Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

WFDEI-GEM-CaPA: A 38-year High-Resolution Meteorological Forcing Data Set for Land Surface Modeling in North America

Zilefac Elvis Asong[1], Howard Simon Wheater[1], John Willard Pomeroy[1, 2], Alain Pietroniro[1, 2, 3], Mohamed Ezzat Elshamy[1], Daniel Princz[1], and Alex Cannon[4]

[1]*Global Institute for Water Security, University of Saskatchewan, 11 Innovation Blvd, Saskatoon, SK, Canada S7N 3H5*

[2]*Centre for Hydrology, University of Saskatchewan, 121 Research Drive, Saskatoon, SK, Canada S7N 3C*

[3]*Environment and Climate Change Canada, 11 Innovation Blvd, Saskatoon, SK, Canada S7N 3H5*

[4]*Climate Research Division, Environment and Climate Change Canada, BC V8W 2Y2, Victoria, Canada*

***Corresponding author:**
Phone: +1 306 491 9565
Email: elvis.asong@usask.ca

Abstract:

Cold regions hydrology is very sensitive to the impacts of climate warming. Future warming is expected to increase the proportion of winter precipitation falling as rainfall. Snowpacks are expected to undergo less sublimation, form later and melt earlier and possibly more slowly, leading to earlier spring peak streamflow. More physically realistic and sophisticated hydrological models driven by reliable climate forcing can provide the capability to assess hydrologic responses to climate change. However, hydrological processes in cold regions involve complex phase changes and so are very sensitive to small biases in the driving meteorology, particularly in temperature and precipitation. Cold regions often have sparse surface observations, particularly at high elevations that generate a major amount of runoff. The effects of mountain topography and high latitudes are not well reflected in the observational record. The best available gridded data in Canada is from the high resolution forecasts of the Global Environmental Multiscale (GEM) atmospheric model and the Canadian Precipitation Analysis (CaPA) but this dataset has a short historical record. The EU WATCH ERA-Interim reanalysis (WFDEI) has a longer historical record, but has often been found to be biased relative to observations over Canada. The aim of this study, therefore, is to blend the strengths of both datasets (GEM-CaPA and WFDEI) to produce a less-biased long record product (WFDEI-GEM-CaPA). First, a multivariate generalization of the quantile mapping technique was implemented to bias-correct WFDEI against GEM-CaPA at 3h × 0.125° resolution during the 2005-2016 overlap period, followed by a hindcast of WFDEI-GEM-CaPA from 1979. The final product (WFDEI-GEM-CaPA, 1979-2016) is freely available at the Federated Research Data Repository (http://dx.doi.org/10.20383/101.0111).

Subject Keywords: cold regions processes, observations, bias correction, North America

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

1 Introduction

Accurate and reliable weather and climate information at watershed-to-basin scale is in increasingly high demand by policy-makers, scientists, and other stakeholders for various purposes such as water resources management (Barnett et al., 2005), infrastructure planning (Brody et al., 2007), and ecosystem modelling (IPCC, 2013). Particularly, the potential impacts of a warming climate on water availability in snow-dominated high latitude regions continue to be a serious concern given that over the past several decades, these regions have experienced some of the most rapid warming on earth (Demaria et al., 2016; Diffenbaugh et al., 2012; Islam et al., 2017; Martin and Etchevers, 2005; Stocker et al., 2013). The on-going science suggests that these warming trends are resulting in the intensification of the hydrologic cycle, leading to substantial recent observed changes in the hydro-climatic regimes of major river basins in North America (Coopersmith et al., 2014; DeBeer et al., 2016; Dumanski et al., 2015). Changes in the timing and magnitude of river discharge (Dibike et al., 2016), shifts in extreme temperature and precipitation regimes (Asong et al., 2016b; Vincent et al., 2015) and changes in snow, ice, and permafrost regimes are anticipated (IPCC, 2013). Substantial evidence also indicates that the long-held notion of stationarity of hydrological processes is becoming invalid in a changing climate. As pointed out by Milly et al. (2008), this loss of stationarity means that there will be an increase in the likelihood and frequency of extreme weather and climate events, including floods, droughts, and heat and cold waves.

Water resources in most land areas north of 30° N are heavily dependent on natural water storage provided by snowpacks and glaciers, with water accumulated in the solid phase during the cold season and released in the liquid phase during warm events and the warm season. Particularly, the Rocky Mountains, the hydrologic apex of North America with headwater streams flowing to the Arctic, Atlantic and Pacific oceans, constitute an integral part of the global hydrologic cycle (Fang et al., 2013). Flows in these high elevation headwaters depend heavily on meltwater from snowpacks and glaciers. However, given that it is characterized by a highly varying cold region hydro-climate, studies indicate that it is in

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

these high elevation regions where climate variability and change is expected to be most pronounced in terms of its impacts on water supply (Beniston, 2003; Kane et al., 1991; Prowse and Beltaos, 2002; Woo and Pomeroy, 2011). More physically realistic and sophisticated hydrological models driven by reliable climate forcing information can enhance our ability to assess short- and long-term regional hydrologic responses to increasing variability and uncertainty in hydro-climatic conditions in a changing climate. Nonetheless, hydrological processes in cold regions involve complex phase changes and so are very sensitive to small biases in the driving meteorology, particularly in temperature and precipitation.

Cold regions often have sparse surface observations, particularly at the high elevations that generate a major amount of runoff. The effects of mountain topography and high latitudes are currently not well reflected in the observational record. Ground-based measurements (e.g. gauges) are limited especially over the Rocky Mountains, and suffer from gross inaccuracies associated with cold climate processes (Asong et al., 2017; Wang and Lin, 2015; Wong et al., 2017). The advent and use of weather radar systems have addressed some of the short-comings of gauge coverage, at least where radar exists. Unfortunately, in Canada, for example, the spatial coverage of weather radar is limited to the southern (south of 55° N) part of the country (Fortin et al., 2015b). Recently, improved satellite products have emerged such as the Global Precipitation Measurement (GPM) mission that provides meteorological information at fine spatiotemporal resolutions and regular intervals. But, the GPM is still at its early stage and only covers the region south of 60° N (Asong et al., 2017; Hou et al., 2014).

The capability of the current generation of Earth System Models (ESMs) to represent meteorological variables is therefore of major interest for hydrological climate change impact studies in cold regions watersheds. Despite substantial progress being made, raw outputs from regional and global ESMs still differ largely from observational reference meteorology due partly to spatial scale mismatches and systematic biases (Taylor et al., 2012). Therefore, ESM outputs are often downscaled and biases are adjusted statistically before being used in hydrological simulations (Asong et al., 2016b; Chen et al., 2013;

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

Chen et al., 2018; Gudmundsson et al., 2012). Apart from uncertainty due to the many empirical statistical techniques which have been developed to post-process ESM outputs (Maraun, 2016), the quality and length of the reference observational data set for bias correction remains a major issue (Reiter et al., 2016; Schoetter et al., 2012; Sippel et al., 2016). In Canada and other regions of North America, regional gridded data sets such as the combined Global Environmental Multiscale (GEM) atmospheric model forecasts (Yeh et al., 2002) and the Canadian Precipitation Analysis—CaPA (Mahfouf et al., 2007) have been found to perform comparably to ground observations, both statistically and hydrologically (Alavi et al., 2016; Boluwade et al., 2018; Eum et al., 2014; Fortin et al., 2015a; Gbambie et al., 2017; Wong et al., 2017). However, GEM-CaPA is too short to be used to directly correct ESM climate due to unsynchronized internal variability—the recommended minimum record length for bias correction is 30 years (Maraun, 2016; Maraun et al., 2017). Other gridded products such as the EU WATCH ERA-Interim reanalysis—WFDEI (Weedon et al., 2014) and Princeton (Sheffield et al., 2006) have a longer historical record, but have been found to be biased relative to observations over Canada (Wong et al., 2017) and the United States (Behnke et al., 2016; Sapiano and Arkin, 2009). However, the WFDEI has been found to outperform other long-record gridded products (Chadburn et al., 2015; Park et al., 2016; Wong et al., 2017).

The aim of this study, therefore, is to combine the strengths of both datasets (GEM-CaPA and WFDEI) to produce a less-biased long record product (WFDEI-GEM-CaPA) using a multi-stage bias correction framework. First, a multivariate generalization of the quantile mapping technique was implemented to bias-correct WFDEI against GEM-CaPA at 3h × 0.125° resolution during the 2005-2016 period, followed by a hindcast of WFDEI-GEM-CaPA from 1979.

2 Methodology

2.1 Data sources

Hourly archived forecast data from the GEM model were acquired from Environment and Climate Change Canada (http://collaboration.cmc.ec.gc.ca/cmc/cmoi/product_guide/submenus/rdps_e.html,

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

last access: 28 September 2018). The fields include downward incoming solar radiation, downward incoming longwave radiation and pressure at the surface, as well as specific humidity, air temperature, and wind speed at approximately 40 m above ground surface. The 40 m level was used because surface variables (2 m temperature, 2 m specific humidity, and 10 m wind speed) are only available from 2010 in the archive. The GEM data are approximately 24 km resolution from October 2001, approximately 15 km from June 2004, and approximately 10 km resolution from November 2012, and are provided on a rotated latitude/longitude grid in Environment and Climate Change Canada—ECCC 'standard file' format. The archived data are of former operational forecasts, and contain model outputs from versions of GEM prior to 2.0.0 through 5.0.0. A field for total precipitation (6-hourly) was acquired from the complementary CaPA product (http://collaboration.cmc.ec.gc.ca/cmc/cmoi/product_guide/submenus/capa_e.html, last access: 28 September 2018), which incorporates observed precipitation from meteorological weather stations, and more recently from radar, into the precipitation field from GEM. The CaPA data are approximately 10 km resolution from January 2002, also on a rotated latitude/longitude grid in ECCC 'standard file' format. The data contain reanalysis outputs from CaPA 2.4b8 from 2002-2012, and of former operational analyses from versions of CaPA 2.3.0 through 4.0.0 from November 2012 onward. The fields from GEM and CaPA were spatially interpolated and re-projected to a regular latitude/longitude grid at 0.125° resolution. From GEM, they were interpolated using a bilinear algorithm, while CaPA was interpolated using nearest neighbor (Schulzweida et al., 2004). Where necessary, GEM fields were converted to SI units and CaPA was converted to a precipitation rate in SI units for better compatibility with certain simulation models.

We also used the gridded WFDEI meteorological forcing data which has a global 0.5° spatial resolution and 3-h time step covering the period 1979-2016 (http://www.eu-watch.org/data_availability, last access: 25 July 2018). Weedon et al. (2014) used the ERA-Interim surface meteorology data as baseline information to derive the WFDEI product. Firstly, ERA-Interim data were interpolated at half-degree

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

spatial resolution to match the land–sea mask defined by the Climatic Research Unit (CRU). Subsequently, corrections for elevation and monthly bias of climate trends in the ERA-Interim fields were applied to the interpolated data. The WFDEI data have two sets of precipitation data: the Global Precipitation Climatology Centre product (GPCC) and CRU Time Series version 3.1 (CRU TS3.1). Thus, two variants of the WFDEI product are available—WFDEI-GPCC and WFDEI-CRU. We used the WFDEI-CRU data set because it goes up to 2016 while the WFDEI-GPCC had only been updated until 2013 at the time of our analysis.

2.2 Data processing and bias correction workflow

The workflow for the multi-stage bias correction is shown in Fig.1. Bias correction was done after aggregating 1-h GEM-CaPA estimates to 3-h (the values at each time step represent the mean of the previous 3-h period, to make it consistent with WFDEI) and interpolating both WFDEI and GEM-CaPA to 0.125° resolution. For bias correction, a multi-stage approach was implemented as follows. A multivariate generalization of the quantile mapping technique (Cannon, 2018) which combines quantile delta mapping (Cannon et al., 2015) and random orthogonal rotations to match the multivariate distributions of two data sets was implemented to bias-correct WFDEI against GEM-CaPA at 3-h*0.125° resolution during the 2005-2016 period. Models were fitted to data for each calendar month while accounting for inter-variable dependence structure. Using the fitted models (2005-2016), a hindcast was made of WFDEI between 1979-2004. Finally, the corrected WFDEI data derived from the fitted (2005-2016) and hindcast (1979-2004) periods were concatenated to obtain the bias-corrected WFDEI-GEM-CaPA product (1979-2016).

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

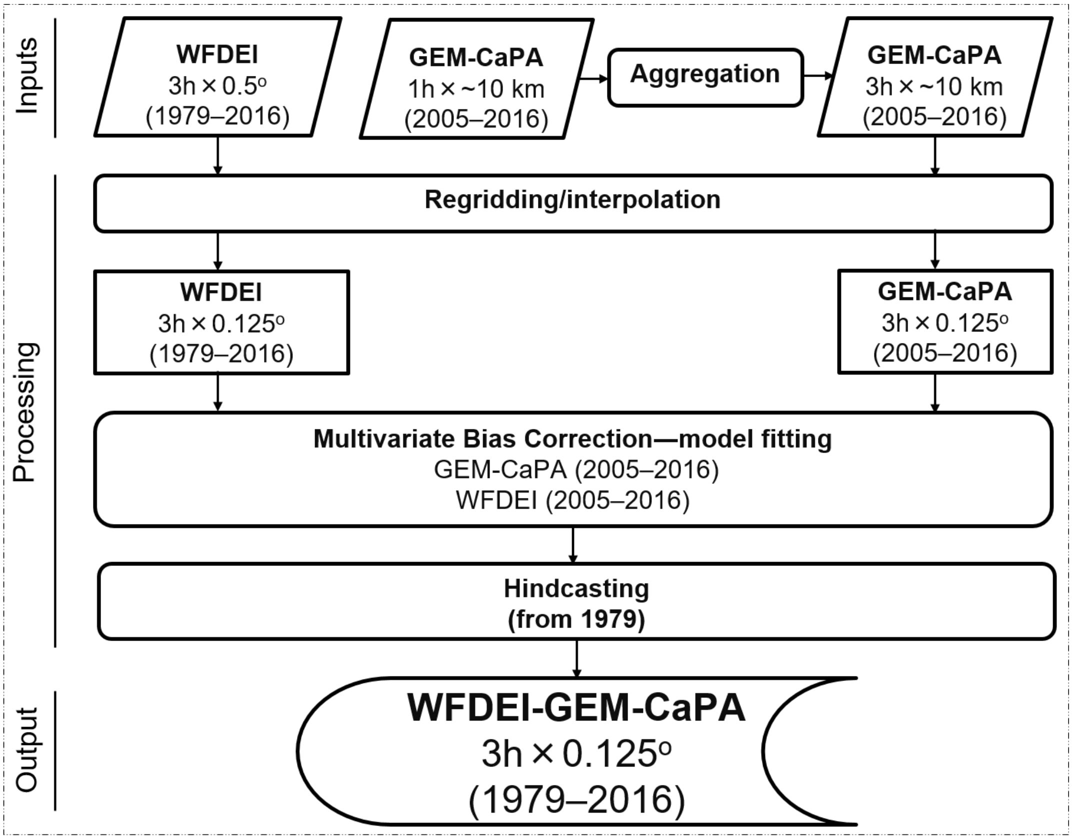

Figure 1. A schematic representation of inputs and bias correction procedure used to produce the WFDEI-GEM-CaPA meteorological forcing data set.

3 Results and discussion

Table 1 presents an overview of the seven variables processed in this study. Note that the GEM 40 m variables are used directly to correct WFDEI surface variables (2 m temperature, 2 m specific humidity, and 10 m wind speed). Therefore, the corrected WFDEI-GEM-CaPA data reflect 40 m variables. The spatial coverage of the WFDEI-GEM-CaPA data is depicted in Fig. 2. It spans the land region between longitude 50.0625° W to 149.9375° W and latitude 31.0625° N to 71.9375° N.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

Open Access Earth System Science Data Discussions

Table 1: List variables processed in this study with heights and units in each dataset.

	WFDEI		GEM-CaPA		WFDEI-GEM-CaPA	
Variable	**Height**	**Unit**	**Height**	**Unit**	**Height**	**Unit**
Precipitation	Surface	kg m^{-2} s^{-1}	surface	kg m^{-2} s^{-1}	surface	kg m^{-2} s^{-1}
Air Temperature	2 m	K	40 m	K	40 m	K
Specific Humidity	2 m	kg kg^{-1}	40 m	kg kg^{-1}	40 m	kg kg^{-1}
Wind Speed	10 m	m s^{-1}	40 m	m s^{-1}	40 m	m s^{-1}
Surface Pressure	Surface	Pa	Surface	Pa	Surface	Pa
Surface Downwelling Shortwave Radiation	Surface	W m^{-2}	Surface	W m^{-2}	Surface	W m^{-2}
Surface Downwelling Longwave Radiation	Surface	W m^{-2}	Surface	W m^{-2}	Surface	W m^{-2}

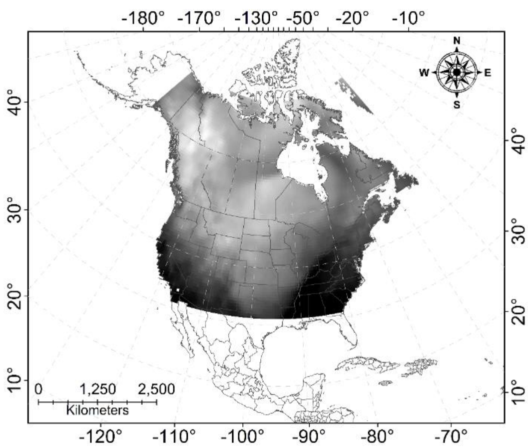

Figure 2: Spatial domain of the WFDEI-GEM-CaPA dataset spanning the region between longitude 50.0625° W to 149.9375° W and latitude 31.0625° N to 71.9375° N

The suitability of the bias correction algorithm to reproduce the observed annual cycle and inter-annual variability of the variables was assessed for the fitting (2005-2016) and hindcast (1979-2004) periods. Data extracted over the entire Mackenzie River basin is used to demonstrate the quality of the bias correction exercise and uniqueness of the resulting output. Fig. 3 shows the annual cycle for GEM-CaPA, WFDEI and WFDEI-GEM-CaPA during the fitting period. Overall, the monthly distributions show that the bias was removed for all variables resulting in the very close distributions between GEM-CaPA and WFDEI-GEM-CaPA. The bias was particularly large for wind speed, an important variable for both mountainous and prairie hydrological processes, but was successfully removed. Fig. 4 shows the mean annual time series of the seven variables over the 1979-2016 period. It is noticeable that the bias is corrected while the inter-annual variability is well preserved between WFDEI and WFDEI-GEM-CAPA, excerpt for shortwave radiation where the inter-annual variability is not fully preserved as shown by the correlation between the WFDEI and WFDEI-GEM-CaPA annual series. However, this should not be a major issue when impact models are forced with these data.

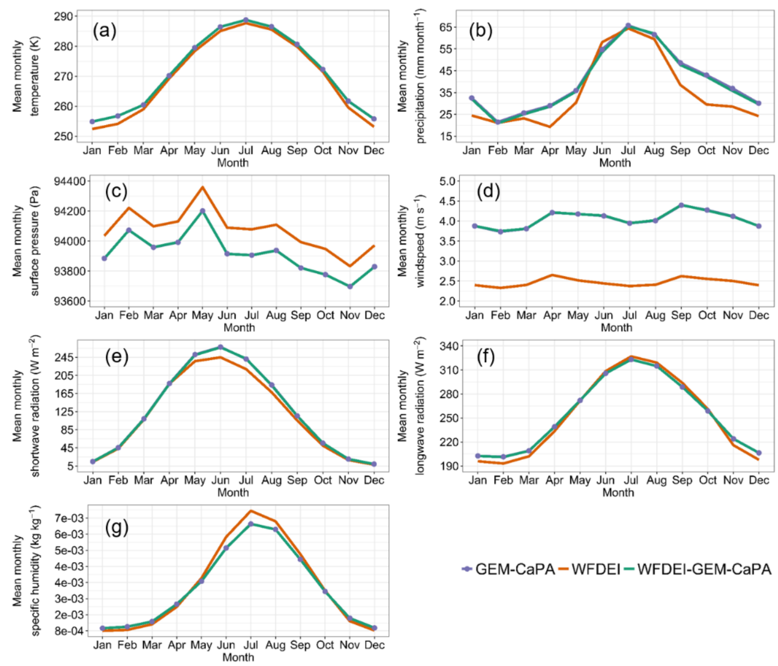

Figure 3: Annual cycle of GEM-CaPA (dark slate blue), WFDEI (orange) and bias corrected data—WFDEI-GEM-CaPA (green) for air temperature (a), precipitation (b), surface pressure (c), wind speed (d), shortwave radiation (e), longwave radiation (f), and specific humidity (g) during the fitting period (2005-2016).

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

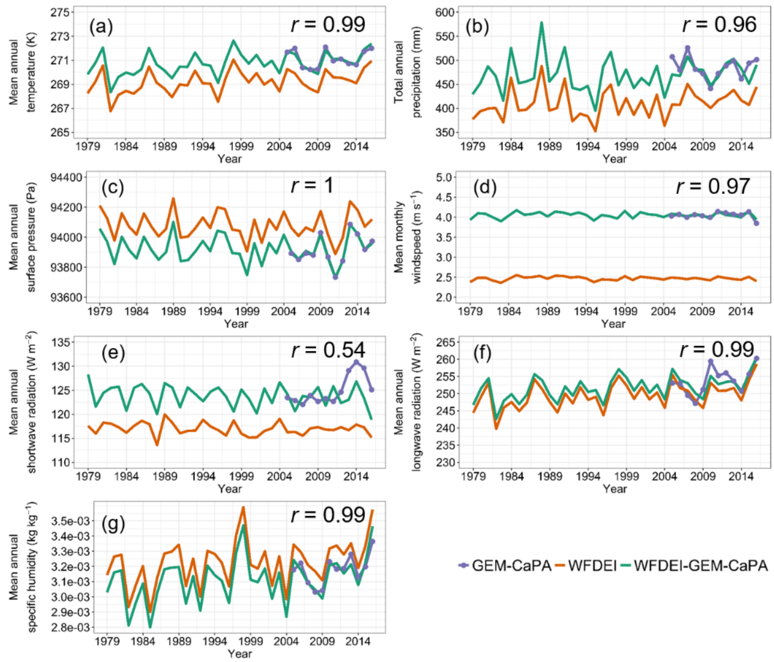

Figure 4: Time series of GEM-CaPA (dark slate blue), WFDEI (orange) and bias corrected data—WFDEI-GEM-CaPA (green) for air temperature (a), precipitation (b), surface pressure (c), wind speed (d), shortwave radiation (e), longwave radiation (f), and specific humidity (g) during the periods 2005-2016 (GEM-CaPA) and 1979-2016 (WFDEI and WFDEI-GEM-CaPA). The correlation (*r*) between the WFDEI and WFDEI-GEM-CaPA annual series is indicated for each variable.

The foregoing analyses have shown that the bias in the WFDEI data was removed for both the fitting and hindcast periods. However, some potential limitations remain—for example, WFDEI was interpolated directly from 0.5° to 0.125° and bias-corrected against GEM-CaPA at 0.125°. The interpolation does not add any event-scale spatial variability for a variable like precipitation which is very variable across different scales. These issues have been reviewed extensively by (Cannon, 2018; Maraun, 2013; Maraun et al., 2010; Storch, 1999).

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

4 Conclusions

Cold regions hydrology is very sensitive to the impacts of climate warming. More physically realistic hydrological models driven by reliable climate forcing can provide the capability to assess hydrologic responses to climate variability and change. However, cold regions often have sparse surface observations, particularly at high elevations that generate a significant amount of runoff. By making available this long-term dataset, we hope it can be used to better understand and represent the seasonal/inter-annual variability of hydrological fluxes and the timing of runoff, and their long-term trends. This unique data set will also prove valuable for bias correction of climate model projections to assess potential impacts of future climate change on the hydrology and water resources of North America.

5 Data availability

The latest dataset is available at the Federated Research Data Repository (http://dx.doi.org/10.20383/101.0111).

Author contribution

Z.E., H.W., J.P., A.P., and M.E. conceived of and designed the experiment. D.P. preprocessed the GEM-CaPA data, A.C. developed the bias correction model code and guided the computing procedures while Z.E. performed the simulations. M.E extracted the sample data used in generating Fig.3 and 4. Z.E. prepared the manuscript with contributions from all co-authors.

7 Competing interests

The authors declare that they have no conflict of interest.

8 Acknowledgements

The financial support from the Canada Excellence Research Chair in Water Security, and Changing Cold Regions Network is gratefully acknowledged. Thanks are due to the Meteorological Service of Canada for providing access to the GEM-CaPA data used in this study. We also thank Dr. Graham Weedon for

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

Open Access Earth System Science Data Discussions

making available the WFDEI data set. We also appreciate the efforts of Amber Peterson, Data Manager, Global Institute for Water Security toward archiving the data at the Federated Research Data Repository.

9 References

Alavi, N., Bélair, S., Fortin, V., Zhang, S., Husain, S. Z., Carrera, M. L., and Abrahamowicz, M.: Warm Season Evaluation of Soil Moisture Prediction in the Soil, Vegetation, and Snow (SVS) Scheme, Journal of Hydrometeorology, 17, 2315-2332, 2016.

Asong, Z. E., Khaliq, M. N., and Wheater, H. S.: Projected changes in precipitation and temperature over the Canadian Prairie Provinces using the Generalized Linear Model statistical downscaling approach, Journal of Hydrology, 539, 429-446, 2016b.

Asong, Z. E., Razavi, S., Wheater, H. S., and Wong, J. S.: Evaluation of Integrated Multi-satellitE Retrievals for GPM (IMERG) over Southern Canada against Ground Precipitation Observations: A Preliminary Assessment, Journal of Hydrometeorology, 0, null, 2017.

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438, 303, 2005.

Behnke, R., Vavrus, S., Allstadt, A., Albright, T., Thogmartin, W. E., and Radeloff, V. C.: Evaluation of downscaled, gridded climate data for the conterminous United States, Ecological Applications, 26, 1338-1351, 2016.

Beniston, M.: Climatic change in mountain regions: a review of possible impacts. In: Climate variability and change in high elevation regions: Past, present & future, Springer, 2003.

Boluwade, A., Zhao, K. Y., Stadnyk, T. A., and Rasmussen, P.: Towards validation of the Canadian precipitation analysis (CaPA) for hydrologic modeling applications in the Canadian Prairies, Journal of Hydrology, 556, 1244-1255, 2018.

Brody, S. D., Zahran, S., Maghelal, P., Grover, H., and Highfield, W. E.: The Rising Costs of Floods: Examining the Impact of Planning and Development Decisions on Property Damage in Florida, Journal of the American Planning Association, 73, 330-345, 2007.

Cannon, A. J.: Multivariate quantile mapping bias correction: an N-dimensional probability density function transform for climate model simulations of multiple variables, Climate Dynamics, 50, 31-49, 2018.

Cannon, A. J., Sobie, S. R., and Murdock, T. Q.: Bias Correction of GCM Precipitation by Quantile Mapping: How Well Do Methods Preserve Changes in Quantiles and Extremes?, Journal of Climate, 28, 6938-6959, 2015.

Chadburn, S. E., Burke, E. J., Essery, R. L. H., Boike, J., Langer, M., Heikenfeld, M., Cox, P. M., and Friedlingstein, P.: Impact of model developments on present and future simulations of permafrost in a global land-surface model, The Cryosphere, 9, 1505-1521, 2015.

Chen, J., Brissette, F. P., Chaumont, D., and Braun, M.: Finding appropriate bias correction methods in downscaling precipitation for hydrologic impact studies over North America, Water Resources Research, 49, 4187-4205, 2013.

Chen, J., Li, C., Brissette, F. P., Chen, H., Wang, M., and Essou, G. R. C.: Impacts of correcting the inter-variable correlation of climate model outputs on hydrological modeling, Journal of Hydrology, 560, 326-341, 2018.

Coopersmith, E. J., Minsker, B. S., and Sivapalan, M.: Patterns of regional hydroclimatic shifts: An analysis of changing hydrologic regimes, Water Resources Research, 50, 1960-1983, 2014.

DeBeer, C. M., Wheater, H. S., Carey, S. K., and Chun, K. P.: Recent climatic, cryospheric, and hydrological changes over the interior of western Canada: a review and synthesis, Hydrol. Earth Syst. Sci., 20, 1573-1598, 2016.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

Demaria, E. M. C., Roundy, J. K., Wi, S., and Palmer, R. N.: The Effects of Climate Change on Seasonal Snowpack and the Hydrology of the Northeastern and Upper Midwest United States, Journal of Climate, 29, 6527-6541, 2016.

Dibike, Y., Prowse, T., Bonsal, B., and O'Neil, H.: Implications of future climate on water availability in the western Canadian river basins, International Journal of Climatology, doi: 10.1002/joc.4912, 2016. n/a-n/a, 2016.

Diffenbaugh, N. S., Scherer, M., and Ashfaq, M.: Response of snow-dependent hydrologic extremes to continued global warming, Nature Climate Change, 3, 379, 2012.

Dumanski, S., Pomeroy, J. W., and Westbrook, C. J.: Hydrological regime changes in a Canadian Prairie basin, Hydrological Processes, 29, 3893-3904, 2015.

Eum, H.-I., Dibike, Y., Prowse, T., and Bonsal, B.: Inter-comparison of high-resolution gridded climate data sets and their implication on hydrological model simulation over the Athabasca Watershed, Canada, Hydrological Processes, 28, 4250-4271, 2014.

Fang, X., Pomeroy, J. W., Ellis, C. R., MacDonald, M. K., DeBeer, C. M., and Brown, T.: Multi-variable evaluation of hydrological model predictions for a headwater basin in the Canadian Rocky Mountains, Hydrol. Earth Syst. Sci., 17, 1635-1659, 2013.

Fortin, V., Jean, M., Brown, R., and Payette, S.: Predicting snow depth in a forest–tundra landscape using a conceptual model allowing for snow redistribution and constrained by observations from a digital camera, Atmosphere-Ocean, 53, 200-211, 2015a.

Fortin, V., Roy, G., Donaldson, N., and Mahidjiba, A.: Assimilation of radar quantitative precipitation estimations in the Canadian Precipitation Analysis (CaPA), Journal of Hydrology, 531, Part 2, 296-307, 2015b.

Gbambie, A. S. B., Poulin, A., Boucher, M.-A., and Arsenault, R.: Added Value of Alternative Information in Interpolated Precipitation Datasets for Hydrology, Journal of Hydrometeorology, 18, 247-264, 2017.

Gudmundsson, L., Bremnes, J. B., Haugen, J. E., and Engen-Skaugen, T.: Technical Note: Downscaling RCM precipitation to the station scale using statistical transformations – a comparison of methods, Hydrol. Earth Syst. Sci., 16, 3383-3390, 2012.

Hou, A. Y., Kakar, R. A., Neeck, S., Azarbarzin, A. A., Kummerow, C. D., Kojima, M., Oki, R., Nakamura, K., and Iguchi, T.: The Global Precipitation Measurement Mission, Bulletin of the American Meteorological Society, 95, 701-722, 2014.

IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Islam, S. u., Déry, S. J., and Werner, A. T.: Future Climate Change Impacts on Snow and Water Resources of the Fraser River Basin, British Columbia, Journal of Hydrometeorology, 18, 473-496, 2017.

Kane, D. L., Hinzman, L. D., Woo, M.-k., and Everett, K. R.: Arctic hydrology and climate change. In: Arctic ecosystems in a changing climate, Elsevier, 1991.

Mahfouf, J. F., Brasnett, B., and Gagnon, S.: A Canadian precipitation analysis (CaPA) project: Description and preliminary results, Atmosphere-Ocean, 45, 1-17, 2007.

Maraun, D.: Bias Correcting Climate Change Simulations - a Critical Review, Current Climate Change Reports, 2, 211-220, 2016.

Maraun, D.: Bias Correction, Quantile Mapping, and Downscaling: Revisiting the Inflation Issue, Journal of Climate, 26, 2137-2143, 2013.

Maraun, D., Shepherd, T. G., Widmann, M., Zappa, G., Walton, D., Gutiérrez, J. M., Hagemann, S., Richter, I., Soares, P. M. M., Hall, A., and Mearns, L. O.: Towards process-informed bias correction of climate change simulations, Nature Climate Change, 7, 764, 2017.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

Maraun, D., Wetterhall, F., Ireson, A. M., Chandler, R. E., Kendon, E. J., Widmann, M., Brienen, S., Rust, H. W., Sauter, T., Themeßl, M., Venema, V. K. C., Chun, K. P., Goodess, C. M., Jones, R. G., Onof, C., Vrac, M., and Thiele-Eich, I.: Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user, Reviews of Geophysics, 48, 2010.

Martin, E. and Etchevers, P.: Impact of Climatic Changes on Snow Cover and Snow Hydrology in the French Alps. In: Global Change and Mountain Regions: An Overview of Current Knowledge, Huber, U. M., Bugmann, H. K. M., and Reasoner, M. A. (Eds.), Springer Netherlands, Dordrecht, 2005.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., and Stouffer, R. J.: Stationarity Is Dead: Whither Water Management?, Science, 319, 573-574, 2008.

Park, H., Yoshikawa, Y., Oshima, K., Kim, Y., Ngo-Duc, T., Kimball, J. S., and Yang, D.: Quantification of Warming Climate-Induced Changes in Terrestrial Arctic River Ice Thickness and Phenology, Journal of Climate, 29, 1733-1754, 2016.

Prowse, T. D. and Beltaos, S.: Climatic control of river-ice hydrology: a review, Hydrological processes, 16, 805-822, 2002.

Reiter, P., Gutjahr, O., Schefczyk, L., Heinemann, G., and Casper, M.: Bias correction of ENSEMBLES precipitation data with focus on the effect of the length of the calibration period, Meteorologische Zeitschrift, 25, 85-96, 2016.

Sapiano, M. R. P. and Arkin, P. A.: An Intercomparison and Validation of High-Resolution Satellite Precipitation Estimates with 3-Hourly Gauge Data, Journal of Hydrometeorology, 10, 149-166, 2009.

Schoetter, R., Hoffmann, P., Rechid, D., and Schlünzen, K. H.: Evaluation and Bias Correction of Regional Climate Model Results Using Model Evaluation Measures, Journal of Applied Meteorology and Climatology, 51, 1670-1684, 2012.

Schulzweida, U., Kornblueh, L., and Quast, R.: Climate data operators, Max-Planck-Institute for Meteorology, Hamburg and http://www. mpimet. mpg. de/~ cdo, 2004. 2004.

Sheffield, J., Goteti, G., and Wood, E. F.: Development of a 50-Year High-Resolution Global Dataset of Meteorological Forcings for Land Surface Modeling, Journal of Climate, 19, 3088-3111, 2006.

Sippel, S., Otto, F. E. L., Forkel, M., Allen, M. R., Guillod, B. P., Heimann, M., Reichstein, M., Seneviratne, S. I., Thonicke, K., and Mahecha, M. D.: A novel bias correction methodology for climate impact simulations, Earth Syst. Dynam., 7, 71-88, 2016.

Stocker, T. F., Qin, D., Plattner, G.-K., Alexander, L. V., Allen, S. K., Bindoff, N. L., Bréon, F.-M., Church, J. A., Cubasch, U., Emori, S., Forster, P., Friedlingstein, P., Gillett, N., Gregory, J. M., Hartmann, D. L., Jansen, E., Kirtman, B., Knutti, R., Krishna Kumar, K., Lemke, P., Marotzke, J., Masson-Delmotte, V., Meehl, G. A., Mokhov, I. I., Piao, S., Ramaswamy, V., Randall, D., Rhein, M., Rojas, M., Sabine, C., Shindell, D., Talley, L. D., Vaughan, D. G., and Xie, S.-P.: Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (Eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Storch, H. v.: On the Use of “Inflation” in Statistical Downscaling, Journal of Climate, 12, 3505-3506, 1999.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the Experiment Design, Bulletin of the American Meteorological Society, 93, 485-498, 2012.

Vincent, L. A., Zhang, X., Brown, R. D., Feng, Y., Mekis, E., Milewska, E. J., Wan, H., and Wang, X. L.: Observed Trends in Canada’s Climate and Influence of Low-Frequency Variability Modes, Journal of Climate, 28, 4545-4560, 2015.

Wang, X. L. and Lin, A.: An algorithm for integrating satellite precipitation estimates with in situ precipitation data on a pentad time scale, Journal of Geophysical Research: Atmospheres, 120, 3728-3744, 2015.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-128
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 24 October 2018

Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J., and Viterbo, P.: The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data, Water Resources Research, 50, 7505-7514, 2014.

Wong, J. S., Razavi, S., Bonsal, B. R., Wheater, H. S., and Asong, Z. E.: Inter-comparison of daily precipitation products for large-scale hydro-climatic applications over Canada, Hydrol. Earth Syst. Sci., 21, 2163-2185, 2017.

Woo, M.-K. and Pomeroy, J.: Snow and Runoff: Processes, Sensitivity and Vulnerability. In: Changing Cold Environments, John Wiley & Sons, Ltd, 2011.

Yeh, K.-S., Côté, J., Gravel, S., Méthot, A., Patoine, A., Roch, M., and Staniforth, A.: The CMC–MRB Global Environmental Multiscale (GEM) Model. Part III: Nonhydrostatic Formulation, Monthly Weather Review, 130, 339-356, 2002.