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Evaluation of various daily precipitation products for large-scale hydro-climatic applications over Canada

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Abstract

A number of global and regional gridded climate products based on multiple data sources and models are available that can potentially provide better and more reliable estimates of precipitation for climate and hydrological studies. However, research into the reliability of these products for various regions has been limited and in many cases non-existent. This study identifies several gridded precipitation products over Canada and develops a systematic analysis framework to assess the characteristics of errors associated with the different datasets, using the best available adjusted precipitation-gauge data as a benchmark over the period 1979 to 2012. The framework quantifies the spatial and temporal variability of the errors over 15 terrestrial ecozones in Canada for different seasons at the daily time scale. Results showed that most of the products were relatively skillful in central Canada but tended to underestimate precipitation amounts on the east coast and overestimate on the west. The global product by WATCH Forcing Data ERA-Interim (WFDEI) augmented by Global Precipitation Climatology Centre (GPCC) data (WFDEI [GPCC]) performed best with respect to different metrics. The Canadian Precipitation Analysis (CaPA) product of Meteorological Service of Canada, performed comparably with WFDEI [GPCC], however it only provides data from 2002. All the products performed best in summer, followed by autumn, spring, and winter in order of decreasing quality. Due to the sparse observational network, northern Canada (above 60° N) was most difficult to assess with the majority of products tending to significantly underestimate total precipitation. Results from this study can be used as a guidance for potential users regarding the performance of different precipitation products for a range of geographical regions and time periods.

Keywords: precipitation; evaluation and comparison; datasets; reanalysis; hydro-climatology; Canada

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1. Introduction

The availability of accurate data, especially precipitation, is essential for understanding the climate system and hydrological processes, as precipitation is a vital element of the water and energy cycles and a key forcing variable in driving hydrological models. Precipitation measurements provide valuable information for meteorologists, climatologists, hydrologists, and other decision makers in many applications, including climate change and/or land-use change studies (e.g. Cuo et al., 2011;Huisman et al., 2009;Dore, 2005), agricultural and environmental studies (e.g. Zhang et al., 2012;Hively et al., 2006), natural hazards (e.g. Taubenbock et al., 2011;Kay et al., 2009;Blenkinsop and Fowler, 2007), and hydrological and water resource planning (e.g. Middelkoop et al., 2001;Hong et al., 2010). With respect to land-surface hydrology, the increasing sophistication of distributed hydrological modeling has urged the requirement of better and more reliable gridded precipitation estimates with at a minimum, daily temporal resolution. Before incorporating precipitation measurements, quantifying their uncertainty becomes an essential prerequisite for hydrological applications and is increasingly critical for potential users who are left without guidance and/or confidence in the myriad of products for their specific hydrological problems over different geographical regions. This paper attempts to address this issue by comparing and examining the error characteristics of different types of gridded precipitation products and assessing how these precipitation products perform geographically and temporally over Canada.

Precipitation measurements and their limitations

With the technological and scientific advancements over the past three decades, tremendous progress has been made in the various methods of precipitation measurement, each one with its own strengths and limitations. Conventional measurements through the use of rain gauges continue to play an important role in precipitation observations, as they are the only source that provide the direct physical readings and provide relatively accurate measurements at specific points. However, such measurements are subject to various errors arising from wind effects (Nešpor et al., 2000;Ciach, 2003), evaporation (Strangeways, 2004;Mekis and Hogg, 1999), undercatch (Yang et al., 1998;Adam and Lettenmaier, 2003;Mekis and Hogg, 1999), and instrumental problems like basic mechanical and electrical failure. Moreover, since many applications such as distributed hydrological models and hydraulic models require areal precipitation estimates, rain-gauge measurements are often spatially interpolated. Interpolation, however, may not capture the true spatial variability of precipitation field due to sparsity of gauge networks, particularly in complex terrains like mountainous regions or remote high latitude locations. Radars, as alternative ground-based measurements, can estimate precipitation over a relatively large area (radius of 200 to 300 km), but are also prone to inaccuracies as a result of beam spreading, curvature of the earth, and terrain blocking (Dinku et al., 2002;Young et al., 1999), and errors in the rain rate-reflectivity relationship, range effects, and clutter (Jameson and Kostinski, 2002;Austin, 1987). Development of satellite-based precipitation estimates has provided coverage over vast gauged/ungauged regions with continuous observations regardless of time of day, terrain, and weather condition of the ground (Gebregiorgis and Hossain, 2015). However, satellite-based estimates also contain inaccuracies resulting primarily from temporal sampling errors due to infrequent satellite visits to a particular location, instrumental errors due to calibration and measurement noise, and algorithm errors related to approximations to the cloud physics used (Nijssen and Lettenmaier, 2004;Gebremichael et al., 2005).

Recognizing the limitations inherent in the individual sources of precipitation observation, a number of attempts to combine information from multiple sources have been undertaken (Xie and Arkin, 1996;Maggioni et al., 2014;Shen et al., 2010). Numerous approaches have been developed to produce high-resolution precipitation estimates through combining infrared and microwave data (e.g. Huffman et al., 2007;Turk et al., 2010), merging multi-satellite products with gauge observation (e.g. Huffman et al., 1997;Huffman et al., 2010;Adler et al., 2003;Xie and Arkin, 1997;Wang and Lin, 2015), and implementing different precipitation retrieval techniques (e.g. Joyce et al., 2004;Hsu et al., 2010). Reanalysis data provide an alternative source of precipitation estimates that mitigate the sparse distribution of precipitation observations by assimilating all available data (rain-gauge stations, aircraft, satellite, etc.) into a background forecast physical model. However, they are only an estimate of the real state of the atmosphere which do not necessarily match the observations (Bukovsky and Karoly, 2007;West et al., 2007). Inaccuracies in reanalysis precipitation might also arise from the complex interactions between the model and observations that depend on the specific analysis-forecast systems and the choice of physical parameterizations, especially in regions of missing observations (Betts et al., 2006). Numerical coupled models including Atmosphere-Ocean General Circulation Models (AOGCMs) and Regional Climate Models (RCMs) offer another potential source of precipitation estimates, as well

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as future precipitation simulations. GCMs remain relatively coarse in resolution (approximately 100 to 250 km) and are not able to resolve important sub-grid scale features such as topography, land cover, and clouds (Grotch and Maccracken, 1991), resulting in the requirement of downscaling to provide fine resolution climate parameters for hydrological analyses. Two families of downscaling approaches are commonly used including statistical and dynamical approaches and they have their own advantages and disadvantages (Wilby and Wigley, 1997). In general, precipitation estimates from climate models often produce systematic bias due to imperfect conceptualization of the models, discretization and spatial averaging within grid cells (Teutschbein and Seibert, 2010;Xu et al., 2005).

Objectives and Scope

Numerous evaluation efforts among the precipitation products have been limited into three groups of inter-comparison of (1) satellite-derived products (e.g. Adler et al., 2001;Xie and Arkin, 1995;Turk et al., 2008); (2) reanalysis data (e.g. Janowiak et al., 1998;Bosilovich et al., 2008;Betts et al., 2006;Bukovsky and Karoly, 2007); and (3) climate model simulations (e.g. Covey et al., 2003;Christensen et al., 2007;Mearns et al., 2006;2012). Despite the tremendous aforementioned efforts, few studies have conducted a detailed inter-comparison among different types of precipitation products. Gottschalck et al. (2005) was one of the very few studies which compared the seasonal total precipitation of several satellite-derived, rain-gauge-based, and model-simulated datasets over contiguous United States (CONUS) and showed the spatial root mean square error of seasonal total precipitation and mean correlation of daily precipitation between each product and the impacts of these errors on land surface modelling. Additionally, Ebert et al. (2007) examined 12 satellite-derived precipitation products and four numerical weather prediction models over the United States, Australia, and northwestern Europe and found that satellite-derived precipitation estimates performed best in summer and model-induced ones performed best in winter. However, a number of questions regarding the reliability of the precipitation products remained in doubt, including: to what extent do the users have the knowledge about the error information associated with all these different types of precipitation products; how do the error distribution of precipitation products vary by location and season; and which product(s) should the users choose for their regions of interest. Answering these questions is, therefore, a crucial first step in quantifying the spatial and temporal variability of the precipitation products so as to improve their reliability as forcing inputs in hydrological modelling and other related studies.

Given the emergence of various products derived from different methods and sources (Tapiador et al., 2012), accuracy comparison studies of precipitation products have been reported over several regions; examples include the globe (e.g. Gebregiorgis and Hossain, 2015;Adler et al., 2001;Tian and Peters-Lidard, 2010), Europe (e.g. Frei et al., 2006;Chen et al., 2006;Kidd et al., 2012), Africa (e.g. Dinku et al., 2008;Asadullah et al., 2008), North America (e.g. Tian et al., 2009;West et al., 2007), South America (e.g. Vila et al., 2009), China (e.g. Shen et al., 2010;Wetterhall et al., 2006). However, less attention has been paid to high-latitude regions like Canada where a considerable proportion of precipitation is in the form of snow (Behrangi et al., 2016). Given the aforementioned, this study aims to (1) evaluate various daily gridded precipitation products against the best available precipitation-gauge measurements; and (2) characterize the error distributions of different types of precipitation products over time and different geographical regions in Canada. Evaluation of the products over specific climatic/hydrological regions will in turn help assess the performance of the precipitation products under different circumstances.

The rest of this paper is organized as follows: brief description of study area and precipitation data used is provided in Sect. 2 and 3. The methodology for evaluating precipitation products against the precipitation-gauge station data is described in Sect. 4. Results and discussion are provided in Sect. 5 and 6 respectively, with a summary and conclusion following in Sect. 7.

2. Study Area

Canada, which covers a land area of 9.9 million km^2, extends northward from 42° N to 83° N latitude and spans between 141° W to 52° W longitude. With substantial variations over its landmass, the country can be divided into many regions according to aspects such as climate, topography, vegetation, soil, geology, and land use. The National Ecological Framework for Canada classified ecologically distinct areas with four hierarchical levels of generalization (15 ecozones, 53 ecoprovinces, 194 ecoregions, and 1021 ecodistricts from broadest to the smallest) (Ecological Stratification Working Group, 1996;Marshall et al., 1999). Similarly, the Standard Drainage Area Classification (SDAC) in 2003 was developed to delineate hydrographic areas to cover all the land and interior freshwater lakes of the country with three levels of classification (11 major drainage areas, 164 sub-drainage areas, and 974 sub-sub-drainage areas) (Brooks et al., 2002;Pearse et al., 1985). The precipitation comparisons in this study incorporate both the ecological and hydrological delineations. This involved classifying the Canadian landmass into 15 ecozones for the main study (Fig. 1) and 14 major drainage areas (the Arctic Major Drainage Area was further divided into Arctic and Mackenzie, whereas the St. Lawrence Major Drainage Area was further split into St. Lawrence, Great Lakes, and Newfoundland). Results presented in the body of the paper are based on the ecozone classification; while those based on drainage areas are reported in the supplementary materials, for the sake of brevity.

In many regions of Canada, precipitation-gauge stations are sparsely distributed and the information required for hydrological modelling may not be available at the site of interest. This is especially true in northern regions (north of 60° N) and over mountainous regions where rain-gauge stations are usually 500 to 700 km apart or at low elevations (Wang and Lin, 2015). Meanwhile, the decline and closure of manual observing rain-gauge stations further reduced the spatial coverage and availability of long-term precipitation measurements (Metcalfe et al., 1997;Mekis and Hogg, 1999;Rapaic et al., 2015). Of additional concern, the observations for solid precipitation (snow, snow pellets, ice pellets, and ice crystals) and precipitation phase (liquid or solid) changes make accurate measurement of precipitation more difficult and challenging, and the measurement errors have been found to range from 20 to 50 % for automated systems (Rasmussen et al., 2012). The Meteorological Service of Canada has implemented a network of 31 radars (radar coverage at full range of 256 km) along the southern Canada (see Fortin et al. (2015b) Fig. 1 for spatial distribution). This Canadian radar network has been employed as an additional source of observations in generating the gridded product CaPA (see Sect. 3.2.2 for details). Yet, the shortcomings of using the radar data are twofold: (1) many areas of the country (north of 60° N) are not covered by this network; and (2) the implementation of the network began in 1997 and thus did not have sufficient lengths of data for any long-term hydro-climatic studies. The availability, coverage, and quality of precipitation-gauge measurements are thus obstacles to effective hydrological modelling and water management in Canada. However, the availability of several global and regional gridded precipitation products which provide complete coverage of the whole country at applicable time and spatial scales may provide a viable alternative for regional- to national-scale precipitation analyses in Canada.

3. Precipitation Data

3.1. Precipitation-gauge station data

Climate data collection is coordinated by the Federal government of Canada. Agriculture and Agri-Food Canada maintains a few stations nationally especially in Alberta province. Also, most hydro-power companies collect their own data. However, their data are not made available to the public but are sent to Environment and Climate Change Canada for archiving prior to release. In other words, the National Climate Data Archive of Environment Canada provide the basis for all the available climate data. Based on the National Climate Data Archive of Environment Canada, there are a total of 1499 precipitation-gauge stations (as in 2012) across Canada. However, due to the addition and subtraction of climate stations over the past few decades, the number of stations with available precipitation data for specified time intervals varies greatly. For instance, the numbers of precipitation-gauge stations that were active in any given years over the period of 1961 to 2003 ranged from 2000 to 3000 (see Hutchinson et al. (2009) Figs 1 and 2 for details). The issue with these data is they are subject to various errors, among which the errors due undercatch are quite significant in Canada (Mekis and Hogg, 1999). In order to account for various measurement issues, Mekis and Vincent (2011) provided adjusted daily rainfall and snowfall data for 464 stations over Canada that were based on the Adjusted Precipitation for Canada dataset (Mekis and Hogg, 1999). The data extend back to 1895 for a few long-term stations and run through 2014. For these data, daily rainfall gauge and snowfall ruler data were extracted from the National Climate Data Archive of Environment Canada and adjustments of rain and snow were done separately. Regarding each rain gauge type, corrections for wind undercatch, evaporation and wetting losses were performed based on field experiments at various locations (Devine and Mekis, 2008). For snowfall, a density correction based on coincident ruler and Nipher gauge observations was applied to all snow measurements (Mekis and Brown, 2010). Adjustments were also implemented to account for trace precipitations and accumulated amounts from multiple days were distributed over the affected days to minimize the impact on extreme values and preserve the monthly totals. Observations from nearby stations were sometimes combined to create longer time series and adjustments were done either based on overlapping observations or standardized ratios between test sites and their neighbours (Vincent and Mekis, 2009). As a result of adjustments, total rainfall amounts were concluded to be 5 to 10 % higher in southern Canada and more than 20 % in the Canadian Arctic

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-511, 2016
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Published: 13 October 2016

than the original observations. The effect of the adjustments on snowfall were larger and more variable throughout the country. Despite the lack of a measure of associated uncertainty, this adjusted precipitation-gauge station dataset has been recognized and widely used for different analyses (e.g. Nalley et al., 2012;Shook and Pomeroy, 2012;Wan et al., 2013). Therefore, this dataset was used in this study as the reference to represent the best available precipitation measurement and as the benchmark for all gridded precipitation product comparisons.

3.2. Gridded precipitation products

Seven precipitation datasets were assessed. Table 1 provides a concise summary of these datasets, including their full names, and original spatial and temporal resolutions for the versions used. These particular datasets were chosen based on the following criteria: (1) a complete coverage of Canada; (2) minimum of daily temporal and 0.5° (~50 km) spatial resolutions; (3) sufficient lengths of data (>30 years) for long-term study and cover recent years up to 2012; and (4) representation of a range of sources/methodologies (e.g. station based, remote sensing, model, blended products). Note that other commonly used datasets including the monthly Canadian Gridded temperature and precipitation (CANGRD) dataset (Zhang et al., 2000) and the coarser resolution Japan Meteorological Agency 55-year Reanalysis (JRA-55) (Onogi et al., 2007;Kobayashi et al., 2015) and the Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al., 2011) products were excluded as they do not meet criteria # 2 above.

3.2.1. Station-based product – ANUSPLIN

With the application of the Australian National University Spline (ANUSPLIN) model (Hutchinson, 1995;Hutchinson, 2004), Hutchinson et al. (2009) developed a climate dataset of daily precipitation and daily minimum and maximum air temperature over Canada at a spatial resolution of 300 arc-second of latitude and longitude (0.0833° or ~10 km) for the period of 1961 to 2003, using observed stations (from 2000 to 3000 in any given years over the period) recorded in the National Canadian Climate Data Archives of Environment Canada. However, to retain a better spatial coverage, no adjustments were done on the archive station data before the generation of the product. The dataset was generated to model the complex spatial patterns by using tri-variate thin-plate smoothing splines method that incorporated spatially continuous functions of latitude, longitude, and elevation. Hopkinson et al. (2011) subsequently extended this original dataset to include the period of 1950 to 2011. This ANUSPLIN product for Canada (hereafter the

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-511, 2016
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ANUSPLIN) has first been quality controlled with various flags indicating trace values, accumulated values over multiple days, and missing and estimated values. The accuracy of the product was then assessed by withholding from the analyses 50 stations broadly representing the southern half of Canada and by examining the error statistics for the withheld stations. The ANUSPLIN dataset has further been updated to 2013 and has recently been used as the basis of ‘observed’ data for evaluating different climate datasets (e.g. Eum et al., 2012) and for assessing the effects of different climate products in hydrological applications (e.g. Eum et al., 2014;Bonsal et al., 2013;Shrestha et al., 2012a).

3.2.2. Station-based model-derived product – CaPA

Initiated in November 2003 through collaborations within the Meteorological Service of Canada, the Canadian Precipitation Analysis (CaPA) was developed to produce a dataset of 6-hourly precipitation accumulation over North America in real-time at a spatial resolution of 15 km from 2002 onwards (Mahfouf et al., 2007). The dataset was generated based on an optimum interpolation technique (Daley, 1993), which required a background field and a specification of error statistics between the observations and the background field (e.g. Bhargava and Danard, 1994;Garand and Grassotti, 1995). For Canada, the short-term precipitation forecasts from the Canadian Meteorological Centre (CMC)’s regional model, the Global Environmental Multiscale (GEM) (Cote et al., 1998a;1998b), were used as the background field with the rain-gauge measurements from the observational network as the observations. The analysis was created by simple kriging to interpolate the differences between the transformed data of GEM and stations, which was then re-transformed and applied back to GEM. The quality of rain-gauge stations was controlled by cross-checking with the neighbouring stations and by comparing with the radar-derived precipitation. The accuracy of the product was assessed by generating an analysis error that represented the amount of additional information gained from the multiple observations with regard to the background field. CaPA has become operational at the CMC in April 2011, with updates to the statistical interpolation method (Lespinas et al., 2015), increase of spatial resolution to 10 km and the assimilation of Quantitative Precipitation Estimates from the Canadian Weather Radar Network as an additional source of observations (Fortin et al., 2015b). With its continuous improvement and different configurations, CaPA has been employed in Canada for various environmental prediction applications (e.g. Eum et al., 2014;Fortin et al., 2015a;Pietroniro et al., 2007;Carrera et al., 2015). However, the study period of these applications only extended back to 2002.

3.2.3. Reanalysis-based multiple-source products – Princeton, WFDEI, and NARR

Princeton

The Terrestrial Hydrology Research Group at the Princeton University initially developed a dataset of 3-hourly near-surface meteorology with global coverage at a 1.0° spatial resolution (~120 km) from 1948 to 2000 for driving land surface models and other terrestrial systems (Sheffield et al., 2006). The global dataset at the Princeton University (called hereafter the “Princeton”) was constructed based on the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (2.0° and 6-hourly) (Kalnay et al., 1996;Kistler et al., 2001), combining with a suite of global observation-based data including the Climatic Research Unit (CRU) monthly climate variables (2000, 1999), the Global Precipitation Climatology Project (GPCP) daily precipitation (Huffman et al., 2001), the Tropical Rainfall Measuring Mission (TRMM) 3-hourly precipitation (Huffman et al., 2002), and the NASA Langley Research Center monthly surface radiation budget (Gupta et al., 1999). Regarding precipitation, the dataset has undergone several stages in terms of spatial downscaling with the use of GPCP data, temporal downscaling based on sampling from TRMM data, and the sophistication of the correction methods (a correction to the wet-day statistics (Sheffield et al., 2004), and monthly bias corrections to match those of the CRU data (Adam and Lettenmaier, 2003)). The Princeton dataset has been evaluated against the Second Global Soil Wetness Project (GSWP-2) product (Zhao and Dirmeyer, 2003). With the inclusion of new temperature and precipitation data (e.g. Willmott et al., 2001), Princeton has been updated and is currently available at 1.0° (plus 0.5° and 0.25°), 3-hourly (plus daily and monthly) resolution globally for 1948 to 2008. Experimental updates including a 1901-2012 version at 1.0° (plus 0.5°), 3-hourly (plus daily and monthly) resolution are also available. Studies employing Princeton to study different hydrological aspects have been carried out over different parts of Canada (e.g. Kang et al., 2014;Su et al., 2013;Wang et al., 2013;Wang et al., 2014).

WFDEI

To simulate the terrestrial water cycle using different land surface models and general hydrological models, the European Union Water and Global Change (WATCH) Forcing Data (WFD) were created to provide datasets of sub-daily (3-hourly or 6-hourly) and daily meteorological data with global coverage at a 0.5° spatial resolution (~50 km) from 1901 to 2001 (Weedon et al., 2011). Similar to the composition of the Princeton dataset, the WFD were derived from the 40-year European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) (1.0° and 3-hourly) (Uppala et al., 2005) and combined with the CRU monthly variables and the Global Precipitation Climatology Centre (GPCC) monthly data (Rudolf and Schneider, 2005;Schneider et al., 2008;Fuchs, 2009). The generation of the WFD for 1958 to 2001, which was based on the ERA-40, followed the procedures developed by Ngo-Duc et al. (2005) and Sheffield et al. (2006) whereas the dataset for 1901 to 1957 was generated by using the reordered ERA-40 a year at a time. With respect to precipitation, the creation of the data (Weedon et al., 2010) involved spatially downscaling using the CRU data, sequential elevation correction, wet-day correction, monthly precipitation bias correction to match the GPCC data, and adjustment for gauge undercatch (Adam and Lettenmaier, 2003), however no corrections were made for orography effect (Adam et al., 2006). The same monthly bias corrections were also done using the CRU precipitation totals, resulting in two sets of precipitation data. The WFD were assessed by the FLUXNET data for selected years at seven sites (Araujo et al., 2002;Persson et al., 2000;Suni et al., 2003;Meyers and Hollinger, 2004;Grunwald and Bernhofer, 2007;Urbanski et al., 2007;Gockede et al., 2008). The WATCH Forcing Data methodology applied to ERA-Interim (WFDEI) dataset has further been generated covering the period of 1979 to 2012 (Weedon et al., 2014). The WFDEI used the same methodology as the WFD, but based on the ERA-Interim (Dee et al., 2011) with higher spatial resolution (0.7°), better data assimilation technique, updated monthly observation-based data, more extensive incorporation of observations, and correction of the most extreme cases of inappropriate precipitation phase. As for the WFD, the WFDEI had two sets of rainfall and snowfall data generated by using either CRU or GPCC precipitation totals (hereafter the WFDEI [CRU] and WFDEI [GPCC] respectively). To date, specific studies using the WFDEI related to Canada has been limited to the studies of permafrost in the Arctic regions (e.g. Chadburn et al., 2015;Park et al., 2015;Park et al., 2016) but the WFDEI could be a potential source in other environmental applications in Canada.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-511, 2016
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Published: 13 October 2016

NARR

Concerning the spatial and temporal water availability in the atmosphere, the North American Regional Reanalysis (NARR) was developed to provide datasets of 3-hourly meteorological data for the North America domain at a spatial resolution of 32 km (~0.3°) covering the period of 1979 to 2003 as the retrospective system and is being continued in near real-time (currently up to 2015) as the Regional Climate Data Assimilation System (R-CDAS) (Mesinger et al., 2006). The components in generating NARR included the NCEP-DOE reanalysis (Kanamitsu et al., 2002), the NCEP regional Eta Model (Mesinger et al., 1988;Black, 1988) and its Data Assimilation System, a recent version of the Noah land-surface model (Mitchell et al., 2004;Ek et al., 2003), and the use of numerous additional data sources (see Mesinger et al., 2006 Table 2). The use of NCEP-DOE reanalysis was a major improvement upon the earlier NCEP-NCAR reanalysis in both resolution and accuracy to provide lateral boundary conditions. Regarding precipitation assimilation scheme, the NARR adjusted the accumulated convective and grid-scale precipitation, assimilated the precipitation observations as latent heating profiles based on the differences between the modelled and observed precipitation (Lin et al., 1999), and disaggregated into hourly resolution using different sources over lands and oceans. For the period from 1979 to 2003 when NARR was run as the retrospective system, precipitation analyses over the continental United States (CONUS), Mexico, and Canada were derived solely from a gridded analysis of 24-hour rain-gauge measurements. For the period from 2004 onwards, NARR was generated in near-real time by the R-CDAS, which was identical to the retrospective NARR except for changes in input sources and their processing because of the real-time production constraints. One of the major differences was the use of radar-dominated precipitation analyses derived from the National Land Data Assimilation System (NLDAS) (Mitchell et al., 2004) over CONUS to disaggregate the 24-hour rain-gauge analysis to hourly precipitation whereas no assimilation was done over Canada due to the paucity of rain-gauge observations. On the basis of hydrological modelling in Canada, Choi et al. (2009) found that NARR provided reliable climate inputs for northern Manitoba while Woo and Thorne (2006) concluded that NARR had a cold bias resulting in later snowmelt peaks in subarctic Canada. In addition, Eum et al. (2012) identified a structural break point in the NARR dataset over the Athabasca River basin.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-511, 2016
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3.2.4. GCM statistically downscaled products – PCIC

The Pacific Climate Impacts Consortium (PCIC), which is a regional climate service centre at the University of Victoria, British Columbia, has offered datasets of statistically downscaled daily precipitation and daily minimum and maximum air temperature under three different Representative Concentration Pathways (RCPs) scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) (Meinshausen et al., 2011) over Canada at a spatial resolution of 300 arc-second (0.833° or ~10 km) for the historical and projected period of 1950 to 2100 (Pacific Climate Impacts Consortium; University of Victoria, Jan 2014). These downscaled datasets were a composite of 12 GCM projections from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) (Taylor et al., 2012) and the ANUSPLIN dataset. The historical 1950 to 2005 period of the ANUSPLIN was used to drive the GCMs and the statistical properties and spatial patterns of the downscaled outputs tended to resemble those of the ANUSPLIN. However, the timing of natural climate variability (e.g. El Niño-Southern Oscillation) in the observational record were not considered since GCMs were solved as a 'boundary value problem'.

Two different downscaling methods were used to downscale to a finer resolution. The first one was Bias Correction Spatial Disaggregation (BCSD) (Wood et al., 2004) following Maurer and Hidalgo (2008) and the second was Bias Correction Constructed Analogues (BCCA) with Quantile mapping reordering (BCCAQ) which was a post-processed version of BCCA (Maurer et al., 2010) . In general, the most important distinction between the two methods was BCCAQ obtained spatial information from a linear combination of historical analogues for daily values and retained the daily sequencing of weather events from the coarse resolution, while BCSD only used monthly averages to reconstruct daily patterns by randomly resampling a historic month and scaling its daily values to match the monthly projected values.

The ensemble of the PCIC dataset has currently been used in studying the hydrological impacts of climate change on river basins mainly in British Columbia (e.g. Shrestha et al., 2011;Shrestha et al., 2012b;Schnorbus et al., 2014) and Alberta (e.g. Kienzle et al., 2012;Forbes et al., 2011) in Canada. In this study, only four GCMs with two respective statistically downscaling methods under RCP 4.5 and 8.5 were chosen for comparison (see Table 2 for details). The choice of selecting the four GCMs under RCP 4.5 and 8.5 only in the PCIC dataset was to match those GCMs available in the NA-CORDEX dataset (see next section for details).

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-511, 2016
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Published: 13 October 2016

3.2.5. GCM-driven RCM dynamically downscaled products – NA-CORDEX

Sponsored by the World Climate Research Programme (WCRP), the COordinated Regional climate Downscaling EXperiment (CORDEX) over North America domain (NA-CORDEX) was launched to provide dynamically downscaled datasets of 3-hourly or daily meteorological data over most of North America (below 80° N) at two spatial resolutions of 0.22° and 0.44° (or 25 and 50 km) under two different RCPs (RCP 4.5, and RCP 8.5) for the historical and projected period of 1950 to 2100 (Giorgi et al., 2009). Within the NA-CORDEX framework, a matrix of six GCMs from the CMIP5 driving six different RCMs was selected to compare the performance of RCMs and characterize the uncertainties underlying regional climate change projections and thus provided climate scenarios for further impact and adaption studies. On top of the knowledge and experience gained from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2012), the selection of GCM-RCM matrix of simulations, with higher spatial resolution and greater sampling of uncertainty, was based on model climate sensitivity and quality of boundary conditions. In addition, to determine the large variations in future climate due to internal variability of the GCMs on downscaled outputs, samples among multiple realizations of GCM simulations were used to drive the RCMs. The performance of participating RCMs in reproducing historical and projected climate was then assessed by comparing the ERA-Interim-driven RCM simulations. Current studies using NA-CORDEX datasets were mainly focused on evaluating the model performance of different GCM-driven RCM simulations over North America (e.g. Lucas-Picher et al., 2013;Martynov et al., 2013;Separovic et al., 2013) but the NA-CORDEX dataset could also be a potential source in hydro-climatic studies in Canada. In this study, only two GCMs with three RCMs were chosen for comparison due to the availability of the NA-CORDEX dataset (see Table 3 for details).

4. Methodology

To identify the most consistent gridded dataset corresponding to different seasons and regions across Canada, comparisons of each gridded product with direct precipitation-gauge station data from the Canadian adjusted and homogenized precipitation datasets of Mekis and Vincent (2011) (see Sect. 2.1) were carried out. It is recognized that the same gauged stations are utilized in both gridded precipitation products (ANUSPLIN and CaPA), however, the generation of these gridded data used archive (unadjusted) values from these stations. Also, as aforementioned, the Canadian radar network has been used in generating CaPA and thus could not be used as an independent source for evaluation of the gridded products. Two screening processes were done to select the suitable precipitation-gauge stations. The first was to eliminate those stations that did not cover the period from 1979 to 2012. This resulted in 169 out of 464 stations across Canada being retained. The drastic drop in stations was due to 271 of them ending before or after early 2000s and 23 not having a complete year of 2012. The second step was to eliminate any of the 169 stations where the percentage of missing values exceeded 10 % in the time series of the study period. This resulted in a total of 145 and 137 stations across Canada for long-term and short-term comparison respectively (see Fig. 1 for locations). Note that most of the stations are located in southern Canada with only 15 stations above 60° N.

Due to the different spatial and temporal resolutions of the various precipitation products, the first step was to re-grid each onto a common 0.5° x 0.5° resolution to match the lowest-resolution dataset. Those having sub-daily time scale were also aggregated to daily accumulation for comparison. Two common time spans were selected since CaPA covered a shorter time frame when compared to the rest of the products: (1) long-term comparison from January 1979 to December 2012 with the exclusion of CaPA; and (2) short-term comparison from January 2002 to December 2012 when CaPA are available. The analysis was performed by summing up the daily values for four seasons (spring: March to May, summer: June to August, autumn: September to November, and winter: December to February) to evaluate how well the precipitation products work in capturing the seasonal differences in precipitation.

Gridded-based precipitation estimates at the coordinates of the precipitation-gauge station were extracted by employing an inverse-distance-square weighting method (Cressman, 1959), which has been used to interpolate climate data for simple and efficient applications (Eum et al., 2014;Shen et al., 2001). This method assumes that an interpolated point is solely influenced by the nearby gridded points based on the inverse of the distance between the interpolated point and the gridded points. The interpolations are carried out on an individual ecodistrict basis and are based on both the number of precipitation-gauge stations and number of 0.5° x 0.5° grid cells within the ecodistrict in question. For instance, when a single precipitation-gauge station is located within an ecodistrict, the value of the interpolated point is calculated by using all of the gridded points within that ecodistrict. When two or more precipitation-gauge stations are within the same ecodistrict,

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-511, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 13 October 2016

their interpolated values are calculated by using the same numbers of gridded points but with different weightings based on inverse distance. In the case when an ecodistrict contains one grid cell, no weighting is used and the interpolated value is equal to the nearest gridded point.

4.1. Comparison of probability distributions using Kolmogorov-Smirnov test

A two-sample non-parametric Kolmogorov-Smirnov (K-S) test compared the cumulative distribution functions (CDFs) for each type of precipitation product at 5 % significance level ($\alpha = 0.05$) to support the null hypothesis (H_0) that the two datasets came from same population. Monthly total precipitation data were used and aggregated for each season because the existence of numerous zero values in the daily precipitation data might reduce the statistical identification of significant differences to support the null hypothesis. The K-S test was repeated for all precipitation-gauge stations and a measure of reliability (in percent) was calculated to show how reliable each type of precipitation products was among all the precipitation-gauge stations, as shown by Eq. (1).

$$\%\ of\ reliability = \frac{no\ of\ station\ that\ support\ H_0}{total\ no\ of\ precipitation\ gauge\ station} \cdot 100 \tag{1}$$

4.2. Evaluation of gridded precipitation data using performance measures

Since the generation of the climate model-based precipitation products (PCIC dataset and NA-CORDEX dataset) only preserved the statistical properties without considering the timing of precipitation events in the observational record, these two datasets were excluded from the following evaluation, which only focused on the station-based and reanalysis-based gridded products. In particular, these two products were assessed in their ability to represent the daily variability of precipitation amounts and occurrence in different ecozones by four performance measures: percentage of bias ($PBias$) (P_{Bias}), root-mean-square-error ($RMSE$) (E_{rms}), correlation coefficient (r), and standard deviation ratio (σ_G/σ_R), as shown by Eqs (2) to (5), respectively.

$$P_{Bias;s} = \frac{\sum_i^N (G_i - R_i)}{\sum_i^N (R_i)} \cdot 100 \tag{2}$$

$$E_{rms;s} = \sqrt{\frac{\sum_i^N (G_i - R_i)^2}{N}} \tag{3}$$

$$r_s = \frac{\sum_i^N (G_i - \bar{G})(R_i - \bar{R})}{\sqrt{\sum_i^N (G_i - \bar{G})^2}\sqrt{\sum_i^N (R_i - \bar{R})^2}} \quad (4)$$

$$(\sigma_G/\sigma_R)_s = \frac{\sqrt{\frac{\sum_i^N (G_i - \bar{G})^2}{N}}}{\sqrt{\frac{\sum_i^N (R_i - \bar{R})^2}{N}}} \quad (5)$$

where s is the season, G and R are the spatial average of the daily gridded precipitation product and the reference observation dataset (precipitation-gauge stations) respectively, $\bar{G}$ and $\bar{R}$ are the daily mean of gridded precipitation product and point station data over the time spans (1979-2012 and 2002-2012), respectively, i is the i-th day of the season, and N is the total numbers of day in the season. These four performance measures examined different aspects of the gridded precipitation products, with $PBias$ for accuracy of product estimation, $RMSE$ for magnitude of the errors, r for strength and direction of the linear relationship between gridded products and precipitation-gauge station data, and σ_G/σ_R for amplitude of the variations.

5. Results

5.1. Cumulative distribution function of all products

The percentage of reliability of each precipitation dataset in each of the four seasons for the periods of 1979 to 2012 and 2002 to 2012 across Canada is shown in Fig. 2. The higher the percentage, the more reliable the precipitation datasets are for the precipitation gauges in question. In general, for long-term comparison (Fig. 2 left panel), WFDEI [GPCC] provided the highest percentage of reliability for the individual seasons (from spring to winter: 72.5 %, 81.4 %, 70.3 %, and 50.3 %) while NARR had the lowest percentage (24.8 %, 45.5 %, 27.6 %, and 11.7 %). Therefore in spring, WFDEI [GPCC] is not significantly different for 72.5 % of the 145 precipitation-gauge stations while for NARR it is only 24.8 %. ANUSPLIN is second in spring and summer (56.6 % and 73.1 %) and WFDEI [CRU] in autumn and winter (63.4 % and 45.5 %).

Regarding the PCIC ensembles, the different GCMs provided a range of reliabilities for the individual seasons. GFDL-ESM2G performed the best in spring (58.6 %) while CanESM2 in autumn (43.8 %). MPI-ESM-LR generally gave more reliable estimates in summer and winter (64.5 % and 38.3 %). The performance of HadGEM2-ES RCP 8.5 with BCCAQ statistical

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-511, 2016
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Published: 13 October 2016

downscaling method was significantly poorer than the rest of the GCM ensembles, especially in summer (13.1 %). Overall, the performance of MPI-ESM-LR (49.1 %) was the best among the GCMs, followed by GFDL-ESM2G (47.0 %), CanESM2 (42.2 %), and HadGEM2 (36.7 %). In terms of statistical downscaling methods, the BCCAQ method was on average slightly better than BCSD (47.5% versus 45.4 %) with the former having a greater similarity in spring and summer as opposed to autumn and winter. These small differences therefore suggest that both methods are similar. With respect to the NA-CORDEX ensembles, the CRCM5 RCM gave the most reliable estimates in summer and autumn regardless of the GCM used. CanRCM4 had the best reliability in spring (46.9 %) whereas RegCM4 had the poorest reliability in spring and summer (22.1 % and 36.6 %). In addition, the CanESM2-driven CanRCM4 with RCP 4.5 and RCP 8.5 were equally reliable in four seasons. Overall, the reliability of MPI-ESM-LR (44.8 %) was better than that of CanESM2 (40.6 %) regardless of the RCMs used whereas the reliability of CRCM5 (43.3 %) was the best among the RCMs, followed by CanRCM4 (39.5 %), and RegCM4 (33.3 %). It should also be noted that in all cases, the station-based and reanalysis-based products outperformed the climate model-simulated products.

With regard to the short-term comparison (Fig. 2 right panel), ANUSPLIN had the best performance in summer with 94.1 % of reliability among the 137 precipitation-gauge stations while CaPA was the best in winter with 68.6 % of reliability. Again, WFDEI [GPCC] in general provided the most consistent and reliable estimates with over 65 % of reliability in four seasons. Similar performances were seen among the PCIC ensembles and the NA-CORDEX ensembles in the period of 2002 to 2012 as compared with the long-term performance. It is interesting to note that for the most part, there is a higher percentage of reliability in short-term period compared to long-term period. Reasons for this are not clear but can be partly attributed to the fact that the power of K-S test (i.e. the probability of rejecting the null hypothesis when the alternative is true) decreases with the number of samples.

Figures 3 and 4 display the seasonal distributions of *p*-value using the K-S test in the 15 ecozones for long-term and short-term comparison, respectively. Due to the uneven distribution of precipitation-gauge stations across Canada, the numbers of stations in each ecozone are different (Table 4), with no stations in Region 1 (Arctic Cordillera), and Regions 2 to 5, 10, 12, and 15 have less than 10 stations. The percentage of missing values in precipitation-gauge station in Region 11

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-511, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 13 October 2016

exceeded 10 % in the period of 2002 to 2012 and thus the station was dropped out for analysis, resulting in no stations in Region 11 for short-term comparison. As a result, two representations were used to show the distributions of *p*-values. Regions having more than or equal to 10 stations (6 to 9 and 13, 14) were shown in box-whisker plots with bottom, band (thick black line), and top of the box indicating the 25th, 50th (median), and 75th percentiles, respectively. Regions having less than 10 stations were given by hollow circles with each representing one *p*-value at one precipitation-gauge station. Different colours in the figures correspond to the various precipitation products. The more numbers of high *p*-values (> 0.05) are in one ecozone (either represented by a cluster of hollow circles or a thick black line in box-whisker plots towards 1 in y-axis in Figs 3 and 4), the more confidence (more consistent) one has that the gridded precipitation datasets provide reliable estimates in that ecozone.

From 1979 to 2012 (Fig. 3), in regions where more precipitation-gauge stations were available (6 to 10, 13, and 14), the consistency of each type of precipitation products is explored by assessing the median of the *p*-values. Overall, all the precipitation products showed very low reliability and consistency in winter among these ecozones and in every season in Regions 13 and 14 (Pacific Maritime and Montane Cordillera) as the medians were close to zero, despite a couple of locations having higher chance of same CDFs as in the precipitation-gauge station data. The WFDEI [GPCC] dataset provided the highest consistency in the remaining three seasons except for Region 7 (Atlantic Maritime) where ANUSPLIN showed higher medians (0.51 and 0.46) than WFDEI [GPCC] (0.42 and 0.42) in spring and autumn respectively. Noticeably NARR provided the lowest median among the reanalysis-based datasets in all four seasons in Regions 6 to 8 but gave fairly consistent estimates in Regions 9 and 10, especially in summer in Region 9 (Boreal Plain) where it came second after WFDEI [GPCC]. The medians of Princeton were similar with that of ANUSPLIN on average in these regions except for summer in which ANUSPLIN offered higher medians than Princeton. WFDEI [CRU] generally showed consistent estimates among these ecozones with medians well above 0.05 except for Region 7 (Atlantic Maritime) in spring and autumn. The PCIC ensembles and the NA-CORDEX ensembles showed different degrees of consistency among their GCM members with generally higher *p*-values using BCCAQ method than BCSD method in spring and summer regardless of GCMs in the PCIC datasets, whereas CanESM2 was generally having higher consistency and reliable estimates than MPI-ESM-LR in spring and summer but opposite case in autumn in the NA-CORDEX ensembles.

In ecozones above 60° N (Regions 2 to 5, 11, and 12), almost all the precipitation products had lower chance of having same CDFs as the precipitation-gauge stations, especially in spring, autumn, and winter in Region 3 (Southern Arctic) and spring and summer in Region 11 (Taiga Cordillera). The WFDEI [GPCC] and WFDEI [CRU] generally tended to provide higher p-values in these regions in spring and summer, followed by the NARR dataset. The NA-CORDEX ensembles provided slightly higher chance of having same CDFs as the precipitation-gauge stations than the PCIC ensembles in Regions 2 to 5 in spring and autumn whereas the opposite case was shown in Region 12 (Boreal Cordillera) in spring.

For the shorter time period of 2002 to 2012 (Fig. 4), CaPA showed the highest consistency in winter in Regions 6, 8, 9, and 13 whereas ANUSPLIN was the highest in summer in Regions 8, 13, and 14, echoing the results found in Fig. 2. However, the reliability and consistency of CaPA in summer was not particularly high, especially in Regions 8 and 13 where the medians were approaching zero. In addition, in ecozones above 60° N, the performances of CaPA were generally similar to that of the WFDEI [GPCC] with higher chance of providing reliable estimates in autumn. Similar performances were seen among the other precipitation products in the period of 2002 to 2012 as compared with the long-term performance, despite some regional and seasonal differences.

5.2. Daily variability of precipitation (Station-based and reanalysis-based products)

The accuracy ($PBias$), magnitude of the errors ($RMSE$), strength and direction of the relationship between gridded products and precipitation-gauge station data (r), and amplitude of the variations (σ_G/σ_R) are shown in Figs 5 and 6 for the period of 1979 to 2012 and 2002 to 2012, respectively. In general, the gridded precipitation products that agree well with the precipitation-gauge station data should have relatively high correlation and low RMSE, low bias and similar standard deviation (indicated as light grey or dark grey square in Figs 5 and 6).

With respect to long-term comparison, in terms of overall accuracy among the four seasons, ANUSPLIN performed the best in Region 11 (Taiga Cordillera) with smallest positive $PBias$ (+0.5 %) while the rest of the gridded products had negative $PBias$ ranging from -1.4 % (NARR) to -67.6 % (Princeton). However, ANUSPLIN was associated with a generally negative $PBias$ for the rest of the ecozones ranging from -5.3 % (Region 13 Pacific Maritime) to -29.6 % (Region 3 Southern Arctic), except for Regions 12 (Boreal Cordillera) and 14 (Montane Cordillera). On the other hand, WFDEI [CRU] and WFDEI [GPCC] had similar performances across different regions except in spring when the former underestimated the precipitation amounts by 63.0 % but the latter overestimated by 5.3 % in Region 11 (Taiga Cordillera). Differences could also be found in Region 7 (Atlantic Maritime) where WFDEI [CRU] overestimated in spring, autumn, and winter by 10.6 %, 7.1 %, and 7.5 % while the accuracy of WFDEI [GPCC] was within -3.5 % to 0.5 % and it was the opposite case in Region 12 (Boreal Cordillera) in autumn and winter. With the exception of Regions 13 and 14, Princeton generally provided the overall largest underestimation of precipitation amounts across different ecozones by -25.9 %, -24.8 %, and -34.6 % in spring, autumn, and winter respectively. NARR came second in spring (-19.0 %), autumn (-20.3 %), and winter (-27.1 %) and first in summer (-18.1 %). In general, all gridded products tended to overestimate in Regions 12 to 14 and Region 14 (Montane Cordillera) had the overall highest positive $PBias$ ranging from 17.1 % (WFDEI [GPCC]) to 44.2 % (WFDEI [CRU]).

When examining the magnitude of errors, ANUSPLIN, generally agreed best with precipitation-gauge station data, providing the overall lowest $RMSE$ across ecozones in four seasons (2.50 mm/day, 3.24 mm/day, 2.79 mm/day, and 2.45 mm/day) with the only exception in spring in Region 15 (Hudson Plain). Moreover, ANUSPLIN had the overall highest r across ecozones in four seasons (0.75, 0.78, 0.80, and 0.74). On the contrary, Princeton had the worst performance in both magnitude of errors and correlation with observations no matter across different ecozones or among different seasons, with the grand $RMSE$ and r of 5.65 mm/day and 0.17 respectively. The performances of WFDEI [CRU], WFDEI [GPCC], and NARR were in between ANUSPLIN and Princeton and they shared similar $RMSE$ and r across different regions and seasons, with very high magnitude of errors in Regions 6 to 8, and 13 and fair correlation in Regions 6 to 14 and minor regional and seasonal differences.

Regarding the amplitude of variations, NARR had the lowest variability across different regions in four seasons (0.70, 0.67, 0.68, and 0.60), followed by ANUSPLIN (0.84, 0.77, 0.76, and 0.75). WFDEI [GPCC] had the most similar standard deviations as that of precipitation-gauge station data in Regions 5 to 8, 13, and 14 in autumn and winter while WFDEI [CRU] had about the same standard deviations in Regions 6 to 8 in autumn only. Unlike ANUSPLIN and NARR which were consistently having too little variability across different ecozones, Princeton estimated the amplitude of variations with more diversified regional and seasonal patterns. Princeton estimated

σ_G/σ_R the best in Regions 4 to 10 in summer and Regions 9, 10, and 12 in autumn. However, the dataset had variations that were much larger than precipitation-gauge station data in Regions 7 and 8 in four seasons except summer, Region 13 in four seasons except winter, Region 14 in all seasons but too little variability in Regions 3, 11, and 15 in all seasons.

Concerning the short-term comparison, the performance of CaPA generally resembled that of ANUSPLIN in terms of accuracy, with general underestimation of precipitation amounts in Regions 4 to 10 in four seasons and overestimation in Region 12 and 13 especially in spring. CaPA had similar overestimation in Region 14 (Montane Cordillera) in winter as the rest of the gridded products but performed the best in estimating the precipitation amounts in other seasons of the region. CaPA also performed the best in Regions 5 and 15 in autumn among the gridded precipitation products. However, while all the gridded products experienced negative $PBias$ in Region 3 (Southern Arctic) in summer, CaPA performed the opposite with a positive $PBias$ of 10.8 %. Similar to ANUSPLIN, CaPA was able to minimize the magnitude of errors and had strong association with precipitation-gauge station data, providing the second lowest overall $RMSE$ (2.70 mm/day, 3.74 mm/day, 3.35 mm/day, and 3.05 mm/day) and r (0.72, 0.73, 0.75, and 0.70) across ecozones in four seasons respectively. Despite its better performances in $RMSE$ and r, CaPA was generally not able to capture the right amount of the amplitude of variations, with consistently less than that of the precipitation-gauge station data across different regions in four seasons (0.83, 0.82, 0.85, and 0.72). CaPA, however, estimated σ_G/σ_R better than ANUSPLIN (0.72, 0.76, 0.74, and 0.64) and NARR (0.75, 0.75, 0.72, and 0.63).

Some regional and seasonal differences could be seen in the other gridded precipitation products. For instance, WFDEI [CRU] performed well in Region 8 (Mixedwood Plain) in four seasons in terms of having low $PBias$ (within -1.7 % to 4.3 %) for the period of 1979 to 2012 but started to have higher positive $PBias$ in autumn and winter (7.1 % and 5.3 %) for the period of 2002 to 2012. WFDEI [GPCC] also started to have higher positive $PBias$ in Region 2 (Northern Arctic) in summer (7.4 % as compared to 1.2 %) and in winter (33.3 % as compared to 9.9 %). In terms of magnitude of errors and correlation with observations, the five gridded products in the long-term comparison performed similarly in the period of 2002 to 2012, with ANUSPLIN having the lowest grand $RMSE$ and r of 2.88 mm/day and 0.78 and Princeton being the worst again with the highest grand $RMSE$ and r of 6.12 mm/day and 0.16 respectively. Equally, the performances of

ANUSPLIN and NARR in capturing the amplitude of variations were again consistently having too little variability across different ecozones. Princeton also demonstrated similar regional and seasonal differences as in the long-term comparison with higher variability in Regions 6 to 8 in all seasons except summer. WFDEI [CRU] and WFDEI [GPCC] both performed well in Regions 6 to 8, 12, and 14 in autumn.

6. Discussion

The preceding has provided insight into the relative performance of various precipitation products over Canada when compared to adjusted gauge measurements over different seasons and geographical regions. Results showed that there is no particular product that is superior for all performance measures although there are various datasets that do perform better.

Based on the performances in the four measures, one could broadly characterize the station-based and reanalysis-based precipitation products into four groups, (1) ANUSPLIN and CaPA, as having negative $PBias$, low $RMSE$, high r, and small σ_G/σ_R; (2) WFDEI [CRU] and WFDEI [GPCC], as relatively small $PBias$, high $RMSE$, fair r, and similar standard deviation; (3) Princeton, as having negative $PBias$, high $RMSE$, low r, and a mixture of large and small σ_G/σ_R; and (4) NARR, as having negative $PBias$, high $RMSE$, fair r, and small σ_G/σ_R. Among the reanalysis-based gridded products, Princeton performed the worst in all seasons and regions in terms of minimizing error magnitudes (Figs 7 and 8). Princeton was especially poor in winter (Fig. 7) and showed significant underestimation in regions above 60° N (Fig. 8). This could be due to the use of the NCEP-NCAR reanalysis as the basis to generate the dataset, which have been shown to be less accurate than NCEP-DOE reanalysis (used in NARR) and ERA-40 reanalysis (used in WFD) (Sheffield et al., 2006). The better performance of NARR in capturing the timings and amounts of precipitation than Princeton was probably because NCEP-DOE reanalysis was a major improvement upon the earlier NCEP-NCAR reanalysis in both resolution and accuracy. However, the overall reliability of NARR was among the poorest mainly because of non-assimilation of gauge precipitation observations over Canada from 2004 onwards, as reported by Mesinger et al. (2006). ANUSPLIN and CaPA performed well in capturing the timings and minimizing the error magnitudes of the precipitation, despite their general underestimation across Canada ($PBias$ ranging from -7.7 % (Region 13) to -40.7 % (Region 3) and -2.0 % (Region 15) to -17.1 % (Region 8) in the period of 2002 to 2012) (Fig. 8) and too little variability (grand σ_G/σ_R of 0.72 and 0.80

of the same period). This was not surprising given the generation of the products was based on the unadjusted precipitation-gauge stations where the total rainfall amounts were increased after adjustment (Mekis and Vincent, 2011). WFDEI [CRU] and WFDEI [GPCC], on the other hand, performed well in estimating the accuracy and amplitude of variations, but not the timings and error magnitudes of the precipitation. This could probably due to the positive bias offsetting the negative bias resulting in small mean bias, but was picked up by $RMSE$ that gives more weights to the larger errors. The larger errors could be come from a mismatch of occurrence of precipitation in the time series, as reflected by the fair correlation coefficients (grand r of 0.52 and 0.50 for WFDEI [CRU], 0.54 and 0.53 for WFDEI [GPCC], for time periods of 1979 to 2012 and 2002 to 2012 respectively).

By matching the statistical property of the adjusted gauge measurements at monthly time scale, one could establish the confidence in using the climate model-simulated products for long-term hydro-climatic studies. Comparing the overall reliability of the PCIC and NA-CORDEX datasets, it was found that for the individual seasons the PCIC ensembles (from spring to winter: 52.2 %, 56.0 %, 41.9 %, and 32.4 %) outperformed the NA-CORDEX ensembles (34.5 %, 41.4 %, 38.3 %, and 31.7 %) under RCP 8.5 scenario. This result was the same under RCP 4.5 scenario except in autumn when the NA-CORDEX ensembles (46.2 %) provided slightly higher reliability than the PCIC ensembles (42.5 %). The better reliability of the PCIC datasets could be due to the use of ANUSPLIN to train the GCMs and thus, the statistical properties of the downscaled outputs are guided by those of the ANUSPLIN. Similarly, for ecozones where more than 10 precipitation-gauge stations could be found (Regions 6 to 9, 13 and 14), the PCIC ensembles (reliability ranging from 36.4 % to 68.1 %) also outperformed the NA-CORDEX ensembles (from 16.8 % to 49.9 %). This would suggest that the PCIC ensembles may be the preferred choice for long-term climate change impact assessment over Canada, although further research is required.

The evaluations of this comparison study are impacted by the spatial distribution of adjusted precipitation-gauge stations Mekis and Vincent (2011), which were assumed to be the best representation of reality owing to the efforts in improving the raw archive of the precipitation-gauge stations by accounting for various measurement issues like wind undercatch, evaporation and wetting loss, and snowfall adjustment. However, this dataset was not error free and the major limitation was the numbers of precipitation-gauge stations that could be used for comparison in this study. As aforementioned, due to temporal coverage not encompassing the entire study period and not having a complete year of 2012, over half of the precipitation-gauge stations were dropped out for analysis. Although the locations of the remaining stations covered much of Canada, there are only one or a few stations located in some of the ecozones (e.g. Region 3 to 5, 11, and 15). Even in Region 10 (Prairie) there are only nine precipitation-gauge stations for analysis. While the reliability of different types of gridded products could be tested in these ecozones, the consistency of the performance of each gridded product could not be established due to small sample sizes. In addition, results from the above analysis should be interpreted with care because the precipitation-gauge station data are point measurements whereas the gridded precipitation products are areal averages, of which the accuracy and precision of the estimates could be very different given the non-linear responses of precipitation (Ebert et al., 2007). However, the authors believe that given the current data situation, the preceding was the best methodology for evaluating the performance of different daily gridded precipitation products.

7. Conclusion

A number of gridded climate products incorporating multiple sources of data have recently been developed with the aim of providing better and more reliable measurements for climate and hydrological studies. There is a pressing need for characterizing the quality and error characteristics of various precipitation products and assessing how they perform at different spatial and temporal scales. This is particularly important in light of the fact that these products are the main driver of hydrological models in many regions, including Canadian watersheds where precipitation-gauge network is typically limited and sparse. This study was conducted to understand and quantify the spatial and temporal variability of the errors associated with five different types of gridded precipitation products in Canada, so as to provide some insights for potential users in selecting the products for their particular interests and applications. Based on the above analysis, the following conclusions can be drawn:

- In general, all the products performed best in summer, followed by autumn, spring, and winter in order of decreasing quality. The lower reliability in winter is likely the result of difficulty in accurately capturing solid precipitation.
- Overall, WFDEI [GPCC] and CaPA performed best with respect to different performance measures. WFDEI [GPCC], however, may be a better choice for long-term analyses as it

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Published: 13 October 2016

covers a longer historical period. ANUSPLIN and WEDEI [CRU] also performed comparably, with considerably lower quality than WFDEI [GPCC] and CaPA. Princeton and NARR demonstrated the lowest quality in terms of different performance measures.

- Station-based and reanalysis-based products tended to underestimate total precipitation across Canada except in southwestern regions (Pacific Maritime and Montane Cordillera) where the tendency was towards overestimation. This may be the due to the fact that the majority of precipitation-gauge stations are located at lower altitudes which might not accurately reflect areal precipitation due to topographic effect.
- In southern Canada, WFDEI [GPCC] and CaPA demonstrated their best performance in the western cold interior (Boreal Plain, Prairie, Montane Cordillera) in terms of timing and magnitude of daily precipitation.
- In Atlantic and Pacific coastal regions (Atlantic Maritime and Pacific Maritime) station-based and reanalysis-based products demonstrated their poorest performance in reproducing the timing and magnitude of daily precipitation.
- In northern Canada (above 60° N), the different products tended to moderately (ranging from -0.6 % to -40.3 %) (and in cases significantly (up to -60.3 % in Taiga Cordillera)) underestimate total precipitation, while reproducing the timing of daily precipitation rather well. It should be noted that this assessment was based on only a limited number of precipitation-gauges in the north.
- Comparing the climate model-simulated products, PCIC ensembles generally performed better than NA-CORDEX ensembles in terms of reliability and consistency in four seasons across Canada.
- In terms of statistical downscaling methods, the BCCAQ method was slightly more reliable than the BCSD method across Canada on the annual basis.
- Regarding GCMs, MPI-ESM-LR provide the highest reliability, followed by GFDL-ESM2G, CanESM2, and HadGEM2. With respect to RCMs, CRCM5 performed the best regardless of the GCM used, followed by CanRCM4, and RegCM4.

The findings from this analysis provide additional information for potential users to draw inferences about the relative performance of different gridded products. Although no clear-cut product was shown to be superior, researchers/users can use this information for selecting or excluding various datasets depending on their purpose of study. It is realized that this analysis only focused on the daily time scale at a relatively coarse 0.5° x 0.5° resolution suitable for large-scale hydro-climatic studies. In addition, further research is required toward the performance assessment of various products with respect to precipitation extremes, which often have the greatest hydro-climatic impacts. As new products become available, similar comparisons should be conducted to assess their reliability.

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Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-511, 2016
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Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 13 October 2016

List of Tables

Table 1 A summary of different types of precipitation products used in this comparison study.

Dataset	Full Name	Type	Spatial Resolution	Temporal Resolution	Duration	Coverage	Reference
ANUSPLIN	Australian National University Spline	Station-based Interpolated	300 arc-second (~0.0833°/ ~10 km)	24 hr	1950 – 2013	Canada	Hutchinson et al. (2009)
CaPA	Canadian Precipitation Analysis	Station-based Model-derived	10 km (~0.0833°)	6 hr	2002 – 2014	North America	Mahfouf et al. (2007)
Princeton	Global dataset at the Princeton University	Reanalysis-based multiple source	0.5° (~50 km)	3 hr	1901 – 2012	Global	Sheffield et al. (2006)
WFDEI [CRU]	Water and Global Change Forcing Data methodology applied to ERA-Interim [Climate Research Unit]	Reanalysis-based multiple source	0.5° (~50 km)	3 hr	1979 – 2012	Global	Weedon et al. (2014)
WFDEI [GPCC]	Water and Global Change Forcing Data methodology applied to ERA-Interim [Global Precipitation Climatology Centre]	Reanalysis-based multiple source	0.5° (~50 km)	3 hr	1979 – 2012	Global	Weedon et al. (2014)
NARR	North American Regional Reanalysis	Reanalysis-based multiple source	32 km (0.3°)	3 hr	1979 – 2015	North America	Mesinger et al. (2006)
PCIC	Pacific Climate Impacts Consortium	Station-driven GCM	300 arc-second (~0.0833°/ ~10 km)	24 hr	Historical: 1950 – 2005 Projected: 2006 – 2100	Canada	Pacific Climate Impacts Consortium; University of Victoria (Jan 2014)
NA-CORDEX	North America COordinated Regional climate Downscaling EXperiment	GCM-driven RCM	0.22° (25 km)	3 hr	Historical: 1950 – 2005 Projected: 2006 – 2100	North America	Giorgi et al. (2009)

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-511, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 13 October 2016

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Table 2 A summary of the GCMs chosen in the PCIC dataset.

PCIC	Full Name	Country	Statistical Downscaling Method	Representative Concentration Pathway (RCP)
GFDL-ESM2G_BCCAQ_RCP85	Geophysical Fluid Dynamics Laboratory Earth System Model 2G	USA	Bias Correction Constructed Analogues with Quantile mapping reordering	8.5
GFDL-ESM2G_BCSD_RCP85				8.5
HadGEM2-ES_BCCAQ_RCP85	Hadley Global Environmental Model 2 – Earth System	UK	Bias Correction Constructed Analogues with Quantile mapping reordering	8.5
HadGEM2-ES_BCSD_RCP85				8.5
CanESM2_BCCAQ_RCP45	Second generation Canadian Earth System Model	Canada	Bias Correction Constructed Analogues with Quantile mapping reordering	4.5
CanESM2_BCCAQ_RCP85				8.5
CanESM2_BCSD_RCP45			Bias Correction Spatial Disaggregation	4.5
CanESM2_BCSD_RCP85				8.5
MPI-ESM-LR_ BCCAQ_RCP45	Max-Planck-Institute Earth System Model running on low resolution	Germany	Bias Correction Constructed Analogues with Quantile mapping reordering	4.5
MPI-ESM-LR_ BCCAQ_RCP85				8.5
MPI-ESM-LR_ BCSD_RCP45			Bias Correction Spatial Disaggregation	4.5
MPI-ESM-LR_ BCSD_RCP85				8.5

Table 3 A summary of the GCMs-RCMs chosen in the NA-CORDEX dataset.

NA-CORDEX	Full Name		Representative Concentration Pathway (RCP)
	Global Circulation Model (GCM)	Regional Climate Model (RCM)	
CanESM2 – CanRCM4_RCP45	Second generation Canadian Earth System Model	Fourth generation Canadian Regional Climate Model	4.5
CanESM2 – CanRCM4_RCP85			8.5
CanESM2 – CRCM5_UQAM_RCP45		Fifth generation Canadian Regional Climate Model	4.5
MPI-ESM-LR – CRCM5_UQAM_RCP45	Max-Planck-Institute Earth System Model running on low resolution		4.5
MPI-ESM-LR – RegCM4_RCP85		Fourth generation Regional Climate Model	8.5

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-511, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 13 October 2016

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Table 4 Numbers of precipitation-gauge stations within each Ecozone.

Region (Ecozone)		Number of Precipitation-gauge Station	
		1979 – 2012	2002 – 2012
1	Arctic Cordillera	0	0
2	Northern Arctic	4	4
3	Southern Arctic	1	1
4	Taiga Plain	2	2
5	Taiga Shield	4	5
6	Boreal Shield	31	29
7	Atlantic Maritime	10	9
8	Mixedwood Plain	18	16
9	Boreal Plain	14	14
10	Prairie	9	7
11	Taiga Cordillera	1	0
12	Boreal Cordillera	6	6
13	Pacific Maritime	15	15
14	Montane Cordillera	28	26
15	Hudson Plain	2	3
Total		145	137

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Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 13 October 2016

Hydrology and Earth System Sciences
Open Access
Discussions

List of Figures

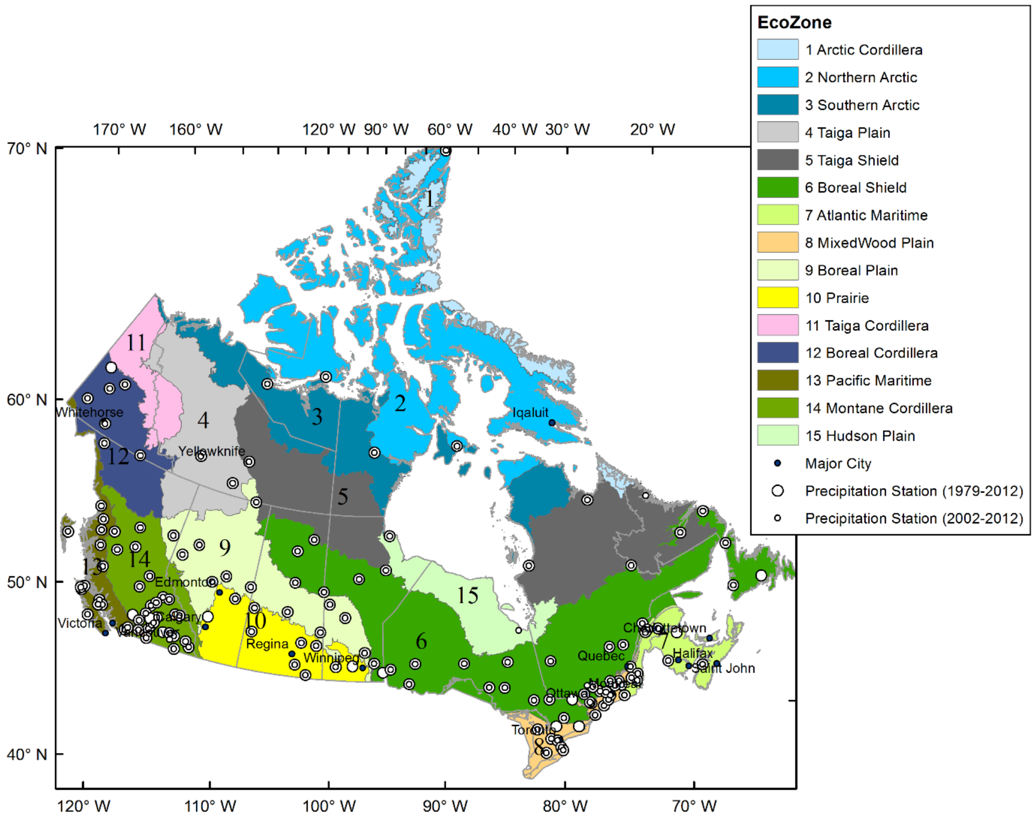

Figure 1. 15 terrestrial ecozones of Canada with numerical codes indicating Region from 1 Arctic Cordillera to 15 Hudson Plain. Big (a total of 145) and small (a total of 137) white dots are the extracted precipitation-gauge stations from the Canadian adjusted and homogenized precipitation datasets of Mekis and Vincent (2011) for the period of 1979 to 2012 and 2002 to 2012 respectively. Black dots are major cities in Canada.

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Open Access
Discussions

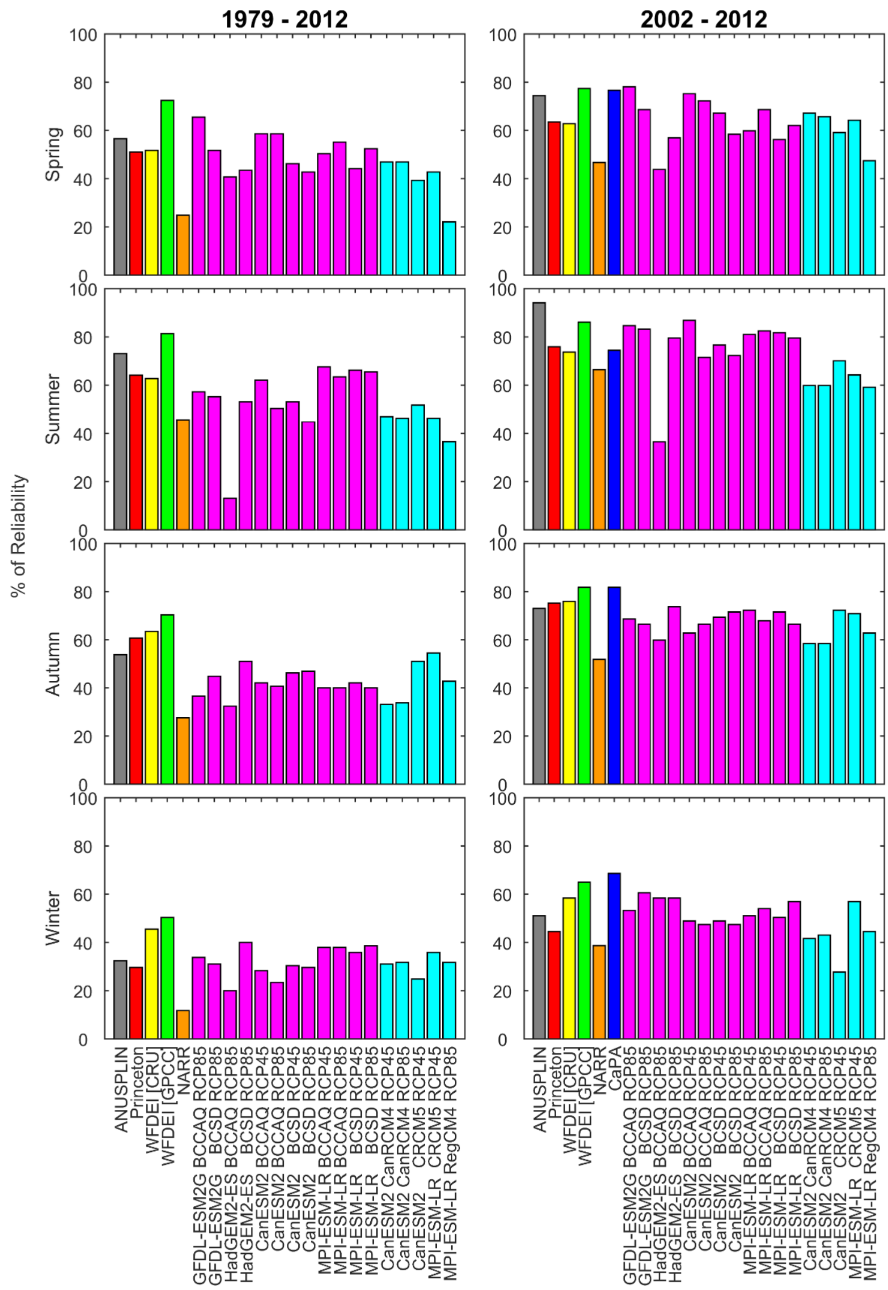

Figure 2. The percentage of reliability, calculated by the Eq. (1), of each precipitation dataset in four seasons for the period of 1979 to 2012 (left panel) and 2002 to 2012 (right panel) across Canada. The higher the percentage, the more reliable the precipitation dataset. Different colours represent different precipitation products, with magenta representing the whole PCIC datasets and cyan representing the whole NA-CORDEX datasets. The full names of the precipitation products are provided in Tables 1, 2, and 3.

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Discussions
Open Access

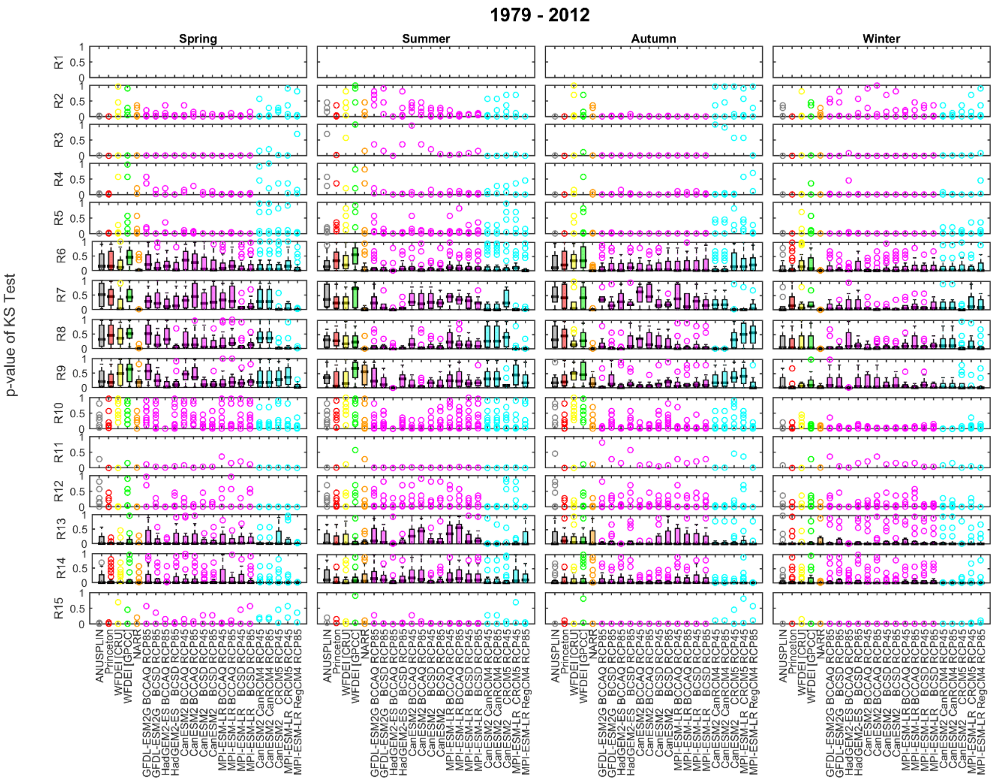

Figure 3. Distributions of p-value of the K-S test in the 15 ecozones in four seasons for the period of 1979 to 2012 (long-term comparison without CaPA). Note that the numbers of precipitation-gauge stations in each ecozone are different (see Table 4). Each hollow circle represents one p-value of the K-S test conducted at one precipitation-gauge station, with no stations in Region 1 (R1). The p-values of Regions 6 to 9, and 13 to 14 (R6-R9, and R13-R14), which have more than or equal to 10 stations, were shown in box-whisker plots with bottom, band (black thick line) and top of the box indicating the 25th, 50th (median), and 75th percentiles, respectively.

Hydrology and Earth System Sciences
Open Access
Discussions

Figure 4. Distributions of p-value of the K-S test in the 15 ecozones in four seasons for the period of 2002 to 2012 (short-term comparison with the inclusion of CaPA). Note that the numbers of precipitation-gauge stations in each ecozone are different (see Table 4). Each hollow circle represents one p-value of the K-S test conducted at one precipitation-gauge station. The percentage of missing values in precipitation-gauge station in Region 11 (R11) exceeded 10% and thus no K-S test was conducted. The p-values of Regions 6, 8 to 9, and 13 to 14 (R6, R8-R9, and R13-R14), which have more than or equal to 10 stations, were shown in box-whisker plots with bottom, band (black thick line) and top of the box indicating the 25th, 50th (median), and 75th percentiles, respectively.

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Hydrology and Earth System Sciences
Discussions
Open Access

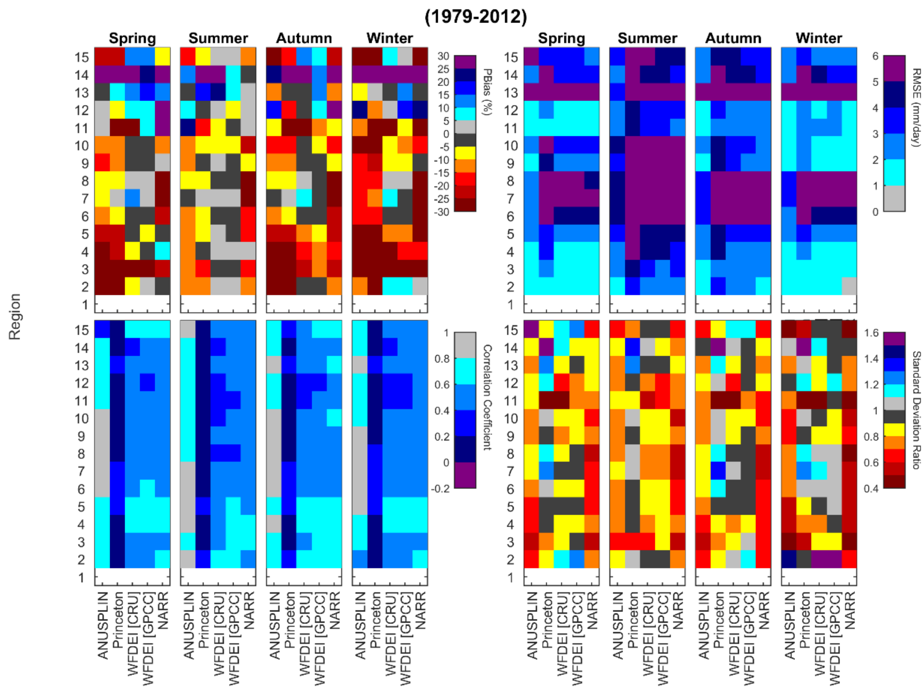

Figure 5. Portrait diagram showing the accuracy ($PBias$) (top left), magnitude of the errors ($RMSE$) (top right), strength and direction of relationship between gridded products and precipitation-gauge stations (r) (bottom left), and amplitude of the variations (σ_G/σ_R) (bottom right) of each type of gridded precipitaiton products when evaluating against the precipitation-gauge station data in each ecozone (Region 1 to 15) in four seasons for the time period of 1979 to 2012. Each column indicates one gridded precipitation product and each row represents one ecozone with numerical code corresponding to region shown in Fig. 1. White indicates that no data are available due to no precipitation-gauge stations exisiting in that region.

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Hydrology and Earth System Sciences
Open Access
Discussions

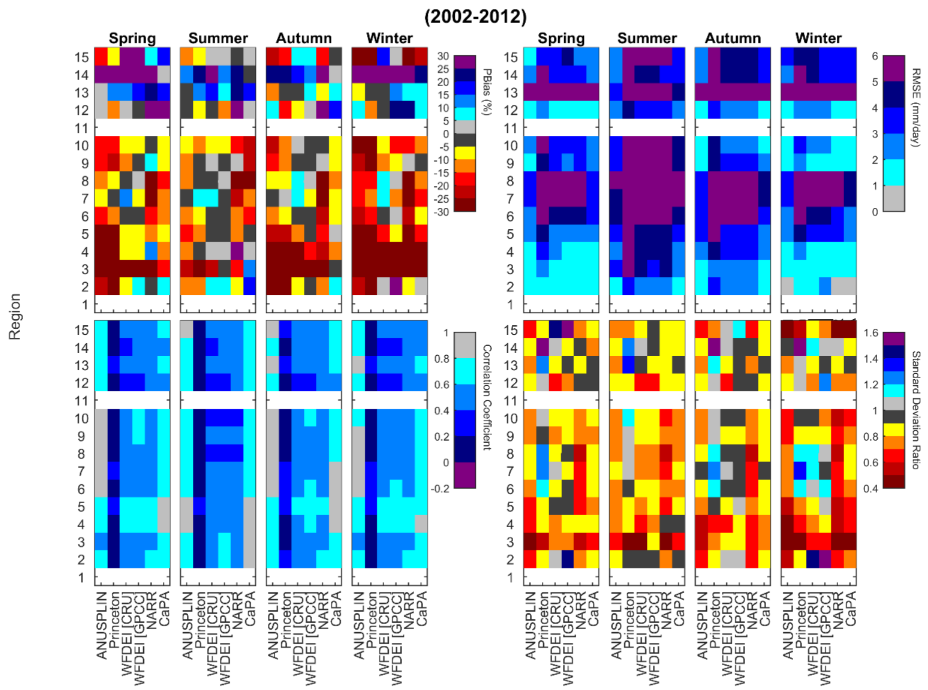

Figure 6. Portrait diagram showing the accuracy ($PBias$) (top left), magnitude of the errors ($RMSE$) (top right), strength and direction of relationship between gridded products and precipitation-gauge stations (r) (bottom left), and amplitude of the variations (σ_G/σ_R) (bottom right) of each type of gridded precipitaiton products when evaluating against the precipitation-gauge station data in each ecozone (Region 1 to 15) in four seasons for the time period of 2002 to 2012. Each column indicates one gridded precipitation product and each row represents one ecozone with numerical code corresponding to region shown in Fig. 1. White indicates that no data are available due to no precipitation-gauge stations exisiting in that region.

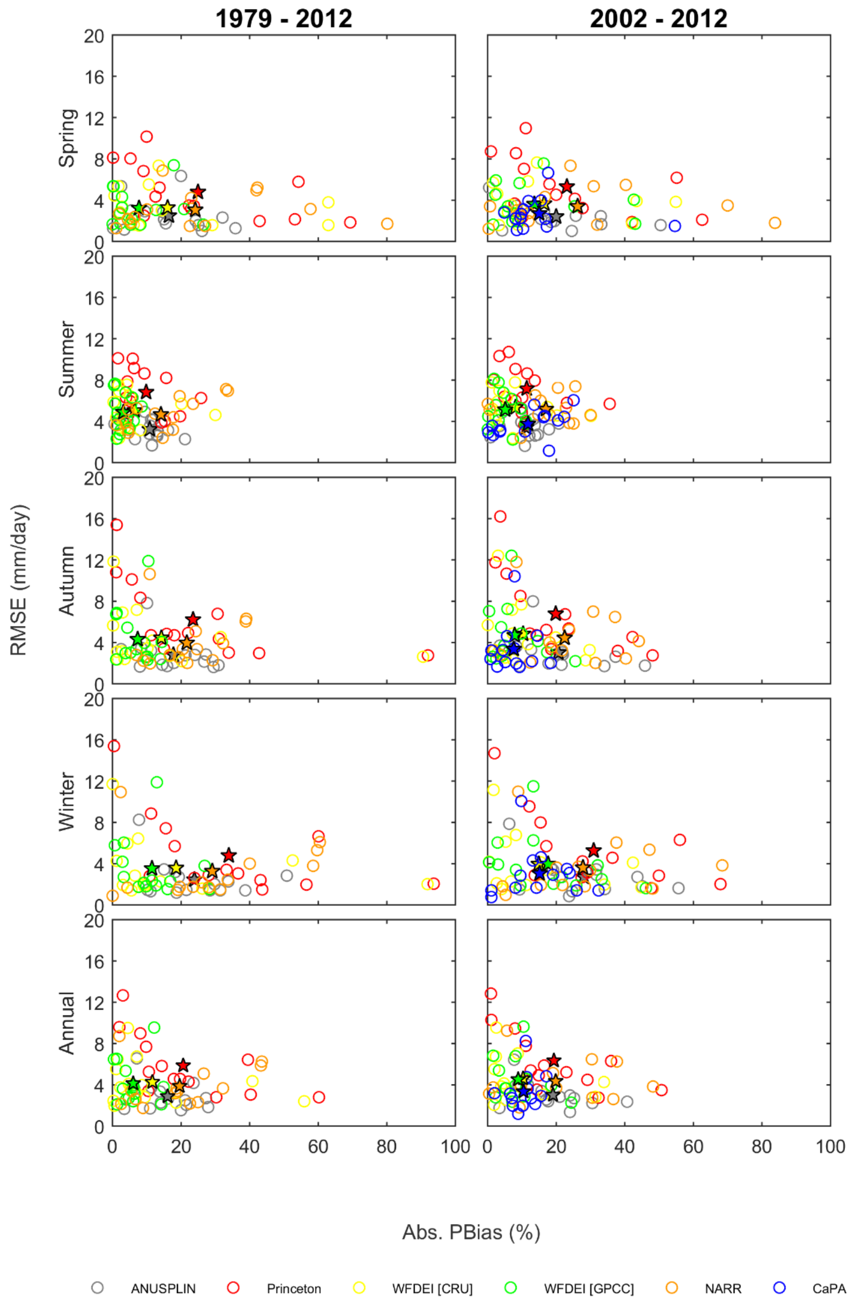

Figure 7. Scatter plots showing absolute PBias (x-axis) versus RMSE (y-axis) of each precipitation dataset in four seasons and the entire year for the period of 1979 to 2012 (left panel) and 2002 to 2012 (right panel). Each hollow circle represents one ecozone and the solid stars indicate the overall average across ecozones.

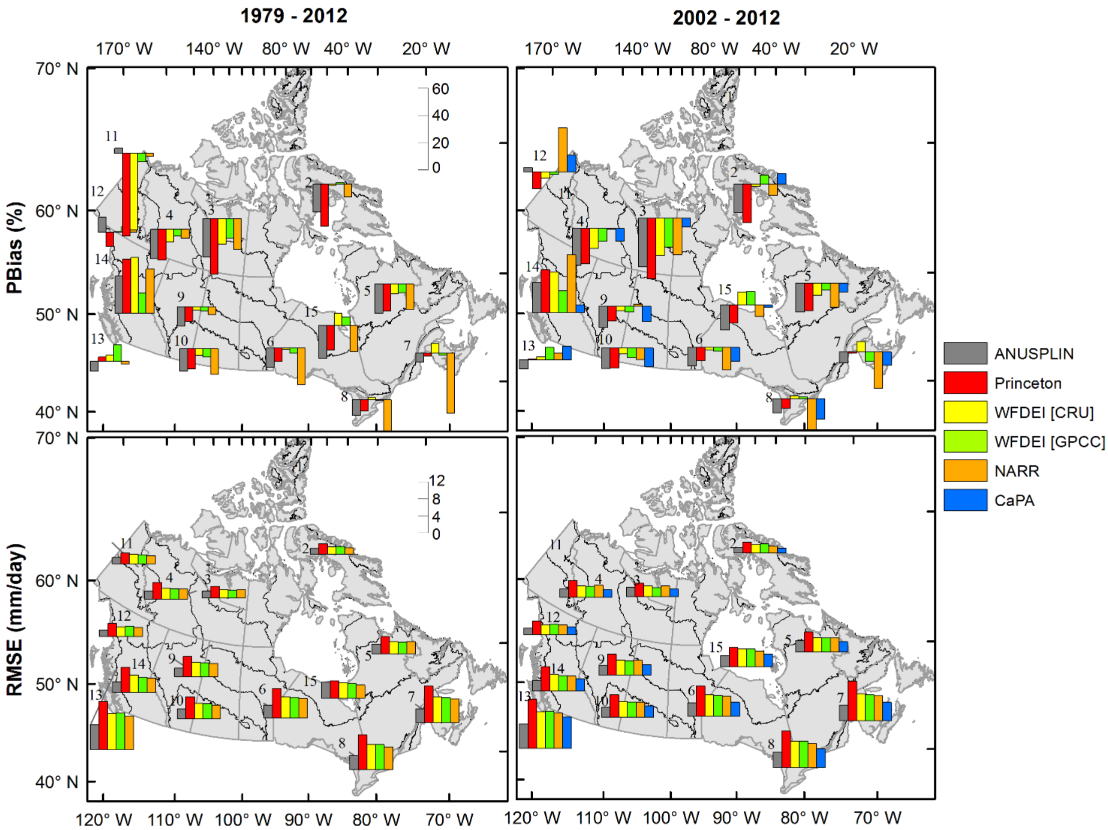

Figure 8. Bar graphs showing the annual accuracy (PBias) (first row) and magnitude of the errors (RMSE) (second row) of each precipitation dataset for the period of 1979 to 2012 (left panel) and 2002 to 2012 (right panel) in different ecozones. The white bar shows the scale of the bars with number beside it indicating the value of the bar.