.

are downscaled to the 250-m spatial grid of bands B1 and B2 so that all MODIS spectral bands B1-B7 designed for land applications are coregistered to the same 250-m spatial resolution. The downscaling scheme utilizes the adaptive regression and normalization as described in Trishchenko et al. (2006). Only the MODIS imagery available from the *Terra* spacecraft is processed and downscaled because of band-to-band coregistration issues and the significant number of dead SWIR detectors in MODIS imagery on the *Aqua* platform (Khlopenkov and Trishchenko 2008; Xiong et al. 2005, 2006). The scene identification used a method described by Luo et al. (2008). It generates a mask of clear-sky, cloudy, and cloud shadow pixels, as well as the basic surface types. The input images are aggregated into 10-day clear-sky composites separately for the forward-scattering and backward-scattering geometry using the clear-sky mask (Luo et al. 2008). The sequence of 10-day top-of-the-atmosphere composites from April to September for each year then undergoes five-point temporal median filtering to remove data outliers. The filtered time series are employed to produce snow/ice flags using simple threshold tests as described in Trishchenko et al. (2016). The sequence of snow/ice flags for the entire warm season for every pixel is converted into the probability of snow/ice presence by dividing the total number of snow/ice flags by the total number of valid observations in the temporal sequence for each pixel. The maximum number of valid values in the temporal sequence for each pixel is 17 in our processing scheme. An example of the probability map is shown in Fig. 3 for two seasons, 2000 (Fig. 3a) and 2016 (Fig. 3b), when the total MSI extent for our study area reached maximum and minimum values. Despite the large size of the area and therefore relatively small size of the local features on the probability image, the overall higher prevalence of the dark red colors associated with high probability can be visually distinguished on the 2000 image relative to the 2016 image. The annual warm-season snow/ice probability maps utilized in this study to derive the MSI extent can be accessed online (<ftp://ftp.ccrs.nrcan.gc.ca/ad/Trishchenko/Circumpolar.MSI/>).

Minimum snow/ice extent

We utilized a threshold probability $\geq 94\%$ (i.e., ≥ 16 snow/ice flags out of 17) to label areas with persistent snow/ice presence

Fig. 3. Example of the warm-season snow/ice probability maps for (a) year 2000 (large MSI extent) and (b) 2016 (small MSI extent). Water pixels are masked in dark gray using the Global Self-Consistent, Hierarchical, High-Resolution Shoreline Database (GSHHS), version 2.4 (Wessel and Smith 1996).

during the warm season. The land–water mask derived from the GSHHS dataset has been applied to select pixels over land and to mask out water areas. After a preliminary analysis, we found that this mask leads to systematic detection of frequent snow/ice presence in the coastal zone in high-latitude areas where persistent sea ice is also observed. Trishchenko and Wang (2018) observed similar results in the Canadian Arctic archipelago as an abnormal increase of the MSI extent as function of altitude at the lowest elevation interval. Detailed analysis revealed that this occurs due to mismatch between the MODIS imagery and the GSHHS coastline vectors. The geolocation accuracy of MODIS imagery is known to be very high (Wolfe et al. 2002; Khlopenkov and Trishchenko 2008; Trishchenko 2018). This is also confirmed by excellent image geospatial consistency during the clear-sky compositing process when thousands of MODIS scenes in different spectral bands overlay each other with high precision. These facts exclude MODIS imagery as a probable source of land–water labeling error and point to issues with GSHHS data and/or possible uncertainties with GSHHS vector data remapping and rasterization. The refinement of the GSHHS coastline vectors is beyond the scope for our study, as it requires extra technical capacity and resources. Instead, we developed a simple correction procedure. The high snow/ice probability pixels were excluded from analysis when (i) they fall within ± 1.5 km of the GSHHS coastline and (ii) the pixel is not included in the rasterized RGI map; i.e., it may potentially be the coastal glacier or ice shelf included in the RGI database.

Time series of MSI extent processed with correction procedure described above for 10 RGI regions and for the entire study area are shown in Figs. 4a–i. Results are displayed for regions 1–4 and 6–11, while regions 5 (Greenland periphery), 12 (Caucas and Middle East), and 13 (central Asia) have been excluded from analysis for the reasons described earlier. The RGI baseline statistics are also plotted. Figure 4i shows results for the area outside of the standard RGI regions (see Fig. 2) where the RGI database reports no glaciers. Each panel in Fig. 4 except Fig. 4i shows several lines that correspond to different spatial masks applied to compute the MSI statistics: 10-, 20-, 50-, 100-, 200-, and 500-km distances (L) from the RGI glaciers and the entire extent of each region within our study area (i.e., all data without masking). The masks have been computed by enlarging each RGI glacier pixel with pixel-line location (i, j) on 250-m resolution LAEA map by a square with pixel range $[i - 4 \times L, i + 4 \times L]$ and line range $[j - 4 \times L, j + 4 \times L]$, where L is distance in kilometers. The coefficient 4 corresponds to the number of 250-m pixels in 1 km. Effectively, this procedure means replacing each 250-m RGI glacier pixel by pixel with size $250 \text{ m} \times 8 \times L$. This spatial masking procedure has two main objectives: (i) to determine the compactness of MSI spatial distribution with respect to glaciers, (ii) to define a suitable spatial mask for computation of spatially averaged surface air temperature for correlation with MSI time series. Including the entire region in computing the mean surface air temperature is not fully justified logically for very large regions, where most of the area may not be covered by snow or ice. The application of a constant spatial mask that embraces most, if not all, of MSI extent in the vicinity of glaciers seems to be logical and physically more meaningful when correlating time series of the MSI extent and surface air temperature.

Results are generally very consistent and close to each other for all distances, except for a few years and some regions, such as region 2 (western Canada and United States) in 2004, 2005, 2018, and 2019; region 3 (Arctic Canada, north) in 2001, 2004, 2013, and 2017–19; region 4 (Arctic Canada, south) in 2004 and 2014; region 6 (Iceland) in 2014 and 2016; region 9 (Russian Arctic) in 2006–07, 2010, and 2017; and region 10 (Asia, north). For region 10 (Asia, north) the spread between results can be explained by its very big size and large variability in climate conditions. The absolute values of MSI extent for region 10 are among the smallest between all regions, as such, they have little impact on the overall statistics. The

Fig. 4. Multiannual variations of the MSI extent and the RGI 6.0 glacierized area for various regions as labeled on each panel. Different lines (10 to 500 km) show the MSI extent derived within corresponding distance from RGI glaciers. Label "all" denotes the MSI extent for the entire area of corresponding region. (i) The MSI extent for the area of our study region not included in the RGI database (see Fig. 2).

scene identification errors leading to MSI extent commission and omission errors can also be a source of uncertainty. Analysis of results showed that the region-mean differences due to selection of variable distance are less than 0.5%, and they mostly saturated after 100 km. As a result, we selected 100 km as a representative value to compute the spatial mask for temperature and

correlation analyses. The average surface air temperatures (T2m) for all regions computed for 100-km spatial mask are plotted in Fig. 5 as mean values for May–September period. Figure 5a shows time series of T2m. Figure 5b displays the spatial mask corresponding to 100-km distance used in computing the regional average temperature. The region labels are shown only for regions considered in further analysis. Regions 5, 12, and 13 are excluded as explained earlier.

The RGI 6.0 baseline, i.e., glacierized areal extent is always smaller than MSI extent for regions 3—Arctic Canada, north; 7—Svalbard and Jan Mayen; and 9—Russian Arctic. This is also mostly true for region 4, Arctic Canada, south, except for 2012, 2016, and 2019 when surface air temperature was among the warmest on record for this region (Fig. 5). These four regions are the coldest among all the regions in our study area. Their average warm-season (May–September) temperatures are close to or below the freezing point. The MSI extent can be larger or smaller than the RGI 6.0 baseline for all other regions. This is quite an interesting fact that raises several questions and is discussed below. Because MSI extent of the four coldest regions dominates the total MSI extent, the total MSI extent of the study area is always larger than the RGI 6.0 baseline for the entire area. Results shown in Fig. 4 point to significant contribution of minimum seasonal snow cover residing outside of RGI glacierized areas. The region-average snow extent that survives the summer melt in excess of RGI area (Fig. 4k) can be as high as 15% or $53 \times 10^3 \text{ km}^2$. It can reach 41% or $43 \times 10^3 \text{ km}^2$ for the northern Canadian Arctic region (Fig. 4c).

MSI extent trends and correlation with surface air temperature

The linear temporal trends of the MSI extent and T2m from ERA5 data are summarized in Tables 1 and 2 and correlation results between them are summarized in Table 3. Regions where trends are statistically not significant at the 95% level ($p > 0.05$) are shaded in green. The temporal trends in the MSI extent (Table 1) are mostly negative except the two regions: 6—Iceland and 9—Russian Arctic. The temporal trends in the MSI extent are statistically significant for three regions: 1—Alaska; 2—western Canada and United States; and 11—central Europe. The combined temporal trend in the MSI extent for all RGI regions within our study area is also statistically significant and negative, meaning a steady decline in the minimum snow/ice cover from 2000 to 2019. The average declining trend is equal to $-1,477 \text{ km}^2 \text{ yr}^{-1}$.

Fig. 5. (a) Average T2m from ERA5 over the RGI regions computed within 100-km distance from each glacier pixel. (b) Map used in computing results in (a), i.e., areas within 100-km distance for each RGI glacier point. Greenland (hatched) is excluded from analysis.

Table 1. Linear temporal trends of the MSI extent. Regions where trends are not statistically significant at the 95% level ($p > 0.05$) are shaded in green.

Region	Temporal slope ($10^3 \text{ km}^2 \text{ yr}^{-1}$)	Pearson's R	p value
1) Alaska	−0.889	−0.72	3.1×10^{-4}
2) Western Canada and United States	−0.282	−0.53	1.7×10^{-2}
3) Arctic Canada, north	−0.082	−0.06	0.82
4) Arctic Canada, south	−0.148	−0.27	0.25
6) Iceland	+0.013	+0.09	0.70
7) Svalbard and Jan Mayen	−0.020	−0.06	0.81
8) Scandinavia	−0.023	−0.14	0.56
9) Russian Arctic	+0.037	+0.08	0.75
10) Asia, north	−0.035	−0.35	0.13
11) Central Europe	−0.046	−0.63	3.1×10^{-3}
Outside of RGI regions	−0.022	−0.39	8.6×10^{-2}
All regions (1–4, 6–13)	−1.477	−0.65	1.7×10^{-3}

Table 2. As in Table 1, but for T2m.

Region	Temporal slope [$\text{K} (10 \text{ yr})^{-1}$]	Pearson's R	p value
1) Alaska	+0.79	0.52	1.9×10^{-2}
2) Western Canada and United States	+0.95	0.75	1.6×10^{-4}
3) Arctic Canada, north	+0.55	0.28	0.23
4) Arctic Canada, south	+0.22	0.13	0.59
6) Iceland	+0.05	0.05	0.85
7) Svalbard and Jan Mayen	+0.62	0.60	5.4×10^{-3}
8) Scandinavia	+0.18	0.13	0.58
9) Russian Arctic	+0.75	0.60	4.8×10^{-3}
10) Asia, north	+0.35	0.58	7.1×10^{-3}
11) Central Europe	+0.43	0.34	0.15
All regions (1–4, 6–13)	+0.54	0.80	2.6×10^{-5}

Table 3. Correlation between MSI extent and T2m. Shading is as in Table 1.

Region	Pearson's R	p value
1) Alaska	−0.82	7.8×10^{-6}
2) Western Canada and United States	−0.74	2.0×10^{-4}
3) Arctic Canada, north	−0.72	3.6×10^{-4}
4) Arctic Canada, south	−0.73	2.5×10^{-4}
6) Iceland	−0.37 (−0.52)	0.11 (0.026)
7) Svalbard and Jan Mayen	−0.39	0.09
8) Scandinavia	−0.72	3.7×10^{-4}
9) Russian Arctic	−0.58	7.8×10^{-3}
10) Asia, north	−0.57	8.5×10^{-3}
11) Central Europe	−0.67	1.2×10^{-3}
All regions (1–4, 6–13)	−0.78	4.5×10^{-5}

The temporal trends in T2m from ERA5 are all positive. They are statistically significant for five regions: 1—Alaska; 2—western Canada and United States; 7—Svalbard and Jan Mayen; 9—Russian Arctic; and 10—Asia, north. The combined temporal trend in T2m for all RGI regions within our study area is highly statistically significant. Temperature

demonstrates positive trend of $0.54 \text{ K decade}^{-1}$; i.e., over the last 20 years the T2m increased by almost 1.1 K.

The results of linear correlation between the MSI extent and T2m are presented in Table 3 and Fig. 6. The highest correlation (-0.82) is observed for region 1—Alaska. The region-average correlation coefficient is equal to -0.78 . The Pearson's correlation coefficients are negative

Fig. 6. Correlation between the MSI extent and the T2m from ERA5. Spatial mask corresponding to a spatial distance of 100 km around RGI 6.0 glaciers has been applied as discussed in the text.

for all regions and statistically significant for all but two regions: 6—Iceland and 7—Svalbard and Jan Mayen. One possible reason for reduced correlation for region 6—Iceland, can be the strong impact of volcanic eruptions that caused deposition of soot, ash, and dust over large glaciated areas for prolonged periods, such as volcanic eruption of Eyjafjallajökull in 2010 and volcanic eruption of Grímsvötn in 2011 (Trishchenko et al. 2016; Möller et al. 2019). If data for 2010 and 2011 are excluded, then correlation between the MSI extent and T2m for Iceland also becomes significant. The corresponding corrected values for region 6—Iceland, are included in parentheses in Table 3.

Statistically significant correlation of the MSI extent with surface air temperature is logical from the physics point of view and reflects increased melting of frozen water in the warming environment. Similar results have been reported for the Canadian Arctic archipelago by Trishchenko and Wang (2018). They also described an impact of solid precipitation and radiation budget components on the interannual MSI variations. It should be emphasized that the linear correlation reflects just a simple linear response model, while actual physical processes of snow/ice melt are more complex (Armstrong and Brun 2008).

Discussion and conclusions

The study addresses the topic of the annual minimum snow/ice extent, which is an important parameter for human activities, ecosystem functions, and the understanding and characterization of climate change impacts. The study area covers the northern landmass region with size of 9,000 km × 9,000 km (Fig. 2). The MSI extent has two components: (i) the snow and ice over glaciers and ice caps (glacierized areas), and (ii) the *seasonal or semipermanent snow cover that survives the summer melt* and resides outside of glacierized regions. There is still no consensus about the properties of this climate variable despite the apparent simplicity of this concept. The most suitable candidate for this parameter is the “snow/ice” land-cover class. The WMO considers land cover as an essential climate variable, which is expected to contain well-defined quantities. The common requirement is an annual update cycle for moderate-resolution land-cover maps (250 m and coarser). We analyzed several approaches for mapping this variable and found no consistent definition or even a commonly accepted name for this land-cover category. The definitions vary from snow/ice that covers land surface “throughout the year” to “at least 10 months of the year.” The list of suggested names contains “snow and ice,” “permanent snow and ice,” “perennial snow/perennial ice,” and “snow and glaciers.” The mapping approaches also vary from using a static input data layer to multitemporal analysis of satellite composites. To address this problem, the current study suggests the name “minimum snow/ice (MSI) extent,” which suits most mapping cases ranging from multiple scenes and multiyear mapping periods. For mapping the MSI extent on an annual basis, we suggest the use of snow/ice probability map derived for the warm season, i.e., April–September in the Northern Hemisphere (Fig. 3). The current study employed a sequence of 10-day clear-sky composites generated from MODIS/Terra land bands downscaled to 250-m spatial resolution and processed with technology developed at the Canada Centre for Remote Sensing. The MSI identification in this study utilized a 94% threshold probability, i.e., ≥16 snow/ice flags out of 17, which was the maximum value in our processing scheme. The data are available for the 20-yr period 2000–19 online (<ftp://ftp.ccrs.nrcan.gc.ca/ad/Trishchenko/Circumpolar.MSI/>).

Our study region includes 13 first-order regions defined by the Randolph Glacier Inventory (RGI 2017), version 6.0 (Fig. 2). Due to partial overlap and difficulties with interpretation, only 10 regions (1–4, 6–11) have been analyzed in detail. Results for the entire study area have been also evaluated. The key findings are summarized below:

- 1) Despite some spread between regions, there is a systematic declining trend since 2000 in the MSI extent over the entire study area. It is equal to $-1,477 \text{ km}^2 \text{ yr}^{-1}$ (Table 1, Fig. 4).

- 2) The MSI extent variations correlate very well with ERA5 surface air temperature (T2m) averaged over the warm season. The overall correlation coefficient is -0.78 . This correlation reflects increased melting of the warming cryosphere. The observed trend in the T2m is about 1.1K over the 20-yr period 2000–19 (Tables 1 and 2, Figs. 5 and 6).
- 3) The semipermanent seasonal snow cover that survives the summer melt and resides outside of glacierized regions has been derived by subtracting the RGI baseline level from the MSI extent (Fig. 4). Analysis of this variable showed that for coldest regions (3—Arctic Canada, north; 7—Svalbard and Jan Mayen; 9—Russian Arctic; and 4—Arctic Canada, south), and the entire study region, it is positive; i.e., our method points to the systematic presence of snow outside of glacierized area. The region-average area of this semipermanent seasonal snow can be as high as 15% or $53 \times 10^3 \text{ km}^2$. It can reach 41% or $43 \times 10^3 \text{ km}^2$ for the northern Canadian Arctic region.
- 4) The MSI extent below the RGI baseline has been detected for several regions in many years. There may be several possible explanations for this fact:
 - (i) The RGI 6.0 database includes all types of glaciers (RGI 2017). Significant percentage of the RGI glacierized areas can represent debris-covered glaciers, which appear as dark surfaces and cannot be straightforwardly detected using optical MODIS imagery. Some methods to deal with these cases have been proposed (Racoviteanu and Williams 2012). However, their automated applicability for large regions is a challenging task (Painter et al. 2009; Painter et al. 2012).
 - (ii) The RGI database may include some uncertainties and outdated information about glaciers due to difficulties in production, collecting and maintenance of a detailed databased assembled from multiple sources, over long and variable time intervals (RGI 2017).
 - (iii) Points (i) and (ii) above are illustrated in Fig. 7 for the Malaspina Glacier and surrounding areas located in the RGI region 1—Alaska. Figure 7 shows the MODIS warm-season composite image for 2019 overlaid with RGI 6.0 glacier vector data (white contours). The image contains numerous debris-covered glacier's tongues that contain no exposed snow and ice. In some cases, vegetation-covered areas (displayed in green color) are labeled as glaciers. This may be an evidence of significant retreat of glacier terminus not reflected in the RGI data or the presence of land ice buried deep in the ground as a result of complex processes associated with glacier dynamics (Muskett et al. 2008; Cotton et al. 2014). These details require further investigations.

Summarizing the above, one can recommend the 250-m MSI time series, derived in this study, as a source of validation data and annual updates of land snow and ice maps over the northern circumpolar land-mass to the scientific community interested in the land-cover and glacier mapping activities.

Fig. 7. MODIS warm-season composite image for 2019 overlaid with RGI 6.0 glacier vector data (white contours) for the Malaspina Glacier and surrounding areas. The image emphasizes challenges with identification of debris-covered glaciers from optical satellite data as well as the need for annual updates of glacier vector data.

Acknowledgments. This work was conducted as part of the Climate Change Geoscience Program and CCRS Long-Term Satellite Data Records (LTSDR) activity as part of the Cumulative Effects project at CCRS, Department of Natural Resources Canada (NRCan). The annual warm-season snow/ice probability maps utilized in this study to derive the MSI extent can be accessed at <ftp://ftp.ccrs.nrcan.gc.ca/ad/Trishchenko/Circumpolar.MSI/>. Authors gratefully acknowledge the use of MODIS data acquired from the NASA Distributed Archive Center and the ERA5 temperature data distributed by Copernicus Climate Change Service. Authors are grateful to G. Choma from CCRS/NRCan for careful editing of the manuscript. The manuscript was assigned the Department of Natural Resources Contribution Number 20200561.

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