Synoptic climatological approach associated with three recent summer heatwaves in the Canadian Arctic
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ABSTRACT

The observed unusually high temperatures in the Arctic during recent decades can be related to the Arctic sea ice declines in summer 2007, 2012 and 2016. Arctic dipole formation has been associated with all three heatwaves of 2007, 2012 and 2016 in the Canadian Arctic. Here, the differences in weather patterns are investigated and compared with normal climatological mean (1981–2010) structures. This study examines the high-resolution datasets from the North American Regional Reanalysis model. During the study periods, the north of Alaska has been affected by the low-pressure tongue. The maximum difference between Greenland high-pressure centre and Alaska low-pressure tongue for the summers of 2012, 2016 and 2007 are 8 hPa, 7 hPa and 6 hPa, respectively, corresponding and matching to the maximum summer surface Canadian Arctic temperature records. During anomalous summer heatwaves, low-level wind, temperatures, total clouds (%) and downward radiation flux at the surface are dramatically changed. This study shows the surface albedo has been reduced over most parts of the Canadian Arctic Ocean during the mentioned heatwaves (∼5–40%), with a higher change (specifically in the eastern Canadian Arctic region) during summer 2012 in comparison with summer 2016 and summer 2007, agreeing with the maximum surface temperature and sea ice decline records.

Key words | Arctic dipole, Canadian arctic, cloud anomaly, heatwaves, wind anomaly

HIGHLIGHTS

- Summer (monthly averaging of the June, July and August) time series of Arctic sea ice extents and surface air temperatures of Canadian Arctic from 2000 to 2018 have shown three recent sea ice declines during 2007, 2012 and 2016 corresponding to three peaks in Canadian Arctic low-level air temperatures.
- During the normal period (1981–2010), the north of Alaska in the Arctic Ocean is completely affected by a strong high-pressure system. However, in the abnormal study periods, the north of Alaska has been affected by the low-pressure tongues.
- The highest differences between Greenland high-pressure centre and Alaska low-pressure tongue for summer of 2012, 2016 and 2007 are 8hPa, 7hPa and 6hPa corresponding to the highest surface Canadian Arctic temperature records for the same times respectively.
- During the study periods in anomalous summer heatwaves, low-level wind, temperatures, total clouds (%) and downward radiation flux at the surface have been dramatically changed.
- The surface Albedo has been reduced over most parts of the Canadian Arctic Ocean during mentioned heatwaves ∼5–40% with higher changes (specifically in the eastern Canadian Arctic region) during summer 2012 in comparison with summer 2016 and summer 2007, agreeing with the surface temperatures and sea ice decline records.

INTRODUCTION

The Arctic summer sea ice has been reduced rapidly in recent decades (Serreze et al. 2007; IPCC 2013; Hoegh-Guldberg et al. 2019). For example, the Arctic sea ice extent from 1979 to 2014 has been diminished by 15% per decade (IPCC 2013; http://nsidc.org/arcticseaicenews/). The minimum sea ice extent during September has declined at around $13 \times 10^5$ km$^2$ per decade from 1997 to 2014 (IPCC 2013; http://nsidc.org/arcticseaicenews/) and it has been linked to the northern hemisphere meridional near-surface air temperature gradient reduction and the geopotential heights increasing in the Arctic area (Cohen et al. 2014). The Arctic sea ice changing processes are unpredictable and they are not yet very well understood. One of the key important factors which can be related to Arctic sea ice changing processes is the large-scale atmospheric circulation (Ogi & Wallace 2007; Maslanik et al. 2007; Kapsch et al. 2013, 2014). One of the main patterns considered to cause the changes in Arctic circulation is the Arctic dipole anomaly. The Arctic dipole pattern was suggested for the first time by Wu et al. (2006) and then Zhang et al. (2008) showed a relationship between the significant Arctic sea ice decline from 2001 to the essential change in the Arctic atmospheric circulation, named the Arctic Rapid Change Pattern. The Arctic dipole abnormal pattern is defined when the high pressure is seated over the North American Arctic (in the western Arctic) along with a low-pressure system which is settled over the Eurasian region (eastern Arctic). The Arctic dipole has also been studied in recent research (Lindsay et al. 2009; Wang et al. 2009; Stroeve et al. 2011; Overland et al. 2012). This atmospheric circulation pattern results in a pressure gradient across the Arctic and drives to increase the south winds which bring the heat and moisture toward the central Arctic Ocean (Graversen et al. 2010; Screen et al. 2011; Wood et al. 2013; Kapsch et al. 2014, 2016). The Arctic dipole anomaly can also influence the Arctic sea ice, cloudiness and surface radiative balance (Kay et al. 2008; Schweiger et al. 2008; Graversen et al. 2010; Stroeve et al. 2011; Kapsch et al. 2014; Boisvert et al. 2016; Woods & Caballero 2016; Hegyi et al. 2017; Hegyi & Taylor 2017).

The assessment of the recent Arctic changes’ impact on the global weather changes is one of the major scientific challenges and is not properly understood (Jeffries et al. 2013). For example, some recent reviews about the linkage of the midlatitudes’ weather and Arctic changes are presented by Cohen et al. (2014), Vihma (2014) and Walsh (2014). There has been uncertainty, especially in the recent Arctic amplification short records and midlatitudes’ chaotic variability (Overland 2016). However, these viewpoints often have the problem of the link between the development of the random weather patterns and the external shift causing the occurrence probability (Otto et al. 2012). In fact, the influences of the changes in the Arctic on the midlatitude weather are necessary to understand the dynamical responses of the atmospheric circulation. For example, meander jet stream, blocking systems like blocking high pressure and cut off lows or tropospheric stratosphere coupling and large-scale wave propagation changes which could be the link to sea ice declines (Duarte et al. 2012). Since it seems that any changes in the atmospheric Arctic circulation may affect the Canadian Arctic weather, as part of the Arctic, it is studied in this work. This study investigates the abnormal weather pattern associated with the Arctic dipole anomaly during the summers of 2007, 2012 and 2016 (study periods). This abnormal structure can be linked to the three recent minimums in Arctic sea ice declines which have been caused by three heatwaves during the mentioned times in Canadian Arctic regions. The recent atmospheric changes in the Canadian Arctic have been considered because this area is one of the Arctic region parts and it can contribute to an extra-local (Fazel-Rastgar, in press) and global warming. The recent climate change studies in the Canadian Arctic, for example, in the Baffin Island (Fazel-Rastgar 2020a) and Hudson Bay region have revealed dramatic changes in near-surface air temperatures, precipitation and wind circulation (Fazel-Rastgar 2019, 2020b). A recent study shows that from 2007, the sea surface temperatures in the Beaufort Sea located in the west of Canada’s Arctic islands have been getting warmer during the summer (Wood et al. 2013). This has...
been caused by the fall freeze-up delay with the large surface air temperature anomalies due to the ocean heat released into the atmosphere consistently in comparison to the past years (Wood et al. 2013). Ding et al. (2014) have shown that the highest surface warming has been recorded along the southern marginal seas over the north-eastern Canadian borders and Greenland. Also, the sea surface temperature during fall 2011 and 2012 along with the surface air temperature anomalies in Arctic marginal seas were the highest detected values in the northern hemisphere (Wood et al. 2013). From 2007, the winds have changed to easterlies, helping in Arctic amplification due to sea ice advecting. These winds are related to the Beaufort High intensification which has been linked to the surface warming and sea ice loss acceleration in the Beaufort Sea (Wood et al. 2013).

**METHODOLOGY AND DATA**

This study evaluates the high-resolution climate datasets from the National Centers for Environmental Prediction (NCEP) and the North American Regional Reanalysis (NARR) reanalysis model. The NARR model is a regional reanalysis for the North America region which covers the Canadian Arctic region (study area) containing temperatures, winds, moisture, soil data, and dozens of other parameters. This model captures and assimilates a high amount of observational data to generate long-term features of weather patterns over the North America region. The large amount of data can be assimilated due to the initialization of the model to a real-world condition. The model inputs the meteorological data like temperatures, winds and moisture from radiosondes and the pressure data from surface observations. In addition, data are obtained from aircraft (such as temperatures and winds), dropsondes, pibals, and satellite radiance (a measure of heat) from polar orbit satellites. Furthermore, cloud drift winds can be observed from geostationary satellites. The NARR (Mesinger et al. 2006) reanalysis model has been accessible since 1979 and NCEP monthly datasets (Kalnay et al. 1996) are available from 1948 to the present. The composite mean and anomaly maps for this study were formed with support from the NOAA/ERSL Physical Sciences Division (www.ersl.noaa.gov/psd). Here, the mean composites were considered as the variable average over the months of the summer and the anomalies were calculated as the monthly average departure from the climatological normal mean (1981–2010). This period (1981–2010) is based on the World Meteorological Organization standard reference period for a climatological standard normal change, and it refers to the most recent 30-year period. It has been considered as a standard reference period for assessments of long-term climate change. Here, the normal mean climatological patterns of the mean sea level pressure and 500 hPa geopotential heights are compared with the anomaly structure during the abnormal periodic times. Also, the anomaly patterns of the air temperatures, low-level winds, clouds, surface albedo and shortwave radiation at the surface in the Canadian Arctic have been synoptically analysed. These parameters are important and basic meteorological and physical factors which can give good information about the local warming and possible ice melting (i.e., air temperatures, clouds, surface albedo and shortwave radiation at the surface) and low-level circulation (i.e., low-level winds). Here, the influences of the quasi-stable high- and low-pressure systems settled over the Canadian Arctic during the anomaly period are investigated.

**CANADIAN ARCTIC AND ITS IMPLICATIONS OF CHANGING CLIMATE FOR THE ARCTIC ENVIRONMENT**

The Canadian Arctic is one of the Arctic environmental areas of the cryosphere which includes sea ice, seasonal coverage of snow, glaciers and permafrost. These are altogether very sensitive to the change in climate effects. All of them are climatic trend indicators and are very important in different climate feedbacks due to energy change because of moisture and gas fluxes (IPCC 2007; Lemke et al. 2007; Trenberth 2007). Thus, the atmospheric changes in the study area as a sensitive region can be attributed to an extra-local and global warming. The Canadian Arctic is located in the Arctic Ocean and it contains the Canadian north mainland, specifically the Arctic Archipelago. The Canadian Arctic Archipelago covers $3.3 \times 10^6 \text{ km}^2$ of the North American continental shelf. Approximately 40% of the Canadian Arctic Archipelago is covered by land and the remainder is covered by
marine areas at around $1.9 \times 10^6$ km$^2$ \citep{Cook2019}. Figure 1 shows a map of the Canadian Arctic.

**RESULTS AND DISCUSSION**

**Arctic sea ice extent and the Canadian Arctic surface temperatures during summer**

Figures 2 and 3 show the summer (monthly averaging of the June, July and August) time series of Arctic sea ice extents and mean surface air temperatures in the Canadian Arctic from 2000 to 2018. The autocorrelation of the mean summer Arctic sea ice and Canadian Arctic summer surface temperature obtained via simple regression indicates the existence of a strong negative linear relationship ($\sim 0.86$) between these two variables between 2000 and 2018 (Figure 3(b)). There are three recent sea ice declines during 2007, 2012 and 2016 corresponding to three peaks in Canadian Arctic surface air temperatures. The lowest value of sea ice is for the year 2012 which is properly matched to the highest summer surface air temperatures over the Canadian Arctic at the same time.

Based on the new National Snow and Ice Data Center (NSIDC) data processing by using DMSP (Defense Meteorological Satellite Program) in early September, the sea ice extent (from both F-17 and F-18 sensors’ records but with a slightly higher value from F-17) has indicated that the minimum extent for 2016 is a little lower than the year 2007 minimum (4.15 million square kilometres which was reached on September 18). Even so, the measurement correctness is at around $\pm 25,000$ square kilometres for a 5-day trailing average daily extent measurement. This means that at this level the year 2016 shows a statistical tie for the second-lowest sea ice extent after 2012.

**Normal mean maps for summer mean sea level pressure and 500 hPa geopotential heights (1981–2010)**

Figure 4 shows the normal mean of the summer mean sea level pressure (MSLP) (a) and 500 hPa geopotential heights (b) during 1981–2010. Figures 4(a) and 4(b) show the map projection over the north polar areas (latitude from 60 to 90°N). Figure 4(a) shows a dominated low-pressure system extending from the Siberian region towards the pole and centred there (1,009 hPa) accompanying a cyclonic cell of
5,420 gpm at 500 hPa geopotential height (Figure 4(b)). Also, there is an additional low-pressure system, the tongues of which are extended from the south in North America to the south-east of the Canadian Arctic region along with a small closed low-pressure cell (1,00 8hPa) placed over Greenland’s centre. However, in the north of Alaska and the western Canadian Arctic (with a cell of 1,014 hPa), the north-west of the Eurasian region in the Arctic Ocean and north, east and south of Greenland (isobar 1,012 h Pa) are affected by the high-pressure systems. An anti-cyclonic ridge of 500 hPa can be seen in eastern Greenland (Figure 4(b), depicted by the wavy line). The westerly 500 hPa trough (dashed line in Figure 4(b)) can be seen in the east of the Canadian Arctic. The north of Alaska in the Arctic Ocean is completely affected by a strong high-pressure system (~1,015.5 hPa).

**Mean sea level pressure and 500 hPa geopotential height composite mean (summer 2007)**

Figure 5(a) shows the MSLP composite mean and Figure 5(b) displays the composite mean of the 500 hpa geopotential heights for summer 2007. As Figure 5(a) shows, the Arctic high-pressure systems have been elongated from Greenland (centred with 1,017 hPa) to the north of Alaska and the Canadian Arctic in the Arctic Ocean (centred with 1,019 hPa). On the other side in the eastern Arctic, an elongated low-pressure system is sited in the north-east of the Eurasian area (no closed cell over the North Pole in comparison with normal mean shown in Figure 4(a)) with three closed cells of 1,005 hPa. This pattern is representative of the Arctic dipole anomaly. These two high-pressure tongues (in Greenland and western Arctic) are accompanied by two mid-tropospheric anti-cyclonic ridges at 500 hPa (shown with the wavy line in Figure 5(b)). In the north of Hudson Bay, a westerly 500 hPa cyclonic trough is extended to the James Bay region (dashed line). The north and west parts of the Canadian Arctic are mostly affected by the high-pressure system. However, the south-eastern areas, for example, Baffin Island, are influenced by the cyclonic system. It is worth mentioning that the quasi-stable structures of high- and low-pressure centres work in connection forces with different regional actions in the atmosphere. A large surface high-pressure system along with the upper anti-cyclonic ridge may cause clear skies, warm temperatures, and sometimes lead to a record of Arctic sea ice melting. However, a large surface low pressure along with the upper trough may cause cloudy skies, rather colder temperatures and storms. Thus, it seems that the Arctic dipole anomaly developed very well during the summer of 2007 in the Arctic region. However, the highest difference between Greenland high pressure (1,017 hPa) and Alaska low (1,011 hPa) pressure is around 6 hPa.
Canadian Arctic MSLP and 500 hPa geopotential height composite anomalies during summer 2007

Figure 6 shows the anomaly maps (subtracting the values of the summer 2007 as the study period from the normal mean values during 1981–2010) for the MSLP (Figure 6(a)) and the 500 hpa geopotential heights (Figure 6(b)) for summer 2007’s departure from the normal mean in the northern hemisphere polar stereographic map projection over the Canadian Arctic. During the anomaly period (summer 2007), the northern high-pressure system was intensified ~100–600 Pa from the central areas to the north parts along with the increase in the 500 hPa geopotential height from 10 to 110 gpm. However, in some small parts in the south with a dominated low-pressure system centred over the north of the Hudson Bay, it was intensified from 100 to 200 Pa, accompanied by a decrease in the 500 hPa geopotential height of ~10–30 gpm for the same area. However, there are no changes in some other parts of the Canadian Arctic region (see white colour during summer 2007 in Figure 6).
Mean sea level pressure and 500 hPa geopotential height composite mean during summer 2012

Figure 7 shows the MSLP composite mean (Figure 7(a)) and the composite mean of the 500 hPa geopotential heights (Figure 7(b)) for summer 2012. As Figure 7(a) demonstrates, the Greenland high-pressure system with a centre of 1,017 hPa was extended to the northern Canadian Arctic (isobar 1,014 hPa). The elongated Eurasian low-pressure system drifted to the Arctic Ocean and centred at 1,005 hPa in the north-west of Alaska, showing the Arctic dipole anomaly pattern. The high-pressure tongues are accompanied by two mid-tropospheric anti-cyclonic ridges (wavy line in Figure 7(b)) at 500 hPa in Greenland and the eastern
Canadian Arctic, respectively. In the north of the Canadian Arctic islands, the 500 hPa cyclonic trough has been extended to the north-east of the Hudson Bay (dashed line), associated with a surface low-pressure system centred over the north-east of Hudson Bay. Most parts of the Canadian Arctic Archipelago, except the areas in central and southern parts, have been affected by the high-pressure system. Here, the Greenland high-pressure system is strong and positioned over the northern Canadian Arctic. However, the north of Alaska has been affected by a stronger low-pressure tongue (1,009 hPa rather than 1,011 hPa) in comparison with summer 2007. Hence, the highest difference between the Greenland high (1,017 hPa) and Alaska low (1,009 hPa) is around 8 hPa.
Canadian Arctic MSLP and 500 hPa geopotential height composite anomalies during summer 2012

Figure 8 shows the anomalies for the MSLP (Figure 8(a)) and the 500 hPa geopotential heights (Figure 8(b)) for summer 2012 departure from the normal mean in northern hemisphere polar stereographic map projection over the Canadian Arctic. During the anomaly period (summer 2012), the high-pressure tongue in the northern and eastern areas was intensified from 50 to 350 Pa with the maximum in the eastern areas. However, in the south-east and southern parts, the dominated low-pressure system centred in the north of the Hudson Bay was intensified from 50 to 250 Pa. The geopotential heights at 500 hPa increased from 10 gpm in all parts with the highest change in the eastern areas (~90 gpm), except for small areas in the south with no change. A comparison of Figures 8 and 6 shows a more intensive anti-cyclonic system during 2012 rather than 2007.

Mean sea level pressure and 500 hPa geopotential height composite mean during summer 2016

Figure 9 shows the MSLP composite mean (Figure 9(a)) and a composite mean of the 500 hPa geopotential heights (Figure 9(b)) for summer 2016. As Figure 9(a) demonstrates, the Greenland high-pressure system is centred at 1,016 hPa and has been extended to the northern Canadian Arctic (with an isobar of 1,015 hPa). The Eurasian low-pressure, in the form of the cut off system, has drifted to the Arctic Ocean and it is very strong (centred at 1,005 hPa). This pattern is the typical example of an Arctic dipole anomaly. The Greenland high-pressure tongue is accompanied by a mid-tropospheric anti-cyclonic ridge (Figure 9(b)) at 500 hPa (see the short wavy line). In the north of Hudson Bay, a 500 hPa cyclonic shallow westerly trough was sited in the north (see the short dashed line) associated with a surface low-pressure system centred over the east of Hudson Bay. Here, the Greenland high-pressure system is strong and was positioned over the northern Canadian Arctic. However, the north of Alaska has been affected by a rather weaker low-pressure tongue (~1,011 hPa rather than 1,009 hPa) in comparison to summer 2012. Hence, the highest difference between the Greenland high (1,016 hPa) and Alaska low (1,011 hPa) is around 7 hPa.

Canadian Arctic MSLP and 500 hPa geopotential height composite anomalies during summer 2016

Figure 10 shows the anomalies for the MSLP (Figure 10(left)) and the 500 hPa geopotential heights (Figure 10(right)) for summer 2016’s departure from the normal mean in the northern hemisphere polar stereographic map projection over the Canadian Arctic. During the anomaly period (summer 2016), the Greenland high-pressure system from

![Figure 8](image-url) | Anomalies for the MSLP (a) and the 500 hpa geopotential heights (b) during summer 2012 in the Canadian Arctic. The anomalies are departures from normal climatology mean (1981–2010).
the north-east intensified in the eastern Canadian Arctic from 50 to 450 Pa, mostly in the eastern Canadian Arctic, with a maximum value in the north of Baffin Island. However, in the north-west, the high-pressure system was weakened from 50 to 400 Pa. In the south-west of the Canadian Arctic, the mean sea level pressure has not changed either or has a slight increase in the south-west corner. The geopotential heights at 500 hPa have increased from 40 gpm in all parts (with the highest change in the north part of Baffin Island (~80 gpm)), except for the small area in the north-west corner of the map which has a slight decrease between 0 and 30 gpm.

**Canadian Arctic air temperatures at 925 hPa anomalies**

Figure 11 shows the anomalies of the air temperatures at 925 hPa departure from the normal climatological mean (1981–2010) in the Canadian Arctic in 2007 (a), 2012 (b)
and 2016 (c). During the summer of 2007, in all parts of the Canadian Arctic, the near-surface air temperatures increased from 0.5 to 3 °C except in some small areas in Nunavut which decreased from ~0.5 to 1.5 °C (Figure 11(a)). This is due to the downstream flow anomalies of the cycloonic system which can be seen in the MSLP anomaly map along with the 500 hPa geopotential heights decreasing over the same area (Figures 5(a) and 5(b)). During summer 2012 (with the highest surface temperature record in comparison with the summers of 2007 and 2012) the Canadian Arctic air temperatures at 925 hPa increased in most parts from 0.5 to 4 °C, except in some small areas in the north of Baffin Island which had a 0.5 °C decrease or in the central part of the Canadian Arctic where there was no change. During 2016, all parts of the Canadian Arctic were getting warmer in 925 hPa air temperature rather than normal mean at around between 0.5 and 3 °C. Some small areas in Ellesmere Island and Baffin Island do not show any changes in respect to their normal values. A comparison of these figures shows a higher value change for the low-level temperature for the year 2012 rather than 2016 and 2007.

**Vertical cross section of temperature anomalies**

Figure 12 shows the air temperature anomalies as a function of height (from 1,000 to 300 hPa) and latitude (between 60 and 85°N), averaged for the longitudes between 230 and 300°E. Temperatures are for summer periods of 2007 (a), 2012 (b) and 2016 (c) compared to normal mean averages for the years from 1981 to 2010. In Figure 12(a), all parts between 68 and 85°N have ~0.5–2 °C above the normal (from 1,000 hPa to 400 hPa). The latitudes between 72°N and 76°N are found up from 950 to 850 hPa, more than 2 °C above the normal, and the abnormal temperatures are extended for higher latitudes up to 400 hPa. The pattern...
for 2012 shows higher temperatures changing from 1 °C to more than 2.4 °C for all parts, mostly for a low level between 70 and 72°N and between 80 and 85°N at levels between 950 and 850 hPa. The vertical cross section for the year 2016 shows the most changes for latitudes between 68 and 72°N from low level to 400 hPa at around 2 °C. The comparison of these results shows the highest change in Canadian Arctic vertical air temperatures (both in extent and values) for the year 2012 and the lowest change is for the year 2007 corresponding to the Arctic sea ice extent records (Figure 3).

**Low-level wind vector anomalies**

Figure 13 shows the low-level wind vector (level of 925 hPa) anomalies’ departure from normal mean for summer 2007 (a), summer 2012 (b) and summer 2016 (c) in the Canadian Arctic. In summer 2007, the low-level flows turned to the south-easterly winds, mostly over the east and south-east regions. In general, the southerly winds favour ice melt and may push the ice away from the coastline and cause open water to be left in the Arctic region. However, the anomaly pattern for the low-level flows in the north-east, north-west and south-west is north-westerlies or northerly. It is notable that, in the east side of the cyclonic pressure anomaly pattern (Figure 5(a)), the upstream flow (wind direction from southern areas to the northern areas which carry the rather warmer air masses from the south to the northern latitudes) anomalies lead to Arctic sea ice loss. This is due to ice transport by winds out of the Arctic Ocean into the north. Figure 13(b) shows the low-level wind flows during the summer heatwave of 2012 over the Canadian Arctic region. The pattern clearly shows the intensification of the south-easterly currents over most parts of the Canadian Arctic, particularly over the Baffin Island region with the highest values (≈0.5–5 m/s) rather than the
year of 2007 (0.5–3.5 m/s). Figure 13(c) shows the low-level wind flows for the heatwave of 2016 over the Canadian Arctic region. The pattern shows the intensification of the south-easterly, south and south-westerly currents over most parts of the Canadian Arctic except in the eastern areas. In this year, in a small area over the west of Ellesmere Island, the south-westerly winds intensified up to ∼5.5 m/s. The comparison of these results shows the highest change in Canadian Arctic low-level winds turning to the southerly structures is for the year 2012 and the lowest change is for the year 2007 corresponding to the Arctic sea ice extent records (Figure 3(a)).

Anomalies of the total clouds and downward radiation flux at the surface

Figures 14 and 15 show the total clouds’ forecast at entire atmosphere (%) and downward radiation flux at surface anomalies during summer 2007 (a), 2012 (b) and 2016 (c). Figures 14(a) and 15(a) display the reduction (negative anomaly) of the total clouds (2.5–20%) along with an increased (positive anomaly) downward radiation flux at the surface (10–30 Wm⁻²) during summer 2007, mostly in the north and western areas associated with the influence of the high-pressure system over these areas. However, in the south and south-east areas which are affected by the cyclonic system, the total clouds have increased (2.5–12.5%) and downward radiation flux at the surface has decreased (10–40 Wm⁻²). In summer 2012, the total clouds have decreased mostly in the western areas (2.5–17.5%) along with an increase of downward radiation flux at the surface (10–30 Wm⁻²). In the south-east part of the Canadian Arctic, the cloud covers have increased (2.5–17.5%) and the downward radiation flux at the surface has decreased (10–50 Wm⁻²). In the summer of 2016, the total clouds decreased (1.5–15.5%), mostly over the entire
region except in a small part in the north which had an increase of around 1.5–12.5%. These are accompanied by an increase and a decrease in the downward radiation flux at the surface at around 10–30 and 10–40 Wm$^{-2}$, respectively, which is associated with the high-pressure system intensification over most parts of the Canadian Arctic except the north-west part (Figure 10). Therefore, the areas with negative anomalies in cloudiness have an increased downward radiation flux at the surface which is associated with the rather clear skies.

**Albedo at surface anomalies**

Figure 16 shows albedo anomalies during summer 2007 (a), 2012 (b) and 2016 (c). Figures 16(a)–16(c) clearly show the negative anomalies for albedo surface for most parts of the Canadian Arctic Ocean during the mentioned heatwaves, ~5–40%, with the higher changes (mostly in the eastern areas) during summer 2012 in respect to summer 2016 and summer 2007 corresponding to the higher temperatures and sea ice decline records. In Figures 16(b) and 16(c), in some parts, the positive albedo anomalies mostly in Baffin Island may be related to the Arctic summer-time vegetation change coverages due to global warming. Earlier studies demonstrated that the changes in vegetation coverage, for example from evergreen to deciduous, may cause a surface cooling due to the albedo increase and latent cooling (Liu et al. 2005; Swann et al. 2010).

**CONCLUSIONS**

The summer-time series of the Arctic sea ice extent and Canadian Arctic surface air temperatures from 2000 to 2018 have indicated three recent sea ice declines in 2007, 2012 and 2016 corresponding to three peaks in Canadian Arctic surface air temperatures. The lowest value of the Arctic sea ice for the year 2012 has matched with the highest surface temperature in the summer average Canadian Arctic surface air temperatures. The mean sea level pressure and
500 hPa geopotential heights during the summers of 2007, 2012 and 2016 have revealed an abnormal patterns’ departure from the normal climatology mean patterns in the Canadian Arctic associated with the Arctic dipole anomaly structure. During the normal period (1981–2010), the north of Alaska in the Arctic Ocean has been completely affected by a strong high-pressure system. However, during the abnormal times in summer 2007, 2012 and 2016, the north of Alaska was affected by the low-pressure tongues. The highest differences between Greenland high-pressure centre and Alaska low-pressure tongue for the summers of 2012, 2016 and 2007 are 8 hPa, 7 hPa and 6 hPa, corresponding to the highest surface Canadian Arctic temperature records for the same times, respectively. The positive anomalies in air temperatures rather than normal values in low-level (at 925 hPa are ~0.5–4 °C) and in the vertical temperature profiles up to 300 hPa height (averaged over 230–300°E are ~0.5–2.4 °C) during three recent heatwaves years of 2007, 2012 and 2016 have been revealed for most parts of the Canadian Arctic region with a higher peak for the year 2012 rather than 2016 and 2007, respectively. Also, the low-level wind flows during these heatwaves have turned and accelerated (~0.5–3.5 m/s) anomalously to the southerly patterns in southern and eastern areas during 2007, in almost all parts (~0.5–4.5 m/s) during 2012 and over most parts of the Canadian Arctic (~0.5–4.5 m/s) except the eastern areas during 2016. The highest change in Canadian Arctic low-level winds with the southerly structures is recorded for the year 2012 and the lowest change is shown for 2007 corresponding to the Arctic sea ice extent records. During the study periods in anomalous summer heatwaves, the total clouds’ forecast (%) and downward radiation flux at the surface dramatically changed. The areas with negative anomalies in cloudiness

Figure 15 | Downward radiation flux at surface anomalies during summer 2007 (a), 2012 (b) and 2016 (c).
have an increase in downward radiation flux at the surface linking to the rather clear skies. Higher values in downward radiation flux at the surface can cause amplification of the sea ice declines. Also, this study has shown that the surface albedo has reduced over most parts of the Canadian Arctic Ocean during the mentioned heatwaves (~5–40%) (particularly in the eastern Canadian Arctic region) with higher changes during summer 2012 in comparison with summer 2016 and summer 2007. This has corresponded to the surface temperatures and sea ice decline records.

The present work has some limitations, such as local real-time data analysis (despite the lack of observational data in the remote Arctic areas), and in planning for improvements in future directions a comparison of the observational data and climate models has to be considered. By comparison of the model results and real-time data, the climate models' simulations can be improved. Also, this work can be conducted for ensemble climate projection finding suitable climate models (i.e., Homsi et al. 2020). In addition, this work can study local evaporation as an important factor for better understanding of the study area during the study periods (i.e., by using techniques like that of Moazenzadeh et al. (2018). Also, novel modelling techniques, such as the machine learning method, can make more accurate and efficient climate prediction over the study area (i.e., Mosavi et al. 2018).

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Data Availability Statement

All relevant data are included in the paper or its Supplementary Information.

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