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Regional Assessment of GCM-Simulated Current Climate over Northern Canada

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ABSTRACT. Several international Global Climate Models (GCMs) are evaluated on their ability to simulate the mean values and spatial variability of current (1961–90) temperature and precipitation over four regions across Canada's North. A number of observed climate data sets for Arctic Canada are also assessed. Results reveal a close correspondence, particularly for temperature, among the four observed climate data sets assessed. However, the various GCM simulations of this observed climate show considerable inter-regional and seasonal variability, with temperature more accurately simulated than precipitation. Temperature findings indicate that the British HadCM3, German ECHAM4, and Japanese CCSR-98 models best replicate annual and seasonal values over all sub-regions. The Canadian CGCM2 and U.S. NCAR-PCM models have intermediate accuracy, and the Australian CSIRO-Mk2b and U.S. GFDL-R30 models are least representative. Temperature simulations from the various GCMs collectively display a similar degree of accuracy over all sub-regions, with no clear evidence of superiority in any given area. Precipitation, conversely, is accurately simulated by the majority of models only over northern Quebec/Labrador. All GCMs substantially overestimate annual and seasonal precipitation amounts in the western and central Canadian Arctic.

Key words: global climate models, climate change impacts, Arctic, northern Canada, temperature, precipitation, gridded climate data

RÉSUMÉ. Plusieurs modèles de climats du globe (MCG) internationaux ont été évalués quant à leur aptitude à simuler les valeurs moyennes et la variabilité spatiale de températures et de précipitations récentes (1961-1990) dans quatre régions du Nord canadien. Certains ensembles de données sur le climat observé dans l'Arctique canadien sont également évalués. Les résultats révèlent une correspondance étroite, surtout pour ce qui est de la température, entre les quatre ensembles de données de climats observés qui font l'objet d'une évaluation. Cependant, les diverses simulations de MCG quant au climat observé affichent une grande variabilité entre les régions et les saisons, les températures faisant l'objet de simulations plus précises que les précipitations. Les constatations en matière de précipitations laissent supposer que les modèles HadCM3 britannique, ECHAM4 allemand et CCSR-98 japonais répliquent mieux les valeurs annuelles et saisonnières dans toutes les sous-régions. Pour leur part, les modèles CGCM2 canadien et NCAR-PCM américain présentent une exactitude intermédiaire, tandis que les modèles CSIRO-Mk2b australien et GFDL-R30 américain sont les modèles les moins représentatifs. Ensemble, les simulations de températures des divers modèles MCG affichent un degré semblable d'exactitude dans toutes les sous-régions, sans qu'il n'y ait de modèle nettement supérieur dans une région donnée. Réciproquement, les précipitations sont simulées avec exactitude par la majorité des modèles dans le nord du Québec et le Labrador seulement. Tous les MCG surestiment, de manière substantielle, les quantités de précipitations annuelles et saisonnières dans l'ouest et dans le centre de l'Arctique canadien.

Mots clés : modèles de climats du globe, incidences sur le changement climatique, Arctique, Nord canadien, température, précipitation, données rectangulaires sur le climat

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INTRODUCTION

Climate change is projected to considerably alter future physical, biological, and socioeconomic systems over many regions of the world. Of particular concern are high-latitude areas, which are extremely sensitive to climate variations and are expected to experience the greatest impacts as the result of climate change. Over the Arctic, significant changes to temperature and precipitation will affect several physical processes, such as the magnitude and timing of freshwater entering and exiting the Arctic Ocean, the duration of sea ice, the extent of permafrost and snow cover, and the timing of lake and river freeze-up and breakup. These changes in turn will have profound impacts on a range of sensitive hydro-climatic and cryospheric processes: for example, the North Atlantic thermohaline circulation; snow/ice duration and associated feedbacks; and large-scale hydrologic regimes, including seasonal shifts in discharge and reductions in the severity of ice breakup on major northward flowing rivers (Anisimov et al., 2001; Walsh et al., 2005). Projected changes to Arctic climate will also affect various biological and socio-economic activities, with impacts on aquatic productivity and

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diversity of terrestrial and freshwater ecosystems (Wrona et al., 2005), indigenous people, infrastructure, and natural resource exploration. The importance of the Arctic is further discussed in the recent Arctic Climate Impact Assessment (ACIA, 2004, 2005), an international project designed to evaluate and synthesize knowledge on climate variability and change, including future impacts on the environment, human health, and economy of the Arctic region.

Much of the Arctic has experienced statistically significant trends towards warmer temperatures and increased precipitation during the period of instrumental record. However, these trends have shown considerable variability in both time and space (e.g., Overland et al., 2004). Since the 1950s, for example, there has been a strong winter and spring warming over Eurasia and northwestern North America, but significant cooling over northeastern Canada and the subpolar North Atlantic (Serreze et al., 2000; Zhang et al., 2000). In northern Canada, spatial differences were also evident in the timing of spring 0˚C isotherm dates, with western regions showing significant trends toward earlier springs, central areas having smaller (generally insignificant) trends toward earlier springs, and extreme eastern regions experiencing later springs during the last half-century. The spatial characteristics observed in 0˚C-isotherm trends were also reflected in past variations in several hydro-cryospheric variables over northern Canada, including the timing of snowmelt and the dates of freshwater ice breakup (Bonsal and Prowse, 2003; Duguay et al., 2006). From approximately 1900 to 1960, annual precipitation increased significantly over most Northern Hemisphere high latitudes (e.g., Serreze et al., 2000; New et al., 2001). Since 1960, although precipitation has shown little change over most of the Arctic, significant increases have been observed over much of northern Canada and the North Atlantic (Groisman and Easterling, 1994; Zhang et al., 2000).

Projections of amplified global warming in polar regions and further increases to high-latitude precipitation (e.g., Walsh et al., 2002) suggest even more change to hydro-climatic and cryospheric processes over the Arctic. However, large differences exist in the spatial patterns of these projected changes because of the complexities and numerous feedbacks in the Arctic climate system. These differences could act to intensify impacts in certain areas and perhaps suppress them in others. To assess regional impacts, credible models that provide accurate climate-change scenarios at the appropriate spatial scales are required. At present, researchers rely primarily on coupled Global Climate Models (GCMs) for projections of future climate. Finer-resolution Regional Climate Models (RCMs) are becoming increasingly available; at present, however, their use is limited to specific areas for selected periods. One criterion for selecting GCMs to construct regional climate scenarios involves the validity of the model, which is evaluated by examining the GCM's ability to simulate present-day and past climates, both globally and for regional areas of interest (IPCC-TGCIA, 1999; Walsh et al., 2002). Detailed intercomparisons of GCM-simulated past climate (such as the Coupled Model Intercomparison Project, Covey et al., 2003) have been and continue to be undertaken, with their primary focus on larger scales, such as global and zonal means. Specifically for the Arctic, Walsh et al. (2002) compared present-day climate simulations from several uncoupled and coupled GCMs for the entire Arctic region and determined spatial differences in terms of simulated temperature, while precipitation was substantially overestimated by all the models. The ACIA (Kattsov et al., 2005) assessed five GCMs on their ability to replicate the 1981–2000 baseline climate over four circumpolar Arctic regions. They found that the large-scale distribution of annual mean temperature, on average, was reasonably well replicated; however, there was considerable variability between models and seasons on a regional scale. As in other assessments, major, systematic overprediction of precipitation was found, with winter and spring amounts overestimated by a factor of two in all regions except the northeastern North Atlantic and northwestern Eurasia.

Although there have been previous GCM assessments of current climate over various areas of the globe, including the circumpolar Arctic, none have specifically examined regional characteristics over northern Canada. Given the spatial differences in recent hydro-climatic trends over Arctic Canada and the potential for similar variability in the future, this study evaluates several international GCMs on their ability to simulate the mean values and spatial variability of current (1961–90) northern Canadian temperature and precipitation on a regional basis. The sparsity of climate data over northern Canada results in uncertainty about archived values of current climate. Therefore, several gridded sets of observed temperature and precipitation data are also compared. This evaluation of how several international GCMs perform in replicating current climate over Canada's North at seasonal and annual scales will help to assess which models are best suited for future regional hydro-climatic impact studies in Arctic Canada.

METHODS

GCM Data

Data from seven international GCMs (Table 1) were obtained from the web site of the Canadian Climate Impacts and Scenarios project (http://www.cics.uvic.ca/scenarios). The current-climate simulations for each model run consisted of warm-start, transient experiments that incorporated historic equivalent CO_2 and sulfate concentrations. These runs, which at the time of writing represented the latest available GCM versions from the various modeling centres, were also incorporated into the IPCC Third Assessment Report (Houghton et al., 2001). The variables extracted include monthly climatological values (minimum and maximum surface air temperature and total

TABLE 1. GCM simulations used in this investigation.

Modeling Centre	Version	Resolution (lat/long)
Canadian Centre for Climate Modeling and Analysis	CGCM2	3.75° × 3.75°
Hadley Centre for Climate Prediction and Research (United Kingdom)	HadCM3	2.5° × 3.75°
Commonwealth Scientific and Industrial Research Organisation (Australia)	CSIRO-Mk2b	5.6° × 3.2°
Max Planck Institut für Meteorologie (Germany)	ECHAM4/OPYC3	2.8° × 2.8°
Geophysical Fluid Dynamics Laboratory (United States)	GFDL-R30	2.25° × 3.75°
Japanese Centre for Climate Research Studies	CCSR-98	5.6° × 5.6°
National Centre for Atmospheric Research (United States)	NCAR-PCM	2.8° × 2.8°

TABLE 2. Gridded observed-climate data sets used in this investigation.

Data Set	Methodology	Resolution
Climatic Research Unit (CRU)	Thin-plate splines; function of latitude, longitude, elevation	0.5° × 0.5°
IDW	Inverse distance weighting; does not take into account topography	50 km
ANUSPLIN	Thin-plate splines; more stations than CRU data set	5 arc minutes
Square-Grid	Multivariate regression; elevation, local slope, distance to ocean; adjusted data	1 arc minute

precipitation) for 1961 to 1990. Mean temperature and total precipitation were compared on annual and seasonal scales, with seasons defined as winter (Dec–Feb), spring (Mar–May), summer (Jun–Aug), and autumn (Sep–Nov). Note that mean temperature refers to the average of minimum and maximum values (to match the value used in the climatological archives).

Observed Data

Northern Canada is a vast area with large variations in topography, ranging from the high-altitude Mackenzie Mountains in the west to the Hudson Bay lowlands in the east-central Arctic. The region contains few long-term climate stations. The resulting uncertainty regarding observed climate is increased by measurement biases such as gauge undercatch, which for frozen precipitation in windy environments can be greater than 50% (Goodison et al., 1998). Recently, several gridded sets of monthly temperature and precipitation data for 1961–90 have become available (Table 2). The four data sets used in this study differ in terms of gridding procedure or number of input climate stations, or both.

The Climatic Research Unit (CRU) global climate data set (available from the Data Distribution Centre of the Intergovernmental Panel on Climate Change, http://ipcc-ddc.cru.uea.ac.uk/) consists of monthly climatologies of mean temperature and precipitation over global land areas on a 0.5° latitude/longitude grid. The climate surfaces were constructed from station normals made available from various national climate centres. Station data were interpolated as a function of latitude, longitude, and elevation using thin-plate splines (New et al., 1999).

The second (IDW) data set incorporates the inverse distance weighting interpolation procedure (Isaaks and Srivastava, 1989) on all available climate records from the Meteorological Service of Canada archives. The procedure interpolates to a common grid, giving more weight to the closest stations and less to those that are farther away. The method is easy to apply, but it does not model any physical dependencies, such as topography (Milewska et al., 2002). The data are at a 50 km resolution and were obtained from the web site of the Canadian Institute for Climate Studies (http://www.cics.uvic.ca/climate/data.htm).

Australian National University Spline Interpolator (ANUSPLIN) temperature and precipitation data exist for all of Canada at a 5 arc minute resolution. Like the CRU data, these values are based on the thin-plate spline surface fitting technique; however, the ANUSPLIN database incorporates more climate stations in the gridding procedure (McKenney et al., 2001). The method involves fitting a surface described by mathematical functions onto the data points, incorporating elevation, latitude, and longitude. The degree of smoothing is optimized objectively by minimizing the predictive error of the fitted function as measured by cross validation.

The final (square-grid) data set uses the square-grid method of interpolation. Multivariate regression of climate normals is performed on the station's geographic coordinates, elevation, local slope, distance to ocean, and other physiographic parameters. Values are interpolated to a 1 arc minute resolution (Seglenieks et al., 2000). Unlike the other data sets, which use Meteorological Service of Canada archived values, the square-grid procedure uses adjusted data that are designed to account for changes in instrumentation, observing techniques, and station location (Mekis and Hogg, 1999; Vincent and Gullett, 1999). Precipitation amounts are higher since the adjustments take into account phenomena such as gauge undercatch and wetting loss. The adjusted data set also consists of a smaller subset of stations.

Study Area and Statistical Methods

The study area encompasses the continental region of northern Canada extending from the Yukon Territory to

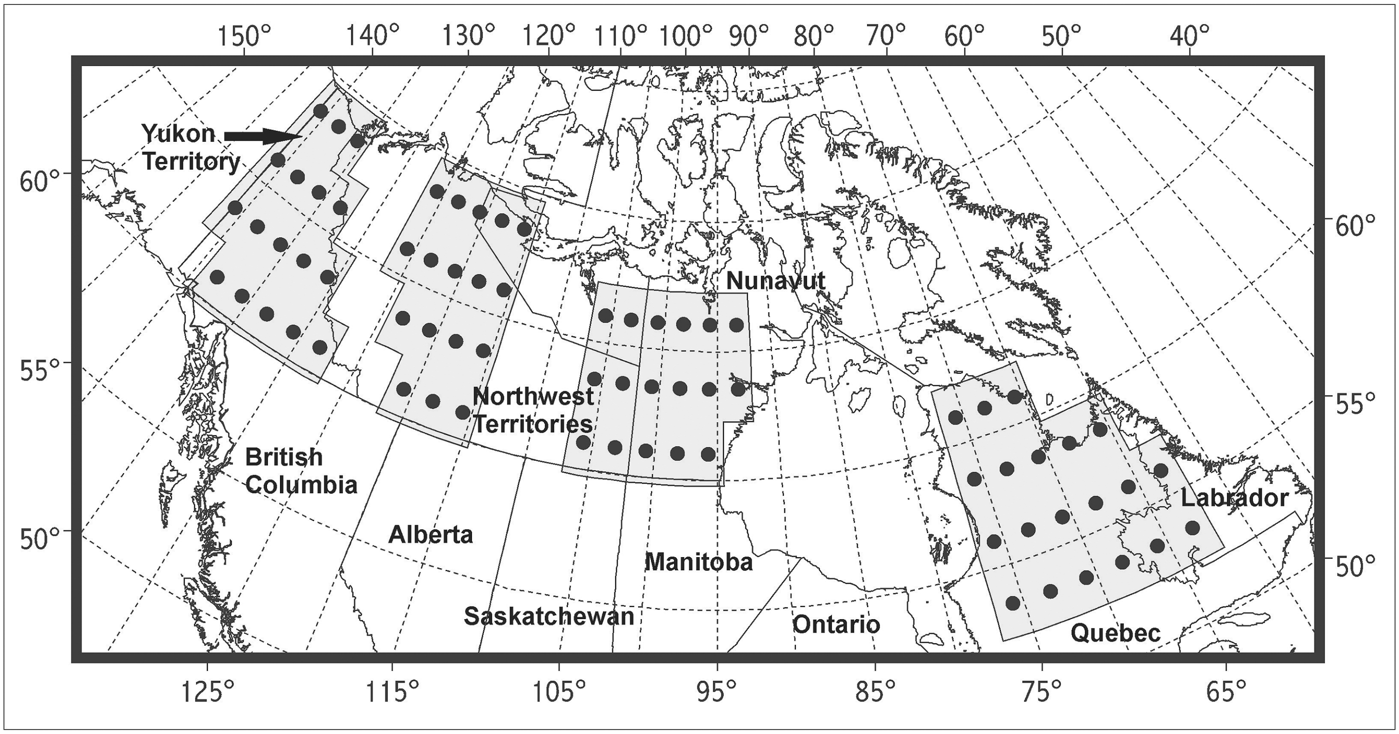

FIG. 1. Study area used in this investigation (shaded regions). The four sub-regions, from west to east, are the Yukon, the west-central Arctic, the east-central Arctic, and northern Quebec/Labrador. All data are interpolated to a 2.5˚ latitude/longitude grid. Black dots represent centres of grid cells.

Labrador (Fig. 1). The High Arctic islands are excluded because they do not have sufficient observational stations and because oceanic GCM grids, which may bias results over land, would be needed to calculate their regional climate. GCM comparisons are carried out over four subregions (from west to east): the Yukon, the west-central Arctic, the east-central Arctic, and northern Quebec/Labrador. These regions are large enough for GCM representation and characterize the four distinct climatological/geographical areas found across Canada's North. The Yukon is a cordilleran region that supplies critical runoff to major northward-flowing rivers such as the Mackenzie. The west-central Arctic has lower relief and has recently become an important area for oil and gas exploration and transmission. Both the Yukon and the west-central Arctic have been associated with a significant warming trend in the last 50 years. The east-central Arctic is characterized by Canadian Shield topography and has shown much less warming in recent decades than the Yukon and west-central Arctic. Northern Quebec/Labrador is climatically different from the other regions in that it receives higher precipitation and has been associated with a cooling trend during the last half century. The Canadian Shield also dominates this area, which is economically important for hydroelectric production.

Because of different resolutions of the GCM and observed data, all monthly values are interpolated to a common 2.5˚ latitude/longitude grid, resulting in 17 grid points for the Yukon, west-central Arctic, and east-central Arctic regions, and 20 points over northern Quebec/Labrador (Fig. 1). This resolution is comparable to the GCM grid boxes and has been used in several GCM intercomparison studies (e.g., Gates et al., 1998) and reanalysis products, such as those provided by the National Center for Environmental Prediction. Seasonal and annual values of mean temperature and total precipitation are then derived from the monthly data.

An important criterion in the GCM assessment is the models' ability to simulate the mean value of current climate over the study regions. Average regional values for each variable and season were determined for all GCM and observed data sets in order to facilitate comparison of the models. Differences between these average values were assessed using the standard t-test (e.g., Ebdon, 1985) at the 0.05 significance level. Areal averages provide useful information on mean climate, but reveal little about the spatial consistency of the data. Taylor (2001) devised a diagram that provides a statistical summary of pattern similarities in terms of their correlation coefficients, their root mean square errors (RMSE), and the ratio of their spatial standard deviations. The statistic most often used to quantify pattern similarity is the spatial pattern correlation coefficient (R), defined as:

$$R = [\frac{1}{N}\sum_{n=1}^{N}(f_n - \bar{f})(r_n - \bar{r})] / \sigma_f \sigma_r$$

where f is the modeled values, r is the observed values, n is the number of grids, and σ is the spatial standard deviation. Pattern similarity can also be quantified by the RMSE, defined as:

$$E = [\frac{1}{N}\sum_{n=1}^{N}(f_n - r_n)^2]^{1/2}$$

To isolate the differences in the patterns from differences in the means of the two fields, E can be resolved into two components. The overall bias is:

$$\overline{E} = \bar{f} - \bar{r},$$

and the pattern RMSE (PRMSE) is defined by:

$$E` = \left\{\frac{1}{N}\sum_{n=1}^{N}[(f_n - \bar{f}) - (r_n - \bar{r})]^2\right\}^{1/2}$$

The two components add quadratically to yield the full mean square difference:

$$E^2 = \overline{E}^2 + E`^2$$

The PRMSE is indicative of the RMSE once the overall bias (difference in the means) has been removed. The value approaches zero as the two patterns become alike. The correlation coefficient and PRMSE supply complementary statistical information describing the similarity between two patterns. To provide a more complete description of the fields, the spatial standard deviations of the modeled and observed data are also given. The closer these two parameters, the better the models are at simulating the magnitude of spatial variability over the study area.

All of these pattern statistics are geometrically related and thus can be displayed on a Taylor diagram (see for example, Fig. 2). In these diagrams, the radial distance from the origin is proportional to the standard deviations of the data (the solid arcs). The PRMSEs (dashed arcs) between modeled and observed values are proportional to their distance apart, and have the same units as the standard deviation. Correlation coefficients (dashed lines) are given by the azimuthal position of the model points with respect to the origin.

RESULTS

Observed Data Comparisons

An initial step is to evaluate the observed climate data sets over regions within northern Canada. To facilitate comparison of the four data sets, Taylor diagrams of annual mean temperature and total precipitation are given in Figures 2 and 3. Note that comparisons are made to the CRU data, denoted by ‘C.’ Mean values for each data set and the average of all four data sets are also given. Asterisks indicate significant differences from the CRU data. Regarding temperature, Figure 2 shows that the means of all four data sets are similar, with no significant differences in any region. Over the high-altitude Yukon region, the IDW data show slightly warmer averages than the other data sets, probably because the IDW gridding procedure did not incorporate topography. The square-grid values are warmer over the east-central Arctic and northern Quebec/Labrador regions. Reasons for these higher temperatures are not clear, but they may reflect the fewer input stations over these particularly data-sparse regions. Spatial variability is consistent among the observed products, as evidenced by the data-set cluster in the Taylor diagrams, which includes similar spatial standard deviations (e.g., 2.2˚C to 2.5˚C over the Yukon), high correlation coefficients (> 0.93), and low PRMSEs (< 1.0˚C) for all regions. Seasonal temperature comparisons (not shown) exhibit results similar to the annual values in Figure 2.

Annual precipitation (Fig. 3) displays somewhat higher variations, which are likely due to the higher degree of variability inherent in precipitation and to the different methodologies used in the gridding procedures. Most notable are the significantly higher mean values associated with the square-grid method over all regions. Except for the CRU over the Yukon, this amounts to around 20% more precipitation for the square-grid data than for other data sets. Differences are even more pronounced (> 30%) during winter (not shown), when measurement errors such as gauge undercatch are particularly problematic. The higher values are the result of incorporating adjusted data, which take into account factors such as gauge undercatch and wetting loss, into the square-grid interpolation procedure. In terms of spatial variability, the Taylor diagrams generally reveal close correspondence among the data sets, particularly over the west-central Arctic, east-central Arctic, and northern Quebec/Labrador regions. An exception is the low correlation coefficient associated with the square-grid values over the east-central Arctic. As expected, larger differences (lower correlation coefficients and higher PRMSEs) occur over the topographically diverse Yukon region. Standard deviations are generally consistent among all data sets (except for a lower IDW value, again likely the result of not accounting for topography). As with temperature, seasonal comparisons produce results similar to the annual values.

Thus the four observed temperature data sets correspond closely over the various regions of northern Canada. The precipitation data have slightly higher spatial variability, particularly over the Yukon. The most notable precipitation difference involves higher square-grid values over all sub-regions resulting from the incorporation of adjusted data. The sparseness of climate stations over northern Canada makes it difficult to determine which data best represent the region’s climate. The fact that all data sets (which incorporate different methodologies and input stations) display relatively consistent values suggests that any one or all of them could be used to represent current temperature and precipitation in this study. The next section compares GCM-simulated climate with observations over northern Canada. For reasons outlined above, the observed climate is represented by the average of all four data sets, as shown in Figures 2 and 3. Comparisons were

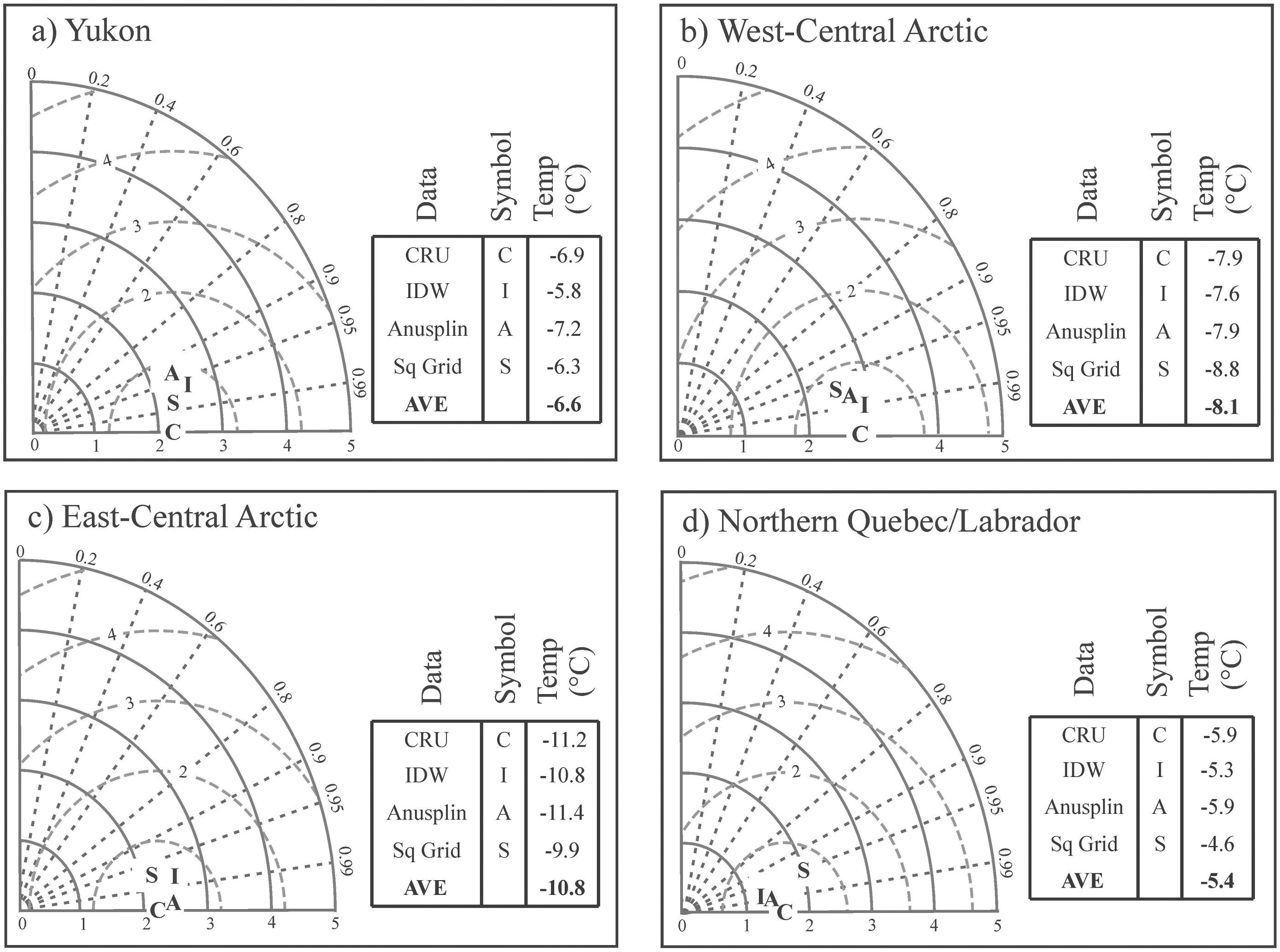

FIG. 2. Taylor diagrams showing annual mean temperature comparisons for the gridded observed–climate data sets from (a) the Yukon, (b) the west-central Arctic, (c) the east-central Arctic, and (d) northern Quebec/Labrador (see text for explanation of the diagram). Values are given with respect to the CRU data. Standard deviations and PRMSEs are in ˚C, with a contour interval of 1˚C. The corresponding tables show mean temperatures (in ˚C) for each data set, as well as the average for all four data sets. Asterisks signify significant differences in mean temperature values (with respect to the CRU data) obtained from a two-tailed t-test at the 0.05 significance level.

also carried out with each individual data set, and unless otherwise noted, results were statistically similar to those using the four-data set average.

GCM Comparisons

Mean Temperature: Comparisons of annual mean temperature simulated by the seven GCMs with observed values over the four northern Canadian sub-regions are given in Figure 4. For mean value comparisons, average observed and GCM differences from observed are also provided. Asterisks indicate models with mean temperatures significantly different from observed. Although regional differences are apparent, the majority of models accurately simulate the mean value and spatial variability of observed annual temperatures over the different areas. For the Yukon, the CGCM2, HadCM3, CSIRO, and ECHAM models simulate temperatures not significantly different from the observed -6.6˚C. The GFDL and CCSR temperatures are significantly warmer than observed, and the NCAR-PCM temperature, significantly colder. Spatial variability is consistent among the GCMs as evidenced by the model cluster in the Taylor diagram. The HadCM3, NCAR-PCM, GFDL, ECHAM, and CSIRO models have standard deviations that are slightly lower than the observed 2.3˚C, while the CGCM2 and CCSR have standard deviations near 3.0˚C. All PRMSEs are low, ranging from 0.6˚C (HadCM3) to 1.2˚C (CSIRO). Every model also has a very high correlation coefficient, indicating that the models accurately represent the spatial pattern of variation over the region.

Temperature simulations over the west-central Arctic and east-central Arctic regions (Figs. 4b and 4c) display some differences from those over the Yukon. The CGCM2, CSIRO, and GFDL temperatures are significantly warmer than the observed annual temperatures of -8.1˚C (west-central Arctic) and -10.8˚C (east-central Arctic), while the HadCM3, ECHAM, CCSR, and NCAR-PCM values are

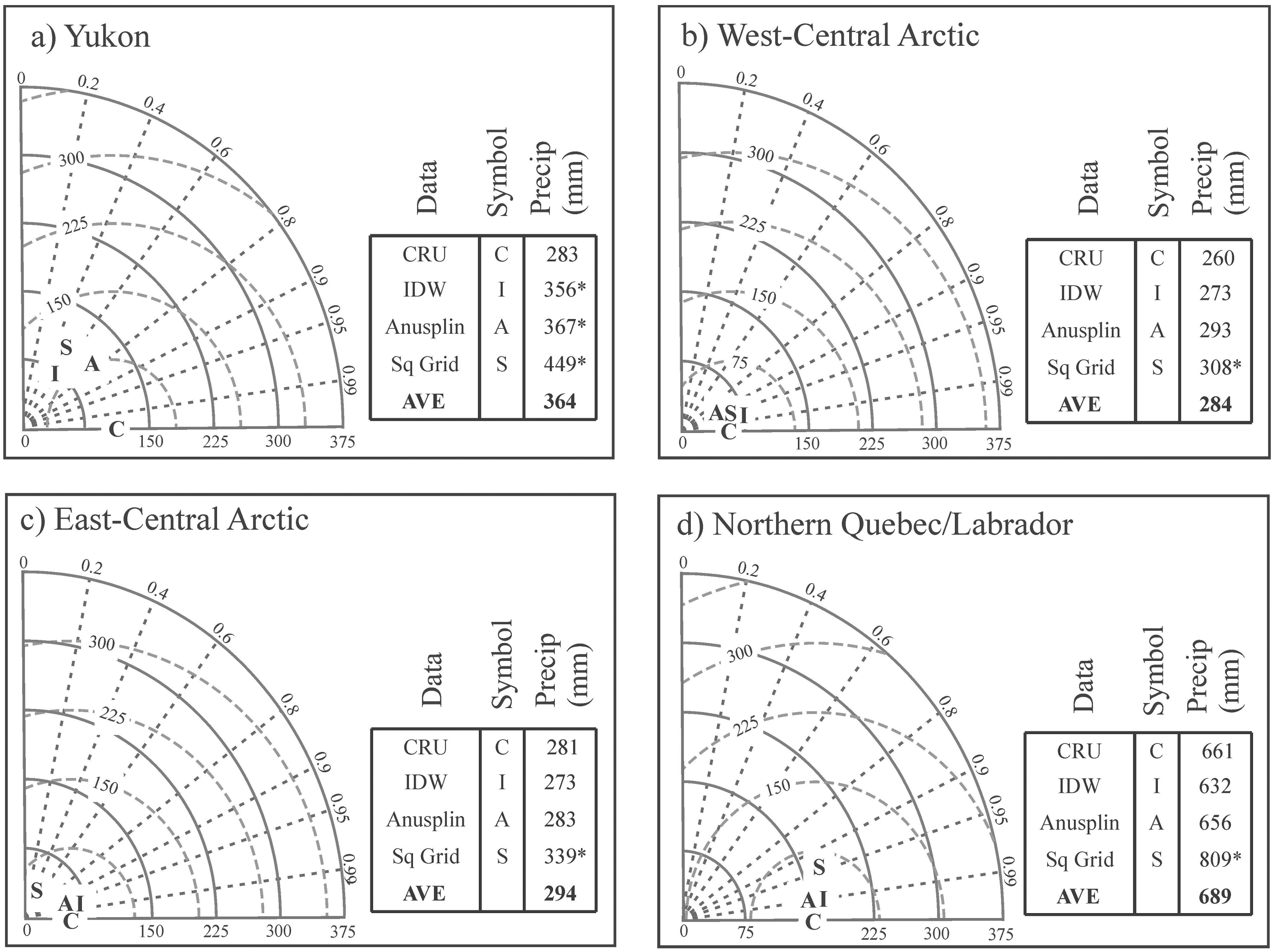

FIG. 3. Annual precipitation (in mm), with a contour interval of 75 mm. Details as in Figure 2.

not significantly different. With the exception of the CSIRO and CCSR models, most GCMs accurately represent the spatial variability of annual temperature over the east-central Arctic. Over the west-central Arctic, however, the models show greater variability, particularly in their ability to simulate the observed standard deviation of 2.7˚C. For the most part, PRMSEs are low and correlation coefficients are high for both the west-central Arctic and east-central Arctic regions.

For northern Quebec/Labrador, three GCMs (CGCM2, ECHAM, and CCSR) simulate annual temperatures not significantly different from the observed -5.4˚C. As is the case with the majority of the other sub-regions, the CSIRO and GFDL models give warmer temperatures, and the NCAR-PCM colder temperatures, than observed. Here, in contrast to the other areas, the HadCM3 gives an annual temperature that is significantly colder than observed. The GFDL and ECHAM models best represent spatial variability since they are associated with standard deviations near the observed value of 1.6˚C and have low PRMSEs and high correlation coefficients. The NCAR-PCM, HadCM3, and CGCM2 are intermediate, while the CCSR and CSIRO models give the poorest representation of spatial variability in this region.

Bar graphs showing the models' ability to simulate mean values of seasonal temperature over the four sub-regions are provided in Figure 5. Significant differences between modeled and observed temperatures are denoted by an 'X.' The GCMs display a great range in simulations, with no clear evidence of superiority for any region. Overall, the HadCM3, ECHAM, and CCSR tend to be better, in that the majority of their seasonal temperatures are not significantly different from those observed. The CGCM2 and NCAR-PCM are of intermediate ability, while the CSIRO and GFDL are least representative over all regions. On a seasonal basis, winter tends to be associated with the largest differences, likely attributable to greater temperature variability at this time of year. Spring is best characterized by the models, particularly over the Yukon, west-central Arctic, and east-central Arctic regions, while summer temperatures are best simulated by most models over northern Quebec/Labrador. Reasons for these seasonal preferences are unclear and warrant further investigation. Most GCMs can simulate the spatial

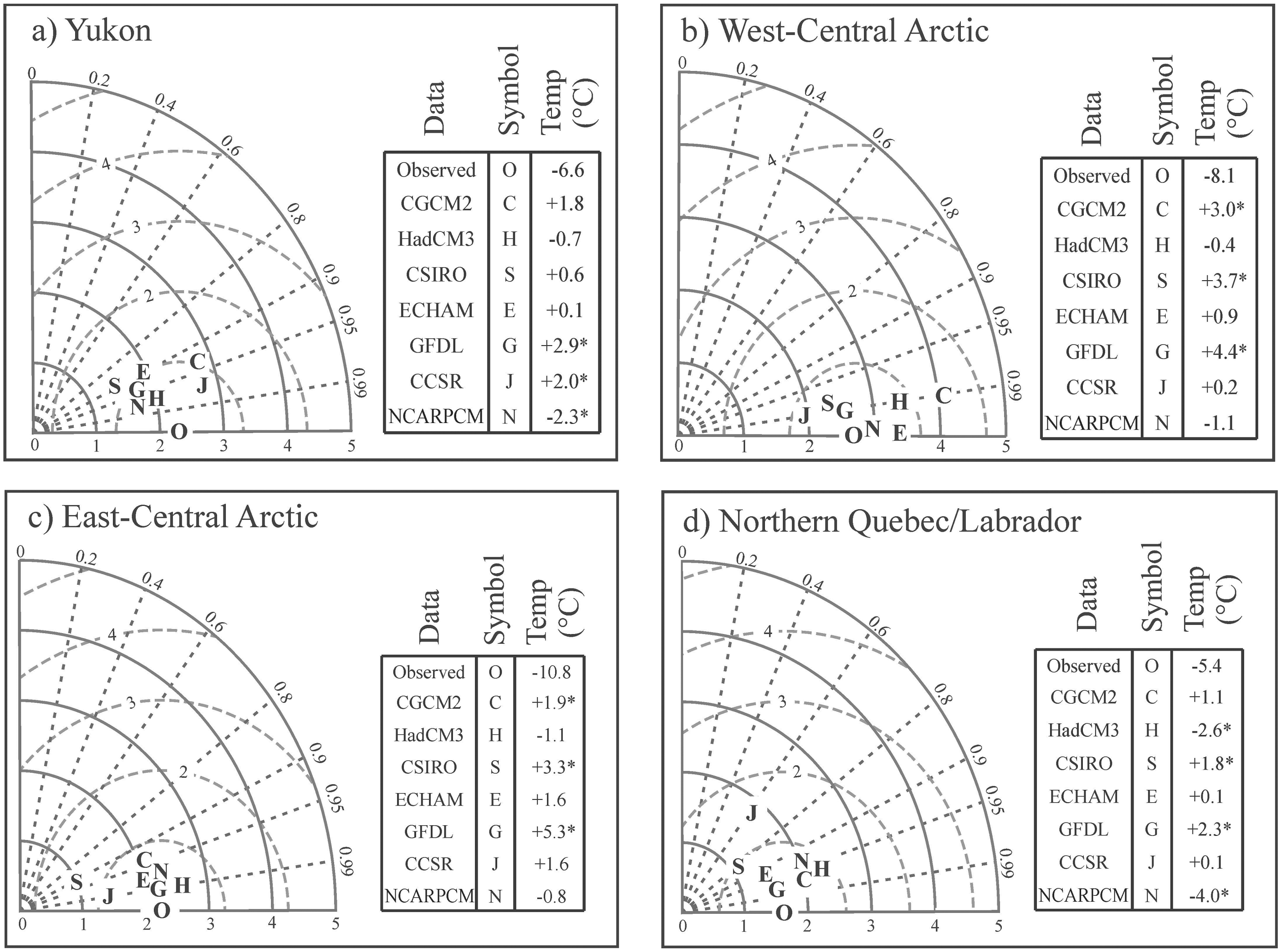

FIG. 4. Taylor diagrams showing comparisons of GCM and observed annual mean temperature values over (a) the Yukon, (b) the west-central Arctic, (c) the east-central Arctic, and (d) northern Quebec/Labrador. Standard deviations and PRMSEs are in ˚C, with a contour interval of 1˚C. The corresponding tables show mean temperatures (in ˚C) for the observed data and differences from observed values (GCM minus observed) for each of the seven models. A model point is close to the observed value if it has a similar standard deviation, a low PRMSE, and a high correlation, indicating that the two spatial patterns are similar. Asterisks signify significant differences between model and observed mean temperature values obtained from a two-tailed t-test at the 0.05 significance level.

variability of seasonal temperature over all four regions with a high degree of accuracy. These results (not shown) are consistent with the annual value analyses provided in Figure 4.

In summary, the models vary in their ability to replicate the mean temperature values, and to a lesser extent, their spatial variability over northern Canada. The temperature simulations also have a similar degree of accuracy over all sub-regions, with no clear evidence of superiority in any given area. Although substantial regional and seasonal variability exists among the models, Figures 4 and 5 suggest that the HadCM3, ECHAM, and CCSR best replicate annual and seasonal temperatures over northern Canada. The CGCM2 and NCAR-PCM are of intermediate accuracy, with the former simulating temperatures that are generally warmer than observed, and the latter, temperatures colder than observed. For the most part, the CSIRO and GFDL models are least representative of temperature in Arctic Canada; both simulate temperatures that are significantly warmer than those observed.

Total Precipitation: Annual precipitation comparisons (Fig. 6) show substantially higher variations than the temperature comparisons. The most prominent feature is that all GCMs considerably over-predict precipitation in the Yukon, west-central Arctic, and east-central Arctic regions. For the Yukon, the CCSR, CGCM2, and ECHAM values are more than twice the observed value of 364 mm. The HadCM3, NCAR-PCM, GFDL, and CSIRO do marginally better, but still over-estimate by 187 to 337 mm. The simulations are significantly higher even when compared to the larger square-grid observed value of 449 mm (Fig. 3). Figure 6a reveals that the Yukon has substantially higher spatial variability than the other three areas, reflecting the diverse topography in this region. All GCMs are associated with correlation coefficients near 0.6, while the HadCM3, GFDL, and CCSR have the lowest PRMSEs and are closest to the observed standard deviation.

In the west-central Arctic and east-central Arctic, all models also significantly over-predict precipitation (Figs. 6b and 6c). The HadCM3, CSIRO, ECHAM, and

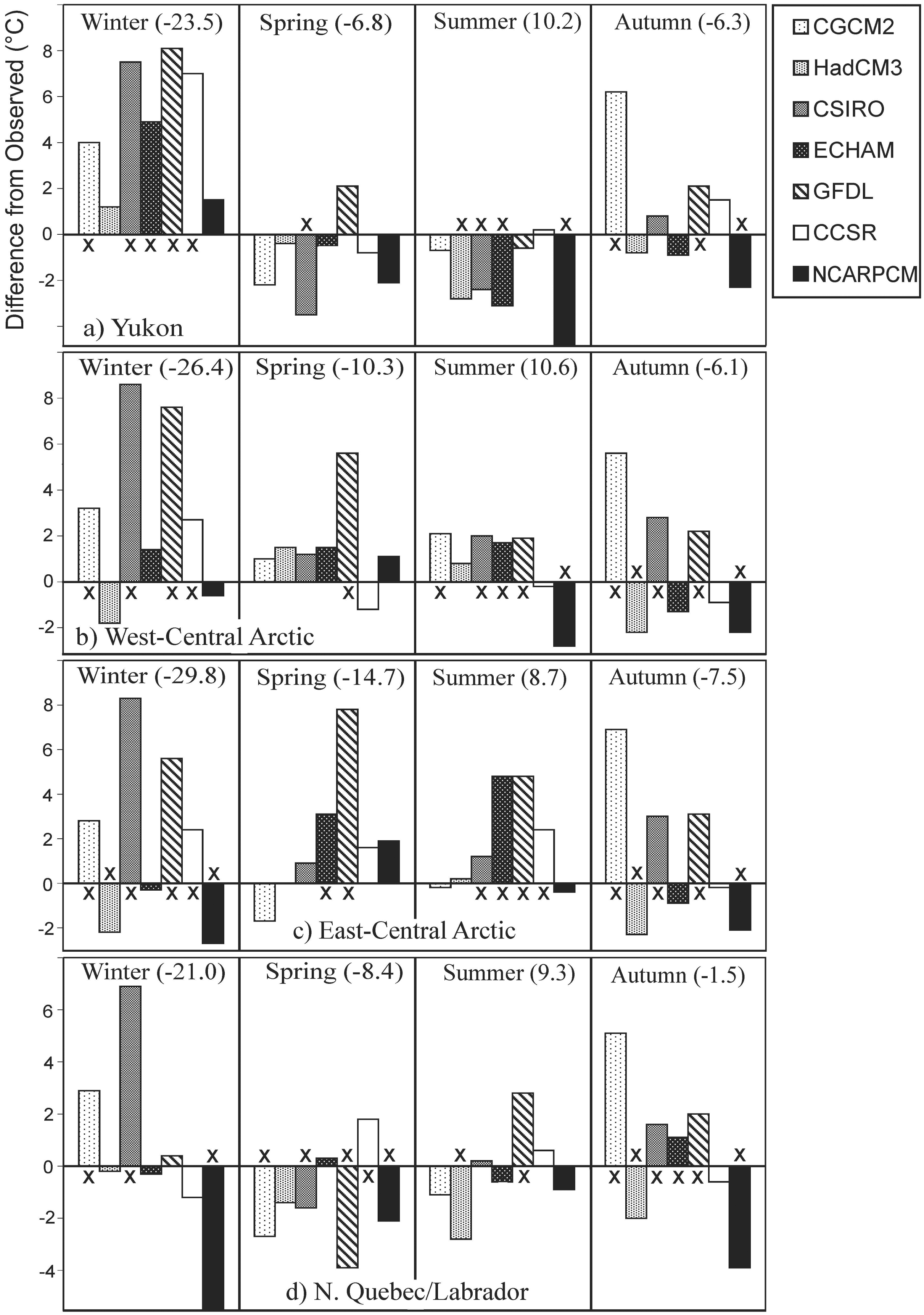

FIG 5. Seasonal comparisons of GCM-simulated mean temperature over (a) the Yukon, (b) the west-central Arctic, (c) the east-central Arctic, and (d) northern Quebec/Labrador. Units are in ˚C. The GCM values are given as differences (GCM minus observed) from the observed values provided in parentheses. An 'X' signifies a significant difference between modeled and observed temperatures obtained from a two-tailed t-test at the 0.05 significance level.

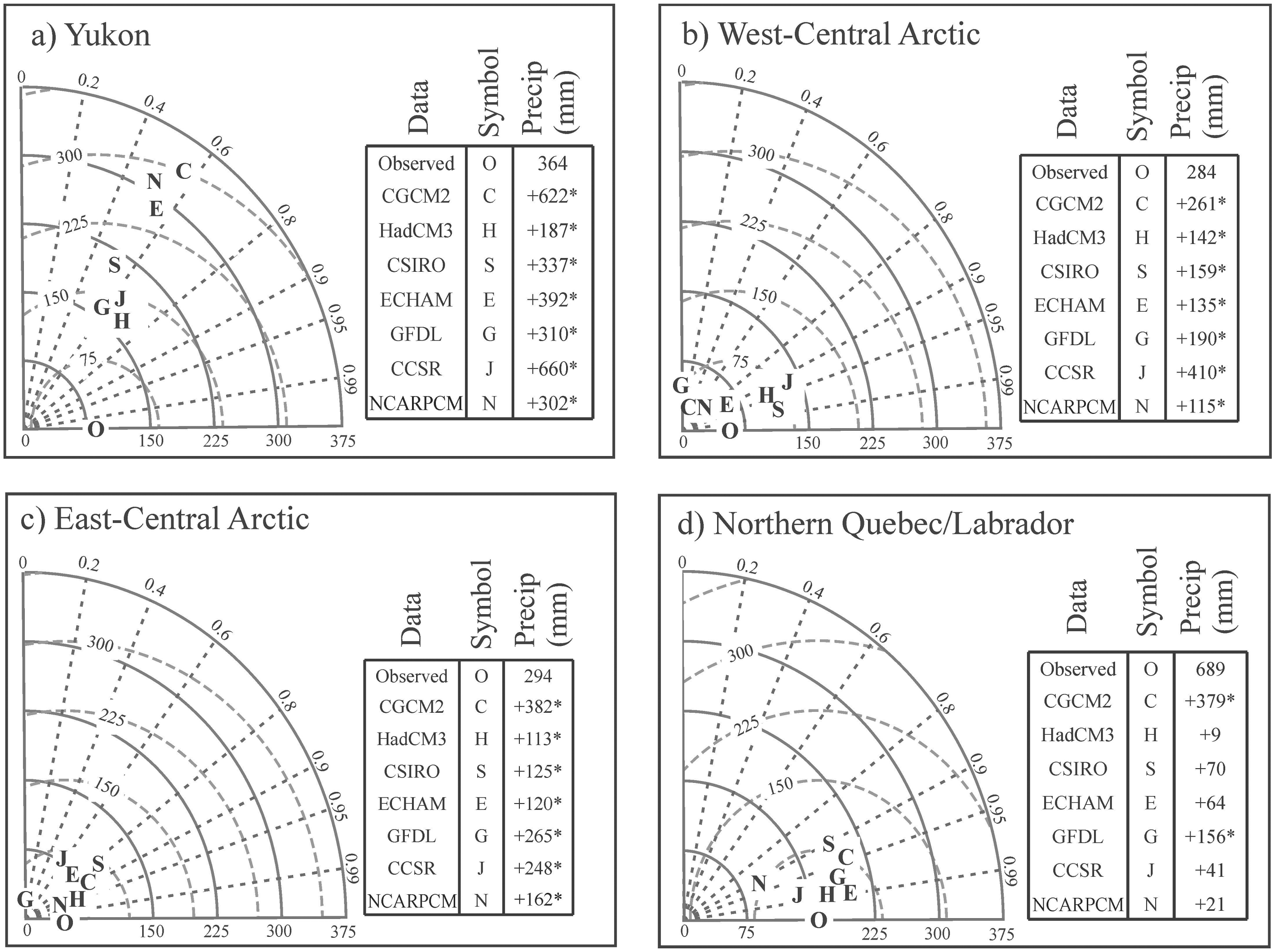

FIG. 6. Annual precipitation (in mm), with a contour interval of 75 mm. Details as in Figure 4.

NCAR-PCM best represent precipitation for both areas; however, they still simulate values 110 to 160 mm higher than those observed. The CGCM2, GFDL, and CCSR show the poorest precipitation skill over interior regions of the Canadian Arctic. In general, the majority of models accurately represent the spatial variability of observed precipitation over the east-central Arctic and to a lesser extent, the west-central Arctic regions. Low correlation coefficients and standard deviations much smaller than observed are associated with the GFDL over both areas and with the CGCM2 and NCAR-PCM over the west-central Arctic. The CCSR, CSIRO, and HadCM3 models have higher PRMSEs and high standard deviations, particularly in the west-central Arctic.

Precipitation results over northern Quebec/Labrador are quite different, in that almost all models simulate annual values that are not significantly different from the observed 689 mm. Only the CGCM2 and GFDL simulations are significantly higher. It therefore appears that most GCMs are superior at simulating the mean value of observed precipitation over eastern regions of the Canadian Arctic. Figure 6d shows that most models also simulate the spatial variability of annual precipitation in northern Quebec/Labrador with a high degree of accuracy. All correlation coefficients exceed 0.9, and PRMSEs are within 75 mm. All standard deviations are near the observed 159 mm except for the NCAR-PCM model, which simulates a much lower value of approximately 90 mm.

Figure 7 provides model comparisons of seasonal precipitation over the four northern Canadian regions. Seasonal values, like annual values, are best simulated by the majority of models over northern Quebec/Labrador. In this region, the HadCM3 displays no significant differences during all seasons. The CSIRO significantly overestimates precipitation only during summer, and the ECHAM and CCSR, only during spring. The GFDL accurately represents northern Quebec/Labrador precipitation in winter and autumn, and the NCAR-PCM, during spring and autumn, while the CGCM2 vastly over-predicts precipitation in all seasons. The majority of GCMs better simulate seasonal precipitation during autumn and winter in the northern Quebec/Labrador region. Over the other three areas, all GCMs substantially overpredict precipitation, especially in the Yukon. Exceptions include HadCM3

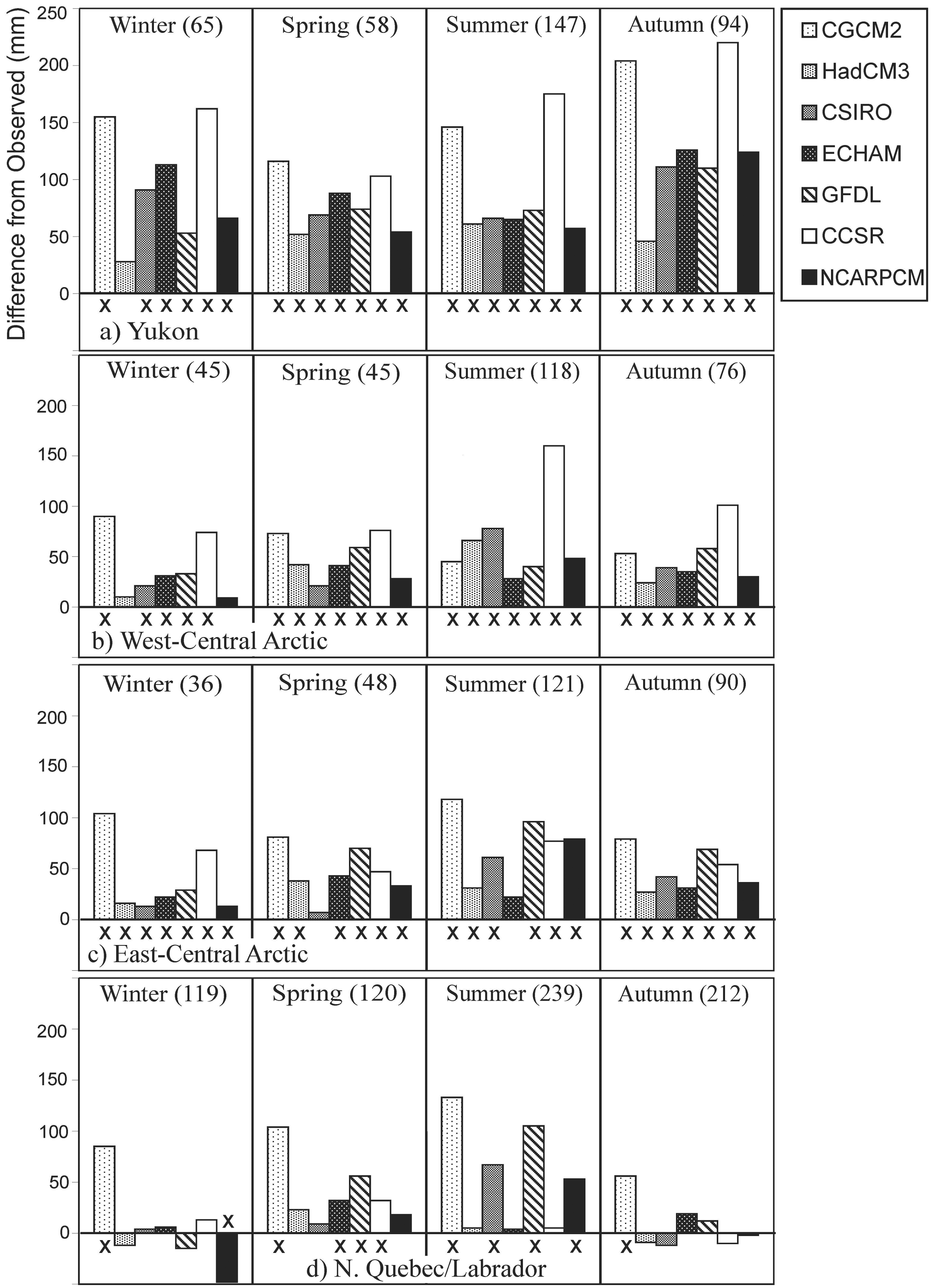

FIG. 7. Seasonal precipitation (in mm). Details as in Figure 5.

precipitation over the Yukon and west-central Arctic in winter, the CSIRO and ECHAM simulations over the east-central Arctic during spring and summer, respectively; and the NCAR-PCM model over the west-central Arctic during winter. In terms of spatial variability, model results for the individual seasons (not shown) closely match those for annual precipitation shown in Figure 6.

The preceding demonstrates that, except for northern Quebec/Labrador, the vast majority of GCMs significantly overestimate the mean value of observed annual and seasonal precipitation over northern Canada. For the Yukon, west-central Arctic, and east-central Arctic regions, annual precipitation is generally over-predicted by hundreds of millimetres, with the HadCM3, NCAR-PCM, GFDL, and CSIRO models being closest to observed. Over the northern Quebec/Labrador region, all GCMs except the CGCM2 and GFDL accurately simulate annual precipitation amounts, with autumn and winter tending to be the best seasons. For all regions, there is no clear distinction among the various models in their ability to simulate the spatial variability of precipitation. The poorest skill for all GCMs occurs in the Yukon, a result that can be attributed to the diverse topography of the region.

SUMMARY AND DISCUSSION

This study assessed the relative ability of seven GCMs to simulate current (1961–90) temperature and precipitation over various regions of northern Canada. Results revealed that temperature simulations were closer to observations than precipitation simulations. Figures 4 and 5 show that the majority of models reasonably replicate the mean values and spatial variability of observed temperature. Although there is considerable inter-regional and seasonal variability, it appears that the HadCM3, ECHAM, and CCSR models are generally superior, the CGCM2 and NCAR-PCM are of intermediate accuracy, and the CSIRO and GFDL are least accurate at replicating annual and seasonal temperatures. The analysis also indicates that GCM temperatures have a similar degree of accuracy over all sub-regions, with no clear evidence of superiority in any given area of northern Canada.

Conversely, there is a distinct regional difference for precipitation. All models substantially over-estimate values in the Yukon, west-central Arctic, and east-central Arctic, but the majority of GCMs (with the exception of CGCM2 and GFDL) accurately represent annual and seasonal values over northern Quebec/Labrador. Results over the western and central study regions are consistent with previous GCM comparison studies for the entire Arctic, which found that all GCMs greatly over-estimated observed precipitation (Walsh et al., 1998, 2002; Kattsov et al., 2005). A potential reason for over-estimation in the three westernmost regions involves smoothing of the western mountains in the relatively coarse-resolution GCMs. The lower topography would cause the incoming Pacific air to lose less moisture on the windward side, thus leaving more available moisture for precipitation in the interior regions. The differences in precipitation between western and eastern portions of northern Canada may also be related to the GCMs' ability to simulate sea-level pressure (SLP) patterns over various regions of the Arctic, particularly the dominant precipitation generating Icelandic and Aleutian Lows. Walsh et al. (2002) found that the coupled GCMs evaluated in their study (most of which were used in this analysis) closely replicated observed annual SLP over eastern Canada and the western North Atlantic (i.e., the Icelandic Low), but simulated surface pressures much lower than those observed over the western Canadian Arctic and Alaskan coast (i.e., a deeper Aleutian Low) (see their Figs. 1 and 2b). The lower than normal SLP may account for the over-estimation of precipitation in the western and central Canadian Arctic, particularly during autumn and winter. However, additional research into these potential links is required.

Because of the vast expanse of the Canadian North and the sparseness of the observing network in this region, there is uncertainty regarding observed temperature and precipitation. Measurement biases such as gauge undercatch (which for snow can be greater than 50%; Goodison et al., 1998) increase this uncertainty. The comparison of observed data sets (Figs. 2 and 3) shows consistency in terms of temperature, but greater variability in precipitation, especially for the adjusted square-grid data. However, this variability does not change the precipitation findings in this study, since the results in Figures 6 and 7 are not affected even when the higher square-grid values are incorporated. In addition, the over-estimation of precipitation in the western and central Canadian Arctic is consistent with other GCM comparison studies of Arctic climate (e.g., Walsh et al., 2002).

This investigation was not designed to provide definite answers as to which GCMs should be used for future impact studies over northern Canada, but rather to assess the relative ability of the current generation of climate models to replicate the regionality of observed temperature and precipitation on annual and seasonal scales. It is possible that certain GCMs could realistically simulate future temperature and precipitation changes even if they do not accurately replicate current climate over the region in question. However, it is suggested that more confidence can be placed in those models that give better simulations of observed climate. This degree of confidence also depends on the spatial and temporal aspects of the impact study. For example, it was shown that some GCMs perform better over different regions during certain seasons. These factors require consideration for particular hydro-climate impact studies (e.g., the magnitude and timing of the freshwater spring pulse, the ice-free seasonal heating of lakes, the late summer melting of permafrost) that require spatially accurate projections of future climate at specific times during the year. The results of this analysis can also be used by the GCM community to assess past climate simulations over various regions of the world, for example, to determine what areas are associated with consistent biases in the simulations (e.g., the over-estimation of precipitation).

This study focused on temperature and precipitation, since they are the most frequently observed and readily available climatic variables. However, more reliable estimates of climate-change impacts over the Arctic will likely require that future conditions be modeled with more physically based approaches that incorporate major heat and mass fluxes. This necessitates a broader suite of variables than simply temperature and precipitation. To date, evaluations of the reliability of such variables in GCMs and RCMs have been rare. Accurate modeling of future hydro-climatic conditions will therefore require the creation of spatially extensive and reliable sets of observed data, similar to the gridded records of temperature and precipitation employed in this analysis. In addition, the ability of GCMs to model past variability and future changes in large-scale circulation features such as El Niño/Southern Oscillation, the Aleutian and Icelandic Lows, and the North Atlantic Oscillation (which significantly affect northern Canadian climate; e.g., Bonsal et al., 2001) is uncertain. Future assessments of the models' ability to simulate large-scale circulation features are therefore also required.

In conclusion, this study has improved the knowledge regarding GCM simulations of current temperature and precipitation over various regions of northern Canada. This information, along with additional assessments of other variables and other models (e.g., RCMs), can help researchers to produce more reliable future hydro-climatic scenarios over high-latitude regions of the world.

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