ARCTIC
VOL. 76, NO. 3 (SEPTEMBER 2023) 244–264
https://doi.org/10.14430/arctic77263

Performance of Climate Projections for Yukon and Adjacent Northwest Territories, 1991–2020

Astrid Schetselaar,[1] Trevor Andersen[1] and Christopher R. Burn[1,2]

(*Received 29 October 2022; accepted in revised form 14 February 2023*)

ABSTRACT. The design of permafrost foundations now takes into account the impact of climate change on soil bearing capacity, as exemplified in the 2019 Canadian Standards Association (CSA) guideline CSA PLUS 4011:19. To date, however, no guidance exists to help developers discern which climate scenarios would be most prudent for adoption in this design area. We have compared climate change scenarios that were outlined in 2003 for the design of the proposed Mackenzie Gas Project with climate data for 1991–2020 in order to determine the projections that are most representative of what did, in fact, occur. In Canada, the greatest change in climate during the last 50 years has been measured in the western Arctic where fluctuations in annual air temperatures are regionally consistent. The rate of change in annual mean air temperature for 1971–2020 has ranged from 0.77˚C decade^{-1} at Inuvik, NT, to 0.30˚C decade^{-1} at Komakuk Beach, YT, with warming concentrated in winter. No statistically significant trends in total annual precipitation have been observed, and these records are poorly correlated within the region. In 2003, in the context of MGP design, a specially assembled group of scientists and other experts examined 29 climate projections from seven global climate models; these scenarios were revisited separately in 2005 to support research into forest fires in Yukon. Based on our analysis, the observed climate warming in Yukon and adjacent Northwest Territories during 1991–2020 was close to the upper projections for mean annual and winter air temperature. For example, at Inuvik, the 2.3˚C increase observed in mean annual air temperature between 1961–90 and 1991–2020 exceeds the median projection for change by 2010–39 of +1.6˚C and approaches the upper value of +2.4˚C. Our analysis did not determine any consistency between observed and projected precipitation. These results indicate that, when required, developers concerned with future projections of temperature in northwest Canada may prudently adopt more extreme scenarios because these have been the most realistic to date. The results also imply that near-surface permafrost may soon become unsustainable in southern parts of the region, so site investigations to locate thaw-stable soils will likely be cost effective for new projects.

Keywords: climate change; Yukon; Mackenzie Valley; climate scenarios; temperature; precipitation; engineering design; infrastructure foundations

RÉSUMÉ. La conception des fondations dans le pergélisol tient désormais compte de l’impact du changement climatique sur la capacité portante du sol, tel qu’exemplifié dans la norme canadienne CSA PLUS 4011:19 de 2019. Toutefois, jusqu’à maintenant, il n’existe aucune ligne directrice pour aider les promoteurs à déterminer quels scénarios climatiques il serait plus prudent d’adopter à cet égard. Nous avons comparé les scénarios de conception en vue du changement climatique énoncés en 2003 pour la proposition de projet gazier Mackenzie aux données climatiques de 1991 à 2020 afin de déterminer les projections les plus représentatives de ce qui s’est réellement produit. Au Canada, le plus grand changement climatique enregistré ces 50 dernières années a été mesuré dans l’ouest de l’Arctique, où les fluctuations des températures annuelles de l’air sont uniformes sur le plan régional. Le taux de changement de la température moyenne annuelle de l’air pour les années allant de 1971 à 2020 a varié de 0,77 °C décennie^{-1} à Inuvik, Territoires du Nord-Ouest à 0,30 °C décennie^{-1} à Komakuk Beach, Yukon, le réchauffement étant concentré en hiver. Sur le plan des précipitations annuelles totales, aucune tendance statistiquement significative n’a été observée, et ces données sont mal corrélées dans la région. En 2003, dans le contexte de la conception du projet gazier Mackenzie, un groupe de scientifiques et d’autres spécialistes constitué à cette fin a examiné 29 projections climatiques provenant de sept modèles climatiques mondiaux. Ces scénarios ont été réexaminés séparément en 2005 dans le cadre de recherches sur les feux de forêt du Yukon. Selon notre analyse, le réchauffement climatique observé au Yukon et dans les Territoires du Nord-Ouest adjacents de 1991 à 2020 s’approchait des projections supérieures de la température moyenne annuelle et hivernale de l’air. Par exemple, à Inuvik, l’augmentation de 2,3 °C qui a été observée sur le plan de la température moyenne annuelle de l’air de 1961 à 1990 et de 1991 à 2020 dépasse la projection médiane de +1,6 °C pour le changement d’ici 2010 à 2039 et s’approche de la valeur supérieure de +2,4 °C. Notre analyse n’a pas permis de déterminer d’uniformité entre les précipitations observées et les précipitations projetées. Selon les résultats, au besoin, les promoteurs s’inquiétant

[1] Department of Geography and Environmental Studies, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada
[2] Corresponding author: christopher.burn@carleton.ca

des projections des températures dans le nord-ouest du Canada pourraient prudemment adopter des scénarios plus extrêmes parce que ce sont ces scénarios qui s'avèrent les plus réalistes jusqu'à maintenant. Les résultats impliquent également que le pergélisol subaffleurant pourrait bientôt devenir insoutenable dans les parties sud de la région. Par conséquent, des études visant à localiser les sols stables au dégel seraient probablement rentables dans le cadre de nouveaux projets.

Mots-clés : changement climatique; Yukon; vallée du Mackenzie; scénarios climatiques; température; précipitations; conception technique; fondations d'infrastructures

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

The Arctic as a whole is warming more rapidly than the rest of the planet (Zhang et al., 2019; Rantanen et al., 2022), and the western Canadian Arctic experienced the greatest warming of all regions in the country during 1946–2012 (Fig. 2 in Vincent et al., 2015). Projections of future climate depend on which simulation of greenhouse gas emissions are used, but all indicate continued warming over the next two decades at least, with Arctic warming exceeding the global average (Bush and Lemmen, 2019; IPCC, 2021a). Long-term trends in precipitation are not as clear, but rainfall is expected to increase as temperatures rise and snow is replaced by rain in spring and early autumn (Vincent et al., 2015; Bintanja and Andry, 2017). The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report projects increases in precipitation as well as temperature "everywhere in Canada over the 21st century" (IPCC, 2021a: Atlas 9.4).

Prior to the environmental assessment of the Mackenzie Gas Project (2004–10), Indian and Northern Affairs Canada assembled a group to provide scenarios of climate change during the proposed service life of the pipeline and its associated facilities (~2010–40) (Burn, 2003). The group included representatives from industry, non-governmental organizations, regulatory agencies, academia, and federal science agencies. In October 2003, the group met and achieved consensus on climate change scenarios to be used in the pipeline's environmental assessment. Immediately afterwards, Indian and Northern Affairs published a report (Burn, 2003), and Burn et al. (2004) disseminated the results more widely with a conference paper. These publications presented climate projections for Mackenzie Valley. Subsequently, during the research on forest fire incidence and intensity, McCoy and Burn (2005) made a similar selection for Yukon.

There has been considerable interest in the ecological consequences of climate change in northern Canada (e.g., Fraser et al., 2014; Wilcox et al., 2019) and in the effects of climate change on permafrost terrain (e.g., Kokelj et al., 2017; Burn et al., 2021a). Similarly, the potential degradation of carbon currently stored in permafrost and its release as CO_2 or CH_4 has stimulated substantial research (e.g., Schuur et al., 2015; Miner et al., 2022). Of immediate financial consequence, however, are the effects of permafrost degradation beneath surface infrastructure (Melvin et al., 2017; Hjort et al., 2018, 2022). Projections of such effects depend on which scenarios owners of infrastructure use to outline the anticipated scale of climate change. Owners require adequate awareness of potential climate change that may occur over the intended service life of their projects in order to: (1) assess the extent of capital investment required for the physical foundation during initial construction, (2) estimate the degree of rehabilitation and maintenance that will be required during project life, and (3) settle on a balance between these costs that adequately manages the risks associated with permafrost degradation.

The Canadian Standards Association (2019) has published a technical guideline, Infrastructure in Permafrost: A Guideline for Climate Change Adaptation (CSA PLUS 4011:19), to outline a process whereby climate change may be assessed in foundation design. Key components of the process are first, to determine the risk posed to infrastructure by permafrost thaw due to climate change, and second, contingent numerical modelling to specify required ground cooling to maintain foundation integrity. Hayley and Horne (2008) have presented case studies describing applications of the process in the design of the Inuvik Regional Health Centre, NT, and in the reclamation of several Distant Early Warning Line sites. The guideline relies on climate change projections published by the IPCC, but it does not provide categorical criteria to enable a developer to select a likely future climate for planning purposes. This is primarily because future emissions pathways are unknown.

Nevertheless, over 20 years ago, in its Third Scientific Assessment, the IPCC (2000) published climate change scenarios driven by various emissions pathways. The Canadian Climate Impacts and Scenarios project (CCIS) at the University of Victoria subsequently assembled these scenarios for Canada. Examination of these projections with respect to the accumulated record, as Bonsal and Kochtubajda (2009) have done, may provide evidence to guide developers regarding a choice of future scenario.

The purpose of this paper is to examine the projections available in 2003 for Yukon and Mackenzie Valley (Fig. 1) and compare them with the subsequent record. The intention is to determine if the scenarios underestimated, overestimated, or were consistent with recent observations. The scenarios relate to air temperature and precipitation on annual and seasonal bases, projecting changes in these indices with respect to baseline conditions in 1961–90. In 2003, the CCIS project presented scenarios formulated for 2010–39, 2040–69, and 2070–99 but without indication

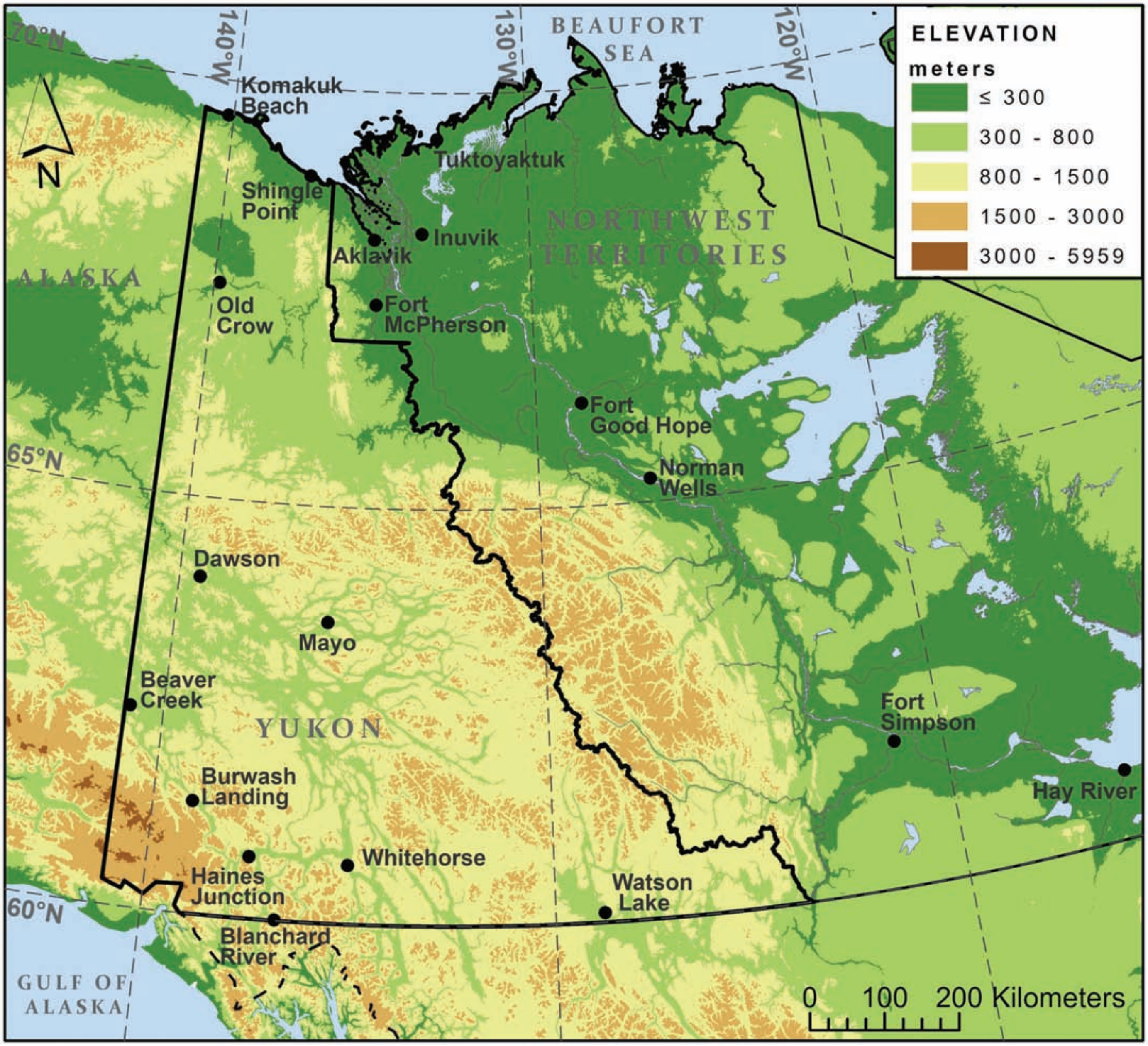

FIG. 1. Yukon Territory and western Northwest Territories, including Mackenzie Mountains and adjacent Mackenzie River Valley, with locations of all weather stations used in this paper, except Fort Smith, ESE of Hay River. Elevation data retrieved from ArcticDEM (Porter et al., 2018).

of relative probability of occurrence. At the time, the suite of projections represented the best assessment of potential future climates. We are now able to compare three climatic periods, 1971–2000, 1981–2010, and 1991–2020 with the trajectory from the 1961–90 climate towards projections for 2010–39.

CLIMATE OF WESTERN ARCTIC CANADA

The climate of Yukon and Mackenzie Valley, including the Mackenzie Delta and western Arctic coast, is influenced by its latitude and the Saint Elias and Coast mountains of the Western Cordillera (Fig. 1) (Wahl et al., 1987). The physiography of the region creates a continental climate that supports permafrost (Burn, 1994, 2012). The principal physiographic effects on regional climatology stem from the efficacy of the coastal mountains in blocking Pacific maritime air masses from entering the region (Wahl et al., 1987). Due to the topography, the interior is dryer than the coast, with greater seasonal range in temperature (Fig. 2). For example, the 98.3˚C range in recorded air temperature extremes for 1925–2022 at Mayo, YT (Fig. 1), −62.2 to +36.1˚C, is the greatest in Canada (Wahl et al., 1987, see also ECCC, 2023a). The dissected Cordilleran terrain of much of Yukon facilitates development of steep atmospheric inversions in winter, with cold air that pools in valley bottoms; the air remains poorly heated due to

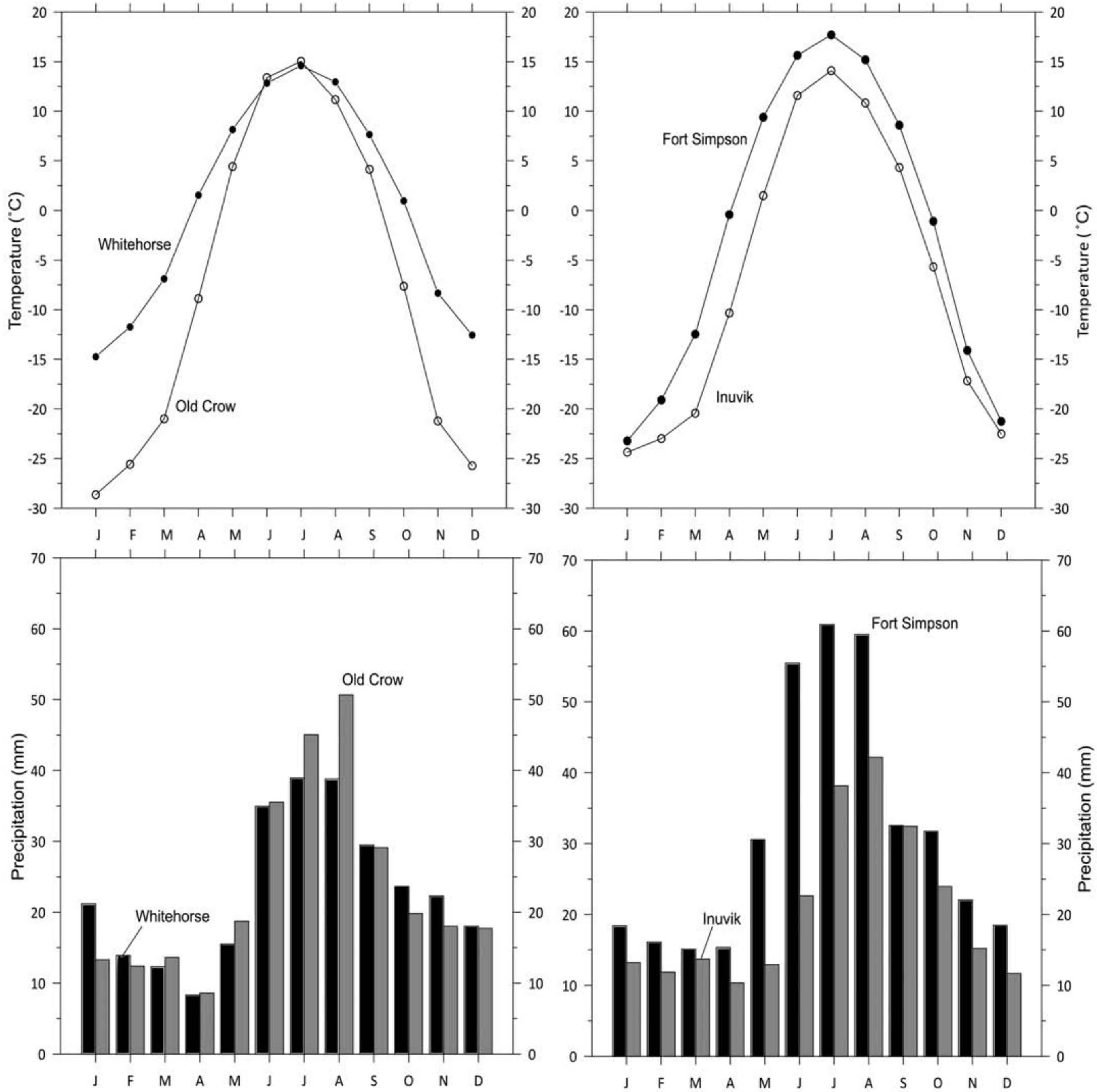

FIG. 2. Monthly mean temperature and precipitation for 1991–2020 at Whitehorse and Old Crow, YT (left-hand panels) and at Fort Simpson and Inuvik, NT (right-hand panels). Whitehorse and Old Crow are 790 km apart, while the distance between Fort Simpson and Inuvik is 920 km. Homogenized ECCC data used for temperature and historical data for precipitation.

the low angle of the sun (Fig. 3) (Wahl et al., 1987; Burn, 1993). The climatic gradient in the region is responsible for variation in permafrost distribution from discontinuous permafrost near Whitehorse, YT, and Fort Simpson, NT, through to continuous permafrost near Old Crow, YT, and Inuvik, NT. Mean annual air temperatures (MAAT) for 1981–2010 published by Environment and Climate Change Canada (ECCC, 2023b) as climate normals for the study area ranged from −0.1˚C at Whitehorse, in southern Yukon, to −10.1˚C at Tuktoyaktuk, NT, on the western Arctic coast. Mean total annual precipitation in the same period ranged from 161 mm at Tuktoyaktuk to 533 mm at Blanchard River, YT (Fig. 1).

The low spatial density of climate stations in the region is due to the dispersed population and communities, but the climate records for Yukon and Mackenzie Valley are among the longest in northern Canada. The published ECCC record for Fort Simpson began in 1895 and for Dawson in 1897; continuous records have been available since 1940 for Whitehorse and since 1910 for the lower Mackenzie

FIG. 3. Valley of Lightening Creek, near Keno, central Yukon, in shadow at noon, 23 November 2003. The valley is aligned east – west and is shaded from solar radiation for several months each winter. Photograph © C.R. Burn

TABLE 1. Grid cell size for seven GCMs used to develop climate scenarios for the Mackenzie Gas Project (following Table 3 in Burn et al., 2004).

GCM	Country	Width (˚Latitude)	Width (˚Longitude)	Area (km^2)
CCSR98	JPN	5.6	5.6	168,000
CGCM2	CAN	3.75	3.75	74,000
CSIROMk2B	AUS	3.2	5.6	95,000
ESCHAM4	GER	2.8	2.8	41,000
GFDLR30	USA	2.2	3.75	44,000
HADCM3	UK	2.5	3.75	50,000
NCARPCM	USA	2.8	2.8	41,000

Valley, with data collected from Fort McPherson, Aklavik, Fort Good Hope, and, after 1957, Inuvik. Climate warming during the late twentieth century is evident from the record at Dawson and Herschel Island (Fig. 6 in Burn and Zhang, 2009). Thienpont et al. (2013) identified 1970 as the date when the most recent climate warming began in the Mackenzie Delta area. In northwest Canada, MAAT have increased by more than 3˚C at some locations since the mid-twentieth century, while the rest of Canada experienced an increase of 1.7˚C in this period (Zhang et al., 2019). The rate of increase for annual mean air temperatures (AMAT) in 1970 – 2018 has been reported for the Mackenzie Delta area as 0.71˚C and 0.61˚C decade^{-1} for Inuvik and Tuktoyaktuk, respectively (Burn et al., 2021a) recalling that MAAT is the mean of several annual means, AMAT is the mean of one year's data. Seasonally, rates of temperature increase are greatest in winter (Vincent et al., 2015). These trends are consistent with changes in the annual number of days with snow cover in northern Canada; data show decreases of between two and four days decade^{-1} between 1951 and 2015 (Brown et al., 2017).

CLIMATE SCENARIOS FOR CANADA'S WESTERN ARCTIC

The Special Report on Emission Scenarios (SRES) (IPCC, 2000) provided several projections of future climate conditions and formed a basis of the Third Assessment Report (IPCC, 2001). These scenarios included storylines for future greenhouse gas emissions based on assumptions regarding demographic, social, economic, technological, and environmental driving forces. Forty scenarios were divided into four families (A1, A2, B1, B2). The A1 family assumed rapid population and economic growth and was

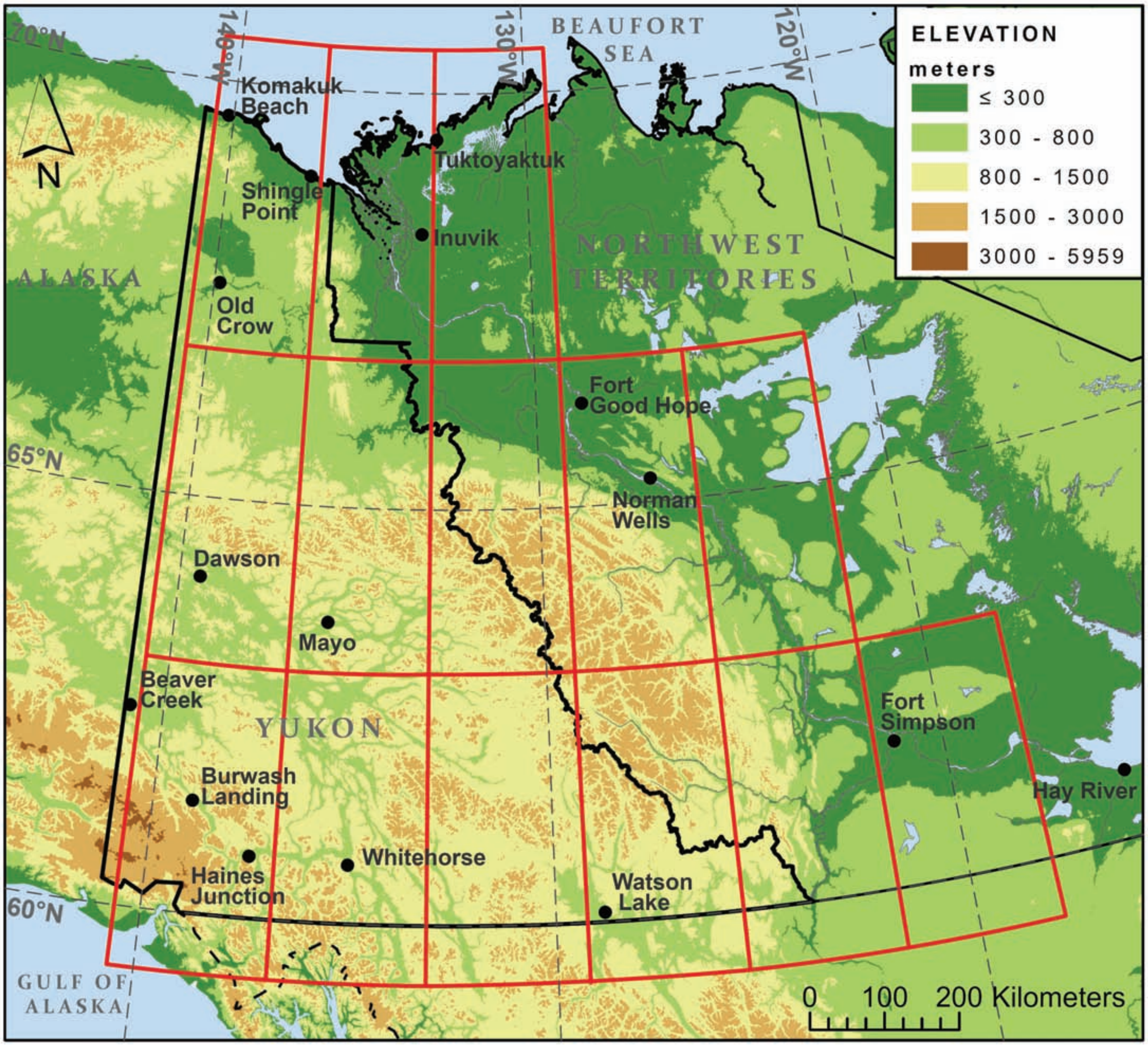

FIG. 4. Grid cells of global climate model CGCM2 from which projections were obtained for comparison with observations of air temperature and precipitation for Yukon and western Northwest Territories. The cell sizes varied between models from which projects were compiled (see Table 1). All stations used to determine regional correlation fields, except Fort Smith, NT, are indicated.

further subdivided into three groups based on energy sources: heavy reliance on fossil fuels (A1F1), non-fossil fuel energy sources (A1T), and balanced use of these sources (A1B). The A2 family was regionally focused with respect to development and included a presumption of a continuously increasing population. The B1 and B2 scenarios considered interventions to reduce emissions at the global and local scales respectively (IPCC, 2000). Global emissions have been within the range of these scenarios and have increased at a rate slightly above the median projection (Fig. 1.28 in IPCC, 2021a).

Since the Fifth Assessment Report of 2013, the IPCC (2013) has relied on representative concentration pathway (RCP) scenarios, which define four different emission trajectories, RCP2.6, RCP4.5, RCP6.0, and RCP8.5, based on the magnitude of radiative forcing (W m^{-2}) compared to pre-industrial values. The trajectories indicate the heating derived from radiative gases added to the atmosphere, i.e., the enhanced greenhouse effect (Burn et al., 2021b). The low-emission RCP2.6 scenario is not comparable to any SRES scenario, but intermediate emission scenario RCP4.5 is comparable to SRES B1, and RCP6.0 lies between SRES B2 and A1B. The high emission scenario RCP8.5 is most similar to the highest SRES scenario, A1F1 (van Vuuren and Carter, 2014). Further emissions-scenario development is reported in the Sixth Assessment Report (IPCC, 2021a, section 1.6.1.4), but with respect to 2020–50, the range of projected emissions is accommodated by the SRES group, although the specific composition of emissions may vary (Fig. 1.28 in IPCC, 2021a). At a global scale, projections of change in temperature have been borne out by observations (Hausfather et al., 2020), demonstrating that the models used by the IPCC are reliable assessments of the global ocean-atmosphere system.

In this paper, we compare the climate scenarios available in 2003 (i.e., the SRES group) with the regional climates they projected for northwest Canada. CCIS provided 29 climate scenarios from seven global climate models (GCMs) (Table 1). In each case, we extracted data for four main regions of interest: central Yukon, southern Yukon, lower (north) Mackenzie Valley, and upper (south) Mackenzie Valley. Northern Yukon has no stations with records of sufficient length to determine baseline and evolving climate conditions. We derived data for each sub-region from appropriate grid cells of the various GCMs (Fig. 4). We represented output data by incremental adjustments from the baseline period of 1961–90 for three projection periods through the twenty-first century (2010–39, 2040–69, and 2070–99). In this analysis, we consider the baseline period and the projections to 2010–39 only.

DATA AND METHODS

The primary data used in this paper are ECCC climate normals for temperature and precipitation. At the time of writing, ECCC had not published data for 1991–2020, the most recent normal period. We calculated normals based on homogenized historical climate records made available by ECCC up to 2020 (ECCC, 2023c). By correcting for variations in non-climatic factors, including changes to instrumentation, local site conditions, observation methodologies, and site relocation, Vincent et al. (2020) homogenized these data across the country specifically for use in trend analysis and climate change monitoring. We also used the homogenized ECCC records in temperature analyses in order to determine spatial consistency in climate variation and to identify representative sub-regional stations with a relatively long record. These are secondary elements of our paper but provide the climatic context for the results of our primary assessment.

Nationally, Mekis and Vincent (2011) examined and corrected precipitation data for various factors associated with gauge design, station positioning, and recording interval. Such corrections have made little material difference to the identification of trends in precipitation across Canada, which are spatially inconsistent (ECCC, 2023d). Unlike the homogenized temperature data, ECCC has not homogenized precipitation data through to 2020. As a result, we used historical ECCC data available to 2020 (ECCC, 2023a) to calculate the most recent precipitation normals. We also used historical ECCC data to calculate the most recent temperature normal for Beaver Creek because, unlike all other stations within the study area (Fig. 4), the temperature record has not yet been homogenized for this site. Published normal values were unavailable in some cases for earlier periods, so we used historical ECCC precipitation data to calculate those missing values.

Climate Records

We selected several ECCC climate stations with relatively long and complete records for analysis in Mackenzie Valley and Yukon (Fig. 4). For each of the four regions of interest, we assigned one station to be the representative station based on length and completeness of record and consistency of data compared to other nearby stations. The representative stations are: Dawson or Mayo (central Yukon), Whitehorse (southern Yukon), Inuvik (lower Mackenzie Valley), and Fort Simpson (upper Mackenzie Valley). Both Dawson and Mayo are in central, rather than northern, Yukon, but temperature and precipitation records from Old Crow (Fig. 4) have been mainly complete only since 1985 and are insufficient for the analysis. The representative station for central Yukon differed depending on whether we considered temperature (Dawson) or precipitation (Mayo). Dawson has a longer temperature record, while Mayo has a more complete and consistent precipitation record. The precipitation record for Dawson began in 1901 but has 88 months with missing daily data compared with 23 months at Mayo, where observations began in 1925. At Dawson, the station measuring precipitation has also moved from the townsite to the airport; in Mayo the station has been at the airport throughout the period of record.

We tabulated ECCC historical meteorological data for each location to produce monthly temperature and precipitation records. We compared these tabulated historical temperature and precipitation data with the homogenized series in order to compare the correlation structures of these series in the region. We amalgamated data from multiple historical records per location to produce relatively long, complete overall series. The most recent data were commonly from airports, with earlier observations at townsites. We considered the different stations at most communities to be close enough that spatial variability in historical temperature and precipitation would be minimal. The airports at Dawson and Fort Simpson are, respectively, 15 km and 12 km from the townsites. We only used Dawson as a representative station for temperature, since spatial variability in air temperature is less than for precipitation (Vincent et al., 2015, 2018).

ECCC (2023b) provides guidelines on the calculations of monthly and normal values. When determining average temperatures for climate normals, monthly values are excluded if more than three consecutive or five days in total are missing (the “3 and 5 rule”). We followed the 3 and 5 rule for our tabulations of historical monthly temperatures. For normal total precipitation, monthly values are excluded if any daily data are missing (ECCC, 2020). However, Vincent et al. (2015, 2018) loosened the guideline for

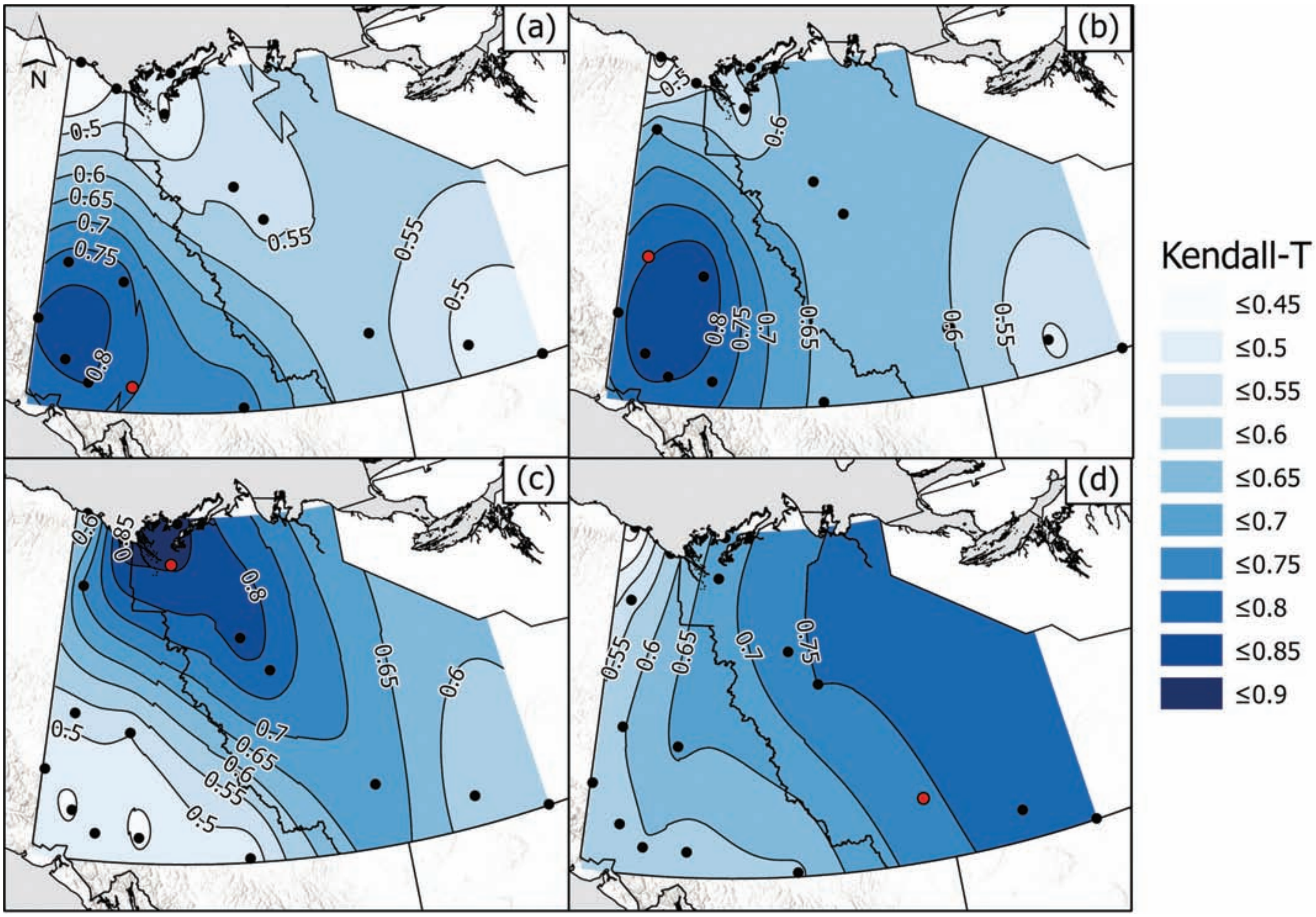

FIG. 5. Spatial correlation fields (Kendall-τ coefficients) for annual mean air temperature relative to the four representative stations of (a) Whitehorse, (b) Dawson, (c) Inuvik, and (d) Fort Simpson. The correlation fields were generated from homogenized climate data.

precipitation and used the 3 and 5 rule in their assessments of climate change in Canada. To improve completeness of the data sets, we chose instead to keep months with up to 48 hours or two days of missing precipitation data, a more stringent criterion than used by Vincent et al. (2015, 2018).

In the last 10 to 15 years, many of the stations in the study area have stopped specifically recording rainfall and snowfall, and now only report total precipitation. Of the four representative stations, Mayo and Fort Simpson continue to record precipitation by type. Inuvik has recorded total precipitation since October 2007, and Whitehorse since November 2012. Although we are mainly concerned with total precipitation, we still tabulated monthly rainfall and snowfall for stations that maintain records of these phases. We also tabulated daily data from these stations to allow for assessments of trends in short-duration, high-intensity summer precipitation events.

Gap Filling

In order to improve the completeness of the historical temperature records at the four representative stations and to present a long-term context for climate change, we reconstructed monthly values that did not meet the 3 and 5 rule using least-squares linear regression with nearby stations, as described by Kokelj et al. (2022) (see also Henn et al., 2013) (Table A1). We reconstructed missing daily temperature values at the representative stations based on these relations and combined them with available daily temperature values at the representative stations to calculate monthly means. No months required gap filling for Whitehorse. We reconstructed four months for Dawson with data from Mayo (July 1927, August 1933, October 2008, and November 2008). We reconstructed one month for Inuvik with data from Aklavik (November 1959). With data from Hay River, we reconstructed many months prior to 1937 and subsequent months (115 months total) for Fort Simpson. Additionally, to extend the record at Inuvik before 1957 back to 1910, we produced a composite temperature record for the lower Mackenzie Valley using reconstructions with Aklavik (337 months), Fort McPherson (8 months), and Fort Good Hope (218 months).

Regional Correlation

We obtained regional temperature (Fig. 5) and precipitation surfaces by correlating the homogenized AMAT and historical total annual precipitation (TAP)

TABLE 2. Kendall-τ correlation coefficients and n for correlation of homogenized annual mean air temperature series from stations in northwest Canada, $p < 0.05$ in all cases. The length of the records at the principal stations, n, are: Whitehorse 76 years, Dawson 112 years, Inuvik 61 years, and Fort Simpson 97 years.

Station	Whitehorse		Dawson		Inuvik		Fort Simpson	
	τ	n	τ	n	τ	n	τ	n
Beaver Creek	0.808	28	0.783	30	0.456	28	0.570	30
Burwash	0.813	43	0.829	43	0.442	43	0.565	43
Dawson	0.772	72	–	–	0.525	59	0.603	89
Fort Good Hope	0.540	47	0.636	46	0.827	36	0.739	47
Fort Simpson	0.553	72	0.603	89	0.689	58	–	–
Fort Smith	0.450	69	0.515	85	0.557	57	0.783	78
Haines Junction	0.802	53	0.803	50	0.493	40	0.607	52
Hay River	0.477	70	0.493	100	0.557	59	0.786	89
Inuvik	0.439	60	0.525	59	–	–	0.689	58
Komakuk Beach	0.288	30	0.362	29	0.562	29	0.319	30
Mayo	0.775	72	0.847	83	0.503	59	0.677	80
Norman Wells	0.532	70	0.631	69	0.787	57	0.760	69
Old Crow	0.517	36	0.653	35	0.706	34	0.560	36
Shingle Point	0.458	29	0.534	28	0.875	30	0.584	28
Tuktoyaktuk	0.470	45	0.590	45	0.878	46	0.676	45
Watson Lake	0.727	72	0.636	76	0.463	57	0.580	75
Whitehorse	–	–	0.772	72	0.439	60	0.553	72

TABLE 3. Kendall-τ correlation coefficients and n for correlation of historical total annual precipitation between stations in northwest Canada. Values in bold indicate $p < 0.05$. The length of the records at the principal stations, n, are: Whitehorse 76 years, Mayo 89 years, Inuvik 61 years, and Fort Simpson 104 years.

Station	Whitehorse		Mayo		Inuvik		Fort Simpson	
	τ	n	τ	n	τ	n	τ	n
Beaver Creek	0.188	32	**0.366**	30	−0.088	31	0.149	32
Burwash	0.083	41	**0.261**	41	−0.117	44	0.127	43
Dawson	0.041	69	**0.315**	80	0.069	53	0.059	90
Fort Good Hope	−0.027	48	−0.043	61	0.170	33	−0.066	72
Fort Simpson	0.119	76	0.104	86	−0.001	61	–	–
Fort Smith	0.096	75	**0.199**	86	0.045	61	**0.167**	90
Haines Junction	0.116	42	0.036	41	−0.159	31	0.056	43
Hay River	0.171	74	0.118	86	0.045	59	**0.261**	96
Inuvik	−0.047	59	0.067	59	–	–	0.001	61
Komakuk Beach	−0.241	29	−0.037	28	0.049	29	−0.030	29
Mayo	0.079	72	–	–	0.067	59	0.104	86
Norman Wells	0.096	75	0.080	72	**0.288**	60	**0.217**	76
Old Crow	0.014	30	0.058	28	0.066	27	**0.320**	30
Shingle Point	−0.243	22	−0.104	22	0.043	22	0.035	22
Tuktoyaktuk	0.180	45	−0.014	45	0.072	41	0.057	46
Watson Lake	**0.227**	71	0.106	73	0.125	56	0.080	76
Whitehorse	–	–	0.079	72	−0.047	59	0.119	76

records for each station with the four representative stations. Following Vincent et al. (2015, 2018), we determined Kendall-τ correlation coefficients, since they are derived from a non-parametric method resistant to effects of outliers (Tables 2 and 3) (Reimann et al., 2008). Tables 2 and 3 also present the number of overlapping years of data between each station pair for temperature and precipitation. We used ArcGIS to produce the spatial correlation surfaces with ordinary kriging using Kendall-τ coefficients for the station pairs. We do not present TAP correlation surfaces, since precipitation is poorly correlated among the stations (Table 3). For comparative purposes, we also computed Kendall-τ correlation coefficients for adjusted ECCC historical records of temperature and homogenized records of precipitation (Tables A2, A3). The difference in correlation coefficients (τ) between the two data sets for temperature was not large, with values for the homogenized data on average 0.02 higher than the historical data set. For the 60 station pairs, the change in correlation coefficient was > 0.1 at only eight of the pairs (13%) and > 0.05 at 17 of the pairs (28%). Summary data from Student's t-tests for paired values showed that the means of correlation coefficients for historical and homogenized data were only significantly different at $\alpha = 0.05$ for the 15 correlations of temperature series with Dawson where the difference between means was 0.05 (Table A2). For precipitation, the correlation coefficients were on average 0.03 higher for the homogenized data set. Student's t-tests suggested that the differences between the means of the correlation coefficients for the historical and homogenized data sets were only significantly different at $\alpha = 0.05$ for the 15 Mayo pairs, where the difference

TABLE 4. Seasonal and annual rates of change in air temperature for 1971–2020 (dT/dt, ˚C decade^{-1}) for all stations included in the analysis. Homogenized data used for all stations except Beaver Creek.

Months Station	DJF		MAM		JJA		SON		Annual	
	dT/dt	n	dT/dt	n	dT/dt	n	dT/dt	n	dT/dt	n
Dawson	1.15	50	0.39	50	0.22	50	0.22	48	0.48	48
Whitehorse	0.97	48	0.31	48	0.31	48	0.13	48	0.43	48
Inuvik	1.10	50	0.94	50	0.26	50	0.81	48	0.77	48
Fort Simpson	0.92	50	0.27	48	0.22	50	0.40	49	0.44	47
Beaver Creek	0.97	33	0.74	32	0.30	32	0.50	31	0.57	28
Burwash	0.83	46	0.34	49	0.22	48	0.20	45	0.43	41
Fort Good Hope	1.09	36	0.90	34	0.23	34	0.78	34	0.77	29
Fort Smith	0.83	49	0.01	49	0.39	48	0.37	49	0.43	46
Haines Junction	1.17	34	0.26	35	0.18	36	0.06	38	0.38	29
Hay River	0.81	49	0.08	50	0.26	49	0.29	50	0.38	49
Komakuk Beach	0.59	38	0.40	41	0.23	40	0.31	40	0.30	28
Mayo	1.19	48	0.20	48	0.20	49	0.18	48	0.41	47
Norman Wells	1.02	50	0.46	48	0.10	50	0.54	48	0.46	46
Old Crow	1.05	38	0.78	44	0.11	47	0.56	41	0.62	35
Shingle Point	0.78	38	1.01	44	0.24	39	0.64	40	0.62	25
Tuktoyaktuk	0.66	40	0.80	47	0.20	45	0.67	46	0.53	36
Watson Lake	1.03	48	0.27	49	0.20	49	0.19	49	0.43	46

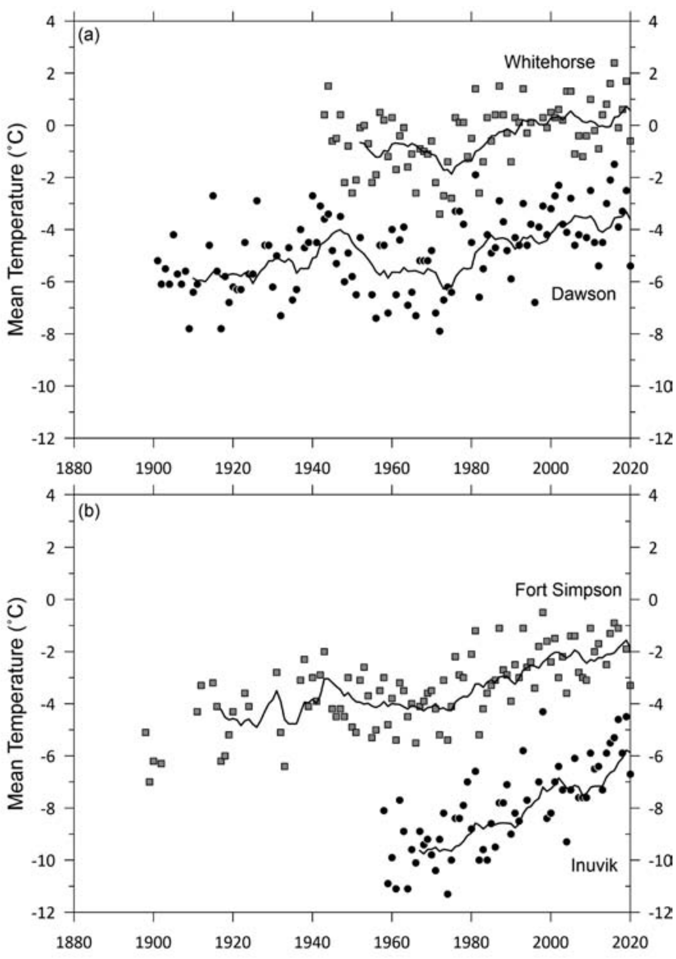

FIG. 6. Annual mean air temperatures for (a) Whitehorse and Dawson, and (b) Fort Simpson and Inuvik. The lines show the running mean of the previous ten years of data. Homogenized data used.

between means was 0.04 (Table A3). These comparisons suggest that there is little fundamental difference between the correlation structures of homogenized and historical ECCC data, but that the homogenization process eliminated some site-specific variation in the data sets.

Climate Trends

In this paper, we report climate trends in 1971 – 2020 for several stations (Table 4; Fig. 6). These are the coefficients from least-squares linear regression of the climate variable on time. We have plotted time on the abscissa (x-axis) and temperature or precipitation on the ordinate (y-axis). Least-squares linear regression is the appropriate method to obtain the coefficients of the relations between the series because time (year) is known with certainty (Mark and Church, 1977).

Scenarios

Following Burn et al. (2004), we have ranked the 29 scenarios by projected annual and seasonal changes in both temperature and precipitation and selected high, medium, and low projections (Tables 5 and 6). The projections correspond to the climate scenarios ranked 4th, 15th, and 26th. These rankings are based on the projected changes for the climate variable by the 2010 – 39 normal period relative to the baseline period of 1961 – 90. In order to obtain a conservative estimate of the extremes and to exclude far outliers, we did not use the three highest and lowest projections.

CLIMATE CHANGE IN CANADA'S WESTERN ARCTIC

Temperature – Spatial Coherence

Figure 5 presents maps displaying correlation fields for AMAT in the study region. We present correlation fields with respect to Whitehorse, Dawson, Inuvik, and

TABLE 5. Climate change scenarios for 2010–39 relative to the baseline (1961–90) for four regions in NW Canada ranked by increase in mean seasonal or annual temperature (°C) (Burn et al., 2004). Climate normals for homogenized data (Vincent et al., 2020) are provided for the baseline with observed relative changes for the three following intervals.

Months	DJF	MAM	JJA	SON	Annual
Southern Yukon (Whitehorse)					
Ranked projected increase in seasonal or annual temperature					
4th	2.5	1.7	1.9	2.2	1.8
15th	1.0	1.0	1.2	1.4	1.1
26th	0.4	0.6	0.5	0.7	0.9
Observed baseline temperature					
1961–90	−15.6	−0.1	12.6	−0.5	−0.9
Observed change relative to baseline					
1971–2000	+0.7	+0.6	+0.2	+0.2	+0.4
1981–2010	+2.3	+0.8	+0.5	+0.2	+1.0
1991–2020	+2.5	+1.0	+0.9	+0.6	+1.2
Central Yukon (Dawson)					
Ranked projected increase in seasonal or annual temperature					
4th	3.0	1.8	2.7	2.9	2.2
15th	1.6	1.2	1.1	1.9	1.4
26th	0.9	0.7	0.5	1.1	1.1
Observed baseline temperature					
1961–90	−26.1	−2.6	13.4	−5.5	−5.2
Observed change relative to baseline					
1971–2000	+0.6	+1.0	+0.5	−0.3	+0.5
1981–2010	+2.3	+1.3	+0.6	+0.0	+1.1
1991–2020	+2.8	+1.5	+0.9	+0.3	+1.4
Lower Mackenzie Valley (Inuvik)					
Ranked projected increase in seasonal or annual temperature					
4th	3.1	2.2	2.2	3.3	2.4
15th	2.0	1.6	1.1	2.1	1.6
26th	1.1	0.9	0.4	1.1	1.3
Observed baseline temperature					
1961–90	−26.5	−12.4	11.2	−8.5	−9.0
Observed change relative to baseline					
1971–2000	+1.1	+1.1	+0.5	+0.4	+0.7
1981–2010	+2.1	+1.7	+0.7	+0.9	+1.3
1991–2020	+3.2	+2.6	+1.0	+2.3	+2.3
Upper Mackenzie Valley (Fort Simpson)					
Ranked projected increase in seasonal or annual temperature					
4th	2.5	2.4	1.9	2.7	2.1
15th	1.5	1.4	1.1	1.5	1.3
26th	0.6	0.6	0.6	0.9	1.0
Observed baseline temperature					
1961–90	−23.8	−2.5	15.4	−3.5	−3.6
Observed change relative to baseline					
1971–2000	+0.9	+1.0	+0.3	+0.3	+0.7
1981–2010	+1.9	+1.1	+0.5	+0.7	+1.1
1991–2020	+2.5	+1.3	+0.8	+1.3	+1.5

Fort Simpson. During kriging, we omitted correlation of temperature series with themselves to avoid presenting an artificially peaked distribution centred on the station. The correlation coefficients are relatively high for stations near the representative locations, indicating the sub-regional coherence of climate variation throughout the extant record. Correlation of AMAT is consistently high along Mackenzie Valley and within south and central Yukon. Data from northern Yukon are most closely correlated with stations in the Mackenzie Delta area.

Temperature – Temporal Records

Air temperatures have been increasing nationally since 1970, with particularly high rates of warming in Canada's western Arctic (Zhang et al., 2019). Warming in the region has been concentrated in winter (Vincent et al., 2015; Bush and Lemmen, 2019). Both of these phenomena are consequences of polar amplification of climate change due to reduction in ice cover and albedo, increased transport of latent heat to polar latitudes, and reduced net loss of long-wave radiation with near-surface warming (IPCC, 2021a, Section 7.4.4.1.1). In Yukon and Mackenzie Valley (Fig. 6, Table 4), the greatest increase in AMAT in 1971–2020, using homogenized values, has been at Inuvik, at a rate of 0.77°C decade^{-1}. At Dawson, Whitehorse, and Fort Simpson, AMAT has increased between 0.43 and 0.48°C decade^{-1}. The lowest rate of increase in AMAT, 0.30°C decade^{-1}, was recorded over the relatively short record of 28 complete years at Komakuk Beach, YT, in 1971–2015. Seasonal warming in winter has been between 0.59 and 1.19°C decade^{-1} at Komakuk Beach and Mayo, respectively (Table 4).

Increases in 10-year average temperatures more readily demonstrate the magnitude of climate change than the 30-year climate normals in cases where change has been unidirectional and continuous. For Inuvik, the difference in MAAT between 1961–70 and 2011–20 has been 3.7°C, and at Whitehorse 1.7°C. At Dawson and Fort Simpson, the increases in MAAT over the same period have been similar to data from Whitehorse, namely 2.0°C at Dawson and 2.3°C at Fort Simpson. The MAAT, calculated over 10 years, is now −5.9°C at Inuvik, −3.6°C at Dawson, −1.8°C at Fort Simpson, and 0.6°C at Whitehorse.

Temperature – Projections

The warming recorded at each of the four representative stations indicates the 30-year MAAT may meet or exceed the upper CCIS projections for annual and winter air temperatures in 2010–39 (Table 5, Fig. 7). MAAT in 1991–2020 increased by between 1.2°C at Whitehorse and 2.3°C at Inuvik relative to 1961–90 (Fig. 7). Mean winter temperatures have already exceeded the upper projections for 2010–39 at Inuvik and are approaching the upper projections for the other three locations 20 years in advance of this period (Fig. 7). Winter conditions in lower Mackenzie Valley are now warmer than they were in upper Mackenzie Valley 30 years ago. For spring, summer, and autumn, current temperature trends are progressing towards the mid- to upper-level projections. Mean spring temperatures have already exceeded the change projected for 2010–39 in the lower Mackenzie Valley (Table 5).

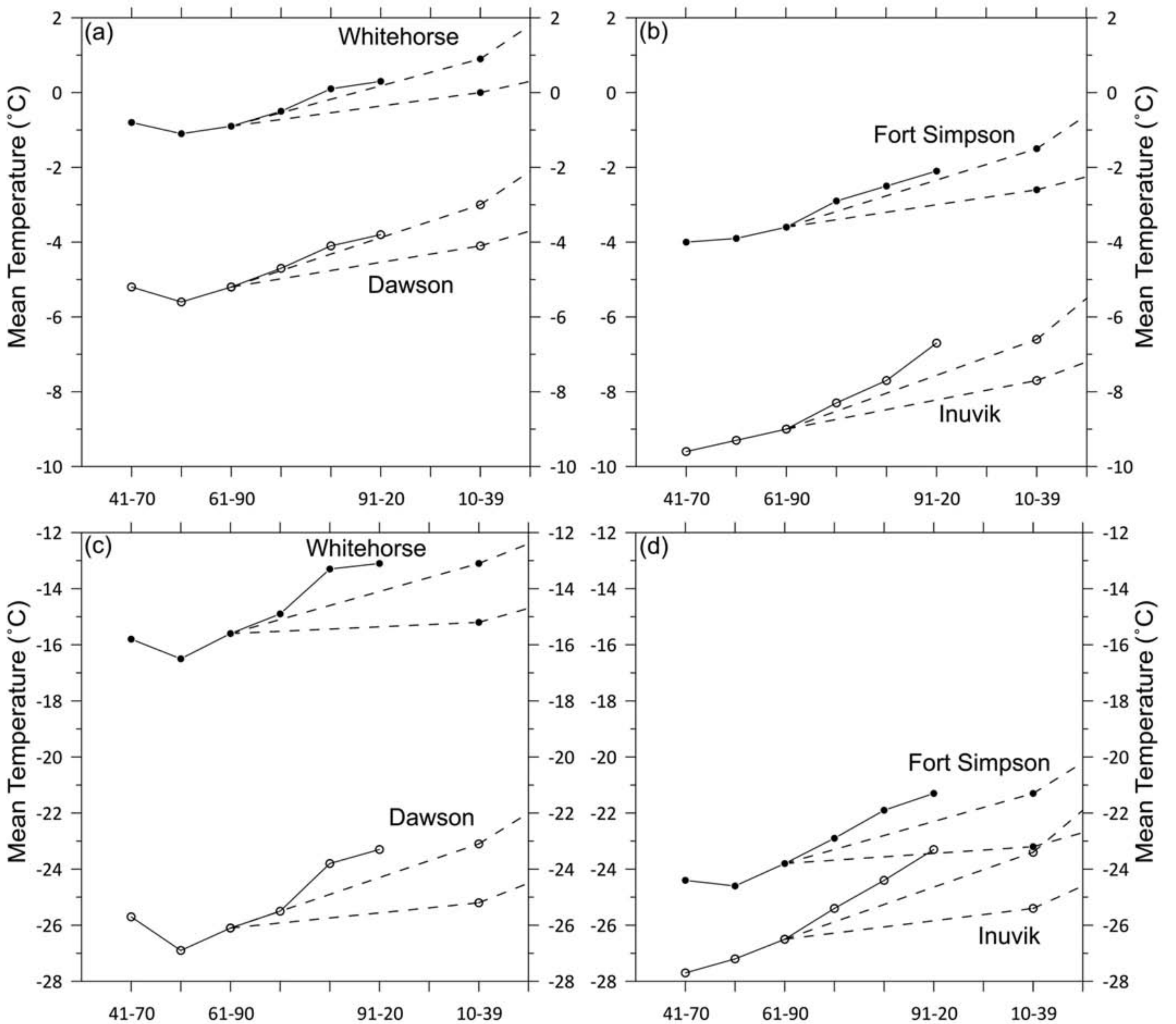

FIG. 7. Comparison of observed and projected (a, b) mean annual and (c, d) mean winter air temperatures for the four representative stations. Solid lines show the observed air temperature as climate normals for 1941–70 to 1991–2020 computed from homogenized series (see text). Dashed lines show projections from the 1961–90 baseline.

Precipitation – Spatial Coherence

Precipitation records are poorly correlated between stations with Kendall-τ coefficients generally ranging from 0.1 to 0.3 (Table 3). The majority of correlations between stations are not statistically significant. Long-term precipitation records are available for Whitehorse, Mayo, Inuvik, and Fort Simpson (Fig. 8). Figure 8 displays considerable variation between stations in precipitation trends, even though the climate scenarios generally anticipated greater precipitation within the region over time (Table 6).

Precipitation – Temporal Trends

Hartmann et al. (2013) and Bintanja and Andry (2017) suggest that certain aspects of the precipitation regime may be expected to change with temperature. Figure 9 presents the frequency distributions of total annual rainfall (TAR), TAP, and August and September rainfall for Mayo and Norman Wells as normal probability plots. We have plotted precipitation magnitude against probability of exceedance. We present data for 1961 – 2020, i.e., 60 years of observations. If events were distributed evenly through the 60 years, each 20-year interval would contribute six or seven events to the upper, middle, and lower thirds of the distributions. In fact, recent TAR values (2001 – 20) are overrepresented in the upper end of the distribution (Figs 9a, 9b). At both Mayo and

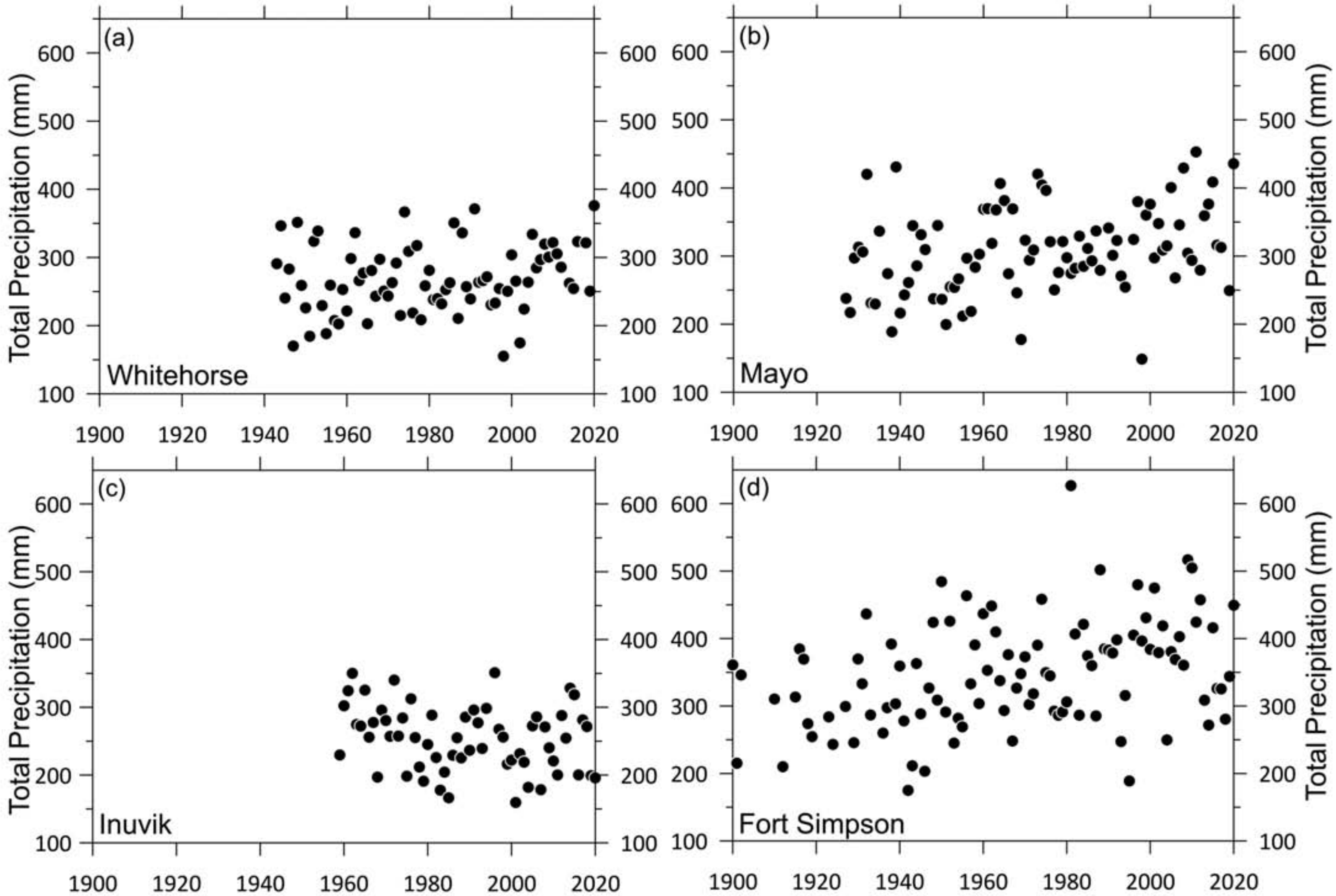

FIG. 8. Annual total precipitation for (a) Whitehorse, (b) Mayo, (c) Inuvik, and (d) Fort Simpson over the period of record. ECCC historical data used. No extension or gap filling of records has been undertaken due to the spatial variability of this index.

Norman Wells, nine of the 20 years in 2001 – 20 are in the upper third of the distributions. Similar results are observed in the frequency distribution of TAP for Mayo and Norman Wells (Figs 9c, 9d), where eight and nine of the respective wettest years occurred during 2001 – 2020. Warming of the shoulder seasons (i.e., early autumn and spring) has resulted in a change in form of precipitation, with snowfall replaced by rainfall (Vincent et al., 2015). With respect to August and September rainfall, Figs 9e and 9f show that the most recent years are overrepresented in the upper third of the frequency distributions, with 11 and 12 years from 2001 to 2020 for Mayo and Norman Wells, respectively. Similar analyses for Fort Simpson and Hay River also suggest increases in precipitation, especially for TAR and August and September rainfall. The proportion of total precipitation falling as rain has increased recently at Mayo, where 10 years of 2001 – 20 are represented in the upper third of the distribution (Fig. 10). The proportion is not as great at the other three stations, where rainfall is specifically recorded.

For infrastructure, changes in short-term, high-intensity precipitation events may be of greater concern than overall changes on an annual basis (Zhang et al., 2019). However, maximum one-, two-, and three-day summer (June – September) precipitation totals do not appear more frequently than the expected six or seven times in the upper 20 years of the distributions.

Precipitation – Projections

Figure 11 and Table 6 present the observed seasonal and projected annual total precipitation relative to the 1961 – 90 baseline. No consistent behaviour with respect to the projections can be identified for mean (normal) TAP. The values recorded at Inuvik have been lower than projected, while data for Mayo, Whitehorse, and Fort Simpson are consistent with middle projections in 1991 – 2020. Relative to the 1961 – 90 climate, total annual precipitation for 1991 – 2020 increased by 2.6% at Mayo, 3.2% at Whitehorse, and 4.4% at Fort Simpson, and decreased by 3.3% at Inuvik. On an annual or seasonal basis, no common trend over time can be determined in total precipitation for these four stations (Fig. 11; Table 6).

DISCUSSION

The purpose of this paper is to determine which scenarios for climate change available in the early 2000s

TABLE 6. Climate change scenarios for 2010–39 ranked by change from the baseline (1961–90) in total seasonal or annual precipitation (%) for all four regions (Burn et al., 2004). Climate normal data (mm) are provided for the baseline with observed relative changes for the three following intervals. Normal values in italics were calculated from ECCC historical climate data while other values were obtained directly from ECCC.

Months	DJF	MAM	JJA	SON	Annual
Southern Yukon (Whitehorse)					
Ranked projected change in seasonal or annual precipitation (%)					
4th	+12.3	+13.8	+8.9	+12.2	+9.6
15th	+5.6	+6.5	+4.2	+6.6	+7.4
26th	+0.4	+1.9	-2.3	+3.7	+2.1
Observed baseline precipitation (mm)					
1961–90	47.7	34.8	109.0	77.1	268.8
Observed change relative to baseline (%)					
1971–2000	−2.3	−6.3	1.9	0.0	-0.5
1981–2010	−3.8	−3.4	−2.5	−0.6	−2.4
1991–2020	*9.9*	*2.6*	*3.4*	*−2.3*	*3.2*
Central Yukon (Mayo)					
Ranked projected change in seasonal or annual precipitation (%)					
4th	+13.7	+13.1	+10.4	+16.3	+10.4
15th	+8.0	+7.7	+4.1	+8.6	+6.8
26th	+0.4	+1.4	−2.1	+1.5	+1.7
Observed baseline precipitation (mm)					
1961–90	55.8	39.4	137.2	85.9	318.4
Observed change relative to baseline (%)					
1971–2000	−13.6	8.4	−0.4	−0.7	−1.7
1981–2010	−8.4	6.3	−2.5	1.0	−1.5
1991–2020	*−7.3*	*4.1*	*7.5*	*2.4*	*2.6*
Lower Mackenzie Valley (Inuvik)					
Ranked projected change in seasonal or annual precipitation (%)					
4th	+15.4	+17.9	+14.6	+14.6	+11.8
15th	+6.0	+5.6	+6.1	+9.3	+7.4
26th	+0.8	+0.2	−0.1	2.0	+2.1
Observed baseline precipitation (mm)					
1961–90	43.5	42.5	100.2	71.3	257.4
Observed change relative to baseline (%)					
1971–2000	−5.5	−9.4	−5.0	3.5	−3.5
1981–2010	−7.1	−8.2	−8.5	−2.2	−6.5
1991–2020	*−17.4*	*−12.9*	*3.9*	*0.4*	*−3.3*
Upper Mackenzie Valley (Fort Simpson)					
Ranked projected change in seasonal or annual precipitation (%)					
4th	+17.6	+22.5	+9.7	+12.6	+9.6
15th	+7.8	+8.2	+2.7	+6.0	+6.2
26th	−1.0	−1.6	−1.4	+2.3	+0.9
Observed baseline precipitation (mm)					
1961–90	56.3	63.8	148.3	92.0	360.5
Observed change relative to baseline (%)					
1971–2000	−3.0	−5.8	10.7	−2.0	2.4
1981–2010	−1.2	−3.1	17.2	4.8	7.5
1991–2020	*−5.3*	*−4.4*	*18.6*	*−6.2*	*4.4*

have best projected the subsequent record. With respect to precipitation, there has been little overall correspondence between projections and observations. Variations in precipitation over time within the region are neither spatially nor temporally consistent. While all scenarios indicated that precipitation would be higher in 2010–39 than during the 1961–90 baseline period, we observed no clear trends in TAP in 1991–2020 (Table 6). There is, however, some evidence that the nature of precipitation is changing, with a greater proportion of the total now falling as rain (Fig. 10). This has been anticipated in other articles (e.g., Bintanja and Andry, 2017). The trend is not (yet) statistically significant due to the variability in observations throughout the records. But it is visually apparent that data since 2000 are overrepresented in the higher tails of the rainfall distributions examined here (Fig. 9).

In contrast, annual and seasonal mean air temperatures are spatially coherent within the region, and all have increased since 1971 (Figs 5, 6). The rates of annual increase are generally highest in the lower Mackenzie Valley and northern Yukon. The rates of warming exceed or approach the higher projections of the increase between the baseline and 2010–39 (Figs 6, 7). The highest projections published in 2000 were from scenarios that mimic the high emissions pathway for RCP8.5. During 1991–2020, therefore, regional temperature has followed the projections of high emission scenarios. The rate of increase in AMAT has varied spatially within the region from 0.30 to 0.77°C decade^{-1} since 1971. If scenarios of future climate change are to be chosen on the basis of past performance, our analysis shows that developers should seriously consider the projections for highest climate change.

The changes in temperature that we compared with climate projections are 30-year averages. We noted that the continuous warming appears greater when examined at 10-year resolution. The IPCC's Sixth Assessment projects that under any climate scenario, warming will continue globally for at least two more decades, and for longer if reductions are not made in anthropogenic greenhouse gas emissions (Fig. SPM.8 in IPCC, 2021b). The Sixth Assessment also states that "it is *virtually certain* that the Arctic will continue to warm more than global surface temperature, with *high confidence* above two times the rate of global warming" (IPCC, 2021b, SPM B.2.1, italics in original; see also Rantanen et al., 2022). The regional distribution of this projected warming includes much of the study area of this paper (Fig. SPM.5 in IPCC, 2021b). The historical record, its correspondence with higher projections for temperature change in 1991–2020, and the IPCC's confidence that climate change will be more rapid at high latitudes all suggest that it is prudent to consider relatively high model projections for climate change in the study area over the next 20–30 years. If present rates of change are sustained (1971–2020; Table 4), then current values for climate normal MAAT (1991–2020; Table 5) of +0.3, −2.1, −3.8, and −6.7°C at Whitehorse, Fort Simpson, Dawson, and Inuvik, respectively, may rise to +2.5, +0.1, −1.4, and −2.8°C by 2041–2070. Taken on a decadal basis, current values for MAAT (2011–20) of +0.6, −1.8, −3.6, and −5.9°C may rise to +2.8, +0.4, −1.2, and −2.0°C at the respective locations by 2061–70, i.e., in 50 years' time. Fifty years is a normal service life for infrastructure.

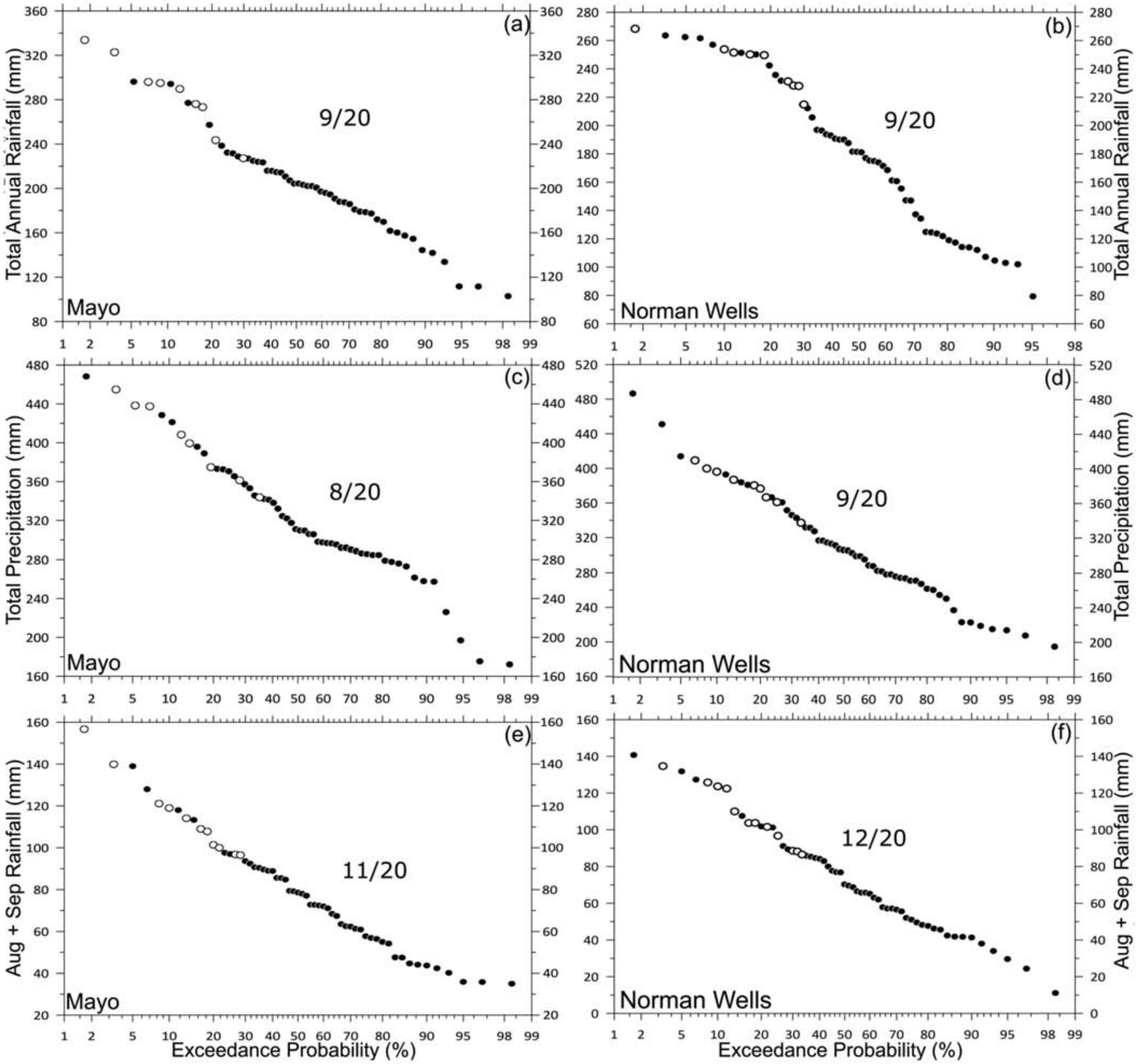

FIG. 9. Exceedance probability distributions for (a) TAR, (c) TAP, (e) August and September rainfall at Mayo, YT, and (b) TAR, (d) TAP, and (f) August and September rainfall at Norman Wells, NT, 1961–2020. Open circles are years from 2001–20 in the upper third of the distribution (also listed as a fraction of the 20 upper years). The exceedance probability is normally distributed.

Air temperature is one of the variables that controls the state of permafrost, which responds to changes in surface conditions, including climate (Burn and Kokelj, 2009). Mean annual ground temperatures are commonly higher than MAAT, principally due to the effects of snow (Smith and Riseborough, 2002). Research has shown (e.g., Burn and Kokelj, 2009; Smith et al., 2012, 2022) that changes in surface conditions, including atmospheric warming, have induced increases in near-surface permafrost temperatures within the Canadian western Arctic and circumpolar world. Warming of near-surface permafrost characteristically lags behind increases in air temperature due to latent heat sinks associated with melting pore and excess ground ice (Smith et al., 2022) and propagation of heat into colder permafrost at depth (see Burn and Zhang, 2009, 2010). Nevertheless, given the record of regional climate warming exceeding the upper-level scenarios, the millennial time scales required to reverse recent changes to atmospheric greenhouse-gas concentrations (Burn et al., 2021b), and MAAT already > 0˚C, near-surface permafrost will likely become unsustainable, that is, it will begin or continue to thaw at locations in central and southern Yukon and adjacent Mackenzie Valley over the next two decades. The literature (e.g., Burn, 1998) suggests that it may still take centuries for permafrost to thaw at depth.

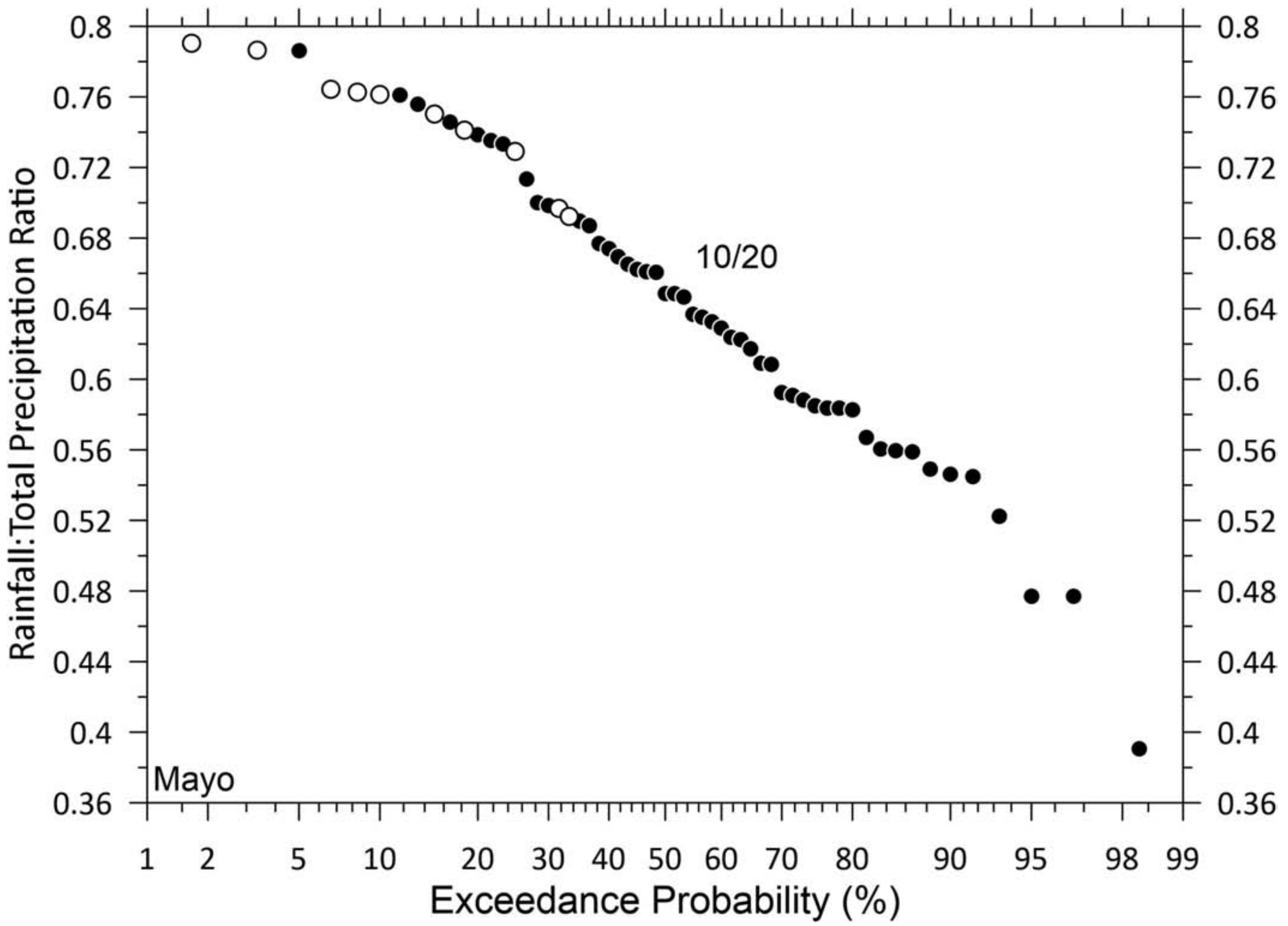

FIG. 10. Exceedance probability distribution for ratio of TAR to TAP in 1961–2020 at Mayo, YT. Open circles are years from 2001–20 in the upper third of the distribution (also listed as a fraction of the 20 upper years). The exceedance probability is normally distributed.

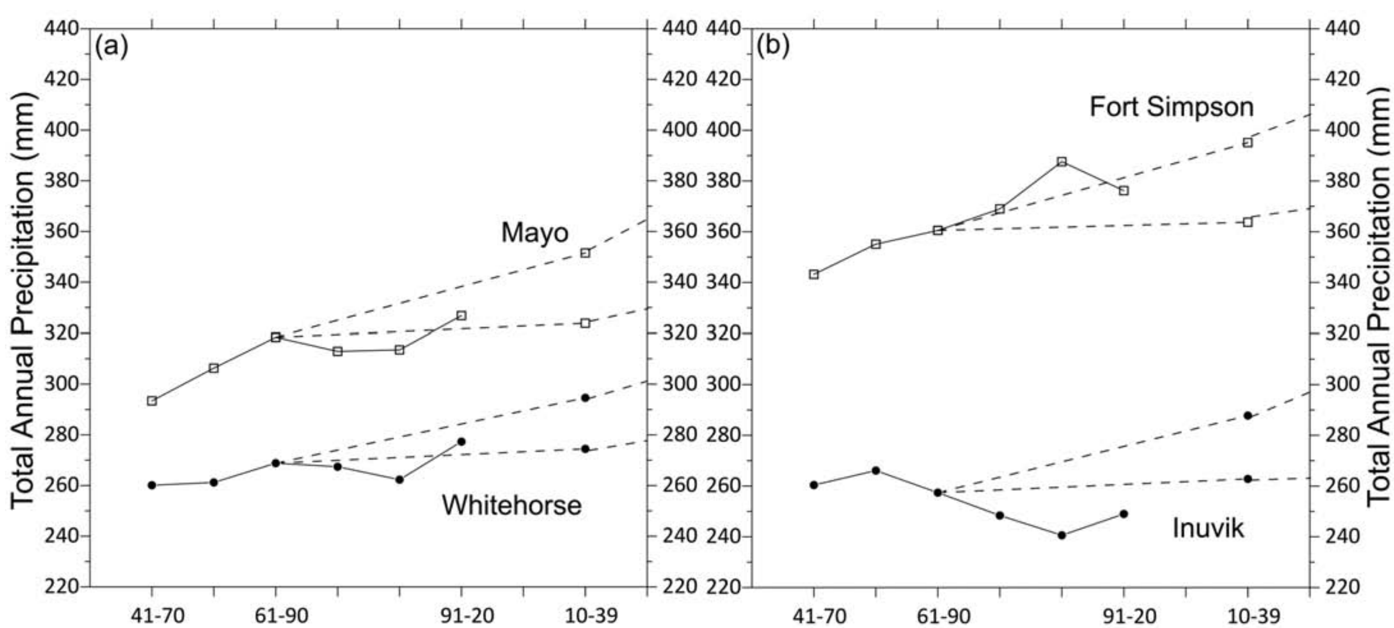

FIG. 11. Comparison of observed and projected total annual precipitation for (a) Mayo and Whitehorse, and (b) Fort Simpson and Inuvik. Solid lines show the observed precipitation from climate normals in 1941–70 to 1991–2020. Data for 1941–71 to 1981–2010 from Canadian Climate Normals (ECCC 2020); 1991–2020 means computed from historical data (see text). Dashed lines show projections from the 1961–90 baseline.

FIG. 12. Thermosyphons installed along the Alaska Highway at Dry Creek, YT (km 1840). These passive ground cooling installations are required to prevent a body of massive ice beneath the road from thawing. Photograph taken on 31 July 2021, © C.R. Burn.

Warming of permafrost has two principal geotechnical consequences for engineering design: reduction in strength of adfreeze bonds for pile foundations, and acceleration of creep deformation under an applied load (Hjort et al., 2022). In addition, thawing of ice-rich permafrost leads to substantial loss of bearing strength. The thermal regimes of infrastructure foundations are affected by the structures themselves and by lateral heat exchange with the surrounding ground. As a result, infrastructure stability is not isolated from the effects of climate change on the permafrost thermal regime. Using geothermal simulation for buildings at Inuvik, Zhou et al. (2008) demonstrated the sensitivity of foundation integrity to various scenarios for climate warming. They projected that under an upper-level climate scenario, as has occurred to date, the foundations of a majority (74%) of the buildings in the town will be adversely affected by 2069 (Table 1 in Zhou et al., 2008). They propose that the proportion of affected buildings will vary with near-surface ground conditions within the town site.

The prospect of relatively high rates of climate warming continuing in Yukon and Mackenzie Valley has two principal implications for foundation design in permafrost. First, it suggests that increased investment in site investigation to identify thaw-stable sites may be a prudent planning strategy for infrastructure projects, especially for municipal and transportation infrastructure that occupy a large footprint. The National Standard of Canada and Bureau de Normalisation du Québec's (2017) newest standard from 2017 takes the impact of climate change on permafrost into account by establishing a more consistent methodology for permafrost site investigations. In the southern portions of the permafrost regions such a strategy may mean facilities might not be located with great convenience, but their service life would be extended. Second, rising winter temperatures imply that the operational efficacy of thermosyphons, used to chill foundations, may be impeded. As a result, at sites where preservation of frozen ground is essential for infrastructure integrity, the number of required thermosyphons may increase, and detailed design configurations will be required (Hayley and Horne, 2008; Canadian Standards Association, 2019). This will almost certainly lead to cost increases, as already seen in 2020 at the Dry Creek site at km 1840 on the Alaska Highway in southwest Yukon, where installation of 58 thermosyphons to prevent thawing of massive ice below less than half a kilometre of the highway in 2020 cost CAD $4 million (Fig. 12) (Loranger et al., 2015; Muhammad Idrees, Yukon Highways and Public Works, pers. comm., 2021). Such expenses prohibit installation of thermosyphons beneath numerous kilometres of highway embankment and raise the cost effectiveness of thorough site investigations and alternative route selections.

CONCLUSIONS

The following conclusions may be drawn from this paper:

1. Temperature variation is sub-regionally consistent. We can therefore identify two climatic sub-regions within the Yukon and adjacent Northwest Territories: south and central Yukon and Mackenzie River Valley.
2. Within the region, the rate of increase in recorded annual mean temperatures has ranged from 0.30 to 0.77˚C decade^{-1} since 1971; the magnitude of the warming has been up to 2.3˚C in 30-year mean temperatures and 3.7˚C in 10-year means.
3. The observed changes in MAAT have exceeded the track to the higher projections, made in 2000, of climate warming for 2010–39.

4. Warming in winter has exceeded the track to the higher projections, made in 2000, for 2010 – 39.
5. There has been little spatial consistency in regional total precipitation series, but at two of four sites where rainfall is specifically recorded, more annual rainfall totals from 2001–20 were observed in upper portions of the 60-year record than would be expected at stationary sites.
6. Due to the high rate of climate change, developers may consider enhancing site investigations for projects in southern parts of the region to select locations with thaw-stable soils for construction.

ACKNOWLEDGEMENTS

This paper was stimulated through conversations with D.W. Hayley who co-led the Canadian Standards Association's development of CSA PLUS 4011:19 in 2009 – 10 and its revision in 2018 – 19. The research is part of a long-term program assessing climate change and its effects on the permafrost environment in Yukon and the western Arctic that is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC); the Polar Continental Shelf Project, Natural Resources Canada; the Northern Transportation Adaptation Initiative, Transport Canada; the Yukon Department of Highways and Public Works; the First Nation of Na-Cho Nyak Dun; the Aurora Research Institute; and the Northern Science Training Program, Crown-Indigenous Relations and Northern Affairs Canada. We thank Lucie Vincent and Ian McKendry for help during preparation of this paper, and three anonymous referees for their kind, generous, and helpful comments. Their suggestions are appreciated by adoption. Astrid Schetselaar is supported by the NSERC Permafrost Strategic Network (funding reference number NETGP 523328 – 18).

REFERENCES

Bintanja, R., and Andry, O. 2017. Towards a rain-dominated Arctic. Nature Climate Change 7(4):263 – 267.
https://doi.org/10.1038/nclimate3240

Bonsal, B.R., and Kochtubajda, B. 2009. An assessment of present and future climate in the Mackenzie Delta and the near-shore Beaufort Sea region of Canada. International Journal of Climatology 29(12):1780 – 1795.
https://doi.org/10.1002/joc.1812

Brown, R., Schuler, D.V., Bulygina, O., Derksen, C., Luojus, K., Mudryk, L., Wang, L., and Yang, D. 2017. Arctic terrestrial snow cover. In: Symon, C., ed. Snow, water, ice and permafrost in the Arctic (SWIPA). Oslo: Arctic Monitoring and Assessment Programme. 25 – 64.
https://www.amap.no/documents/doc/snow-water-ice-and-permafrost-in-the-arctic-swipa-2017/1610

Burn, C.R. 1993. Comments on "Detection of climatic change in the western North American Arctic using a synoptic climatological approach" by Laurence S. Kalkstein, Paul C. Dunne, and Russel S. Vose. Journal of Climate 6(7):1473−1475.
https://doi.org/10.1175/1520-0442(1993)006<1473:COOCCI>2.0.CO;2

———. 1994. Permafrost, tectonics, and past and future regional climate change, Yukon and adjacent Northwest Territories. Canadian Journal of Earth Sciences 31(1):182 – 191.
https://doi.org/10.1139/e94-015

———. 1998. The response (1958 – 1997) of permafrost and near-surface ground temperatures to forest fire, Takhini River valley, southern Yukon Territory. Canadian Journal of Earth Sciences 35(2):184 – 199.
https://doi.org/10.1139/e97-105

———. 2003. Climate change scenarios for the Mackenzie Gas Project. Northern Water Resource Studies, Water Resources Division. Yellowknife: DIAND.

———. 2012. Permafrost distribution and stability. In: French, H., and Slaymaker, O., eds. Changing cold environments. A Canadian perspective. Chichester, UK: John Wiley & Sons Ltd. 126 – 146.
https://doi.org/10.1002/9781119950172.ch7

Burn, C.R., and Kokelj, S.V. 2009. The environment and permafrost of the Mackenzie Delta area. Permafrost and Periglacial Processes 20(2):83 – 105.
https://doi.org/10.1002/ppp.655

Burn, C.R., and Zhang, Y. 2009. Permafrost and climate change at Herschel Island (Qikiqtaruq), Yukon Territory, Canada. Journal of Geophysical Research: Earth Surface 114(F2): F02001.
https://doi.org/10.1029/2008JF001087

———. 2010. Sensitivity of active-layer development to winter conditions north of treeline, Mackenzie delta area, western Arctic coast. In: Kwok, C., Moorman, B., Armstrong, R., and Henderson, J., eds. 63rd Canadian Geotechnical Conference and 6th Canadian Permafrost Conference: Proceedings of a conference held 12 – 15 September in Calgary. Paper 194. 1458 – 1465.
https://members.cgs.ca/documents/conference2010/GEO2010/pdfs/GEO2010_194.pdf

Burn, C.R., Barrow, E., and Bonsal, B. 2004. Climate change scenarios for Mackenzie River Valley. Proceedings of the 57th Canadian Geotechnical Conference and 5th Joint CGS-IAH Groundwater Specialty Conference: Geoengineering for the Society and Environment. 24 – 27 October, Québec City.
https://www.osti.gov/etdeweb/biblio/20588051

Burn, C.R., Lewkowicz, A.G., and Wilson, M.A. 2021a. Long-term field measurements of climate-induced thaw subsidence above ice wedges on hillslopes, western Arctic Canada. Permafrost and Periglacial Processes 32(2):261 – 276.
https://doi.org/10.1002/ppp.2113

Burn, C.R., Cooper, M., Morison, S.R., Pronk, T., and Calder, J.H. 2021b. The Canadian Federation of Earth Sciences scientific statement on climate change – its impacts in Canada, and the critical role of earth scientists in mitigation and adaptation. Geoscience Canada 48(2):59 – 72.
https://doi.org/10.12789/geocanj.2021.48.173

Bush, E., and Lemmen, D.S. 2019. Canada's changing climate report. Ottawa: Government of Canada.
https://doi.org/10.4095/314614

Canadian Standards Association. 2019. Technical guide: Infrastructure in permafrost, a guideline for climate change adaptation. CSA PLUS 4011:19. Toronto: CSA Group.

ECCC (Environment and Climate Change Canada). 2020. Canadian climate normals 1981 – 2010. Gatineau: ECCC.
https://climate.weather.gc.ca/doc/Canadian_Climate_Normals_1981_2010_Calculation_Information.pdf

———. 2023a. Historical data.
https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

———. 2023b. Canadian climate normals.
https://climate.weather.gc.ca/climate_normals/index_e.html

———. 2023c. Climate data: Homogenized surface air temperature data access.
https://www.canada.ca/en/environment-climate-change/services/climate-change/science-research-data/climate-trends-variability/adjusted-homogenized-canadian-data/surface-air-temperature-access.html

———. 2023d. Climate data: Adjusted precipitation data.
https://www.canada.ca/en/environment-climate-change/services/climate-change/science-research-data/climate-trends-variability/adjusted-homogenized-canadian-data/precipitation.html

Fraser, R.H., Lantz, T.C., Olthof, I., Kokelj, S.V., and Sims, R.A. 2014. Warming-induced shrub expansion and lichen decline in the western Canadian Arctic. Ecosystems 17(7):1151 – 1168.
https://doi.org/10.1007/s10021-014-9783-3

Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L.V., Brönnimann, S., Charabi, Y.A-R., Dentener, F.J., et al. 2013. Observations: Atmosphere and surface. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J. Nauels, A., et al., eds. Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. Intergovernmental Panel on Climate Change (IPCC). 159 – 254.
https://www.ipcc.ch/report/ar5/wg1/

Hayley, D.W., and Horne, B. 2008. Rationalizing climate change for design of structures on permafrost: A Canadian perspective. In: Kane, D.L., and Hinkel, K.M., eds. Ninth International Conference on Permafrost: Proceedings of a conference held 29 June – 3 July 2008 at the University of Alaska Fairbanks. Vol. 1. 681 – 686.
https://www.permafrost.org/event/icop9/

Hausfather, Z., Drake, H.F., Abbott, T., and Schmidt, G.A. 2020. Evaluating the performance of past climate model projections. Geophysical Research Letters 47(1): e2019GL085378.
https://doi.org/10.1029/2019GL085378

Henn, B., Raleigh, M.S., Fisher, A., and Lundquist, J.D. 2013. A comparison of methods for filling gaps in hourly near-surface air temperature data. Journal of Hydrometeorology 14(3):929 – 945.
https://doi.org/10.1175/JHM-D-12-027.1

Hjort, J., Karjalainen, O., Aalto, J., Westermann, S., Romanovsky, V.E., Nelson, F.E., Etzelmüller, B., and Luoto, M. 2018. Degrading permafrost puts Arctic infrastructure at risk by mid-century. Nature Communications 9: 5147.
https://doi.org/10.1038/s41467-018-07557-4

Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella, K., and Luoto, M. 2022. Impacts of permafrost degradation on infrastructure. Nature Reviews Earth & Environment 3(1):24 – 38.
https://doi.org/10.1038/s43017-021-00247-8

IPCC (Intergovernmental Panel on Climate Change). 2000. Emissions scenarios. Nakicenovic, N., and Swart, R., eds. Cambridge: Cambridge University Press.
https://www.ipcc.ch/report/emissions-scenarios/

———. 2001. Climate change 2001: The scientific basis. Contribution of Working Group 1 to the Third Assessment Report. Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A., eds. Cambridge: Cambridge University Press.
https://www.ipcc.ch/report/ar3/wg1/

———. 2014. Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M., eds. Cambridge: Cambridge University Press.
https://doi.org/10.1017/CBO9781107415324

———. 2021a. Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Chen, Y., Goldfarb, L., et al. Cambridge: Cambridge University Press.
https://www.ipcc.ch/report/ar6/wg1/

———. 2021b. Climate change 2021: The physical science basis. Summary for policymakers. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Chen, Y., Goldfarb, L., et al. Cambridge: Cambridge University Press.
https://www.ipcc.ch/report/ar6/wg1/chapter/summary-for-policymakers/

Kokelj, S.A., Beel, C.R., Connon, R.F., Graydon, C.E.D., Kokelj, S.V., and Burn, C.R. 2022. Peel Plateau climate data, Northwest Territories. Northwest Territories Geological Survey Report 2022-005.
https://doi.org/10.46887/2022-005

Kokelj, S.V., Lantz, T.C., Tunnicliffe, J., Segal, R., and Lacelle, D. 2017. Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada. Geology 45(4):371–374.
https://doi.org/10.1130/G38626.1

Loranger B., Jr., Doré, G., Fortier, D., and Lemieux, C. 2015. Massive ice and ice-rich soil detection by gravimetric surveying at Dry Creek, southwestern Yukon Territory, Canada. In: Guthrie W.S., ed. 16th International Conference on Cold Regions Engineering: Proceedings of a conference held 19–22 July, Salt Lake City. 46–56.
https://doi.org/10.1061/9780784479315.005

Mark, D.M., and Church, M. 1977. On the misuse of regression in earth science. Journal of the International Association for Mathematical Geology 9(1):63–75.
https://doi.org/10.1007/BF02312496

McCoy, V.M., and Burn, C.R. 2005. Potential alteration by climate change of the forest-fire regime in the boreal forest of central Yukon Territory. Arctic 58(3):276–285.
https://doi.org/10.14430/arctic429

Mekis, É., and Vincent, L.A. 2011. An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. Atmosphere-Ocean 49(2):163–177.
https://doi.org/10.1080/07055900.2011.583910

Melvin, A.M., Larsen, P., Boehlert, B., Neumann, J.E., Chinowsky, P., Espinet, X., Martinich, J., et al. 2017. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. Proceedings of the National Academy of Sciences 114(2): E122–E131.
https://doi.org/10.1073/pnas.1611056113

Miner, K.R., Turetsky, M.R., Malina, E., Bartsch, A., Tamminen, J., McGuire, A.D., Fix, A., Sweeney, C., Elder, C.D., and Miller, C.E. 2022. Permafrost carbon emissions in a changing Arctic. Nature Reviews Earth & Environment 3(1):55–67.
https://doi.org/10.1038/s43017-021-00230-3

National Standard of Canada and Bureau de Normalisation du Québec. 2017. Geotechnical site investigations for building foundations in permafrost zones. CAN/BNQ 2501-500/2017. Québec.
https://www.bnq.qc.ca/images/pdf/Sommaire_SOD/SOD_2501-500_EN_2017.pdf

Porter, C., Morin, P., Howat, I., Noh, M.-J., Bates, B., Peterman, K., Keesey, S., et al. 2018. ArcticDEM, Version 3. Harvard Dataverse.
https://doi.org/10.7910/DVN/OHHUKH

Rantanen, M., Karpechko, A.Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., and Laaksonen, A. 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment 3. 168.
https://doi.org/10.1038/s43247-022-00498-3

Reimann, C., Filzmoser, P., Garrett, R.G., and Dutter, R. 2008. Statistical data analysis explained: Applied environmental statistics with R. Chichester: John Wiley & Sons.
https://doi.org/10.1002/9780470987605

Schuur, E.A.G., McGuire, A.D., Schädel, C., Grosse, G. Harden, J.W., Hayes, D.J., Hugelius, G., et al. 2015. Climate change and the permafrost carbon feedback. Nature 520(7546):171–179.
https://doi.org/10.1038/nature14338

Smith, M.W., and Riseborough, D.W. 2002. Climate and the limits of permafrost: A zonal analysis. Permafrost and Periglacial Processes 13(1):1–15.
https://doi.org/10.1002/ppp.410

Smith, S.L., Throop, J., and Lewkowicz, A.G. 2012. Recent changes in climate and permafrost temperatures at forested and polar desert sites in northern Canada. Canadian Journal of Earth Sciences 49(8):914–924.
https://doi.org/10.1139/e2012-019

Smith, S.L., O'Neill, H.B., Isaksen, K., Noetzli, J., and Romanovsky, V.E. 2022. The changing thermal state of permafrost. Nature Reviews Earth & Environment 3(1):10–23.
https://doi.org/10.1038/s43017-021-00240-1

Thienpont, J.R., Rühland, K.M., Pisaric, M.F.J., Kokelj, S.V., Kimpe, L.E., Blais, J.M., and Smol, J.P. 2013. Biological responses to permafrost thaw slumping in Canadian Arctic lakes. Freshwater Biology 58(2):337–353.
https://doi.org/10.1111/fwb.12061

van Vuuren D.P., and Carter, T.R. 2014. Climate and socio-economic scenarios for climate change research and assessment: Reconciling the new with the old. Climatic Change 122(3):415–429.
https://doi.org/10.1007/s10584-013-0974-2

Vincent, L.A., Hartwell, M.M., and Wang, X.L. 2020. A third generation of homogenized temperature for trend analysis and monitoring changes in Canada's climate. Atmosphere-Ocean 58(3):173–191.
https://doi.org/10.1080/07055900.2020.1765728

Vincent, L.A., Zhang, X., Brown, R.D., Feng, Y., Mekis, É., Milewska, E.J., Wan, H., and Wang, X.L. 2015. Observed trends in Canada's climate and influence of low-frequency variability modes. Journal of Climate 28(11):4545–4560.
https://doi.org/10.1175/JCLI-D-14-00697.1

Vincent, L.A., Zhang, X., Mekis, É., Wan, H., and Bush, E.J. 2018. Changes in Canada's climate: Trends in indices based on daily temperature and precipitation data. Atmosphere-Ocean 56(5):332–349.
https://doi.org/10.1080/07055900.2018.1514579

Wahl, H.E., Fraser, D.B., Harvey, R.C., and Maxwell, J.B. 1987. Climate of Yukon. Ottawa: Environment Canada, Atmospheric Environment Service.
https://publications.gc.ca/site/eng/9.883308/publication.html

Wilcox, E.J., Keim, D., de Jong, T., Walker, B., Sonnentag, O., Sniderhan, A.E., Mann, P., and Marsh, P. 2019. Tundra shrub expansion may amplify permafrost thaw by advancing snowmelt timing. Arctic Science 5(4):202–217.
https://doi.org/10.1139/as-2018-0028

Zhang, X., Flato, G., Kirchmeier-Young, M., Vincent, L., Wan, H., Wang, X., Rong, R., Fyfe, J., Li, G., and Kharin, V.V. 2019. Temperature and precipitation across Canada. In: Bush, E., and Lemmen, D.S., eds. Canada's changing climate report. Ottawa: Government of Canada. 112–193.
https://doi.org/10.4095/327811

Zhou, F., Zhang, A., and Hoeve, E. 2008. Cost impact of climate change-induced permafrost degradation on building foundations in Inuvik, Northwest Territories. In: Kane, D.L., and Hinkel, K.M., eds. Ninth International Conference on Permaforst. Conference proceedings, 28 June–3 July 2008, University of Alaska, Fairbanks. Vol. 2. 2089–2094.
https://www.permafrost.org/event/icop9/